energies

MDPI

Article

Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects

Roberta Moschetti * and Helge Brattebø

Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway; helge.brattebo@ntnu.no

* Correspondence: roberta.moschetti@ntnu.no or roberta.moschetti@gmail.com

Received: 12 October 2017; Accepted: 3 November 2017; Published: 13 November 2017

Abstract: Buildings currently play a fundamental role for the achievement of the sustainable development goals as they are responsible for several environmental, social, and economic impacts. Energy renovation projects of existing buildings can support the reduction of environmental impacts by leading, at the same time, to economic and social advantages. In this paper, the life cycle assessment and life cycle costing methodologies were used in a combined performance assessment applied to a case study, i.e., the energy renovation project of a single-family house in Norway. Several scenarios based on alternative energy efficiency measures were analyzed, and life cycle environmental and economic indicators were computed, i.e., global warming potential (GWP), cumulative energy demand (CED), and net present cost (NPC). The results demonstrated the close to negative linear regression between the environmental and economic indicators computed. However, the values of CED and GWP for the best scenarios in environmental terms were respectively 50% and 32% lower than the values of the worst scenarios, while their NPC was around 6% higher than the lowest values. The findings can be helpful in the decision-making context towards a meaningful combination of environmental and economic assessments in building energy renovation projects for selecting the most sustainable scenario.

Keywords: buildings; energy renovation; dynamic energy simulation; life cycle assessment (LCA); life cycle costing (LCC); sensitivity analyses

1. Introduction

Buildings play a fundamental role for the achievement of the sustainable development goals as they are responsible for several environmental, social, and economic impacts [1]. In recent years, policies and laws have been increasingly introduced with the objective of increasing the energy efficiency of new and existing buildings. In 2010, the Energy Performance of Buildings Directive (EPBD recast) focused on the minimum energy performance requirements for new buildings, and introduced the nearly zero-energy building concept [2]. Moreover, the EPBD recast mentioned that certain energy performance requirements should also be met by existing buildings subject to major renovations. Existing buildings are responsible for most energy use and greenhouse gas (GHG) emissions, while their replacement rate is currently very low, 1.0–3.0% per year [3]. Therefore, energy renovation projects can help improving the energy performance of the existing building stock through the implementation of energy efficiency measures (EEMs) for the building envelope and/or the technical building systems. The effectiveness of EEMs has been extensively examined, in recent years, for different existing building categories, with cost-benefit analyses mainly focused on the evaluation of the annual energy savings and the payback period [4–7].

Building energy renovation projects are significant not only for lowering the environmental impacts, but also for their economic and social consequences, such as the reduction of utility bills and maintenance costs, the generation of new job opportunities, and the improvement of the well-being within the built environment [8–10]. Therefore, the assessment of building renovation effects on the environmental and economic dimensions is important for defining the overall optimal sustainability performance. For environmental and economic assessments, the life cycle assessment (LCA) and life cycle costing (LCC) are among the most solid and used methodologies.

LCA allows the examination of the environmental impacts of a given product, system or service throughout the whole life cycle [11,12]. LCA studies were carried out in many different sectors and, more recently, also in the construction field for building components and entire buildings [13]. The use of LCA in the building sector is rather recent, particularly in energy renovation projects. Although a complete LCA in a building project is a complicated task depending on several factors, the importance of evaluating the environmental impacts throughout the whole life span has been increasingly acknowledged [14]. LCA allows the evaluation of the increased impacts resulting from the consumption of additional materials and components related to the renovation measures, together with the subsequent lower energy use during the post-renovation phase [15].

The time horizon after the renovation project considered in LCA analyses can highly vary among different studies, as well as the system boundaries. A life span in the range 20–60 years is often used, together with the cradle-to-grave option, which includes the material production, building construction, operation, and end-of-life (EOL) phases [16,17]. The impact assessment is usually based on information from Environmental Product Declarations (EPDs) or from generic databases, such as Ecoinvent [18,19]. The environmental impacts are evaluated through specific impact assessment methods, and the impact categories considered can be both midpoint and endpoint, including climate change, primary energy demand, and eco-indicator points [20].

LCC represents a valuable economic approach for assessing the total costs of products or projects during a period. It involves all the relevant economic factors, and provides the discounting of future costs to their present value, which is particularly relevant for systems with a long life span, such as buildings [21]. The LCC methodology was first adapted to the building field in the 1960s [22]. In recent years, several studies focused on the optimal building renovation strategies by identifying their economic value over the entire building life cycle through LCC [23,24]. The calculation period in LCC analyses can be equivalent to the building life span after the renovation project, 20–60 years; while the system boundaries can be the same as in LCA, although they often include only the construction and operation phases [16]. The cost categories considered are in accordance with the life phases analyzed, and can include investment costs, maintenance costs, replacement costs, operational costs, and EOL costs [25]. Due to the calculation of the economic effects in a relatively long time span, the future cash flow evaluation is particularly relevant. To this aim, several calculation techniques are available, such as the annual cost (AC), the payback period, and the net present value (NPV); therefore, specific discount factors are used to actualize future costs to the starting year of calculation [26].

In the literature, life cycle environmental and economic assessments in building energy renovation projects have been more often performed separately [8,23,27–31]. However, combined analyses have been increasingly carried out in recent years [32–35]. In the existing studies analyzed, the EEMs concern three main categories, i.e., the renovation of the building envelope, the improvement of the technical building systems, and the implementation of renewable energy technologies. However, these three categories are often separately considered, and the life cycle environmental and economic impacts of an overall renovation project has been rarely evaluated. Moreover, the methodological approach for properly combining the environmental and economic indicator results is not always object of study. The lack of comprehensive LCA/LCC studies for building energy renovation projects leads to the need of further research in this field. Additional studies would, in fact, be significant towards a more standardized methodological approach and the increase in the availability of representative case studies. Sensitivity analyses should also be performed for reducing the limitations and uncertainties in the key input parameters.

This paper, after a careful review of the literature, presents a methodological approach for combining life cycle environmental and economic assessments in building energy renovation projects. This approach is then applied to a case study, i.e., the project of a single-family house that has recently been subjected to a deep energy renovation in Norway. In particular, several scenarios including different EEMs are examined, in addition to the project as realized. Specific environmental and economic indicators are computed for all scenarios, and the possibility of identifying the optimal sustainable scenario is discussed.

The paper is organized as follows: in Section 2, the case study is introduced and described, along with the assumptions and input data for the analyses performed, i.e., the life cycle environmental assessment, the life cycle economic assessment, and the sensitivity analyses. In Sections 3 and 4, the results are illustrated and critically discussed. Finally, in Section 5, the conclusions are presented.

2. Methods

This section presents the methodological approach followed in this paper (Figure 1), which is also generalizable to other building renovation projects.

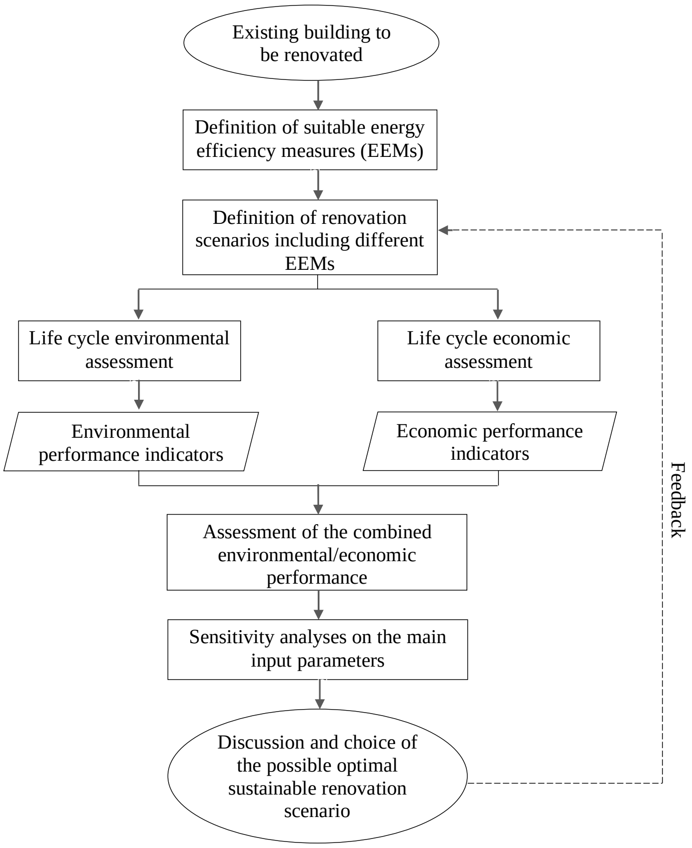

Figure 1. Methodological framework for combined life cycle environmental and economic assessments in building energy revocation projects.

2.1. Case Study

The case study is the energy renovation project of a single-family house located in Oslo, as shown in Figure 2.

(**Basement floor**) (**First floor**)

(**Second floor**) (**Perspective**)

Figure 2. Floor plans and perspective of the single-family house analyzed. Reprint with permission [SINTEF Byggforsk]; Copyright 2017, http://seopp.net/forside/.

The case building analyzed is part of a Norwegian research project, Systematisk EnergiOppgradering av småhus (SEOPP, http://seopp.net/forside/), which aimed at developing methods and solutions for the systematic energy renovation of single-family houses. SEOPP project selected the renovation of the house examined in this paper as a representative typical project in the Norwegian and, more generally, the Nordic context. The renovation measures adopted in this project were the following: design of a more functional internal layout by slightly increasing the floor area; upgrade of the building envelope with extra insulation in the roof, new cladding in external walls, extra insulation in external walls, new insulation in the basement floor and walls, new triple pane windows, and new external doors; bathroom renovation; new external drainage; exterior/interior painting; new balanced mechanical ventilation system with heat recovery; new electric radiators; new electric floor heating; and a new clean burning wood stove.

Note that all the renovation measures adopted in the project were considered in this paper, including those not focused on the building energy efficiency. The objective was to have an overall picture of the life cycle environmental and economic impacts of a typical renovation project. The EEMs of the project mainly addressed the renovation of the building envelope, with the objective of improving its energy efficiency by complying with the requirements of the Norwegian technical regulation, Byggteknisk Forskrift TEK 10 for new buildings [36]. Regarding the technical building systems, the project contemplated the replacement of the old systems for space heating purpose, a new balanced ventilation system, and a new energy efficient wood stove; however, no new renewable energy technologies (RETs), such as photovoltaic (PV) panels, were provided.

In this paper, seven alternative scenarios (S) were defined and explored, in addition to the reference scenario (S1) that concerned the renovation project as it was implemented for the case building. In particular, the scenarios S2–S7 present all the renovation measures of S1 with some differences in terms of the space heating system and the RETs, which were defined through the following combinations:

- S1: electric radiators, electric floor heating, air-to-air heat pump, and wood stove;
- S2: electric radiators, electric floor heating, and no RETs;
- S3: multi-split air-to-water heat pump with water radiators;
- S4: electric radiators, electric floor heating, wood stove, and no RETs;
- S5: electric radiators, electric floor heating, and PV system;
- S6: electric radiators, electric floor heating, PV system, and solar thermal system;
- S7: multi-split air-to-water heat pump with water radiators, PV system, and solar thermal system.

In S1, S2, S4, S5, and S6, the electric radiators are located in all rooms, excluding the bathrooms, where the electric floor heating is used. In S1 and S4, the wood stove is located in the living room, as well as the heat pump of S1. In S3 and S7, the water radiators are in all rooms, while the PV system and solar thermal system of S5, S6, and S7 are placed on the roof. All scenarios have the same domestic hot water (DHW) system and a balanced mechanical ventilation system with 85% heat recovery. Geometrical data and information on the building envelope are shown in Table 1. Moreover, detailed information on the main components of the building envelope is summarized in Table S1 of Supplementary Materials.

Table 1. Main geometrical data and building envelope features for the case building.

Description	Value
Total number of floors (-)	3
Net floor area (m^2)	159.0
Gross internal floor area (m^2)	176.7
Gross external floor area (m^2)	211.8
Gross volume (m^3)	563.50
External wall area (m^2)	386.54
Window area (m^2)	29
Average thermal bridge ($W/m^2/K$)	0.03
Air leakage, 50 Pa (1/h)	1

2.2. *Analyses Performed*

In this sub-section, the analyses performed are presented with all assumptions and main information.

2.2.1. Life Cycle Assessment

A LCA was performed for the various scenarios, considering the four stages defined in the standards ISO 14040:2006 and ISO 14044:2006: goal and scope definition, inventory analysis, impact assessment, and result interpretation. The goal of the analysis was to assess the environmental impacts of the scenarios over the building life span after the renovation, which was initially set equal to 50 years. The functional unit of the analysis was 1 m^2 of gross internal floor area, which is measured to the internal face of the external walls, including partitions, chimney, and stairwell. Henceforth, the term 'floor area' is used to refer to the gross internal floor area of the building.

The inventory analysis involved the following three life cycle phases: the construction phase, which regarded the material production and transport to the construction site; the operation phase, which concerned the energy demand for space heating, DHW, lighting, and electric appliances; and the EOL phase, including the material waste transport, processing, and final disposal.

For the analysis of the construction phase, the quantity of the materials used for renovating both the building envelope and the technical building systems was defined. The materials were also associated to a waste factor (WF) based on [37], which expresses the cutting waste generated during the construction phase. All the materials were assumed to be transported by lorries (16–32 t) and the distance between the manufacturing place and the construction site was defined on the basis of the project documentation, assuming a distance of 100 km in case of lacking information.

Note that the direct energy used for the construction and maintenance activities, e.g., for assembling materials and running the construction site, was neglected since no information were available from the project documentation. Tables S2 and S3 of Supplementary Materials show the inventory for the materials of the building envelope and the technical building systems, respectively.

For the analysis of the operation phase, the annual energy use for space heating purpose was assessed by means of the dynamic energy simulation tool IDA-ICE (EQUA Simulation AB, Stockholm, Sweden) [38], which presents equation-based modelling and a variable time step differential-algebraic (DAE) solver. The information about the average energy use for indoor lighting, electric appliances, and DHW stemmed from the Norwegian standards NS 3031:2014 [39] and NS 3700:2013 [40]. These standards were also used to define the main parameters for the energy simulations in IDA-ICE, which are summarized in Table S4 of Supplementary Materials. The International Weather for Energy Calculation 2.0 (IWEC2) database [41] represented the source of the hourly weather data for a typical meteorological year in Oslo. It is worth noting that, in scenarios S1 and S4, the annual energy use for space heating was assumed to be covered by the wood stove to an extent of 20% and 40%, respectively. Furthermore, in S5, S6 and S7, the electricity production by the PV panels was evaluated by means of the Photovoltaic Geographical Information System (PVGIS) tool [42]; however, in S6 and S7, the energy produced by the solar thermal system was assessed through the f-chart method [43]. Table S5 of Supplementary Materials shows the main input data for the PV and solar thermal system design.

Certain maintenance measures during the operation phase were assumed for all scenarios, based on [44,45], as shown in Table S6 of Supplementary Materials. Note that the replacement of certain technical building systems, i.e., the DWH boiler and heat pump, was considered even if they were not part of the initial EEMs, and it was assumed to happen after 15 years of the renovation project occurrence.

Regarding the EOL phase, the waste transport, handling, and disposal were considered for all materials involved in the energy renovation project, and a worst-case scenario was defined. In particular, steel, aluminum, iron, glass, concrete, ceramic, and glass wool were assumed to be entirely landfilled. Wood was assumed to be treated in an incineration plant, along with other materials, such as polyethylene, polypropylene, expanded polystyrene, paper, and rubber. Furthermore, waste materials were assumed to be transported by lorries (16–32 t), with an average distance of 85 km from the construction site to all the treatment plants. No gains from the potential material recycling and the energy recovery from incineration were considered.

For the impact assessment stage, data from Ecoinvent 3.1 database (The Ecoinvent Centre, St.Gallen, Switzerland) [46] were used for materials, energy carriers, and processes. The model was run in SimaPro 8.1.1 software (PRé Sustainability, Amersfoort, The Netherlands) [47], and the attributional modelling approach was used, with the 'Allocation, recycled content' model available in Ecoinvent. The 'unit processes' data library was used, together with transforming activities mostly characterized by the geographic location 'Europe (RER)'.

The total delivered energy throughout the life cycle was calculated from the annual energy use, which was assumed to be constant for the whole period. The Nordel electricity mix was used in the Ecoinvent database (0.17 kg CO_2 eq./kWh and 7.67 MJ/kWh) [48]. Furthermore, the combustion of the wood consumed by the wood stove in S1 and S4 was also implemented in the model.

Two impact assessment methods were used for the impact definition, i.e., the ReCiPe method, to assess the global warming potential (GWP) indicator (over a time horizon of 100 years), as in Equation (1); and the cumulative energy demand (CED) method, to compute the CED indicator, as in Equation (2).

$$\mathrm{GWP} = \sum_i GWP_i m_i + \sum_j GWP_j t_j + \sum_k GWP_k e_k + \sum_n GWP_n m_n \tag{1}$$

where GWP is the total global warming potential during the building life cycle after the renovation [CO_2 eq.]; GWP_i is the global warming potential of the material/construction product i used for building construction and maintenance [kg CO_2 eq./kg]; m_i is the mass of the material/construction product i [kg]; GWP_j is the global warming potential of a transport activity j of the material/construction product j [kg CO_2 eq./tkm]; t_j is the payload distance of the material/construction product j [tkm]; GWP_k is the global warming potential of the energy carrier k [kg CO_2 eq./kWh]; e_k is the operational delivered energy of the carrier k [kWh]; GWP_n is the global warming potential of the EOL treatment of the waste material n [kg CO_2 eq./kg]; m_n is the mass of the waste material n [kg].

$$\mathrm{CED} = \sum_i CED_i m_i + \sum_j CED_j t_j + \sum_k CED_k e_k + \sum_n CED_n m_n \tag{2}$$

where CED is the total cumulative energy demand during the building life cycle after the renovation, including non-renewable and renewable energy [MJ]; CED_i is the cumulative energy demand of the material/construction product i used for building construction and maintenance [MJ/kg]; m_i is the mass of the material/construction product i [kg]; CED_j is the cumulative energy demand of the transport activity j of the material/construction product j [MJ/tkm]; t_j is the payload distance of the material/construction product j [tkm]; CED_k is the cumulative energy demand factor of the energy carrier k [MJ/kWh]; e_k is the operation delivered energy of the carrier k [kWh]; CED_n is the cumulative energy demand of the EOL treatment of the waste material n [MJ/kg]; m_n is the mass of the waste material n [kg].

The hierarchist perspective of the ReCiPe method was applied, and this implied a time horizon of 100 years for GWP. Finally, in the impact definition phase, a neutral CO_2 balance was adopted for wood products, therefore neither CO_2 sequestration nor CO_2 emissions from combustion were considered.

2.2.2. Life Cycle Costing Analysis

A LCC analysis was performed for the seven scenarios, and the total net present cost (NPC) was calculated. NPC represents the NPV of certain cost categories over the building life span after the renovation, with reference to the starting year of calculation, i.e., the year when the renovation took place. NPC was calculated as shown in Equation (3), based on ISO 15686-5:2008 [26]:

$$\mathrm{NPC}\ (\tau) = C_i + \sum_{i=1}^{\tau} \frac{C_{f,i}}{(1+r)^i} + \sum_j \left[\frac{C_{EOL,\tau}(j) - V_{f,\tau}(j)}{(1+r)^{\tau}} \right] \tag{3}$$

where NPC (τ) is the net present cost linked to the duration of the calculation period, τ, and referred to starting year of calculation [NOK (1 Norwegian krone (NOK) = 0.11 EUR at the date of writing)]; C_i is the initial investment cost [NOK]; $C_{f,i}$ is a future cost at the year i (including annual maintenance costs, annual energy costs, and periodic replacement costs) [NOK]; r is the real discount rate [%]; $C_{EOL,\tau}$ (j) is the waste handling cost of the building component j at the end of the calculation period [NOK]; and $V_{f,\tau}$ (j) is the final value of the building component j at the end of the calculation period [NOK].

To compare different building life spans after the renovation, the equivalent annual cost (EAC) was also calculated, as shown in Equation (4). EAC represents the uniform annual amount equivalent to the net cost of the project evenly distributed over the building life span analyzed:

$$\text{EAC} = \text{NPC}\cdot a(n), \text{ with } a\ (n) = \frac{r}{1-(1+r)^{-n}} \tag{4}$$

where EAC is the equivalent annual cost [NOK/y]; $a(n)$ is the annuity factor depending on the number of years of analysis, n, and on the real discount rate, r [%].

The investment cost category included the prices of the materials, technical building systems, and labor, which were assessed through the available project documentation and the Norwegian Price Book [49]. Economic support for certain EEMs was provided by Enova SF (https://www.enova.no), which is a Norwegian government enterprise responsible for the promotion of environmentally friendly production and consumption of energy. This support consisted of: 125,000 NOK for the envelope upgrading; 20,000 NOK for the balanced ventilation system; 20,000 NOK for the air-to-water heat pump; 10,000 NOK for the PV system plus 1,250 NOK for each installed kW; and 10,000 NOK for the solar thermal system plus 200 NOK for each m^2 of solar thermal panels.

The periodic replacement costs for building component substitution were defined based on the maintenance measures shown in Table S6 of Supplementary Materials. The Norwegian Price Book was used as the main source of average Norwegian market prices, and it was complemented by information from suppliers in case of lacking data. A summary of the prices used is shown in Table S7 of Supplementary Materials.

The annual maintenance costs of the technical building systems were defined according to the Annex A of EN 15459:2007, as a percentage of their initial investment cost. The annual energy costs for electricity and wood were estimated from available statistical prices. Particularly, the electricity price was considered as 0.9 NOK/kWh, as the average price in Norway over the last five years; while the wood cost was set equal to 0.7 NOK/kWh [50,51].

As concerns the costs due to EOL, waste handling-related costs were deduced from the Norwegian Price Book. Furthermore, the final value of building components by the end of the calculation period was calculated from the remaining life time of the building components divided by life span and multiplied with the last replacement cost, then actualized to the starting year of calculation.

All the costs were computed with the value-added tax (VAT) included, and a calculation period equal to the building life span after the renovation, 50 years, was considered. Future costs were actualized to the starting year of calculation through the real discount rate, which was initially set equal to 4%, as in NS 3454:2013 [52].

2.2.3. Sensitivity Analyses

Sensitivity analyses were performed to test the robustness of the LCA and LCC results in relation to the uncertainty of the main input parameters. In particular, these analyses allowed to quantify the effect on the LCA outcomes resulting by the change in the building life span after the renovation and in the electricity mix of the energy use during the operation phase. Besides, the effect on LCC outcomes resulting by the change in the building life span after the renovation and in the real discount rate was also assessed. Note that the changes in the input parameters were defined based on the initial input parameter values used in LCA and LCC analyses, which represented the base case.

3. Results

In this section, the results of all the analyses performed are illustrated.

3.1. Life Cycle Assessment

The results of the annual delivered energy for all the scenarios analyzed are illustrated in Table 2. The various scenarios differ mainly in the energy requirements for the space heating. The total annual delivered energy can be reduced down to −56% in S7 compared to the project as realized (S1), through the adoption of different RETs.

Table 2. Delivered energy breakdown during the annual operation phase, normalized by the floor area.

Description	S1	S2	S3	S4	S5	S6	S7
Electric space heating (kWh/m^2)	27.0	28.3	16.9	30.3	28.3	28.3	16.9
Wood fuel (kWh/m^2)	6.6	-	-	13.3	-	-	-
Heating & ventilation auxiliaries (kWh/m^2)	8.2	8.2	8.3	8.2	8.2	8.2	8.2
Domestic hot water (kWh/m^2)	31.4	31.4	31.4	31.4	31.4	31.4	31.4
Electric appliances (kWh/m^2)	17.5	17.5	17.5	17.5	17.5	17.5	17.5
Lighting (kWh/m^2)	11.4	11.4	11.4	11.4	11.4	11.4	11.4
PV system (kWh/m^2)	-	-	-	-	−22.5	−22.5	−22.5
Solar thermal system (kWh/m^2)	-	-	-	-	-	−21.1	−21.1
Total annual delivered energy (kWh/m^2)	95.5	96.8	85.5	98.8	74.3	53.1	41.8

Figure 3 shows the results of GWP of the main life cycle activities analyzed, for the seven scenarios examined.

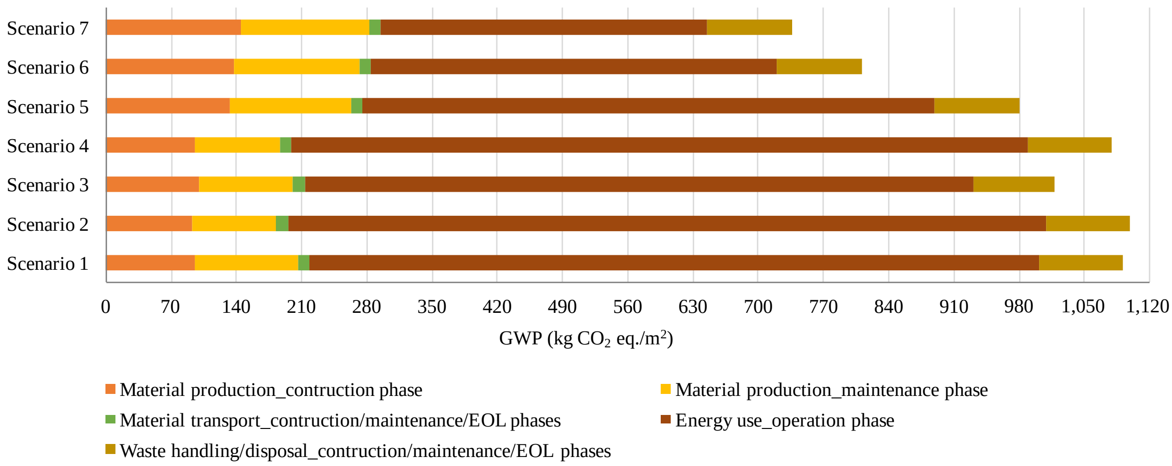

Figure 3. Global warming potential results normalized by the floor area and referred to 50 years of building life span after the renovation.

The highest contribution to the total GWP is from the energy use during the operation phase, ranging from 43% in S7 to 74% in S2; while the lowest contribution is from the material transport, which is in the range of 1.2–1.6% among all alternatives. Moreover, the other life cycle phases, i.e., the material production during the construction phase, the material production during the maintenance phase, and the waste handling/disposal, contribute to GWP in the range of 9–18%, 9–17%, and 8–11%, respectively. S7 is the scenario with the lowest value of GWP, while S2 is the scenario with the highest value. The use of several RETs in S7 allows to reduce GWP down to −33% with respect to the highest value achieved by S2, which is characterized by the highest use of electricity among the scenarios.

The predominance of the energy use during the operation phase is also evident in CED results, with a contribution to the total CED ranging from 71% in S7 to 88.5% in S4. Furthermore, the other life cycle phases, i.e., the material production during the construction phase, the material production during the maintenance phase, the material transport, and the waste handling/disposal, contribute to CED in the range of 7–16%, 4–11%, 0.5–1%, and 0.15–0.3%, respectively. The highest CED value is achieved by S4, mainly due to the inefficiency of the wood stove used for space heating purpose; this value is reduced to about −50% by adopting efficient RETs in S7. Note that the self-produced energy in S5, S6, and S7 allows a reduction of the delivered energy in the operation phase with a subsequent higher contribution of the material production during the construction and maintenance phases, in both GWP and CED results.

Figure 4 illustrates the results of CED of the main life cycle activities analyzed, for the seven scenarios examined.

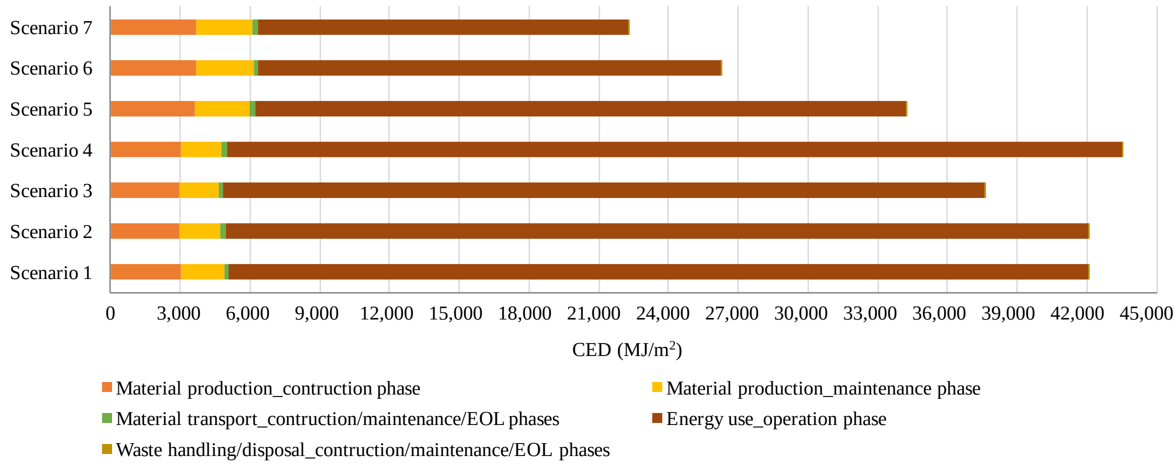

Figure 4. Cumulative energy demand results normalized by the floor area and referred to 50 years of building life span after the renovation.

3.2. Life Cycle Cost Analysis

The results of NPC, split into the cost categories analyzed, are shown in Figure 5 for all the scenarios examined.

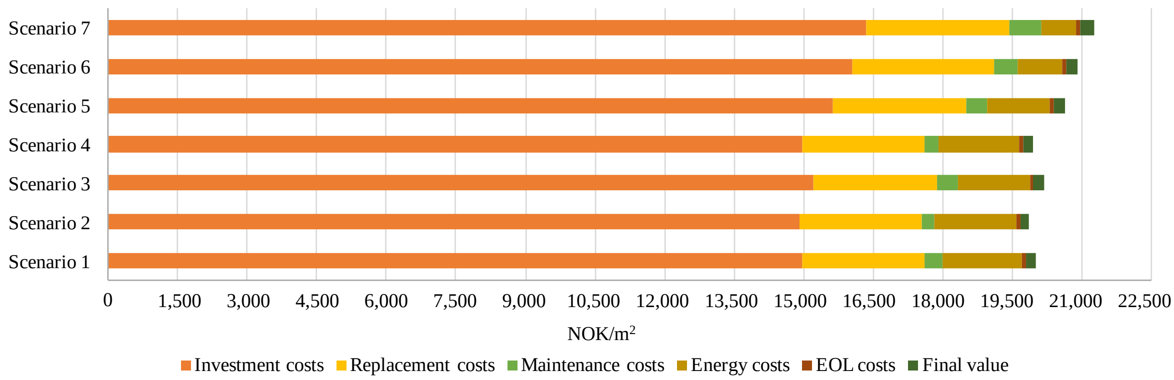

Figure 5. Net present cost results normalized by the floor area and referred to 50 years of building life span after the renovation.

The investment costs constitute the leading component in NPC, ranging from 76% in S1 to 79% in S7. Besides, the annual energy costs for electricity and wood contribute to NPC with a percentage ranging from 4% to 9%. The replacement costs concur to NPC with a percentage ranging from 14% to 15%, while maintenance costs contribute in the range of 2–3%. Lastly, the final value and EOL costs contribute with the lowest percentage to NPC, around 1% and 0.5% respectively, in all scenarios. Overall, S7 shows the highest value of NPC, approximately 6% higher than in S2, which presents the lowest value. Therefore, the difference in terms of NPC among the various scenarios is not very significant, and this means that the higher investment costs required by certain scenarios can be partly compensated over the building life time, particularly by the lower expenses for the annual energy use.

3.3. Combined Life Cycle Assessment & Life Cycle Costing Results

The results obtained from the LCA and LCC analyses were reported on the same graph and plotted against the NPC results, as shown in Figure 6.

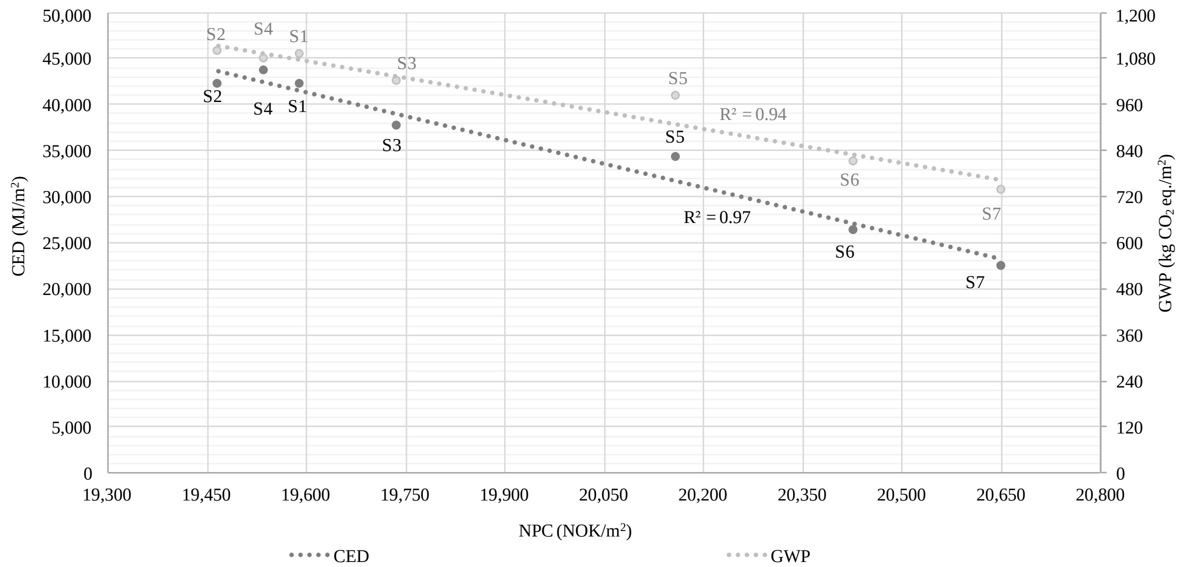

Figure 6. Global warming potential and cumulative energy demand results plotted against the net present cost results.

Figure 6 shows that the increase of NPC is generally accompanied by a decrease of both GWP and CED, and the correlation is close to a negative linear regression, with a high correlation factor (R^2). Such correlation is as expected; however, it is remarkable that a modest increase in NPC gives surprisingly large reductions in GWP and CED.

In GWP result trend, S7 is the scenario showing the highest NPC and the lowest GWP, while S2 is the scenario showing the lowest NPC and the highest GWP. However, the extent of discrepancy of the scenarios in terms of GWP and NPC is rather different. For instance, S7 has a NPC that is 6% higher than S2, but a GWP 32% lower than S2.

In CED result trend, S7 is again the scenario showing the highest NPC and the lowest CED, while S2, and S4 show the lowest NPC and the highest CED. Furthermore, unlike the NPC-GWP graph, S4 has overtaken S2 in terms of CED due to its higher delivered energy during the operation phase (electricity and wood fuel), which lead to a higher CED, but a slightly lower GWP than in S2.

3.4. Sensitivity Analyses

Figure 7 illustrates the values of GWP (a) and CED (b) for different building life spans after the renovation for all scenarios. In both GWP and CED graphs, the outcome trends for the various life spans are rather proportional to the base case results. Overall, the higher the building life span after the renovation, the lower the total annual GWP and CED. The component showing the highest change is the material production during the construction phase, which increases up to +150% in 20 year-life span compared to the base case.

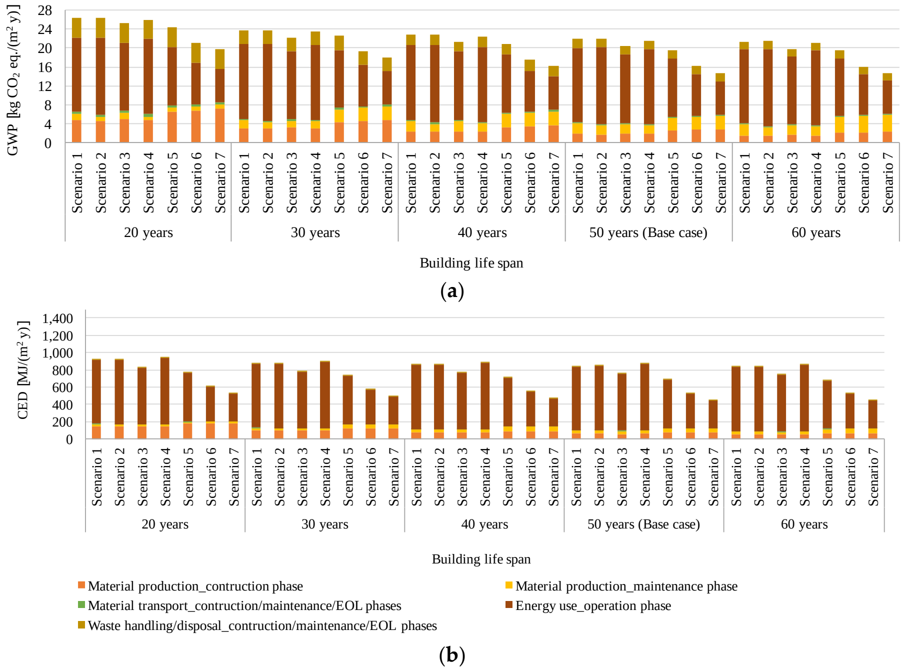

Figure 7. Results of global warming potential (**a**) and cumulative energy demand (**b**) for different building life spans after the renovation, normalized by the floor area and number of years.

Figure 8 illustrates the values of GWP (a) and CED (b) for two electricity mixes other than the Nordel electricity mix, which was initially considered in the LCA analysis. In particular, the Norwegian electricity mix (0.025 kg CO_2 eq./kWh and 4.41 MJ/kWh) and the European electricity mix (0.54 kg CO_2 eq./kWh and 11.46 MJ/kWh) were examined.

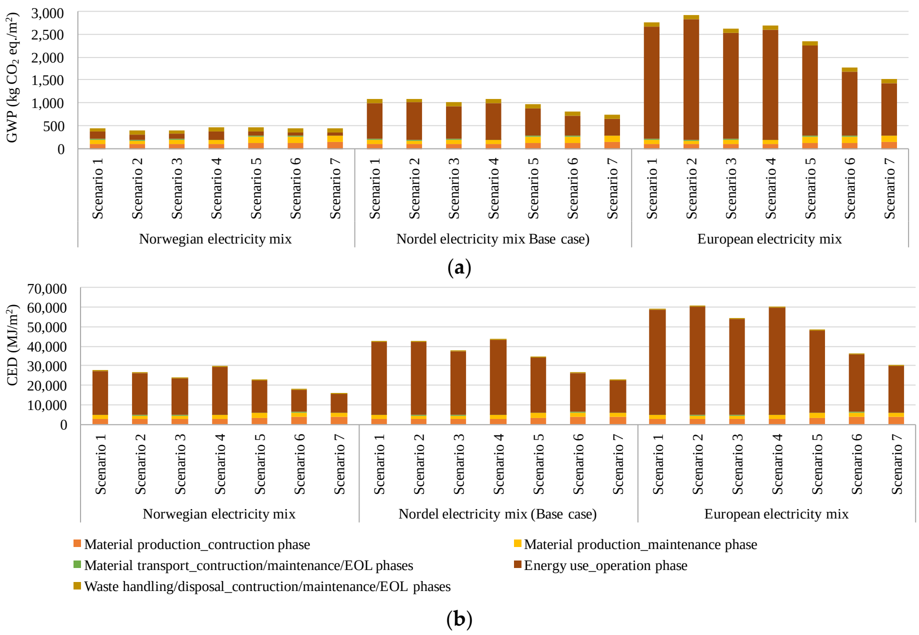

Figure 8. Results of global warming potential (**a**) and cumulative energy demand (**b**) for different electricity mixes, normalized by the floor area and referred to 50 years of building life span after the renovation.

On one hand, the use of the Norwegian electricity mix leads to a decrease in the GWP and CED of the energy use in the operation phase down to −85% and −42% respectively, compared to the results obtained with the Nordel electricity mix. On the other hand, the use of the European electricity mix leads to an increase in the GWP and CED of the energy use up to +220% and +50% than the results obtained with the Nordel electricity mix.

Figures 9 and 10 illustrate the results of the LCC analysis in relation to the change in the building life span after the renovation and the real discount rate, respectively.

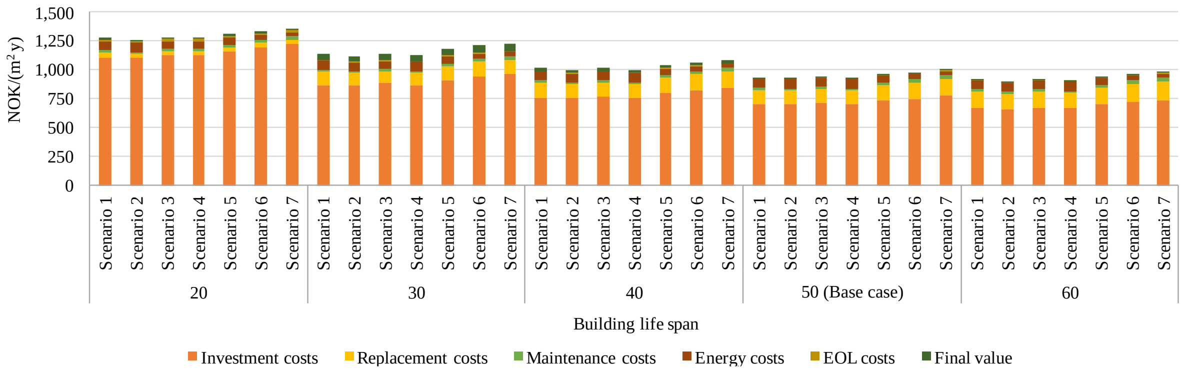

Figure 9. Equivalent annual cost results for different building life spans after renovation, normalized by the floor area.

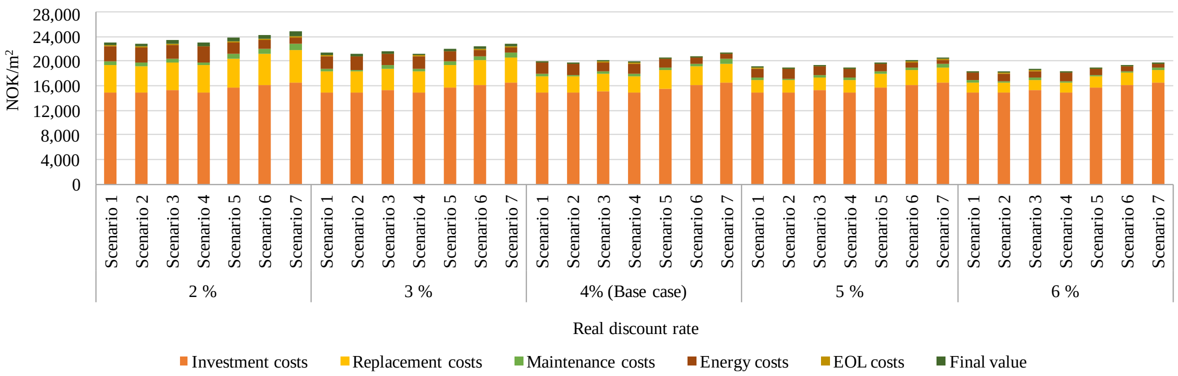

Figure 10. Net present cost results for different real discount rates, normalized by the floor area.

In the comparison of different building life spans after renovation and real discount rates, the result trends are rather proportional to base case results. Overall, the higher the building life span after the renovation and the real discount rate, the lower the total cost.

It should be noted that in the graph in Figure 9, the maintenance and energy costs are the same in all building life spans as they are expressed as annual costs. Investment costs represent a dominant component, which shows an increase against low life spans, up to around +60% in 20-year life span compared to the base case. In the graph in Figure 10, the investment cost category presents no changes for different real discount rates because of its independence from this parameter. Replacement costs represent a dominant component, which shows an increase against low life spans, up to around +70% in 20-year life span compared to the base case.

4. Discussion

The methodological approach adopted in this paper allowed the analysis of the combined life cycle environmental and economic performance of several scenarios for a building energy renovation project. The LCA and LCC results confirm the high contribution of the energy use in the operation phase for both GWP and CED, and the high contribution of the investment costs for NPC. The outcomes also demonstrate the close to negative linear regression between NPC and GWP and between NPC and CED. In particular, the results obtained for the LCA are consistent with those of similar LCA studies [31,53], where the operation phase prevails in the whole building life cycle. It should be noticed that, in energy renovation projects, the material production phase involves a more limited quantity of materials compared to new building projects, where the operation phase can significantly reduce its contribution, particularly in low-energy buildings [54].

The results obtained for NPC are overall comparable to those of similar studies [55,56], especially with respect to the cost category contribution. However, LCC studies are very specific and related to the case study, as well as to the assumptions for the main economic parameters.

The sensitivity analyses allowed to test the robustness of the results based on the relative change in certain main input parameters. Such analyses are significant in life cycle examinations to reduce the limitations and uncertainties of the results.

The combination of the LCA and LCC outcomes on a common graph allows a direct comparison of different scenarios in environmental and economic terms. This combination would be meaningful for the main actors involved in the renovation project, such as the building owner and the project team, whose main priorities might tend to lower the life cycle costs, to decrease the environmental impacts or to find an equilibrium of both the environmental and economic performance. Therefore, the stakeholders' priorities should indeed be considered according to a trade-off procedure, where each of the indicators is weighted in line with the stakeholders' main purposes.

This paper presents certain limitations that suggest further research. Only three representative performance indicators were chosen among the most common ones, as a higher number of indicators would have made less straightforward the direct comparison of the results for all scenarios. However, further representative environmental indicators could be considered in the LCA analysis, including other midpoint indicators, such as ozone depletion potential and acidification potential, or also endpoint indicators, such as damage to human health, ecosystem, and resource availability. Another economic indicator to compute in LCC analysis could be the payback period. Furthermore, the overall methodological approach could also consider the social sustainability dimension, by including key social indicators, along with the environmental and economic ones; this would be noteworthy to define the global sustainability level of the energy renovation project.

Future research could be focused on the computation of the indicators chosen in this paper, along with other relevant indicators, in several case studies with the objective of defining threshold values, as a basis for comparison of similar projects. Furthermore, a possible index including both economic and environmental indicator results might be defined and serve as a support means in the decision-making context. However, this would require a careful normalization and weighting process carried out by the project's main stakeholders.

5. Conclusions

In this paper, a methodological approach for combined environmental and economic performance assessments in building energy renovation projects was proposed. The use of the life cycle assessment (LCA) and life cycle costing (LCC) methodologies in such projects was investigated, and a combined LCA/LCC assessment was performed on a case study, which regarded the energy renovation of a single-family house in Norway. Several scenarios including different EEMs were examined, and certain environmental and economic indicators were computed for all scenarios. Sensitivity analyses were also run to understand the robustness of the results in relation to the uncertainty of the main input parameters.

The study shows the feasibility of combined LCA/LCC analyses, and highlights the importance of a balanced trade-off between environmental and economic indicators in building energy renovation projects. Furthermore, it provides a possible approach for a multi-criteria evaluation in the design stage of such projects, based on the integration of LCA and LCC assessments.

The results could be helpful in the decision-making context to evaluate both the environmental impacts and the economic consequences of different renovation scenarios with the objective of delivering sustainability.

Supplementary Materials: The following are available online at www.mdpi.com/1996-1073/10/11/1851/s1, Table S1: Main features of the building envelope components for all the scenarios analyzed, Table S2: LCA inventory for building components in all the scenarios analyzed, Table S3: LCA inventory for technical building systems in all the scenarios analyzed, Table S4: Main input data for the dynamic energy simulations in all scenarios, Table S5: Main features of the PV and solar thermal systems for the scenarios S5, S6, and S7, Table S6: Maintenance measures for all the scenarios analyzed, and Table S7: Main costs used for the replacement measures in all the scenarios analyzed.

Acknowledgments: The authors are grateful to Anne G. Lien and Kristian S. Skeie from SINTEF Byggforsk for providing the documentation about the case study within the framework of the Norwegian project 'Systematisk EnergiOPPgradering av småhus' (SEOPP).

Author Contributions: Roberta Moschetti collected the primary data, performed the analyses, and wrote the paper; Helge Brattebø supervised the research project and contributed to conceive and design the research framework.

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

References

1. Sev, A. How can the construction industry contribute to sustainable development? A conceptual framework. *Sustain. Dev.* **2009**, *17*, 161–173. [CrossRef]
2. European Parliament; Council of the European Union. *Energy Performance of Buildings (Recast)*; Directive 2010/31/EU; European Parliament: Brussels, Belgium, 2010.
3. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
4. Pisello, A.L.; Petrozzi, A.; Castaldo, V.L.; Cotana, F. On an innovative integrated technique for energy refurbishment of historical buildings: Thermal-energy, economic and environmental analysis of a case study. *Appl. Energy* **2016**, *162*, 1313–1322. [CrossRef]
5. Tiberi, M.; Carbonara, E. Comparing Energy Improvements and Financial Costs of Retrofitting Interventions in a Historical Building. *Energy Procedia* **2016**, *101*, 995–1001. [CrossRef]
6. Panthi, K.; Das, K.; Abdel-Salam, T. Sustainability and cost assessment of coastal vacation homes for energy retrofits. *Built Environ. Proj. Asset Manag.* **2017**, *7*, 185–198. [CrossRef]
7. Cellura, M.; Ciulla, G.; Guarino, F.; Longo, S. Redesign of a Rural Building in a Heritage Site in Italy: Towards the Net Zero Energy Target. *Buildings* **2017**, *7*, 68. [CrossRef]
8. Beccali, M.; Cellura, M.; Fontana, M.; Longo, S.; Mistretta, M. Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. *Renew. Sustain. Energy Rev.* **2013**, *27*, 283–293. [CrossRef]
9. Xu, P.; Chan, E.H.-W.; Qian, Q.K. Success factors of energy performance contracting (EPC) for sustainable building energy efficiency retrofit (BEER) of hotel buildings in China. *Energy Policy* **2011**, *39*, 7389–7398. [CrossRef]
10. Ferreira, M.; Almeida, M. Benefits from energy related building renovation beyond costs, energy and emissions. *Energy Procedia* **2015**, *78*, 2397–2402. [CrossRef]
11. International Organization for Standardization (ISO). *Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO 14040; ISO: Geneva, Switzerland, 2006.
12. International Organization for Standardization (ISO). *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO 14044; ISO: Geneva, Switzerland, 2006.
13. European Committee for Standardization (CEN). *Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method*; EN 15978; CEN: Brussels, Belgium, 2011.
14. 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]
15. Dong, B.; Kennedy, C.; Pressnail, K. Comparing life cycle implications of building retrofit and replacement options. *Can. J. Civ. Eng.* **2005**, *32*, 1051–1063. [CrossRef]

16. Pombo, O.; Rivela, B.; Neila, J. The challenge of sustainable building renovation: Assessment of current criteria and future outlook. *J. Clean. Prod.* **2016**, *123*, 88–100. [CrossRef]
17. Oregi, X.; Hernandez, P.; Hernandez, R. Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects. *Energy Build.* **2017**, *136*, 12–25. [CrossRef]
18. International Organization for Standardization (ISO). *Environmental Labels and Declaration—Type III Environmental Declarations—Principles and Procedures*; ISO 14025; ISO: Geneva, Switzerland, 2006.
19. Khasreen, M.M.; Banfill, P.F.G.; Menzies, G.F. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability* **2009**, *1*, 674–701. [CrossRef]
20. Frischknecht, R.; Jungbluth, N.; Althaus, H.-J.; Bauer, C.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Köllner, T.; et al. *Implementation of Life Cycle Impact Assessment Methods. Ecoinvent Report No. 3, v. 2.0*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
21. Flanagan, R. *Life Cycle Costing: Theory and Practice*; BSP Professional Books: Oxford, UK, 1989.
22. Goh, B.H.; Sun, Y. The development of life-cycle costing for buildings. *Build. Res. Inf.* **2015**, *44*, 319–333. [CrossRef]
23. Amstalden, R.W.; Kost, M.; Nathani, C.; Imboden, D.M. Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations. *Energy Policy* **2007**, *35*, 1819–1829. [CrossRef]
24. Ouyang, J.; Ge, J.; Hokao, K. Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. *Energy Policy* **2009**, *37*, 140–149. [CrossRef]
25. Islam, H.; Jollands, M.; Setunge, S. Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 129–140. [CrossRef]
26. International Organization for Standardization (ISO). *Buildings and Constructed Assets—Service-Life Planning—Part 5: Life-Cycle Costing*; ISO 15686–5; ISO: Geneva, Switzerland, 2008.
27. Dodoo, A.; Gustavsson, L.; Sathre, R. Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard. *Resour. Conserv. Recycl.* **2010**, *54*, 1152–1160. [CrossRef]
28. Ouyang, J.; Wang, C.; Li, H.; Hokao, K. A methodology for energy-efficient renovation of existing residential buildings in China and case study. *Energy Build.* **2011**, *43*, 2203–2210. [CrossRef]
29. Bin, G.; Parker, P. Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home—The REEP House. *Appl. Energy* **2012**, *93*, 24–32. [CrossRef]
30. Desogus, G.; Di Pilla, L.; Mura, S.; Pisano, G.L.; Ricciu, R. Economic efficiency of social housing thermal upgrade in Mediterranean climate. *Energy Build.* **2013**, *57*, 354–360. [CrossRef]
31. Passer, A.; Ouellet-Plamondon, C.; Kenneally, P.; John, V.; Habert, G. The impact of future scenarios on building refurbishment strategies towards plus energy buildings. *Energy Build.* **2016**, *124*, 153–163. [CrossRef]
32. Nemry, F.; Uihlein, A.; Colodel, C.M.; Wetzel, C.; Braune, A.; Wittstock, B.; Hasan, I.; Kreißig, J.; Gallon, N.; Niemeier, S.; et al. Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs. *Energy Build.* **2010**, *42*, 976–984. [CrossRef]
33. Ostermeyer, Y.; Wallbaum, H.; Reuter, F. Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 1762–1779. [CrossRef]
34. Cetiner, I.; Edis, E. An environmental and economic sustainability assessment method for the retrofitting of residential buildings. *Energy Build.* **2014**, *74*, 132–140. [CrossRef]
35. Pombo, O.; Allacker, K.; Rivela, B.; Neila, J. Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock. *Energy Build.* **2016**, *116*, 384–394. [CrossRef]
36. The Norwegian Building Authority (DIBK). Chapter 14: Energy. In *Guidance on Technical Requirements for Construction Works (TEK 10)*; DIBK: Oslo, Norway, 2010.
37. Dixit, M.K.; Culp, C.H.; Fernández-Solís, J.L. System boundary for embodied energy in buildings: A conceptual model for definition. *Renew. Sustain. Energy Rev.* **2013**, *21*, 153–164. [CrossRef]
38. EQUA Simulation AB. *IDA Indoor Climate and Energy (IDA ICE), Version 4.7*; EQUA Simulation AB: Stockholm, Sweden, 2016.
39. Standard Norge. *Calculation of Energy Performance of Buildings—Method and Data*; NS 3031; Standard Norge: Oslo, Norway, 2014.

40. Standard Norge. *Criteria for Passive Houses and Low Energy Buildings—Residential Buildings*; NS 3700; Standard Norge: Oslo, Norway, 2013.
41. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *International Weather Files For Energy Calculations 2.0 (IWEC2)*; ASHRAE: Atlanta, GA, USA, 2012.
42. Joint Research Centre. *Photovoltaic Geographical Information System (PVGIS). Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology*; Joint Research Centre: Brussels, Belgium, 2001.
43. Beckam, W.A.; Klein, S.A.; Duffie, J.A. *Solar Heating Design, by the F-Chart Method*; Wiley: New York, NY, USA, 1977.
44. European Committee for Standardization (CEN). *Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings*; EN 15459; CEN: Brussels, Belgium, 2007.
45. SINTEF Byggforsk. Intervals for Maintenance and Replacement of Building Parts. SINTEF Byggforsk, 2010. Available online: https://www.byggforsk.no/dokument/3312/intervaller_for_vedlikehold_og_utskifting_av_bygningsdeler (accessed on 30 March 2017).
46. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
47. PRé Sustainability. *SimaPro Classroom, Version 8.1.1*; PRé Sustainability: Amersfoort, The Netherlands, 2016.
48. Itten, R.; Frischknecht, R.; Stucki, M. *Life Cycle Inventories of Electricity Mixes and Grid*; Paul Scherrer Institut (PSI): Villigen, Switzerland, 2014.
49. Norconsult Informasjonssystemer AS and Bygganalyse AS. *Norsk Prisbok*; Norconsult Informasjonssystemer AS and Bygganalyse AS: Sandvika, Norway, 2016.
50. Statistisk Sentralbyrå, Electricity Prices. 2016. Available online: https://www.ssb.no/energi-og-industri/statistikker/elkraftpris (accessed on 30 March 2017).
51. Enova SF, Clean Burning Wood Stove. 2017. Available online: https://www.enova.no/privat/alle-energitiltak/biovarme/rentbrennende-vedovn/ (accessed on 30 March 2017).
52. Standard Norge. *Life Cycle Costs for Construction Works—Principles and Classification*; NS 3454; Standard Norge: Oslo, Norway, 2013.
53. Dahlstrøm, O.; Sørnes, K.; Eriksen, S.T.; Hertwich, E.G. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. *Energy Build.* **2012**, *54*, 470–479. [CrossRef]
54. Blengini, G.A.; Di Carlo, T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy Build.* **2010**, *42*, 869–880. [CrossRef]
55. Risholt, B.; Time, B.; Hestnes, A.G. Sustainability assessment of nearly zero energy renovation of dwellings based on energy, economy and home quality indicators. *Energy Build.* **2013**, *60*, 217–224. [CrossRef]
56. Moschetti, R.; Mazzarella, L.; Nord, N. An overall methodology to define reference values for building sustainability parameters. *Energy Build.* **2015**, *88*, 413–427. [CrossRef]