energies

Article

Life-Cycle Assessment of a Rural Terraced House: A Struggle with Sustainability of Building Renovations

Karel Struhala * and Milan Ostrý

Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic; ostry.m@fce.vutbr.cz
* Correspondence: struhala.k@fce.vutbr.cz

Abstract: Contemporary research stresses the need to reduce mankind's environmental impacts and achieve sustainability. One of the keys to this is the construction sector. New buildings have to comply with strict limits regarding resource consumption (energy, water use, etc.). However, they make up only a fraction of the existing building stock. Renovations of existing buildings are therefore essential for the reduction of the environmental impacts in the construction sector. This paper illustrates the situation using a case study of a rural terraced house in a village near Brno, Czech Republic. It compares the life-cycle assessment (LCA) of the original house and its proposed renovation as well as demolition followed by new construction. The LCA covers both the initial embodied environmental impacts (EEIs) and the 60-year operation of the house with several variants of energy sources. The results show that the proposed renovation would reduce overall environmental impacts (OEIs) of the house by up to 90% and the demolition and new construction by up to 93% depending on the selected energy sources. As such, the results confirm the importance of renovations and the installation of environmentally-friendly energy sources for achieving sustainability in the construction sector. They also show the desirability of the replacement of inefficient old buildings by new construction in specific cases.

Keywords: building renovation; environmental impacts; energy efficiency, energy sources; life-cycle assessment; sustainable construction

check for updates

Citation: Struhala, K.; Ostrý, M. Life-Cycle Assessment of a Rural Terraced House: A Struggle with Sustainability of Building Renovations. *Energies* **2021**, *14*, 2472. https://doi.org/10.3390/en14092472

Academic Editor: F. Pacheco Torgal

Received: 31 March 2021
Accepted: 24 April 2021
Published: 26 April 2021

1. Introduction

Technological advances combined with population growth mean that mankind affects Earth's ecosystems more than ever before. IPCC (Intragovernmental Panel for Climate Change) reports state that anthropogenic greenhouse gas emissions are the highest in history [1]. This fact likely relates to the current increase in average global temperatures between 0.8 and 1.2 °C above pre-industrial levels [2]. Adverse effects of resulting climate change have prompted international actions such as the ratification of the Paris Agreement [3] or the European Green Deal [4]. The efficiency of these actions and their impact on societies is yet to be seen [5]. However, it is clear that they will significantly influence the construction sector, which is a major energy consumer and GHG and waste producer: for illustration, 40% of the European Union's energy is consumed in buildings (26% in households) [6,7]. This promotes the development and application of sustainable low-energy and low-carbon (or zero energy and zero carbon) building solutions, on-site renewable energy sources, etc. [8–10]. The problem is the application of these solutions in existing buildings. There are recent projects such as IEA EBC (International Energy Agency's Energy in Buildings and Communities Programme) Annex 56, Annex 75, or ALDREN that both promote and provide guidelines for "deep" renovations [11–13]. Still, the average age of a European building is 55 years and only approximately 1% of them undergo renovation each year, according to [14,15].

The development of sustainable buildings goes in hand with the development of suitable assessment methods: multi-criteria certification schemes such as LEED or BREEAM [16,17], cost-benefit or life-cycle cost assessments [18], energy certificates [19,20], carbon balance [21,22] or other environmental impact assessments [23], etc. A lot of these methods promote a life-cycle approach to buildings based on the life-cycle assessment (LCA). LCA originated in the 1960s [24] and is currently a well-established, standardized method for the holistic evaluation of environmental impacts of any "product system" (construction material, building, etc.). The general framework of the LCA was standardized in 1997 in ISO 14040 standard [25]. LCA of buildings and related products is further specified in standards such as ISO 21931-1 [26], EN 15978 [27] or EN 15804 [28]. Thanks to this, the number of LCAs in the construction sector has been steadily growing since the 1990s [29–31]. Currently, there are thousands of studies covering various fields in the sector such as material development [32], residential and non-residential construction [30,33], waste management [34], circular economy [35,36], or municipal LCAs [37–39]. LCA proved to be a viable tool for optimization that could help mitigate environmental impacts in all these fields. As such, it became an integral part of the construction sector, from research and development to building and material certification [40–42].

Projects such as Annex 56, Annex 57, or ALDREN, cited above, have shown the versatility and benefits of LCA in the optimization of building renovations. Yet, the number of works covering this field is proportionally smaller, compared to LCA of new construction. Recent literature reviews provided in [11,31,43] identified only approximately 50 such publications (mostly journal papers). There are several other publications such as [44–46] dealing with this field, but this number is still negligible compared to the thousands of publications describing other building-related LCAs. Moreover, only a few of these publications analysed the efficiency of renovations in comparison to new construction: eight papers cited in [11], five in [31], and handful of others, such as [46,47]. Overall, these studies confirm that the renovation of existing (especially older) buildings can significantly reduce environmental impacts related to their life cycle. Savings between 30–50% are rather common and occasionally they even exceed 90% [11,43]. A renovation could be even more beneficial than comparable new construction, especially regarding embodied environmental impacts (EEIs), where it saves resources otherwise needed for demolition and completely new construction. For example, [46] compared the conversion of a two-storey warehouse into offices with the new construction of the offices. They calculated 89% material savings (mostly load-bearing materials) resulting in up to 75% EEI savings. It should be noted that literature suggests that renovations of residential buildings provide lower savings compared to new construction as they often require more extensive changes of structures. Similarly, [48] compared embodied carbon emissions of twelve new buildings (only housing) and seven renovations (housing and offices) in Hong Kong. The results show that renovations have on average 33% lower embodied carbon than new construction. Several variants of a 1975 apartment building renovation and replacement new construction were also compared in [49]. The paper concludes that an "advanced refurbishment" would provide 17% embodied and 9% total greenhouse gas savings compared to new construction complying with contemporary standards. In contrast, [47] identified an increase of approximately 20% in EEIs of residential building renovations in USA. This increase was outweighed by only 1.6 to 5 years of resulting operational energy savings. Such results might encourage and promote building renovations as means to improve sustainability. On the other hand, the number of published works is currently limited, which reduces the accuracy and validity of their conclusions for designers and decision-makers.

This paper aims to provide new data on the environmental impacts of residential building renovations in order to contribute to the ongoing debate regarding the necessity of environmental impact mitigation. For this purpose, it utilizes LCA methodology and evaluates the environmental impacts of a real-life renovation of a traditional rural terraced house in South Moravia (Czech Republic, Central Europe). The house represents a common building type in the region (and neighbouring regions along the Danube river) in the past, which was not yet analysed in this manner. The LCA compares the hypothetical prolonged use of the original house (variant V-1) with intended (but not executed) major renovation (variant V-2) and executed demolition and new construction (variant V-3). It also introduces several hypothetical sub-variants evaluating the effect of different energy sources on overall environmental impacts (OEIs). A description of the boundary conditions of the LCA and description of the case studies is provided in Section 2 of the manuscript. LCA results are provided in Section 3. The section includes OEIs as well as analysis of operational (energies) and embodied (materials and equipment) environmental impacts. Implications and limitations of the results are subsequently discussed in Section 4. As such, the paper should provide useful insight for experts dealing with similar houses worldwide.

2. Methods and Case Study Description

The study utilizes LCA to calculate environmental impacts of the case study house(s). Following sections specify the LCA methodology and boundary conditions (Section 2.1) as well as briefly describe individual variants and sub-variants of the assessed house: prolonged use of the original house (V-1, Section 2.2), intended major renovation (V-2, Section 2.3), and executed demolition and new construction (V-3, Section 2.4). The LCA also includes several hypothetical sub-variants of V-2 and V-3 described in Section 2.5. These variants evaluate the influence of different heating and domestic hot water (DHW) energy sources (see Tables 1 and 2) on the OEIs of the house: *E (electricity + firewood), *S (natural gas + firewood + solar thermal system), *W (wood pellet + firewood).

Table 1. Size and energy consumption of the evaluated V1–V3 houses.

	Treated/Gross Floor Area [m^2]	Treated Volume [m^3]	Average U-Value of the Envelope [$W·m^{-2}·K^{-1}$]	Energy Consumption			
				Heating [$GJ·a^{-1}$]	DHW [$GJ·a^{-1}$]	Lighting, etc. [$GJ·a^{-1}$]	Total [$GJ·a^{-1}$]
V-1	79/169	224	1.40	171.01	8.33	1.41	180.76
V-2	227/244	761	0.66	202.30	17.32	2.80	222.42
V-3	259/297	766	0.34	136.94	7.53	3.31	147.78

Table 2. Energy sources considered in the LCAs.

	Heating	DHW	Lighting, etc.
V-1	100% Electricity	100% Electricity	100% Electricity
V-2	90% Natural gas 10% Firewood	100% Natural gas	100% Electricity
V-2E	90% Electricity 10% Firewood	100% Electricity	100% Electricity
V-2S	70% Natural gas 20% Solar thermal 10% Firewood	80% Solar thermal 20% Natural gas	100% Electricity
V-2W	90% Wood pellets 10% Firewood	100% Wood pellets	100% Electricity
V-3	90% Natural gas 10% Firewood	100% Natural gas	100% Electricity
V-3E	90% Electricity 10% Firewood	100% Electricity	100% Electricity
V-3S	70% Natural gas 20% Solar thermal 10% Firewood	80% Solar thermal 20% Natural gas	100% Electricity
V-3W	90% Wood pellets 10% Firewood	100% Wood pellets	100% Electricity

2.1. LCA and Its Boundary Conditions

In general, the study described in this paper follows LCA methodology as defined in ISO 14040 and EN 15978 standards [27,50]. The method was selected due to its broad scope and robustness that make it less susceptible to issues such as monetary value inflation or changing certification benchmarks that might compromise other methods cited in Section 1. The environmental impacts of the assessed house(s) were calculated using Eco-Bat 4.0: a Swiss software for building LCA [51] utilized successfully by the participants of Annex 56 project [52]. The software was selected due to its availability to authors, ease of use, and simplicity of result presentation, which makes it desirable for the general public or practitioners without previous knowledge of a specialized LCA software. The boundary conditions of the LCA are:

- The LCA results are presented in following building life cycle stages and modules defined in EN 15978 to increase their clarity and comparability with other studies: A1–A3 Product stage, A4–A5 Construction process stage (necessary material transport, excavations, and demolitions), B4 Replacement, B6 Operational energy, C1–C4 End of life stage. Other stages and modules defined in the EN standard are not included in the software as their impacts would be presumably negligible. It should be also noted that the structure of the result presentation in the software differs from the standardized structure. Further processing and rearrangement were therefore necessary. As a result, the environmental impacts related to material manufacturing (equivalent to Product stage) and elimination (equivalent to End-of-life stage) cannot be broken down into individual modules (A1–A3 and C1–C4, respectively);
- The Ecological Scarcity (UBP) method described in [53] is used for the presentation of results. Eco-Bat 4.0 software provides results in four impact categories: UBP, Cumulative Energy Demand (CED), Non-Renewable Energy (NRE), and Global Warming Potential (GWP). The UBP is selected over other impact categories in the software or impact categories in EN 15978 (and other reviewed sources) due to the simplicity of presentation. It is a single value representing multiple environmental impacts (e.g., GWP, CED or land use), which increases the clarity of the results to the general public. It should be noted that the version of the method utilized in the software is adjusted for Switzerland. A pan-European version [54] was not available at the time of the development of the software;
- The 60-year reference service life of the house is considered. It starts with the completion of the "initial" renovation (V-1 and V-2) or the new construction (V-3) is considered. The value is selected based on ISO 15686-1 [55] standard and Annex 56 methodology [56]. The service life of individual building parts and systems is predefined in the Eco-Bat 4.0 software: 60 years for load-bearing parts, 30 years for non-loadbearing parts above ground, and 20–30 for building-integrated technical systems (BITS);
- The functional equivalent of the LCA is 1 m^2 of the treated floor area (TFA) and year of operation. This decision is based on the literature review (e.g., [11,56,57]) and EN 15978 guidelines [27]. The literature indicates that TFA is the least-affected value during renovations;
- The Eco-Bat 4.0 database includes several hundred material and energy datasets from the ecoinvent v2.2 database. Still, several small-scale materials included in the designs had to be replaced by closest similar materials. For example, plastic windowsills are represented by "PVC pipe" dataset in the LCA;
- The following energy-related datasets were utilized for calculation of OEIs in individual variants: "low-voltage Czech Republic" as electricity, "boiler, condensing (<100 kW), with modulation" as natural gas, "logs, hardwood (6 kW)" as firewood for the stove, and "wood pellets (50 kW)" as firewood for pellet boiler. The LCA does not consider the EEIs and OEIs of the original house prior to the start of the renovation (or demolition). Only demolition and waste management of the original construction materials removed from the site are included in the calculations;

- The LCA considers 5% construction material losses for the materials that are processed on site such as concrete or masonry based on consultations with contractors and literature such as [58,59]. The amount of these materials in the inventory is rounded up to full packages or pieces: e.g., one pack of insulation panels or 25 kg bag of cement;
- Transport distances of construction materials predefined in Eco-Bat 4.0 software are used;
- The LCA uses average dimensions of BITS (e.g., length of piping and wiring) predefined in Eco-Bat 4.0 software. These are based on Swiss KBOB statistics [60].

2.2. Description of the Original House Assessed in V-1 LCA

The LCAs evaluate the environmental impacts of a rural terraced house and its variants. The original single-story house (V-1) was built approximately in the middle of 19th century (according to study of historical cadastral maps). It was a typical representative of local vernacular architecture in South Moravia (Czech Republic), but also in the adjacent regions along the Danube river in Austria, Slovakia, and Hungary. It consisted of a habitable part (79 m^2 of TFA) adjacent to the street and later added vernacular outbuildings in the backyard. The outbuildings included a garage, barn, storages, and a cellar. The attic space of the house was also utilized for storage of crops in winter. The owner originally intended only repairs and minor renovations of the house, which is modelled in V-1 variant LCA (see Figure 1). Data for this variant are based on a survey carried out in winter 2011. The survey revealed that the house was in rather poor state. Most finishes (including roofing), windows, doors, BITS, and other equipment required replacement. There were also structural issues such as cracks in the walls of the outbuildings that required extensive repairs. Unnecessarily high costs of necessary repairs and operation of the original V-1 house led to design of V-2 and V-3 variants, described in following sections.

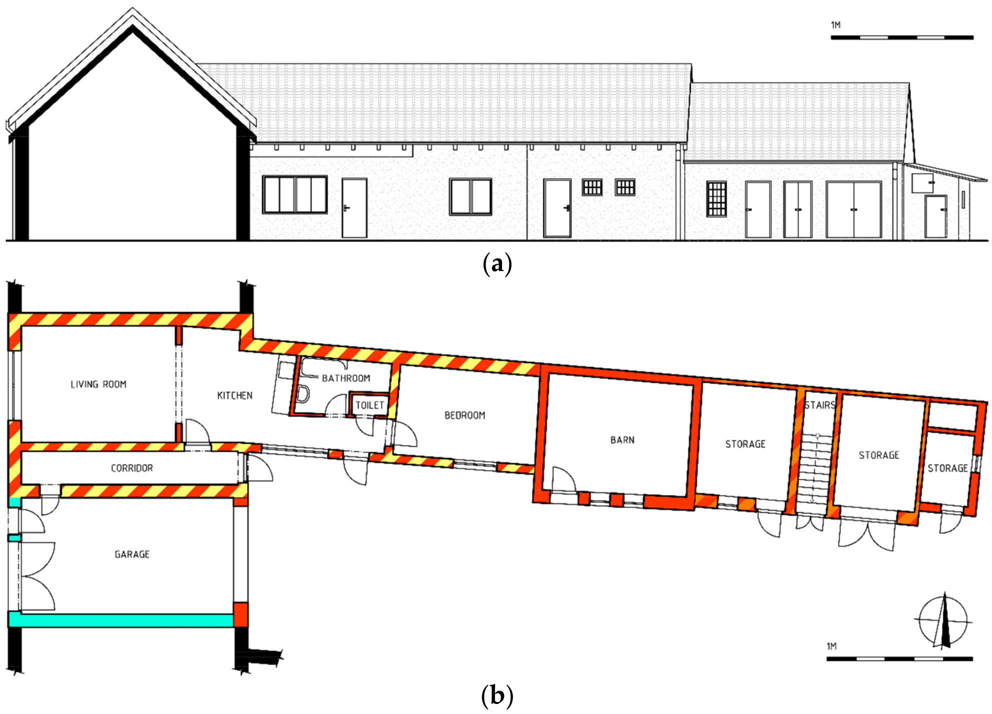


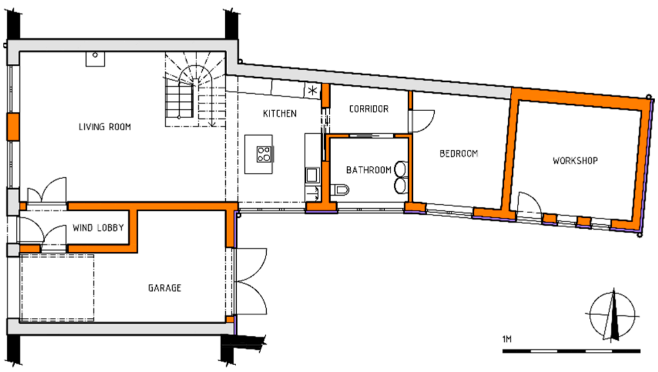
Figure 1. Original terraced house evaluated in V-1 LCA: (**a**) southern elevation with black hatching indicating envelope of adjacent house; (**b**) ground floor plan with coloured hatching indicating different construction materials identified during surveys. Black = envelope walls of adjacent houses, red = solid fired ceramic bricks, blue = aerated concrete blocks, red-yellow stripes = mix of solid fired bricks and adobe bricks, red-orange stripes = mix of solid fired bricks and hollow ceramic bricks.

The foundations of the house were made of rammed earth and stones. Foundations under the later extensions were made of plain concrete. The walls of the original house were made of a mixture of adobe and solid ceramic bricks, while the walls of later extensions were made of solid and hollow core ceramic bricks (barn and storages) or aerated concrete blocks (part of garage), as indicated in Figure 1b. The original house had timber joist ceiling covered with a layer of clay and bricks. The adjacent garage had a ceiling made of steel I-beams and ceramic panels. Storages and barns had ceilings made of steel I-beams and flat brick vaults. Most of the walls and ceilings were covered by lime or lime-cement plaster. The house had a gabled roof with timber roof truss, ceramic tiles, and galvanized steel flashing and gutters. Probes revealed that only some of the habitable rooms had a damp proof course. The house had no thermal insulation. Windows in the habitable rooms had wooden frames and double glazing. Other windows had metal frames and single glazing. Doors were made of wood or wood-based materials (such as particleboard). V-1 omits described structural issues and models hypothetical repairs, maintenance, and prolonged use of the original house. This would require 58.7 t of new construction materials during the expected service life of the house.

At the time of the survey, the house was connected to public electricity (above ground service cable), water, and sewage mains (steel service pipes). There was also an unused (and filled with debris) underground rainwater tank on the plot. Heating of the house was provided by electric radiators and DHW was provided by an electric boiler. Ventilation of the house was natural. Lighting was provided by fluorescent tubes and bulbs.

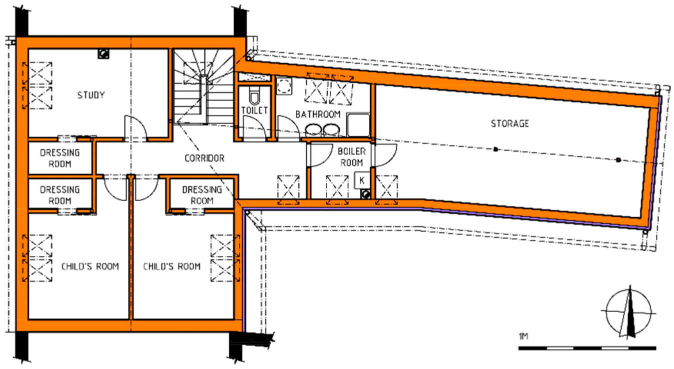
2.3. Description of the Hypothetical Renovation Assessed in V-2 LCA

LCA of the V-2 variant assesses renovation of the original house proposed in 2011 by the owner (see Figure 2). It consisted of a demolition of the outbuildings as well as part of the structures in habitable rooms. This should have enabled the extension of the habitable rooms on the ground floor as well as the addition of a habitable attic. It should be noted that the design did not meet contemporary energy standards for new construction. It was abandoned before energy optimization (e.g., addition of more thermal insulation to the envelope) as further surveying identified hidden structural damage that made preservation of any original structures impossible.



(**a**)

Figure 2. *Cont.*



(**b**)

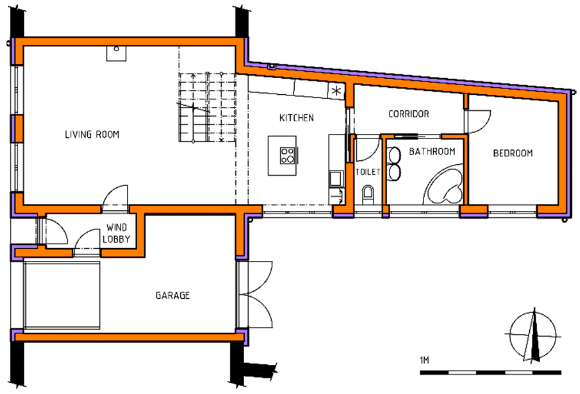
Figure 2. Renovated terraced house evaluated in V-2 LCA: (**a**) ground floor plan and (**b**) habitable attic plan with coloured hatching indicating different construction materials. Black = envelope walls of adjacent houses, grey = original structures, orange = hollow ceramic blocks, purple = additional EPS thermal insulation of the façade.

Foundations under new walls were designed of reinforced concrete. Walls were designed of hollow ceramic blocks. Original ceilings should have been replaced by a reinforced concrete floor structure. Both floors should have been connected by a timber staircase in the living room. New timber roof truss should have been supported with metal columns and covered with ceramic tiles and galvanized steel flashing. The ceiling under the roof should have been made of plasterboard panels with mineral wool insulation. Floors should have been insulated by EPS. Backyard facades should have been also insulated by EPS. Additional external insulation of the street façade and northern facade was impossible due to the fact that the insulation layer would exceed the plot boundary. The house should have had bituminous waterproofing, lime, or gypsum (interior) and synthetic plasters (exterior), wooden windows with double glazing, plastic and wooden doors, aluminium garage door, and ceramic or wooden floor tiling. Described construction works as well as future renovations would require 331.0 t of new construction materials during the service life of the renovated house.

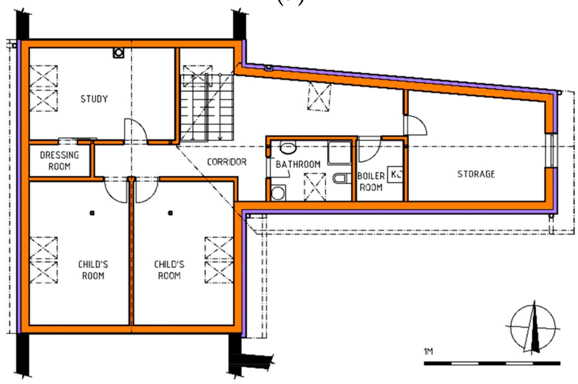
The renovation considered a complete overhaul of the BITS. Heating and DHW should have been provided by a gas boiler supplemented by an auxiliary fire-burning stove (10% of heating) in the living room. Ventilation should have been natural with auxiliary ventilators in kitchen, toilets, and bathrooms. All new piping should have been made of plastic (gas, DHW, water, sewage), copper, and steel (heating). Wastewater should have been discharged into municipal sewage; rainwater should have been collected in restored underground storage tank on the plot. Lighting should have been provided by energy saving bulbs.

2.4. Description of the Executed Demolition and New Construction in V-3 LCA

V-3 LCA evaluates the executed demolition and new construction in 2012. The new construction described in V-3 is an evolution of the V-2 design (see Figure 3). The structural and material design, as well as the BITS design, are similar to V-2. There are only two major differences. Firstly, the amount of the construction materials (345.7 t) as well as the amount of construction waste is higher compared to V-2. Secondly, the energy efficiency of the V-3 is significantly improved due to reduced heat losses through the fully insulated envelope (compared to lack of insulation in part of the V-2 facades). Still, it should be noted that the house does not meet nZEB requirements that came in force in 2020.



(a)



(b)

Figure 3. Newly constructed terraced house replacing the original as evaluated in V-3 LCA: (**a**) ground floor plan and (**b**) habitable attic plan with coloured hatching indicating different construction materials. Black = envelope walls of adjacent houses, grey = original structures, orange = hollow ceramic blocks, purple = additional EPS thermal insulation of the façade.

2.5. Description of the Assessed Sub-Variants

Table 1 summarizes data on the energy consumption of the evaluated variants of the house based on available energy calculations and certificates. In addition to the described real-life variants V1 to V3, this paper introduces several hypothetical sub-variants to evaluate the efficiency of various energy sources (summarized in Table 2). These variants represent alternatives commonly available in Czech Republic at the time of the renovation, according to consultations with local building designers.

- V-2E and V-3E, where the natural gas boiler is replaced with an electric boiler, similar to the original V-1 house. These sub-variants should enable better comparison of the renovation efficiency;
- V-2S and V-3S, where 20% of heating and 80% DHW is covered by a solar thermal system (STS) with 25 m^2 (V-2S) and 15 m^2 (V-3S) of flat plate collectors installed on the roof. A larger collector area was not considered for two reasons. Firstly, suitable area of the roof is limited by its shape and size as well as position and size of adjacent shading houses. Secondly, the designed boiler room has less than 5 m^2 in both V-2 and V-3. This fact limits maximum size of storage tank for heat accumulation;
- V-2W and V-3W, where the natural gas boiler is replaced with a wooden pellet boiler.

It should be noted that the change of the energy source does not influence related EEIs of heating or DHW system due to Eco-Bat 4.0 limitations (see Section 2.1). Therefore, EEIs of V-2, V2-E, and V2-W as well as V-3, V-3E, and V-3W are identical. The only difference is in V-2S and V-3S, where the STS (panels, etc.) is added.

3. Results

This section describes the results of the LCAs grouped primarily according to the standardized building life cycle structure defined in EN 15978. Figure 4 and Table 3 provide the overall results of all LCAs. Both the V-2 renovation as well as V-3 demolition and new construction have significantly lower OEIs compared to prolonged use of the original V-1 house. The difference reaches up to 93.1% in the case of V-3S. Figure 5 shows that this is due to the dominant share of operational energy on OEIs of the house. Particularly, heating-related impacts have 43.4% (V-3S) to 92.3% (V-1) share. In absolute numbers, this means, for example, that (electric) heating of the original V-1 house has more than four times higher environmental impacts than the whole life cycle of the V-3W and V-3S house variants.

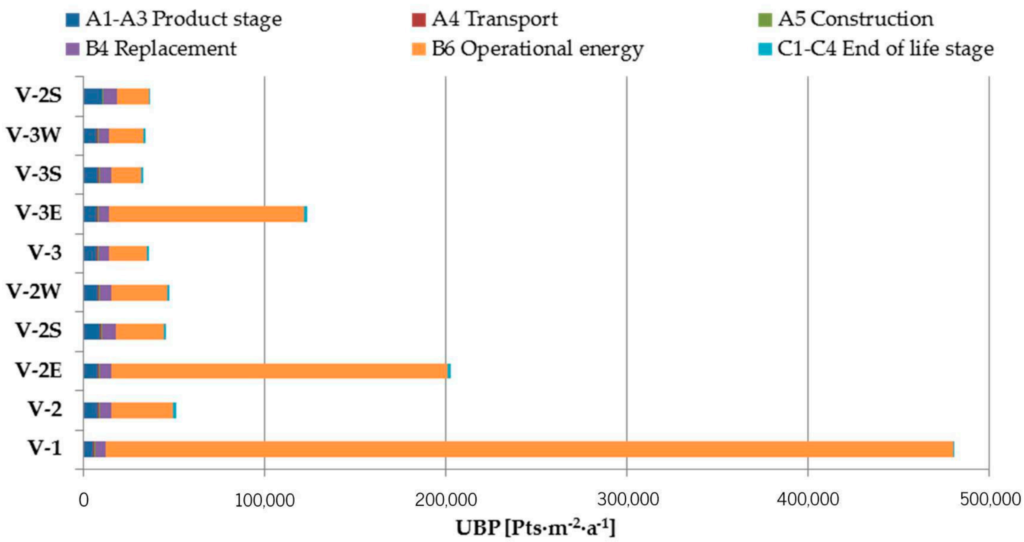


Figure 4. Overall environmental impacts (OEIs) of individual variants of the house per 1 m^2 of treated floor area (TFA) and year of operation in relevant LCA stages and modules, according to EN 15978.

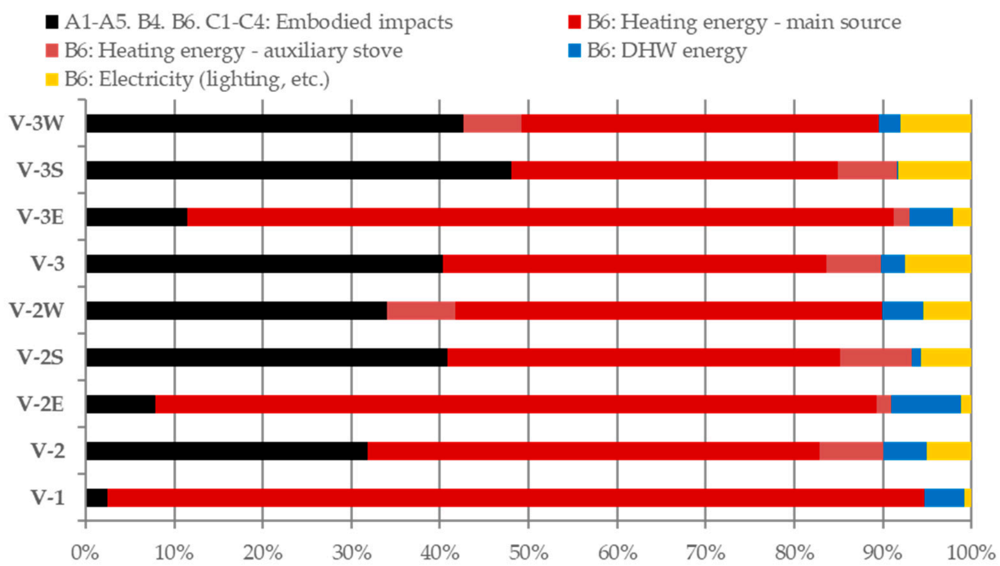
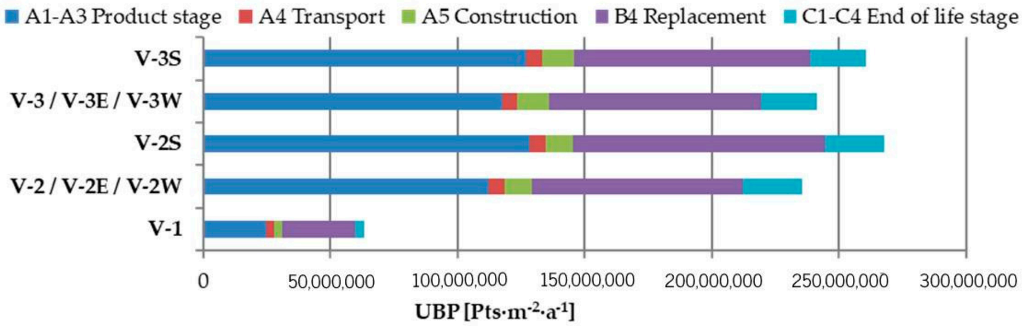


Figure 5. Shares of the particular systems on operational energy consumption and overall environmental impacts (OEIs) of the house variants.

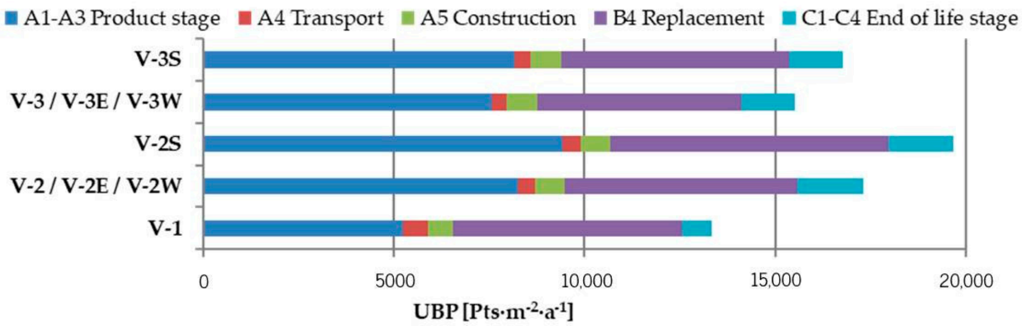
Table 3. Overall environmental impacts (OEIs) of individual variants of the house per 1 m^2 of treated floor area (TFA) and year of operation in relevant LCA stages and modules, according to EN 15978.

UBP [$Pts \cdot m^{-2} \cdot a^{-1}$]	V-1	V-2	V-2E	V-2S	V-2W	V-3	V-3E	V-3S	V-3W
A1–A3 Product stage	5.24×10^3	8.24×10^3	8.24×10^3	9.43×10^3	8.24×10^3	7.55×10^3	7.55×10^3	8.18×10^3	7.55×10^3
A4 Transport	6.47×10^2	4.59×10^2	4.59×10^2	4.59×10^2	4.59×10^2	3.98×10^2	3.98×10^2	3.98×10^2	3.98×10^2
A5 Construction	6.69×10^2	7.85×10^2	7.85×10^2	7.85×10^2	7.85×10^2	8.05×10^2	8.05×10^2	8.05×10^2	8.05×10^2
B4 Replacement	6.01×10^3	6.11×10^3	6.11×10^3	7.30×10^3	6.11×10^3	5.36×10^3	5.36×10^3	5.98×10^3	5.36×10^3
B6 Operational en.	4.68×10^5	3.38×10^4	1.86×10^5	2.62×10^4	3.05×10^4	2.06×10^4	1.08×10^5	1.64×10^4	1.87×10^4
C1–C4 End of life st.	7.71×10^2	1.72×10^2	1.72×10^2	1.72×10^2	1.72×10^2	1.42×10^2	1.42×10^2	1.42×10^3	1.42×10^2

Overall results show that additional EEIs related with V-2 and V-3 are overshadowed by operational energy. Still, it is desirable to evaluate their contribution to the results. Figure 6 shows the EEIs in two forms: total values and values per functional equivalent (see Section 2.1). Total values (Figure 6a) favour the original V-1 house. It has up to 4.4 times lower EEIs compared to V-2 and V-3 (and their variants) due to the limited number of changes and related new materials. On the other hand, V-1 has the least TFA. Therefore, the difference in results per the functional equivalent (Figure 6b) is much smaller: 14.1–32.3%.



(**a**)



(**b**)

Figure 6. Embodied environmental impacts (EEIs) of the assessed variants of the house per life cycle stages and modules according to EN 15978: (**a**) total results; (**b**) results per 1 m^2 of treated floor area (TFA) and year of operation.

Figures 7 and 8 provide yet another view of the EEIs. Figure 7 shows shares of individual structures on the total values: BITS have the highest share (20.3% on average) followed by flooring (11.7% on average) and doors and windows (11.3% on average). This explains, why V-2S have the highest EEIs as it includes 25 m^2 solar collectors. In contrast, the chimney, staircase, and non-loadbearing walls have all less than a 3% share (0.1–2.5%, respectively).

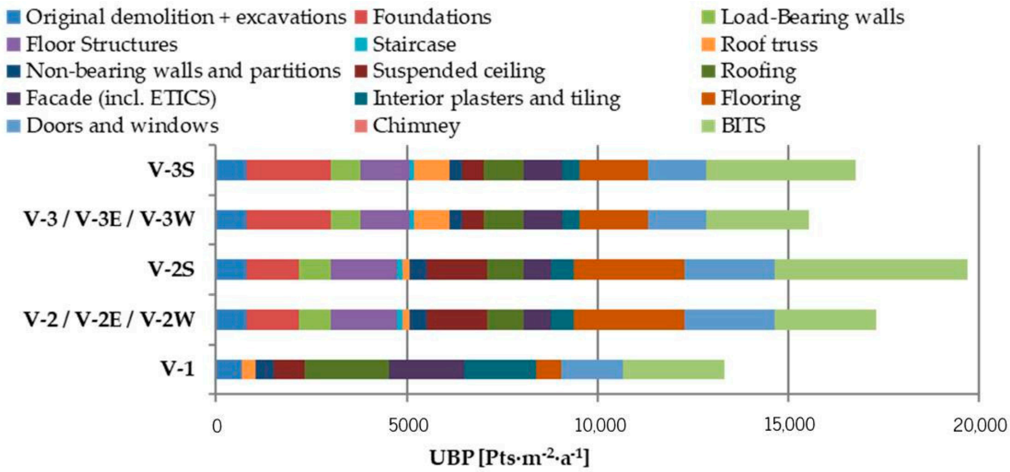


Figure 7. Embodied environmental impacts (EEIs) of the assessed variants of the house divided per construction elements.

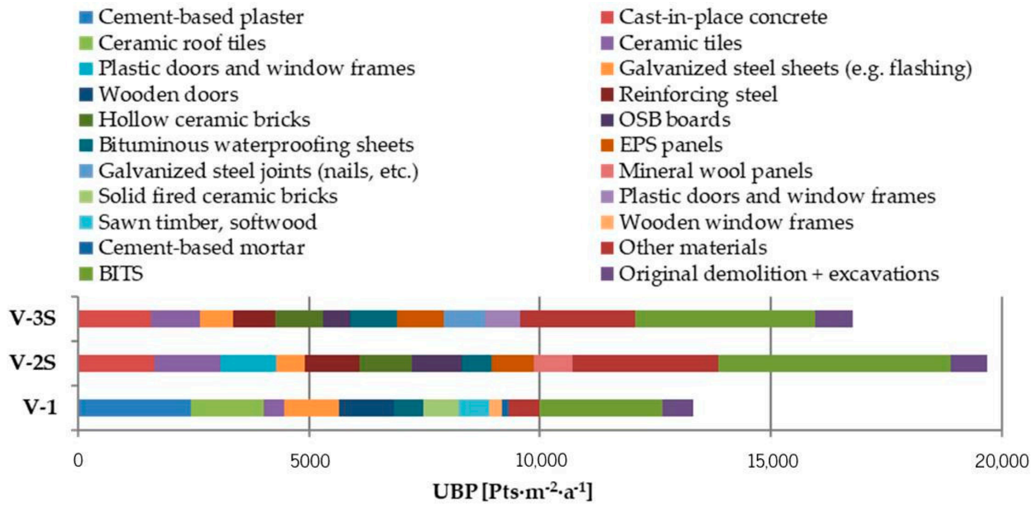


Figure 8. Shares of the ten most-demanding construction materials on the embodied environmental impacts (EEIs) of selected variants of the house.

Figure 8 further elaborates on EEIs. It highlights the shares of the ten most-demanding materials in V-1, V-2S, and V-3S (highest in each variant). These ten materials are responsible for 54.4% (in V-2S) to 70.0% (in V-1) of EEIs. In addition, in case of V-1, these materials make 91.7% of EEIs related with construction materials. Unsurprisingly, the most demanding materials in V-1 are related to finishes such as plasters (18.3% share on total EEIs) or roof tiles (11.8% share). In contrast, the most demanding material in V-2S and V-3S is concrete in foundations and floor structures with approximately 8.9% share of total EEIs. It is followed by ceramic tiles. There are two reasons for this result. Firstly, ceramic tiles have EEIs in UBP comparable with steel, according to the Eco-Bat 4.0 database. Secondly, finishes such as wall tiling have to be replaced several times during the house's service life.

4. Discussion and Conclusions

4.1. Efficiency of Assessed Renovation and New Construction

The results provide insight on the energy and environmental efficiency of renovations of traditional rural houses (in the South Moravian region). Overall, a comparison of the V-1, V-2, and V-3 results shows that even a significant increase in EEIs due to demolition of the original structures and subsequent new construction is outweighed by operational environmental savings. These correlate with energy savings (especially heating) achieved through the renovation or the new construction: Table 1 shows that V-2 and V-3 have

57.2% and 75.1% lower annual energy consumption per m^2 than V-1. The difference in OEIs per functional equivalent is 60.3% and 76.9%, respectively, with the same energy source (V-1, V-2E, V-3E). Further improvements are achievable with more efficient energy sources. Switching to natural gas as the main source of heating and DHW energy (as really designed) would result in an 89.4% (V-2) and 92.5% (V-3) reduction of OEIs compared to V-1. The resulting environmental "payback" times of the increased EEIs are less than a year in both V-2 and V-3. Consistency of these findings with other literature varies. Overall, the improvement of OEIs achieved by V-2 (and its variants) is similar to literature reviewed in Section 1. Resulting environmental payback time of the renovation is even lower than that in [47] due to the installation of a less-demanding energy source. The results also correlate with LCAs of several high-rise buildings in Hong Kong by [48], as the new construction is more efficient than the renovation of the original buildings. On the other hand, paper [61] comparing the refurbishment and replacement of a single-family house in Portugal concluded that new construction is less desirable than renovation due to approximately 30% higher embodied energy. The reason for the conclusion is in boundary conditions of the study, specifically operational energy consumption; the authors considered the same size and energy consumption for both new construction and renovation in [61]. This highlights the importance of energy efficiency in the reduction of environmental impacts of renovations or replacement of older buildings. The situation would be similar in the case study presented in this paper, if the V-2 and V-3 variants of the house had the same operational energy consumption, energy source, and TFA. This is illustrated by the comparison in Table 4. The comparison shows that such conditions would slightly favour major renovation V-2 instead of new construction V-3 as it requires fewer construction materials.

Table 4. Hypothetical overall environmental impacts (OEIs) of V-2 and V-3 recalculated per 229 m^2 treated floor area (equalling that of V-2) and total energy consumption equalling that provided in energy certificates in each variant.

Hypothetical Total Energy Consumption [GJ·a^{-1}]	**UBP [Pts·m^{-2}·a^{-1}]**	
	V-2	**V-3**
222.42 (equalling that of V-2)	5.11×10^5	5.15×10^5
147.78 (equalling that of V-3)	4.08×10^5	4.12×10^5

Table 4 also highlights another limit of comparing buildings with different shapes and sizes described, for example, in [11]. The interpretation of LCA results depends on the functional equivalent (unit). In this particular case study, the introduction of TFA to the functional equivalent has a significant impact on the interpretation of the results as there are large unheated spaces in the original house. The impact of this decision is illustrated in Figure 6. Both charts in Figure 6 show EEIs of selected variants, but the presentation could differ. As described in Section 3, Figure 6a shows a major advantage of V-1 over other variants since it includes only repairs and maintenance of the original house. The advantage is notably reduced in Figure 6b as the floor area of the (unheated) vernacular outbuildings is not included in the TFA. The issue of interpretation is further elaborated in Figure 9, showing percentage ratios of annual environmental impacts of the assessed variants: total annual impacts (Figure 9a), annual impacts per 1 m^2 of TFA (as in Section 3; Figure 9b), per 1 m^2 of gross floor area (Figure 9c), and per 1 m^3 of treated volume (Figure 9d). These functional equivalents are selected based on [11] and the available data. The charts mostly confirm the conclusions of Section 3 showing that V-2 renovation and even V-3 new construction are more environmentally sound than the prolonged use of the original V-1 building. The only exception is Figure 9a, showing that V-2E is 17.5% worse than V-1 as it is larger and has higher energy consumption (see Table 1). As such, the general conclusions regarding the efficiency of renovation vs. new construction should be comparable with reviewed literature. On the other hand, the figure confirms the dependence of the ratio between the worst and best house variant on the functional unit: the difference between the best (V-3S) and worst (V1 or V2-E) house variant ranges between 81.4% in Figure 9a and 93.5% in Figure 9d. The median variation of the results between charts in Figure 9 is 14.9%. This makes the accuracy of any comparison of numeric values in literature questionable, as the selection of a functional equivalent might be more important for the interpretation of the results than the actual results in some LCA modules (see Figure 5).

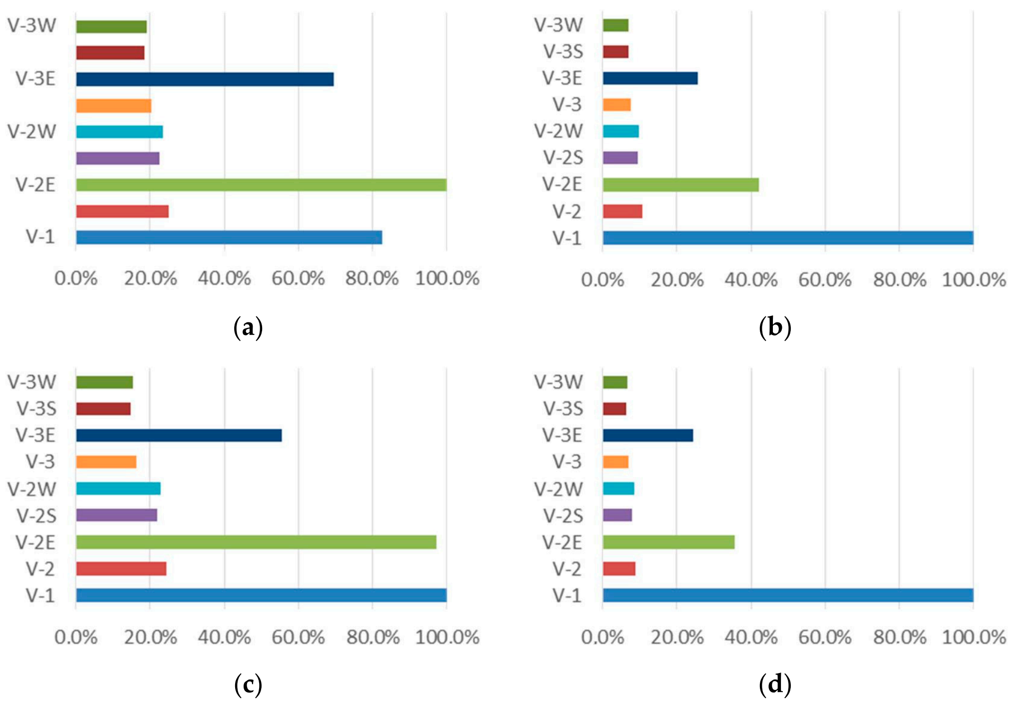


Figure 9. Influence of the functional equivalent on the interpretation of LCA results. Percentage ratios of environmental impacts of the assessed house variants per (**a**) year of operation, (**b**) year of operation and 1 m^2 of treated floor area (TFA), (**c**) year of operation and 1 m^2 of gross floor area, and (**d**) year of operation and 1 m^3 of treated volume.

4.2. Role of Energy Sources in Reducing Environmental Impacts of Buildings

The results clearly show that the reduction of environmental impacts of older buildings depends not only on improving energy efficiency, but also on the selection of suitable energy sources. Figure 4 and Table 3 show that the installation of a natural gas boiler helps reduce the environmental impacts of V-2 and V-3 by 89.4% and 92.5%, respectively, compared to electricity in V-1. Further improvements could be achieved with the utilization of renewables as in V-2S, V-2W, V-3S, and V-3W. Interestingly, the results show that these scenarios with renewables provide an additional reduction of OEIs of only approximately 1%: the difference is up to 93.1% when comparing V-1 and V-3S (most efficient scenario). The reasons for such a small difference between natural gas and renewables in the assessed houses are both technical and methodical:

- The benefits of solar energy in V-2S and V-3S are reduced due to increased EEIs related with installation and use of the STS and the fact that the system provides only 20% of heating energy. It should be noted that accuracy of this result is influenced by the limitations of the Eco-Bat 4.0 software. It is impossible to model state-of-art solutions such as STS utilizing latent heat storage (Phase Change Materials) that could have higher efficiency than traditional systems [62,63];
- The benefits of biomass in V-2W and V-3W are reduced due to the UBP methodology, as wood pellets and natural gas have similar environmental impacts in UBP: 27.8 and 31.5 Pts MJ^{-1}, respectively (compared to 204.3 Pts MJ^{-1} in case of electricity). The result could therefore change if different impact categories are considered. For

example, wood pellets have 98% lower environmental impacts than natural gas in GWP according to Eco-Bat 4.0 software;

- The benefits of renewables in general are seemingly reduced due to the inefficiency of the original V-1 house. A closer look at the results in Table 3 shows that the utilization of a wood pellet boiler results in up to 6.4% reduction of environmental impacts in V-2W and V-3W compared to V-2 and V-3, respectively. Similarly, OEIs of V-2S and V-3S are up to 10.2% lower compared to V-2 and V-3. This makes the STS the most (environmentally) desirable heating source for the described house. Literature such as [64,65] show that larger STS could provide even above 90% reduction environmental impacts compared to natural gas (depending on assessed impact categories). However, a larger solar system was not considered in the presented case study due to limitations described in Section 2.5.

It should be noted that the UBP methodology is not the only methodical choice influencing operational environmental impacts of the assessed houses. There are also significant differences in electricity datasets. Czech energy mix described in "Low-voltage Czech Republic" (see Section 2.1) has environmental impacts in UBP (in Eco-Bat 4.0) equalling 12,260 Pts MJ^{-1}. This is the highest value of any country in the region where this building type is common: Austrian low-voltage mix has UBP equalling 5644 Pts MJ^{-1}, Slovakian 10,987 Pts MJ^{-1} and Hungarian 12,218 Pts MJ^{-1}. As such, the benefits related to energy savings would be notably lower in these countries, making variants such as V-3S or V-3W less desirable from an environmental point of view.

4.3. Possible Simplification in Life-Cycle Inventory of Buildings

Standards such as EN 15978 suggest that it is possible to omit materials that are utilized in low amounts (weight) without lowering the accuracy of the LCA results. The LCAs in this paper considered all construction materials to evaluate the accuracy of this suggestion. Figure 8 shows the dominant share of the ten most-demanding construction materials on EEIs of each variant of the assessed house: from 54% in V-2 to 70% in V-1. Another 20–26% of EEIs are related to BITS. If we consider only materials (no BITS, excavations, etc.), then only 9 out of 20 materials in V-1, 15 out of 37 materials in V-2, and 14 out of 38 materials in V-3 have above 90% of the material-related EEIs. These materials also make up 93%, 95%, and 96%, respectively, of all construction materials used during initial renovation (or construction) and following the 60-year service life of the house(s). In contrast, from eight materials in V-1 to 21 materials in V-3 have below a 1% share on the material-related EEIs: plastic insulation anchors, windowsills, vapour barriers, nails or screws, etc. These materials combined have only a 3.7 to 4.3% share on the weight of all considered construction materials. This confirms a correlation between the amount of material and its importance for calculation of EEIs suggested by the standard. Obvious exceptions of this correlation are lightweight insulation materials such as EPS or rare materials used in small quantities (e.g., non-ferrous metals). For example, EPS has a 0.4% share on weight (1.6 t), but a 6.3% share on material-related EEIs in V-3. Similarly, 1.6 t of plastic window and door frames have a 0.5% share on construction material weight and a 6.4% share on material-related EEIs in V-2. Thus, while the automated omission of small-scale or lightweight materials could conserve time and simplify the calculations, it could also lead to unintentional reduction of LCA accuracy.

4.4. Concluding Remarks and Future Research Prospects

Overall, the results of the case study confirm the importance of building renovations for the reduction of anthropogenic environmental impacts necessary to fulfil global sustainable development goals. Even demolition of the original low-quality V-1 house and its replacement by new construction V-3 is favourable in the assessed case study due to reduced operational energy consumption and related environmental impacts. This shows importance of energy sources for the reduction of OEIs of inefficient buildings. Additionally, the advantage of on-site renewables over traditional energy sources (in the Central

European context) is visible even if their application is limited by the boundary conditions of the case study. On the other hand, the interpretation of the case study results highlights the issue of LCA accuracy. Small differences between the OEIs of renovations and new constructions makes their interpretation susceptible to the selection of boundary conditions, functional equivalent, and software limitations.

Future research should focus on providing more detailed LCA case studies that would allow the creation of databases similar to energy performance certificate databases available in some countries and regions referenced in [18]. This would allow the creation of guidelines and recommendations that are more accurate than those currently available as deliverables of projects such as ALDREN or Annex 56 [12,13]. Such guidelines would be beneficial for any practitioner dealing with the design and assessment of an efficient building with minimal impact on the environment. Additionally, future research should address the following issues:

- Influence of boundary conditions on LCA results;
- Sensitivity analysis on the omission of construction materials with minimum share on total weight of the house;
- Accuracy of the described LCAs and their conclusions for wider sample of buildings;
- Limits and benefits of wide-spread application of renewable energy sources, optimum mix of renewable energy sources for different building types and regions, and possible overuse of resources.

Author Contributions: Conceptualization, K.S. and M.O.; methodology, K.S.; software, K.S.; validation, K.S.; formal analysis, K.S.; investigation, K.S. and M.O.; resources, K.S. and M.O.; data curation, K.S.; writing—original draft preparation, K.S.; writing—review and editing, K.S. and M.O.; visualization, K.S.; supervision, K.S. and M.O.; project administration, M.O.; funding acquisition, M.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Czech Science Foundation, grant number 19-20943S "Compatibility of plastics and metals with latent heat storage media for integration in buildings".

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the In-Tergovernmental Panel on Climate Change*, 1st ed.; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; Intragovernmental Panel for Climate Change (IPCC): Geneva, Switzerland, 2014; 151p. Available online: https://bit.ly/3m9EHM7 (accessed on 29 March 2021).
2. IPCC. Summary for Policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 1st ed.; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; Intragovernmental Panel for Climate Change (IPCC): Geneva, Switzerland, 2018; p. 24. Available online: https://bit.ly/3cuaHHE (accessed on 29 March 2021).
3. UN. *Paris Agreement*; United Nations (UN): Paris, France, 2015; p. 27. Available online: http://unfccc.int/paris_agreement/items/9485.php (accessed on 29 March 2021).
4. EC. *The European Green Deal*; European Commission (EC): Brussels, Belgium, 2019; p. 24. Available online: https://bit.ly/3sxKhdK (accessed on 29 March 2021).
5. Bauer, A.; Menrad, K. Standing up for the Paris Agreement: Do global climate targets influence individuals' greenhouse gas emissions? *Environ. Sci. Policy* **2019**, *99*, 72–79. [CrossRef]
6. D'Agostino, D.; Mazzarella, L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *J. Build. Eng.* **2019**, *21*, 200–212. [CrossRef]
7. European Union. *Energy Data—2020 Edition*, 1st ed.; Publications Office of the European Union: Luxembourg, 2020; p. 334. Available online: https://bit.ly/3w9Unne (accessed on 29 March 2021).

8. Birgisdottir, H.; Moncaster, A.; Wiberg, A.H.; Chae, C.; Yokoyama, K.; Balouktsi, M.; Seo, S.; Oka, T.; Lützkendorf, T.; Malmqvist, T. IEA EBC annex 57 'evaluation of embodied energy and CO_{2eq} for building construction'. *Energy Build.* **2017**, *154*, 72–80. [CrossRef]
9. Satola, D.; Balouktsi, M.; Lützkendorf, T.; Wiberg, A.H.; Gustavsen, A. How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72. *Build. Environ.* **2021**, *192*, 107619. [CrossRef]
10. Wei, W.; Skye, H.M. Residential net-zero energy buildings: Review and perspective. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110859. [CrossRef]
11. Thibodeau, C.; Bataille, A.; Sié, M. Building rehabilitation life cycle assessment methodology-state of the art. *Renew. Sustain. Energy Rev.* **2019**, *103*, 408–422. [CrossRef]
12. Terés-Zubiaga, J.; Bolliger, R.; Almeida, M.G.; Barbosa, R.; Rose, J.; Thomsen, K.E.; Montero, E.; Briones-Llorente, R. Cost-effective building renovation at district level combining energy efficiency & renewables—Methodology assessment proposed in IEA EBC Annex 75 and a demonstration case study. *Energy Build.* **2020**, *224*, 110280. [CrossRef]
13. Sesana, M.M.; Rivallain, M.; Salvalai, G. Overview of the Available Knowledge for the Data Model Definition of a Building Renovation Passport for Non-Residential Buildings: The ALDREN Project Experience. *Sustainability* **2020**, *173*, 642. [CrossRef]
14. D'Agostino, D.; Zangheri, P.; Castellazzi, L. Towards Nearly Zero Energy Buildings in Europe: A Focus on Retrofit in Non-Residential Buildings. *Energies* **2017**, *10*, 117. [CrossRef]
15. Göswein, V.; Silvestre, J.D.; Monteiro, C.S.; Habert, G.; Freire, F.; Pittau, F. Influence of material choice, renovation rate, and electricity grid to achieve a Paris Agreement-compatible building stock: A Portuguese case study. *Build. Environ.* **2021**, *195*, 107773. [CrossRef]
16. Awadh, O. Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *J. Build. Eng.* **2017**, *11*, 25–29. [CrossRef]
17. Qiu, Y.; Kahn, M.E. Impact of voluntary green certification on building energy performance. *Energy Econ.* **2019**, *80*, 461–475. [CrossRef]
18. Bottero, M.; Dell'Anna, F.; Morgese, V. Evaluating the Transition Towards Post-Carbon Cities: A Literature Review. *Sustainability* **2021**, *13*, 567. [CrossRef]
19. Li, Y.; Kubicki, S.; Guerriero, A.; Rezgui, Y. Review of building energy performance certification schemes towards future improvement. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109244. [CrossRef]
20. Li, C.Z.; Lai, X.; Xiao, B.; Tam, V.W.; Guo, S.; Zhao, Y. A holistic review on life cycle energy of buildings: An analysis from 2009 to 2019. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110372. [CrossRef]
21. Zhang, X.; Liu, K.; Zhang, Z. Life cycle carbon emissions of two residential buildings in China: Comparison and uncertainty analysis of different assessment methods. *J. Clean. Prod.* **2020**, *266*, 122037. [CrossRef]
22. Piccardo, C.; Dodoo, A.; Gustavsson, L. Retrofitting a building to passive house level: A life cycle carbon balance. *Energy Build.* **2020**, *223*, 110135. [CrossRef]
23. Strantzali, E.; Aravossis, K. Decision making in renewable energy investments: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 885–898. [CrossRef]
24. Laurin, L. Overview of LCA—History, Concept, and Methodology. In *Encyclopedia of Sustainable Technologies*, 1st ed.; Abraham, M.A., Ed.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 217–222.
25. International Organization for Standardization. *ISO 14040:1997 Environmental Management—Life Cycle Assessment—Principles and Framework*, 1st ed.; International Organization for Standardization: Geneva, Switzerland, 1997; p. 12.
26. ISO. *ISO 21931-1:2010 Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental Performance of Construction Works—Part 1: Buildings*, 1st ed.; International Organization for Standardization (ISO): Geneva, Switzerland, 2010; p. 26.
27. CEN. *EN 15978:2011 Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method*, 1st ed.; European Committee for Standardization (CEN): Brussels, Belgium, 2011; p. 64.
28. CEN. *EN 15804:2012+A2:2019 Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products*, 1st ed.; European Committee for Standardization (CEN): Brussels, Belgium, 2019; p. 76.
29. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
30. Anand, C.K.; Amor, B. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 408–416. [CrossRef]
31. Saade, M.R.M.; Guest, G.; Amor, B. Comparative whole building LCAs: How far are our expectations from the documented evidence? *Build. Environ.* **2020**, *167*, 106449. [CrossRef]
32. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Integrated Assessment and Visualization of Building Elements' Embodied Impacts for Design Guidance in Early Stages. *Procedia CIRP* **2018**, *69*, 218–223. [CrossRef]
33. Nwodo, M.N.; Anumba, C.J. A review of life cycle assessment of buildings using a systematic approach. *Build. Environ.* **2019**, *162*, 106290. [CrossRef]
34. Christensen, T.; Damgaard, A.; Levis, J.; Zhao, Y.; Björklund, A.; Arena, U.; Barlaz, M.; Starostina, V.; Boldrin, A.; Astrup, T.; et al. Application of LCA modelling in integrated waste management. *Waste Manag.* **2020**, *118*, 313–322. [CrossRef] [PubMed]

35. Hossain, U.; Ng, S.T. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *J. Clean. Prod.* **2018**, *205*, 763–780. [CrossRef]
36. Hopkinson, P.; Chen, H.-M.; Zhou, K.; Wang, Y.; Lam, D.; Wong, Y. Recovery and reuse of structural products from end-of-life buildings. *Eng. Sustain.* **2019**, *172*, 119–128. [CrossRef]
37. Francart, N.; Larsson, M.; Malmqvist, T.; Erlandsson, M.; Florell, J. Requirements set by Swedish municipalities to promote construction with low climate change impact. *J. Clean. Prod.* **2019**, *208*, 117–131. [CrossRef]
38. Zhang, B.; Su, S.; Zhu, Y.; Li, X. An LCA-based environmental impact assessment model for regulatory planning. *Environ. Impact Assess. Rev.* **2020**, *83*, 106406. [CrossRef]
39. González-García, S.; Caamaño, M.R.; Moreira, M.T.; Feijoo, G. Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis. *Sustain. Cities Soc.* **2021**, *64*, 102546. [CrossRef]
40. Schlegl, F.; Gantner, J.; Traunspurger, R.; Albrecht, S.; Leistner, P. LCA of buildings in Germany: Proposal for a future benchmark based on existing databases. *Energy Build.* **2019**, *194*, 342–350. [CrossRef]
41. Durão, V.; Silvestre, J.D.; Mateus, R.; de Brito, J. Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes. *Resour. Conserv. Recycl.* **2020**, *156*, 104703. [CrossRef]
42. Sartori, T.; Drogemuller, R.; Omrani, S.; Lamari, F. A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS). *J. Build. Eng.* **2021**, *38*, 102180. [CrossRef]
43. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montañes, B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build.* **2017**, *135*, 286–301. [CrossRef]
44. Galimshina, A.; Hollberg, A.; Moustapha, M.; Sudret, B.; Favre, D.; Padey, P.; Lasvaux, S.; Habert, G. Probabilistic LCA and LCC to identify robust and reliable renovation strategies. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012058. [CrossRef]
45. Palacios-Munoz, B.; Peuportier, B.; Gracia-Villa, L.; López-Mesa, B. Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach. *Build. Environ.* **2019**, *160*, 106203. [CrossRef]
46. Hasik, V.; Escott, E.; Bates, R.; Carlisle, S.; Faircloth, B.; Bilec, M.M. Comparative whole-building life cycle assessment of renovation and new construction. *Build. Environ.* **2019**, *161*, 106218. [CrossRef]
47. Shirazi, A.; Ashuri, B. Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta. *Build. Environ.* **2020**, *171*, 106644. [CrossRef]
48. Langston, C.; Chan, E.H.W.; Yung, E.H.K. Hybrid Input-Output Analysis of Embodied Carbon and Construction Cost Differences between New-Build and Refurbished Projects. *Sustainability* **2018**, *10*, 3229. [CrossRef]
49. Weiler, V.; Harter, H.; Eicker, U. Life cycle assessment of buildings and city quarters comparing demolition and reconstruction with refurbishment. *Energy Build.* **2017**, *134*, 319–328. [CrossRef]
50. ISO. *ISO 14044: 2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines*, 1st ed.; International Organization for Standardization: Geneva, Switzerland, 2006; p. 20.
51. Favre, D.; Citherlet, S. Eco-Bat: A design tool for assessing environmental impacts of buildings and equipment. *Build. Simul.* **2008**, *1*, 83–94. [CrossRef]
52. Romagnoni, P.; Cappelletti, F.; Peron, F.; Dalla Mora, T.; Ruggeri, P.; Almeida, M.; Ferreira, M. *Tools and Procedures to Support Decision Making for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)*, 1st ed.; University of Minho: Minho, Portugal, 2017; p. 80. Available online: https://bit.ly/32seuPP (accessed on 18 April 2021).
53. Frischknecht, R.; Büsser Knöpfel, S. *Swiss Eco-Factors 2013 According to the Ecological Scarcity Method. Methodological Fundamentals and Their Application in Switzerland. Environmental Studies no. 1330*, 1st ed.; Federal Office for the Environment: Bern, Switzerland, 2013; p. 254. Available online: https://bit.ly/3u4BjVr (accessed on 29 March 2021).
54. Muhl, M.; Berger, M.; Finkbeiner, M. Development of Eco-factors for the European Union based on the Ecological Scarcity Method. *Int. J. Life Cycle Assess.* **2019**, *24*, 1701–1714. [CrossRef]
55. ISO. *ISO 15686-1: 2011 Building and Constructed Assets—Service Life Planning: Part 1, General Principles and Framework*; International Organization for Standardization: Geneva, Switzerland, 2011; p. 21.
56. De Almeida, M.G.; Ferreira, M.A.P.S. Cost effective energy and carbon emissions optimization in building renovation (Annex 56). *Energy Build.* **2017**, *152*, 718–738. [CrossRef]
57. Lasvaux, S.; Favre, D.; Périsset, B.; Bony, J.; Hildbrand, C.; Citherlet, S. Life Cycle Assessment of Energy Related Building Renovation: Methodology and Case Study. *Energy Procedia* **2015**, *78*, 3496–3501. [CrossRef]
58. Delem, L.; Wastiels, L.; Van Dessel, J. Assessing the Construction Phase in Building Life Cycle Assessment. In Proceedings of the [avniR] LCA Conference 2013, Lille, France, 4–5 November 2013; Available online: https://bit.ly/3dk6JjT (accessed on 29 March 2021).
59. Kleemann, F.; Laner, D.; Laner, D. Waste Prevention in the Prefabricated Building Sector. *Appl. Mech. Mater.* **2019**, *887*, 361–368. [CrossRef]
60. Koordinationskonferenz der Bau- und Liegenschaftsorgane der Öffentlichen Bauherren KBOB. Available online: https://www.kbob.admin.ch/kbob/de/home.html (accessed on 29 March 2021).
61. Gaspar, P.L.; Santos, A.L. Embodied energy on refurbishment vs. demolition: A southern Europe case study. *Energy Build.* **2015**, *87*, 386–394. [CrossRef]

62. Allred, P.M. Phase Change Materials for Solar Thermal Energy Storage. Master's Thesis, Dalhousie University, Halifax, NS, Canada, 2014; p. 83.
63. Bonamente, E.; Aquino, A. Environmental Performance of Innovative Ground-Source Heat Pumps with PCM Energy Storage. *Energies* **2019**, *13*, 117. [CrossRef]
64. Comodi, G.; Bevilacqua, M.; Caresana, F.; Pelagalli, L.; Venella, P.; Paciarotti, C. LCA Analysis of Renewable Domestic Hot Water Systems with Unglazed and Glazed Solar Thermal Panels. *Energy Procedia* **2014**, *61*, 234–237. [CrossRef]
65. Ozturk, M.; Dincer, I. Comparative environmental impact assessment of various fuels and solar heat for a combined cycle. *Int. J. Hydrogen Energy* **2019**, *44*, 5043–5053. [CrossRef]