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Selection of Favourable Concept of Energy Retrofitting Solution for Social Housing in the Czech Republic Based on Economic Parameters, Greenhouse Gases, and Primary Energy Consumption

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Abstract: Energy retrofitting of existing building stock has significant potential for the reduction of energy consumption and greenhouse gas emissions. Roughly half of the CO_2 emissions from Czech building stock are estimated to be allocated to residential buildings. Approximately one-third of the Czech residential building stock have already been retrofitted, but retrofitting mostly takes place in large cities due to greater income. A favourable concept for the mass retrofitting of residential building stock, affordable even in low-income regions, was of interest. For a reference building, multi-criteria assessment of numerous retrofitting measures was performed. The calculation involved different building elements, materials, solutions, and energy-efficiency levels in combination with various heating systems. The assessment comprised environmental impact, represented by operational and embodied primary energy consumption and greenhouse gas emissions, and investment and operational costs using the annuity method. Analysis resulted in the identification of favourable retrofitting measures and showed that complex building retrofitting is advantageous from both a cost and an environmental point of view. The environmental burden could be decreased by approximately 10–30% even without photovoltaic installation, and costs per year could be decreased by around 40%.

Keywords: building stock retrofitting; life cycle analysis; primary energy; greenhouse gas emissions; costs; multi-criteria analysis

1. Introduction

Climate action and the transition to affordable and clean energy are two of the 17 goals of the United Nations (UN) [1]. In the European Union (EU), buildings consume 40% of energy, and the share of related emissions of greenhouse gases (GHG) is 36% [2]. Thus, energy retrofitting of existing EU building stock has significant potential for the reduction of energy consumption and, consequently, of GHG. Moreover, according to the UN, "*the building sector has the most potential for delivering significant and cost-effective GHG emission reductions*" [3].

In 2017, the share of operational emissions of the Czech building stock on total national CO_2 emissions was approximately 43%, of which roughly half could be allocated to residential buildings [4]. Energy-saving features are usually included in the set of retrofitting measures of Czech residential buildings, and approximately one-third of Czech residential building stock older than 20 years has already been retrofitted [5]. Retrofitting is not evenly distributed in the country, but takes place in large cities where income is greater than that in regions. Therefore, energy retrofitting of existing residential buildings is a challenge, especially in low-income regions, in buildings with low-income tenants, and in social housing. The energy-poverty situation in the Czech Republic is not currently as severe as that in Southern Europe [6], but the desired energy standard is still as high as possible to prevent future energy poverty of financially vulnerable tenants.

An important part of the Czech residential building stock is represented by multi-family housing with more than two million flats in 211,252 objects. Approximately 74% of those buildings were constructed before 1979, when the first version of the Czech Standard defining requirements on the building-envelope thermal resistance (ČSN 73 0540:1979) was issued [7].

The focus of this paper is on the evaluation of various sets of energy retrofitting measures suitable for Czech multi-family residential buildings built between 1945 and 1960 since, based on statistics [7], this period was when the most multi-family residential buildings in the Czech Republic were built. In this category of buildings, the dominating typology is a simple building of up to four floors, with flats of minimum floor area, massive structural external walls made of bricks with a typical thickness of 45 cm, and a pitched roof with ceramic tiles on timber rafters with a free loft area, typically with partially underground cellars. The building typology is described more in detail in the report of the TABULA project under code CZ.N.AB.03 [8].

According to previous estimations described in [9], the potential for energy savings by applying energy saving measures to this segment of residential buildings for the 7 million m^2 of unretrofitted floor area is 2.9% of the total energy consumption in Czech residential buildings. For estimated emission factor 376 t CO_2/GWh, this represents annual savings of about 670 kt CO_2 emissions (based on 2017 energy mixes).

The main objective of this paper was to find an optimal combination of retrofitting packages for the abovementioned building segment in order to minimize its primary energy consumption, GHG emissions, and costs, while considering embodied and operational impact, as well as investment and operational costs.

There is a variety of relevant methods available for the optimization of building improvement measures, from fast simplified methods to robust ones that use neural networks [10–12], genetic algorithms [13–16], or specialized computer-aided multi-criteria analyses [17–20]. These approaches are suitable for large data arrays and benefit from connection of energy simulation (TRNSYS, Matlab, EnergyPlus, etc.) with optimization algorithms. On the other hand, the advantage of simple methods is that they require less time and effort, and a lower level of skills or experience for model composition or usage, are easier to gather input data and as they are more available.

Building retrofitting and energy related optimization work has been done for different locations and parameters. For example, Penna et al. [13] investigated the influence of climatic conditions of two Italy locations on a retrofitting strategy optimum considering primary energy, costs and comfort. The influence of different climatic conditions was also analysed by Karmellos et al. [21], who used primary energy consumption and initial investment cost for the prioritization of energy efficiency measures. Martinaitis et al. [22] examined building retrofitting from the perspective of energy efficiency and investments costs. Chantrelle et al. [23] compared energy and financial factors, as well as environmental and social factors. Jaggs and Palmer [24] also included building user preferences by using questionnaire survey data.

The work presented in this paper was driven by the design development of the MORE-CONNECT project [25,26], providing a complex system for the rapid refurbishment of residential buildings. This particular solution was developed taking into account experience from past similar projects, mainly EIA EBC Annex 56 [27,28] and others, like TES Energy Façade and smartTES [29–31], E2VENT [32], TU Delft's Second Skin [33,34], and MeeFS Retrofitting [35]. The main aim of the MORE-CONNECT project work was to drive the development and design process to examine the feasibility of the solution in different European regions [36,37].

The novelty of this paper lies mainly in focusing on Czech conditions and building stock where such an approach is still not common. For multi-family residential building stock, conservative and standard solutions tend to consist of insulating facades and roofs or ceilings, reaching certain *U*-values, and window replacement, mostly using double-pane glazing. Retrofitting usually focuses on minimal investment costs. Various solutions of different retrofitting levels, including ones that are not common or newly developed, providing a higher standard of living, in combination with various heat sources, were evaluated with respect to the environment and both investment and operational cost, bringing a new view on retrofitting in the Czech practice.

This paper is based on MORE-CONNECT project deliverable [38].

2. Methods and Input Data

To identify a favourable retrofitting concept of residential building stock from the considered period, a reference building was taken into account that represented typical multi-family housing stock that needed energy retrofitting. For the reference building, multi-criteria assessment was performed, evaluating and comparing the state before and after retrofitting, taking into account various retrofitting measures. The assessment considered embodied and operational non-renewable primary energy consumption, embodied and operational GHG emissions, and investment and operational costs. On the basis of the results, a favourable retrofitting concept was identified. The favourable concept in the scope of this text was understood as an advantageous solution from the point of view of the considered criteria within the assessment, i.e., low environmental burden connected with low costs. In some cases, non-energy benefits were taken into account during the decision process.

2.1. Reference Building

The investigated reference building is a real building built in 1958 as a part of a social housing settlement in Milevsko, South-Bohemian Region (see Figure 1). Such type of building covers about 5% of the entire multi-family housing stock and belongs to the most common multi-family residential building in the Czech Republic [39].

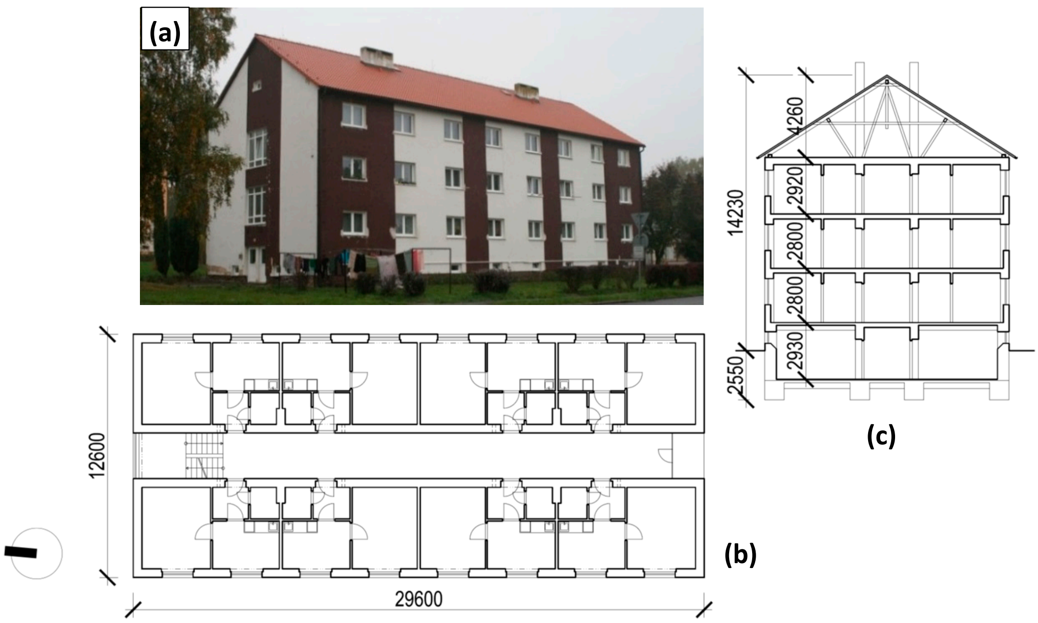

Figure 1. The reference building in Milevsko, Czech Republic. (**a**) Photo; (**b**) floor plan of typical storey; (**c**) cross section.

In the three upper storeys, this particular building has 24 studios oriented either to the east or to west, with a central hall between them. Each flat has two windows and consists of a room, kitchen, bathroom, and hall, providing a floor area of 31 m^2. Technical and housing facilities, and cellars are in the basement storey. The building has a gable roof (33°) and attic space is unused. The building has a longitudinal wall structural system made of brick (450 mm), and ceilings are made of reinforced cast concrete. Façades are plastered. Original windows and exterior doors in this particular building have already been replaced with insulating double-glazed windows with plastic frames (in other buildings of this type, the original windows and door could remain). The building uses a district heating system that is also utilized for hot water preparation. Typical problems of the reference building are unsatisfying winter thermal comfort, overall energy performance, plaster ruptures, devastated common areas, and insufficient ventilation supporting mould growth, mostly in the basement floor or even in the bathrooms or kitchens. Table 1 summarizes the dimensions and characteristics of the reference building.

Table 1. Dimensions and characteristics of the reference building.

Parameter	Unit	Value	Parameter	Unit	Value
Building period		1946–1960	Typical indoor temperature	°C	20
Upper storeys	-	3	Average electricity consumption (excluding heating, cooling, ventilation and user (plug-in) electricity)	kWh/(m^2 a)	8.8
Basement storeys	-	1			
Building dimensions (length × width)	m	29.6 × 12.6			
Gross heated volume	m^3	3567.9			
Gross heated floor area	m^2	993.3	U-value wall	W/(m^2 K)	1.4
Wall area (excl. windows)	m^2	776.9	U-value attic floor	W/(m^2 K)	0.9
Attic floor area (unheated)	m^2	410.4	U-value ceiling of cellar	W/(m^2 K)	2.2
Area of basement ceiling	m^2	369.1	U-value windows	W/(m^2 K)	1.2
Area of windows to north	m^2	11.1	g-value windows	-	0.67
Area of windows to east	m^2	51.8	Airflow rate (estimated)	h^{-1}	0.3
Area of windows to south	m^2	17.7	Internal heat gains	W/m^2	4.8
Area of windows to west	m^2	51.8	Energy need for hot water preparation (calculated*)	kWh/(m^2 a)	35.2
Average heated gross floor area per person	m^2/person	20.7	Energy need for heating (calculated*)	kWh/(m^2 a)	186.6

* Calculated on the basis of monthly method from EN ISO 13790 [40].

2.2. Investigated Retrofitting Packages and Favourable Package Selection Method

2.2.1. Retrofitting Packages

For the identification of a favourable retrofitting concept, an assessment of possible sets of retrofitting measures (called "packages") was carried out with respect to greenhouse gas emissions, primary energy use, and costs. The retrofitting packages were grouped into steps, as described below.

The investigated retrofitting packages partly covered solutions commonly used in the Czech Republic, partly environmentally friendly solutions focused on natural materials and sources used, and contained also a MORE-CONNECT solution, recently developed within the H2020 project (see Section 2.2.3 and [25]). A detailed description of the investigated retrofitting packages is provided in Table 2. It was expected that commonly used solutions would generally be favourable as they have been preselected by the market, while environmentally friendly solutions created a target boundary from the environmental perspective. A comparison of packages covering these approaches allowed an evaluation of how far or close environmentally friendly concepts are from the market preselection.

The retrofitting packages were assessed within the framework of different heating systems that were possible in the case of the reference building. The considered heating systems were:

- district heating (current heating system),
- heat pump,
- natural gas, and
- wooden pellets.

Table 2. Retrofitting packages taken into account during analyses of favourable retrofitting concept.

Step	Renov. Pack.	Description
Step 1	Ref-anyway	In the reference case ("anyway" renovation), façade plasters were renovated and repainted, and water-proofing failures in the basement and the attics were renovated. These measures did not improve the energy performance of the building.
	Ref	In addition to Ref-anyway, considered change of heating system.
	P1	In addition to Ref, walls were supplemented with external thermal insulation composite system (ETICS) with 10 cm of expanded polystyrene (EPS), U-value = 0.26 W/(m^2 K); existing windows retained since they had already recently been replaced by plastic ones with double glazing.
	P2	In addition to Ref, walls were supplemented with ETICS with 20 cm of EPS, U-value = 0.15 W/(m^2 K); existing windows retained since they had already been replaced by plastic ones with double glazing recently
	P2+win	Ditto P2, but windows assumed to have been replaced (to assess the potential for buildings where windows have not yet been renovated); entire window U_w = 1.2 W/(m^2 K).
	P3	In addition to Ref, walls were supplemented with a MORE-CONNECT panel containing 10 cm of mineral wool within the main insulation layer; new double-glazed windows with plastic frames as a part of the panel; wall U-value = 0.16 W/(m^2 K); window U_w = 1.2 W/(m^2 K)
	P4	In addition to Ref, walls were supplemented with a MORE-CONNECT panel including 20 cm of mineral wool within the main insulation layer, new double-glazed windows as a part of the panel; wall U-value = 0.12 W/(m^2 K); window U_w = 1.2 W/(m^2 K); window frame material impact was investigated for plastic, wooden, and aluminium frames).
Step 2	P6	In addition to Step 1 optimum, ceiling of last storey (attic floor) was supplemented with 20 cm of mineral wool (U-value = 0.21 W/(m^2 K)), basement with 6 cm of mineral wool (U-value = 0.54 W/(m^2 K))
	P7	In addition to Step 1 optimum, ceiling of last storey (attic floor) was supplemented with 40 cm of mineral wool (U-value = 0.11 W/(m^2 K)), basement with 14 cm of mineral wool (U-value = 0.27 W/(m^2 K))
	P7x9	In addition to Step 1 optimum, ceiling of last storey (attic floor) was reinforced with 40 cm of wood blown insulation (U-value = 0.11 W/(m^2 K)), basement with 14 cm of mineral wool (U-value = 0.27 W/(m^2 K))
	P8	In addition to Step 1 optimum, ceiling of last storey (attic floor) was supplemented with 20 cm of wood blown insulation (U-value = 0.21 W/(m^2 K)), basement with 6 cm of wood-fibres insulation (U-value = 0.51 W/(m^2 K))
	P9	In addition to Step 1 optimum, ceiling of last storey (attic floor) was supplemented with 40 cm of wood blown insulation (U-value = 0.11 W/(m^2 K)), basement with 14 cm of wood-fibres insulation (U-value = 0.25 W/(m^2 K))
Step 3	P10	In addition to Step 2 optimum, windows were replaced with new triple-glazed windows; U-value for entire window of 0.7 W/(m^2 K); plastic, wooden, and aluminium frames were considered.
Step 4	P11	In addition to Step 3 optimum, mechanical ventilation system with heat recovery was installed for ventilation (airflow rate 860 m^3/h)
	P12	In addition to Step 3 optimum, mechanical ventilation system with heat recovery was installed for both ventilation and warm air heating (airflow rate 2400 m^3/h).
	P0+vent	In addition to Ref-anyway, mechanical ventilation system with heat recovery was installed for ventilation.
	P2+win+vent	In addition to P2+win, mechanical ventilation system with heat recovery was installed for ventilation.
	P4 +vent	In addition to P4, mechanical ventilation system with heat recovery was installed for ventilation.
Step 5	P13	In addition to P11, photovoltaic (PV) panels of 8 kWp were installed.
	P14	In addition to P11, PV panels of 20 kWp were installed.
	P15	In addition to P11, PV panels of 30 kWp* were installed.
	P16	In addition to P12, PV panels of 8 kWp were installed.
	P17	In addition to P12, PV panels of 20 kWp were installed.
	P18	In addition to P12, PV panels of 30 kWp* were installed.
	P19	In addition to P11, PV panels of such power to reach net zero primary energy on annual basis.
	P20	In addition to P12, PV panels of such power to reach net zero primary energy on annual basis.

* Czech legislation restricts installed PV power to a maximum of 30 kWp when connected to a grid.

2.2.2. Favourable Package Selection

The assessment process was multistep (see Figure 2). Each of the retrofitting steps improved a certain part of a building and consisted of several variants (packages) of given improvement. The variants were delimited by the used material or technology and/or by improvement level. From each retrofitting step, on the basis of multi-criteria assessment, a favourable solution (partial "optimum" with low environmental impact and costs) was selected that subsequently advanced to the next step as an initial state. Assessment steps were:

- First, "anyway" renovation was considered as the basic case. It comprised the restoration of the functionality of the renovated building elements (plasters, leakages, etc.), but without improvement of their energy performance.
- Second, a change of heating system was considered. No other improvement was supposed. This case served as a reference for further retrofitting steps.
- Step 1: External walls were improved considering their thermal insulation and possibly also window replacement.
- Step 2: Attic floor and basement ceiling were provided with thermal insulation.
- Step 3: Triple-pane glazing windows were used.
- Step 4: A mechanical ventilation system with heat recovery was used (considering either only mechanical ventilation or warm-air heating system).
- Step 5: Photovoltaic (PV) panels of various sizes were added (applied to both variants from Step 4).

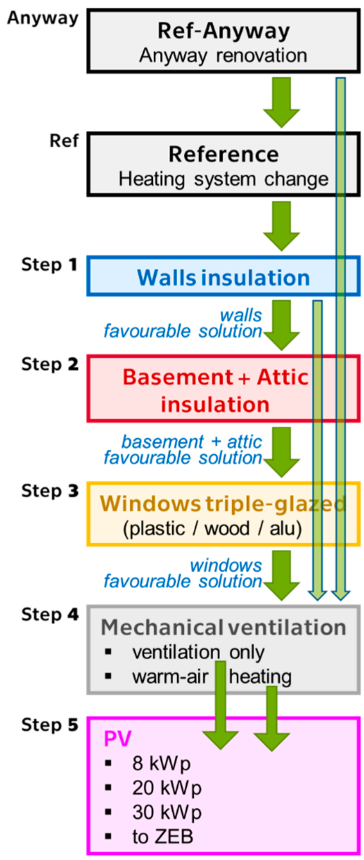

Figure 2. Assessment steps.

2.2.3. MORE-CONNECT solution

The considered retrofitting packages also involved a solution developed under the H2020 MORE-CONNECT project [25]. The main aim of the MORE-CONNECT project was to provide a complex technical solution for the rapid retrofitting of residential buildings that decreases the overall energy consumption of the building to a nearly-zero energy level. The speed of the process was ensured by massive prefabrication of the system.

Specifically, the Czech MORE-CONNECT solution consists of integrated prefabricated timber-framed add-on modules, façade, and optional roof ones, and engine room with necessary energy sources.

The usual wall module consists of a layer of soft, fibral thermal insulation, a secondary main thermal insulation layer between the main timber frames, and a tertiary layer in façade thermal insulation. This diverse layering allows variation of total thickness or U-value of a complete system. Besides the provision of thermal protection, modules provide a number of other functions: ventilation piping, hydronic heating plumbing, electric-driven shading, and Internet and TV wiring. A detailed composition and system description were published in the project's Deliverable 2.2 [41].

2.3. Multi-Criteria Assessment—Method and Data

For the reference building, environmental impact and costs were calculated. During environmental assessment, the operational and embodied phase were taken into account. During cost assessment, investments and operational costs were considered. The method is described in the following sections.

2.3.1. Embodied Environmental Data

A life cycle assessment (LCA) in the first three life-cycle stages (A1, Raw Material Supply; A2, Transport; and A3, Manufacturing) described in EN 15804:2012 [42] and EN 15978:2011 [43] was performed to determine embodied primary energy and embodied greenhouse gas emissions of the system. The simplified comparison LCA study was only done for newly added materials and technologies. The environmental parameter data of the used materials and technologies were taken from the Ecoinvent 3.3 database [44,45], and the study was carried out according to national calculation method SBToolCZ [46]. Particular inputs used for environmental impact calculation are provided in Appendix A.

The general (European) datasets of the Ecoinvent 3.3 database were used for calculation; more localized general data are not available for the Czech Republic. However, although environmental data carry unspecified uncertainties that relativize overall results, they can still be used to compare variants in the set.

The possible reuse of materials was not specifically assessed, but some relation could be found in both environmental parameters—embodied emissions and embodied energy. Lower values are related to reusable, recycled, or renewable materials used in the design. Recycled materials carry a lower environmental burden thank to life cycle system borders that cut off the burden from the material's primary production.

2.3.2. Operational Environmental Impact

For the reference building, annual energy consumption was calculated using the monthly method from EN ISO 13790 [40] to describe the "B6 Operational Energy Use" life cycle stage from EN 15804 [42] and EN 15978 [43]. The advantage of the monthly method lies in the time efficiency, ease of use, and data accessibility. Typical national operational parameters (occupancy-related internal heat gains from occupants and appliances, heating set-points, domestic hot water need, and lighting) based on national standard ČSN 730331-1 [47] were used.

As external boundary conditions, external air temperature and solar irradiation data for the reference building location were used.

Calculation was made for each considered retrofitting package. The following contributors were included: energy need for heating and hot water preparation, lighting, mechanical ventilation (where available), and auxiliary energies.

On the basis of energy consumption, non-renewable primary energy consumption and greenhouse gas emissions were calculated for each energycarrier using corresponding conversion factors. For variants with PV installation, exported electricity was also taken into account. The environmental impact of exported electricity was accounted for in a yearly balance by using minus conversion and emission factors. Conversion factors of non-renewable primary energy and greenhouse gas emissions ($CO_{2,equiv.}$) related to operational energy consumption were taken from the Czech Gemis database (2009) [48,49]. Factors from this database were expected to be more accurate to the energy mix in the Czech Republic than government-issued factors set for the purpose of declarative calculations. The factors used in the calculations are listed in Table 3.

Table 3. Conversion and emission factors of operational energy consumption [48,49] and energy prices.

Energy Carrier	Primary Energy [kWh/kWh]	$CO_{2,equiv.}$ [kg $CO_{2,\ equiv.}$/kWh]	Energy Price [EUR/MWh]
District heating	2.23	0.79	75.0
Electricity from the grid	3.16 (2.84, 2.53, 2.21)*	0.75 (0.67, 0.60, 0.52)*	149.3
Natural gas	1.46	0.32	48.2
Pellets	0.11	0.03	46.4
Electricity produced (PV)	−3.16 (−2.84, −2.53, −2.21)*	−0.75 (−0.67, −0.60, −0.52)*	16.1 (0–21.4)**

* 10%, 20%, and 30% decrease derived from the basic value, used within sensitivity analysis (see Section 3.2.1). ** range taken into account within purchase electricity price sensitivity analysis (see Section 3.1.5).

2.3.3. Costs

Investment and operational costs were considered. Analysis used the annuity method, transforming investment costs into average annualized costs, yielding constant annual costs during the considered time period—50 years in this study. A detailed description of the method is in [50].

Costs were established on the basis of market prices and, in some cases, by expert estimation after consultation with builders. Only the used material, assembly, and construction expenses are covered. Transportation costs are not included in any variant.

In the Czech Republic, energy prices (operational costs side) vary by location and by energy distributor. Prices for energy typical for the location of the reference building were used for the assessment (see Table 3). Purchase electricity price fluctuates and is not guaranteed. The range of purchase electricity price was thus considered as listed in Table 3. Particular input data used for cost calculation are provided in Appendix A.

3. Results and Discussion

In the first part of the result section, consecutive evaluation of the individual steps introduced in the Section 2.2 is presented on an example of a district heating system. In the second part, overview results for all considered heat sources are presented and compared. Both parts are accompanied by discussion where relevant. In the third part, a general discussion follows. Limitations and strengths of the study are summarized at the end of this chapter in Section 3.4.

3.1. Consecutive Evaluation and Selection of Favourable Package per Each Step

Step-by-step evaluation was carried out, results are presented for the case with district heating (current heating system in the case of the reference building). Evaluation and favourable package selection substantiation are provided.

3.1.1. Step 1: External Wall Insulation

Comparisons of wall insulation variants with each other and with the reference case ("anyway" renovation) are shown in Figure 3. Compared to the reference case, any variant of wall insulation decreased the environmental burden by about 40%. An external thermal insulation composite system (ETICS) is the most common way of wall insulation in the Czech Republic, and both ETICS cases (P1, P2) had the lowest cost from all investigated variants. The ETICS variant with thinner insulation (P1) had higher impact in terms of both primary energy and greenhouse gas emissions since environmental parameters related to operational energy consumption had more influence than that of embodied quantities connected with additional thermal insulation. A package with 20 cm thick ETICS including window replacement (P2+win) showed higher costs by about 3% compared to the case without window renovation (P2) with almost the same environmental impact. The MORE-CONNECT solution with 10 cm of a main insulation layer (P3) had a similar environmental impact as that of 20 cm ETICS (P2, P2+win) and showed only slightly higher costs (by about 3% compared to P2+win). The MORE-CONNECT solution with 20 cm of main insulation (P4) showed slightly lower environmental impact than that of the 10cm MORE-CONNECT solution with subtly lower cost in the case of variant using plastic-frame windows (P4pl). Aluminium frames (P4alu) were connected with a 4% cost increase, wooden frames (P4wd) were the most expensive (cost by 12% higher compared to that of plastic frames).

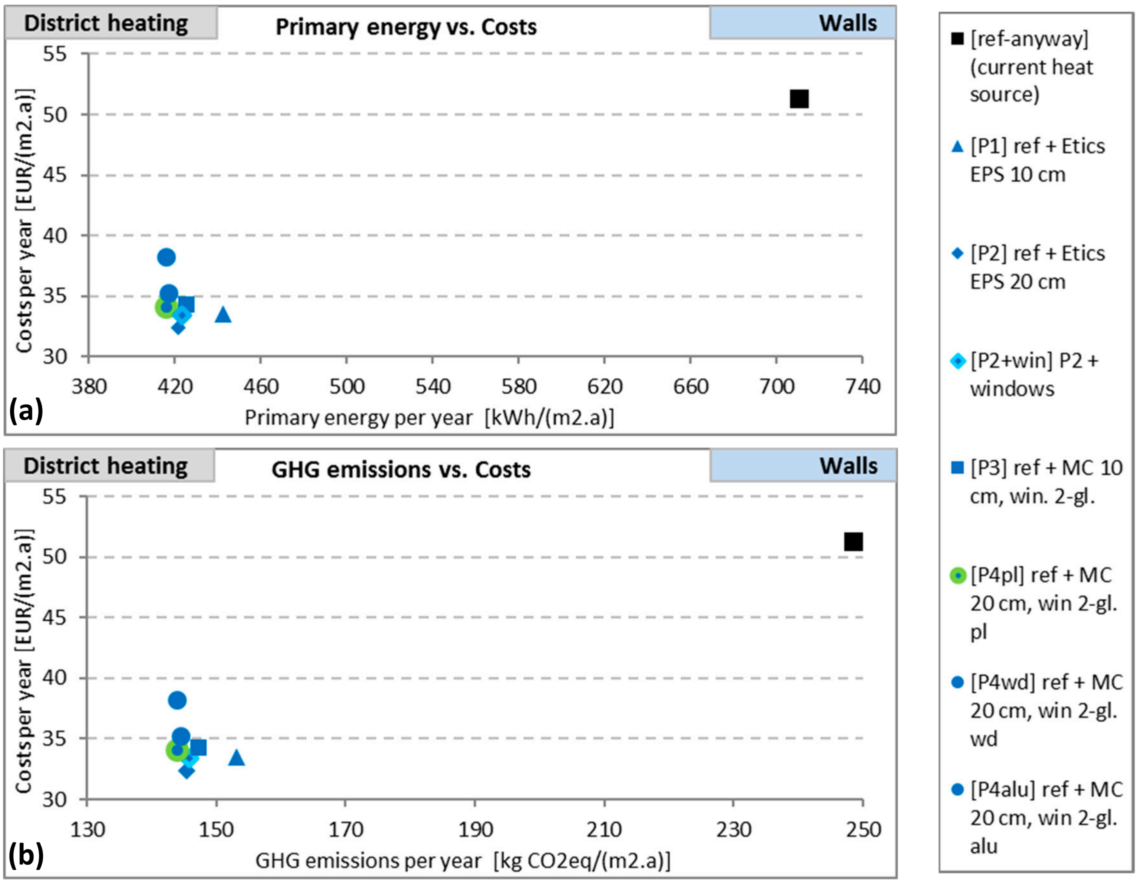

Figure 3. Step 1: Wall insulation—multi-criteria assessment results and selection of favourable package (district heating); favourable variant marked with green circle. (**a**) Primary energy vs. cost impact; (**b**) greenhouse gas emission vs. cost impact.

Comparison of the two different approaches, ETICS and the MORE-CONNECT (both incl. window replacement—P2+win and P4pl), was of interest. Results indicated that MORE-CONNECT solution for walls may be comparable with ETICS with EPS. Prices were found to only be slightly higher in the case of MORE-CONNECT panels, while ETICS resulted in a slightly higher environmental burden. What is not quantitated in the results is that the MORE-CONNECT solution could provide a higher standard of living since thermal insulation is accompanied by other functions in one solution. Such other services comprise, for example, the possibility for mechanical ventilation, new heating piping (for heating system change), electrical wiring including Wi-Fi router, indoor environmental sensors used to control the HVAC system, etc.

The MORE-CONNECT solution has recently been developed. Therefore, costs have not yet been established by the market and, in the future, a certain price decrease can thus be expected as a result of mass production and technology automation. To analyse the potential impact, a decrease of MORE-CONNECT solution costs was considered at the levels of 10%, 20%, and 30%; results can be seen in Figure 4. If costs decreased by at least 20%, retrofitting by using the MORE-CONNECT solution with 20 cm of a main thermal insulation layer and plastic windows (P4pl) had the same total costs as with ETICS in the case of 20 cm insulation and window replacement (P2+win) while providing better wall thermal characteristics. In the case of the package using 10cm main insulation thickness, a decrease in costs by approx. 25% would be needed to have retrofitting using MORE-CONNECT (P3) be at the same cost level as when using 10cm ETICS without window replacement (P1) or 20cm ETICS incl. window replacement (P2+win). However, differences in costs are generally relatively small; the MORE-CONNECT solution seems to be competitive with retrofitting based on ETICS.

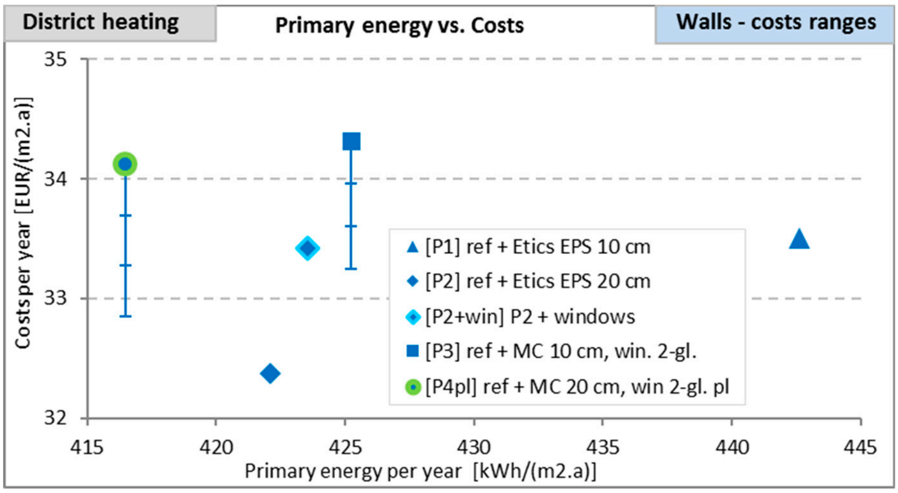

Figure 4. Step 1: Wall insulation—impact of the MORE-CONNECT solution investment cost decrease in comparison with ETICS (district heating).

With respect to the results and to the fact that the MORE-CONNECT solution can provide a higher standard of living, the MORE-CONNECT panel with 20 cm of a main thermal insulation layer and plastic-frame windows (P4pl) was considered as a favourable solution for wall retrofitting and advanced to the next step as an initial option. This solution meant an approx. 42% reduction of primary energy and GHG emissions, and 34% saves of yearly costs compared to the reference case ("anyway" renovation).

3.1.2. Step 2: Attic and Basement Insulation

In Step 2, attic floor and basement ceiling insulation were added. Results are presented in Figure 5.

Compared to the initial point (selected variant from Step 1—P4pl), the addition of basement ceiling and attic floor insulation reduced the environmental burden by about 38% and costs by approx. 28% on average. Higher insulation levels led to better results in all criteria. Variants with similar insulation level but differing in material had almost the same environmental impact and only slightly differed in costs; wood wool insulation was connected with slightly higher costs. Variants P7 and P7×9 were hardly different. Mineral wool for the basement is the safest option from the considered materials in relation to possible higher relative air humidity risks in the basement. Regarding the attic floor, blown wood fibre insulation was considered as more favourable due to the easier application at complicated geometric conditions around attic beams. Therefore, the variant with 14 cm of mineral wool for basement ceiling and 40 cm of blown wood fibre insulation on the attic floor (P7×9) was considered as optimal within this step.

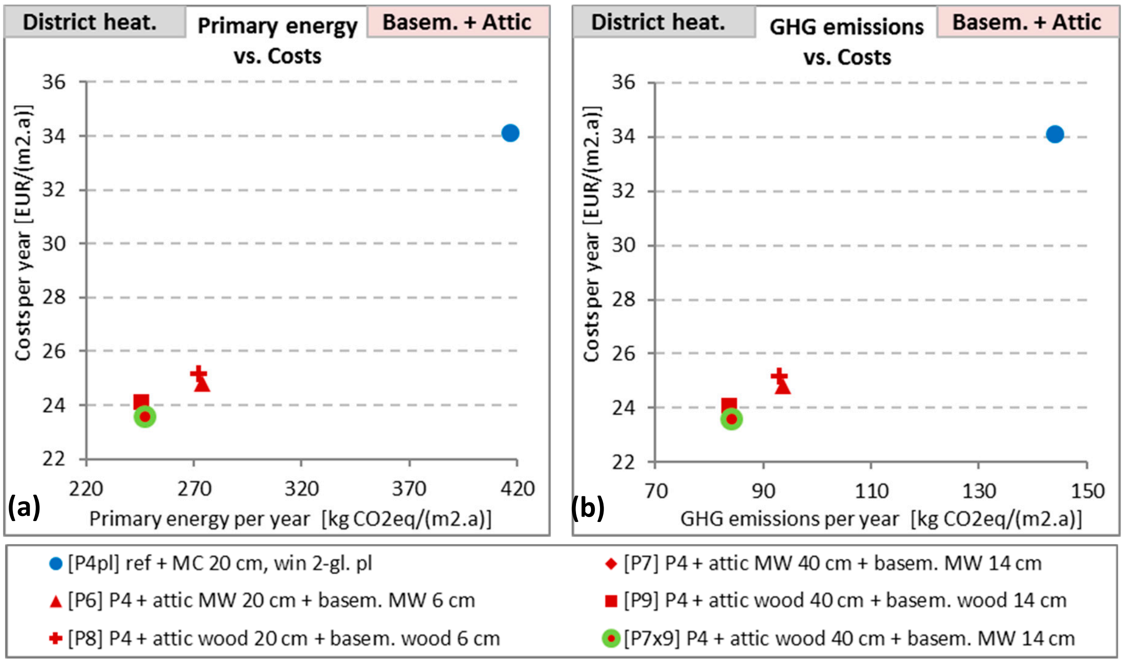

Figure 5. Step 2: Basement and attic insulation—multi-criteria assessment results and selection of favourable package (district heating); favourable package marked with green circle; P4pl (blue) is favourable package in the previous step that served as initial point in this step. (**a**) Primary energy vs. cost impact; (**b**) greenhouse gas emission vs. cost impact).

3.1.3. Step 3: Triple-Pane Glazing Windows

As a subsequent step, for the variant selected as favourable in the previous step, windows with triple-pane glazing were assumed instead of double-pane glazing. Variants differed in window frame material. Results are shown in Figure 6.

Use of triple-glazed windows decreased primary energy use and greenhouse gas emissions compared to double-glazed ones (initial case) regardless of the frame material by about 6%. The differences between the environmental impact of the frame material were rather small. On costs, however, window frame material has significant impact. Only windows with plastic frames (P10pl) led to a cost reduction. Wooden frames (P10wd) had the highest costs, aluminium frame costs (P10alu) were between those of the wooden and plastic frames. Triple-glazed windows were considered as favourable compared to double-pane glazing, so the variant using plastic frames (P10pl) was selected to proceed to the next step.

3.1.4. Step 4: Mechanical Ventilation

First, the addition of a mechanical ventilation system with heat recovery to the case selected in the previous step was analysed. Two variants were considered: P11, only with mechanical ventilation, and P12, with mechanical ventilation combined with a warm air heating system. Results are provided in Figure 7. Both variants resulted in a decrease of environmental impact compared to the naturally ventilated initial case: 24% for P11 and 12% for P12. As far as costs were concerned, the system designed for ventilation only (P11) reduced costs by approx. 5%, while the system combining ventilation with warm-air heating increased costs by about 8% compared to the naturally ventilated case.

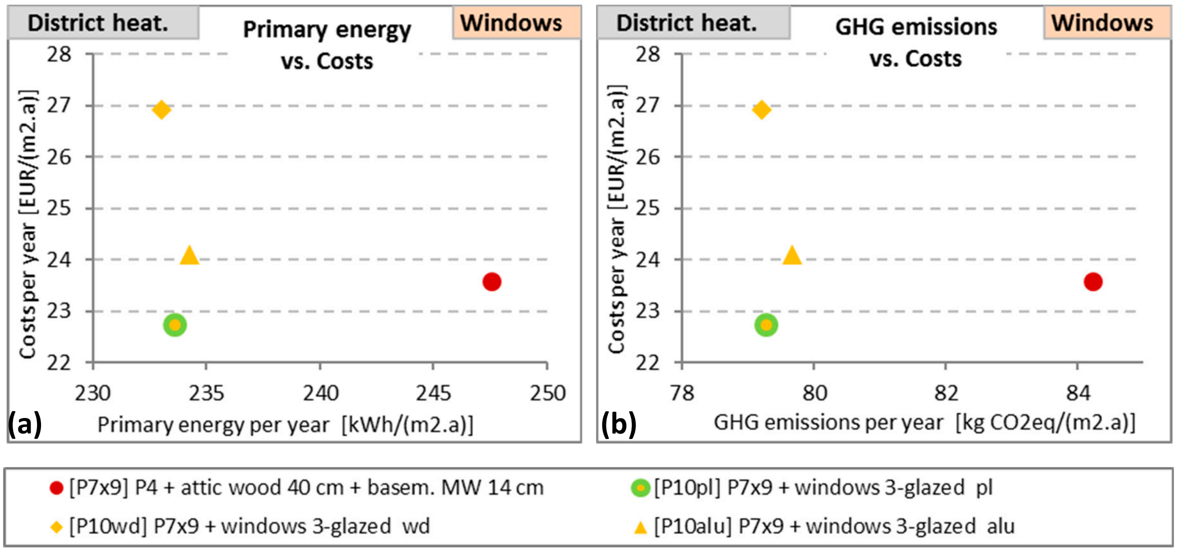

Figure 6. Step 3: Triple-pane glazing windows—multi-criteria assessment results and selection of favourable package (district heating); favourable package marked with green circle; P7×9 (red) is favourable package in the previous step that served as initial point in this step. (**a**) Primary energy vs. cost impact; (**b**) greenhouse gas emission vs. cost impact.

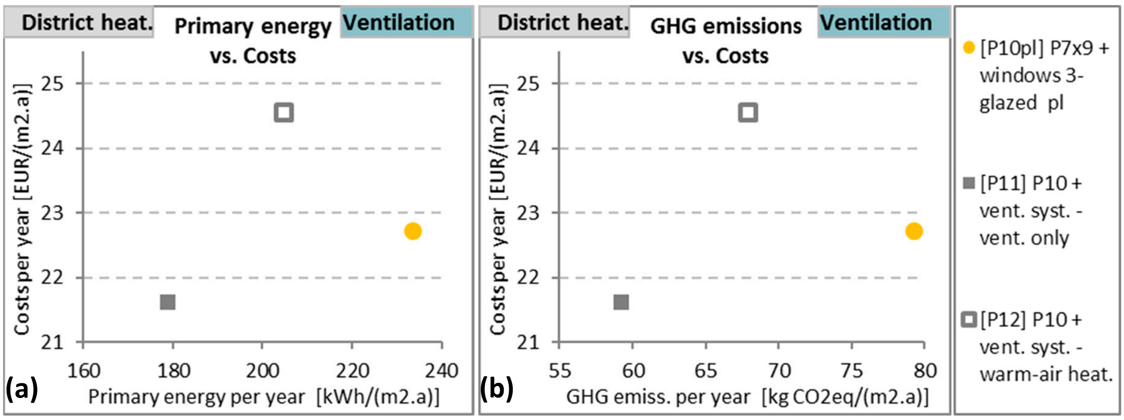

Figure 7. Step 4: mechanical ventilation—multi-criteria assessment results and selection of favourable package (district heating); P10pl (yellow) is favourable package in the previous step that served as initial point in this step. (**a**) Primary energy vs. costs impact; (**b**) greenhouse gas emissions vs. costs impact.

Indoor air quality (IAQ) improvement, although not covered by this analysis, is another argument in favour of mechanical ventilation system installation. The importance of also dealing with IAQ besides energy targets is in line with the findings of other authors [13,51] who refer to poorer air quality after retrofitting consisting of building envelope insulation together with window replacement due to improved airtightness. Therefore, dealing with indoor air quality together with energy efficiency retrofitting should be preferred.

Although the system designed for ventilation only (P11) was favourable in all assessed criteria, the decision whether to preserve the original hot-water heating system and only supplement it with mechanical ventilation, or whether to replace it by warm-air heating system, depended on factors beyond the scope covered by the presented analysis. For that reason, both variants using mechanical ventilation proceeded as a basis for further steps.

The type of the building chosen as the reference building often serves as social housing, where complex retrofitting might exceed the available budget. In the case that internal air quality improvement is preferred to energy-related issues, a partial retrofitting scenario was also considered: A mechanical ventilation system with heat recovery was added directly to the "anyway" renovation case and to some of the wall insulation packages from Step 1—P2+win and P4pl. How internal air quality improvement stands with partial retrofitting was of interest. Analysis was only done for district heating system; results are shown in Figure 8. In all cases, retrofitting enhancement by a ventilation system resulted favourable from both an environmental and a cost point of view. Compared to naturally ventilated cases, mechanical ventilation decreased the environmental burden by about 15% in cases with insulated walls (P2+win+vent, P4+ven), and approx. 10% in the case of "anyway" renovation (P0+vent). Cost savings connected with mechanical ventilation addition (owing to operational energy consumption decrease) ranged around 3–5%. Indoor air quality improvement was not quantified within the results. It could also be concluded that the combination of only wall insulation and mechanical ventilation could be advantageous in the case of a lack of funding, especially when emphasis is placed on indoor environment quality. However, overall favourableness was lower compared to complex retrofitting. Furthermore, the combination of mechanical ventilation with "anyway" renovation may be unreasonable, especially in connection with the original windows and their generally poor airtightness, which need to be considered in such a case.

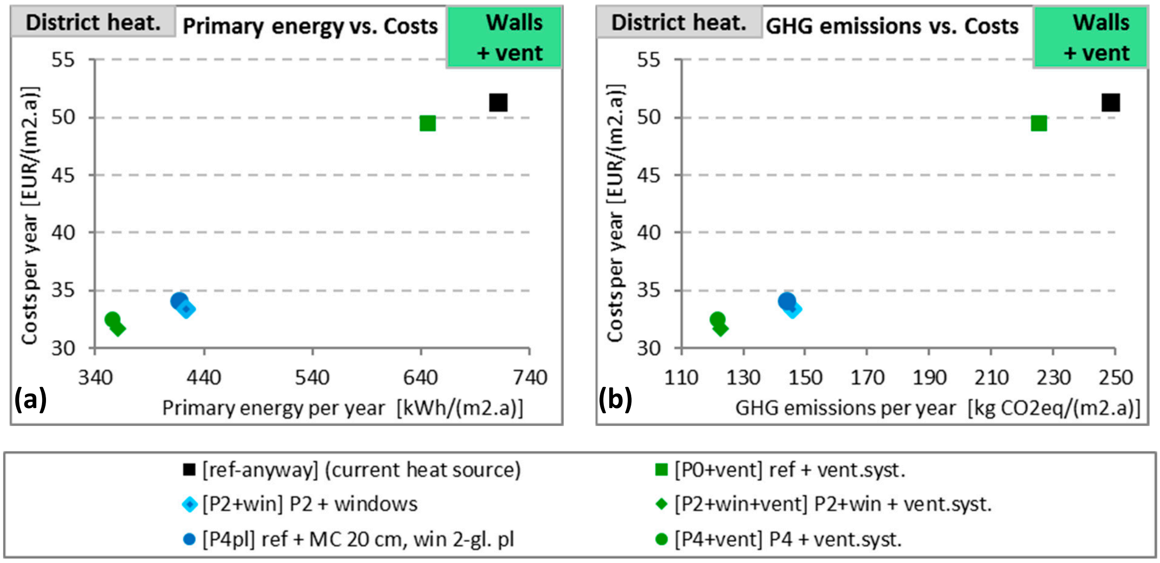

Figure 8. Step 4: mechanical ventilation directly added to only wall retrofitting and to "anyway" renovation (packages at Step 2 and Step 3 skipped; district heating). (**a**) Primary energy vs. cost impact; (**b**) greenhouse gas emission vs. cost impact.

3.1.5. Step 5: PV Panel Installation

Step 5 involved the installation of PV panels onto the reference building (no battery storage was considered). Variants differed in installed power: 10 kWp, 20 kWp, and 30 kWp were considered. Furthermore, how much power would be needed to reach a net-zero-energy building (ZEB) on an annual basis was of interest. Areas available for installation were:

- pitched roof—east and west orientation, slope 33°, 180 + 180 m^2;
- south gable wall—90 m^2; and
- west and east façades—80 + 80 m^2.

Purchase electricity price was included within the cost evaluation. However, prices fluctuate and are not guaranteed in the Czech Republic; hence, it may happen that the price is almost zero, or that the produced electricity is even not purchased, or, on the contrary, that the maximal price is collected. Therefore, as a basic value of purchase electricity price, 0.016 EUR/kWh was assumed, and a range of purchase electricity price was considered between 0 EUR/kWh and the maximal price, which was approx. 0.021 EUR/kWh.

Results are depicted in Figure 9. Installation of PV panels led to primary energy and greenhouse gas emission decrease (the higher the installed power was, the higher the decrease). Profitability of the PV installation strongly depended on the purchase electricity price and it may make PV unfavourable from a cost point of view. The decision on favourableness of PV installation and the power to be installed lies beyond the scope of this study as it depends on, among others, actual energy setup, real electricity consumption profile, purchase electricity price, and possibility to build a smart grid with other buildings.

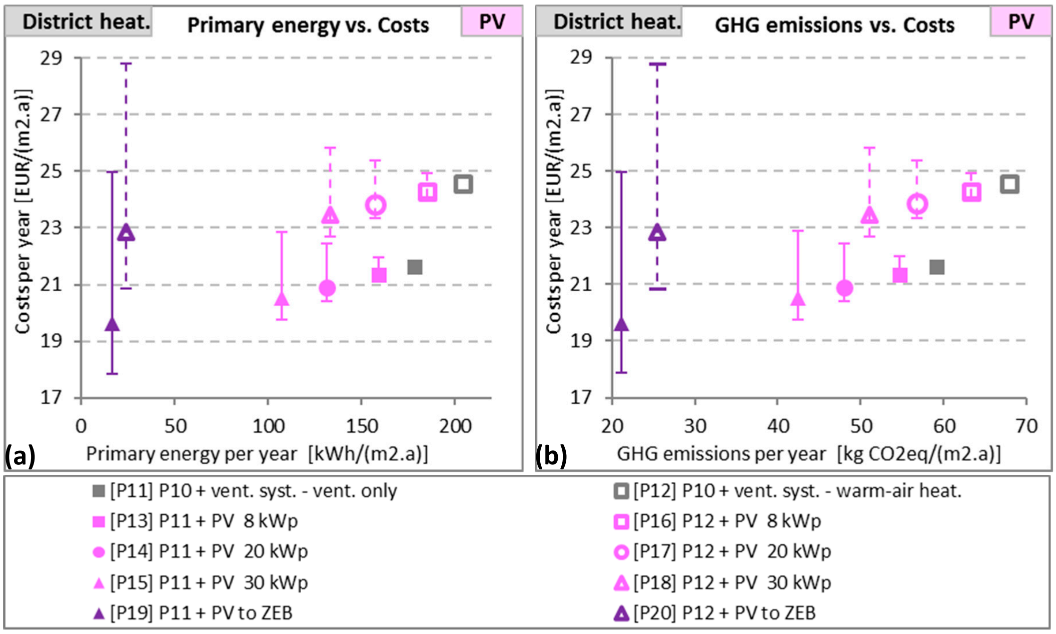

Figure 9. Step 5: PV installation—multi-criteria assessment results (district heating). Purchase electricity price range considered between 0 EUR/kWh and approx. 0.021 EUR/kWh with a basic value of 0.016 EUR/kWh. P11 and P12 (grey) are packages from the previous step serving as initial point in this step. (**a**) Primary energy vs. cost impact; (**b**) greenhouse gas emission vs. cost impact. Note: The zero-primary-energy-building (ZEB) approach takes into account operational impact only while the presented calculations also take into account embodied impact; hence, ZEB variants (P19 and P20) do not reach zero on environment-related axis in (**a**).

If the goal were to reach net zero primary energy level (ZEB) with district heating, for the variant with only mechanical ventilation (P19), an installed PV power of 81 kWp would be needed, which corresponds to the following size of PV installation: fully covered roof and gable wall (i.e., 180 + 180 m^2 on roof, 90 m^2 on gable wall) and 15 + 15 m^2 on façades. The variant assuming warm-air heating (P20) would not reach net zero primary energy even with a fully utilized available area for PV, which produced 103 kWp. Current legislation in the Czech Republic, however, restricts installed power to a maximum of 30 kWp if connected to a grid (limit was not taken into account as far as purchase electricity price was concerned). Joining the buildings within so-called zero energy building clusters enables energy exchanges between individual buildings. The efficiency of the whole cluster can then be higher than individual building efficiency [52].

3.2. Overview Results and Heat Source Comparison

The overview impact of the investigated retrofitting packages of the reference building considering different heating systems is shown in Figures 10 and 11. It should be noted that the environmental assessment strongly depends on conversion and emission factors, which usually reflect the current energy mix and/or the political convention. Therefore, results are valid for current Czech Republic conditions and are not generalizable.

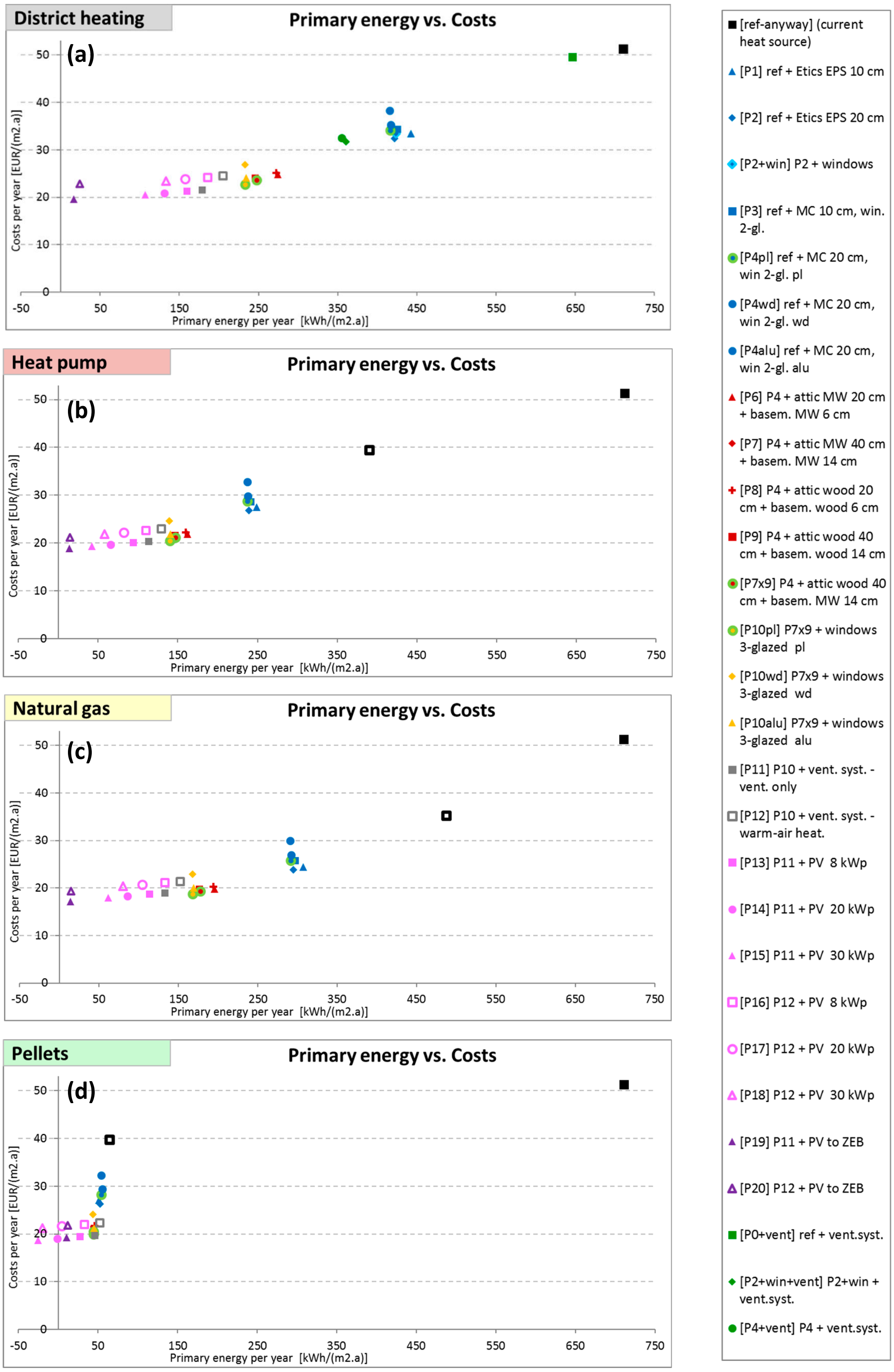

Figure 10. Impact on primary energy use and costs of considered retrofitting packages for the reference building—differences among various heat sources: (**a**) district heating, (**b**) heat pump, (**c**) natural gas, (**d**) pellets.

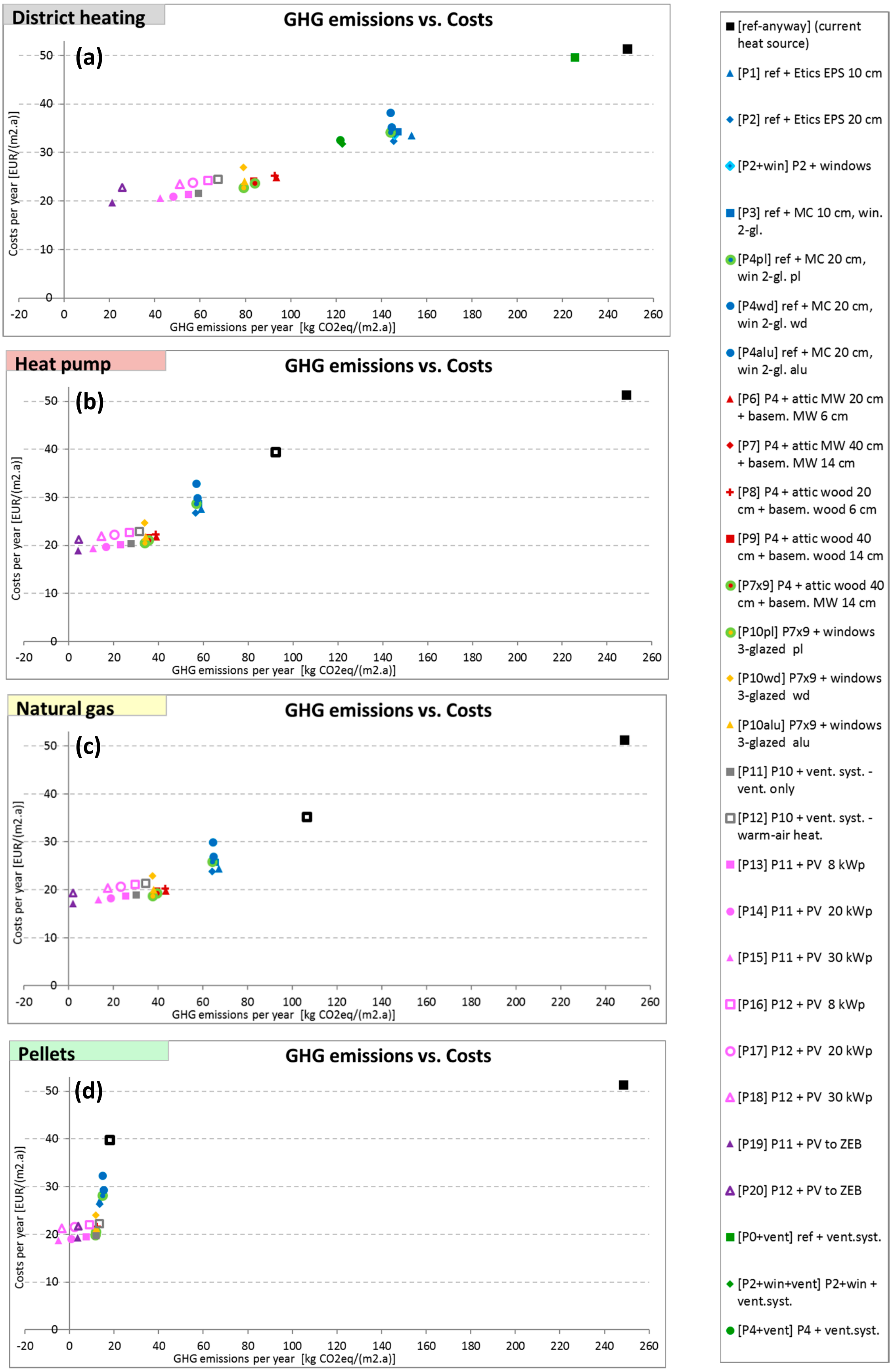

Figure 11. Impact on greenhouse gas emissions and costs of considered retrofitting packages for the reference building—differences among various heat sources: (**a**) district heating, (**b**) heat pump, (**c**) natural gas, (**d**) pellets.

Absolute values of environmental impact and costs differ among heat sources. District heating is the current heat source at the reference building. District heating in the Czech Republic is mainly based on brown coal that is reflected in conversion factors; therefore, environmental burden with this source is the highest from all considered sources. The lowest environmental burden is connected with pellets; environmental impact is at about 1/5 to 1/10 compared to other sources. Heat pump and natural gas cases lie between district heating and pellets; the heat pump has slightly lower environmental impact than that of natural gas.

In the Czech Republic, prices for energy vary depending on the locality and energy distributor. However, as far as prices from Table 3 are concerned, natural gas would be the most favourable source, followed by pellets and the heat pump at almost the same level, while preservation of the district heating system would be the least favourable solution.

Without regard to the heat source, almost each of the consecutive retrofitting steps was advantageous compared to the previous step. Only mechanical ventilation combined with warm air heating had slightly higher cost in comparison with the previous step. Further, in the case of natural gas, costs subtly rise with the addition of a mechanical ventilation system even without warm air heating.

From the perspective of reaching ZEB level, such PV power and areas would be needed (P19 is package with only mechanical ventilation; P20 assumes warm-air heating):

- District heating
    - P19: 81 kWp; fully covered roof and gable wall (i.e., 180 + 180 m^2 on roof, 90 m^2 on gable wall) and 15 + 15 m^2 on façades.
    - P20: did not reach net zero primary energy even with fully utilized available area for PV (i.e., 180 + 180 m^2 on roof, 90 m^2 on south gable wall, and 80 + 80 m^2 on west and east façades), producing 103 kWp in total.
- Heat pump (COP = 2.6 was considered)
    - P19: 42 kWp; 124 + 124 m^2 on roof.
    - P20: 48 kWp; 143 + 143 m^2 on roof.
- Natural gas
    - P19: 50 kWp; 148 + 148 m^2 on roof.
    - P20: 58 kWp; 171 + 171 m^2 on roof.
- Pellets
    - P19: 15 kWp; 44 + 44 m^2 on roof.
    - P20: 17 kWp; 50 + 50 m^2 on roof.

Since only the renovated and newly added components were included in the embodied quantity, it comprises the minority of total environmental impact within the calculations. Shares of the embodied part on total environmental impact for packages with mechanical ventilation (P11, P12) and various heat sources are as follows: In the case of district heating, the embodied parameters comprise about 5% of the total. In the case of the heat pump, it is about 9%, and about 7% for natural gas. The largest share is occupied by the embodied part in the case of wooden pellets (which, as an environmentally friendly heat source, have a low primary energy conversion factor for operational impact), where it comprises slightly above 20% of the total.

Analyses proved that complex retrofitting is reasonable under the condition assumed within the calculation: retrofitting investment costs, energy prices, possibility of heat source change, and embodied and operational environmental parameters. The favourableness of renewable energy sources (extent of PV installation) is strongly dependent on the actual situation of the building: possibility of smart grid connection, purchase electricity price, and other factors.

3.2.1. Result Sensitivity on Electricity Conversion and Emission Factor Changes

Environmental assessment depends on the conversion and emission factor setting. Factors usually reflect the current energy mix and/or the political convention. However, the share of renewable energy generally rises. Therefore, analysis was performed to verify result sensitivity to changes in the electricity conversion factor. The decrease of factors was considered at levels of 10%, 20%, and 30%. Results for the selected packages are presented in Figure 12.

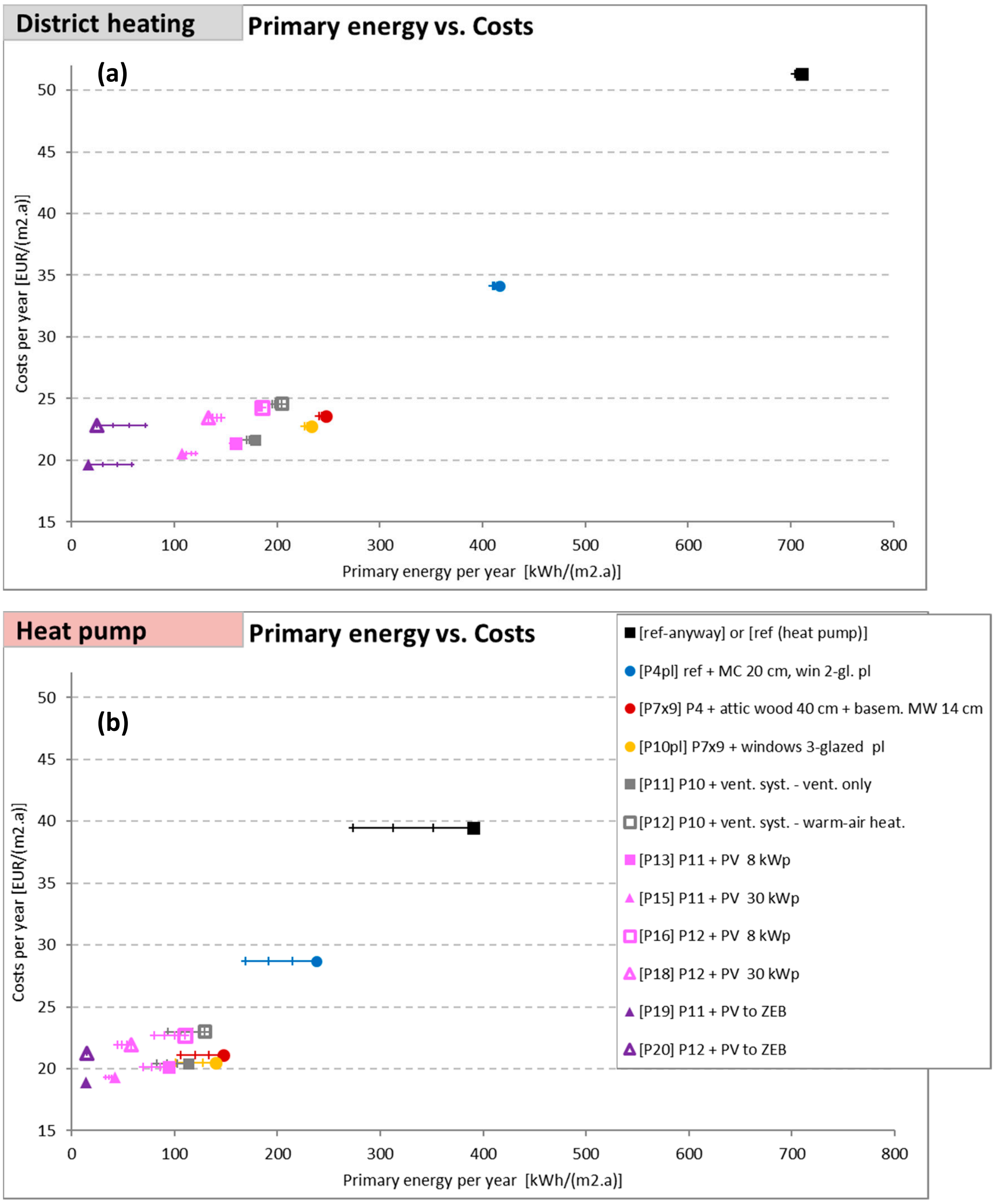

Figure 12. Sensitivity of primary energy results on changes of electricity conversion factor for (**a**) district heating and (**b**) heat pump.

In case the heat source is not electricity-based (district heating, Figure 12a), the impact of conversion factor changes is rather small, as only electricity consumption related to lighting, ventilation, and auxiliary energy is taken into account (in calculations according to Czech regulations). Impact was in the range of 1–5% for a 30% decrease of the conversion factor (the higher the operational energy consumption is, the lower the relative impact). However, as soon as PV are added, the reduced conversion factors make PV disadvantageous from a primary energy point of view, as the subtracted primary energy produced by the PV is also reduced. The larger the PV installation is, the less advantageous it is. Similar tendencies could be found also in the cases of natural gas and wooden pellets. Lowering the electricity conversion factor thus makes reaching the ZEB level from a primary energy consumption point of view more difficult with non-electricity-based heat sources.

In the case of electricity-based heat sources, such as heat pumps (Figure 12b), the impact of conversion factor changes is much more substantial and has the opposite tendency than that in the previous case. The largest impact is perceptible in packages with greater energy consumption, without regard to PV existence. With a 30% decrease of the conversion factor, impact ranges from 43% in the case of the "ref" package ("anyway" renovation with heat source change to heat pump) to 26% in the case of the P15 package (30kWp PV added to mechanical ventilation package P11). With a 10% decrease of the conversion factor, impact was in the range of 11–7.5% for the same packages. The higher the installed PV power is, the less advantageous it is from a primary energy point of view.

Generally, a reduction of conversion factors influences the favourableness of certain energy-saving measures if assessed from the point of view of primary energy consumption or GHG emissions. A lower electricity conversion factor privileges electricity-based heat sources; non-electricity-based heat sources make PV installation disserviceable from the point of view of primary energy consumption.

3.3. General Discussion

Different motivations drive energy retrofit processes; research done in Denmark, Cyprus, and Sweden found the moisture, deterioration, or regular maintenance to be the main technical driver for retrofitting [53]. The cost of the retrofit, use of eco-friendly products, and energy savings are also mentioned among the main reasons. These reasons are also valid for the reference building used in this study.

Jensen et al. [54] pointed out that the main stakeholders in the refurbishment process are building owners and users. The decision on a retrofit scenario must be done by the building owner, but it has an effect on building users [55]. This paradox creates the most important barrier to starting the retrofit, so the real decision for the retrofit of particular buildings may not comply with the findings in this study.

Results are sensitive to several assumptions, for example, to energy performance before retrofitting [56]. The higher the initial heating needs are, the more economically efficient the retrofitting is [13].

In Czech conditions, heating need is dominant in the residential building stock, and operational energy consumption comprises the main portion of both costs and the environmental criteria of retrofitting measures. Energy and cost favourableness thus rise by improving the thermal insulation quality of structures (i.e., lowering *U*-values). This concurs with findings in, e.g., [13] and other studies. In warmer climates, tendencies might differ, and energy efficiency measures needed to improve unsuitable building performance may be different [13,21].

There are many aspects influencing real building energy performance; occupant behaviour is one of the most significant [11]. Occupants influence, for example, ventilation rates that are generally lower in winter and higher in warm days and months. Inappropriate ventilation can cause increase in heating needs above the expectations coming from calculations, but can also increase mould growth risk after retrofitting, or worsen thermal comfort in summer. These aspects are not covered by this study. Potential negative influence connected with users' ventilation-related behaviour may, however, be reduced to some extent by mechanical ventilation installation. Other aspects related to occupant behaviour influencing energy needs are, for instance, set-point temperatures, internal heat gains connected with the presence of occupants, housing equipment, and appliances, shading operations, and others. Climatic conditions and the forthcoming climate change also significantly influence energy consumption [57]. In general, the energy performance results of building calculations are always burdened with uncertainties and differ from real energy performance regardless of method or input data used. The generally known phenomenon of the energy performance gap covers various causes of this discrepancy [58,59].

One of the solutions considered within the study was the MORE-CONNECT system. It uses the majority of building technologies for sustainable and cost-effective building retrofits described by Pacheco-Torgal et al. [60]. The MORE-CONNECT solution was found to be favourable on the basis of assessment criteria and taking into account aspects beyond the scope of this study. This solution provides, besides a higher standard of living, the advantage of minimal disturbance for occupants during renovation. This is common with other similar systems, e.g., [61]. Especially in the case of the addition of a ventilation system, which is advisable from an IAQ point of view, this can be found as a significant strength of such solutions.

3.4. Limitations and Strengths

The applicability of the result is limited to the national context due to use of the national electricity emission factors, which are quite high compared to other European countries (lower than those in Poland, and similar to those in Bulgaria—all countries that are still heavily dependent on electricity from brown coal). Further, there are uncertainties in market prices for some of the used components. The local prices of construction materials and works on the Czech construction market used for cost estimations are close to those in Slovakia, Poland, or Hungary. Another limitation is in the fact that the focus of the study was on one subcategory of the national building stock.

Certain limitations lie in the method. The social context and user preferences related to indoor environmental quality (IEQ) were not investigated. The focus of this work was on energy, GHG emissions, and costs, while the quality of the indoor environment was the boundary condition. IEQ was strived to be kept at least at the same level as for standard new buildings. In most cases, it was even improved when compared with this standard because the designed *U*-values of the retrofitted building envelope ensure higher indoor surface temperatures over the winter season and significantly reduce risks of indoor mould growth. Further, the proposed installation of a mechanical ventilation system with heat recovery can be controlled on the basis of indoor CO_2 concentrations, so the suggested solution improves the indoor air quality.

For energy-demand calculations of the variants, only the simplified monthly method was used. On the other hand, the presented step-by-step method applied in the study has the advantage of not requiring special tools, being simple and easy to use, understand, and communicate to most stakeholders participating in decision-making in the retrofitting project. It does not require specialized software and complex simulations, so there is high potential for applicability in common construction practice. Application of the monthly calculation method is a common skill among Czech designers, and there is a sufficient body of background information, such as standardized sets of climatic boundary conditions or solar irradiation for the calculation of solar heat gains, in [47]. It should also be pointed out that, in general, use of a more detailed method may not necessarily lead to more accurate results [62].

Unlike studies using detailed simulation methods, the monthly method does not allow the evaluation of thermal comfort. However, buildings of the considered typology in this study have enough thermal mass and were designed with a reasonable window-to-wall ratio. The possibility of shading with outer blinds is expected to be sufficient to ensure thermal comfort. Nevertheless, this point should be kept in mind when defining a particular retrofitting setup, and the need for shading should not be neglected.

In the presented study, a favourable solution was manually selected for each evaluation step. Compared to using more sophisticated optimization methods, e.g., Pareto optimization, a manual approach allows the observation of proportions among the solutions and effects on criteria. Personal "weighting" or giving case-to-case preferences when some aspects are not covered by the study but may be prioritized, is possible.

Many decision support tools exist globally that can facilitate performance estimation, criteria weighting, and design alternative generation. They are mainly used in the early stages of retrofitting projects (pre-design and design phases) [63]. Among the most widely spread decision support tools for residential buildings are EPIQR and INVESTIMMO [54].

In the presented study, both investment and operational costs were considered. Involving operational as well as investment costs allows to better evaluate the impact of the considered retrofitting variants and energy-related aspects on costs.

Geometry, window-to-wall ratio, and dwelling unit disposition were not varied within the study. Orientation also remained unchanged, although the reference building represents a widely spread building stock typology, and various orientations could thus occur. This limitation influenced the absolute values of the results, but the relation between the considered retrofitting packages is expected to remain very similar.

4. Conclusions

The presented study showed the comparison and evaluation of numerous retrofitting packages involving different building elements, materials, and energy efficiency levels in combination with various heating systems. For each retrofitting package and for each combination with a heating system, the impact on environmental burden and costs differs. In order to select a favourable retrofitting concept, a choice had to be made taking into account two dimensions—environmental, represented with primary energy use and greenhouse gas emissions, and costs.

Analysis showed that complex building retrofitting is favourable. The environmental impact and costs were gradually assessed for groups of retrofitting measures—walls, ceilings, windows, ventilation, and PV installation. Each step led to a decrease in environmental impact compared to the previous step. The differences between the environmental burden of complex retrofitting and of the reference case were significant. Depending on retrofitting level and possible heat source replacement, total environmental impact could decrease up to around 10–30% (about 90–70% savings) even without PV installation. As far as costs are concerned, not all investigated packages brought a cost reduction compared to the previous case, but some variant connected with lower costs was always available. In the case of complex retrofitting, costs per year could decrease to around 40%, taking into account the considered period (50 years).

A comparison of the two different solutions, ETICS and the MORE-CONNECT prefabricated system, was made. Differences in costs between the two solutions were generally small, so the MORE-CONNECT solution seemed to be competitive with retrofitting based on ETICS. With respect to the fact that solutions like the MORE-CONNECT can provide a higher standard of living and internal air quality since it integrates other services besides the thermal insulation function (e.g., mechanical ventilation, new heating piping, electrical wiring including Wi-Fi router, etc.), they can be found beneficial from the point of view of sustainability and complex building stock retrofitting. On the other hand, such solutions have special requirements with regard to worker skills and expertise, as techniques needed for assembling and completing the system are rather different from common practice [64].

The installation of PV panels led to a decrease in primary energy and in greenhouse gas emissions. Cost favourableness strongly depends on purchase electricity price. The final decision about PV installation and/or suitable installed power lies beyond the scope of this study, as it depends on, besides purchase electricity price, actual energy setup, real electricity consumption profile, the possibility to build a smart grid with some other buildings etc. Current legislation in the Czech Republic restricts installed power to a maximum of 30 kWp if the building is connected to a grid. If the goal were to reach a net-zero-energy building level (in annual balance) at current legislation limits, the goal is only achievable with biomass as a heat source. However, this kind of heat source usually has additional requirements on storage space and fuel supply that may penalize this source from an operational point of view.

The heat source issue also strongly depends on the local conditions. In the case of the particular building used as the reference building, district heating was the current source, and the possibility of heat source change was not expected: both the building and the district heating system are owned by the same owner—the municipality—which pushes on improvements in the environmental parameters of district heating rather than disconnect consumers. On the other hand, this condition might change in future, as a recent EU Directive [65] that must be implemented by member states within two-year implementation period requires that: "*Member States shall lay down the necessary measures and conditions to allow customers of district heating or cooling systems which are not efficient district heating and cooling systems, or which are not such a system by 31 December 2025 on the basis of a plan approved by the competent authority, to disconnect by terminating or modifying their contract in order to produce heating or cooling from renewable sources themselves*."

In general, conversion to natural gas can be expected as the most probable when not giving special consideration to the reduction of environmental impact due to the accessibility of such a source, low space demands, being an almost maintenance-free solution, and having low costs. The heat pump solution has, considering the current electricity mix in the Czech Republic, similar advantages as natural gas, but results in higher initial costs. With respect to the socio-economic situation of inhabitants, it can therefore be seen as unfavourable under current framework conditions. When the share of renewable energy sources in the electricity mix increases, it can be expected that heat pump solutions will become more interesting to investors as they may offer a cost-effective way of reducing non-renewable primary energy use and greenhouse gas emissions when required by Czech or European regulations.

It should be kept in mind that the environmental assessment strongly depends on conversion and emission factors, and on available embodied environmental data available. The available factors reflect the current energy mix in the Czech Republic and, partially, the political convention, while embodied environmental data carry unspecified uncertainties. Both relativize the overall results. The presented results are therefore not generalizable; they are only valid for the Czech Republic and should only be used to compare variants in the set.

Author Contributions: Conceptualization, K.S., A.L., R.B., and M.V.; methodology, K.S and R.B.; formal analysis, K.S., T.V., and M.V.; resources, K.S., T.V., and M.V.; data curation A.L., and K.S.; writing—original-draft preparation, K.S.; writing—review and editing, A.L., M.V., and K.S.; supervision, A.L.; project administration, A.L.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Inputs Used for Cost and Environmental Impact Calculation

Table A1. Input data related to building envelope components.

Building Envelope	Costs	Lifetime	Embodied Primary Energy (non-renew.)	Embodied Greenhouse Gas Emissions	*U*-Value (incl. orig. struct.)	Maintenance Costs
	[EUR/m^2]	[years]	[MJ/m^2]	[kg CO_{2eq}/m^2]	[W/m^{2}K]	[EUR/m^2 /year]
Wall insulation						
ETICS – EPS 10 cm	40.15	30	373.4	15.9	0.26	
ETICS – EPS 20 cm	52.52	30	742.7	31.6	0.15	
MORE-CONNECT – mineral wool (10 + 4 cm)	72.01	30	686.0	57.7	0.16	
MORE-CONNECT – mineral wool (20 + 4 cm)	85.08	30	878.8	73.0	0.12	
Attic insulation						
Mineral wool 20 cm	9.70	25	101.1	8.1	0.21	
Mineral wool 40 cm	19.41	25	202.2	16.1	0.11	
Wood blown insulation 20 cm	10.44	25	10.0	0.6	0.21	
Wood blown insulation 40 cm	20.89	25	20.0	1.2	0.11	

Table A1. *Cont.*

Building Envelope	Costs [EUR/m^2]	Lifetime [years]	Embodied Primary Energy (non-renew.) [MJ/m^2]	Embodied Greenhouse Gas Emissions [kg CO_{2eq}/m^2]	*U*-Value (incl. orig. struct.) [W/m^{2}K]	Maintenance Costs [EUR/m^2 /year]
Basement insulation						
Mineral wool 6 cm	19.96	35	97.1	7.7	0.54	
Mineral wool 14 cm	39.30	35	226.5	18.0	0.27	
Wood fibres 6 cm	31.55	20	17.2	1.0	0.51	
Wood fibres 14 cm	52.41	20	40.2	2.4	0.25	
Windows						
Double-glazed window – wood	203.70	30	743.42	58.73	1.2	34.07
Double-glazed window – alum.	337.04	30	1 764.33	163.81	1.2	5.93
Double-glazed window – plastic	159.26	30	1 194.24	71.77	1.2	5.93
Triple-glazed window – wood	225.93	30	1 011.34	80.19	0.7	34.07
Triple-glazed window – alum.	385.19	30	2 032.25	185.28	0.7	5.93
Triple-glazed window – plastic	177.78	30	1 462.16	93.23	0.7	5.93

Table A2. Input data related to heating system change.

New Heating System	Costs [EUR/m^2]	Lifetime [years]	Embodied Primary Energy (non-renewable) [MJ/m^2]	Embodied Greenhouse Gas Emissions [kg CO_{2eq}/m^2]
New natural gas heating system	5 500	10	5 400.37	464.03
New air/water heat pump	10 000	10	22 167.01	5 291.7
New wood pellet heating system	6 000	15	25200	2 116

Table A3. Input data related to PV installation and electricity production.

On-site Renewable Electricity Production		Costs [EUR/full system]	Lifetime [years]	Embodied Primary Energy (non-renewable) [MJ/m^2]	Embodied Greenhouse Gas Emissions [kg CO_{2eq}/m^2]	Installed Power [kWp]	Annual Electricity Production [kWh/a]	PV Area [m^2]
8 kWp		11 000	51	2749	203.7	8	6 200	48
20 kWp		26 000	51	2749	203.7	20	15 500	118
30 kWp		39 000	51	2749	203.7	30	23 250	178
ZEB solutions								
District heating	pack 19	104 223	51	2749	203.7	81	62 775	480
	pack 20	132 381	51	2749	203.7	103	79 825	610
Heat pump	pack 19	54 307	51	2749	203.7	42	32 550	248
	pack 20	61 986	51	2749	203.7	48	37 200	286
Natural gas	pack 19	64 546	51	2749	203.7	50	38 750	296
	pack 20	74 785	51	2749	203.7	58	44 950	342
Pellets	pack 19	19 750	51	2749	203.7	15	11 625	88
	pack 20	22 310	51	2749	203.7	17	13 175	100

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