Chapter

Evaluation of Energy Efficiency of Buildings Based on LCA and LCC Assessment: Method, Computer Tool, and Case Studies

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Abstract

In this chapter, the development of a computer tool for the determination of nearly zero energy buildings (nZEB) metrics upgraded with life cycle assessment (LCA) and life cycle cost (LCC) indicators is presented, following the requirements of the Energy Performance of Buildings Directive (EPBD). The computer tool was developed for the assessment of new and renovated buildings to support the holistic decision-making process. The tool itself consists of two modules: the building description module (BDU), based on the national certification tool of buildings' energy performance, and the LCA tool (E^{tool}). BDU enables the assessment of energy needs, final energy demand, and primary energy needs. According to the EPBD, supporting standards was upgraded with the life cycle inventory database. The database includes data on predefined building materials, envelope components, heat generators, and energy carriers and is used by E^{tool} with which mid-point and end-point life cycle impact assessment can be done by taking into account impact groups and damage factors from IMPACT2002+ and ReCiPe methods. The LCC assessment module, which is also part of E^{tool}, was developed according to Commission Delegated Regulation No. 244/212. The use of computer tools is demonstrated through the case studies.

Keywords: energy performance of buildings directive, nearly zero energy buildings, lifecycle energy demand assessment, life cycle assessment, lifecycle cost assessment, computer tool

1. Introduction

The nearly zero-energy buildings (nZEB) requirements were introduced by the Energy Performance of Building Directive (recast) (EPBD recast) [1]. The EPBD supporting standards include the metrics and calculation procedures. The calculation starts with the determination of energy needs, followed by the determination of the required amounts of energy carriers produced on-site, nearby, or by distant systems.

The energy carriers should consist of a large share of renewable energies, which leads to lower primary energy needs. The directive explicitly requires that on the national level energy efficiency criteria must be set in a way to be cost-effective. Although the life cycle assessment (LCA) is voluntary, such approach can be very helpful in the decision-making process of building design. This challenging task should be performed in the early stage of the planning, requiring the relevant multidisciplinary knowledge [2]. A simplified computational tool can significantly help the implementation of EPBD in the planning process. Such a computer tool that enables building energy efficiency, the environmental impact of selected measures, and life cycle cost (LCC) assessment of new and renovated buildings was developed and is presented in this chapter.

2. Computer tool structure

Computer tool consists of life cycle energy efficiency (LCEA), environment impact (LCIA), and life cycle cost assessment (LCCA) routine, divided into two calculation modules, building description unit (BDU) and LCA tool (E^{tool}).

The BDU module enables the determination of:

- energy needs and final energy demand for operation of the building per energy carriers;
- environmental indicators in form of equivalents of pollutants of materials, building structures, building service systems, and energy carriers; and
- cost of materials, building structures and building service, and energy carriers.

The BDU is developed in a way that allows parallel analyses of two projects (for reference and designed buildings), allowing designers prompt and more convenient way for evaluation of proposed measures for increasing the energy efficiency of the designed building. For the same reason, designers could indicate separately which material, building structure, or building system will be included in the LCA. Such elements, marked as "LCA elements" are taken from the pre-designed database, but relevant data could be entered to form user-defined data.

After completing work in the BDU, data are automatically transferred into the second calculation module, the LCA evaluation module (E^{tool}) in which end-LCA results are determined and displayed taking into account additional user-selected LCA data, for example, lifetime and discount rate and compared for reference and current designed building. The main reason that the evaluation tool is divided into two modules is to use an existing highly distributed tool used for obligatory EPBD evaluation and certification of the buildings with more than 5000 users in Slovenia. A tool, called KI Energija [3] was co-developed by the authors of the presented chapter. Besides that, the tool was developed for use in high-school and master education courses through wizard-designed building service systems. The second module, E^{tool} was developed in an MS Excel environment because of built-in statistical functions and the ability to display results. The structure of the LCA computer tool is presented in **Figure 1**. The monthly method is used for the determination of energy needs for heating and cooling (ISO EN 52016-1 Energy performance of buildings – Energy needs for heating and cooling, internal temperatures, and sensible and latent heat loads – Part 1: Calculation

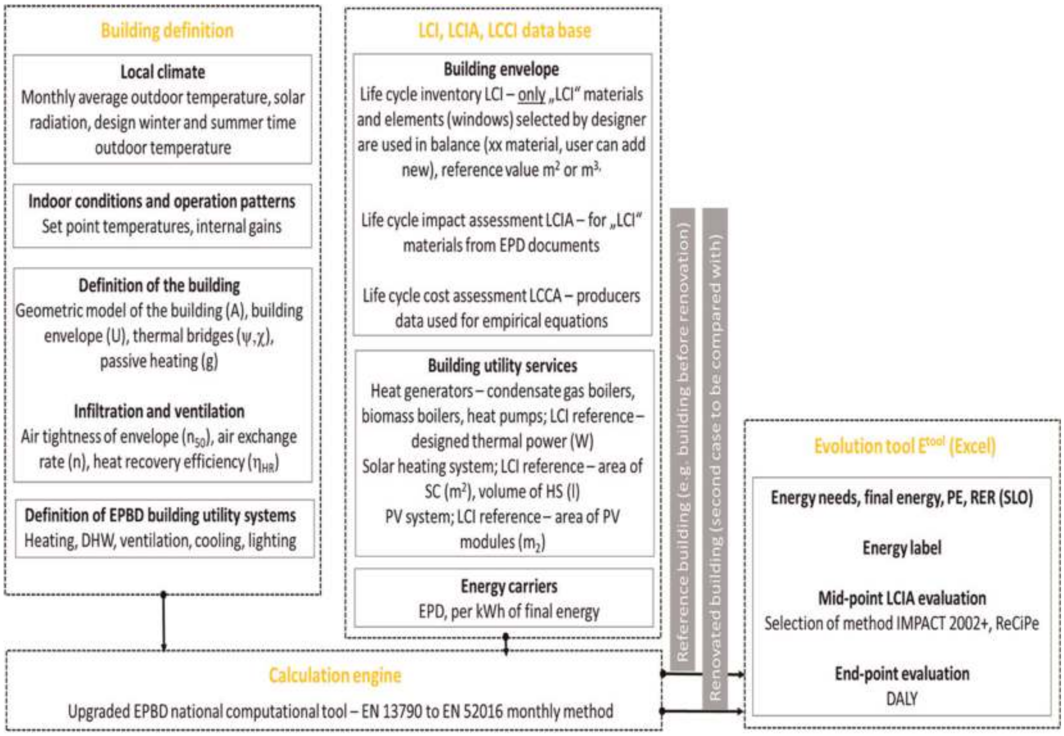

Figure 1.
Structure and interactions between BDU (upgraded EPBD national certification tool KI Energija) and E^{tool} (life cycle assessment tool).

procedure) and other EPBD supporting standards were used for final energy determination. Yearly methods for determining non-energy-related variables (e.g. emissions of pollutant equivalents) are used in the evaluation procedure.

2.1 National buildings' energy performance certification tool

The energy efficiency of the reference and designed building are determined by the following indicators:

- Energy needs for heating Q_{NH} and cooling Q_{NC}; monthly method according to EN ISO 52016-1 [4] (replacing EN ISO 13790 [5]) assuming constant set-point temperature for heating and cooling;

- Amount of each energy carrier as final energy demand for operation of installed building service for heating, cooling, domestic hot water (DHW) heating, ventilation, and lighting is determined per month and year. Several configurations of building service systems were pre-designed in the computer tool. An example of combined space heating and domestic water heating system is shown in **Figure 2**. In this way, the energy balance can be easier overviewed for each element of the system, and heat losses can be minimized most efficiently.

- Using primary energy factors and CO_2 emission factors, yearly primary energy needed for the operation of the buildings and CO_2 emissions are determined according to energy carrier demand. Because the tool is based on the current Slovenian national regulative, primary factors are not split into non- and

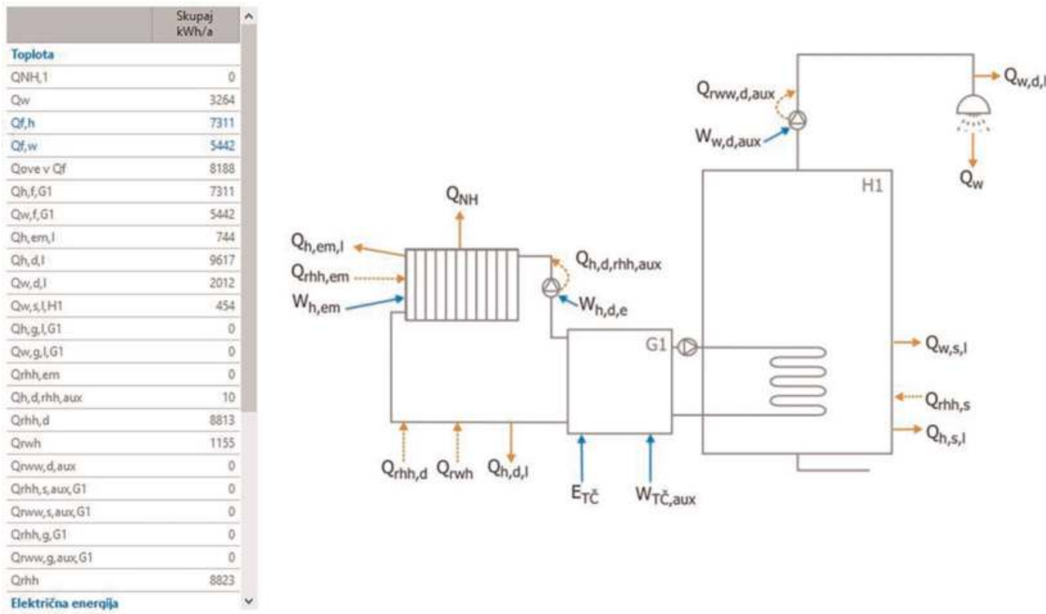

Figure 2.
An example of user's interface in national certification tool KI Energija with the presentation of energy balance for each element of heating and DHW heating system.

renewable energy ones, therefore, non-renewable primary factors for fuels and total primary energy factors for electricity are taken into account. This means that primary energy delivered by renewable energy sources (solar, environment heat) will be equal to zero.

3. Building description unit

The national EPBD certification computer tool was upgraded into the BDU by creating additional database files called "LCA" that includes information on the most recognized environmental impact indicators and cost. If the designer installs the "LCA" marked material into the building structure or the "LCA" marked component of the building service system, this will not only affect energy demand evaluation, but additional inventory data for LCIA and LCCA will be created. Because LCA indicators are developed per functional unit, the total value of each indicator (environmental impact or cost) is determined according to the building plan and stored in BDU. At the current stage of software development, inventory data are available for most commonly used construction materials, windows and doors as building structures, and heat generators as well as photovoltaic (PV) modules. Nevertheless, the inventory LCA database is open source and could be enlarged by the new elements with user-provided data (**Figure 3**).

3.1 Life cycle environmental impact assessment algorithm

The environmental impact indicators were chosen from Environment Product Declaration (EPD) certificates. Following damage categories are included: emissions of greenhouse gases causing global climate change weighted by Greenhouse Warming Potential (GWP) and expressed as CO_2 equivalent, emissions of gases that cause depletion of stratospheric ozone weighted by Ozone Depletion Potential (ODP) and

Figure 3.
If the designer wants to include certain materials (left), building structure, components of heat or electricity generation system (right), or particular energy carrier into the LCA assessment, it should be selected from the predefined "LCA" inventory database.

expressed as CFC-11 equivalent, emissions of gases that cause acidification of precipitation weighted by Acidification Potential (AP) expressed in SO_2 equivalent, eutrophication by weighted emissions by Eutrophication Potential EP as PO_4^{3-} equivalent, tropospheric ozone creation by Tropospheric Ozone Forming Potential (TOFP) as C_2H_4 equivalent, use of abiotic sources as Abiotic Depletion Potential – Elements (ADPE) as Sb equivalent and as Abiotic Depletion Potential – Fossil (ADPF) in MJ. Data from Ökobaudat [6], Environdec EPD Database [7], Eco-Platform [8], IBU [9], and manufactures data (i.e. Knauf Insulation [10]) were used in database integrated in BDU.

3.1.1 Life cycle environmental impact data of materials and building structures

Indicators presented in Chapter 3.1 are defined per reference unit. This is 1 m^3 of built-in material, except for thin layers, such as water vapor or wind barriers for which the reference unit is 1 m^2. BDU was adapted to calculate the total amount of built-in LCA materials and the total value of a particular environmental impact indicator. LCIA data of windows and doors are entered by default as such building structures are most commonly replaced as part of the energy renovation. To enable LCIA regardless of the size and type of the windows, regression models of each environmental impact indicator were developed taking into account the window glazing, spacer, and frame material. Factors are integrated into the BDU in the following form (as an example of greenhouse gas emissions):

$$GWP_w = A_w \cdot f_g \cdot GWP_g + \frac{A_w \cdot (1 - f_g)}{d_{frame}} \left(GWP_{frame} + GWP_{spac}\right) \left(\text{kg } CO_{2eq}\right) \quad (1)$$

where GWP_w is the impact factor of global climate change related to the window with area A_w (m^2), f_g is the ratio of glazing in the total window area, d_{frame} is the width of the frame (by default 0.1 m for wood and 0.15 m for plastic and metal frame), and GWP_g, GWP_{frame}, GWP_{spac} are specific impact factors per unit of glazing, frame, and spacer respectively. Default environment impact factors for windows and reference units are presented in **Table 1**.

	Unit	GWP	ODP	AP	EP	POCP	ADPE	ADPF
		kg eq CO_2	**kg eq CFC11**	**kg eq SO_2**	**kg eq $(PO_4)^{3-}$**	**kg eq C_2H_4**	**kg Sb**	**MJ**
Frame – wood	m	2.45	0.000000712	0.0176	0.00269	0.00874	0.0000360	74.33
Frame – Al	m	12.95	0.000005085	0.0554	0.00382	0.00339	0.0000994	146.90
Frame – PVC	m	8.07	0.000000986	0.0243	0.00267	0.00415	0.0001957	135.00
Window wing frame – wood	m	1.32	0.000000766	0.0195	0.00290	0.00925	0.0000403	80.94
Window wing frame – Al	m	12.44	0.000004885	0.0532	0.00367	0.00326	0.0000955	141.10
Window wing frame – PVC	m	9.09	0.000001202	0.0269	0.00302	0.00469	0.0002060	156.60
Glazing – double (0.75 W/m^2K)	m^2	37.52	0.000000534	0.1578	0.03022	0.01306	0.0002126	435.00
Glazing – triple (0.6 W/m^2K)	m^2	58.64	0.000000911	0.2446	0.04674	0.02026	0.0003254	695.60

Table 1.
Environment impact factors and reference units of window elements; data are average value gathered from oekodatbaudat.de and include A1–A3 LCA modules.

3.1.2 Life cycle environmental impact data of selected heat and electricity generators

Replacement of old heat generators and installing the solar thermal system or photovoltaic system are very common measures to increase energy efficiency and share renewable energy sources in buildings. LCIA data gathered from EPD databases [6–9] are integrated into BDU for the following on-site energy generators of buildings service systems: condensate gas boilers, biomass boilers, heat pumps, and solar thermal systems. Heat storage can also be included in LCIA and LCCA. For each LCIA indicator, the same form of regression model was developed and regression coefficients a_0, a_1, and a_2 were determined from the available database or research sources including A1–A3 LCA module. Coefficients were determined for boilers with design thermal power (as reference unit) between 20 and 400 kW, for heat pumps with design thermal power between 10 and 70 kW, and storage with the volume between 50 and 2500 liters. LCIA regression model was developed for PV modules with different PV cell technologies as well. In this case reference unit is the area of PV modules. Impact factors are integrated into the BDU in the following form (as an example of stratospheric ozone depletion potential):

$$\begin{aligned} ODP_{gen} &= a_{0,gen} + a_{1,gen} \cdot P_{gen} + a_{2,gen} \cdot P_{gen}^2 \ \left(\text{kg CFC } 11_{eq}\right) \\ ODP_{sol} &= 1.25 \cdot a_{1,sol} \cdot A_{sc} \ \left(\text{kg CFC } 11_{eq}\right) \\ ODP_{hs} &= a_{0,hs} + a_{1,hs} \cdot V_{hs} + a_{2,hs} \cdot V_{hs}^2 \ \left(\text{kg CFC } 11_{eq}\right) \\ ODP_{pv} &= a_{1,pv} \cdot A_{pv} \ \left(\text{kg CFC } 11_{eq}\right) \end{aligned} \quad (2)$$

where $a_{0,x}$, $a_{1,x}$, and $a_{2,x}$ are regression coefficients for a particular building service system, P_{gen} (kW) is designed thermal power of heat generator, A_{sc} is the area of solar collectors (m^2), V_{hs} is the volume of heat storage (l), and A_{pv} is the area of PV modules (m^2). Default values of regression coefficients are shown in **Table 2**.

Heat generator – fuel oil					**Heat pump – water–water**				
kW		$a_{2,gen}$	$a_{1,gen}$	$a_{0,gen}$	**kW**		$a_{2,hp}$	$a_{1,hp}$	$a_{0,hp}$
GWP	kg eq CO_2	0.028	1.272	1566.316	GWP	kg eq CO_2	−0.911	258.13	−1088.2
ODP	kg eq CFC11	2.74E-13	1.24E-11	6.42E-08	ODP	kg eq CFC11	1.24E-07	−2.43E-06	2.11E-04
AP	kg eq SO_2	1.03E-04	4.67E-03	7.161	AP	kg eq SO_2	−0.002	0.676	−2.664
EP	kg eq $(PO_4)^{3-}$	9.27E-06	4.18E-04	0.601	EP	kg eq $(PO_4)^{3-}$	−2.72E-04	0.073	−0.305
POCP	kg eq C_2H_4	1.45E-05	6.64E-04	0.768	POCP	kg eq C_2H_4	−6.91E-04	0.175	−0.787
ADPE	kg Sb	2.33E-09	7.37E-08	0.054	ADPE	kg Sb	2.22E-05	−7.98E-05	5.81E-02
ADPF	MJ	0.319	14.443	18,151	ADPF	MJ	−18.73	5734.9	−25,366
Heat generator – kondens.					**Heat pump – ground heat exchanger**				
kW		$a_{2,gen}$	$a_{1,gen}$	$a_{0,gen}$	**kW**		$a_{2,hp}$	$a_{1,hp}$	$a_{0,hp}$
GWP	kg eq CO_2	0.0035	10.166	618.4	GWP	kg eq CO_2	0.093	550.585	116.167
ODP	kg eq CFC11	−1.00E-13	6.00E-10	6.00E-08	ODP	kg eq CFC11	2.46E-07	−7.36E-06	3.44E-04
AP	kg eq SO_2	5.00E-06	4.86E-02	3.6074	AP	kg eq SO_2	3.33E-04	1.164	0.729
EP	kg eq $(PO_4)^{3-}$	6.00E-07	4.00E-03	0.2837	EP	kg eq $(PO_4)^{3-}$	2.79E-05	1.20E-01	5.61E-02
POCP	kg eq C_2H_4	1.00E-06	4.10E-03	0.2605	POCP	kg eq C_2H_4	2.77E-05	2.69E-01	4.22E-02
ADPE	kg Sb	9.00E-07	1.60E-03	0.0835	ADPE	kg Sb	5.43E-05	−1.47E-03	9.82E-02
ADPF	MJ	4.33E-02	1.25E+02	7548.7	ADPF	MJ	1.006	19056.81	−2688.4
Heat generator – fuel oil					**Heat pump – water–water**				
kW		$a_{2,gen}$	$a_{1,gen}$	$a_{0,gen}$	**kW**		$a_{2,hp}$	$a_{1,hp}$	$a_{0,hp}$
GWP	kg eq CO_2	0.0008	17.158	626.8	GWP	kg eq CO_2	1.10E-01	39.655	213.8
ODP	kg eq CFC11	4.00E−14	9.00E-10	6.00E-08	ODP	kg eq CFC11	2.45E-07	7.35E-06	3.44E-04
AP	kg eq SO_2	4.00E-06	7.61E-02	3.8412	AP	kg eq SO_2	3.81E-04	7.97E-02	1.043
EP	kg eq $(PO_4)^{3-}$	3.00E-07	6.40E-03	2.991	EP	kg eq $(PO_4)^{3-}$	3.27E-05	8.31E-03	8.56E-02
POCP	kg eq C_2H_4	3.00E-07	7.00E-03	0.2658	POCP	kg eq C_2H_4	3.35E-05	1.94E-02	8.17E-02

Heat generator – fuel oil						**Heat pump – water–water**				
kW		$a_{2,gen}$	$a_{1,gen}$	$a_{0,gen}$		**kW**		$a_{2,hp}$	$a_{1,hp}$	$a_{0,hp}$
ADPE	kg Sb	9.00E-08	2.90E-03	0.0791		ADPE	kg Sb	6.45E-05	-1.92E-03	1.22E-01
ADPF	MJ	1.09E-02	2.11E+02	7649.3		ADPF	MJ	1.374	1441.48	−1466.2
Heat storage						**Heat pump – air-water**				
l		$a_{2,hs}$	$a_{1,hs}$	$a_{0,hs}$		**kW**		$a_{2,hp}$	$a_{1,hp}$	$a_{0,hp}$
GWP	kg eq CO_2	−1.00E-04	0.769	66.197		GWP	kg eq CO_2	−5.68E-14	45	0.1
ODP	kg eq CFC11	−7.00E-15	4.00E-11	3.00E-09		ODP	kg eq CFC11	1.19E-09	6.48E-05	1.67E-08
AP	kg eq SO_2	−7.00E-07	4.10E-03	3.54E-01		AP	kg eq SO_2	−3.57E-05	1.60E-01	−4.50E-03
EP	kg eq $(PO_4)^{3-}$	−4.00E+08	3.00E-04	2.21E-02		EP	kg eq $(PO_4)^{3-}$	3.57E-06	4.07E-02	3.50E-04
POCP	kg eq C_2H_4	−5.00E-08	3.00E-04	2.54E-02		POCP	kg eq C_2H_4	2.38E-06	1.55E-02	3.33E-04
ADPE	kg Sb	−2.00E-08	1.00E-04	0.0105		ADPE	kg Sb	2.38E-06	2.79E-02	1.33E-04
ADPF	MJ	−1.80E-03	10.215	879.7		ADPF	MJ	2.38E-02	590.929	3.333
Solar collector*		**flat**	**vacuum**		**PV**		**mono.**	**poli.**	**CdTe**	**CuInGaSe**
m^2		$a_{1,sol}$			**m2**		$a_{1,pv}$			
GWP	kg eq CO_2	107	112.70		GWP	kg eq CO_2	247.188	206.807	75.1	86.5
ODP	kg eq CFC11	3.22E-08	1.75E-08		ODP	kg eq CFC11	4.36E-05	4.18E-05	5.66E-06	6.28E-06
AP	kg eq SO_2	0.831	1.205		AP	kg eq SO_2	1.264	1.061	0.472	0.457
EP	kg eq $(PO_4)^{3-}$	0.036	0.046		EP	kg eq $(PO_4)^{3-}$	0.144	0.121	0.065	0.079
POCP	kg eq C_2H_4	0.043	0.061		POCP	kg eq C_2H_4	0.075	0.066	0.045	0.041
ADPE	kg Sb	0.019	0.051		ADPE	kg Sb	0.018	0.014	0.048	0.097
ADPF	MJ	1176	1263		ADPF	MJ	4156.635	3364.239	978.6	1079.4

**Note: Other components of the solar heating system weighting factor is taken into account [12].*

Table 2.
Environment impact factors and reference units of selected elements of building service systems; data represent the average value gathered from Ökobaudat [6], Environdec EPD database [7] and research publications [2, 11], and include A1–A3 LCA modules.

3.1.3 Life cycle environmental impact data of energy carriers

The database of environmental impact indicators of fuels is summarized from the EPD certificates gathered from Ökobaudat [6] and Environdec EPD database [7]. The reference unit is kWh of heat. The values of indicators consist of A1–A3 LCA modules. Impact indicators for electricity were determined based on EPD certificates of various technologies of electricity generation. Values are increased by a unified distribution factor. There is also an option to select electricity from the list of local electricity suppliers. Default values of impact factors of energy carriers are shown in **Table 3**. Besides default data, users can add their own data and this data will be available to use as an "LCA" marked element automatically.

3.2 Life cycle cost assessment

The important requirement of the recast EPBD is that EC Member States must set minimum requirements for energy performance of buildings in such a way that a cost-optimal solution is provided. The Directive [1] also defines the concept of a cost-optimal measure as a measure leading to the lowest total cost during the period of building operation. To assess the cost-effectiveness of energy efficiency measures, the LCCA module has been introduced in BDU. In the frame of the assessment, by discounting costs and savings, cash flow LCCn is determined in a pre-defined time period of n years and the investment with the highest positive cash flow can be found. In the BDU, the total cost of "LCA" elements is determined meanwhile cash flow is determined in E^{tool} in which the value of the investment is comparative, based on the

	Unit	GWP	ODP	AP	EP	POCP	ADPE	ADPF
		kg eq CO_2	kg eq CFC11	kg eq SO_2	kg eq $(PO_4)^{3-}$	kg eq C_2H_4	kg Sb	MJ
Natural gas	kWh	0.23890	1.73E-13	0.000177	0.0000267	0.0000297	1.12E-08	3.8740
Fuel oil	kWh	0.30700	3.17E-13	0.000338	0.0000434	0.0000422	1.15E-08	4.2300
Biomass (pellets)	kWh	0.00000	9.79E-13	0.000136	0.0000214	0.0000129	2.91E-09	0.2938
Electricity	kWh	0.27550	4.84E-07	0.002569	0.003032	0.0001734	7.03E-05	3.8998
District heating	kWh	0.26140	4.24E-13	0.000317	0.0000474	0.0000323	1.78E-08	3.0130
Sun	kWh	0	0	0	0	0	0	0
LG	kWh	0.26453	3.48E-13	0.000209	0.0000136	0.0000341	1.14E-08	4.1900
Environmental heat	kWh	0	0	0	0	0	0	0
Geothermal energy	kWh	0	0	0	0	0	0	0
Electricity (ECE, for households)	kWh	0.00616	2.06E-10	0.000023	0.0000350	0.0001301	1.70E-04	0.0454
Electricity (Gen-i)	kWh	0.46769	7.93E-07	0.004211	0.0049388	0.0002334	3.20E-05	6.6963

Table 3.
Environment impact factors and reference units of energy carriers.

calculated cost savings of the energy carriers in refurbished and reference building. The cash flow at the end of each year and the end of the calculation period n is determined by the equation:

$$LCC_n = \sum_{i=0}^{n}\left[(c_{inv} + c_{man})_i \cdot (1+d)^i + \sum_{j=1}^{m} c_{e,j} \cdot \frac{(1+e_j)^i}{(1+d)^i}\right] - V_{(n)}(€) \quad (3)$$

where i is the year numerator, n is LCA calculation period (years), and m is the number of energy carriers needed for the operation of the buildings. c_{inv} are investment costs (€), c_{man} yearly maintenance costs (/a), and $c_{e,j}$ is yearly costs of jth energy carriers (€/a), d is the discount rate, $c_{e,j}$ is forecasted yearly cost increase of jth energy carrier, and V(n) is the residual value of the built-in LCA element at the end of LCA calculation period. Guidelines accompanying Commission Delegated Regulation [13] suggested that for macroeconomic analysis, an annual discount factor of 3% should be assumed. The same document predicts the annual increase in energy carrier prices – 2.8% for natural gas and light heating oil prices, 2% for coal, and 9% increase in electricity prices (until 2030). The annual cost of maintenance of technical systems is assumed to be between 2 and 5% in cost-effectiveness studies [14]. The residual value of the measures is determined based on the expected lifetime of the measures. Standard EN 15459 [15] predicts the duration period of different energy efficiency measured – 50 years for thermal insulation on the building envelope, 30 years for building furniture, and 15 years for technical systems. According to the proposed LCA calculation period (30 years for residential building), this means that at the end of this period thermal insulation will have a residual discounted value of 16.5% of the investment value, taking into account the discount factor of 3%. The discounted residual value for building furniture will be EUR 0, while at least one replacement of technical systems will be required. For technical systems, the cost of replacement is discounted.

3.2.1 Cost database of materials and building structures

In parallel to inventory data of environmental indicators, costs are stored in BDU. For materials having reference units defined by the volume, costs in the database are defined as constant or as a linear function depending on the depth of the built material layer. Default costs are determined according to market research but could be modified by the user. The regression model for determination of costs of windows and doors was developed based on the hydraulic diameter. In the case of the window c_w, regression model is developed in form of:

$$c_w = b_{0,w} + b_{1,w} \cdot \overbrace{\frac{4 \cdot A_w}{P_w}}^{d_{w,H}} = b_{0,w} + b_{1,w} \cdot \frac{4 \cdot A_w}{\frac{(1-f_g) \cdot A_w}{d_{frame}} + 4 \cdot d_{frame}} \quad (4)$$

where $b_{0,w}$ and $b_{1,w}$ are regression coefficients, $d_{w,H}$ is the hydraulic diameter of window (m), A_w is window area (m^2), P_w in window perimeter (m), f_g is the ratio of glazing in the total window area, d_{frame} is the width of the frame (m). The regression model is valid for the windows with an area up to 4 m^2. In **Figure 4** costs of market available windows with wood frame and according to the hydraulic diameter of the

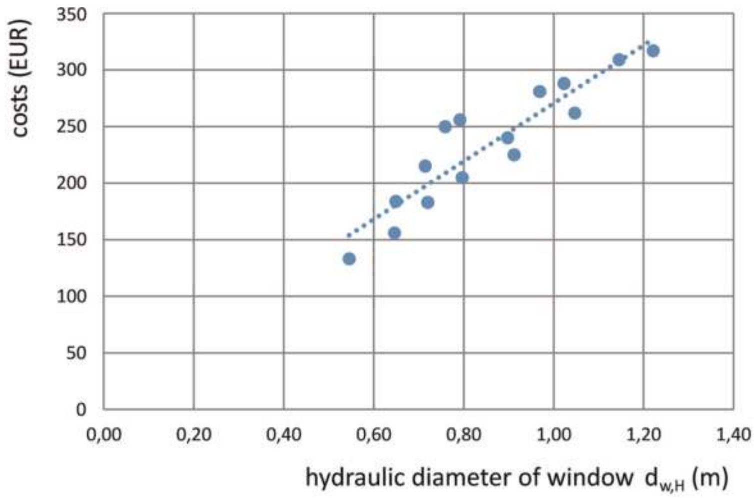

Figure 4.
Cost of windows with a wooden frame and two-layer glazing according to hydraulic diameter of the window; data gathered from Slovenian market overview [2].

window are shown. Data for double and triple glazing, as well as for wooden, plastic, and metal frames were gathered.

3.2.2 Cost database of building service systems elements

Investment cost of elements of building service systems integrated into BDU as default values are available for the following components: condensation gas boilers, biomass boilers, A/W, S/W and W/W heat pumps, solar heating systems with heat storage, mono, poly, CdTe, and CIGS PV modules. Regression models in similar form as environment impacts indicators (Eq. (2)) were developed with new regression coefficients as presented in **Table 4**. Regression coefficients were determined for boilers with design heating power 10–136 kW, for heat pumps thermal power from 5 to 90 kW, and for heat storage with volume 50–2500 liters and 1 m^2 of solar collector or PV module area.

3.2.3 Cost database for energy carriers

The cost of energy carriers was determined per kWh from data published by the Statistical Office of the Republic of Slovenia [16] and the Slovenian market price overview.

4. Life cycle assessment tool

BDU forms necessary data needed for LCEA, LCIA, and LCCA. It is designed in a way that two selected projects' data can be exported in the LCA evaluation tool E^{tool}, one as a reference and the other as a designed one. This allows immediate evaluation of proposed measures for increasing the energy efficiency of buildings. E^{tool} was developed in MS Excel software. Following the requirements of EPBD and content of environmental product declarations (EPD) the LCA metrics includes presentation of:

Heat generator – wood chips					**PV – mono.**				
		$b_{2,gen}$	$b_{1,gen}$	$b_{0,gen}$			$b_{2,pv}$	$b_{1,pv}$	$b_{0,pv}$
c_{gen}	EUR	−0.1836	93.984	3894.6	c_{pv}	EUR	0	260	0
Heat generator – kondens.					**PV – poli.**				
		$b_{2,gen}$	$b_{1,gen}$	$b_{0,gen}$			$b_{2,pv}$	$b_{1,pv}$	$b_{0,pv}$
c_{gen}	EUR	0.3224	−5.3907	1771.3	c_{pv}	EUR	0	230	0
Heat generator – fuel oil					**PV – CdTe**				
		$b_{2,gen}$	$b_{1,gen}$	$b_{0,gen}$			$b_{2,pv}$	$b_{1,pv}$	$b_{0,pv}$
c_{gen}	EUR	−0.1554	16.047	4209.4	c_{pv}	EUR	0	200	0
Heat pump – geosonde					**PV – CuInGaSe**				
		$b_{2,hp}$	$b_{1,hp}$	$b_{0,hp}$			$b_{2,pv}$	$b_{1,pv}$	$b_{0,pv}$
c_{hp}	EUR	−1.2566	947.84	1742	c_{pv}	EUR	0	200	0
Heat pump – ground heat exchanger					**Solar collector – flat**				
		$b_{2,hp}$	$b_{1,hp}$	$b_{0,hp}$			$b_{2,sol}$	$b_{1,sol}$	$b_{0,sol}$
c_{hp}	EUR	−1.2566	447.84	1742	c_{sol}	EUR	0	312.5	0
Heat pump – water–water					**Solar collector – vacuum**				
		$b_{2,hp}$	$b_{1,hp}$	$b_{0,hp}$			$b_{2,sol}$	$b_{1,sol}$	$b_{0,sol}$
c_{hp}	EUR	−1.2566	247.84	1742	c_{sol}	EUR	0	520	0
Heat pump – air-water					**Heat storage**				
		$b_{2,hp}$	$b_{1,hp}$	$b_{0,hp}$			$b_{2,hs}$	$b_{1,hs}$	$b_{0,hs}$
c_{hp}	EUR	−0.3418	282.63	3377.4	c_{hs}	EUR	5.00E-05	0.4354	453.98

Note: Assembly costs are taken into account as 20% (for heat pumps and solar collectors) and 10% (for the rest of the heat generators, PV, and heat storage) of investment costs.

Table 4.
Regression coefficients in regression cost models of selected elements of building service systems.

- LCEA – yearly specific energy needs for heating (Q'_{NH}), final energy (Q'_f) for the operation of EPBD building service systems, primary energy needed (Q'_p), and renewable energy ratio in delivered (final) energy are shown as the specific value per unit of useful area (**Figure 5**). These values allow the designer to overview the fulfillment of nZEB requirements. On the second level of LCEA (**Figure 6**), the absolute energy demand is shown, and delivered (final) energy is presented by energy carriers. Besides energy demand, emission of CO_2, as well as the emission of greenhouse gasses expressed as CO_2 equivalent is shown as the most recognizable environment impact indicators. Meanwhile, emissions of CO_2 are determined by energy carrier use, CO_{2eq} includes LCA emissions (A1–A3) resulting from the implementation of measures taken to increase the energy performance of the building. The impacts of all building elements taken from the "LCA" database or marked as "LCA" are summarized. For analyzed (e.g. renovated) buildings, the decrease of energy demand can be compared with the embodied energy of "LCA" elements through user-selected calculation period. Data of embodied energy is taken as the value of Abiotic Depletion Potential – Fossil (ADPF) environmental impact indicator of "LCA" elements from modules A1–A3.

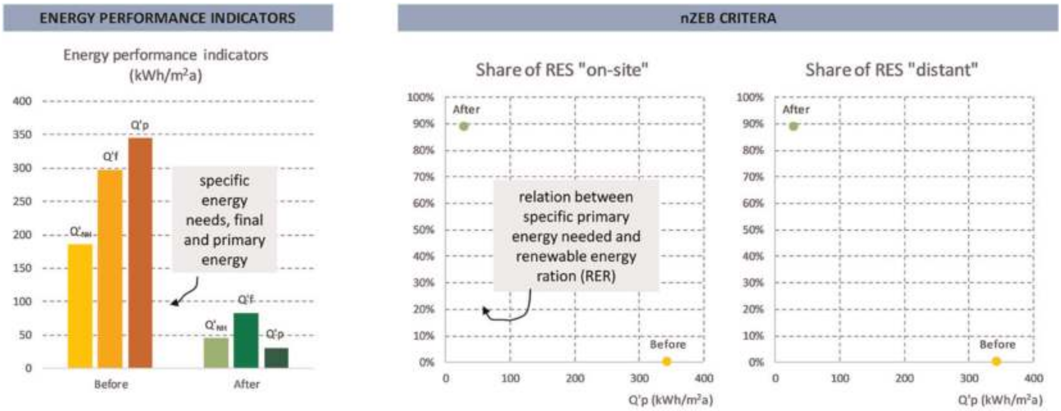

Figure 5.
Display of nZEB energy efficiency metrics at the base level of LCEA.

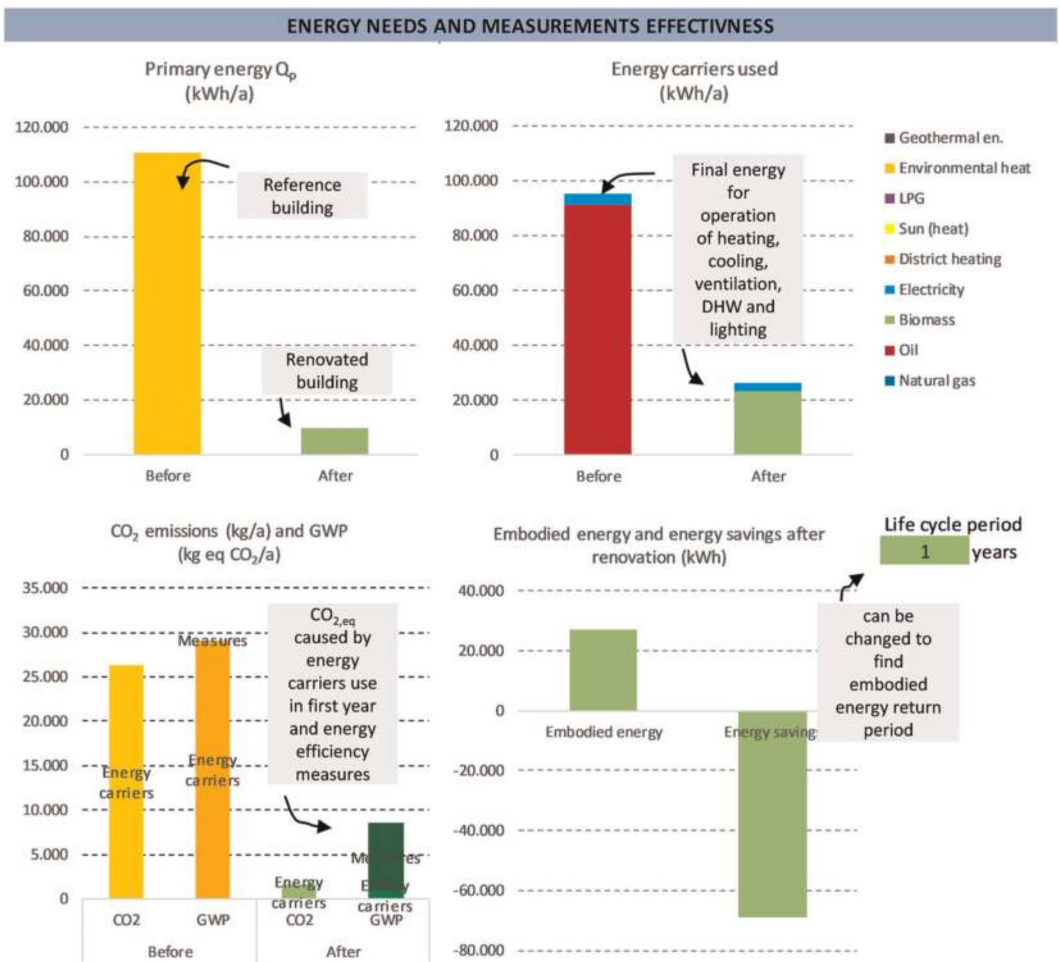

Figure 6.
Second level of LCEA metrics displayed in E^{tool}.

- LCIA – LCA environmental impact assessment is performed in three phases – through classification, characterization, and normalization phase (**Figure 7**). In the classification phase material and energy flows as well as the emission of

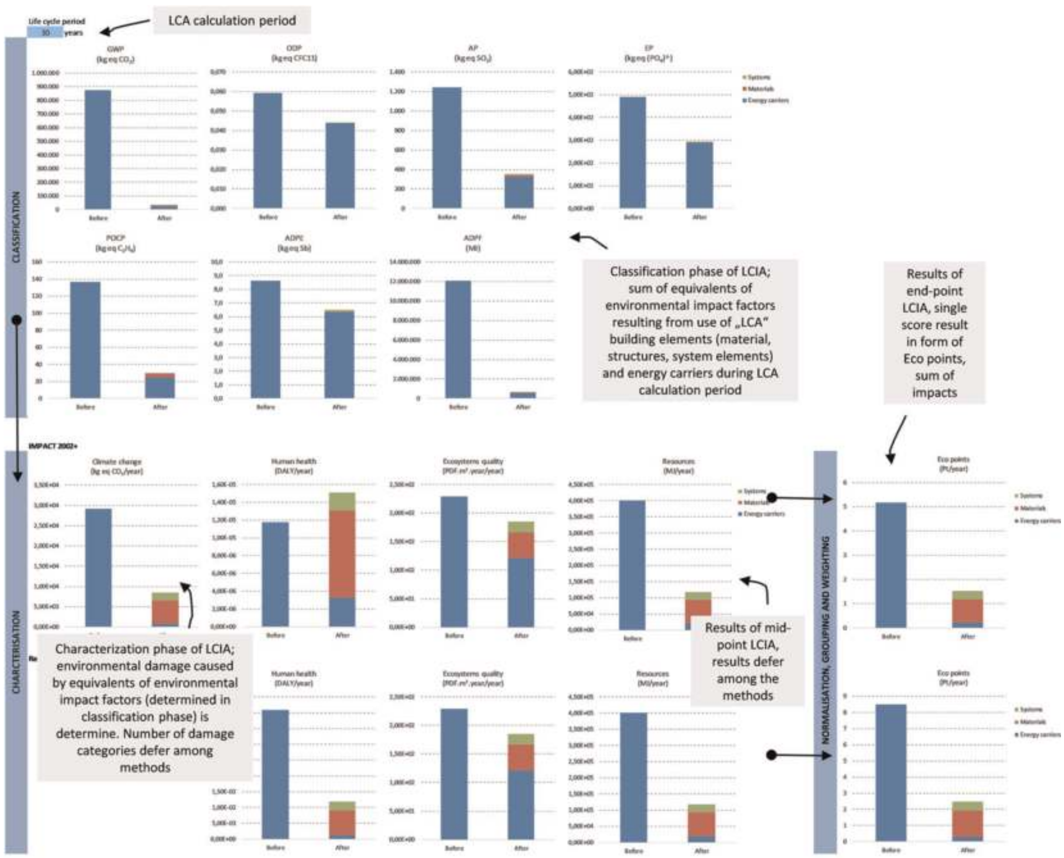

Figure 7.
Results of LCIA metrics.

pollutants equivalents related to LCA building elements, including energy carriers, are summarized during the user-selected LCA calculation period into seven pre-selected impact categories. Values are presented as physical quantities (e.g. kg, MJ). In the characterization phase sum of environmental impacts expressed by equivalents (e.g. AP or EP) are weighed by impact factors (e.g. global warming potential GWP_{100} of particular greenhouse gas) and classified into damage categories. The number of damage categories defers among the methods. As most commonly used, damage categories included in IMPACT 2002+ [17, 18] and ReCiPe [19] method could be evaluated in E^{tool}. IMPACT 2002+ consists of four damage categories: climate change (global warming), human health measured in DALY (Disability Adjusted Life Years), ecosystem quality measured as potential loss of ecosystems as a consequence of acidification and eutrophication and expressed as PDF (Potentially Disappeared Fraction), and damage to reserves of natural resources expressed in MJ. ReCiPe method assessed environmental impact only through three damage categories because global warming is included through the human health damage category. At this point, results are presented as mid-point environmental impacts to the global environment (e.g. DALY per year or MJ per year). By normalization, impacts of the analyzed building (reference and designed) are compared to the total environmental impacts in the reference system e.g. European Union and total impacts could be normalized to each person, with an assumed number of inhabitants 410×10^6. Mid-point LCIA results in E^{tool} are presented as total

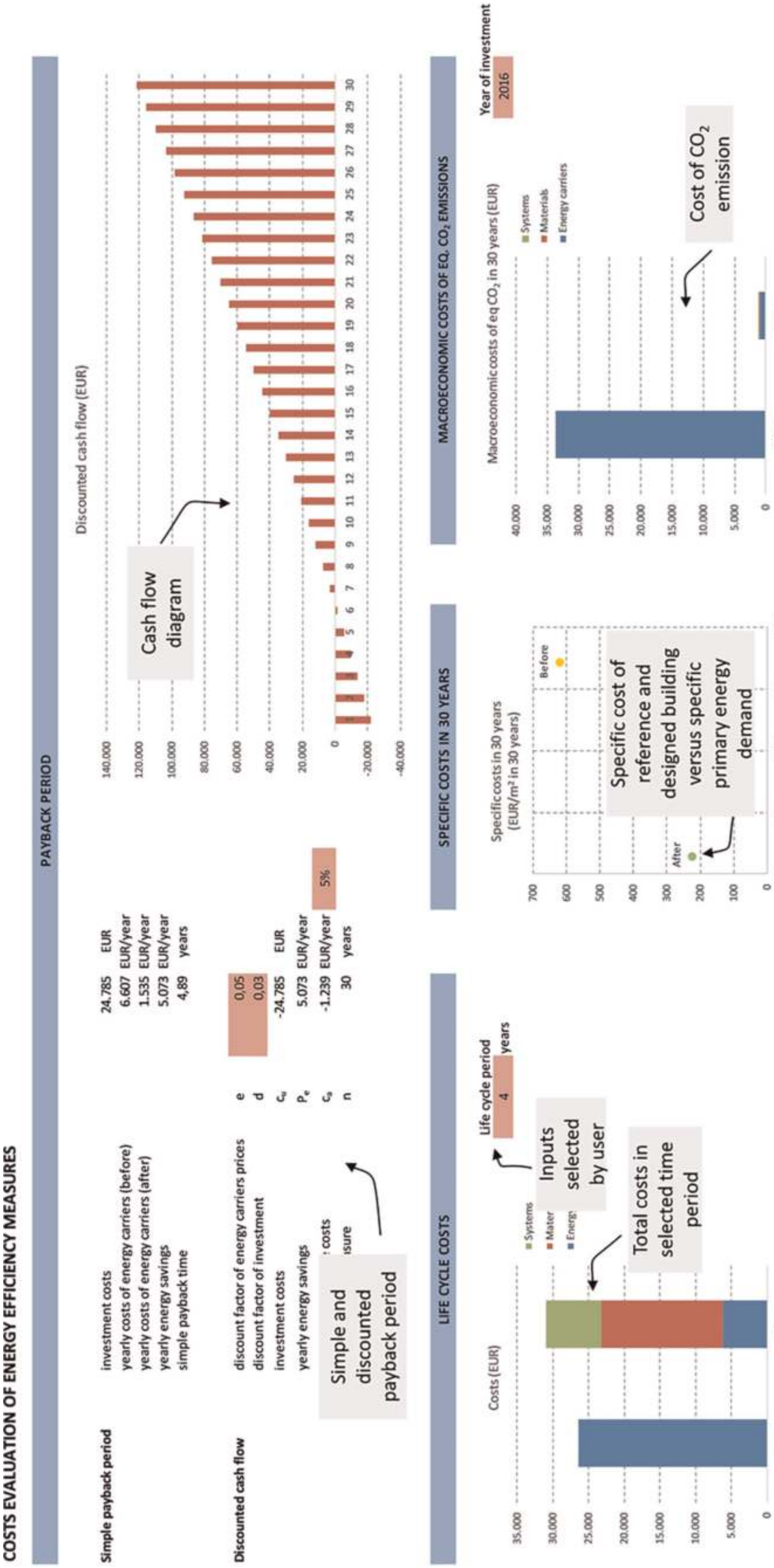

Figure 8.
Results of LCCA metrics.

impacts. By normalization, the end-point in form of a single score can be evaluated by Eco Point per year (PT/y). All indicators are presented in a way that shows the contribution of each group of LCA elements (energy carrier, materials, and building service systems).

- LCCA – It is displayed by values presented in **Figure 8**; taking into account user-defined discount factor, the discounted price of energy carrier, and yearly cost of maintenance of "LCA" elements (as % of investment cost), cash flow diagram is constructed. A simple and discounted payback period is presented as well. The cash flow diagram is shown for the period of 30 years, the period defined for LCA of buildings in [13]; total LCCs for user-selected calculation period are shown next. Costs are shown for each LCA element (energy carriers, investment in materials for renovation, and investments for more efficient building system components). Only building service components presented LCIA can be analyzed. Cost-effective measures can be found from this data. Next, specific (per m^2 of useful area) lifetime costs of investments, building operation, and maintenance related to specific primary energy demand are shown, enabling the designer to choose the most cost-effective measures as requested in recast EPBD. The last LCCA result presents the cost of $eqCO_2$ emissions in the lifetime period as a macroeconomic indicator [11]. Because the cost of a unit of $eqCO_2$ emissions is dynamic, the first year of the calculation period must be defined by the user.

5. Case studies

5.1 Life cycle assessment of energy retrofitting of a public building

Public buildings must fulfill stricter measures and therefore energy retrofitting should be done even more carefully to justify proposed solutions beyond costs. According to that the implementation of LCIA into the decision-making process will be crucial for fulfilling the climate mitigation targets.

As an example, the assessment of energy retrofitting measures of the hospital is presented. District heat is used for heating and preparation of hot water. Hospital has a useful area A_u 7405 m^2 and energy needs for heating Q'_{NH} 1614 kWh/(m^2a). At current (reference) conditions, the primary energy needed for the operation of the building service systems Q_p is 1.865,362 kWh/a. Based on the parametric analysis, the planner decides on the proposed measures, and after the choice of measures, the energy, environmental, and cost assessment of the measures is carried out (**Figure 9**).

Following measures were chosen: windows replacement (U_w 3 W/m^2K → 1.1 W/m^2K), thermal insulation of the facade (U_{wall} 1.3 W/m^2K → 0.168 W/m^2K), and thermal insulation of the ceiling to the unheated attic (U_{roof} 0.957 W/m^2 → 0.094 W/m^2K). The mechanical ventilation with heat recovery was not included.

After the energy retrofitting, the BDU shows the following results, the specific energy needs for heating will be reduced by 75% (Q'_{NH} 161 kWh/m^2a → 39 kWh/m^2a), the final energy by 68% (Q'_f 220 kWh/m^2a → 70 kWh/m^2a), and the required specific primary energy for the operation of the building by 58% (Q'_p 252 kWh/m^2a → 107 kWh/m^2a) (**Figure 10**, left). The use of district heating heat and DHW will be reduced from 1380 to 320 MWh/a (**Figure 10**, middle). At this point, reference and

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Figure 9.
Hospital building in Ljubljana.

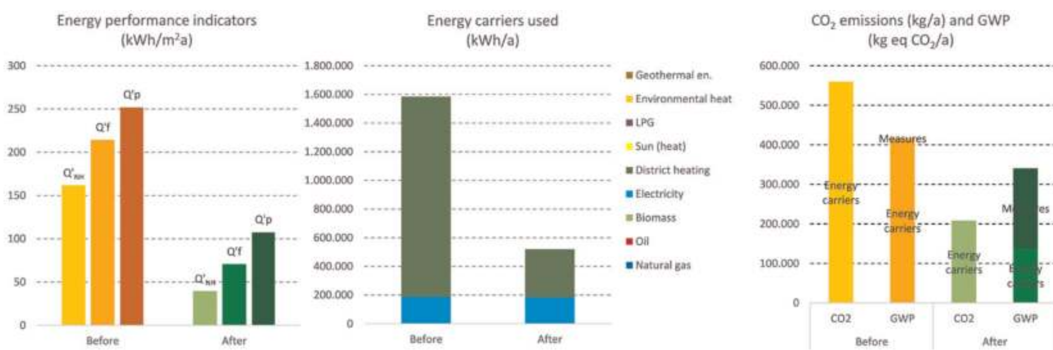

Figure 10.
Results of energy efficiency analysis: Energy performance indicators (left), energy carriers (middle), and CO_2 emissions and GWP (right) for reference project (before) and retrofitted building (after).

renovated building data were exported to E^{tool} for environmental and cost assessment. The results are presented for reference (before) and retrofitted building (after). The CO_2 emissions will decrease by 345 tons per year. The greenhouse gases (GHG) emissions caused by measures will be 202 tons of eqCO_2 per year, nevertheless, in the following years, the GHG emissions will be lower by 278 tons of eqCO_2 each year. Example shows that even measures can be justified according to the environmental impact, as total GHG emissions will be lower compared to the current state (**Figure 10**, right).

The comparison of embodied energy and energy savings of energy efficiency measures shows that "energy payback time" will be shorter than 1 year, which indicates that proposed materials and technologies are sustainable (**Figure 11**).

LCIA analysis shows that all environmental indicators are significantly improved during the assessment period (selected duration of 30 years). It can be seen that the

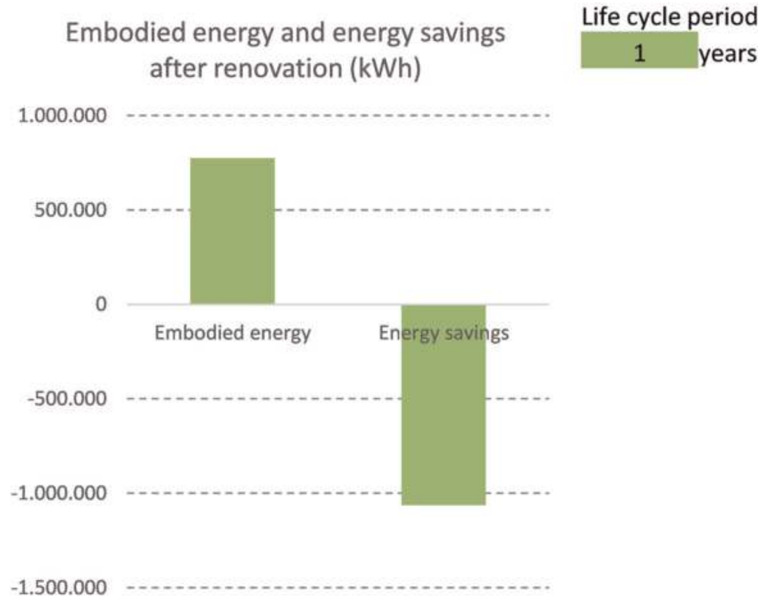

Figure 11.
Comparison of embodied energy in materials and technologies proposed for energy retrofitting and energy savings after 1 year of building operation.

impact of energy efficiency measures (presented as materials) on total GWP emissions is less than 5%, while the impact of measures on the environment is the largest for ODP, while it is smallest for ADP (**Figure 12**).

The reference building causes the population of the EU (431×10^6 inhabitants) 0.58 years of less quality living (DALY, ReCiPe), while the retrofitted building will cause 0.48 DALY in the first year, and 0.19 DALY/a in the following years (**Figure 13**, left). The number of Eco points after retrofitting resulting from the use of energy carriers will be reduced from 68 to 59 Pt/a in the first year and to 24 Pt/a in the rest of the calculation period (**Figure 13**, right).

The LCC results are shown in **Figure 14**. Taking into account the user-defined discount factor d 3% and energy price factor e 2.8%, and assumed maintenance costs of 0.5% of the investment per year, the payback period of the proposed measures will be 16 years, while the cost of energy carriers will be reduced from the current 391 to 268 €/m^2 of the useful building area (**Figure 14**).

5.2 Comparison analysis of on-site heat and electricity generators in a single-family building

The study case illustrates the process of evaluation technologies for heating and domestic water heating (DHW) as well as electricity generation in a single-family building with a useful area of 92 m^2. The buildings are designed according to the passive buildings criteria. The building is mechanically ventilated with a heat recovery system with an efficiency of 75%; the specific power of the fans $P_{v,dov}$ and P_v are 0.31 W/(m^3/h). The energy needs for heating Q'_{NH} are 11.9 kWh/(m^{2}a). The specific power of the built-in lamps is 3 W/m^2. In the reference building, the biomass pellets boiler is installed and connected to heat storage of floor heating system (600 l) and heat storage for DHW (300 l).

Figure 12.
LCIA analysis results of energy efficiency measures after the classification phase.

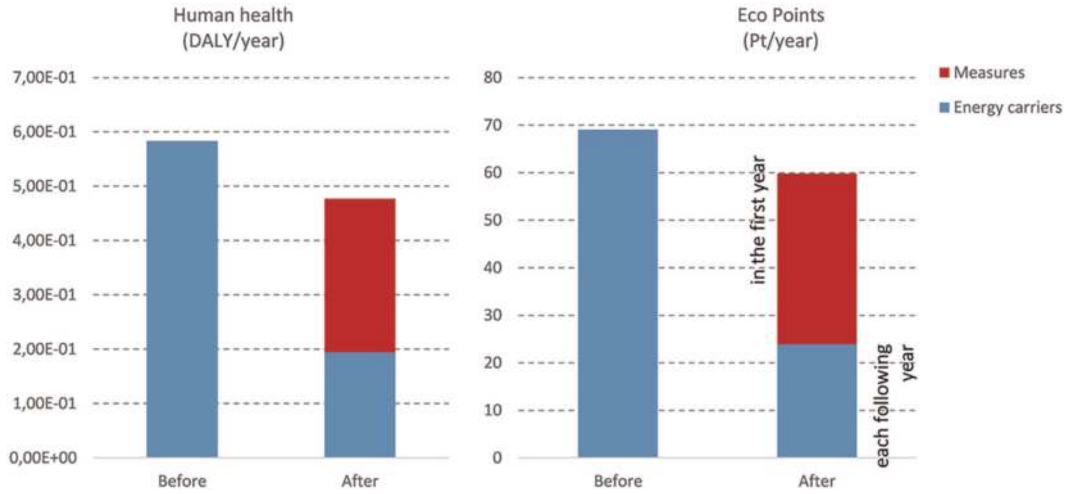

Figure 13.
LCIA analysis results of energy efficiency measures after the characterization phase.

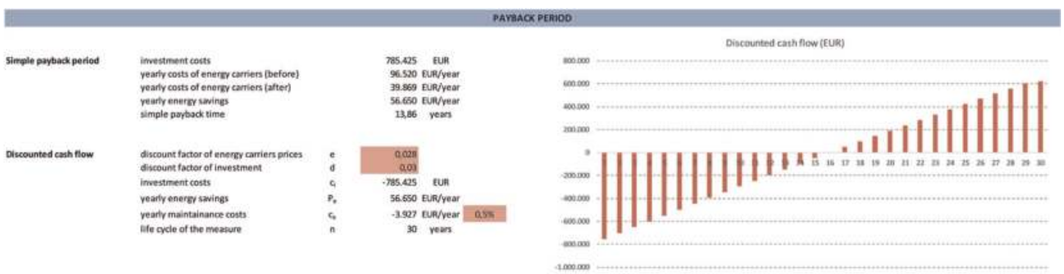

Figure 14.
Payback period analysis of the investment.

The following alternative technologies were analyzed:

- Case 1: heat pump (air-water) with rated heat power 5 kW, heat storage in the DHW system with a capacity of 300 liters;
- Case 2: natural gas condensing boiler and solar collectors, the surface of vacuum solar collectors is 7.5 m^2; the volume of the heat storage is 300 liters;
- Case 3: natural gas condensing boiler, with flow-through DHW heating, and a PV power plant with a power of 1.75 W_p, connected to the grid;

Energy efficiency analysis (LCEA). While the specific energy needs for heating Q'_{NH} are the same for all cases, the specific final energy demand for the operation of building service systems Q'_f is the smallest for Case 3 (42 kWh/(m^2a)), and approximately the same for Cases 1 and 2 (51.3 and 53.4 kWh/(m^2a)), and the highest in the case of a reference building (63 kWh/(m^2a)) (**Figure 15**).

The share of renewable energy sources (RES) for Cases 1 and 2 is provided from solar energy and environmental heat, while the required share of RES in Case 3 is provided by the transmission of electricity produced from the PV power plant to the grid (**Figure 16**).

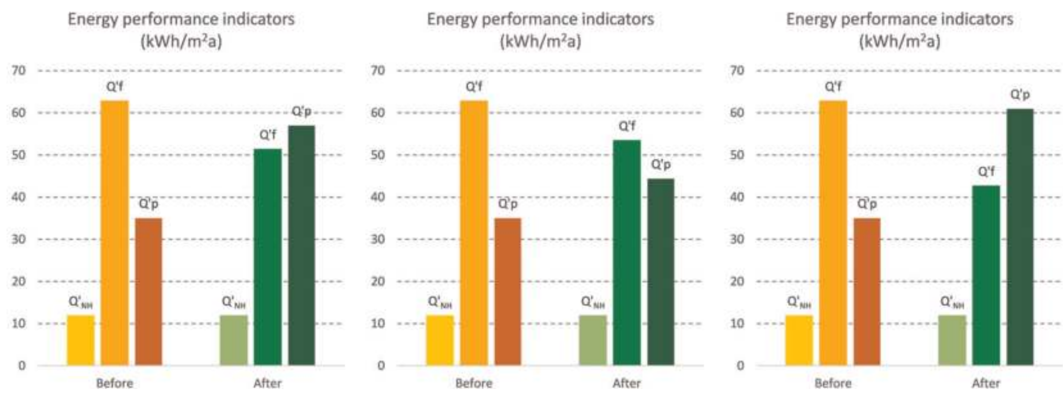

Figure 15.
Energy efficiency indicators for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case (before).

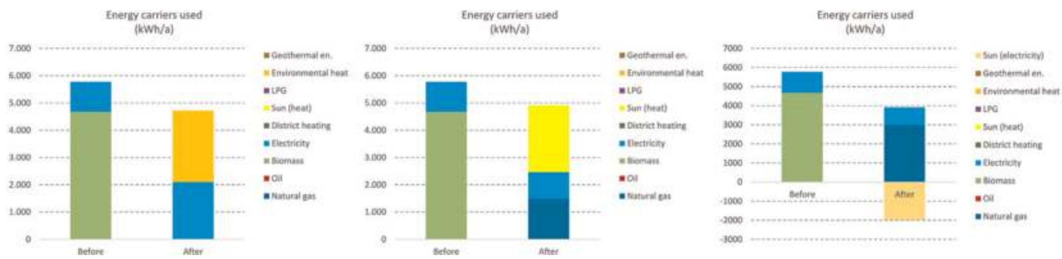

Figure 16.
Structure of energy carriers for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case.

The largest difference in the embodied energy relative to the reference case is in Case 3, and the smallest in Case 1. In Case 3, the difference in total delivered energy is the largest also for the 30-years period (**Figure 17**).

Annual CO_2 emissions according to the Slovenian national legislation [20], are approximate two times higher as in the reference case, and the lowest in Case 2 (750 kg/a), i.e. by 35% compared to Case 1 and by 25% compared to Case 3. The classification of technologies according to GHG emissions (GWP) is the opposite, due to the lower use of energy carriers and the high share of RES in the electricity mix in last years in Slovenia (**Figure 18**). If another electricity supplier was selected, the GWP emissions of Case 1 would be close to 0.

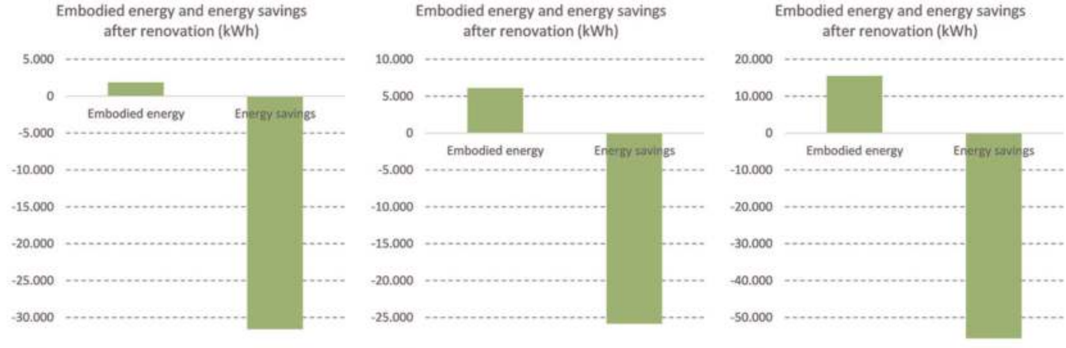

Figure 17.
Embodied energy for Case 1 (left), Case 2 (middle), and Case 3 (right).

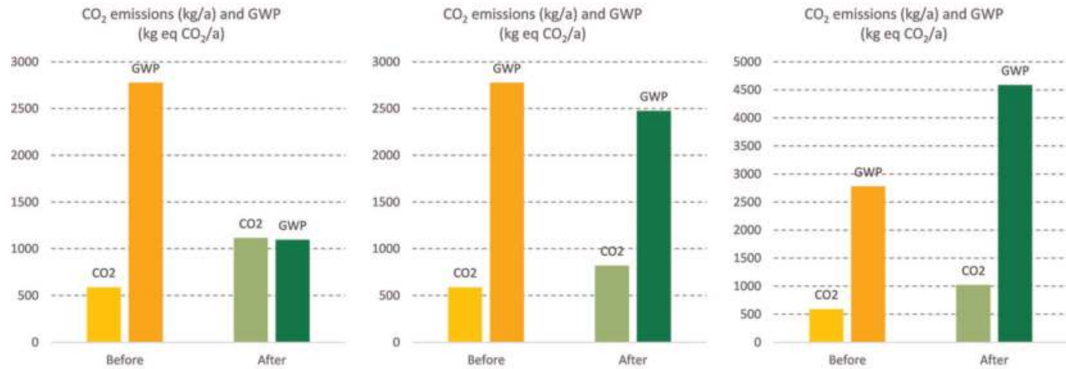

Figure 18.
Annual CO_2 and GWP emissions for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case (before).

Environmental impact analysis (LCIA). The comparison of environmental impact was done based on Eco points of heat generators and delivered energy after the first year of operation. Compared to the reference case (pellet biomass boiler) with an impact of 0.462 Pt, the gas boiler with solar thermal collectors (Case 2) has approximately the same impact (0.427 Pt). The impact is approximately half of that in the case of the heat pump (Case 1, 0.199 Pt) and doubled in the case of the gas boiler with PV (Case 3, 0.870 Pt) (**Figure 19**). The difference mainly results from the environmental pressures caused by the use of materials and the production of system elements. After the first year of operation, damage to the environment is caused only by the use of energy carriers. The use of biomass causes the lowest yearly environmental impact (0.083 Pt/a). The impact of Cases 1 and 2 is higher for 25% and the impact of Case 3 is almost doubled (0,186 Pt/a). This analysis confirmed that LCIA is a very meaningful approach when choosing technologies for nZEB.

Cost analysis (LCCA). Assuming 30 years of operation, the total costs (investments and energy carriers) of reference case, Cases 2 and 3 are more or less the same (between € 18,300 and € 18,500), while total costs of Case 1 are lower by 17% (€ 15,300). The cost of energy carriers is close to the investment for Cases 1 and 3, whereas the investment represents 2/3 of the total costs over the 30-years period for Case 2 (**Figure 20**). The cost input parameters are presented in Section 3 (LCCA).

Macroeconomic costs, evaluated on the basis of eqCO_2 emissions costs [13] over the 30 years of operation, are the lowest at the reference case 610 €, for Case 1675 €, for Case 2750 €, and for Case 31,150 € (**Figure 21**). These ratios would be reasonable to use for creating public non-refundable financial incentives.

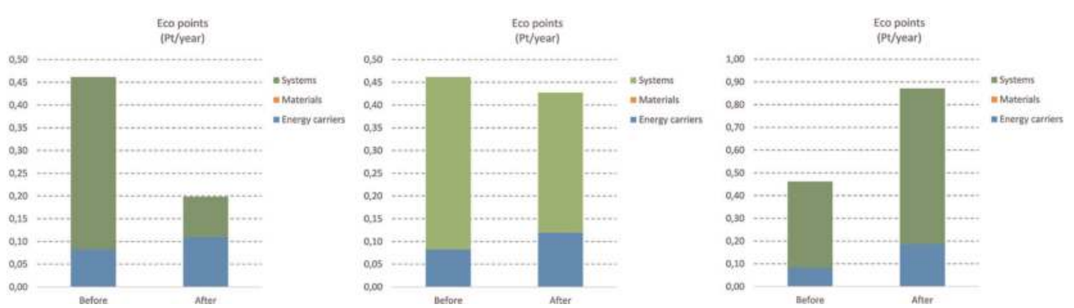

Figure 19.
Eco points for the first year of operation for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case (before).

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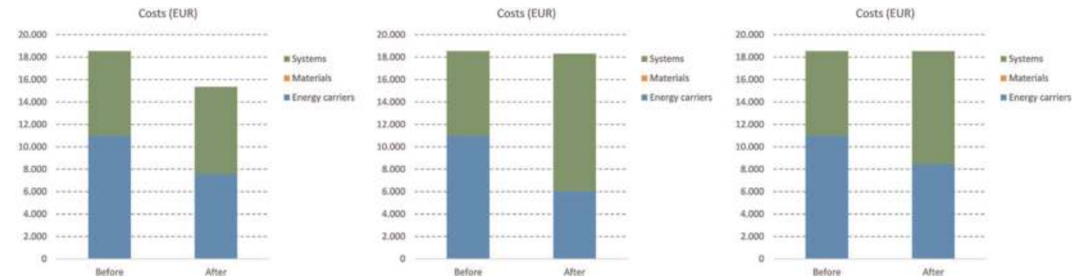

Figure 20.
Costs of the investment and 30-years operation for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case (before).

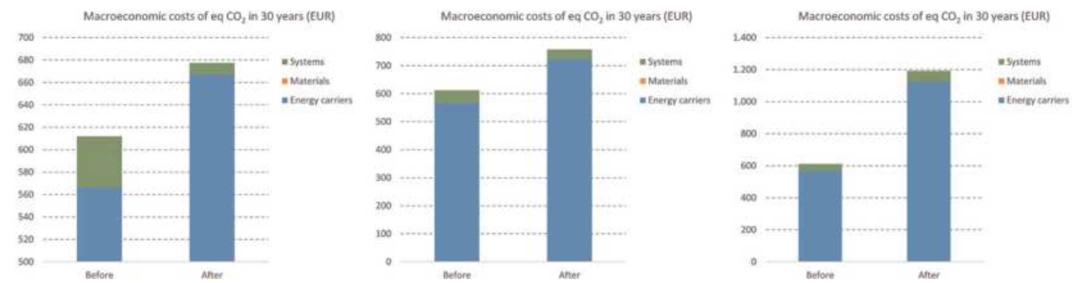

Figure 21.
EqCO_2 emissions costs for the 30-years operation period for Case 1 (left), Case 2 (middle), and Case 3 (right) in comparison with the reference case (before).

5.3 Optimization of multi-family building's energy retrofitting

Retrofitting of multifamily buildings in Ljubljana includes improvement of building's envelope. Building with a useful area 1950 m^2 (**Figure 22**) is heated by a district heating system. The existing building with the brick wall without thermal insulation (U_{wall} = 0.986 W/m^2K) and double paned glass windows with wooden frames

Figure 22.
Multifamily building in Ljubljana analyzed in the case study.

(U_w = 3.0 W/m^{2}K) was taken as a reference project. The ceiling toward the unheated attic was already insulated. The energy needs for heating Q'_{NH} of the reference project is 147.7 kWh/m^{2}a.

Optimization was made according to the specific costs of investment (including all façade layers and labor costs) and energy carriers over the 30-years period. It was found that maximum cost savings of 52 € per m^2 of the useful area can be achieved with thermal insulation's thickness of 25 cm. Such measure will result in decreasing primary energy demand from 251.6 to 196.8 kWh per m^2 of useful area, taking into account all installed building service systems. The cost of eqCO_2 emissions decreases up to the much larger thickness of thermal insulation and no optimum value can be determined. This means that according to the macro-economic cost of eqCO_2 emissions there is no need to limit subsidies based on thermal insulation thickness or U-value of building structures (**Figure 23**).

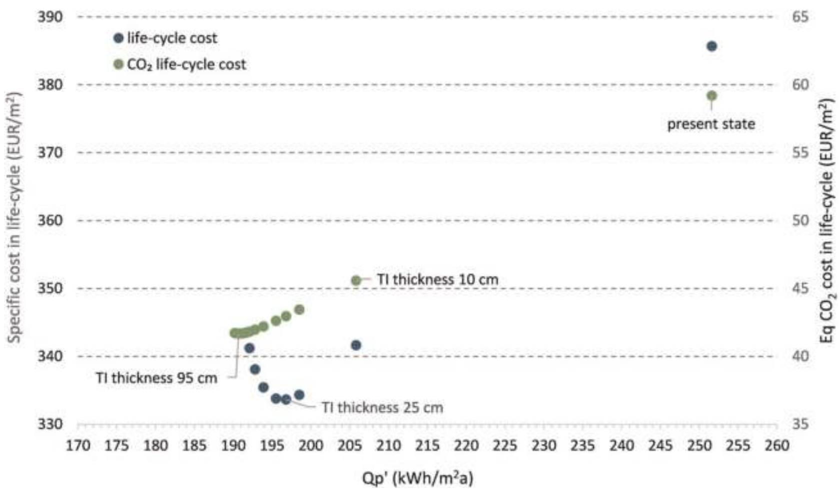

Figure 23.
Thermal insulation thickness optimization based on the criteria of cost-effectiveness in the life-cycle.

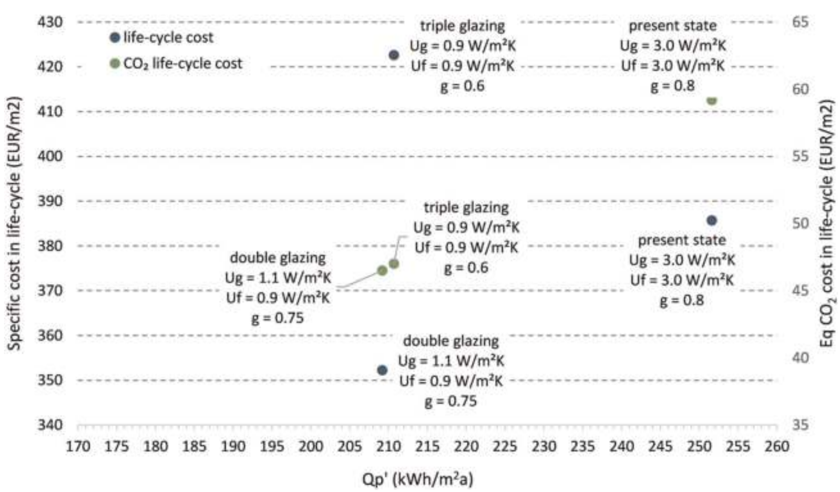

Figure 24.
Windows replacement optimization based on decreasing primary energy demand and the criteria of cost-effectiveness in the life cycle.

The impact of the replacement of windows was evaluated based on heat losses and solar gains. The life-cycle cost assessment showed that double glazed windows provide savings of 33 € per m^2 of useful area, while triple glazed windows are not cost-efficient and besides that such windows do not decrease primary energy demand more than double glazed windows (**Figure 24**). The macroeconomic costs of $eqCO_2$ emissions also give priority to double-glazed windows.

6. Conclusions

Through the use of the developed computer tool and showed cases, it can be pointed out that life-cycle assessment significantly helps in the decision-making process. Design and evaluation of nZEB metric that is nowadays focused on energy balance should be broadened to other aspects of assessment, including environmental impact and cost assessment, all based on life-cycle approach. It can be seen that different approaches give different optimal solutions. Therefore, the designer would not be the one to decide about the aspect of optimization, the weighting factors or, as we propose, the optimal solutions should be found according to the lowest macroeconomic costs of CO_2 emissions. In this way, subsidies schemes can be defined and contributions to the decarburization of the building sector will be presented most efficiently.

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