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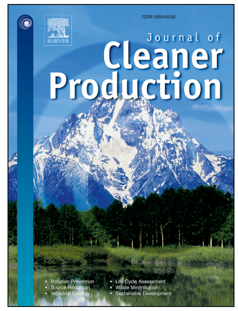

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Performing quantitative analyses towards sustainable business models in building energy renovation projects: analytic process and case study

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Highlights:

- Business models and sustainability analyses in building projects are investigated.
- An analytic process towards sustainable business models of such projects is proposed.
- The application of the analytic process to a case study is shown.
- Quantitative analyses can foster sustainable business models in building projects.

Abstract

The building sector is responsible for several environmental impacts, as well as economic and social consequences. Hence, the adoption of energy efficiency measures in building renovation projects can lead to benefits to several stakeholders in a holistic sustainability perspective. However, these projects require a gradual shift of their business models towards sustainable business models, and performing quantitative sustainability analyses can overcome the traditional focus of business models on economic value and customers, by defining

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wider costs and benefits for environment and society. This paper first provides a review of the state-of-the-art of sustainability analyses and business models for building renovation projects. Then, it proposes an analytic process based on the execution of quantitative sustainability examinations, as a support for the project proposition, creation, and capture of sustainable value, in a multi-stakeholder perspective. The analytic process is applied to a case study that is the energy renovation project of a Norwegian single-family house, and several sustainability criteria are computed for three possible scenarios that are inclusive of different energy efficiency measures. The paper's findings can be relevant for both practitioners and academics who search for new approaches to embed quantitative analyses into the business context of building energy renovation projects. Furthermore, the findings can represent the groundwork for the possible operationalization of sustainable business in such projects, striving for a systematic execution of quantitative sustainability analyses as a key step towards sustainable business models.

Keywords: business models; buildings; energy renovation; sustainability; performance indicators

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1. Introduction

The achievement of the sustainable development goals (SDGs) (UN General Assembly, 2015) requires a joint effort in all areas of human activities by establishing a consensus on the contribution to be realized by each sector, such as buildings (Zimmermann et al., 2005). The building sector is particularly relevant in this regard as it is responsible for several environmental impacts, as well as economic and social consequences. In particular, from an environmental perspective, many negative impacts are attributed to the building sector, such as high energy use, greenhouse gas (GHG) emissions, natural resource depletion, and waste generation (United States Environmental Protection Agency, 2009). From the social and economic perspective, this sector represents an important industrial employer and provides the built environment, which constitutes a main part of the economic resources for individuals and populations (Ortiz et al., 2009).

The adoption of energy efficiency measures (EEMs) for new and existing buildings has been increasingly acknowledged as a very significant and effective means for reducing the negative impacts on the environment (Ma et al., 2012; Li et al., 2013). Hence, as existing buildings are highly responsible for energy use and GHG emissions (Nejat et al., 2015), energy renovation projects have gradually increased in recent years (Jensen and Maslesa, 2015). Such projects refer to the implementation of EEMs for the building envelope and/or the technical building systems, which leads to an upgrade of the energy performance of the building, as inferred from the Energy Performance of Buildings Directive (EPBD recast) (European Parliament and European Council, 2010). In addition to the environmental benefits, the implementation of EEMs in existing buildings can provide economic and social advantages, such as the reduction of utility bills and maintenance costs, the generation of new jobs, and the improvement of indoor well-being (Xu et al., 2011). Energy renovation projects may, therefore, play a key role in sustainability transition; however, they require a gradual shift of their business model (BM) towards sustainable innovations.

In recent years, several scholars and practitioners have focused on the BM definition by offering different interpretations and explanations (Timmers, 1998; Amit and Zott, 2001; Magretta, 2002; Morris et al., 2005). Despite the increase in the literature on BM, disagreement remains among scholars on what a BM is (Zott et al., 2011). Osterwalder et al. (2005) conceptualize BMs through the following nine basic building blocks: 1) value proposition, 2) target costumer, 3) distribution channels, 4) relationship, 5) value configuration, 6) core competency, 7) partner network, 8) cost structure, and 9) revenue models. These blocks constituted the so-called BM ontology, later referred to as a canvas (Osterwalder et al., 2010). Richardson (2008) organizes the BM framework around the concept of value by identifying three main components, as follows: the value proposition, the value creation and delivery, and the value capture.

BMs have been recognized as an important locus of innovation (Amit and

Zott, 2001), where BM innovation can be defined as a means of replacing outdated BMs and creating value, for companies, customers, and society (Osterwalder et al., 2010). BM innovation can be crucial for the alignment of traditional BMs with the sustainability transition objectives towards sustainable BMs (SBMs) that target the generation of higher environmental and social value and the deliverance of economic sustainability for a wide range of stakeholders that are inclusive of the environment and society (Stubbs and Cocklin, 2008; Boons and Lüdeke-Freund, 2013).

The level of analysis adopted in this paper concerns the BMs of projects, which, based on the literature reviewed (Timmers, 1998; Richardson, 2008; Mutka and Aaltonen, 2013) and the objective of this paper, are defined as conceptual tools expressing how a project propose, create, and capture value. The analysis of the BMs of projects helps a better understanding of the logic and dynamics of specific projects. The SBMs of projects are meant as BMs defined in a triple bottom line perspective and regarding the whole network of stakeholders. In particular, the research question investigated is the following: How can quantitative sustainability analysis support the emergence of SBMs in building energy renovation projects?

To address this research question, we propose an analytic process with quantitative sustainability analyses as a core component towards the definition of sustainable business models in building energy renovation projects. A process-based perspective is adopted by emphasizing capabilities, mechanisms, and tools that are needed for successful BM innovation (Cavalcante et al., 2011; Foss and Saebi, 2017).

The paper is organized as follows. Section 2 presents the state-of-the-art in sustainability analyses and BMs for building energy renovation projects, noting the current research gaps. Section 3 introduces the methodological approach adopted in this paper, and presents the case study and the analyses performed. Section 4 shows the main findings and results, which are critically discussed in Section 5. Finally, in Section 6, the conclusions are presented, followed by suggestions for the possible future developments of the research.

2. Sustainability analyses and business models in building energy renovation projects: state-of-the-art

In recent years, sustainability analyses have been increasingly performed in building energy renovation projects with the objective of defining the sustainability performance from the environmental, economic, and social perspective (Chidiac et al., 2011; Xing et al., 2011; Ma et al., 2012; Asadi et al., 2012). However, the choice of the sustainability criteria to consider in such analyses is arbitrary and current legislative frameworks, within the building sector, mainly focus on the environmental issues. For instance, the EPBD recast states that all new buildings should be built as nearly zero-energy buildings by 2020. In addition, the EPBD recast specifies that EEMs should be undertaken also in existing buildings, towards the fulfillment of the 20/20/20 EU objectives, i.e., a 20% reduction in GHG emissions, a 20% increase in energy from renewable sources, and a 20% increase in energy efficiency. Consequently, several research works in this field have initially mainly addressed environmental analyses, although economic and social investigations have gradually increased in recent years (Šijanec Zavrl et al., 2009). Moreover, most works in this particular scope analyze single or aggregated sustainability-related aspects, without covering the whole triple bottom line. Thus, environmental, economic, and social criteria are often investigated alone (Menassa, 2011; Passer et al., 2016) or coupled (Cetiner and Edis, 2014; Liu et al., 2015) but seldom all together (Risholt et al., 2013).

The literature on BMs in the building field remains fragmented and limited (Pan and Goodier, 2012; Abuzeinab and Arif, 2014). Very few researchers have focused on the BMs of building energy renovation projects, e.g., Haavik et al. (2011) and Mahapatra et al. (2013). These researchers introduce the concept of the one-stop-shop BM, as opposed to the traditional individual solution BM. In the former, an overall contractor provides different renovation services, including consulting, energy audit, renovation work, quality control, commissioning, and financing; while in the latter, different measures are offered by several service providers, mainly craftsmen, leading to difficulties in communicating, planning, coordinating, and executing the works. The one-stop-shop concept can also be fulfilled by the so-called Energy Service Companies (ESCOs), which offer specific facilities to improve the energy efficiency of properties by taking also charge of financial risks. Würtenberger et al. (2012) and Paiho et al. (2015) analyzed BMs that can partially be applied to building energy renovation projects, although they focus on the energy renovation of districts and the renewable energy in the built environment. These researchers considered BMs as an approach, a strategy targeted at implementing and financing EEMs, towards an increasing penetration of such measures in the built environment. They mentioned the BMs based on financing schemes, which can be built upon specific programs for overcoming of hindrances related to high investment costs. Furthermore, Würtenberger et al. (2012) also referred to BMs based on new and innovative revenue models, which can result from specific economic incentives or from the use of a voluntary sustainability assessment system for buildings, such as the Building Research Establishment Environmental Assessment Method (BREEAM) (Building Research Establishment, 2016) and Leadership in Energy and Environmental Design (LEED) (U.S. Green Building Council, 2016). A summary of the main features of the BMs noted above in building energy renovation projects is available from Moschetti and Brattebø (2016).

No comprehensive categorizations of SBMs and mechanisms for delivering sustainability in building projects, specifically in energy renovation projects, were found in the literature. Bocken et al. (2014) provided a sound approach for developing general SBM archetypes that could be adapted and exploited for such projects. However, that categorization is beyond the scope of this paper. The lack of approaches for supporting SBMs was noted by Bocken et al. (2013), who proposed a qualitative approach to value analysis. Specifically, a value mapping tool to aid SBM development was defined, although the usefulness of quantitative analytic tools was recognized. The tool illustrated by Bocken et al. (2013) represented the starting point for the research work of Geissdoerfer et al. (2016), who developed a workshop framework based on a value mapping process.

The contribution of quantitative sustainability analyses to SBMs in building energy renovation projects is a novel theme, and the research on it remains very limited. This topic has been partially addressed in two recent EU projects, i.e. NewBEE (2012) and Umbrella (2012), although with a different focus. NewBEE (2012)'s objective was to develop new BMs for small and medium-sized enterprises (SMEs) that are involved in the energy renovation of buildings to boost the adoption of new EEMs. An energy performance assessment tool and a BM assessment tool were developed during the project. The former allows building owners to evaluate potential energy, cost, and carbon footprint savings; the latter allows SMEs to qualitatively rate their company performance. On the contrary, Umbrella (2012)'s objective was to develop a web-based decision-support tool for supporting the actors in understanding and visualizing EEMs applicable to buildings, and aligning these with optimized BMs. Through this tool, users receive information about suitable EEMs to implement and about business solutions, including the services, the technologies required and the service providers who can install and manage these products/solutions.

The analysis of the state-of-the-art allowed us to note several gaps within the research area analyzed. First, most research works including sustainability analysis for energy renovation projects investigate single or aggregated sustainability-related aspects, without covering the whole triple bottom line. Thus, comprehensive evaluations based on environmental, economic, and social criteria are lacking in this field. Second, although the concept of BM has increasingly spread in recent years, the research on SBMs in the building sector remains limited. In particular, few studies have focused on the changes required in the traditional BMs to be on pace with energy efficiency initiatives (Mokhlesian and Holmén, 2012). Third, the current BM perspective is mainly market-oriented and built around the proposition of economic value to customers, so the whole range of stakeholders is not considered. Fourth, there is a lack of research on the use of quantitative information deriving from sustainability analytic tools in the BM field, which is mainly characterized by a qualitative approach (Bocken et al., 2013). Accordingly, there is a need for additional quantitative approaches to SBMs, supported by representative case studies.

3. Methods

The methodological approach adopted in this study is illustrated in Figure 1, and its main steps include: the state-of-the-art review in the field of BMs, quantitative sustainability analyses, and their integration in building energy renovation projects; the identification of current research gaps; the definition of an analytic process, based on the performance of sustainability analyses and aimed at the sustainable innovation of BMs in such projects; the illustration of the analytic process applied to a representative case study; and the discussion on the main findings, focusing on the analytic process effectiveness and applicability.

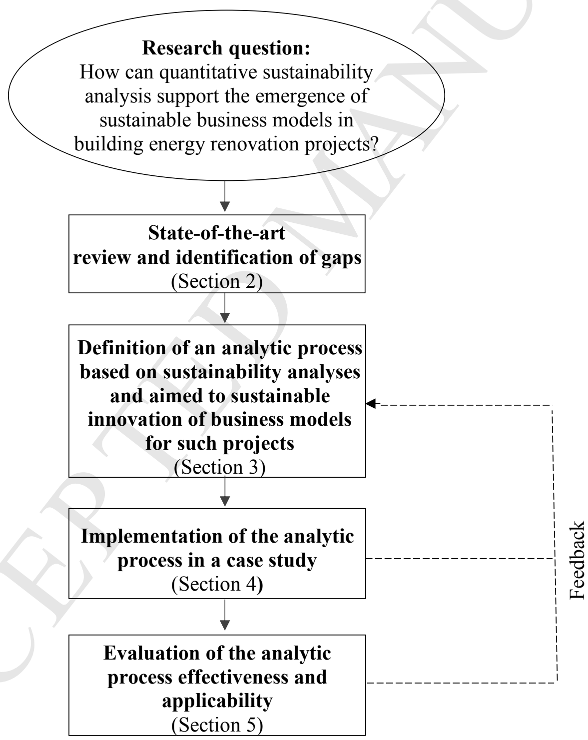

Figure 1: Methodological approach adopted in this paper.

It should be mentioned that the term actors is used henceforth to refer to those individuals, such as investors, suppliers, partners and researchers, who directly participated to the SEOPP project. The SEOPP project actors represent also the stakeholders of this research, together with the environment and the society, as they may all be affected by the outcome of the project.

3.1. Analytic process

The main research methods adopted for defining the analytic process were the literature and practice review. The following main steps were included in the process:

1. Choice of possible renovation scenarios with different implementable EEMs in the building energy renovation project under analysis;
2. Examination of a list of meaningful sustainability criteria, with the subsequent prioritization and choice of those indicators to assess for the renovation scenarios identified in the project;
3. Computation of the overall sustainability performance of the renovation scenarios and numerical/visual illustration of the results;
4. Group discussion and final choice of the renovation scenario to adopt in the project, based on the outcomes of the overall sustainability assessment.

3.2. Case study

An illustrative case study was chosen as the research method for the in-depth and detailed examination of a building energy renovation project, with the subsequent implementation of the proposed analytic process. The case study approach, by focusing on a specific subject of analysis, allows a better understanding of the research question and a holistic view of the topic under investigation (Lavrakas, 2008; Noor, 2008).

The case study analyzed in this paper is the energy renovation project of a single-family house, which is part of a Norwegian research project, i.e., Systematisk EnergiOPPgradering av småhus (SEOPP) (SEOPP, 2013). This project was supported by the Norwegian Research Council, and the renovated house is owned by a four people family. Moreover, the research institute SINTEF Building and Infrastructure led the project, while other partners included a housing construction company, the Norwegian State Housing Bank, a Norwegian government enterprise, the Norwegian Water Resources and Energy Directorate, an energy consulting company, an architecture firm, and several material suppliers.

Figure 2 shows two pictures of the single-family house subject to the renovation project.

(a) (b)

Figure 2: Pictures of the single-family house analyzed: (a) before and (b) after the renovation works. Reprint with permission [SINTEF Byggforsk]; Copyright 2018, `http://seopp.net/forside/`.

3.3. Implementation of the analytic process in the case study

The research methods for the implementation of the analytic process in the case study are illustrated and explained according to the four steps characterizing such process, as described in sub-section 3.1.

3.3.1. Choice of the renovation scenarios

Three possible renovation scenarios inclusive of different EEM were identified for the case study. Scenario 1 includes all the most relevant renovation measures discussed by the involved actors; Scenario 2 is the same as Scenario 1 with the addition of two renewable energy technologies; and Scenario 3 includes renovation measures representing business as usual in renovation projects. The renovation measures considered in the three scenarios are illustrated in Table 1, while the main geometric features of the single-family house analyzed are shown in Table 2. Note that although the analyzed house is always the same, certain renovation measures, such as the new internal layout and the extra insulation in the external walls, lead to differences in certain geometric characteristics in the three scenarios.

Table 1: Renovation measures for the three scenarios analyzed.

Scenario 1	Scenario 2	Scenario 3
New internal space layout	New internal space layout	
Extra insulation in roof	Extra insulation in roof	
Extra insulation in external walls	Extra insulation in external walls	
Extra insulation in basement floor	Extra insulation in basement floor	
Extra insulation in foundation walls	Extra insulation in foundation walls	
New 3 glass wood windows	New 3 glass wood windows	New 2 glass wood windows
New external doors	New external doors	New external doors
New cladding for external walls	New cladding for external walls	New cladding for external walls
Exterior/interior painting	Exterior/interior painting	Exterior/interior painting
New roof covering	New roof covering	New roof covering
Bathroom renovation	Bathroom renovation	Bathroom renovation
New drainage around the house	New drainage around the house	New drainage around the house
New balanced ventilation system	New balanced ventilation system	
New electric radiators	New electric radiators	New electric radiators
New electric floor heating	New electric floor heating	New electric floor heating
New wood stove	New wood stove	New wood stove
	Photovoltaic panels	
	Solar thermal panels	

Table 2: Main geometric data of the single-family house in the three scenarios analyzed.

	Scenario 1	Scenario 2	Scenario 3
Number of floors above ground (-)	2	2	2
Number of floors below ground (-)	1	1	1
Gross internal floor area (m^2)	176.70	176.70	160.50
Gross external floor area (m^2)	211.53	211.53	183.30
Gross volume (m^3)	563.50	563.50	458.55
Gross envelope area (m^2)	386.54	386.54	326.97
Shape factor (gross envelope area/gross volume) (1/m)	0.69	0.69	0.71

3.3.2. Choice of the sustainability criteria

Relevant sustainability criteria to be assessed in building energy renovation projects were identified from the literature in an attempt to adequately cover the triple bottom line (Shen et al., 2007; Sánchez, 2015). The final choice and prioritization of the sustainability criteria was made through a questionnaire [2], which was acknowledged as a proper research method for information and data collection in a building project involving several people (Lavrakas, 2008). The respondents to the questionnaire were identified in the main SEOPP project actors, namely: one of the owners, two researchers from SINTEF, one representative from the Norwegian State Housing Bank, one representative from the involved Norwegian government enterprise, one representative from the Norwegian Water Resources and Energy Directorate, one representative from the involved energy consulting company, two representatives from the involved architecture firm, and three representatives from the material suppliers. The questionnaire was structured as a series of questions, including both multiple-choice and rating questions. In the latter, a scale from 1 to 5 was used, with 1 being the lowest grade and 5 the highest grade. Based on the actors' response, the two highest rated criteria for each sustainability dimension are shown in Table 3, together with possible performance indicators.

In this research work, in addition to the prioritization of the criteria, other general questions were presented to the actors within the questionnaire. These questions regarded, e.g., the actors' use of sustainability tools, their knowledge of BMs, and their interest in the BM for that specific project.

3.3.3. Computation of the chosen sustainability indicators

The chosen environmental performance indicators were assessed through the life cycle assessment (LCA) methodology, as defined in (International Organization for Standardization, 2006b,c). The following life cycle phases were considered: the pre-use phase, including materials production and transport to the construction site; the use phase, regarding the energy use for heating, domestic hot water (DHW), lighting, and appliances; and the end-of-life (EOL) phase, including waste transport, process, and final disposal. Furthermore, a building life span after renovation of 50 years was considered.

[2] The questionnaire is available at `https://docs.google.com/forms/d/e/1FAIpQLSeqb15n4bfP5fa1VM5VF1g2fQsN0FTkHq-LePZ2J30lQn4vKQ/viewform`

Table 3: Analyzed sustainability criteria and performance indicators for each sustainability dimension.

Dimension	Sustainability criteria	Performance indicator
Environmental	Direct/indirect life cycle GHG emissions related to building renovation	Global warming potential (GWP_{100}) [kg CO_2 eq.]
	Direct/indirect life cycle energy related to building renovation	Non-renewable cumulative energy demand (NRCED) [MJ]
Economic	Upfront costs for building owners	Investment cost [NOK*]
	Total life cycle costs for building owners	Global cost [NOK]
Social	Indoor air quality in the renovated building	Indoor CO_2 level [ppm]
	Thermal comfort in the renovated building	Predicted mean vote (PMV) [%]

* 1 Norwegian krone (NOK) = 0.11 EUR at the date of writing.

Concerning the pre-use phase, the total quantities of materials constituting both building envelope and technical building systems of Scenario 1 were collected based on the information available in the SEOPP project documentation. Certain modifications were made for Scenario 2 and Scenario 3, based on the different EEMs implemented. All materials were also associated to a life span factor (LS), indicative of the number of substitutions during the building life span after the renovation project, and a waste factor (WF), representing the percentage of cutting waste generated during the construction process, based on SINTEF Byggforsk (2010),European Committee for Standardization (2007b), and Dixit et al. (2013). The material inventories are shown in Table A1 and Table A2 of the Appendix. Regarding the use phase, the annual energy demand for heating was estimated through the dynamic energy simulation tool IDA-ICE (EQUA Simulation AB, 2016), while average data on the energy use for indoor lighting, appliances, and DHW were derived from the Norwegian standard NS 3031:2014 (Standard Norge, 2014). Table A3 and Table A4 of the Appendix provide more detailed information about the building envelope components and the energy simulation parameters. Furthermore, the electricity production from the photovoltaic (PV) system was estimated through the tool PVGis (Joint Research Centre, 2001), while the energy generated by the solar thermal system was assessed through the f-chart method (Beckman et al., 1977) (see Table A5 of the Appendix). Note that certain assumptions were made for the maintenance actions occurring during the use phase, as shown in Table A6 of the Appendix. Concerning the EOL phase, a few hypotheses were made regarding the material waste disposal and handling, as shown in Table A7 of the Appendix.

The material environmental impacts were assessed by combining data from Environmental Product Declarations (EPDs) (International Organization for Standardization, 2006a) and the Ecoinvent 3.1 database (Weidema et al., 2013). The latter was also used for modeling energy carriers and processes and was run in SimaPro 8.1.1 software (PRé Sustainability, 2016). The Nordel electricity mix was used for the electricity, and the combustion of wood consumed by the wood stove was also considered in the model. Finally, two impact assessment methods (Frischknecht et al., 2007) were used: the cumulative energy demand (CED) method, to evaluate the non-renewable CED (NRCED) indicator, and the ReCiPe method with the hierarchist perspective to evaluate the global warming potential (GWP_{100}) indicator.

As concerns the economic performance indicators, a cost collection and a life cycle costing (LCC) analysis were conducted. In particular, the global cost indicator was assessed, based on EN 15459:2007 (European Committee for Standardization, 2007b), as the sum of the present value of all costs occurring during the building life span starting from the renovation project's year, including investment and annual costs (replacement, maintenance, and energy costs). A calculation period of 50 years was assumed, as for the building life span after renovation of the LCA analyses.

The investment costs were estimated as the sum of the costs for building materials, technical building systems, and renovation works, based on the SEOPP project documentation and the Norwegian Price Book (Norconsult Informasjonssystemer and AS Bygganalyse, 2016). Furthermore, economic support [3] from

[3]The economic support consisted of: 145,000 NOK for envelope upgrading and balanced

Enova, a Norwegian government enterprise (Enova SF, 2016a), was accounted in Scenario 1 and 2. For Scenario 3, no financial support was considered, since it did not comply with the minimum requirements for attaining such subsidies. The replacement costs were defined on the basis of the measures shown in Table A6 of the Appendix, by using the Norwegian Price Book as the main information source. The maintenance costs were defined only for the technical building systems, as a percentage of their initial cost according to Annex A of EN 15459:2007. Finally, the energy costs were estimated by means of the available statistical prices (Statistisk sentralbyrå, 2016; Enova SF, 2016b) and set equal to 0.85 NOK/kWh for electricity and 0.65 NOK/kWh for wood. All the costs were computed with the value-added tax (VAT) included, and future costs were actualized to the starting year of calculation through the real discount rate, which was set equal to 4%, as in the Norwegian standard NS 3454:2013 (Standard Norge, 2013).

As regards social performance indicators, the indoor air quality (IAQ) and thermal comfort levels were assessed for the main building rooms through a dynamic simulation, using the IDA-ICE software. In particular, as IAQ indicator, the average CO_2 level for the main building rooms was assessed over a whole year by considering different ventilation solutions, i.e., a mechanical ventilation system in Scenario 1-2 and natural ventilation in Scenario 3. Note that CO_2 emissions were assumed to be generated only by building occupants, as a function of their metabolic rate. In addition, the average predicted percentage of dissatisfied (PPD) (International Organization for Standardization, 2005) was computed as a thermal comfort indicator for the main building rooms over the winter season, based on certain indoor thermal parameters (see Table A8 of the Appendix).

It is worth noting that, among the various standards addressing IAQ and indoor thermal comfort, EN 15251:2007 (European Committee for Standard-

ventilation system, 10,000 NOK for the solar thermal system plus 200 NOK for each m^2 of solar thermal panels; and 10,000 NOK for the PV system plus 1,250 NOK for each kW installed.

ization, 2007a) suggests indoor CO_2 levels and PPD ranges for certain indoor environmental quality (IEQ) categories, as shown in Table A9 of the Appendix. Specifically, the IEQ categories considered are the following: Category I (high level of expectation); Category II (normal level of expectation); Category III (acceptable level of expectation); and Category IV (low level of expectation).

3.3.4. Group discussion and choice of the final renovation scenario

The last step of the analytic process was not performed for the specific case study due to the strict construction scheduling. However, certain relevant points that could arise from such a group discussion are debated by the authors in sub-section 4.4.

4. Findings and results

The main findings and results from the application of the analytic process to the case study are illustrated in this section, according to the four steps characterizing the analytic process described in sub-section 3.1.

4.1. Choice of the renovation scenarios

The choice of the renovation scenarios was based on several EEMs that the main actors of SEOPP project had previously widely discussed before this research work began. The EEM stemmed from a practice review of similar projects, along with experts consultation. A will to renovate the house from the energy perspective, as well as the functional perspective, emerged from the EEMs discussed, although the business as usual option was also debated as the most economical solution.

4.2. Choice of the sustainability criteria

Out of the twelve SEOPP project actors who received the questionnaire, eight actors provided a response. The performance indicators chosen by the respondents of the questionnaire are shown in Table 3 of Section 3, where a description of the computation methods used is provided. Furthermore, after an analysis of the answers to all the questionnaire questions, the following findings were determined:

1. SEOPP project actors believe that a successful energy renovation project is primarily influenced by the householder, the project team (e.g., engineer, consultant, and project manager), and the contractors (e.g., builder, plumber, and electrician);
2. The designing is the phase where most SEOPP project actors have somehow been involved, while the maintenance and the waste management planning are the ones where they have been least involved;
3. Energy calculation software is the most used sustainability tool, and LCA and LCC are the least used;
4. The majority of SEOPP project actors have heard about BMs and have been involved in their development, but they are skeptical about a possible contribution to the BM of SEOPP project;
5. SEOPP project actors are generally most concerned about economic issues, followed by the environmental and social issues;
6. SEOPP project actors believe that the most important environmental criteria to evaluate in energy renovation projects are total GHG emissions and total energy use, followed by direct GHG emissions, embodied GHG emissions, direct energy use, indirect energy use, renewable energy use, waste creation, construction site consequences, embodied energy, and other environmental criteria;
7. SEOPP project actors believe that the most important economic criteria to evaluate in energy renovation projects are investment and global costs, followed by operation/maintenance costs, payback period, EOL costs, financing, incentives, tax exemptions, total revenues, and salaries/benefits;
8. SEOPP project actors state that the most important social criteria to evaluate in energy renovation projects are IAQ and thermal comfort, followed by end user satisfaction, house functional improvement, acoustic comfort improvement, visual comfort improvement, aesthetic improvement, employee satisfaction, number of workers, and proportion of women.

4.3. Computation of the chosen sustainability indicators

Figure 3 illustrates the results of the two environmental sustainability criteria analyzed for the three scenarios, normalized by the gross internal floor area (measured to the internal face of the external walls, including partitions, chimney, and stairwell). It is evident that the use phase is the main contributor

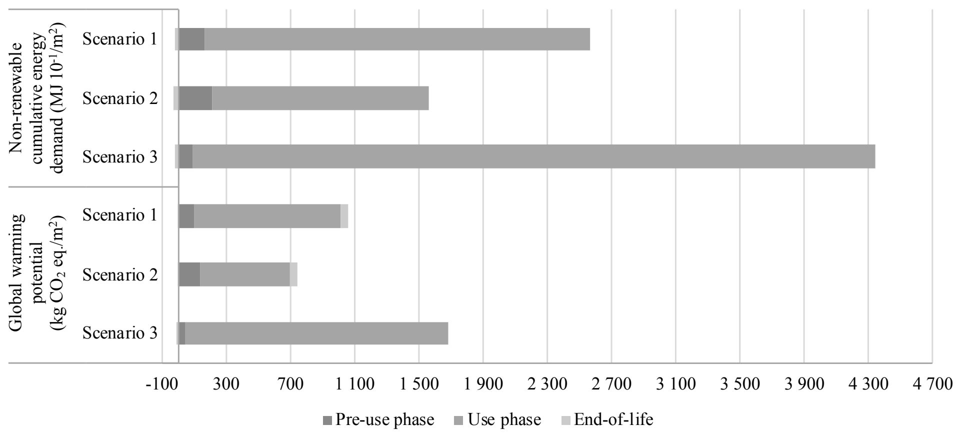

Figure 3: Non-renewable cumulative energy demand and global warming potential for the three scenarios, over the building life span after the renovation project, 50 years, normalized by the gross internal floor area.

to NRCED, from 88% of Scenario 2 to 98% of Scenario 3, while the pre-use and the EOL phases contribute in a range of 2-14% and -1.6-(-0.5)%, respectively. Moreover, in Scenario 2, the self-generated energy allows the reduction of the primary energy in the use phase, with a subsequent higher contribution of the pre-use phase. The results of the annual delivered energy during the operation phase are illustrated in Table A10 of the Appendix. The predominance of the use phase is also evident for GWP_{100}, where the pre-use, use, and EOL phases contribute within the following ranges: 3-18%, 76-97%, and 0.1-6%, respectively. It is worth noticing that the maintenance measures, including the material production, transport, and waste handling, were considered in the use-phase, where they have a proportion ranging from 6% to 24% for GWP_{100} and from 3% to 14% for NRCED.

The results obtained for the environmental indicators are in accordance with the trend characterizing building energy renovation projects (Dodoo et al., 2010; Passer et al., 2016), where the use phase impacts can predominate the whole building life cycle.

The results of the two economic performance indicators are shown in Figure 4, where they are normalized by the gross internal floor area. Note that the global cost for each scenario is split in the main cost categories characterizing such economic indicator, which include also the investment cost.
The investment cost of Scenario 2 is the highest among the three scenarios due to the highest number of EEMs adopted in this scenario. As a component of the global cost, the investment costs represent also the main contributor, ranging between 54% and 78% of the global cost. The annual energy costs for electricity and wood contribute to the global cost with a significant percentage, within a range from 4% to 26%. The replacement costs concur to the global cost with a percentage ranging from 12% to 17%. Note that replacement costs are slightly higher for Scenario 2 than the other scenarios due to the presence of the renewable energy systems, which also implies higher maintenance costs.

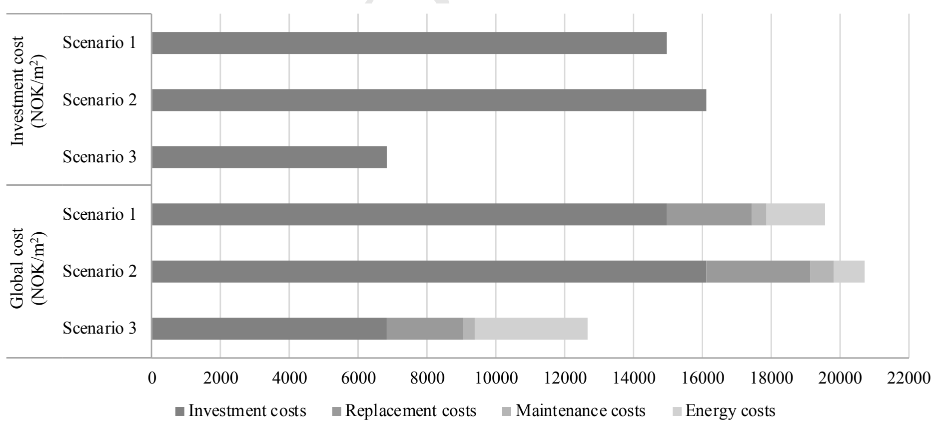

Figure 4: Investment cost and global cost for the three scenarios, over the building life span after the renovation project, 50years, normalized for the gross internal floor area. The global cost is split in the four categories shown in the legend.

The results obtained for the economic indicators appear overall comparable to those of similar studies (Risholt et al., 2013; Moschetti et al., 2015) with respect to the cost category contribution, although LCC analyses are usually very specific and related to the case study, as well as to the assumptions for the economic parameters, such as the real discount rate.

Regarding the social performance indicators, the results for Scenario 1 and Scenario 2 are the same, as the additional EEMs in Scenario 2 does not lead to any change in the analyzed social indicators compared to Scenario 1. The average CO_2 level in the main occupied rooms is illustrated in Table 4. As shown, the average CO_2 level is lower in Scenario 1 and 2 than in Scenario 3. To compare the performance of the three scenarios, a possible scale of scores was defined, according to the four IEQ categories suggested in EN 15251:2007 (see Table A9 of the Appendix). Therefore, considering a range of values between 0 and 8, the scores 8 and 7 were associated to Category IV (lowest), the scores 6 and 5 were associated to Category III, the scores 4 and 3 were associated to Category II, and the scores 2 and 1 to Category I (highest). Thus, for Scenario 1 and 2, an average score of 2 was obtained due to the compliance with Category I; while for Scenario 3, a score of 4 was achieved because of its accordance with Category II.

Table 4: Average indoor CO_2 level in all the main rooms over a year.

Rooms	Scenario 1 and 2 (ppm)	Scenario 3 (ppm)
Living room & kitchen	642.40	690.28
Bedroom1	934.98	1,084.57
Bedroom2	911.74	1,088.06
Bedroom3	921.17	1,081.09
Bedroom4	915.52	
Area-weighted average	741.51	881.72

The average PPD over the winter season for the main occupied rooms is illustrated in Table 5. As shown, slightly better thermal comfort conditions are achieved in Scenario 1 and 2 than in Scenario 3. The values achieved were compared with the PMV-PPD ranges recommended in EN 15251:2007 by assigning the same scores used for the IAQ indicator to the different IEQ categories. Thus, an average score of 2 was assigned to Scenario 1 and 2, since they are

Table 5: Average predicted mean vote values in all main rooms over the winter season.

Rooms	Scenario 1 and 2 (%)	Scenario 3 (%)
Living room & kitchen	5.56	5.58
Bedroom1	6.01	7.55
Bedroom2	6.16	7.02
Bedroom3	6.11	6.80
Bedroom4	6.06	
Area-weighted average	5.74	6.29

in Category I; however, Scenario 3 was accorded a score of 4, since it complies with Category II. The results obtained for the social indicators lie in reasonable magnitude ranges (Rohdin et al., 2014; Moschetti and Carlucci, 2017), although they should be considered as merely indicative of possible differences in terms of IEQ level for the three scenarios as they are not based on experimental or detailed examinations.

The results obtained for all sustainability criteria were grouped together and shown in radar charts on a common scale from 0 (best level) to 8 (worst level), as in Figure 5. To make the chart display consistent among all the analyzed scenarios, a normalized scale factor was defined for GWP_{100}, NRCED, global cost, and investment cost, whose results were not previously expressed on the noted scale, as was done for the PPD and indoor CO_2 level. Specifically, the normalization factor was 250 for GWP_{100}, 6000 for NRCED, 3500 for global cost, and 3500 for investment cost.

4.4. Group discussion and choice of the final renovation scenario

The radar charts shown in Figure 5 could be used as the starting point for the group discussion and the final choice of the renovation scenario to adopt in the project. The results shown in the radar charts should be interpreted considering that the smaller the area of the geometric shape in the chart, the better the sustainability performance of the scenario.

Overall, Scenario 2 achieves the highest sustainability performance, while Scenario 3 has the lowest performance. In particular, Scenario 1 and 2 have

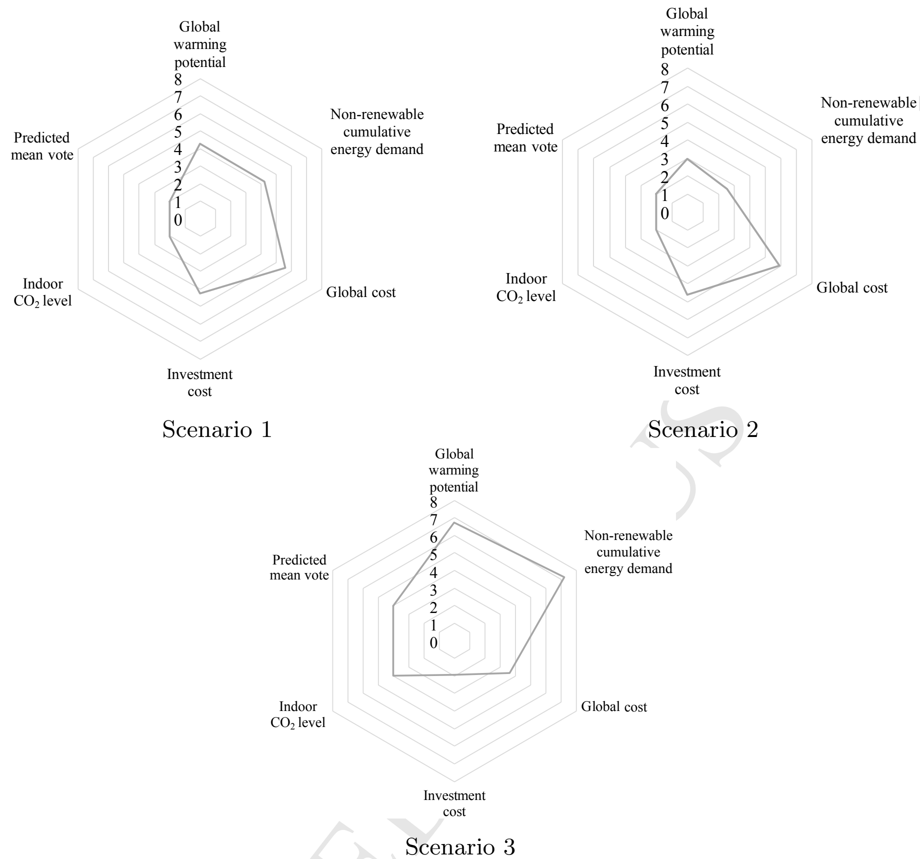

Figure 5: Overall sustainability level of the three scenarios analyzed, based on the results of all sustainability indicators normalized on a common scale from 0 (best level) to 8 (worst level).

a rather comparable sustainability performance, although the use of renewable energy technologies in Scenario 2 allows the achievement of a better environmental performance with a slightly lower economic performance. Scenario 3 shows a considerably worse environmental performance than Scenario 1 and 2, but a better relative economic performance. Finally, from the social perspective, Scenarios 1 and 2 show better results than Scenario 3 due to their more efficient ventilation and building envelope solutions.

5. Discussion

The research question that the authors addressed in this paper concerned the way quantitative sustainability analysis can support the emergence of SBMs in building energy renovation projects. To answer this research question a process-based perspective was adopted, and a possible tool for successful BM innovation was proposed. In particular, an analytic process tailored to the specific project category and based on holistic sustainability analyses was developed and then applied to a case study, with the involvement the whole network of actors. The proposed analytic process is meant as a necessary step in building energy renovation projects towards SBMs, which express the project value proposition, creation, and capture, in a triple bottom line perspective and for the whole network of stakeholders. The analytic process facilitates the definition of a value proposition that is the renovation of the building based on the achievement of a certain overall sustainability level, with value creation for different stakeholders. Therefore, the identification and computation of quantitative performance indicators related to different aspects of sustainability contribute to the value proposition and value creation processes. The final value capture of the project would be also influenced by the application of the proposed process, as cost and revenue streams can be partly foreseen within the choice of the final renovation scenario for the project. The energy renovation of the house is, in fact, undertaken aiming at certain sustainability-related benefits, which can be quantitatively demonstrated and discussed before the starting of the project, e.g., the reduction of environmental impacts, expressed in energy and emissions terms, the reduction of future energy and operating costs, and an overall improvement of the IAQ and thermal comfort.

The application of the analytic process to the case study was meant as an exemplification of the whole process implementation, and allowed to identify its effectiveness and practical implications. Certainly, such application can be strictly related to the involved actors and their commitment to contributing to the general objective of delivering sustainability with the project. Therefore, if the process was included in a more formal framework, the possibility of success would be higher. For example, it might be considered for incorporation into building codes or standards, as well as in Government incentive programs. Furthermore, a successful application of the whole analytic process would require the formulation of specific constraints, such as a minimum number of scenarios to evaluate, a minimum number of sustainability criteria and the related computation methodologies, a weight for the sustainability criteria/indicators, and a minimum overall sustainability level to achieve. Therefore, a standardization of the approach would be needed that also targets the establishment of a possible scale of benchmarks obtainable for the sustainability criteria and for the overall sustainability performance level.

The proposed analytic process should be pursued when the building energy renovation project is conceived, therefore in the planning and design phase. The main actors involved in the project, such as the building owner, the housing construction company, and the project team, should discuss and choose possible scenarios with different implementable EEMs for the project under analysis. Regarding the list of sustainability criteria, another actor, such as the municipality, should be in charge of sending it to the main actors of the project as soon as they send the documentation declaring the project intention. Then, the project actors should prioritize a certain number of sustainability criteria, which will be computed by the project team and/or specific consultants. Afterwards, the sustainability performance level of each scenario should be numerically/visually shown, and a group discussion on the results should occur and be documented to the municipality. Therefore, the approval and the beginning of the project should depend on the accomplishment of the whole process.

The computation methodologies applied in this paper for performing the sustainability analyses are very common in the research field but often considered too work-intensive in real project practices, due to the high amount of information needed, as well as the complexity and the interpretation of results (Malmqvist et al., 2011). Nonetheless, service providers, such as ESCO, could learn from a pool of projects using thorough sustainability assessments and deduce lesson-learned principles and benchmark criteria to apply to other projects, although with a simplified approach.

The findings of this research work differ from those of similar works in the context of the state-of-the-art, such as the EU projects noted above, i.e. NewBEE (2012) and Umbrella (2012). In NewBEE (2012), the tools developed for energy performance evaluation and BM assessment refer to the two main topics of this article, i.e., quantitative sustainability analyses and BMs in the energy renovation projects of buildings. However, these tools are meant for separate use, as the integration of sustainability analyses and BMs is not contemplated and a qualitative approach for BM assessment is adopted. In Umbrella (2012), the developed tools are meant as an aid to the actors in energy renovation projects to understand the implementable EEMs and the appropriate business solutions, while users' priorities are identified through mainly economic sustainability criteria. Thus, the tools are not built on a multi-stakeholder perspective, and the sustainability approach does not fully cover the triple bottom line.

6. Conclusion

This paper, after a review of the state-of-the-art, proposes an analytic process aimed at sustainable business models in building energy renovation projects, based on the exploitation of quantitative sustainability examinations. This process is also implemented in a case study to show its applicability and discuss the main shortcomings.

The paper's findings can be relevant for both practitioners and academics who search for new approaches to embed quantitative analyses into the business context of building energy renovation projects. Furthermore, this research provides a possible way to assess the sustainability level of a building renovation project on quantitative bases, and defines the groundwork for the possible operationalization of sustainable business in such projects. The objective is the systematic use of quantitative sustainability analyses as a key step towards sustainable business models.

This research work presents certain limitations that pave the way for future research. For instance, this paper presents the analysis of a single case study, which is also part of a research project. Certainly, specific adaptations and simplifications would be required for other energy renovation projects, although the main principles in our analytic process could be used. Furthermore, this work assumes an interest from all the involved actors to collaborate on the accomplishment of the analytic process, which would be ideal in certain cases and therefore requires a more formal and standardized path. In this regard, providing incentives or financial support to the project actors complying with certain requirements would be noteworthy.

Future research work could regard the application of the proposed approach to other similar case studies, with the objective of defining possible benchmarks for all the main sustainability criteria in energy renovation projects. This line of investigation would also allow the additional testing of the applicability and suitability of the process in different projects. Moreover, the proposed approach could be adapted to other energy efficiency projects, such as those involving zero-energy buildings, given their current relevance for the achievement of the sustainable development goals.

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Appendix

Table A1: LCA inventory for building envelope components and other building elements for all the scenarios analyzed.

Building component	Main materials	Source		Quantity			WF (-)	LS (-)	Distance from the construction site (km)
		Process in Ecoinvent 3.1	Environmental product declaration (EPD)	Scenario 1	Scenario 2	Scenario 3			
Basement floor	EPS		EPS isolasjon (trykklasse 80), EPS-gruppen	133.95 kg	133.95 kg		0.05	0	60
	Reinforcing steel		Wire mesh reinforcement steel, Norsk Stål AS	150.00 kg	150.00 kg		0.05	0	340
	Concrete	Concrete, normal {CH} | production | Alloc Def, U		6.06 m^3	6.06 m^3		0.05	0	100
	Concrete blocks	Concrete block {DE} |, production |, Alloc Def, U		21.40 kg	21.40 kg		0.05	0	100
	Polyethylene	Polyethylene, high density, granulate {RER} | production | Alloc Def, U		13.14 kg	13.14 kg		0.05	0	130
Foundation walls	EPS		EPS isolasjon (trykklasse 80), EPS-gruppen	234.87 kg	234.87 kg		0.05	0	60
	Fiber cement	Fibre cement facing tile {CH} | production | Alloc Def, U		61.60 kg	61.60 kg		0.05	0	60
	Reinforcing steel		Ribbed reinforcement bars, Norsk Stål AS	55.80 kg	55.80 kg		0.05	0	340
	Concrete	Concrete, normal {CH} | production | Alloc Def, U		1.98 m^3	1.98 m^3		0.05	0	100
Bearing structures	Laminated wood	Glued laminated timber, for indoor use {RER} | production | Alloc Def, U		0.13 m^3	0.13 m^3		0.07	0	450
	Softwood	Sawnwood, softwood, air dried, planed {RER} | planing, softwood, air dried | Alloc Def, U		0.04 m^3	0.04 m^3		0.07	0	220
	Steel	Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Def, U		3.00 kg	3.00 kg		0.05	0	340
External walls	Glass wool		Glava glass wool, Glava AS	287.28 kg	287.28 kg		0.05	0	60
	Softwood	Sawnwood, softwood, air dried, planed {RER} | planing, softwood, air dried | Alloc Def, U		5.61 m^3	5.61 m^3	2.76 m^3	0.07	0	242
	Polyethylene	Polyethylene, high density, granulate {RER} | production | Alloc Def, U		30.50 kg	30.50 kg		0.05	0	160
	Paint	Alkyd paint, white, without water, in 60% solution state {RER} | production | Alloc Def, U		102.43 kg	102.43 kg	101.53 kg	0.05	6	100
	Particleboard		Forestia particleboard, Forestia AS	0.45 m^3	0.45 m^3		0.07	0	160
Internal walls	Glass wool		Glava glass wool, Glava AS	79.26 kg	79.26 kg		0.05	0	60
	Softwood	Sawnwood, softwood, air dried, planed {RER} | planing, softwood, air dried | Alloc Def, U		0.66 m^3	0.66 m^3		0.07	0	418
	Polyethylene	Polyethylene, high density, granulate {RER} | production | Alloc Def, U		28.89 kg	28.89 kg		0.07	0	160
	Paint	Alkyd paint, white, without solvent, in 60% solution state {RER} | production | Alloc Def, U		211.83 kg	211.83 kg	187.27 kg	0.05	3	100
	Gypsum plaster		Gyproc Plasterboard GN13, Saint Gobain	693.81 kg	693.81 kg		0.07	0	95
Ceilings and roof	Glass wool		Glava glass wool, Glava AS	468.81 kg	468.81 kg		0.05	0	60
	Softwood	Sawnwood, softwood, air dried, planed {RER} | planing, softwood, air dried | Alloc Def, U		5.03 m^3	5.03 m^3		0.07	0	357
	Particleboard		Forestia particleboard, Forestia AS	2.78 m^3	2.78 m^3		0.07	0	160
	Laminated wood	Glued laminated timber, for indoor use {RER} | production | Alloc Def, U		0.54 m^3	0.54 m^3		0.07	0	450
	Hardwood/OSB		Masonite I-bjelke, Masonite Beams AB	3.56 m^3	3.56 m^3		0.07	0	800
	Polyethylene	Polyethylene, high density, granulate {RER} | production | Alloc Def, U		14.16 kg	14.16 kg		0.07	0	160
	Polyurethane	Polyurethane, rigid foam {RER} | production | Alloc Def, U		44.00 kg	44.00 kg		0.07	0	160
	Paint	Alkyd paint, white, without solvent, in 60% solution state {RER} | production | Alloc Def, U		90.95 kg	90.95 kg	81.04 kg	0.05	3	100
	Bitumen		Isola Mestertekk, Isola AS	503.37 kg	503.37 kg	350.10 kg	0.07	1	160
	Gypsum plaster		Gyproc Plasterboard GN13, Saint Gobain	844.83 kg	844.83 kg		0.07	0	95
	Ceramic tiles	Ceramic tile {CH} | production | Alloc Def, U		260 kg	260 kg	737.73 kg	0.05	1	100
Windows	Wooden frame	Window frame, wood, U=1.5 W/m^{2}K {RER} | production | Alloc Def, U		8.71 m^2	8.71 m^2	5.70 m^2	0.00	1	350
	Coated glass	Flat glass, coated {RER} | production | Alloc Def, U		195.03 kg	195.03 kg	127.65 kg	0.00	1	350
	Uncoated glass	Flat glass, uncoated {RER} | production | Alloc Def, U		390.06 kg	390.06 kg	127.65 kg	0.00	1	350
External doors	Wood-Aluminum	Door, outer, wood-aluminum, RER | production | Alloc Def, U		3.80 m^2 kg	3.80 m^2	1.90 m^2	0.00	1	100
Sanitary appliances	Ceramic	Sanitary ceramics {CH} | production | Alloc Def, U		105.00 kg	105.00 kg	125.00 kg	0.00	1	100
External drainage	Gravel	Gravel, crushed {CH} | production | Alloc Def, U		23760.00 kg	23760.00 kg	29592.00 kg	0.00	1	100
	Polyethylene	Polyethylene, high density, granulate {RER} | production | Alloc Def, U		142.30 kg	142.30 kg	162.72 kg	0.07	1	100
	Polyethylene pipe	Polyethylene pipe, corrugated, DN 75 RER— production | Alloc Def, U		24.20 m	24.20 m	32.10 m	0.00	1	100

Table A2: LCA inventory for technical building systems for all the scenarios analyzed.

Technical building system	Process in Ecoinvent 3.1	Quantity			WF (-)	LS (-)	Distance from the construction site (km)
		Scenario 1	Scenario 2	Scenario 3			
Ventilation system	Air filter, central unit, 600 m^3/h {RER} | production | Alloc Def, U	1 p*	1 p		0.00	1	100
	Blower and heat exchange unit, Avent E 97 {RER} | production| Alloc Def, U	1 p	1 p		0.00	1	100
	Ventilation duct, steel, 100x50 mm {RER}, production, Alloc Def, U	50 m	50 m		0.00	1	100
	Exhaust air outlet, steel/aluminum, 85x365 mm {CH}, production, Alloc Def, U	15 p	15 p		0.00	1	100
	Outside air intake, stainless steel, DN 370 {RER}, production, Alloc Def, U	3 p	3 p		0.00	1	100
	Supply air inlet, steel/SS, DN 75 {RER}| production | Alloc Def, U	15 p	15 p		0.00	1	100
Wood stove	Furnace, logs, 6kW {CH}| production | Alloc Def, U	1 p	1 p	1 p	0.00	0	100
Electric floor heating	Copper {RER}| production, primary | Alloc Def, U	11.90 kg	11.90 kg	32.20 kg	0.00	1	100
	Polypropylene, granulate {RER}| production | Alloc Def, U	97.54 kg	97.54 kg	263.00 kg	0.00	1	100
Electric heaters	Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Def, U	53.30 kg	53.30 kg	41.00 kg	0.00	2	100
	Polycarbonate {RER}| production | Alloc Def, U	1.95 kg	1.95 kg	1.05 kg	0.00	2	100
	Corrugated board box {RER}| production | Alloc Def, U	3.90 kg	3.90 kg	3.00 kg	0.00	2	100
DHW boiler	Hot water tank, 600l {CH}| production | Alloc Def, U	1 p	1 p	1 p	0.00	2	100
Heat pump	Heat pump, brine-water, 10kW {CH}| production | Alloc Def, U	1 p	1 p	1 p	0.00	2	100
PV system	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Def, U		25 m^2		0.00	1	100
	Inverter, 2.5kW {RER}| production | Alloc Def, U		1 p				
Solar thermal system	Evacuated tube collector {GB}| production | Alloc Def, U		8 m^2		0.00	1	100
	Expansion vessel, 25l {CH}| production | Alloc Def, U		1 p		0.00	1	100
	Pump, 40W {CH}| production | Alloc Def, U		1 p		0.00	1	100

* p=unit

Table A3: Main features of the building envelope for all the scenarios analyzed.

	Scenario 1-2			Scenario 3		
Building envelope components	Area m^2	Thermal transmittance $W/(m^2K)$	Description	Area m^2	Thermal transmittance $W/(m^2K)$	Description
External wall, basement	78.21	0.13	Concrete wall, high insulation	79.52	2.90	Concrete wall, no insulation
External wall, other floors	151.53	0.19	Timber framed wall, high insulation	140.37	0.38	Timber framed wall, low insulation
Roof, original	56.15	0.09	Wood pitched roof, very high insulation	56.15	0.22	Wood pitched roof, high insulation
Roof, new parts	14.28	0.14	Wood pitched roof, very high insulation			
Floor outwards	17.50	0.17	Wood flat roof, very high insulation			
Floor on ground, original	62.40	0.32	Concrete slab, low insulation	62.40	3.10	Concrete slab, no insulation
Floor on ground, new extensions	15.50	0.13	Concrete slab, high insulation			
Windows	29.02	0.88	Low-e triple-pane glass, argon filled, wood frame	19.00	1.50	Low-e double-pane glass, air filled, wood frame
External doors	3.80	1.10	Wood-aluminum frame, high insulation	2.00	1.95	Wood-aluminum frame, medium insulation
Average thermal bridge ($W/m^2/K$)		0.03			0.05	

Table A4: Main input data for the dynamic energy simulations.

	Scenario 1-2	Scenario 3
Heating system	Electric radiators (in all rooms, except bathrooms), electric floor heating (only in bathrooms), wood stove (in living room, 20% of delivered energy), and air-to-air heat pump (only in living room)	
Outdoor temperature (°C)	Dynamic (IWEC2 database by ASHRAE)	
Indoor temperature during operation time (°C)	21	21
Indoor temperature outside of operation time (°C)	19	19
Internal gains from lighting (W/m^2)	1.95	1.95
Internal gains from electric appliance (W/m^2)	1.8	1.8
Internal gains from occupants (W/m^2)	1.5	1.5
Heating, DHW, lighting, electric appliance operation time (hours)	5,824	5,824
People occupation time (hours)	8,736	8,736
Lighting energy need in operation time (W/m^2)	1.95	1.95
Electric appliance energy need in operation time (W/m^2)	3	3
DHW energy need	5.1	5.1
in operation time (W/m^2)		1
Heat pump COP (-)	2.5	2.5
Stove efficiency (%)	85	85
DHW boiler efficiency (%)	95	95
Mechanical air flows ($m^3/h/m^2$)	1.2	
Air leakage, 50 Pa (Air changes per hour, ACH)	1	6
Mechanical ventilation system operation time (hours)	8,736	
Specific fan power in ventilation system ($kW/m^3/s$)	1.5	
Heat exchanger efficiency (%)	85	

Table A5: Main features of the PV and solar thermal systems for Scenario 2.

	PV system	Solar thermal system
Technology	Crystalline silicon	Evacuated tube collectors
Total panel area (m^2)	25	8
Slope (°)	45	45
Azimuth (°)	180	180
Estimated system losses (%)	14	
Peak power (kWp)	4	
Collector efficiency intercept (-)		0.7
Collector efficiency slope (-)		2
Effectiveness of heat exchange (-)		0.7
Collector flow rate (kg/s)		0.7
Storage tank volume (m^3)		0.7
Circulation pump power (W)		70
Total annual energy generated (kWh)	3,980	3,875

Table A6: Maintenance measures for all the scenarios analyzed.

Scenario 1	Scenario 2	Scenario 3
Repainting external walls every 8 years	Repainting external walls every 8 years	Repainting external walls every 8 years
Repainting internal walls every 15 years	Repainting internal walls every 15 years	Repainting internal walls every 15 years
Repainting internal ceilings every 15 years	Repainting internal ceilings every 15 years	Repainting internal ceilings every 15 years
Replacing windows after 30 years	Replacing windows after 30 years	Replacing windows after 30 years
Replacing external doors after 30 years	Replacing external doors after 30 years	Replacing external doors after 30 years
Replacing roof covering after 30 years	Replacing roof covering after 30 years	Replacing roof covering after 30 years
Renovating bathroom after 25 years	Renovating bathroom after 25 years	Renovating bathroom after 25 years
Replacing external drainage after 40 years	Replacing external drainage after 40 years	Replacing external drainage after 40 years
Replacing electric radiators every 20 years	Replacing electric radiators every 20 years	Replacing electric radiators every 20 years
Replacing wood stove after 25 years	Replacing wood stove after 25 years	Replacing wood stove after 25 years
Replacing electric floor heating after 25 years	Replacing electric floor heating after 25 years	Replacing electric floor heating after 25 years
Replacing DHW boiler every 15 years	Replacing DHW boiler every 15 years	Replacing DHW boiler every 15 years
Replacing heat pump every 15 years	Replacing heat pump every 15 years	Replacing heat pump every 15 years
Replacing ventilation system after 25 years	Replacing ventilation system after 25 years	
	Replacing PV system after 25 years	
	Replacing solar thermal system after 25 years	

Table A7: End-of-life assumptions for all the scenarios analyzed.

Material	End-of-life process		
	Municipal landfill	Recycling plant	Incineration plant
Metals	20%	80%	
Plastic materials	20%	80%	
Wood products			100%
All other materials	100%		

[*] The assumptions of this table apply to materials not provided with EPDs.
[**] The distance from the construction site to the waste treatment plants was assumed to be 85 km for all materials.
[***] A neutral CO_2 balance was adopted for all wood products, therefore neither CO_2 sequestration nor CO_2 emissions from combustion were included in the LCA impact assessment.

Table A8: Main input data for IAQ and thermal comfort analysis for all the scenarios analyzed.

	Scenario 1-2	Scenario 3
Assessed rooms	Living room+kitchen= 61.9 m^2 (max number of occupants: 5) Bedroom 1= 9.7 m^2 (max number of occupants: 2) Bedroom 2= 7.1 m^2 (max number of occupants: 1) Bedroom 3= 6.9 m^2 (max number of occupants: 1) Bedroom 4= 10.4 m^2 (max number of occupants: 1)	Living room+kitchen= 43.4 m^2 (max number of occupants: 5) Bedroom 1= 9.7 m^2 (max number of occupants: 1) Bedroom 2= 9.8 m^2 (max number of occupants: 2) Bedroom 3= 21.66 m^2 (max number of occupants: 2)
Occupation time	Living room&kitchen: week days 7:30-9:00, 17:00-22:00 weekend days 8:00-10:00, 12:00-16:00 Bedrooms: week days 22:30-6:30 weekend days: 23:00-7:30	Living room&kitchen: week days 7:30-9:00, 17:00-22:00 weekend days 8:00-10:00, 12:00-16:00 Bedrooms: week days 22:30-6:30 weekend days: 23:00-7:30
Indoor temperature during operation time (°C)	21	21
Indoor temperature outside of operation time (°C)	19	19
Air velocity (m/s)	0.1	0.1
Clothing insulation (m^2K/W)	0.155	0.155
Outdoor CO_2 level (ppm)	400	400
Metabolic rate (W/m^2)	69.6	69.6
Air leakage, 50 Pa (ACH)	1	6
Mechanical air flows ($m^3/h/m^2$)	1.2	

Table A9: PPD values and CO_2 concentrations above outdoors, as recommended by EN 15251:2007 for different IEQ categories.

IEQ Category	PPD (%)	CO_2 level above outdoors (ppm)
I (high level of expectation)	<6	350
II (normal level of expectation)	<10	500
III (acceptable level of expectation)	<15	800
IV (low level of expectation)	>15	>800

Table A10: Annual delivered energy during the operation phase, for all the scenarios analyzed.

	Scenario 1	Scenario 2	Scenario 3
Electric heating (kWh/m^2)	20.4	20.4	94.9
Wood fuel (kWh/m^2)	6.6	6.6	29.0
HVAC auxiliaries (kWh/m^2)	8.2	8.2	
Domestic hot water (kWh/m^2)	31.4	31.4	31.4
Electric appliances (kWh/m^2)	17.5	17.5	17.5
Lighting (kWh/m^2)	11.4	11.4	11.4
PV system (kWh/m^2)		-22.5	
Solar thermal system (kWh/m^2)		-21.1	
Total (kWh/m^2)	95.5	45.2	184.1