EBC

Energy in Buildings and Communities Programme

International Energy Agency

Life Cycle Assessment for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)

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March 2017

EBC is a programme of the International Energy Agency (IEA)

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

– Integrated planning and building design
– Building energy systems
– Building envelope
– Community scale methods
– Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)

Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
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Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Energy Principles
Annex 65: Long-Term Performance of Super-Insulation in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behaviour in Buildings
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle related Environmental Impacts Caused by Buildings

Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Energy Endeavour
Annex 75 Cost-effective building renovation at district level combining energy efficiency and renewable

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Survey on HVAC Energy Calculation Methodologies for Non-residential Buildings

Management summary

Introduction

Buildings are responsible for a major share of energy use and have been a special target in the global actions for climate change mitigation, with measures that aim at improving their energy efficiency, reduce carbon emissions and increase renewable energy use.

The IEA-EBC project "Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation" (Annex 56) intends to develop the basics for future standards, which aim at maximizing effects on reducing carbon emissions and primary energy use while taking into account the cost-effectiveness of related measures. The methodology integrates a life cycle perspective with an environmental Life Cycle assessment (LCA) methodology next to a Life Cycle Cost (LCC) assessment. The LCA methodology is used in order to be able to quantify the *so-called* embodied primary energy and embodied carbon emissions due to the manufacturing, replacement and end-of-life (e.g., disposal or recycling) of construction materials and building integrated technical systems (BITS) added during a building renovation.

The embodied energy and embodied carbon emissions of renovation measures originally represent an increasing share of the remaining overall primary energy use of buildings for new construction. The increasing building renovation towards nearly zero energy building standard is expected to lead to a relative increase of embodied energy and embodied carbon emissions. It is thus important to take these notions into account in the project's methodology.

Objectives and contents of the LCA report

This report presents the Life Cycle Assessment (LCA) methodology, its implementation on six European case studies, the related results and some recommendations related to LCA and the inclusion of embodied energy in building renovation. This LCA report comprises the following parts:

- the LCA methodology for energy related building renovation;
- the implementation of the LCA methodology in six case studies;
- the conversion factors used for primary energy and carbon emissions in the case studies
- the analysis of embodied energy and embodied carbon emissions influence in case studies results;
- recommendations to policy makers and building owners.

Life cycle assessment (LCA) for energy related building renovation

The LCA methodology developed in this project only includes processes with a relevant contribution to the total environmental impacts of renovated buildings which can be put into practice with a reasonable effort. Main focus is the integration of embodied energy and related carbon emissions in the assessments of operational energy use.

Functional unit: In LCA, according to the ISO 14040, the 'functional unit' is defined as the quantification of the performance of a product system, and specifies that is used as the reference unit for the LCA and any comparative assertion. It has a quantity (e.g. 1 m^2), a duration (e.g. 'maintaining the function over 50 years') and a quality e.g. '"to ensure a thermal resistance of 2 m^2/W.K'). The term 'functional equivalent' is also defined in the 15978 standard (2011) and denotes the technical characteristics and functionalities of the building that is being assessed. In practice, units and target values for energy use and carbon emissions in this LCA methodology are expressed in MJ/m^2a or kWh/m^2a and kg CO_2-equivalents per $m^2{*}$a (kg CO_{2e}/m^2a). So, in this project, all results are expressed per unit of surface area per year after having divided the LCA results calculated for the reference study period of the building.

System boundaries: LCA shall be integrated in the assessment and in the optimization of renovation measures. The Life Cycle (LC) impacts of renovation packages are determined by comparing them with the LC impacts of a corresponding renovation solution which occurs «anyway» and which aims at restoring full functionality of the building not improving energy efficiency yet. Hence only LC impacts of measures that affect energy performance of the building are considered (thermal envelope, building integrated technical systems (BITS), energy use for on-site production and delivered energy). Thereby this LCA methodology only includes the operational and embodied energy use and related carbon emissions.

Temporal System boundary: The temporal system boundary for LCA comprises the different stages of the life cycle of building renovation measures (see Figure 1). At least the green stages from Figure 1 are supposed to be taken into account for life cycle assessments in this project. Generally, the time range for LCA (reference study period) should comprise at least the service life time of the building elements with the longest service life. In addition, it is suggested to use a study period of 60 years and to report it if a different period is used.

Physical system boundary: The physical system boundary for LCA defines the materials and energy fluxes which must be taken into account for the LCA. The main impacts stem from construction elements and building integrated technical systems (BITS). The construction elements consist of one or more materials. The BITS consist of components (boilers, pumps, etc.) which are made of materials. In addition, these components use one or more energy vectors. The LC impacts are caused by envelope materials and/or BITS components which are added or replaced by energy related renovation measures as well as by operational energy use of BITS during building operation to deliver the expected energy services (heating, cooling, DHW production, etc.), without accounting for those elements which would be replaced anyway.

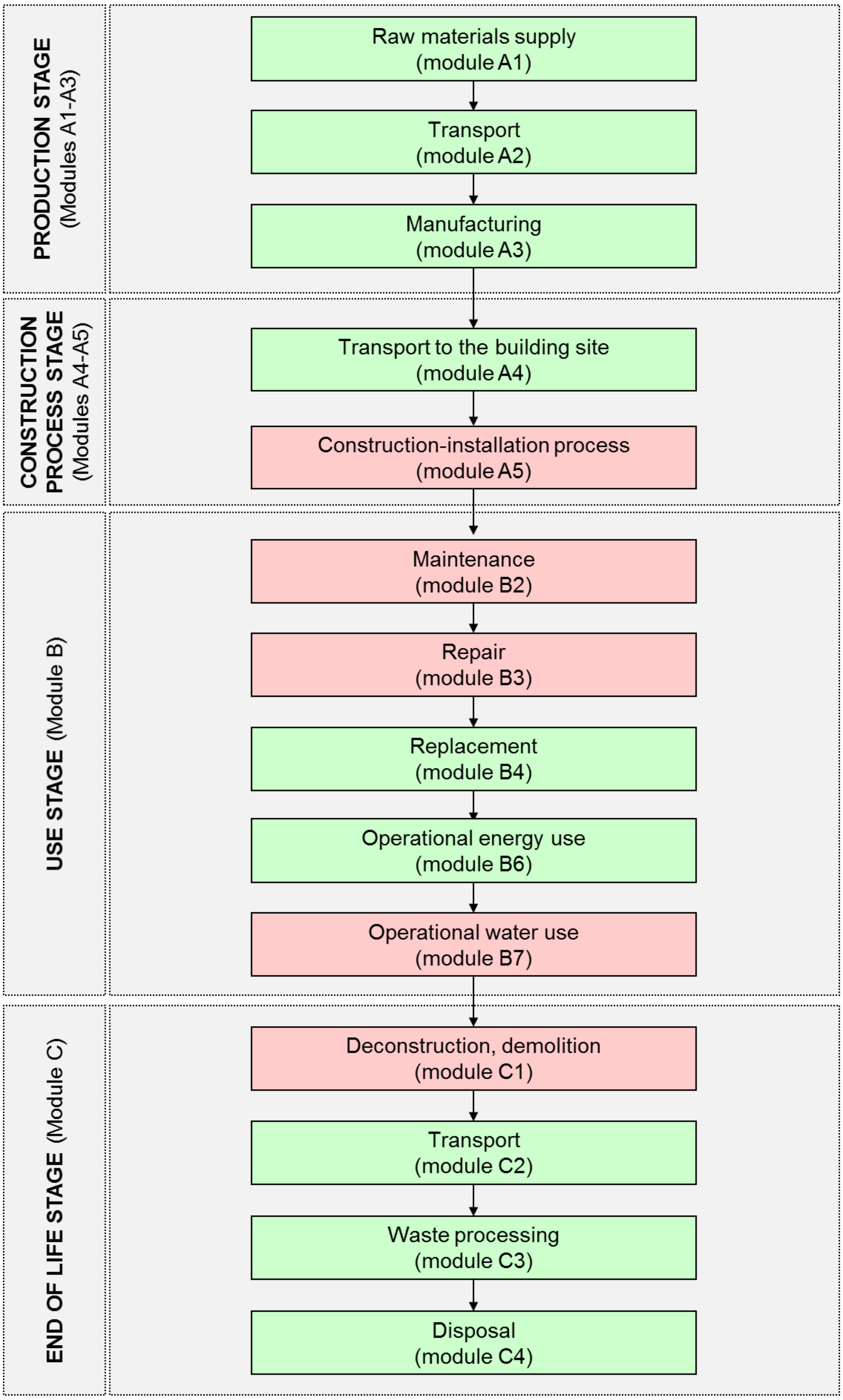

Figure 1 Schematic breakdown of a building's life cycle into elementary stages adapted from EN 15978 standard modules' names; the module D "benefits and loads beyond the system boundary" is not reported here

Calculation rules for the operational energy use: The LCA for the operational energy use comprises the following mandatory energy services:

- Heating;
- Domestic hot water (DHW);
- Air conditioning (cooling & (de)humidifying);
- Ventilation;
- Lighting;
- Auxiliary (pumps, control devices, etc.);
- Integration of energy use from common appliances and home appliances e.g., the white appliances remain optional, it can be included but has to be reported and documented in a transparent way.

In this LCA methodology, the on-site produced energy is in priority allocated to the building related energy use to comply with EN 15978 (2011), the rest being allocated to the non-building related energy use. Similarly, while an hourly approach is probably the most accurate according to the findings of the IEA Task 40/Annex 52 project, the current energy codes or regulations do not require it as a compulsory approach. In this project, the calculation rules for the LCA are thus based on the energy needs calculated with a steady state approach, determining yearly energy demand as building energy codes and labels only calculate the energy consumption and on-site generation on an annual balance.

Calculation rules for the construction materials and BITS:

Elements to include: The system boundary to perform an LCA of a renovated building should include the following elements:

- The materials added for energy related renovation measures of the thermal envelope of the building;
- The materials added for energy related renovation measures for the building integrated technical systems (BITS), including on-site energy generation units (PV, solar thermal, etc.);
- The materials added to provide the same building function before and after renovation.

Service life and replacement: The service life is defined as the time during which a building component (construction element, BITS component (boiler, etc.)) fulfils its function. At the end of its service life, the component must be replaced. Not all layers (materials) of a building element are replaced at the same time, some are never replaced (e.g., the bearing structure).

- Some heavy layers are part of the element structure but might still be replaced during the life cycle of the building.
- A material placed between two layers of the envelope structure will have the same service life as the layer with the shorter service life.
- If a construction element is designed to make it easy to replace some internal parts, only the replaced material is taken into account for the assessment.

Hence, the service life of materials depends on the type of construction element (wall, floor, roof, etc.), the situation of the construction element (against ground, exterior and interior) and the position of the material layer within the construction element.

Figure 2 presents the different aspects that need to be included in the LCA of a renovated building.

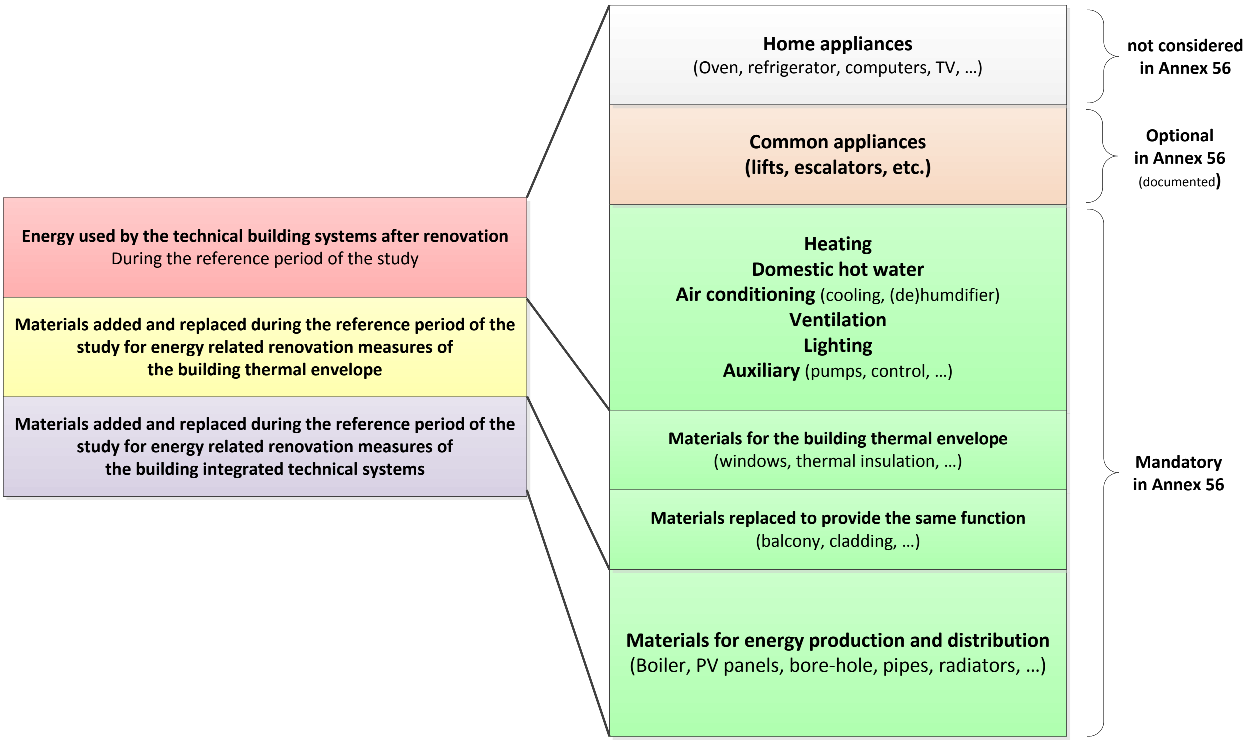

Figure 2 Aspects to be included in the LCA of renovated buildings: materials for the building envelope and for the BITS and the operational energy use

Environmental indicators: the number of indicators used in this project has been limited to the three following indicators:

- **Total Primary Energy (PE_t)**. It represents total primary energy used, renewable or not including feedstock (e.g., materials produced from crude oil, plastic products, wood products) and process primary energy. It includes the non-renewable part (fossil, nuclear, primary forests) as well as the renewable part (hydro, solar, wind, biomass). In this project, PE_t is expressed in [kWh][1].
- **Non-renewable Primary Energy (PE_{nr})**. It represents the non-renewable part of the total primary energy, i.e the non-renewable primary energy used including feedstock (e.g., materials produced from crude oil, plastic products) and process primary energy. It indicates the depletion of non-renewable energy sources (at a human scale), such as fossil fuels, nuclear resources and primary forests. PE_{nr} is also expressed in [kWh].
- **Carbon emissions.** This indicator is related to the emissions of greenhouse gases. It is not measured in an absolute unity, because each gas has a different global warming potential on the greenhouse effect (for the same quantity). In this project, their potential is compared to the CO_2 used as reference for a period of 100 years. This indicator is expressed in [kg- CO_{2e}][2].

Reference study period:

Cost and LCA are carried out on the basis of a chosen reference study period, for which all contributions of materials and energy consumed are calculated. Therefore, the reference period has an important and direct influence on the results. It should be noticed, that the number of energy related renovations during the building's life is limited. The more the building achieves low energy consumption after renovation, the less a major energy related renovation will be undertaken in the future. It is impossible to know, which materials will be used to replace the energy related construction material in the future. It is also impossible to know which future energy vectors will be used when the boiler will be replaced (in about 30 year). In that context, the reference study period should be equal or longer than the service life of the energy related building components analysed in order to avoid any misinterpretation of the results. Therefore, it is suggested to use a reference study period of 60 years. If another reference study period is used, it should be reported and documented.

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1 It is likely that not all countries have primary energy data included fossil, nuclear and primary forests. In that case, adaptation of life cycle inventory and LCA data from existing life cycle assessment databases (e.g., the ecoinvent v3 database) could be a solution to derive country-specific data with the different types of primary energy as defined in this project.

2 The reader should notice that the labelling of this indicator i.e., "carbon emissions" is chosen to comply with the title of this project. However, this indicator quantifies the equivalent CO_2 emissions in the same way as did the greenhouse gases emissions indicator e.g., used in the IEA EBC Annex 57 project.

Implementation of the LCA methodology in building renovation case studies

The LCA methodology was implemented in six case studies of multi-family residential buildings located in Austria, Czech Republic, Denmark, Portugal, Spain, and Sweden. Case studies represent residential and non-technical office buildings (not having air conditioning). All these case studies have renovation measures for both the envelope and the BITS while a few of them integrate also renewable energy systems (e.g., use of PV panels). Table 5 presents a brief overview of these case studies.

Table 1: Overview of case studies used for the LCA

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA[3]
Austria			Johann-Böhmstraße, Kapfenberg	Multi-family building	1960 – 1961	2012 – 2014	2845 m^2
Czech Republic			Kamínky 5, Brno	Elementary School	1987	2009 – 2010	9909 m^2
Denmark			Traneparken, Hvalsø	Multi-family Building	1969	2011-2012	5293 m^3
Portugal			Neighborhood RDL, Porto	Two-family Building	1953	2012	123 m^2
Spain			Lourdes Neighborhood, Tudela	Multi-family Building	1970	2011	1474 m^2
Sweden			Backa röd, Gothenburg	Multi-family Building	1971	2009	1357 m^2

[3] Gross Heated Floor Area (GHFA) after the renovation of the building

For the six investigated case studies, parametric studies were performed to identify the cost effective renovations for the individual real building renovations. The parametric studies were performed based on the developed methodology including the Life Cycle Assessment (LCA)[4].

For the case studies, each partner defined the characteristics of the investigated renovation packages according to what is feasible in each country. The idea was to include different thermal standards (insulation of building envelope) and different energy sources for heating and domestic hot water preparation (fossil fuels and renewables) as well as different ventilation situations (mechanical and natural) in the considerations.

The reference case include only renovation measures which have to be carried out anyway. Therefore the reference case is named as “anyway renovation”. Then, the investigated renovation packages are named in further consequence “renovation package v1”, “renovation package v2” and “renovation package v3”, where v3 represents the actually renovation carried out. More detailed information about the description of the different renovation measures of each country can be found in the findings and conclusions of the case studies report (Venus et al, 2015) [5].

Embodied energy and embodied carbon emissions results from case studies

The LCA of each renovation package and each case study was evaluated according to the total carbon emissions, the Non-Renewable Primary Energy (NRPE) and the total Primary Energy (PE) indicators. The analyses focus on the relevance of including embodied energy and embodied carbon emissions in each renovation measure.

In this study, the following questions were addressed:

- How much operational primary energy and carbon emissions is saved compared to the additional embodied primary energy consumption and carbon emissions?
- The operational primary energy and carbon emissions6 savings compared to embodied primary energy consumption and carbon emissions

[4] More information to the developed methodology can be found on the official IEA EBC Annex 56 website:
http://www.iea-annex56.org/
The Methodology report can be downloaded here:
http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf

[5] For a detailed description of the renovation scenarios (v1, v2, and v3) for each case study, please look at pages 49-56

[6] carbon emissions refer in IEA EBC Annex 56 to the greenhouse gases emissions’ indicator

- Does the integration of embodied energy and embodied carbon emissions in the calculations change the choice of the optimal renovation concept for the carbon emissions, primary energy (total) and primary energy (non renewable) indicators?

The choice of these research questions was motivated by the scope of the project i.e., the determination of cost-effective building renovation packages using a methodology integrating not only the operational primary energy and carbon emissions but also the embodied energy and carbon emissions due to the construction materials and BITS. In that specific context, the influence of integrating the embodied energy and embodied carbon emissions of materials for the envelope and for the BITS needs to be analyzed.

Indeed, in this chapter two hypotheses related to the influence of embodied energy and carbon emissions were assessed and validated. These hypotheses are:

1. **The operational savings are higher than the additional embodied energy and embodied carbon emissions in any cost-effective renovation measures.**
2. **The integration of embodied energy and embodied carbon emissions does not change the cost-effective renovation packages.**

As an illustration of all the results, the next figure presents the results without including embodied carbon emissions and with embodied carbon emissions (results represented with a black edge), for the different renovation packages of the six case studies.

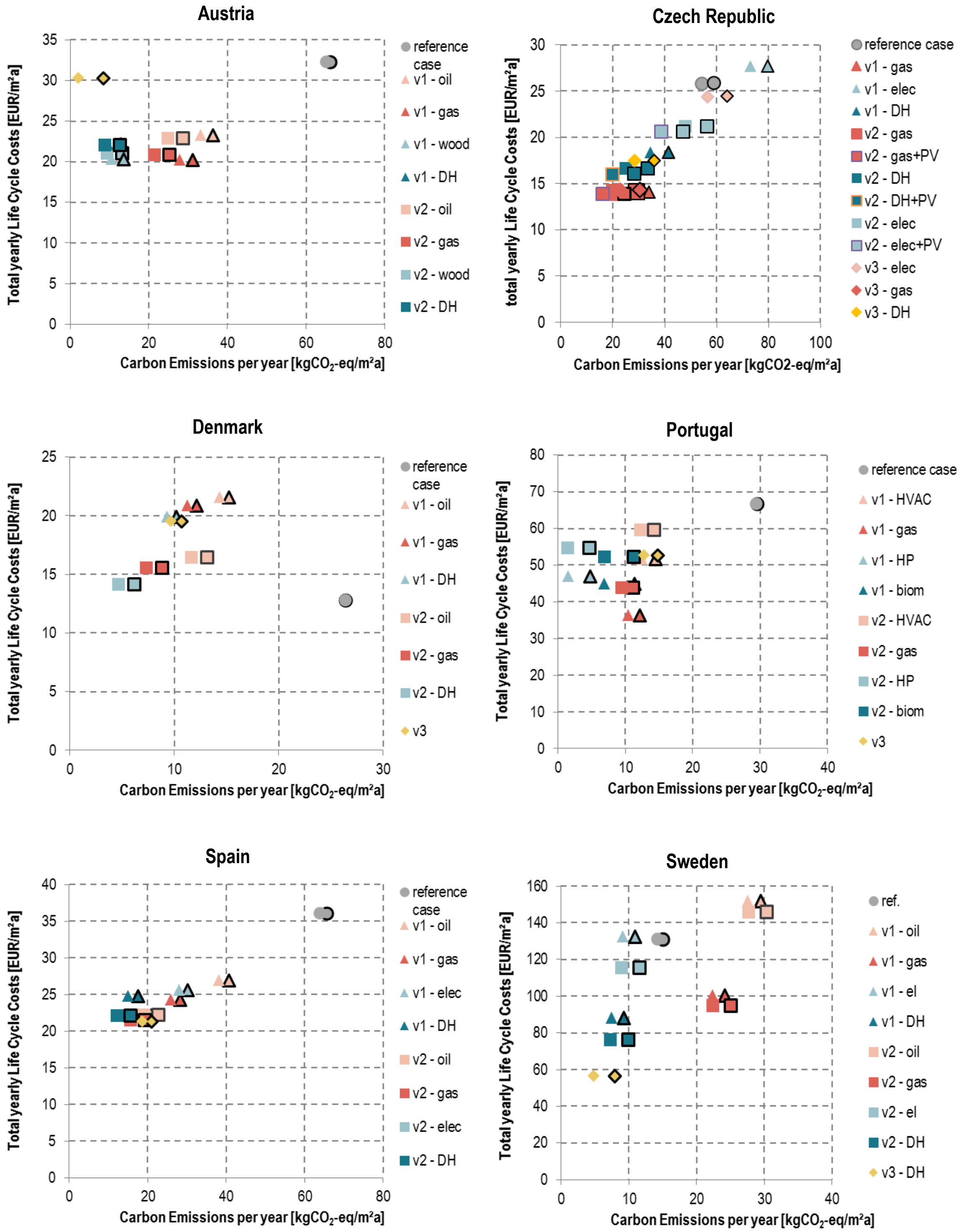

Figure 3 Comparison of calculations for the six case studies, without including embodied carbon emissions and with embodied carbon emissions (results represented with a black edge), for the different renovation packages

Global results show that the inclusion of embodied energy and carbon emissions in the Annex 56 methodology does neither change the cost-effective solutions nor the best renovation packages in terms of total primary energy (TPE), non-renewable primary energy (NRPE) and carbon emissions.

Based on these results, for all the cost-effective renovation measures of each case study, the operational savings where compared with the embodied energy or embodied carbon emissions. As an illustration, Figure 4 presents the results for the particular case of Sweden were four out of nine renovation packages were cost-effective.

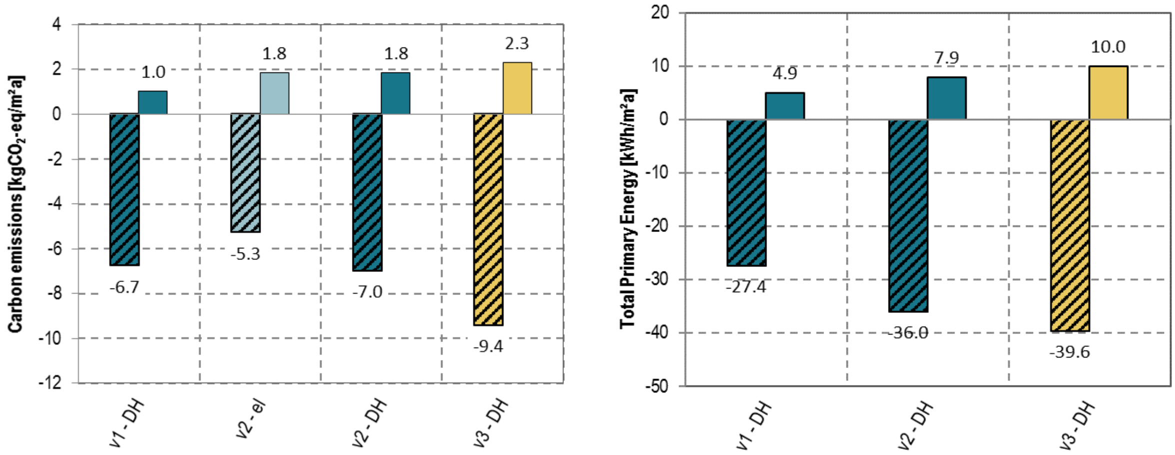

Figure 4 Comparison of operational carbon emissions and total primary energy savings and additional embodied carbon emissions and total primary energy for the cost-effective solutions of the Swedish case studies; the negative bars represent the operational savings while the positive bars represent the additional embodied energy and embodied carbon emissions

Similar results can be retrieved from all case studies and are presented in details in the following report. Finally, summary of findings are presented below:

1. **The operational savings of the energy related renovation measures assessed are higher than the additional embodied energy and embodied carbon emissions in any cost-effective renovation measures.**
2. **The integration of embodied energy and embodied carbon emissions of the energy related renovation measures assessed does not change the cost-effective renovation packages. It only reduces the achievable savings.**

In addition, the payback times for the initial embodied energy and embodied carbon emissions (i.e., for the manufacturing of construction materials and BITS) is rather low and is about 1 to 12 years in all the cost-effective renovation measures[7]. As a result, the initial hypotheses related to the influence of embodied energy and embodied carbon emissions were verified for all cost-effective solutions.

The integration of LCA in the Annex 56 methodology enables to adopt a life cycle perspective in energy-related building renovation by taking into account not only operational energy but also embodied energy and embodied carbon emissions related to the manufacturing, replacement and end-of-life (e.g., disposal or recycling) of construction materials used for the envelope and BITS.

Embodied energy and embodied carbon emissions are not found very influential in the project's building renovation case studies[8] because of the focus towards cost-effective renovation solutions (in other words, the cost-effective solutions "limit" the influence of the embodied energy). However, these results do not mean a LCA approach is not relevant for building renovation. In fact, it is now well accepted in Europe that the primary energy and carbon emissions optimization for both new and existing buildings should be done using a life cycle perspective. This perspective is particularly valid for nearly zero carbon emissions or nearly zero energy renovation, for which the relative contribution of the embodied energy or embodied carbon emissions is likely to rise as far as the renovation becomes significant[9]. Indeed, generally speaking, an optimum where the operational energy use reduction balances the increase of the embodied energy use can be determined.

Recommendations for policy makers

In that context, LCA will be in the near future more and more used in public policies to support a sound implementation of energy efficiency measures.

To date, LCA is already linked to some EU regulations related to the environmental impacts of building products and technical systems. The existing Construction Products Regulation (CPR) contains additional Basic (Work) Requirements (BWR), particularly the addition of 'environment'

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[7] It should be highlighted that this payback time only captures the initial embodied energy and embodied carbon emissions related to the manufacturing. In that sense, it does not account for the recurring embodied energy and embodied carbon related to the replacement of components over the service life of the building.

[8] This result can be explained by the limited scope of the LCA system boundaries only taking into account the materials and BITS than have an influence on the energy performance of the building. This choice does not consider in the embodied energy and embodied carbon emissions the other possible replacement of materials (interior walls, floor coatings etc.) and BITS (e.g., sanitary and electric equipment)

[9] However, in opposite, the measures are not sure to remain cost-effective

to BWR 3 (hygiene and health) and the new BWR 7 (Sustainable use of natural resources), stating that "Environmental Product Declaration (EPD) should be used when available for the assessment of the sustainable use of resources and of the impact of construction works on the environment" (CPR 2011). In this last example, LCA is used as the basis for product assessments, and especially in providing Environmental Product Declaration (EPDs), which form an important data source in Europe for building LCA studies both new or renovation projects according to the EN 15804 and EN 15978 standards.

In that context, it becomes clear that LCA is more and more used as a policy instrument at different levels (products and buildings). The next step is to integrate it in energy efficient related policies for buildings. For instance, LCA can contribute to switch from the limited scope within the recast of the Energy Performance of Building Directive (EPBD) of the European Union[10] (assessment of the operational energy use) towards a broader scope (life cycle perspective from "cradle-to-grave") and a broader set of environmental indicators to assess building renovation projects.

The recent European Commission Communication on Sustainable Buildings is clearly promoting the alignment of energy efficiency policies with LCA related aspects mentioning that:

"Existing policies for promoting energy efficiency and renewable energy use in buildings need to be complemented with policies for resource efficiency which look at a wider range of environmental impacts across the life-cycle of buildings" (European Commission, 2012).

As a result, the following recommendations to policy makers can be drawn for the integration of LCA in building renovation policies.

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[10] European Parliament and Council of the European Union (2010) Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings (recast);
Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31EU on the energy performance of buildings, establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements;
Directive 212/2/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30EU and repealing Directives 2004/8/EC and 2006/32/EC;
European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2012/C 115/01;
European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2012/C 115/01;
European Commission (2011), Meeting Document for the Expert Workshop on the comparative framework methodology for cost optimal minimum energy performance requirements In preparation of a delegated act in accordance with Art 290 TF EU 6 May 2011 in Brussels;

General recommendation for the use of LCA in building renovation (policy makers):

1) If the goal is to increase the energy efficiency of a renovated building, new policy in the field should include a life cycle perspective to require the assessment, next to the operational energy use, the embodied energy and embodied carbon emissions. By doing so, the upcoming policies will contribute to globally minimise the primary energy or carbon emissions of energy-efficient renovation measures.
2) If a LCA is to be promoted in the new policy, precise rules should be developed using the best practice e.g., available LCA database, LCA methodology (e.g., detailed in technical reports or standards) and LCA target values for renovated buildings[11]

Recommendations for professional owners

The previous recommendations for policy makers are also relevant for professional owners. Indeed, once public policies will integrate LCA as a basis of the new assessment framework for a building renovation, professional owners will be likely to use it as part of their decision making tools.

In line with the other IEA EBC parallel project (Annex 57), further recommendations can be drawn for decision makers like the professional owners (Lützkendorf et al, 2016). They may be interested to reduce the embodied energy and embodied carbon emissions of their renovation measures.

Materials and BITS choice to reduce embodied energy and embodied carbon emissions

They should also use construction materials and BITS during a renovation with a minimum embodied energy and embodied carbon value. This choice should be verified by taking also into account the operational energy consumption. This life cycle perspective allows appropriate renovation strategies to be implemented by the professional owners.

Tools for the assessment of materials choice

More and more assessment tools are developed to link embodied energy with operational energy use enabling to identify trade-offs and finally select the most appropriate renovation measure in terms of primary energy or carbon emissions (Passer et al, 2016). Professional owners are recommended to use the existing web-based and software tools that can be used at different stages of the design process to assist them in this task. Some tools combine both a 3D-modeling of the building, an energy calculation and a LCA. The tools can also integrate the

[11] For instance, in Switzerland, database (KBOB), methodology and tools (e.g., the SIA 2031, SIA 2032, SIA 2039 and SIA 2040 technical books) and target values (available in the SIA 2040 target values) allow a practitioner to address this recommendation. Similar tools and methodologies are in development or already exist in Europe with a varying level of maturity

Building Information Modelling (BIM) approach to ease the assessment. Many tools already exist and a detailed review of existing tools incorporating LCA can be found in the EeBGuide Infohub (Lasvaux et Gantner, 2012). For the professional owners interested in using compliant Annex 56 tools, they can use e.g. the Eco-bat (and new Eco-sai) tool developed in Switzerland as well as the ASCOT tool developed in Denmark.

Recommendation for the use of LCA in building renovation (professional owners):

1) If the goal is to increase the energy efficiency of a renovated building, a LCA perspective should be used to assess, next to the operational energy use, the embodied energy and embodied carbon emissions. By doing so, solutions that globally minimise the primary energy or carbon emissions indicators could be promoted.

2) If a LCA is conducted by the decision maker, use the best practice in the corresponding country e.g., available LCA database, LCA methodology (e.g., detailed in technical reports or standards) and LCA target values for renovated buildings[12]

Table of content

[12] For instance, in Switzerland, database (KBOB), methodology and tools (e.g., the SIA 2031, SIA 2031, SIA 2039 and SIA 2040 technical books) and target values (available in the SIA 2040 target values) allow a practitioner to address this recommendation. Similar tools and methodologies are in development or already exist in Europe with a varying level of maturity

Abbreviations

Table 2 List of frequently used abbreviations

Abbreviations	Meaning
AHU	Air Handling Unit
BITS	Building integrated technical systems
COP	Coefficient of Performance
DHW	Domestic hot water
EBC	Energy in Buildings and Communities Programme
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse gases
GWP	Global Warming Potential
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Mega joule; 1 kWh = 3.6 MJ
MVHR	Mechanical ventilation heat recovery
NRPE	Non-renewable primary energy
NZEB	Nearly zero energy building or nearly zero emissions building
PE	Primary energy
PV	Photovoltaic (cell or panel)
Ref	Reference
RES	Renewable energy sources
RSP	Reference study period
SFP	Specific fan power
TPE	Total Primary energy

Definitions

Definitions of embodied energy and embodied carbon emissions (according to this project), life cycle assessment (LCA) and life cycle impact assessment (LCIA) according to ISO 14040:2006:

- **Allocation**: The sub-division of input and output flows between one or more product systems
- **Embodied energy**: Comprises the cumulated primary energy use for the production, transportation, replacement and disposal of building components for the thermal

envelope and building integrated technical systems (e.g., renewable energy generation units, heating systems) used in energy related building renovation. In addition, the embodied energy also includes the anyway renovation actions with materials and technical systems added to restore the functionality of the building after renovation (e.g., painting or repair of a wooden frame, replacement of a conventional heating system with a heating system of the same type etc.). The assessment of the embodied energy is done in this project used a LCA methodology.

- **Embodied carbon emissions**: Comprise the cumulated greenhouse gas emissions for the production, transportation, replacement and disposal of building components for the thermal envelope and for building integrated technical systems (e.g., renewable energy generation units, heating systems) used in energy related building renovation. The assessment of the embodied carbon emissions is done in this project used a LCA methodology.
- **Embodied impacts** (from IEA-EBC Annex 57): Embodied impacts refer to the environmental impacts that arise in the life cycle of a construction materials or a BITS due to their production, transport, replacement and end-of-life; in this project the embodied impacts correspond to the so-called embodied energy and embodied carbon emissions.
- **LCA:** Life cycle assessment: Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
- **LCIA:** Life cycle impact assessment: Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.

Note 1: In this report, the term “LCA” will be used for describing the methodology used to assess the environmental impacts of energy related building renovation while the term “LCIA” will only refer to the step of the impact calculations within this methodology.

Note 2: According to the EBC-decision, the term “carbon emissions” used in all related Annex 56 reports represents all greenhouse gas emissions expressed in kg CO_2-eq and not only CO_2 emissions. It is chosen to be consistent with the title of Annex 56 project. As a result, the “carbon emissions” term will solely be used in this report.

1. Introduction

1.1. General context

Several standards regarding energy consumption have emerged in the last decade, defining increasing requirements, and culminating with the recent emergence of the “nearly-zero energy” buildings concept. However, these standards are mainly focused on new buildings ignoring, most of the time, the existing ones that represent the least efficient, the largest consumers and the largest share of the building stock. These standards do not respond effectively to the numerous technical, functional and economic constraints of this kind of buildings resulting, many times, in very expensive measures and complex procedures, hardly accepted by owners or promoters.

Having in mind the overall objective of slowing down climate change, measures for the use of renewable energy can be as effective as energy conservation and efficiency measures and sometimes be obtained in a more cost effective way. In existing buildings, the most cost-effective renovation solution is often a combination of energy efficiency measures and measures for the use of renewable energy. Hence, it is relevant to understand how far it is possible to go with energy conservation and efficiency measures (initially often less expensive measures) and from which point the use of renewables become more economical and environmental considering the local context. In the same time, it is important to address the life cycle related impacts of such measures by using a life cycle perspective for the building renovation with the quantification of primary energy or carbon emissions of the operational energy use but also of the added materials and technical systems used during the renovation.

These last aspects refer to the so-called “embodied energy” or “embodied carbon emissions” of construction materials or BITS and need a life cycle assessment (LCA) methodology to be correctly determined. As an illustration, Figure 5 presents the general concept of the building renovation concepts used in this project with two types of actions:

1. Reduction of energy demand and carbon emissions by energy conservation and efficiency measures

2. Supply with renewable energy and on-site RES to satisfy the remaining energy demand as much as possible

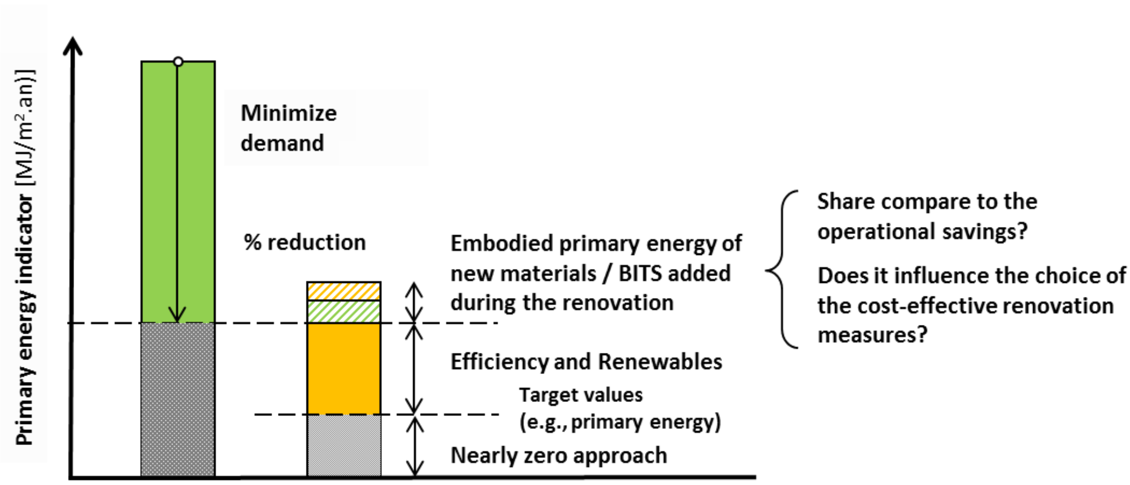

Figure 5 Schematic representation of the effect of energy related renovation measures compared to the existing situation.

For a sound building renovation, both minimization of demand and the increase of efficiency and use of renewables are relevant to reduce e.g., the primary energy demand of the operational phase. However, as illustrated in Figure 5, each of these measures will also be responsible for a certain amount of embodied energy related to the materials added for the enveloppe or the BITS. Indeed, the more the building energy demand is minimized, the more embodied energy is likely to be needed for the materials of the enveloppe (e.g., insulation) or for the BITS (e.g., replacement of the heat pump or boiler). As different renovation measures can be taken, it will result in different operational energy savings and embodied energy values.

As the embodied energy are likely to influence the global primary energy assessment of each renovation measure, there is a need to address the calculation of embodied energy (or embodied carbon emissions) in a consistent way i.e., by defining a consistent LCA methodology to calculate these values.

1.2. Contents of this report

This report delivers the methodological guidelines for the LCA of energy-related building renovation. It presents:

- the state-of-the-art of LCA applied in the building sector;
- the LCA methodology used in this project;
- its implementation on the project’s case studies and the related results focusing on the relevance of the embodied energy and embodied carbon emissions aspects;
- relevant recommendations for policy makers and professional owners.

2. Life cycle Assessment (LCA) methodology for energy related building renovation

The purpose of this section is to present the methodology developed in this project for assessing the environmental impacts of renovated buildings. The proposed methodology is based on the state of the art of the life cycle assessment (LCA) for buildings. It includes only processes having a relevant contribution to the total environmental impacts of renovated buildings. The methodology is defined to be put into practice in a reasonable amount of time.

Some LCA methodological principles have already been described in chapters 2 and 3 of the Methodology Report (Ott et al, 2015). They provide summarized information to the LCA methodology presented in this report.

2.1. Introduction

The assessment of the performance of a building can be based on several indicators, such as cost, operational energy use, environmental impacts and energy use of building components and materials. Whatever the indicators used, the generic pattern of its time evolution can be schematised as shown in Figure 6.

Building construction generates certain initial impacts and costs. During the building operation, there is a flow of yearly operational impacts and costs, primarily due to the energy use. After carrying out a building renovation, there is a new step-like increase of the impacts and costs due to the refurbishment of building elements and technical systems. The importance of this contribution depends on the implemented renovation scenario. During the building operation after renovation, the flow of yearly impacts and costs mainly due to energy use will also depend on the implemented scenario as shown in Figure 6. The more complete and ambitious the energy related renovation package the higher is the initial step of impacts due to the renovation and the lower are the impacts of subsequent building operation).

The main goal of this project is to find scenarios with the lowest impacts and costs during the reference study period. The reference case is based on “anyway renovations” (concept described in Ott et al (2015)), which restore the full functionality of the building but do not improve the energy performance of the building.

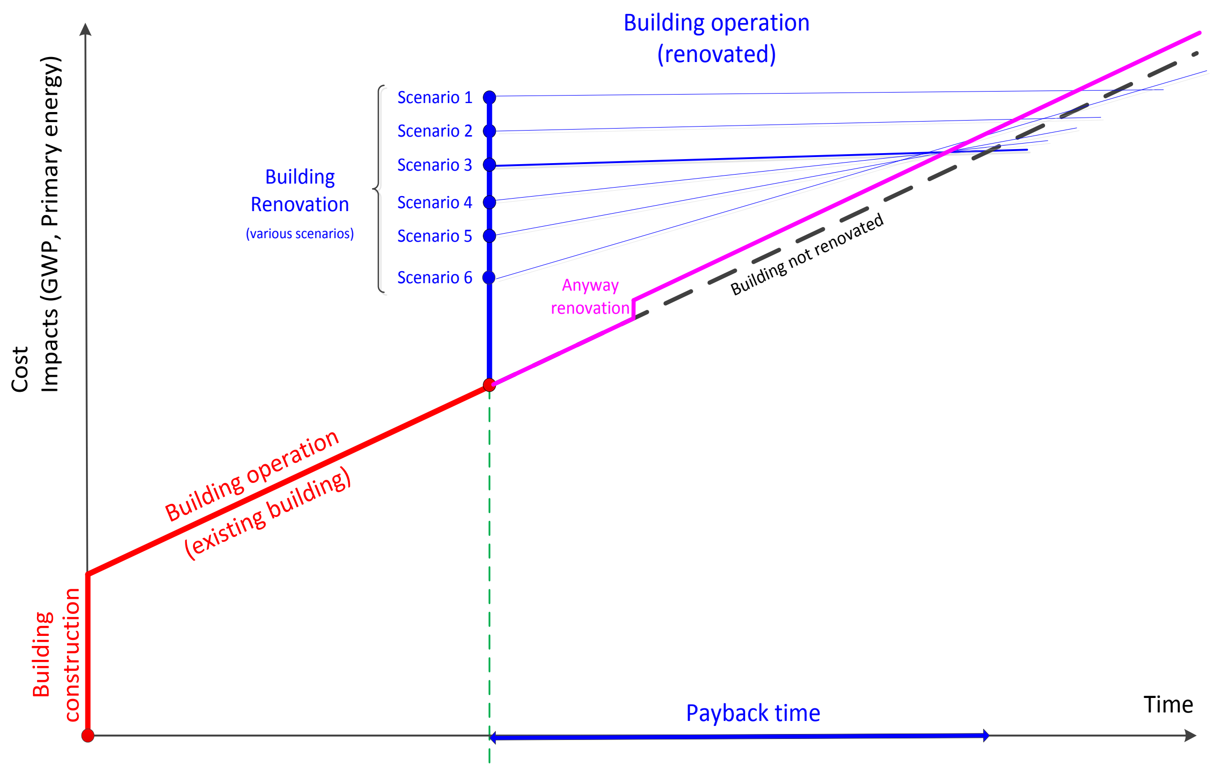

Figure 6 Schematic representation of the effect of energy related renovation measures compared to the existing situation.
Usually, the more sophisticated efficiency related renovation measures, the higher the (initial) investment costs at this point of time and the lower operational energy costs over time (can be observed in the graph by a less inclined cost curve). Scenario 1 increases energy performance most. Consequently initial investment costs are the highest but yearly operational cost the lowest (flattest cost curve over time).

In this project, the LCA is used to compare the environmental impacts of energy related renovation measures. Therefore, it will take into account only measures that affect the energy performance of the building (thermal envelope, building integrated technical systems and energy use for on-site production and delivered energy). Renovation measures which are not related to the energy performance of the building (e.g. such as changing the kitchen sinks) are not included in the assessment of the energy related renovation measures.

2.2. Existing LCA methodologies for buildings

During the last decade, many LCA methodologies have been published at national and international levels in order to present solutions to perform building LCA. These include, for instance, generic approaches such as the ones presented in ISO 14040 and followings (ISO 14040, 2006) or the ILCD Handbook (European Commission, 2011). Although these general LCA approaches tend to present a methodology as complete as possible, they are generally not fully applicable in the building practice, because of the lack of information and guidance for building application. To that purpose, building oriented approaches have been developed such as the EN 15978 (EN 15978, 2011) or the EeBGuide operational guidance document for buildings (Wittstock et al., 2012b) and for building products (Wittstock et al., 2012a). The EeBGuide and the related EN 15978 standard are the latest attempts to propose harmonized guidelines for building LCA at the European level (Lasvaux et al, 2014). At national level, some methodologies have also been developed e.g., in Switzerland with the series of technical books SIA 2032, SIA 2039 and SIA 2040 to assess the embodied primary energy and the operational primary energy due to the operational energy (for heating, ventilation, cooling etc.) and due to the transportation of the occupants of the building (mobility aspects).

The LCA methodology in this project is a compromise, taking into account several constrains such as:

- Coherence with existing approaches mentioned above;
- Inclusion of the relevant sources of impacts in the case of building renovation;
- Availability of information (especially for existing buildings);
- Time and resources required to find the information.

Each part of the LCA methodology is presented in the next sections.

2.3. Functional unit

2.3.1. Functional unit

In LCA, according to the ISO 14040, the ‘functional unit’ is defined as the quantification of the performance of a product system, and is used as the reference unit for the LCA and any comparative assertion. It has a quantity (e.g. 1 m²), a duration (e.g. ‘maintaining the function over 50 years’) and a quality e.g. ‘“to ensure a thermal resistance of 2 m²/W.K’). The term ‘functional equivalent’ is also defined in the EN 15978 standard (2011) and denotes the technical characteristics and functionalities of the building that is being assessed.

In practice, units and target values for energy use and carbon emissions in the LCA methodology are expressed in MJ/m^2a or kWh/m^2a and kg CO_2-equivalents per $m^2{*}a$ (kg CO_{2e}/m^2a). In certain cases, it might also be preferable to have additionally "person" as functional unit since DHW and electricity use are rather depending on the number of persons than on the area [m^2] of (conditioned) net or gross floor area. However, in this project, all results are expressed per unit of surface area per year after having divided the LCA results calculated for the reference study period of the building (see chapter 2.9).

2.4. Environmental indicators for the LCA

Many indicators have been developed in LCA, describing environmental impacts (global warming, ozone depletion, acidification, etc.), resource use (energy and raw materials depletion, etc.) or additional environmental information (hazardous waste, etc.). Some documents, such as EN 15978, may recommend to use a wide range of indicators. But from a practical point of view, comparing different renovation scenarios would become very tedious if more than a few indicators are compared. Therefore, it is important to implement a reduced number of indicators according to the following principles:

- The indicators should achieve widespread consensus and acceptance among the scientific communities. This would reject indicators such as human toxicity, biodiversity, Eco-indicator, Environmental Priority Strategies in Product Design (EPS) or Ecoscarcity (UBP).
- The building sector must have a significant share on the world or local contribution for this indicator (the latter if local impacts matter most).
- The data for components and energy vectors used in the building sector should be available for the indicator.

According to these criteria, the number of indicators used in this project has been limited to the three following indicators:

- **Total Primary Energy (TPE)**. It represents total primary energy used[13], renewable or not. It includes the non-renewable part (fossil, nuclear, primary forests) as well as the renewable part (hydro, solar, wind, biomass). In this report, PE is expressed in [kWh].
- **Non-renewable Primary Energy (NRPE)**. It represents the non-renewable part of the total primary energy, i.e., the non-renewable primary energy used. It indicates the depletion of non-renewable energy sources (at a human scale), such as fossil fuels, nuclear resources and primary forests. NRPE is also expressed in [kWh].
- **Carbon emissions.** This indicator is related to the emissions of greenhouse gases. It is not measured in an absolute unity, because each gas has a different global warming potential on the greenhouse effect (for the same quantity). In this project, their potential is compared to the CO_2 used as reference for a period of time of 100 years. This indicator is expressed in [kg- CO_{2e}][14].

[13] For the primary energy assessment, other terms and abbreviations can be found in the existing literature (e.g., the Cumulative Energy Demand concept) but it is beyond the scope of this report to review all of them.

[14] The reader should notice that the labelling of this indicator i.e., "carbon emissions" is chosen to comply with the title of this project. However, this indicator quantifies the equivalent CO_2 emissions in the same way as the greenhouse gases emissions indicator e.g., used in the IEA EBC Annex 57 project.

These indicators describe primary energy consumption and carbon emissions. They are consistent with the work and recommendations of the IEA-EBC Annex 57 project "Evaluation of Embodied Energy and CO_2 Emissions for Building Construction" (Lützkendorf et al, 2014).

2.5. System boundaries

2.5.1. Object of assessment, physical and temporal system boundaries

To perform a LCA of a package of renovation measures, it is mandatory to define the following system boundaries:

- Temporal system boundary (see chapter 2.5.2): It defines the elementary stages which have to be included, occurring during the life cycle of the building;
- Physical system boundary (see chapter 2.5.3): It defines all materials and energy flows to be included in the assessment.

The following chapters define these system boundaries in more detail. The object of assessment is the renovation package with resulting energy savings, carbon emissions reductions and possibly with its embodied energy effects over its life cycle.

2.5.2. Temporal system boundary

Many breakdowns of the building life cycle into the relevant stages have been proposed within the last decade (Citherlet, 2001; EN 15978, 2011; Wittstock et al., 2012b) and similar breakdowns can be used for building renovation. A generic breakdown into elementary stages and the boundaries of the main stages based on the EN 15978 standard are presented in Figure 7.

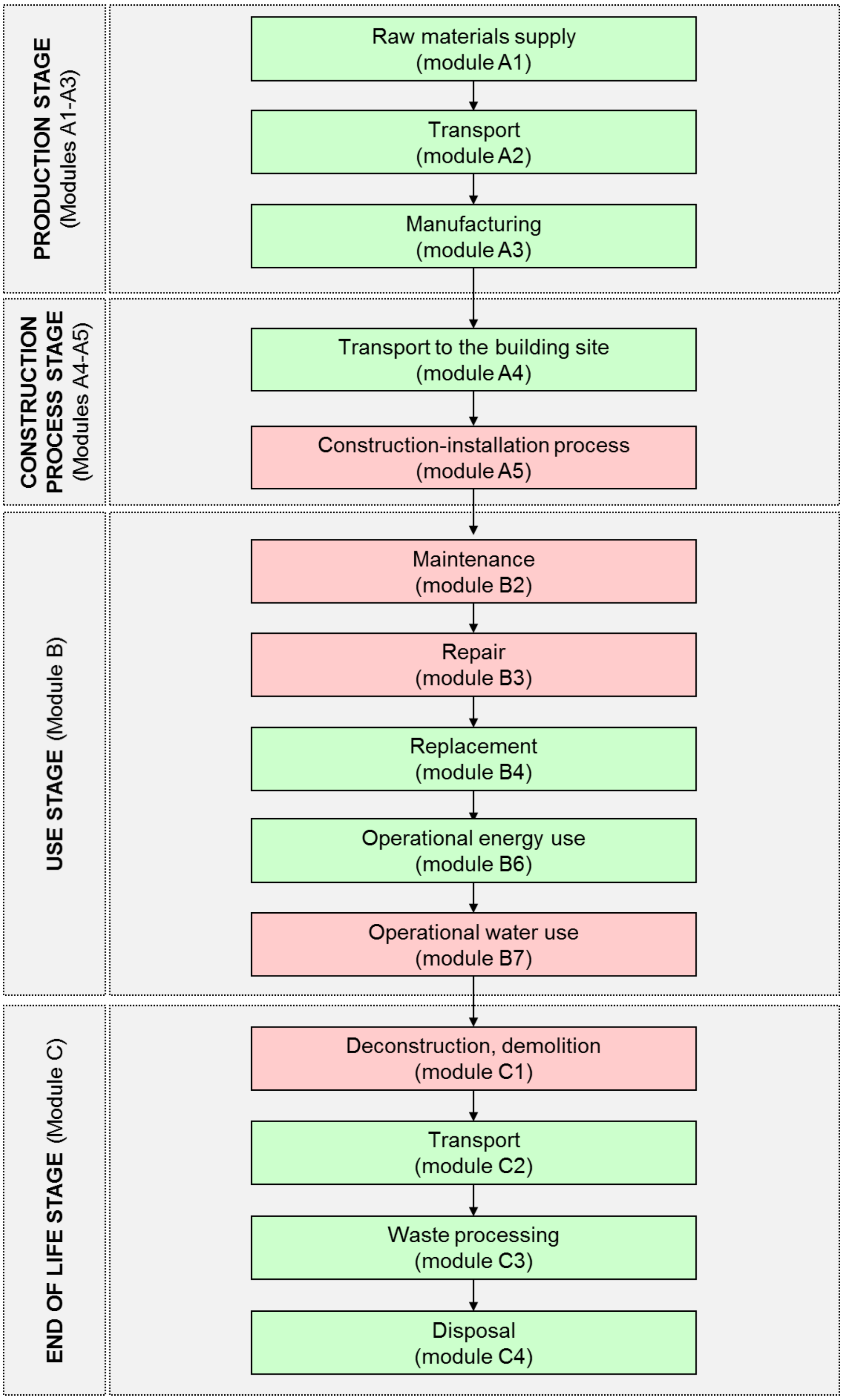

Figure 7 Schematic breakdown of a building's life cycle into elementary stages adapted from EN 15978 standard modules' names; the module D "benefits and leads beyond the system boundary" is not reported here

The different life cycle stages shown in Figure 7 are defined as follows:

- **Materials production stage** (Modules A1-A3): The boundary of this stage covers the 'cradle to gate' processes for manufacturing the materials used in the construction elements and technical systems. It includes all processes from the raw materials extraction to the final products (brick, insulation panel, boiler, pipes, etc.) at the gate of the factory ready to be delivered.
- **Building construction process stage** (Modules A4-A5): The boundary of this stage encompasses the transportation of the materials and construction equipment (cranes, scaffolding, etc.) to the building site and all processes needed for the construction/renovation of the building.
- **Building use stage** (Module B): The boundary of this stage comprises the period during which the building is used by occupants, i.e. from the end of building renovation to the deconstruction of the building. This stage also includes the maintenance, repair and replacement of the construction materials. It also includes the energy used by technical systems during the building operation period (heating, lighting, domestic hot water production, etc.).
- **Building end-of-life stage** (Module C): This stage covers the end-of-life of the building from its demolition to the materials elimination. It includes the processes for building decommissioning and waste transport and management (recycled, reused, incinerated or dumped in a landfill).

It should be kept in mind that Figure 7 presents the different stages of the complete life cycle of a building, in which each stage may use energy and materials and release air, water and soil emissions. Furthermore, not all of the elementary stages contribute to the same extent to the life cycle impacts of a building (new or renovated). Negligible impacts should be excluded from the assessment and calculations, even more if the information is difficult to access.

Life cycle stages assessed in this project:

In order to facilitate the application of LCA in this project, the methodology used to assess the effects of energy related renovation measures is pragmatic and takes into account only the relevant stages. There are several stages that should be definitely taken into account in the LCA of energy related building renovation. They are represented as green boxes in Figure 7:

- **Material production for new materials and for periodic replacement during the reference study period** (Modules A1-A3 according to EN 15978), i.e. all stages required for the materials used (construction elements or BITS) for energy related renovation measures. It includes the extraction of raw materials, transport and transformation required to have the components ready to be used. These stages correspond to the production of materials.

- **Materials transportation between the production site and the building site** (Module A4 according to EN 15978). To calculate the corresponding impacts, it is necessary to know the transportation distance(s) and the mean(s) of transport used for each material or component. The corresponding data can be either based on known information or on default values based on realistic hypotheses. These data should be reported and documented (type of transport, distance). During this stage, some materials may be lost (damage, broken) and have to be replaced (new production). These losses can be neglected.
- **Operational energy used** during building operation for the reference study period (Module B6 according to EN 15978).
- **End of life of the building** (modules C2-C4) with:
    - **Transportation** of wasted materials (added during the reference study period for energy related renovation measures) at the end of the building's life. This corresponds to the transport from the building site to the waste management site. To calculate the corresponding impacts, it is necessary to know the transport distance(s) and the mean(s) of transport used for each material. The corresponding data can be either based on known information or on default values based on realistic hypotheses. These data should be reported and documented (type of transport, distance).
    - **Waste management** of removed materials (removed energy related renovation measures during the reference study period) with waste processing (Module C3) and final disposal (module C4).

Life cycle stages not considered in this project:

On the opposite, the following stages can be neglected (red boxes in Figure 7) due to their assumed marginal contribution:

- **Maintenance**: The maintenance stage includes the processes for maintaining the functional, technical and aesthetic performance of the building fabric and building integrated technical systems (BITS), such as painting work, replacement of filters (ventilation), etc. This stage does not take into account the replacement of a building component that must be changed because it has reached the end of its service life. The replacement impacts are included in the replacement stage (green boxes in Figure 7). As the life cycle impacts from the maintenance stage of energy related renovation measures is insignificant (compared to the total building's LC impact), this stage can be neglected, in contrary to the cost assessment, for which the maintenance must be taken into account.
- **Repair**: Repair of a building element cannot be easily analysed because by definition it happens randomly and there is no reliable information that could help to assess

precisely its contribution. In addition, this contribution happens seldom and therefore, it can be neglected.

- **Building construction-installation process** (module A5 in Figure 7) and **deconstruction** (module C1 in Figure 7): These stages take place on the building's construction site. It should be reminded that the construction equipment will be used not only for one building. Therefore, their contribution per building is highly reduced and these stages can be omitted. In addition, energy used on-site during building construction and demolition can be neglected compared to the energy embodied in the construction materials or the energy used during building operation.

In this project, these three previous stages are not mandatory, but if they are included in the calculation, it should be justified.

2.5.3. Physical system boundary

The physical system boundary defines the materials and energy fluxes which must be taken into account for the LCA. Figure 8 shows a synthetic building model which includes construction elements and building integrated technical systems (BITS). The construction elements consist of one or more materials. The BITS consist of components (boilers, pumps, etc.) which are made of materials. In addition, these components use one or more energy vectors.

In order to perform a LCA of a renovated building, the following aspects should be considered:

Construction elements: the LCA includes the materials of the building elements that are affected by the energy related renovation measures. Each element (roof, facade, etc.) is made of one or more layers and each layer corresponds to a material.

Building-integrated technical systems (BITS): the LCA includes the installed technical equipment to support the operation of a building (as defined for instance in EN 15978). BITS usually comprise different systems, such as heating and ventilation. The LCA also includes the on-site energy production (solar collectors, PV, heat pump). Each system consists of components (boiler, pump, etc.) and each component is composed of materials and may consume energy.

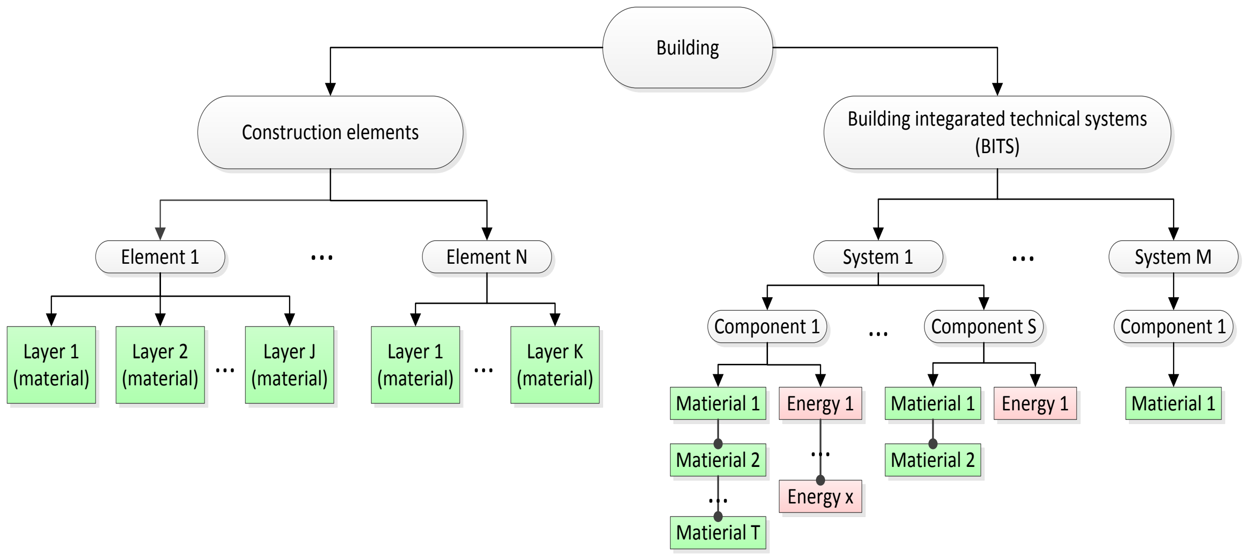

Figure 8 Structure of the building model

In order to calculate the corresponding impacts, the following contributions have to be included in the LCA:

Materials and BITS: Materials added or replaced for energy related renovation measures for building elements (envelope) and for BITS-components (for more details see Appendix 7.1). The stages corresponding to manufacturing, replacement and waste disposal of these components must be included in the calculation.

Operational energy: Energy used by BITS during building operation. This includes the energy used by the BITS to deliver the expected energy services (heating, cooling, DHW production, etc.) during building operation.

Figure 9 shows an illustration of the different aspects to take into account in the LCA of a renovated building.

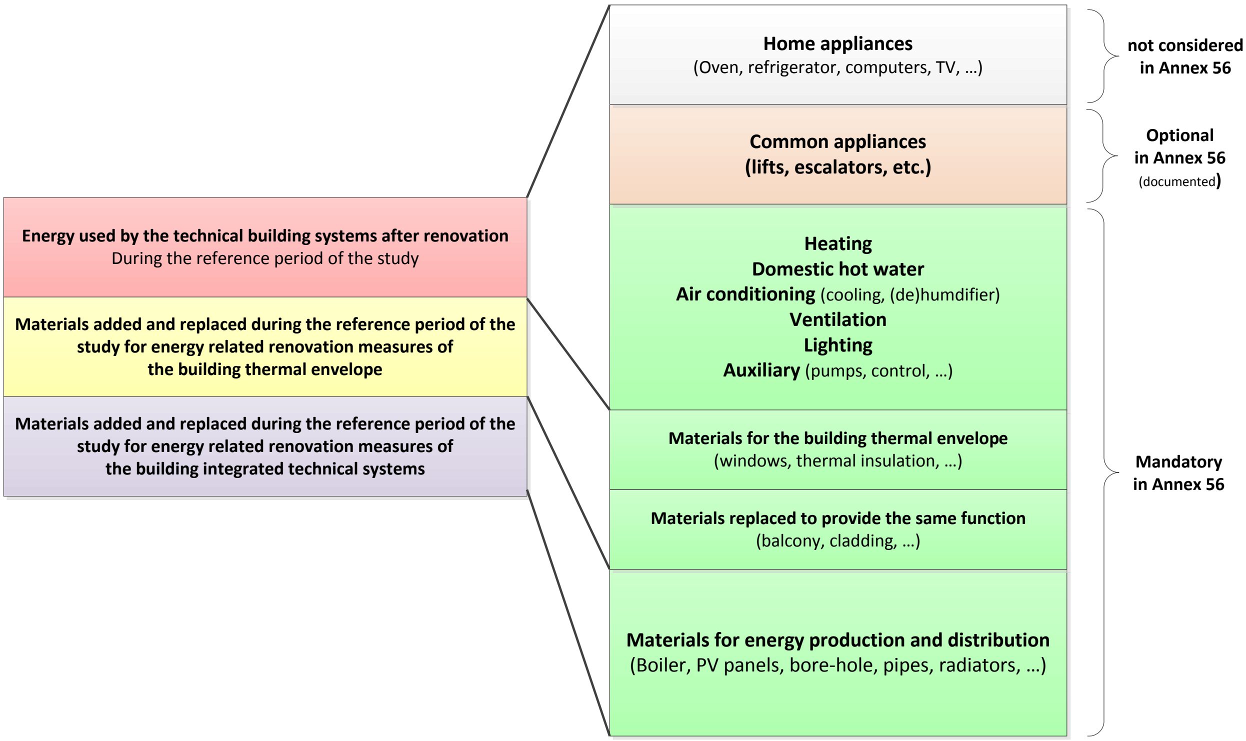

Figure 9 Aspects to be included in the LCA of renovated buildings: materials for the building enveloppe and for the BITS and the operational energy use

2.6. Calculation rules for the materials used for the envelope and BITS including the replacement

To summarize, the system boundary to perform an LCA of a renovated building should include the following elements:

- The materials added for energy related renovation measures of the thermal envelope of the building;
- The materials added for energy related renovation measures for the building integrated technical systems (BITS), including on-site energy generation units[15] (PV, solar thermal, etc.);
- The materials added to provide the same building function before and after renovation.

Figure 9 shows the materials related impacts to take into account in the LCA. Besides the initial impact (e.g., in terms of primary energy or carbon emissions), building materials need to be

15 According to the allocation rules introduced in the previous chapter

replaced during the reference study period of the building. The next sub-sections present the service lives and replacement calculation rules considered.

The service life is defined as the time during which a building component (construction material, BITS component (boiler, etc.)) fulfils its function. At the end of its service life, the product must be replaced. The service life of the building components included in the LCA calculation (construction materials & building integrated technical systems) must be reported and documented, as it has a direct effect on the results.

Service life of constituent parts of buildings

In a construction element, not all layers (materials) are replaced at the same time and some are never replaced. This is for instance the case for the bearing structure that will probably never be replaced during the life cycle of the building. As shown in Figure 10, the construction element can be divided in different parts.

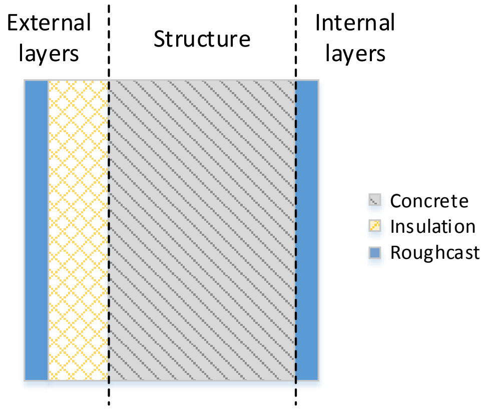

Figure 10 Example of a construction element with a bearing layer (structure) and non-bearing materials

It is not realistic to use a constant service life time for a particular type of material. For instance, the same insulation material does not have the same service life when placed in a roof or in an external wall. For a specific material, its service life will depend on its physical properties (water resistance, moisture sensitivity, etc.) and its context of use (exposed to the outside, the soil, etc.). In order to define the service life of materials, it is therefore important to take into account the following parameters:

- Type of construction element (wall, floor, roof, etc…);
- Location of the construction element (against ground, exterior, interior);
- Position of material layer within the construction element.

Different sources of information can be used to define the service life of building constituents: Official documents such as ISO 15686 and followings (“ISO 15686 Buildings and constructed assets -- Service life planning,” 2012) or national documents. Appendix 7.2 also gives guidelines regarding the service life of internal, external as well as structure layers of construction elements.

Here are some examples that need to be correctly analysed to perform a consistent LCA:

- Some heavy layers which are not part of the bearing structure might be replaced during the life cycle of the building. In the case of a wall with concrete and terracotta bricks on either side of the insulation, the bricks could be replaced during a massive renovation. A floor screed could also be replaced in such a situation. In both cases, the bearing structure is not replaced.
- The insulation between two concrete layers will have the same service life as the two concrete layers, which may probably not be replaced during the building life cycle.
- A construction element might have been designed to allow for the possibility to easily replace some internal parts. In this case, only the replaced material is taken into account in the calculation.

Number of replacements

Due to a limited service life, construction materials will usually be replaced once or several times during the study period. These additional replacements have to be included in the LCA. For the calculation of the number of replacements the following statements need to be taken into account:

- The number of replacements for construction materials and components of a building integrated technical system (BITS) depends on their estimated service life (ESL) and the reference study period for the building.
- No replacement is required when the service life of the building element meets or exceeds the reference study period (foundations, bearing wall, etc.).
- In practice, only a whole number of replacements (no partial replacements) is allowed to calculate the contribution of the replacement stage. In the case of a partial number of replacements resulting from the estimated service life of the component and the reference study period of the building, the value obtained is rounded upward.

$$N_R = Round\left(\frac{SP}{SL} - 1\right)$$

N_R Number of replacements of the element

Round Function that rounds to the nearest integer value

SP Study period of the building

SL Service life of the element (material or building technical system)

2.7. Distinction between embodied and operational primary energy and carbon emissions

In the following sections of this report, the terms “embodied primary non-renewable (or total) energy” or “embodied carbon emissions” will refer to the total primary energy or the carbon emissions due to the life cycle of construction materials added during the renovation for the building enveloppe and BITS. Such terms are used in order to differentiate the primary energy consumption (or the carbon emissions) of the production, transport, replacement and end-of-life of materials/BITS from the operational energy use (heating, DHW, cooling, lighting, auxiliaries and appliances...) as illustrated below with an adaptation of Figure 7.

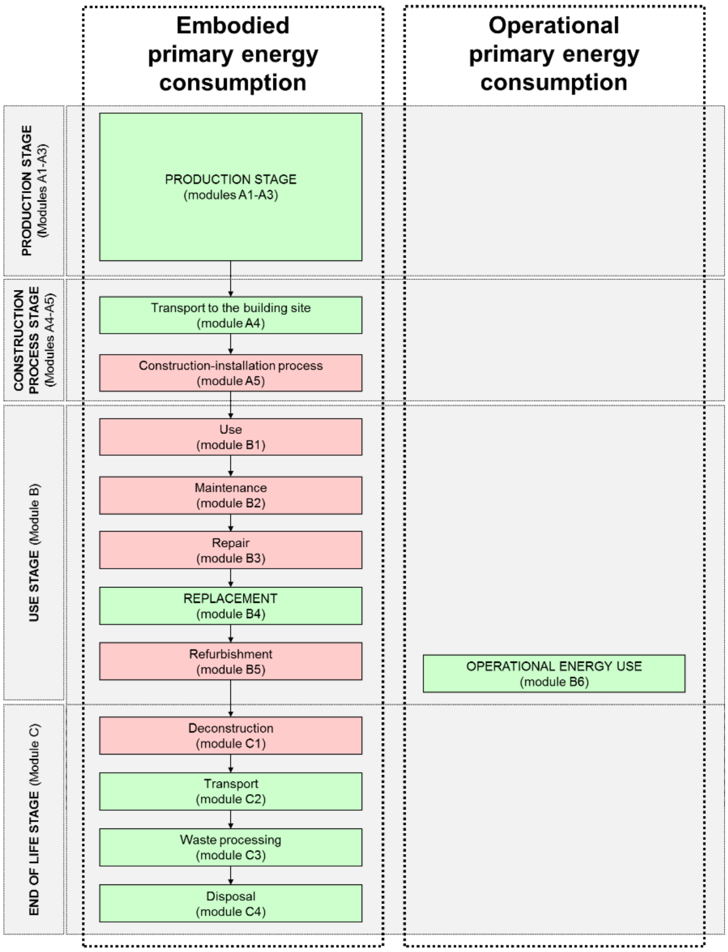

Figure 11 Distinction between embodied primary energy consumption and operational primary energy consumption according to the building life cycle stages (adapted from EN 15978 standard)

As a result, the LCA for a building renovation, taking into account the embodied primary energy for the materials and BITS and the operational primary energy use is then calculated as follows:

$$PE_{building} = PE_{materials} + PE_{BITS} + PE_{op.energy\,use}$$

With

$PE_{building}$ the primary energy of the building renovation

$PE_{op.\ energy\,use}$ the primary energy calculated for the operational energy use (module B6), see chapter 2.8 for the detailed calculation rules

PE_{BITS} the primary energy of the BITS, including the on-site RES systems calculated for the modules A1-A3, A4, B4, C2-C4 according to EN 15978 standard

$PE_{materials}$ the primary energy of all materials added during the renovation calculated for the modules A1-A3, A4, B4, C2-C4 according to EN 15978 standard and the rules defined in chapter 2.6

The same equation also applies for the carbon emissions calculations.

2.8. Calculation rules for the operational energy use

This section presents the energy services included in the LCA, the rules for calculating the operational energy balance and the associated primary energy and carbon emissions especially for electricity and on-site renewable energy generation systrems.

2.8.1. Energy services included

Energy use of building operation comprises energy use for several energy services which can be separated into occupant-related energy use and building-related energy use, as shown in Figure 12. Occupant-related means that the occupants decide on buying and installing the energy consuming device. Building related means that the building owner decides on installing it and that the device is used by all building occupants.

In many countries the "white appliances" like stove, refrigerator, sometimes freezer, washing machine, tumbler or dryer are built in appliances and therefore building related. But there are countries where the tenants rent an apartment without the "white appliances", which they buy and install by themselves. Calculation of heating energy needs require assuming at least a default energy use by appliances to account for internal heat sources. Even if the accurate assessment of these appliances is not mandatory in the methodology, it seems adequate to include them in the assessment by using default values, to account for their increasing share on remaining energy use of buildings.

The LCA for the operational energy use comprises the following mandatory energy services:

- Heating;
- Domestic hot water (DHW);
- Air conditioning (cooling & (de)humidifying);
- Ventilation;
- Lighting;
- Auxiliary (pumps, control devices, etc.);
- Integration of energy use from common appliances and home appliances e.g., the white appliances remain optional, it can be included but has to be reported and documented in a transparent way.

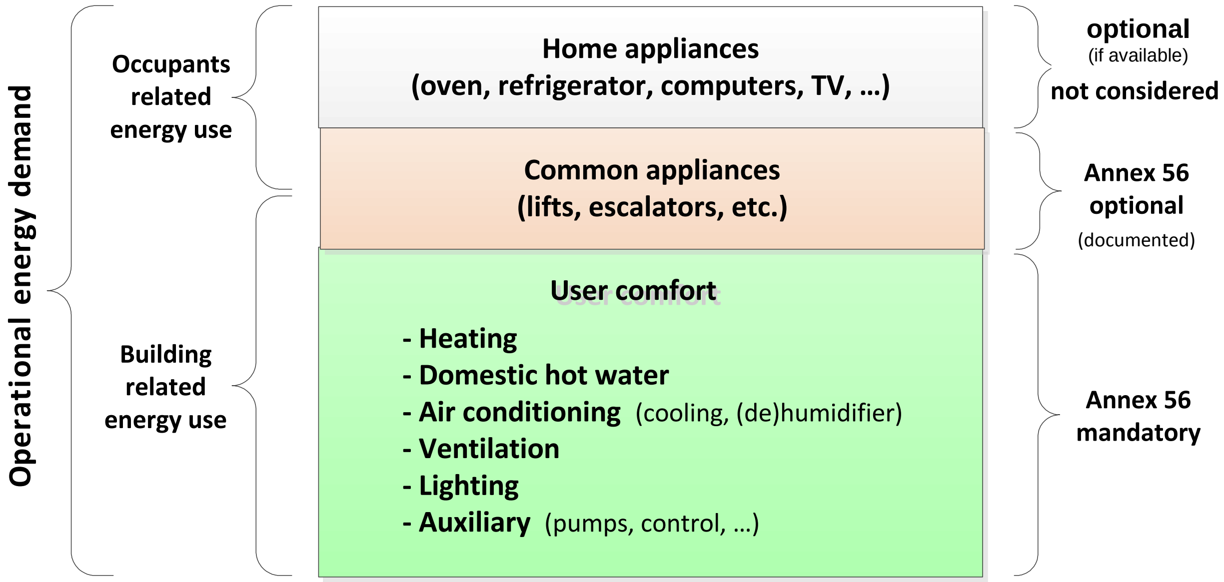

Figure 12 System boundary for the LCA of the operational energy use

On-site renewable energy allocation to energy uses:

In the LCA methodology, we follow the EN 15978 standard's approach. The on-site renewable produced energy is first allocated to the building related energy use (heating, domestic hot water, air conditioning, ventilation, lighting, auxiliary and common appliances such as lifts). The surplus of on-site energy production (if any) is then allocated to the non-building related energy use (e.g., home appliances). The embodied energy and embodied carbon accounting on-site renewable energy systems is taken into account and detailed in section 2.8.3.

2.8.2. *Time step for the calculation of the energy balance of building renovation scenarios with on-site renewable energy generation*

This sub-chapter deals with the calculation rules for energy related building renovation using on-site renewable energy generation (e.g., PV, wind mills, ground or air source type heat pumps etc.). The energy balance as shown in Figure 13 includes the building's energy demand (load), the delivered energy from the grid (imported energy), the on-site generation and the exported energy from on-site generated renewable energy to the grid. In this figure, energy demand and supply have to be weighted by LCA-based primary energy factors to have the primary energy level as a common reference system for impact analyses and evaluations. Accordingly, the energy related carbon emissions are weighted by carbon emission factors to express greenhouse gas emissions from energy deliveries, exports and on-site production as CO_2 equivalent emissions.

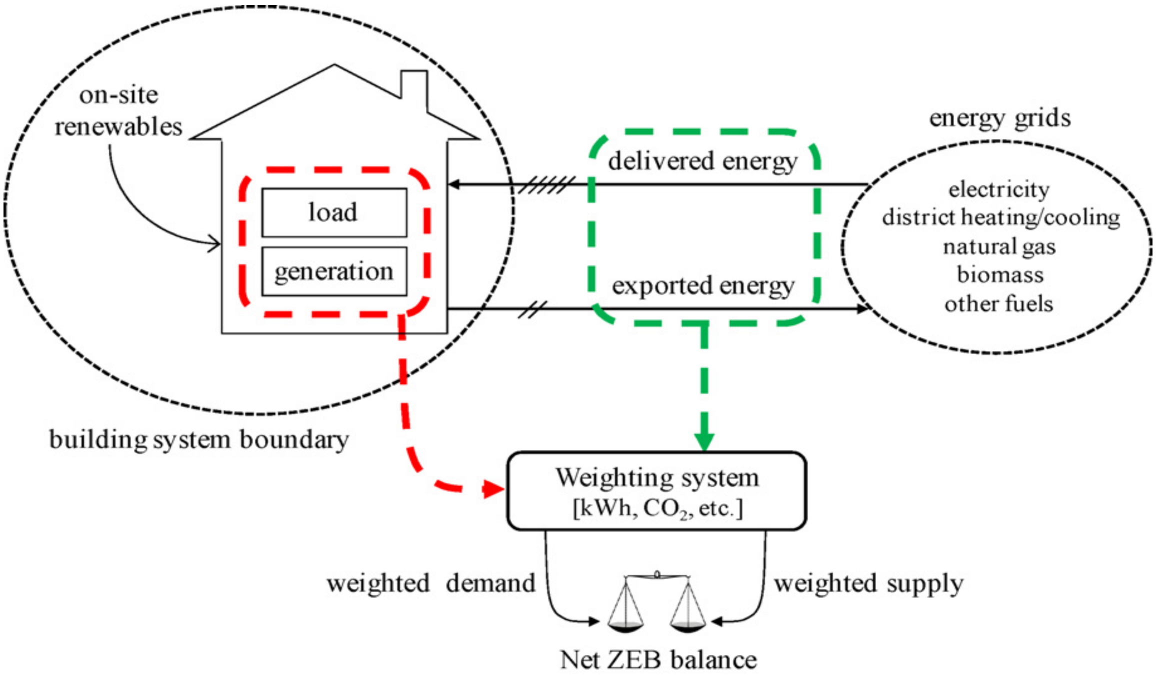

Figure 13 Terminology for building related energy use and renewable energy generation (Sartori I. et al. 2012)

In today's practice, the operational energy consumption can be estimated according to either an annual, monthly or an hourly balance using different steady state or dynamic energy calculation methods. Current studies (e.g., Voss et al, 2010 and more recently Fouquet et al, 2014) show that depending on the time step used for the calculation of the energy consumption and the on-site renewable energy generation (hourly, monthly or annual), the self-consumption can pretty much vary as well as the import/export balance of energy (noted as delivered and exported energy in Figure 13).

For an annual balance, it is possible to reach virtually 100% self-consumption by ensuring that the amount of on-site renewable energy generation matches the amount of building's energy consumption. This case typically applies for the electricity consumption of new or renovated buildings equipped with PV systems.

However, to assess the environmental impacts of such nearly zero energy building (NZEB) renovation, it is also possible to use a more precise time step (e.g., an hourly or monthly time step) for the calculations of the energy balance. Such approaches allow taking into account the daily and monthly variation of both building energy consumption and on-site renewable energy production. Figure 14 illustrates the issue by presenting an example of a PV generation and consumption profile for one day of the year.

Three different areas are found in this figure:

- The excess PV production fed back to the grid is represented by an orange area noted “A”;
- The building loads that need to be covered by the grid are represented with the blue area noted “B”;
- The building load self-covered by the on-site PV generation is represented by the grey-brown area noted “C”;

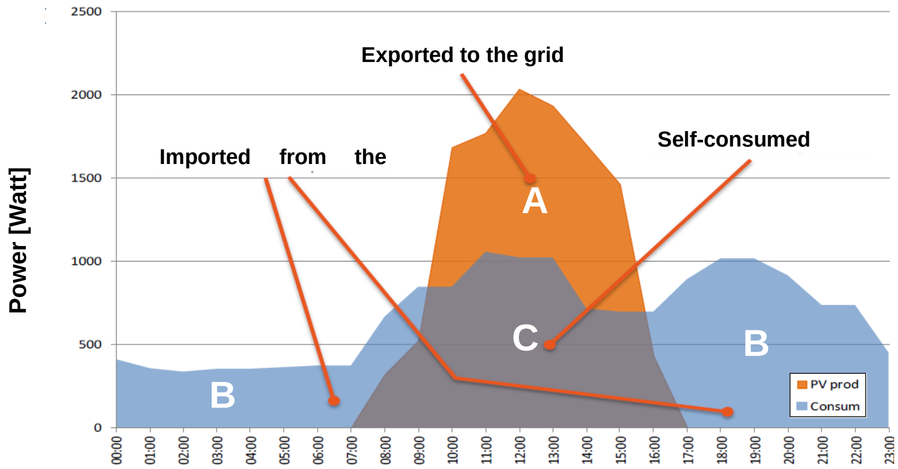

Figure 14 Comparison of a daily building energy generation and consumption profile adapted from the IEA Photovoltaic Power Systems Programme (PVPS) (Masson et al, 2016) ;

From Figure 14, two ratios can be defined to determine the self-consumption and the self-sufficiency of a building using the surface area figures (i.e. A, B, C):

$$self - consumption\ ratio = \frac{C}{A + C}$$

$$self - sufficiency\, ratio = \frac{C}{B + C}$$

These two terms should not be confused. The self-consumption ratio represents the share of the on-site energy generation matching the building's energy loads divided by the total building's on-site energy generation[16]. Findings from IEA-SHC Task 40 and IEA-EBC Annex 52 projects showed that the load match index (equivalent to the self-consumption index) in e.g., net zero energy building varies from 35% in an hourly energy calculation up to 100% for an annual balance (Voss et al, 2010). In opposite, the self-sufficiency ratio represents the share of the on-site energy generation (e.g., PV) matching the building's energy loads divided by the total building energy loads. As stated by Sornes et al (2014), the self-consumption and self-sufficiency ratio should normally be calculated for a hourly time step.

Choice for the LCA methodology of energy-related building renovation in this project:

While an hourly approach is probably the most accurate according to the findings of the IEA-SHC Task 40 and IEA-EBC Annex 52 projects, the current energy codes or regulations do not require it as a compulsory approach. In this project, the calculation rules for the LCA are thus based on the energy needs calculated with a steady state approach, determining yearly energy demand since some building energy codes and labels only calculate the energy consumption and on-site generation on an annual balance.

2.8.3. Allocation rules for on-site renewable energy generation systems

Different allocation rules can be applied in LCA. A renovated nearly zero energy building equipped with on-site renewable energy systems (e.g., PV) becomes a multifunctional system as the building becomes an energy producing unit. According to ISO 14044, two approaches can be used to deal with this issue: the co-product allocation and the avoided burden approach (extension of system boundaries):

- For the co-product allocation, exported electricity is considered as a "co-product" of the building system. The embodied primary energy and embodied carbon emissions of the on-site energy generation systems are allocated to the building according to the self-consumed[17] on-site renewable energy and added to the primary energy use and the carbon emissions of electricity imported from the grid.

[16] It is important to highlight that other definitions for defining the self-consumption and the self-production aspects may be found in the literature.

[17] A similar approach as proposed in the EN 15978 standard (2011) for building LCA is to allocate 100% of the embodied energy of on-site energy generation BITS to the building whatever is the self-consumption value.

Using the terms introduced in Figure 14 in the case of a PV system, the primary energy (PE)[18] of a renovated building is calculated as follows:

$$PE_{building} = PE_{imported\ electricity} + \frac{C}{A+C} \times PE_{PV} + PE_{others\ energy\ use} + PE_{others\ BITS} + PE_{materials}$$

With

$PE_{imported\ electricity}$ the primary energy of the imported electricity from the grid

PE_{PV} the primary energy of the on-site RES system

$PE_{others\ energy\ use}$ the primary energy of the other operational energy use not covered by the on-site RES and covered by other systems

$PE_{others\ BITS}$ the primary energy of the other BITS, excluding the on-site RES system

- The second allocation method is the avoided burden approach. It considers the export of the building's on-site renewable energy (electric, thermal) as an energy which does not need to be produced for the grid, leading to "credits" for the building which depend on the quantity avoided. In that case, 100% of the embodied primary energy and embodied carbon emissions related to the on-site RES systems are taken into account in the building-LCA. Embodied energy (and related carbon emissions) is added to the difference between the imported (delivered) electricity from the grid and the export of on-site generated RES electricity multiplied by the primary energy (or carbon emissions) factor of the electricity grid.

  Using terms introduced in Figure 14 in a case of a PV system, the primary energy (PE)[19] of a renovated building is calculated as follows:

$$PE_{building} = (C_{imported\ electricity} - C_{exported\ PV\ electricity}) \times PE_{grid\ mix} + PE_{PV} + PE_{others\ energy\ use} + PE_{others\ BITS} + PE_{materials}$$

With

$C_{imported\ electricity}$ amount of imported electricity from the grid

[18] It can be either the total primary energy (TPE) or the non renewable primary energy (NRPE)

[19] It can be either the total primary energy (TPE) or the non renewable primary energy (NRPE)

$C_{exported\ PV\ electricity}$ amount of exported PV electricity to the grid

$PE_{grid\ mix}$ the primary energy factor of the electricity grid mix

In addition to the two ISO 14040 allocation methods, the EN 15978 standard for building LCA also introduces its own method:

- The EN 15978 allocation method considers that 100% of the on-site RES embodied energy and embodied carbon emissions are allocated to the building even if a part of the on-site energy production is exported to the grid (e.g., in the case of a building where the on-site energy production excess the total building energy consumption).

  In that case the equation simply becomes:

$$PE_{building} = PE_{imported\ electricity} + PE_{PV} + PE_{others\ energy\ use} + PE_{others\ BITS} + PE_{materials}$$

The same three equations also apply for the carbon emissions calculations.

Choice of the allocation method for on-site RES in this project:

A first study has been conducted in 2014 by Fouquet et al (2014) regarding this topic. The authors showed the influence of the allocation rules for the on-site renewable energy system on comparative LCA comparing alternatives with and without PV systems for a single-family house in the French context. The results do not show any differences in the ranking of the alternatives “single-family without PV” and “single-family house with PV” between using the avoided burden allocation and the co-product allocation.

As a result, in this project, the LCA methodology let open the allocation rules (i.e., either the avoided burden approach, the co-product allocation or the EN 15978 standard[20] can be considered). The choice should however be motivated by the goal and scope of the study[21] and the same allocation method shall be used when comparing different cost-effective renovation measures for a same building case study.

In addition, on-site generated electricity fully sold to an off-site owner of the generation unit is not accounted for in the building LCA (since electricity generated is allocated to the (external) owner of the system, using the building only as a carrier for his generating system).

[20] As the study of Fouquet, Lebert, Lasvaux et al (2014) does not show any comparative bias in comparing solutions with and without on-site renewable electricity generation

[21] A sensitivity check will however be performed in the Annex 56 case studies results with on-site renewable energy systems to ensure the choice of the allocation rules for e.g., PV systems does not bias the comparative LCA results.

2.8.4. *Primary energy and carbon emissions factors for the electricity mix*

When the self-consumption of on-site energy systems is below 100%, a renovated building with on-site renewable electricity generation systems also need some imports of electricity from the grid to meet its electricity needs.

As mentioned by Sartori et al (2012), while it is already common praxis to have seasonal or hourly fluctuating energy prices, for primary energy use and carbon emissions factors, this is not common praxis today but it may become more common in the future.

Carbon emissions and primary energy factors of the electricity mix vary depending on the day, the month and the season. It varies due to the import/export of electricity between a country and the neighbouring countries and due to the running or not of the different energy generation capacities during the year. Electricity grid managers at national level sometimes already started providing the hourly production mix of the electricity allowing the estimation of hourly primary energy and carbon emissions factors of the electricity e.g., in the US[22], in Spain[23] or in France[24]. For example, Figure 15 presents an illustration of the greenhouse gases emissions (expressed in kg eq.-CO_2) for the French context in 2012. While the annual average of the greenhouse gases emissions of the electricity is 0.095 kg eq-CO_2/kWh, it actually varies from 0.04 to 0.22 kg eq-CO_2/kWh depending on the month (x-axis) and the time of the day (y-axis).

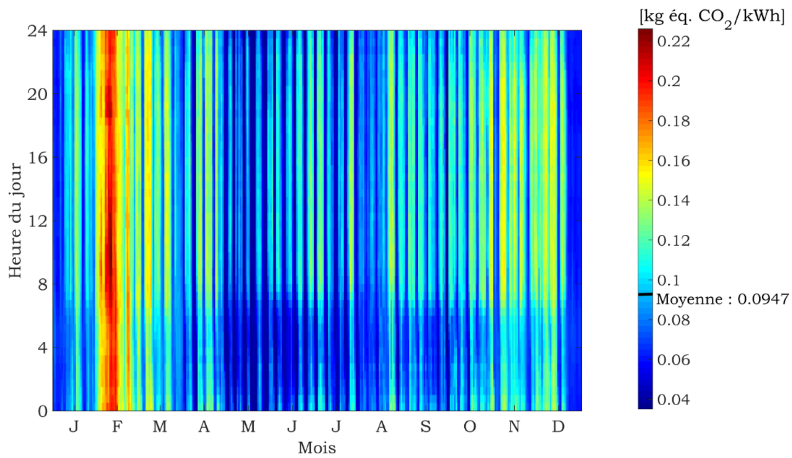

Figure 15 Illustration of the hourly CO2 emissions of the electricity mix in France for the year 2012; the x-axis represents the different months (from January to December) and the y-axis represents the hours of each day (from 0 to 24; figure taken from Fouquet (2016)

22 En.openei.org/datasets/dataset/hourly-energy-emission-factors-for-electrictiy-generation-in-the-united-states

23 www.ree.es/en/activities/realtime-demand-and-generation

24 Clients.rete-france.com/lang/fr/visiteurs/vie/bilan_RTE.jsp

In that context, for near zero energy renovation with on-site renewable energy systems, the hourly energy demand for end-uses like heating, ventilation, lighting and auxiliaries and for the appliances could be matched with the hourly kg eq-CO_2 values of the energy grid (e.g., for electricity) to calculate the LCA of the operational energy consumption and on-site production. By doing so, it would be possible more precisely determine the LCA of building with on-site energy production systems.

Choice of the calculation type for the primary energy and carbon emissions factors for energy carriers in this project:

As the more accurate approach (i.e. hourly primary energy and carbon emissions factors for electricity) has been to date only briefly discussed and not all the countries have publicly available data on that topic, the LCA methodology in this project remains pragmatic and only applies the annual average primary energy and carbon emissions factors for the (usually national) electricity consumption mix. Similarly, the primary energy and carbon emissions factors of other energy carriers are also based on an annual average. Section 3.2 page 30 presents the average annual factors considered in the six European case studies of this project.

2.9. Reference study period of the renovated building

LCA (and LCC) are carried out on the basis of a chosen reference study period, for which all contributions of materials and energy consumed are calculated. Therefore, the reference period has an important and direct influence on the results.

For new buildings, the reference study period is usually defined as the estimated service life of the building. For renovated buildings, the reference study period can be:

- The period between the current renovation and the next one. A typical value is 30 years, which corresponds to the period between the building construction and the first important renovation, which could be motivated by energetic purposes.
- The period between the current renovation and the end of building's life. A typical value is 60 years.

It should be noticed, that the number of energy related renovations during the building's life is limited. The more the building achieves low energy consumption after renovation, the less a major energy related renovation will be undertaken in the future. It is impossible to know, which materials will be used to replace the energy related construction material in the future. It is also impossible to know which future energy vectors will be used when the boiler will be replaced (in about 30 year).

One recent example is related to electrical heating. Thirty years ago it was subsidised or at least promoted by local authorities in several countries. But now, due to political reasons after the nuclear power plant accident in Fukushima, some governments are willing to promote the substitution of electrical heating. The same uncertainty occurs for the replacement of construction materials that will take place in several decades.

The reference study period should be equal or longer than the service life of the energy related building components analysed in order to avoid any misinterpretation of the results. Therefore, it is suggested to use a reference study period of 60 years. If another reference study period is used, it should be reported and documented.

3. Implementation of the LCA methodology in building renovation case studies

Chapter 3 presents how the LCA methodology was implemented in the building renovation case studies. First, an inter-comparison case study exerice is presented in order to validate the different tools that used the LCA methodology presented in chapter 2. Second, the primary energy and carbon emissions LCA-based conversion factors used in each case study (and country) involved in the project are presented. The third sub-section presents the used templates for reporting the LCA (and LCC) results of the case studies. Finally, the last sub-section gives an overview of the case studies and their renovation packages.

3.1. Inter-comparison of LCA tools on a simple case study

Each partner implemented the methodology defined in chapter 2 either by using spreadsheets, existing European LCA tools like the Swiss Eco-Bat or by developing new tools e.g., the ASCOT tool developed for Denmark. In order to ensure a consistent implementation of the LCA methodology in the six detailed case studies, an inter-comparison of LCA tools and spreadsheets used by the different partners was conducted on a simple case study. The goal of this preliminary exercice was to check that each partner is able to get to the same results using the same LCA data for the calculations. The “Appendix 2: inter-comparison exercise for building LCA tools” provides the detailed description of this simple case study while the comparative results.

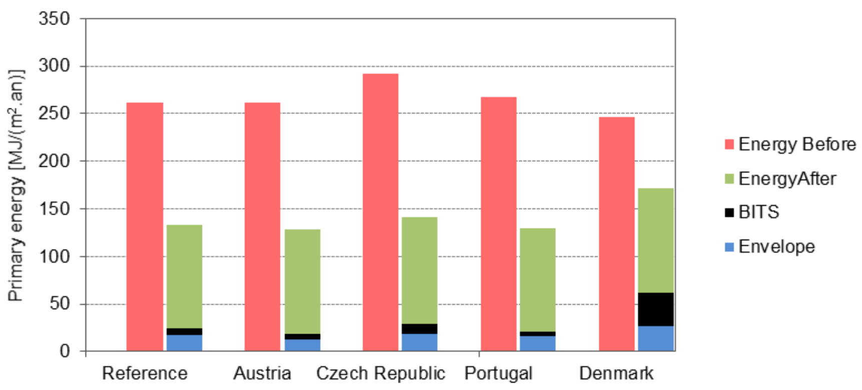

Figure 16 Inter-comparison results for primary energy between Austria, Czech Republic, Portugal, Denmark and the reference

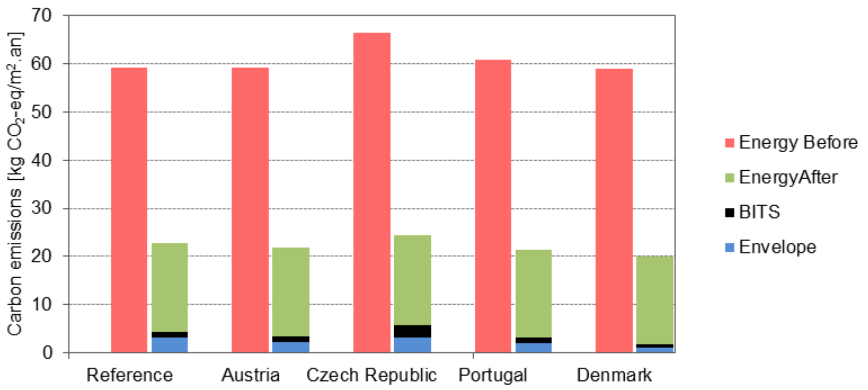

Figure 17 Inter-comparison results for carbon emissions between Austria, Czech Republic, Portugal, Denmark and the reference

It was found that using the same data, all partners were able to get to very similar results. The relative deviation found was about -0.1% to +1.9% for the case study before renovation and -5.8% to +12.2% for the case study after renovation. In any cases, the building after renovation performed better than before renovation. The remaining sources of deviations among the countries can be explained by the different level of expertises of the partners, that are not specifically experts in LCA. After a detailed analysis of LCA results provided by the participating countries, the relative deviations were decreased to less than 5%. In that context, it is assumed that the LCA methodology can be used with confidence enough by all project partners.

3.2. Primary energy and carbon emission conversion factors of the project's case studies

Tables 3 and 4 show an overview of the different conversion factors used in each case study for the LCA calculations. Table 3 presents the conversion factors to calculate the $kgCO_2$-eq emissions based on the final energy use of the building while Table 4 presents the conversion factors to calculate the total Primary Energy, also based on the final energy demand of the building.

Table 3: Carbon emissions conversion factors in $kgCO_2$-eq/kWh_{final}

Country	Austria[25]	Czech Republic[28]	Denmark[26]	Portugal[27]	Spain[28]	Sweden
Oil	0.302	-	0.331	-	0.294	0.295[28]
Natural gas	0.252	0.238	0.251	0.262	0.237	0.238[28]
Wood / biomass	0.052	-	-	0.045	0.012	-
District heating	0.050	0.087	0.202	-	0.114	0.080[29]
Electricity	0.322	0.924	0.413	0.691	0.594	0.100[28]

Table 4: Total Primary Energy conversion factors kWh_{prim}/kWh_{final}

Country	Austria[25]	Czech Republic[28]	Denmark[30]	Portugal[27]	Spain[28]	Sweden
Oil	1.13	-	1.28	-	1.20	1.21[28]
Natural gas	1.20	1.13	1.19	1.24	1.10	1.13[28]
Wood / biomass	1.19	-	-	1.34	1.14	-
District heating	1.60	1.56	0.69	-	1.64	0.30[29]
Electricity	1.83	3.73	1.78	3.22	3.40	2.96[28]

Each partners then used each own LCA data compiling the embodied total primary energy, embodied non-renewable energy and embodied carbon emissions. Very often, LCA data come from the same LCA database as the primary energy and carbon emissios factors for the energy carriers (e.g., GEMIS 4.8, Ecoinvent v2.2. database, DGNB-DK LCA database or the Swiss KBOB LCA recommendations list based on Ecoinvent v2.2).

[25] Reference: GEMIS 4.8

[26] Reference: Danish Energy Agency - 2015

[27] Reference: Ecoinvent v2.2

[28] Reference: Eco-bat 4.0

[29] Reference: Göteborg Energi 2013

[30] Reference: DGNB - DGNB-DK

3.3. Templates for reporting LCA results of case studies

In this project, different templates were proposed in a view of reporting the LCA but also the LCC results of each case study. The first one is described and presented in the case studies report from Venus et al (2015) while the second is presented below[31].

The template named as an Integrated Performance View (IPV) is a document that summarizes the building renovation hypotheses and LCA and LCC results in a more reduced view as the case study template of Venus et al (2015).

Figure 18 presents an extract of the two parts of the template which comprises:

1) The first part gives the general characteristics of the building before and after renovation: location; construction and renovation years, building type, energy reference area before and after renovation, heating degree days, description of construction elements, their U-values, and technical systems.

2) The second part gives the energy, LCA and LCC performances of the building before and after renovation with:

- The energy demand of the building for the heating, domestic hot water, lighting and ventilation;
- The LCC results: annualized costs associated to the operational energy consumption and the investment costs according to the Annex 56 methodology (Ott et al (2015). The template presents the costs expressed in Euros per square meter of construction element and in annualized costs.
- The LCA results are also presented according to the LCA methodology for the three indicators: TPE, NRPE and carbon emissions.

[31] The second template described in this report does not allow to compare different renovation scenarios. It rather aims at presenting the final LCA and LCC results of a building renovation compared to the reference case.

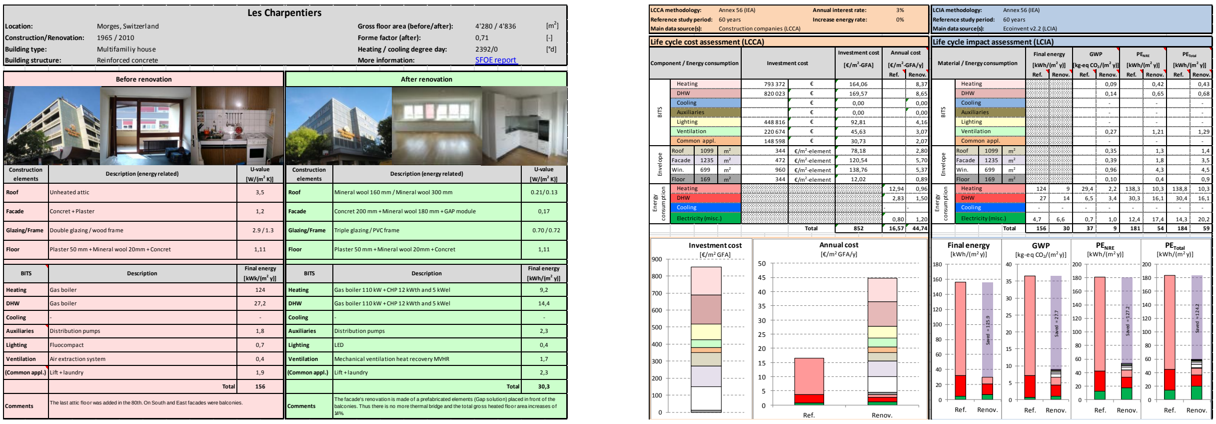

Figure 18 Example of the Integrated Performance View (IPV) of a renovated building comparing the building's LCA and LCC results before and after renovation

In Appendix 3: Integrated Performance View (IPV) template, an example of this template filled for a Swiss case study of a building renovation is presented. This tempate for reporting LCA results together with LCC results can now be used on further building renovation case studies by the interested practitioner.

3.4. Overview of case studies

Table 5 shows an overview of the six building renovation case studies used for testing the LCA methodology. They are located in Austria, Czech Republic, Denmark, Portugal, Spain and Sweden. The evaluated buildings are mainly residential buildings with the exception of the elementary school in Brno, Czech Republic.

The oldest of these buildings dates from 1953, the youngest was constructed in 1987. The gross heated floor area of the buildings varies between 123 m² and more than 9900 m². These building characteristics, together with the country-specific influencing factors, ensure a quite broad overview and application of the LCA methodology for the investigation of the cost-effective renovation based on both LCA and LCC methodologies.

All six case studies have been renovated in the past years. This means that the performed calculations serve mainly as comparisons between the actual renovation carried out and other renovation packages, which would also have been possible to apply. In this case the investigations do not support the real planning of the building renovations.

The following Table 5 shows the main characteristics of the case studies before and after the renovation. More information on the case studies can be obtained from the case studies report (Venus et al, 2015).

Table 5: Overview of case studies used for the LCA

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA[32]
Austria			Johann-Böhmstraße, Kapfenberg	Multi-family building	1960 – 1961	2012 – 2014	2845 m²
Czech Republic			Kamínky 5, Brno	Elementary School	1987	2009 – 2010	9909 m²
Denmark			Traneparken, Hvalsø	Multi-family Building	1969	2011-2012	5293 m³

32 Gross Heated Floor Area (GHFA) after the renovation of the building

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA[32]
Portugal			Neighborhood RDL, Porto	Two-family Building	1953	2012	123 m²
Spain			Lourdes Neighborhood, Tudela	Multi-family Building	1970	2011	1474 m²
Sweden			Backa röd, Gothenburg	Multi-family Building	1971	2009	1357 m²

3.5. Investigated renovation packages and reference case

This section is taken from Venus et al (2015) and aims at giving an overview of the case studies where the LCA methodology was applied.

For the six investigated case studies parametric studies were performed to identify the cost effective renovations for the individual real building renovations. The parametric studies were performed based on the developed methodology including the Life Cycle Assessment (LCA)[33]. For the case studies, each partner defined the characteristics of the investigated renovation packages according to what is feasible in each country. The idea was to include different thermal standards (insulation of building envelope) and different energy sources for heating and domestic hot water preparation (fossil fuels and renewables) as well as different ventilation situations (mechanical and natural) in the considerations.

Besides those renovation measures which lead to a reduction of the energy demand of the building also a reference case was defined, which represents the starting point on the global cost curve and which represents the basis for the comparison with the other defined renovation packages.

The reference case should include only renovation measures which have to be carried out anyway. Therefore this reference case can also be named as “anyway renovation”. Renovation

[33] More information to the developed methodology can be found on the official IEA EBC Annex 56 website:
http://www.iea-annex56.org/
The Methodology report can be downloaded here:
http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf

measures in this package can be for example the repainting of windows and of the outside walls or a roof sealing.

In this reference case the replacement of the entire or part of the existing heating system is also included. This replacement has an implicit influence on the energy performance by an improved level of efficiency. The replacement of the heating system is included in the reference case due to a more realistic depiction of the real situation.

The investigated renovation packages are named in further consequence “renovation package v1”, “renovation package v2” and “renovation package v3”, where v3 represents the actually renovation carried out.

On the next few pages for each country the objective of the defined renovation package v1, v2 and v3 are presented as well as also some short information about the included renovation measures.

More detailed information about the different renovation measures of each country can be found in the findings and conclusions of the case studies report (Venus et al, 2015).

In the following sub-sections, the reference case and the investigated renovation packages of each country are presented in a condensed way to give a short overview of the included renovation measures per country. The presented renovation measures are structured in following way:

- **Building envelope** - measures to improve the thermal quality of the building envelope, i.e. insulation of the façade, the roof and the floor as well as new windows
- **BITS (Building Integrated Technical Systems)** – measures on technical systems for heating, domestic hot water, cooling, auxiliaries, lighting, ventilation and common appliances
- **Investigated energy sources for heating and domestic hot water production** – energy sources that were investigated in the parametric studies
- **RES (renewable energy sources)** – measures for the renewable energy generation on-site, e.g. solar thermal installation, photovoltaic modules etc.

3.5.1. Austria

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Austria			Johann-Böhmstraße, Kapfenberg	Multi-family building	1960 – 1961	2012 – 2014	2845 m²

Renovation package v1	The objective of renovation package v1 is to fulfill only the minimum requirements of the Austrian OIB guideline 6[34]. This minimum requirements concern the U-values of the components, the heating energy demand and the final energy demand. In this renovation package v1 neither mechanical ventilation nor RES on-site are included. Renovation measures include the thermal insulation of the roof and the façade, the mounting of new windows with an external shading system and the renewal of the heating and domestic hot water system to a centralized supply.
Renovation package v2	In renovation package v2 the building has the same U-values as the real renovated building in renovation package v3. The difference between those renovation packages is that in renovation package v2 the U-values are achieved by a conventional composite heat insulation system instead of a prefabricated façade system. Additionally in renovation package v2 no mechanical ventilation system is installed. Furthermore no solar thermal system and no photovoltaic system are included. This means that renovation package v2 does not have active energy production from renewable energy sources on-site. As in renovation package v1 the renovation measures only include the thermal insulation of the roof and the façade, new windows with external shading device and renewal of the heating and DHW system.
Renovation package v3	Renovation package v3 represents the actually executed renovation of the residential building. The executed renovation of the building includes the thermal insulation of the façade by prefabricated wood modules, the thermal insulation of the roof, the mounting of new triple-glazed windows (with an external shading device) which are already integrated in the prefabricated façade modules, the installation of a new mechanical ventilation system with heat recovery, the renewal of the heating and domestic hot water system as well as the installation of a solar thermal system for the heating and domestic hot water preparation and a photovoltaic system for the electricity generation on-site.

34 Austrian Institute of Construction Engineering (2015): Richtlinie 6 – Energieeinsparung und Wärmeschutz (www.oib.or.at)

3.5.2. Czech Republic

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Czech Republic			Kamínky 5, Brno	Elementary School	1987	2009 – 2010	9909 m²

Renovation package v1	This is an ex-post model scenario. It focuses on improving thermal properties of the building envelope (replacement of doors and windows, additional thermal insulation, etc.) to comply with applicable Czech standards in time of renovation (2009/2010). Technical equipment is replaced. DHW, heating and ventilation pipes and ducts are replaced or restored and insulated to minimize heat losses. External shading is installed to reduce overheating during sunny weather. Originally there were only indoor sunblinds installed in the school. These were prone to malfunction and due to their position they proved ineffective, especially in summer.
Renovation package v2	Another ex-post model scenario. It includes further improvements of the thermal properties of school`s envelope. Technical equipment was replaced and repaired similarly to scenario v1.
Renovation package v3	Renovation package v3.1 represents the realized renovation measures. These included improving the thermal properties of the school`s envelope to levels exceeding Czech requirements on low-energy buildings. Technical equipment was replaced and repaired similarly to scenario v1. Other variants assess different energy sources for heating and DHW.

A photovoltaic power plant was installed on the school`s roof during the renovation. Due to the lack of funding it was installed by a private investor who pays a rent for the necessary space. The electricity is supplied to public grid. This “indirect” incorporation of photovoltaic is included in all variants of scenarios v1, variants v2.1, v2.3 and v2.5 as well as in all variants of v3.

Remaining variants of scenario v2 (v2.2, v2.4 and v2.6) model “direct” incorporation of the photovoltaic – generated electricity covers 50 % of DHW energy consumption and the rest is used for lighting, common appliances, etc.

3.5.3. Denmark

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Denmark			Traneparken, Hvalsø	Multi-family Building	1969	2011-2012	5293 m³

Renovation package v1	For this scenario 200 mm insulation was further added to the roof insulation, but the additional wall insulation was reduced to 100 mm – to simulate a situation where it was not possible to add 211 mm to the wall. To reach the same energy conservation level as v3, the mechanical ventilation heat recovery (MVHR) used was given higher heat recovery efficiency – 90% instead of 80% and a lower specific fan power factor of 1.2 instead of 1.4. The size of the PV system was identical to the one used in v3 and the new windows as well.
Renovation package v2	For this scenario the basic idea was to illustrate a situation where it was not possible or realistically cost-efficient to add insulation to the exterior wall. To compensate for this, additional roof insulation and an improved MVHR system like in renovation package v1 was chosen. To further compensate for the lack of savings, a larger PV system of 132 kWp was tested.
Renovation package v3	This renovation package represents the actually implemented renovation and includes following renovation measures: • 211 mm additional (average) external wall insulation • 250 mm additional roof insulation • New triple-glazed low-energy windows • New mechanical ventilation system with heat recovery – MVHR system • 33 kWp PV system.

The heating energy supply of Traneparken is district heating, so in practical terms it is not a real alternative to change this supply to anything else. However, for the purpose of the LCC and LCA analyses the calculations were carried out also for a changed heating supply system, i.e. gas and oil boilers.

The on-site generated electricity counts for the same level as energy savings, with a weighting factor of 0.413 $kgCO_2$-eq/kWh_{final} respectively 1.78 kWh_{prim}/kWh_{final}.

3.5.4. Portugal

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Portugal			Neighborhood RDL, Porto	Two-family Building	1953	2012	123 m²

Renovation package v1

This scenario includes intervention on the roof, the floor and walls. Windows are not changed in renovation package v1.

In total four different energy sources for heating and domestic hot water have been investigated:

- HVAC (multi-split air conditioned for heating and cooling and solar thermal panels backed up by electric heater for DHW)
- Natural gas
- Heap pump + PV
- Biomass

Renovation package v2

In this scenario, the same four combinations of BITS that were tested in renovation package v1 have been evaluated in renovation package v2 too.

Regarding the measures on the building envelope, the best energy performance was searched with all building elements being improved. The insulation material is always cork boards to evaluate the impact of its lower embodied energy.

Renovation package v3

In this scenario, the measures that have been applied in the field have been evaluated.

The chosen renovation scenario presents the most current renovation praxis in Portugal, with significant limitation on the investment costs and no major concerns with Life Cycle Costs, especially in cases such as this where the investor is not the one who pays the future energy bills.

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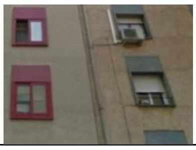
3.5.5. Spain

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Spain			Lourdes Neighborhood, Tudela	Multi-family Building	1970	2011	1474 m²

Renovation package v1	The main objective of renovation package v1 is to achieve only the minimum performance required by the Spanish regulation at the moment of this renovation. The envelope and windows have been improved and a new condensation gas boiler for heating and DHW has been installed. No additional measures have been performed to reduce other energy uses.
Renovation package v2	The performance of the envelope has been improved much more than it is required by regulation and much more than in a business-as-usual new building. An air-water pump is installed for the low heating demand needed and DHW. Solar panels contribute to cover 50% of the DHW demand. Mechanical ventilation is also installed.
Renovation package v3	All the actions performed during the actual renovation are taken into account in this scenario: improvement of the envelope and district heating renewal. Additional measures (not performed in reality) are taking into account for the scenario comparison: prefabrication and on-site photovoltaic system that covers 50% of the electricity demand of the building.

Note: In none of the cases measures to improve the efficiency of lighting, domestic and common appliances have been taken into account.

3.5.6. Sweden

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA
Sweden			Backa röd, Gothenburg	Multi-family Building	1971	2009	1357 m²

Renovation package v1	The objective of renovation package v1 is to fulfill only the minimum requirements of the Swedish building code BBR 2012 for new construction. These minimum requirements concern the building's energy use, that, in normal use during a reference year, needs to be supplied to a building (often referred to as “purchased energy”) for heating, comfort cooling, hot tap water and the building's facility energy. In the renovation package the U-values of the building envelope (exterior walls, roof, floor and windows) are improved and mechanical ventilation with heat recovery (cross flow heat exchanger) is installed. New thermostatic radiator valves are also installed.
Renovation package v2	In renovation package v2, the building has the same U-values as the real renovated building in renovation package v3. The difference between renovation package v2 and v3 is that renovation package v2 includes no heat recovery unit on ventilation.
Renovation package v3	Renovation package v3 represents the actually realized renovation of the demonstration building, and is the most ambitious one. The realized renovation of the building includes substantial improvement of the thermal insulation of the building envelope with e.g. new triple-glazed low energy windows with a light solar protection glazing. A new mechanical balanced ventilation system with rotary heat exchangers was installed. To reduce the use of hot water individual metering was installed. The building was already connected to district heating, based on 81 % renewable energy, and using green electricity.

4. LCA results: embodied energy and embodied carbon emissions in building renovation case studies

4.1. Scope for the analysis of LCA results

The LCA methodology is only one part of the overall methodology of the project together with the Life Cycle Cost (LCC) calculations (Ott et al, 2015). The LCA of each renovation package was evaluated according to the total carbon emissions, the Non-Renewable Primary Energy (NRPE) and the total Primary Energy (PE).

As the LCA methodology is applied in all the case studies' results, it is not in the scope of this report to present all LCA and LCC results of the case studies report (Venus et al, 2015). This section only focuses on the analyses of the LCA results for the materials and BITS (embodied energy and carbon emissions results). The LCA results of the operational energy consumption (illustrated for the primary energy indicators with dotted bars in Figure 19) will be only presented in terms of energy and carbon emissions savings due to the renovation next to the embodied energy and carbon emissions values.

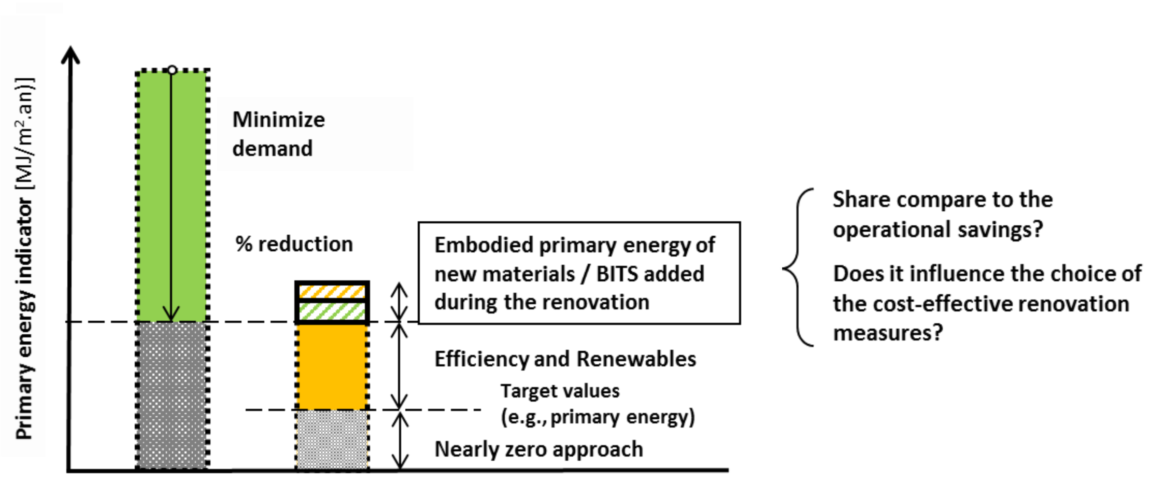


Figure 19 Schematic representation of the effect of energy related renovation measures compared to the existing situation (building before renovation), the dotted bars represent the total primary energy for the operational energy use before/after renovation; the plain bars represent the embodied primary energy of the new materials and BITS added during the renovation

The results of this section answer the following questions:

- How much operational primary energy and carbon emissions are saved for each building renovation compared to the embodied primary energy consumption and carbon emissions due to the materials and BITS added and/or changed during the renovation?
- Does the integration of embodied energy and embodied carbon emissions in the assessments change the choice of the optimal renovation concept for the carbon emissions, primary energy (total) and primary energy (non renewable) indicators?

The choice of these simple research questions is justified by the scope of this project i.e., the determination of cost-effective building renovation packages using a methodology integrating both LCA and LCC. In that specific context, the influence of integrating embodied energy and embodied carbon emissions of materials for the renovation of the envelope and for new BITS needed to be analyzed.

Indeed, in this chapter, two hypotheses related to the influence of embodied energy and carbon emissions are verified for all cost-effective solutions. These hypotheses are:

1. **The operational savings of the energy related renovation measures assessed are higher than additional embodied energy and embodied carbon emissions in any cost-effective renovation measures.**
2. **The integration of embodied energy and embodied carbon emissions of the energy related renovation measures assessed does not change the cost-effective renovation packages.**

4.2. Results with and without taking into account embodied energy and embodied carbon emissions

Figures 20, 21 and 22 present the comparative results with and without embodied carbon emissions for the different renovation packages of the case studies. For the sake of clarity, results of all countries are presented in the same figure for each indicator.

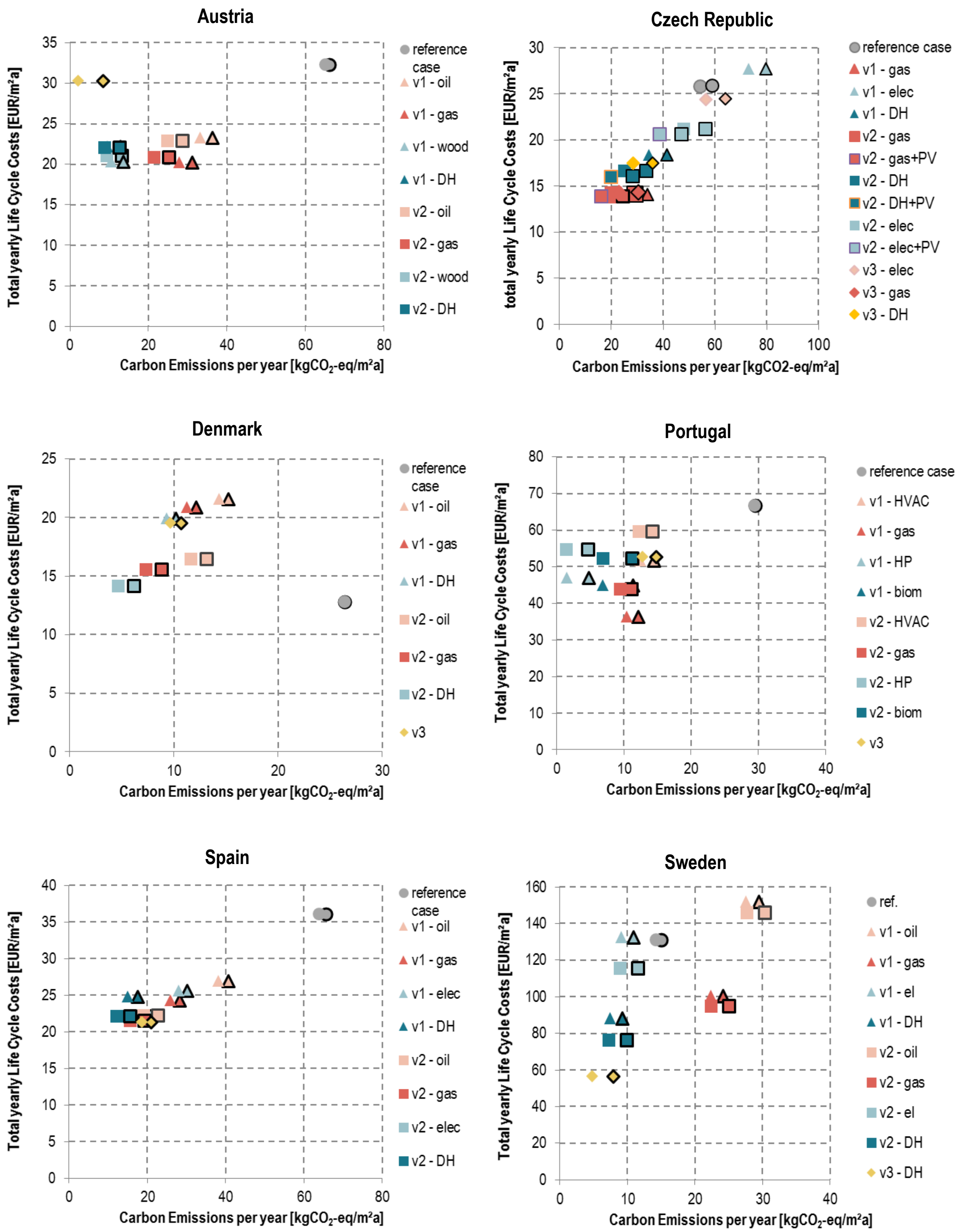


Figure 20 Comparison of carbon emissions reductions and costs for the six case studies, without including embodied carbon emissions and with embodied carbon emissions (results represented with a black edge), for the different renovation packages

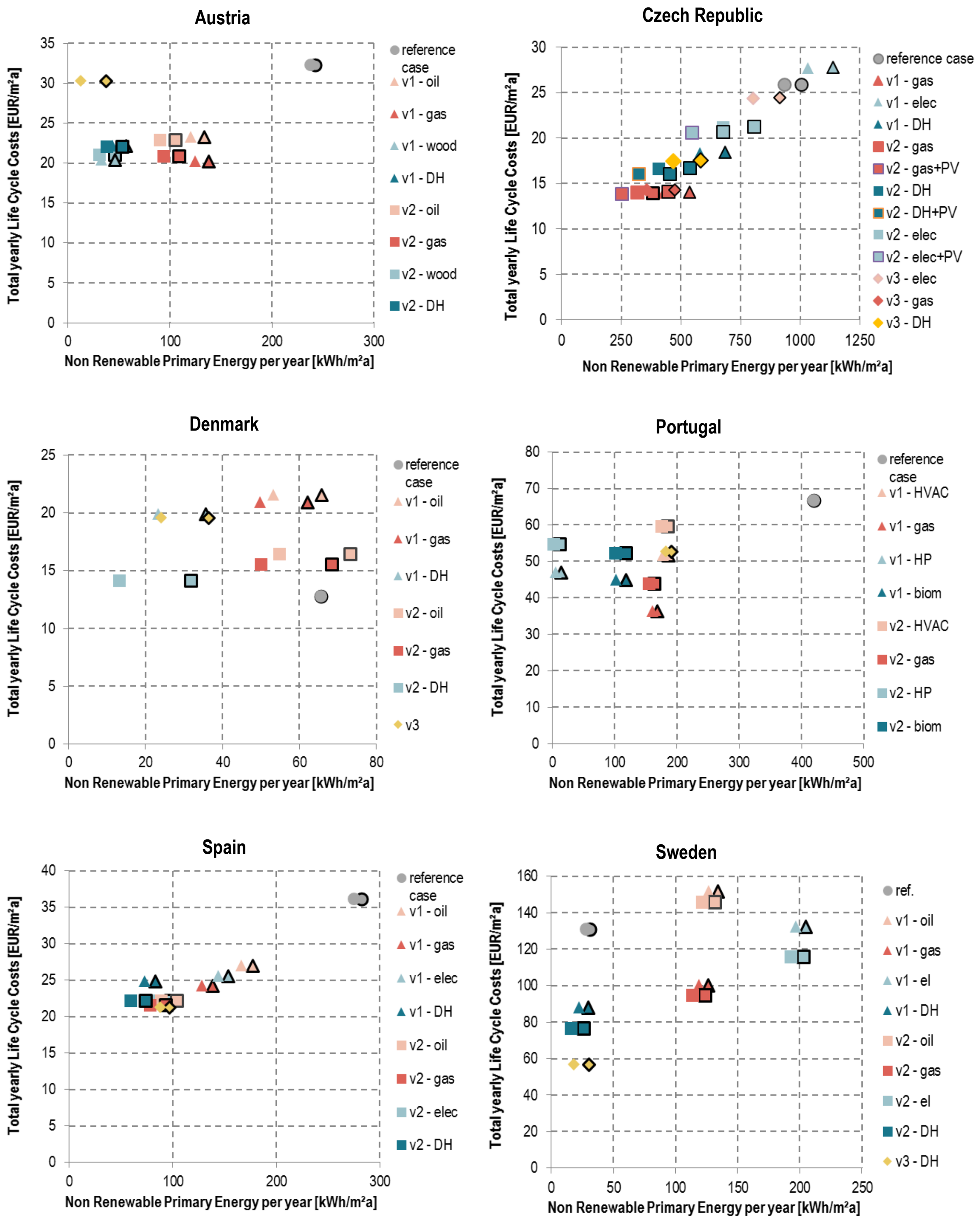


Figure 21 Comparison of carbon emissions reductions and costs for the six case studies, without including embodied non-renewable primary energy and with embodied non-renewable primary energy (results represented with a black edge), for the different renovation packages

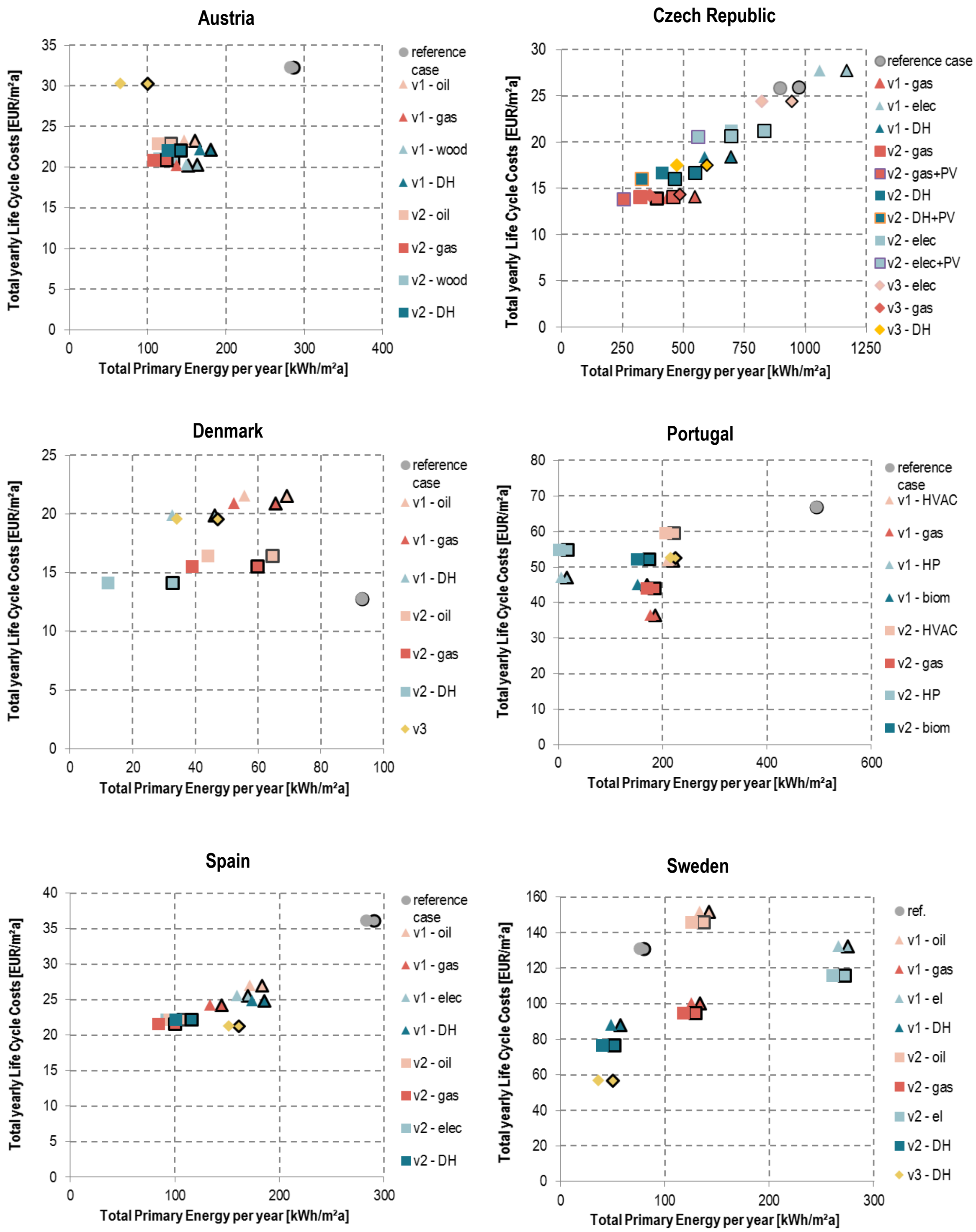


Figure 22 Comparison of carbon emissions reductions and costs for the six case studies, without including embodied total primary energy and with embodied total primary energy (results represented with a black edge), for the different renovation packages

Global results show that the inclusion of embodied energy and carbon emissions in the methodology does neither change the cost-effective solutions nor the best renovation packages in terms of total primary energy (TPE), non-renewable primary energy (NRPE) and carbon emissions.

Indeed, the inclusion of embodied energy and carbon emissions only influences the reduction achievable at some extent depending on the embodied energy and carbon emissions of the measures. For countries where all renovation packages are cost-effective (i.e., Austria, Portugal and Spain) and achieve reduction in carbon emissions, NRPE and TPE, the inclusion of embodied energy and embodied carbon emissions slightly lower the achievable reduction. It is respectively about 4% to 11% for Austria, 2% to 15% for Portugal and 2% to 5% for Spain whatever the indicator (carbon emissions, NRPE, TPE). For the Czech case study, all solutions are cost-effective except the “v1-elec” renovation package and “v3-elec” (only for the carbon emissions indicator). For those cost-effective renovation packages, the integration of embodied energy and carbon emissions lowers the achievable reduction about 5% to 12% whatever the indicator (carbon emissions, NRPE, TPE).

For the Swedish case study, fewer solutions are both cost-effective and achieve reduction in carbon emissions, NRPE and TPE. This can be explained by the already existing district heating in the reference case that slightly biases the analysis with fossil fuel alternatives (e.g., gas or oil). For the cost-effective renovation packages using district heating, the integration of embodied energy lowers the achievable reduction about 15 to 32% for NRPE and 8% to 15% for TPE while figures are about 9 to 19% for the carbon emissions.

Finally, the Danish case study presents no cost-effective renovation packages. The inclusion of the embodied carbon emissions however reduces the achievable savings of 3% to 6% while the inclusion of embodied NRPE and embodied TPE indicators reduces the savings from 14% to 28%.

4.3. Operational savings compared to embodied energy and carbon emissions for cost-effective renovation measures

This section reports the annual operational savings compared to the additional embodied carbon emissions and TPE for each case study. Results are presented depending on the number of cost-effective renovation measures identified in chapter 4.2.

Figure 23 presents the results for the Austrian, Portuguese and Spanish case studies where all solutions are cost-effective.

Results show that the operational carbon emissions savings (resp. the operational TPE savings) are systematically higher than the additional embodied carbon emissions (resp. embodied TPE) i.e., “we save more than we invest in terms of carbon emissions and TPE”. The additional embodied carbon emissions and embodied TPE represents:

- 4% to 8% of the operational carbon emissions savings and 7% to 14% of the TPE savings for the Austrian case study;
- 2% to 7% for the operational TPE savings and 8% to 20% of the carbon emissions savings for the Portuguese case study;
- 1% to 5% of the operational carbon emissions and TPE savings for the Spanish case study.

For the Austrian case study, the chosen renovation scenario (v3) has the highest embodied carbon emissions and embodied TPE with respectively 8% and 14% of relative contribution compared to the operational savings. This is mainly due to the additional renewable energy generation on-site (144 m^2 of solar thermal panel and DHW preparation as well as the 92 kWp PV system for electricity generation on-site).

For the Portuguese case study, the embodied carbon emissions of the chosen renovation scenario represent about 12% in relative contribution of the operational savings while the embodied TPE is only about 3%. The situation is similar for the Spanish case study with respectively 1% and 2% of embodied carbon emissions and embodied TPE compared to the operational carbon emissions and TPE savings.

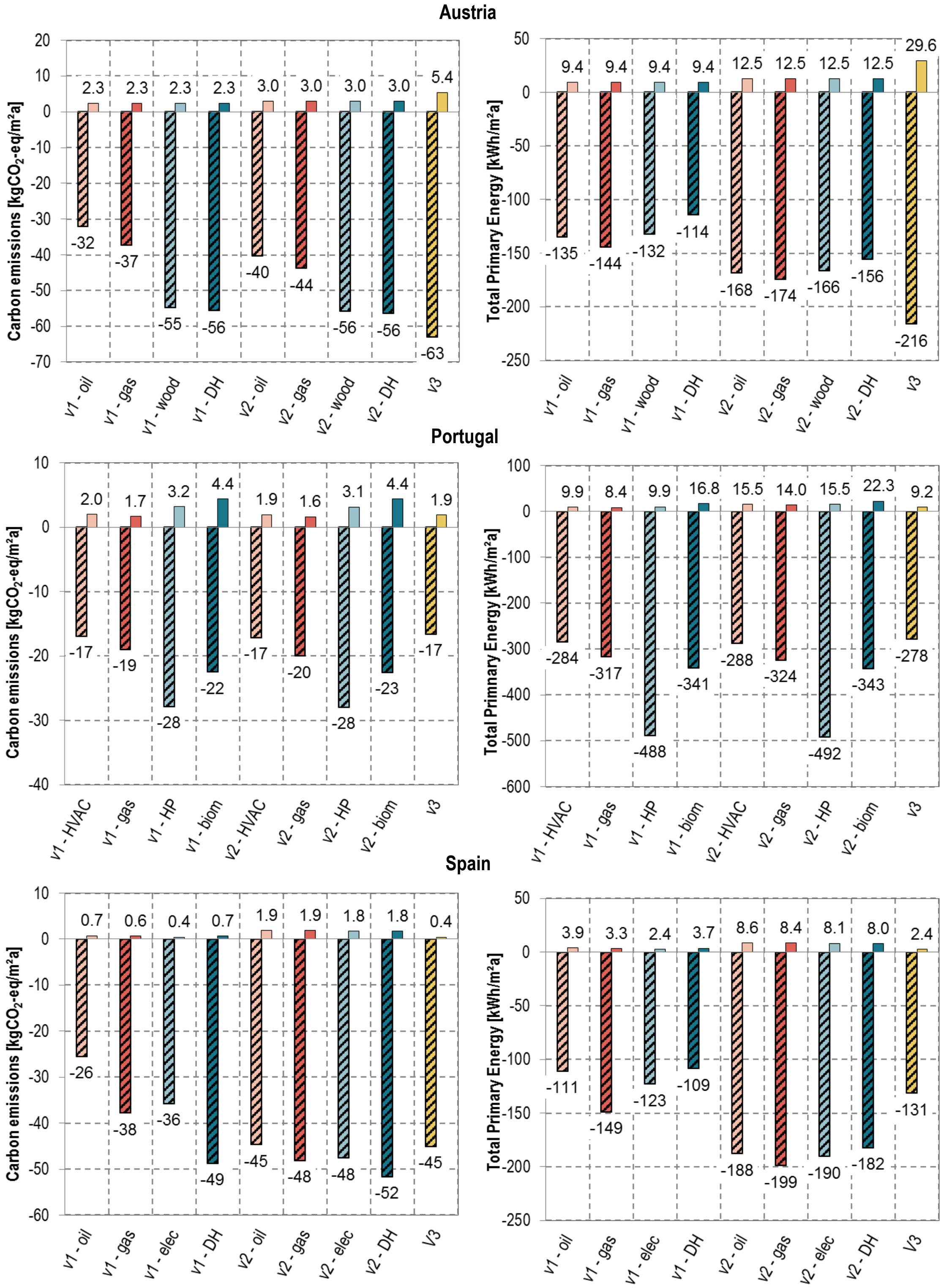


Figure 23 Comparison of operational carbon emissions and total primary energy savings and additional embodied carbon emissions and total primary energy for the cost-effective solutions of the Austrian, Portuguese and Spanish case studies; the negative bars represent the operational savings while the positive bars represent the additional embodied energy and embodied carbon emissions

Figure 24 presents the results for the Czech case study where all solutions are cost-effective except the “v1-elec” solution independent of the LCA indicators. Measure “v3-elec” achieves higher carbon emissions than the reference case but lower life cycle costs.

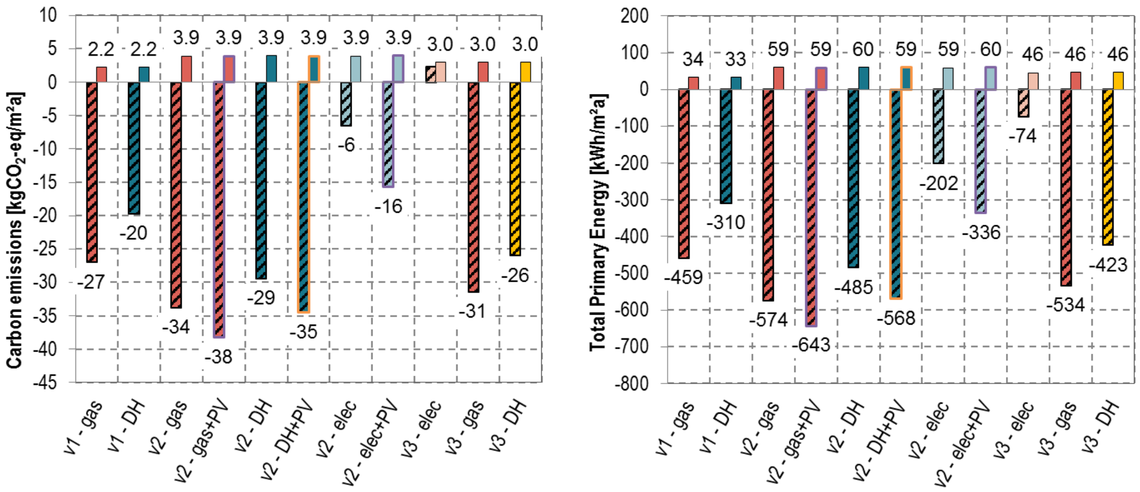


Figure 24 Comparison of operational carbon emissions and total primary energy savings and additional embodied carbon emissions and total primary energy for the cost-effective solutions of the Czech case study; the negative bars represent the operational savings while the positive bars represent the additional embodied energy and embodied carbon emissions

Results again show that the operational carbon emissions savings (resp. the operational TPE savings) are systematically higher than the additional embodied carbon emissions (resp. embodied TPE) i.e., “we save more than we invest in terms of carbon emissions and TPE”. The additional embodied carbon emissions and embodied TPE represents:

- 8% to 61% of the operational carbon emissions savings and 7% to 29% of the TPE savings for the Czech case study;

For the Czech case study, the embodied carbon emissions and embodied TPE represent respectively 11% and 12% of the operational carbon emissions savings and TPE savings for the executed renovation. These values represent one of the lowest values of the relative contribution of embodied carbon emissions and embodied TPE in all the renovation packages investigated.

Figure 25 presents the results for the Swedish case study where only three to four solutions are cost-effective and achieve at the same time carbon emissions and TPE reductions.

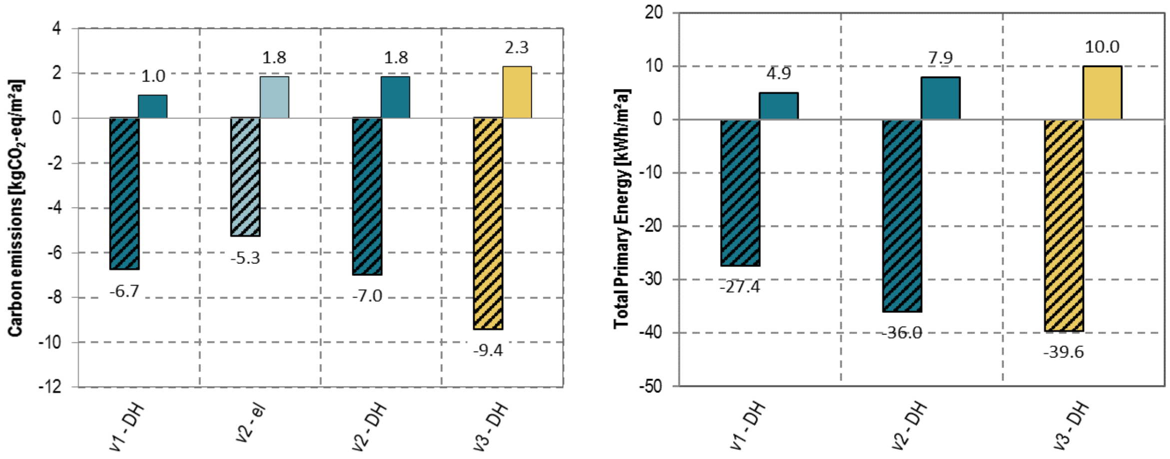


Figure 25 Comparison of operational carbon emissions and total primary energy savings and additional embodied carbon emissions and total primary energy for the cost-effective solutions of the Swedish case studies; the negative bars represent the operational savings while the positive bars represent the additional embodied energy and embodied carbon emissions

Results show that the operational carbon emissions savings (resp. the operational TPE savings) are systematically higher than the additional embodied carbon emissions (resp. embodied TPE) i.e., “we save more than we invest in terms of carbon emissions and TPE”. The additional embodied carbon emissions and embodied TPE represents:

- 15% to 35% of the operational carbon emissions savings and 18% to 25% of the TPE savings for the Swedish case study;

For the Swedish case study, the embodied carbon emissions and embodied TPE represent respectively 24% and 25% of the operational carbon emissions savings and TPE savings. These values are more important compared to the other case studies chosen renovation scenarios where the relative contribution of embodied carbon emissions and embodied TPE are below 12%. This can be explained by the relative environmentally friendly heating system already in place before the renovation (district heating with 81% of renewables). In that context, the operational energy savings are less important e.g., in terms of carbon emissions and the additional embodied energy and embodied carbon have a higher share here. However, they do not change the relevance of undertaking an energy-related renovation of the building as the tenant will save more every year than the additional embodied energy and embodied carbon emissions.

As the Danish case study does not present any cost-effective solutions, the operational savings compared to the additional embodied energy and embodied carbon emissions are not presented in details in this report[35]. However, it has to be mentioned that the same trends as for the other countries were found for all Danish renovation packages i.e., hypotheses 1 and 2 are also verified for non-cost-effective packages.

Further explanations of the share of embodied energy and embodied carbon emissions for the six case studies

The differences in the share of the embodied energy and embodied carbon emissions are mainly due to the reference state of each building including the existing efficiency and environmental impacts of the BITS. For instance, the share of embodied energy and embodied carbon emissions compared to the operational savings is much more important in countries and case studies that have a more efficient heating system before renovation. This is notably the case in Sweden where the building is already connected before renovation to a District Heating with more than 80% of renewables. In that case, the carbon emissions of the building before renovation is already "small" compared to the other renovation case studies where much more inefficient and more environmental harmful systems were in place (e.g., in the Portuguese case study the existing building includes an oil boiler). These reference state of each building mainly explains why the share of embodied energy varies from a very small percentage in the Spanish, Austrian, Portuguese case studies to a more important value in the Swedish case study for instance.

As the Swedish case study is a "good example" of a renovation where the embodied energy and carbon emissions can play a role due to the existing state of the building, a further analysis is presented below for more renovation measures.

4.4. Embodied energy and embodied carbon emissions payback times

To complement the results presented in this chapter, it is also possible to determine the payback time of the embodied energy and embodied carbon emissions. This parameter represents the number of years needed to offset the initial investment in terms of primary

[35] The embodied energy and embodied carbon emissions results are only presented for the cost-effective solutions which are the main focus of the IEA EBC project. Further LCA and LCC results about this case study can be found in Venus et al (2015).

energy or carbon emissions of the manufacturing of construction materials and BITS compared to the annual operational savings[36].

As an illustration, Table 6 and Table 7 present the results of the payback times calculated for some of the case studies of this project. They are presented as a range for all the cost-effective renovation packages.

Table 6 Examples of embodied Total Primary Energy payback times for the cost-effective renovation packages of the Austrian, Portuguese, Spanish and Swedish case studies

Case studies	Embodied Total Primary Energy payback times
Austria	2.5 – 4.5 years
Portugal	5 – 12 years
Spain	0.1 – 0.7 years
Czech Republic	not calculated
Sweden	9 – 11 years
Denmark	(no cost-effective renovation packages)

Table 7 Examples of embodied carbon emissions payback times for the cost-effective renovation packages of the Austrian, Portuguese, Spanish and Swedish case studies

Case studies	Embodied carbon emissions payback times
Austria	4 – 5 years
Portugal	1 – 4 years
Spain	0.1 – 0.3 years
Czech Republic	not calculated
Sweden	1.7 – 2.4 years
Denmark	(no cost-effective renovation packages)

Whatever the indicators (primary energy or carbon emissions), in all cost-effective solutions, results show that the payback times range from 0.1 to 12 years. Generally speaking, when the current state of the building is very poor, the operational energy savings are very high and the

[36] It should be highlighted that this payback time only captures the initial embodied energy and embodied carbon emissions related to the manufacturing. In that sense, it does not account for the embodied energy and embodied carbon related to the replacement of components over the service life of the building as well as the embodied energy and embodied carbon related to the end of life of components.

levels of insulation only comply with current regulations, the embodied energy (and carbon emissions) remain negligible. For example, this is the case for the Spanish case study for which the payback time is very small less than a year (0.1 to 0.7). In opposite, when the current state of the building is already more efficient (e.g., in Sweden with a district heating with a high share of renewables), the operational energy savings are smaller and the contribution of embodied energy and carbon emissions are more important leading to a higher payback time (9 to 11 years for the embodied total primary energy payback time). This is particularly the case for renovation aiming at a very high energy efficiency i.e., more insulation is needed as well as more efficient BITS.

4.5. Summary of findings

In this chapter, LCA results were analyzed for the cost-effective renovation packages of the six case studies. The following hypotheses related to the influence of embodied energy and embodied carbon emissions of energy related renovation measures were verified for all cost-effective solutions.

1. **The operational savings of the energy related renovation measures assessed are higher than the additional embodied energy and embodied carbon emissions in any cost-effective renovation measures.**
2. **The integration of embodied energy and embodied carbon emissions of the energy related renovation measures assessed does not change the cost-effective renovation packages.**

For all the cost-effective solutions analysed in this project, the embodied energy and embodied carbon emissions remain not significant, i.e., “we save more than we invest” in terms of ecological aspects (**validation of hypothesis 1**)[37]. In addition, the integration of embodied energy and embodied carbon emissions does not change the cost-effective renovation packages solutions. It only reduces the achievable operational energy savings (**validation of hypothesis 2**). For all the cost-effective solutions identified in the six case studies, the lower the total primary energy and total carbon emissions, the higher (in relative contribution i.e., in %) the embodied energy and embodied carbon emissions.

[37] However, it is important to mention that according to the LCA methodology defined in this project, this hypothesis is also verified for non-cost-effective solutions even if these solutions are not in the primary scope of the project’s results.

In addition, the payback times for the initial embodied energy and embodied carbon emissions (i.e., for the manufacturing of construction materials and BITS) was found rather low and is estimated about 1 to 12 years in all the cost-effective renovation measures of the different case studies[38,39].

[38] It should be highlighted that this payback time only captures the initial embodied energy and embodied carbon emissions related to the manufacturing. In that sense, it does not account for the recurring embodied energy and embodied carbon related to the replacement of components over the service life of the building as well as the embodied energy and embodied carbon emissions related to the end of life.

[39] Not calculated for Denmark and Czech Republic case studies

5. Recommendations

The integration of LCA in the Annex 56 methodology enables to adopt a life cycle perspective for energy-related building renovation by taking into account not only the operational energy but also the embodied energy and embodied carbon emissions related to the manufacturing, replacement and end-of-life (e.g., disposal or recycling) of construction materials and BITS. It was found that embodied energy and embodied carbon emissions are not very influential in the project's building renovation case studies due to the focus towards cost-effective renovation solutions (in other words, the cost effective solutions "limit" the influence of the embodied energy)[40].

However, these results do not mean a LCA approach is not relevant for building renovation. In fact, it is now well accepted that the primary energy and carbon emissions optimization for both new and existing buildings should be done using a life cycle perspective. This perspective is particularly valid for nearly zero carbon emissions or nearly zero energy renovation, for which the relative contribution of the embodied energy or embodied carbon emissions is likely to rise as far as the renovation becomes significant. Indeed, generally speaking, it theoretically exists an optimum where the operational energy use reduction balances the increase of the embodied energy use. Figure 26 presents an illustration for the determination of the insulation thickness of the building envelope (roof, walls and basement for instance).

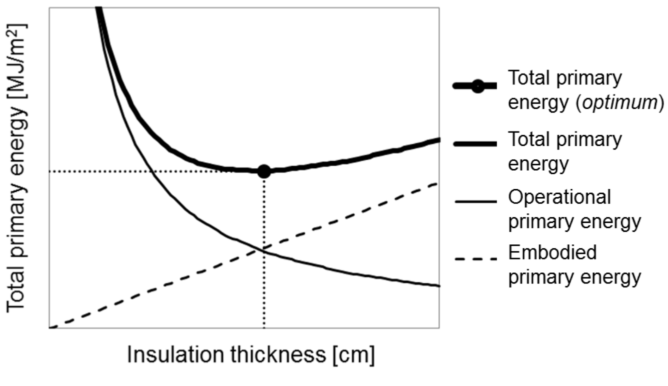


Figure 26 Illustration of the optimum insulation thickness in a fictive building renovation for the total primary energy indicator

[40] This result is also explained by the limited scope of the LCA system boundaries. It only takes into account the materials and BITS that have an influence on the energy performance of the building. This choice does not consider the embodied energy and embodied carbon of the other added construction materials (interior walls, floor coatings etc.) and BITS (e.g., sanitary and electric equipment)

In that context, LCA is a relevant methodology to be recommended in future policies and practices in renovation projects to assess renovation measures over the life cycle of the building.

To date, LCA is already linked to some EU regulations related to the environmental impacts of building products and building integrated technical systems. The recent Construction Products Regulation (CPR) contains additional Basic (Work) Requirements (BWR), particularly the addition of 'environment' to BWR 3 (hygiene and health) and the new BWR 7 (Sustainable use of natural resources), stating that "Environmental Product Declaration (EPD) should be used when available for the assessment of the sustainable use of resources and of the impact of construction works on the environment" (CPR 2011). In this last example, LCA is already promoted by an EU regulation as the basis for product assessments, especially in providing Environmental Product Declaration (EPDs)[41]. These kinds of data form an important data source in Europe for building LCA studies both new or renovation projects according to the EN 15804 and EN 15978 standards (Lasvaux et al, 2014).

Over the last few years, this new Construction Product Regulation (CPR) has created a demand for building product EPDs as a mechanism to meet the additional requirements (mentioned above). Consequently, building product manufacturers are now more and more keen in providing the EPDs of their products in different countries (Passer et al, 2015). In the same time, European construction products association develops common rules to harmonize the LCA application in the building sector see e.g., the ECO Platform initiative (ECO Platform, 2016). So all these data form of basis of assessing the embodied energy and carbon emissions in future building policies.

At the building level, voluntary green building labelling systems that assess the environmental sustainability of buildings like BREEAM (UK), DGNB (Germany), HQE (France), SNBS (Switzerland) more and more rely on LCA for assessing the embodied impacts of construction materials and BITS but also for assessing the operational energy use of both new and existing buildings. Finally, building-level LCA regulations are being discussed in some countries e.g., in UK and Austria (Mistretta et al, 2016).

5.1. Recommendations for policy makers

In that context, it becomes clear that LCA will be more and more used as a policy instrument at different levels (products and buildings) in different countries. The next step is now to integrate it in energy efficient related policies for buildings. For instance, LCA can contribute to switch from

[41] An EPD is a product-specific and/or company-specific LCA that describes the environmental impacts of a product sold in the market (the environmental impacts generally includes the assessment of the primary energy and carbon emissions among other indicators)

the limited scope within the recast of the Energy Performance of Building Directive (EPBD) of the European Union[42] (assessment of the operational energy use) towards a broader scope (life cycle perspective from “cradle-to-grave”) and a broader set of environmental indicators to assess building renovation projects.

The recent European Commission Communication on Sustainable Buildings is clearly promoting the alignment of energy efficiency policies with LCA related aspects mentioning that:

“Existing policies for promoting energy efficiency and renewable energy use in buildings need to be complemented with policies for resource efficiency which look at a wider range of environmental impacts across the life-cycle of buildings” (European Commission, 2012).

As a result, the following recommendations to policy makers can be drawn for the integration of LCA in building renovation policies.

General recommendation for the use of LCA in building renovation (policy makers):

1) If the goal is to increase the energy efficiency of a renovated building, new policy in the field should include a life cycle perspective to require the assessment, next to the operational energy use, the embodied energy and embodied carbon emissions. By doing so, the upcoming policies will contribute to globally minimise the primary energy or carbon emissions of energy-efficient renovation measures.

2) If a LCA is to be promoted in the new policy, precise rules should be developed using the best practice e.g., available LCA database, LCA methodology (e.g., detailed in technical reports or standards) and LCA target values for renovated buildings[43]

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[42] European Parliament and Council of the European Union (2010) Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings (recast);
Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31EU on the energy performance of buildings, establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements;
Directive 212/2/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30EU and repealing Directives 2004/8/EC and 2006/32/EC;
European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2012/C 115/01;
European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2012/C 115/01;
European Commission (2011), Meeting Document for the Expert Workshop on the comparative framework methodology for cost optimal minimum energy performance requirements In preparation of a delegated act in accordance with Art 290 TF EU 6 May 2011 in Brussels;

[43] For instance, in Switzerland, database (KBOB), methodology and tools (e.g., the SIA 2031, SIA 2032, SIA 2039 and SIA 2040 technical books) and target values (available in the SIA 2040 target values) allow a practitioner to address this recommendation. Similar tools and methodologies are in development or already exist in Europe with a varying level of maturity

5.2. Recommendations for professional owners

The previous recommendations for policy makers are also relevant for professional owners. Indeed, once public policies will integrate LCA as a basis of the new assessment framework for a building renovation, professional owners will be likely to use it as part of their decision making tools.

In line with the other IEA EBC parallel project (Annex 57), further recommendations can be drawn for decision makers like the professional owners (Lützkendorf et al, 2016). They may be interested to reduce the embodied energy and embodied carbon emissions of their renovation measures.

Materials and BITS choice to reduce embodied energy and embodied carbon emissions

They should also use construction materials and BITS during a renovation with a minimum embodied energy and embodied carbon value. This choice should be verified by taking also into account the operational energy consumption. This life cycle perspective allows appropriate renovation strategies to be implemented by the professional owners.

Tools for the assessment of materials choice

More and more assessment tools are developed to link embodied energy with operational energy use enabling to identify trade-offs and finally select the most appropriate renovation measure in terms of primary energy or carbon emissions (Passer et al, 2016). Professional owners are recommended to use the existing web-based and software tools that can be used at different stages of the design process to assist them in this task. Some tools combine both a 3D-modeling of the building, an energy calculation and a LCA. The tools can also integrate the Building Information Modelling (BIM) approach to ease the assessment. May tools already exist and a detailed review of existing tools incorporating LCA can be found in the EeBGuide Infohub (Lasvaux et Gantner, 2012). For the professional owners interested in using compliant Annex 56 tools, they can use e.g. the Eco-bat (and new Eco-sai) tool developed in Switzerland as well as the ASCOT tool developed in Denmark.

Recommendation for the use of LCA in building renovation (professional owners):

1) If the goal is to increase the energy efficiency of a renovated building, a LCA perspective should be used to assess, next to the operational energy use, the embodied energy and embodied carbon emissions. By doing so, solutions that globally minimise the primary energy or carbon emissions indicators could be promoted.

2) If a LCA is conducted by the decision maker, use the best practice in the corresponding country e.g., available LCA database, LCA methodology (e.g., detailed in technical reports or standards) and LCA target values for renovated buildings[44]

[44] For instance, in Switzerland, database (KBOB), methodology and tools (e.g., the SIA 2031, SIA 2032, SIA 2039 and SIA 2040 technical books) and target values (available in the SIA 2040 target values) allow a practitioner to address this recommendation. Similar tools and methodologies are in development or already exist in Europe with a varying level of maturity

6. Conclusions

The findings of the Life Cycle Assessment for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation showed that the embodied energy and embodied carbon emissions does not change the cost-effective solutions identified without taking them into account. However, the use of LCA will be more and more relevant in upcoming cost-effective building renovation projects as more and more projects towards near zero energy renovation become cost-effective. For these specific cases (zero energy renovation), the only impacts are then linked to the additional embodied impacts due to the materials and BITS added for the renovation. The methodology defined in this Annex 56 project is then a first contribution towards the integration of LCA in upcoming public policies and in the assessment of decision makers and professional owners.

Perspectives following the IEA EBC Annex 56 (LCA workpackage)

From a more LCA methodological point of view, the shift towards near zero energy building renovation needs also further works in terms of LCA calculation rules. As the on-site RES are intermittent energy generation sources, they have implications on the local energy grids with import/export of energy to supply the demand at all time. In that context, the energy consumption of buildings with on-site RES could be precised (e.g., hourly assessment with dynamic simulation tools). The LCA conversion factors (primary energy and carbon emissions) for energy grids could be adapted (e.g., by using hourly profiles) to match the hourly energy demand of the building e.g., use hourly CO_2 emissions profiles for the electricity. In that context, further works could be done e.g., within the IEA EBC programme to clarify the LCA related environmental impacts between the renovated/new buildings (with different on-site RES systems) and the energy grids (e.g., the electricity grid). Such work concerns the adaptation of the LCA approach for buildings with on-site RES systems. It could start from the works already done e.g., in IEA EBC Annex 56 and Annex 52 and be continued in another LCA-related IEA EBC Annex project in the future.

7. Appendix 1: additional information for the LCA methodology of energy related building renovation

7.1. Components and materials included in the LCA of energy related renovation measures

When performing a comparative LCA of energy related renovation measures, it is important to define which components have to be included in the calculation.

One of the objectives of taking into account building components in an LCA is to analyse the trade-offs between increased environmental impacts due to components added to improve the energy performance of the building and decreased environmental impacts due to the reduction of operational energy demand.

Materials and components to be included in the LCA

The project focuses on cost and environmental benefits of energy related renovation measures. Therefore, the LCA must at least include the environmental impacts of the following components:

- Materials added for the renovation of the thermal envelope of the building (see below) and components for building integrated technical systems (see subsequent paragraphs);
- Materials /components that need to be replaced due to energy related building renovation to provide the same building function before and after energy related renovation (see subsequent paragraphs).

Materials for the thermal envelope

Since the focus of the assessment is on renovation measures that affect the energy use of the building, the impacts of renovating the thermal envelope (walls, windows, roofs, ground floor, etc.) is one major subject of LCA. Thereby, construction elements that do not affect the building's energy performance, like internal walls or doors, are not taken into account.

A wall as an element of the thermal envelope can be decomposed in layers, as schematised in Figure 27.

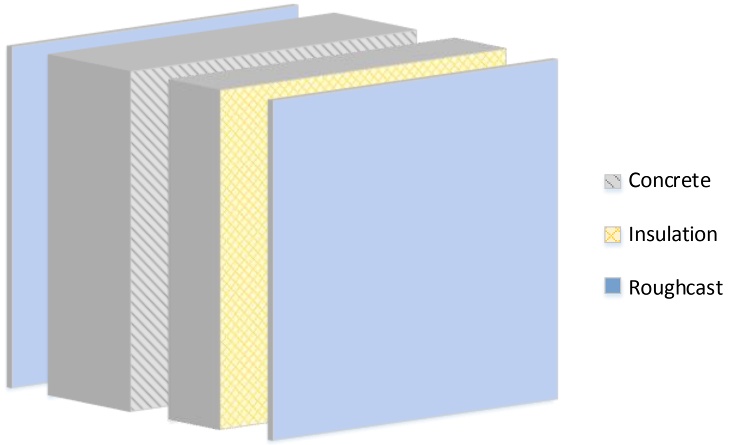


Figure 27 Example of a construction element composed of different materials (layers)

The weight of the layer can be easily calculated. For a homogeneous layer (constant thickness) it can be deducted from the element's surface area, the material's thickness and density. For non-homogenous layers the percentage of area occupied by each material must be defined.

The service life of the materials should also be reported and allows calculating the number of replacements during the life of a building (see subsequent paragraph). The position and role of a material in the construction element, will affect its service life of the component.

Components for building integrated technical systems (BITS)

The components for building integrated technical systems include the components replaced or added, which have an effect on the building's energy performance. For instance:

- Replacing existing components: new radiators; adding insulation of pipes, etc.;
- Adding new components: mechanical ventilation, a solar thermal or PV system, etc.

Components which have no particular influence on energy use, production, distribution and on carbon emissions are not taken into account (for instance: sinks, bathtub, replacement of piping, etc.). If in any renovation scenario (including "anyway" renovation) energy related measures have to be replaced, it is assumed, that they are replaced by the same components not aiming at higher energy efficiency (corresponding to the cost calculations).

Environmental impact data for BITS components might be difficult to find. One possible source of information is the Swiss-KBOB database ("KBOB database"), which provides a complete set of information for energy related BITS. The information is easy to apply in the calculation. Table 8 describes the information required to model the technical equipment of a building using the KBOB database.

Table 8 Information required for assessing the environmental impacts of building integrated technical systems (BITS)

BITS	Example of components	Information required
Heat production	Boiler, heat pump, storage, borehole heat exchanger	Power needed [W/m^2 heated floor area] Presence of borehole heat exchanger
Heat distribution	Radiators, heated floors, distribution pipes, etc.	Type of distribution (radiators, heated floor, air)
Ventilation	Mechanical air handler, ducts, heat exchanger, etc.	Type of channels (steel, synthetic) Channels' length Specific air flow rate [m^3/(h m^2)] Presence of ground-coupled heat exchangers and tubes length
Solar thermal systems	Collectors, assembly, piping	Type of use (DHW, DHW + heating) Type of building (single family house, multiple dwelling, etc.)
PV systems	Collectors, assembly, inverter, wiring	Collector type (mono-Si, poly-Si, etc.) Collector area [m^2] Mountings type (wall, flat or slanted roof)

Materials/components added to provide the same function.

Generally speaking, in LCA comparison of e.g., renovation scenarios should be made on the basis of the same functional equivalent according to EN 15978 (2011)[45] including all the technical functions needed to maintain the safety, comfort level for the occupants. In energy related building renovation, this might not always be the case as some building elements can be removed, replaced or added during the renovation. One typical example is the case of a balcony, which is an extension of the internal storey slab before the renovation. In order to prevent this thermal bridge, the original balcony is removed. The thermal envelope is improved and a new balcony is added alongside the renovated façade. Subsequently, there are some more examples:

- The construction of a larger energy storage room (for instance replacing an electric heating system, with a pellet boiler requiring the construction of additional storage space);
- Reinforcing the roof structure to install solar thermal collectors;
- Etc.

Two different situations can occur:

- If new materials and components, not related to energy related renovation measures (and corresponding to the "anyway renovation" as defined in Ott et al (2015)), are added

[45] Or the same functional unit according to ISO 14'040-ISO 14'044 standards

to provide the same building function (before and after renovation): In this case the impacts of these materials and components have also to be included in the LCA;

- If a material/component, not related to energy related renovation measures, is removed during the renovation and is not replaced, it will not be included in the LCA (for instance a balcony removed to prevent the thermal bridge). In this case, it must be documented as negative or positive co-benefit.

7.2. Service life and replacement period

The service life is defined as the time during which a building component (construction material, BITS component) fulfils its function. At the end of its service life, the product must be replaced.

Service life of construction components

Even if there are values for the average service life for particular types of materials or products, the real service life depends on economic aspects and the conditions of use (in contact with the outside, solar radiation, weather influences, etc.).

Table 9 lists average service life times of BITS and Table 10 average service life times of construction components suggested to be used. The basis taken into account to define these values is the Swiss SIA 2032 technical book regarding embodied energy in buildings (SIA Merkblatt 2032 «Graue Energie von Gebäuden», 2010). They have been reviewed by the project's partners and adapted in order to comply with a global energy renovation context.

Table 9 Service life time of building integrated technical systems suggested to be used in the methodology

Building integrated technical system (BITS)	Service life time [years]
Heat production	20
Heat distribution	30
Ventilation	30
Solar thermal	25
Solar PV	30
Geothermal probe (heat-pump)	30

Figure 28 shows an example for the service life of different layers of a floor in contact with the ground.

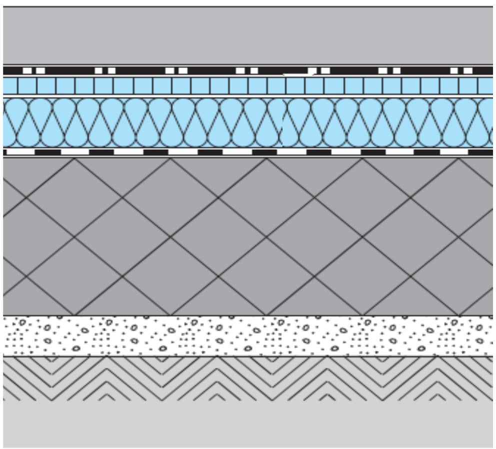


Figure 28 Examples for the service life of components in a construction element

Table 10 Service life time of construction products for the thermal envelope (*RSP = Study period in the reference case, assuming that the product will not be replaced)

Type of element	Position of the material (relative to the structural layer)	Location	Service life [years]	Example(s)
Roof	Structure	-	RSP	Concrete, rafters
Roof	External	Against exterior, flat roof	30	Insulation, waterproofing, vegetal layer, vapour barrier
Roof	External	Against exterior slanted roof	40	Tiles, lathing and counter-lathing, weatherproofing
Roof	External	Against ground	40	
Roof	Internal	-	40	Insulation, vapour barrier, coatings
Wall	External	Against ground	40	
Wall	External	With external insulation	30 15	Insulation, roughcast, boarding Paint, varnish
Wall	External	Without external insulation	40 15	Roughcast, boarding Paint, varnish
Wall	Structure	Bearing or not	RSP	Concrete, bricks, wooden frame
Wall	Internal	-	30	Insulation, vapour barrier, coatings
Window / Door	-	Against exterior	20	
Floor	Internal		30 25 15	Hard coating: Ceramic tiles Medium coating: Wooden or synthetic parquets Soft coating: Carpets
Floor	Internal	Between the structure and interior	30	Floating screed, water sealing, insulation
Floor	Structure	Above ground or cellar	RSP	Concrete, wooden beams
Floor	External	Above ground	RSP	Under floor insulation, light concrete, etc.
Floor	External	Against exterior	40	Insulation, coating

7.3. Reference assessment period of the renovated building

LCA is carried out on the basis of a chosen reference study period, for which all impacts of materials/components and energy consumed are determined.

For new buildings, the reference study period is usually defined as the estimated service life of the building. For renovated buildings, the reference study period can be:

- The period between the current renovation and the next major upcoming one. A typical value is 30 years, which corresponds to the period between the building construction and the first important renovation, which could be motivated by energy purposes or more likely motivated by wear and tear.
- The period between the current renovation and the end of the life of the building. A typical value is 60 years.

The number of energy related renovations is limited by the life of a building. The lower energy demand after renovation, the less a major energy related renovation will be undertaken in the future. It is impossible to know, which products will be used to replace current energy related construction elements in the future. It is also impossible to know which energy vectors will be used if e.g. the boiler will be replaced (in about 30 year).

The reference study period should be equal or longer than the service life of the (energy related) building components analysed in order to avoid any misinterpretation of the results. Therefore, it is suggested to assume a reference study period of **60 years**. If another reference study period is assumed, it should be reported and documented.

Number of replacements during the assessment period

Due to a limited service life, construction products will usually be replaced one or several times before the end of the building's life. The number of future replacements depends on their estimated service life (ESL) and the study or assessment period for the building (SP). No replacement is required if the service life of a building element meets or exceeds the required service life of the building (foundations, bearing wall, etc.).

In practice, only a full number of replacements (no partial replacements) can be taken into the assessment of the impacts of building elements replaced. In the case of a partial number of replacements, the number of replacements is rounded upward.

8. Appendix 2: inter-comparison exercise for building LCA tools

Each partner implemented the methodology defined in chapter 2 either by using spreadsheets, existing European LCA tools like the Swiss Eco-Bat or by developing new tools e.g., the ASCOT tool developed for Denmark. In order to ensure a consistent implementation of the LCA methodology in the six detailed case studies, an inter-comparison of LCA tools and spreadsheets used by the different partners was conducted on a simple test building to check that each partner is able to get to the same results.

The appendix provides the background assumptions and detailed results of the inter-comparison.

8.1. Building description

The building which has to be compared for different national context conditions comprises two dwellings, with the following surface area.

Table 11 Building description

	Unit	Value
Global data		
Heated floor area	m^2	204.7
Thermally active airflow (external heated air flow)	$m^3/(m^2h)$	0.3
Surface area of the individual building elements		
Roof	m^2	105.2
Wood façade	m^2	164.4
Masonry façade ag. Exterior	m^2	91.6
Masonry façade ag. Garage	m^2	11.99
Floor above garage	m^2	20.36
Ground floor	m^2	73.5
Windows (total area)	m^2	20.57
Windows – wooden frame ratio	%	25
Door (total area)	m^2	6.18

8.2. Methodology for the inter-comparison of LCA tools on a test building

8.2.1. Life cycle stages

In this simple case study, the following stages are taken into account for construction materials and BITS components:

- Manufacturing (module A1-A3 according to EN 15978)
- Replacement (module B4 according to EN 15978)
- End of life (module C according to EN 15978)

Other stages such as transport to the building site, maintenance, construction and demolition related impacts can also be taken into account if reported

8.2.2. Service lives

Construction elements

Some tools might evaluate materials service lives automatically. If it is not the case and a help is needed in defining these, the project's partners suggests the following values, depending on element type, location and material type and position (see Table below):

Type of element	Position of the material (relative to the structural layer)	Location	Service life [years]	Example(s)
Roof	Structure	-	RSP	Concrete, rafters
Roof	External	Against exterior, flat roof	30	Insulation, waterproofing, vegetal layer, vapour barrier
Roof	External	Against exterior slanted roof	40	Tiles, lathing and counter-lathing, weatherproofing
Roof	External	Against ground	40	
Roof	Internal	-	40	Insulation, vapour barrier, coatings
Wall	External	Against ground	40	
Wall	External	With external insulation	30 15	Insulation, roughcast, boarding Paint, varnish
Wall	External	Without external insulation	40 15	Roughcast, boarding Paint, varnish
Wall	Structure	Bearing or not	RSP	Concrete, bricks, wooden frame
Wall	Internal	-	30	Insulation, vapour barrier, coatings
Window / Door	-	Against exterior	20	
Floor	Internal		30 25 15	Hard coating: Ceramic tiles Medium coating: Wooden or synthetic parquets Soft coating: Carpets
Floor	Internal	Between the structure and interior	30	Floating screed, water sealing, insulation
Floor	Structure	Above ground or cellar	RSP	Concrete, wooden beams
Floor	External	Above ground	RSP	Under floor insulation, light concrete, etc.
Floor	External	Against exterior	40	Insulation, coating

Technical systems

Technical systems replacements should also to be taken into account during the building lifespan. The LCA methodology suggests the following service lives:

Building integrated technical system (BITS)	Service life time [years]
Heat production	20
Heat distribution	30
Ventilation	30
Solar thermal	25
Solar PV	30
Geothermal probe (heat-pump)	30

8.3. Construction elements

This chapter presents the construction elements that are renovated. The elements not mentioned in this chapter are not renovated. New materials added during the renovation process are displayed in ***RED***. Existing materials are displayed in ***BLACK***.

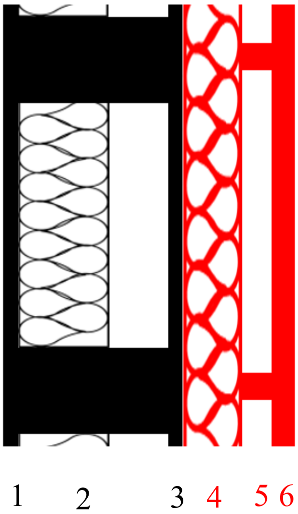
8.3.1. Windows and doors

All windows are replaced by the following type:

- Triple glazing with two low-emissivity layer, with argon in-between. Spacer is in PVC.
- Wooden frame, which represent 25% of the windows area.

Doors are not replaced.

8.3.2. Wood façade

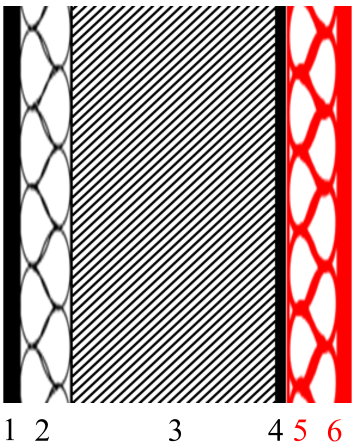


1. Softwood (conifer), 15 [mm], ρ = 520 [kg/m³]
2a. Glasswool insulation, 100 [mm], ρ = 40 [kg/m³]
2b. Air, 40 [mm]
2c. Hardwood, bearing structure, 140 [mm], ρ = 700 [kg/m³
3. Hardwood, 24 [mm], ρ = 700 [kg/m³]
4. EPS insulation, 240 [mm], ρ = 15 [kg/m³]
5a. Hardwood, 45 [mm], ρ = 700 [kg/m³]
5b. Air, 45 [mm]
6. Hardwood, 24 [mm], ρ = 700 [kg/m³]

This is an inhomogeneous element. The renovated part should be modelled with two different sections:

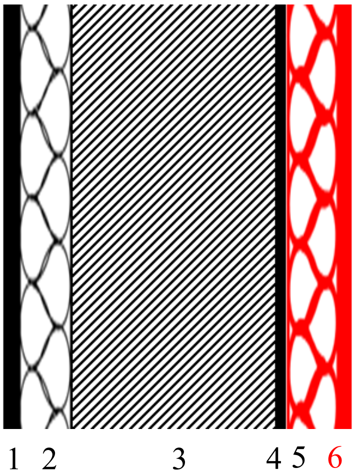
- 1st section: 4 – 5b– 6, covers 90% of the element area
- 2nd section: 4 – 5a –6, covers 10% of the element area

8.3.3. Masonry façade against exterior



1. Softwood (conifers), 15 [mm], ρ = 520 [kg/m³]
2. Glasswool insulation, 100 [mm], ρ = 40 [kg/m³]
3. Cement bricks, 180 [mm], ρ = 1200 [kg/m³]
4. Cement mortar cover coat, 10 [mm], ρ = 1800 [kg/m³]
5. EPS insulation, 220 [mm], ρ = 15 [kg/m³]
6. Cement mortar cover coat, 10 [mm], ρ = 1800 [kg/m³]

8.3.4. Masonry façade against garage



1. Softwood (conifers),15 [mm], ρ = 520 [kg/m³]
2. Glasswool insulation, 100 [mm], ρ = 40 [kg/m³]
3. Cement bricks, 180 [mm], ρ = 1200 [kg/m³]
4. Cement mortar cover coat, 10 [mm], ρ = 1800 [kg/m³]
5. EPS insulation, 40 [mm], ρ = 15 [kg/m³]
6. Particle board, cement bonded, 10 [mm], ρ = 50 [kg/m³]

8.3.5. Ground floor

1. Concrete C30/37, 2[illegible]0 [mm], ρ = 2400 [kg/m³]
2. Vapour barrier (PE), 0.2 [mm], ρ = 920 [kg/m³]
3. PUR insulation, 30 [mm], ρ = 30 [kg/m³]
4. Anhydrite screed, 45 [mm], ρ = 2000 [kg/m³]
5. Ceramic tiles, 9 [mm], ρ = 1900 [kg/m³]

8.3.6. Floor above garage

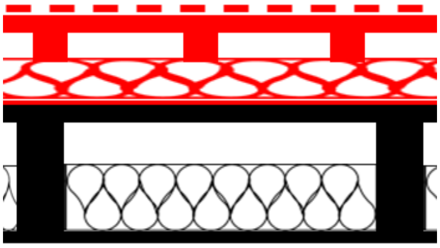
1. Particle board, cement bonded, 5 [mm], ρ = 50 [kg/m³]
2. EPS insulation, 115 [mm], ρ = 15 [kg/m³]
3. Particle board, cement bonded , ép.5 [mm], ρ = 50 [kg/m³]
4. Reinforced concrete C30/37, with 90 kg steel /m³, 160 [mm], ρ = 2400 [kg/m³]

5a. Softwood (conifer), 27 [mm], ρ = 520 [kg/m³]

5b. Air, 27 [mm]

6. Wood parquet, 3 layers, vitrified, 24 [mm], ρ = 900 [kg/m³]

8.3.7. Roof



1. Softwood (conifers), 15 [mm], ρ = 520 [kg/m³]

2a. Glasswool insulation, 10 [mm], ρ = 40 [kg/m³]

2b. Air, 60mm

2c. Hardwood, bearing struc , 160 [mm], ρ = 700 [kg/m³]

3. Hardwood, 18 [mm], ρ = 700 [kg/m³]

4. Bitumer sealing, 1.3 [mm], ρ = 1160 [kg/m³]

5. PUR insulation, 200 [mm], ρ = 30 [kg/m³]

6a. Softwood (conifers), 60 [mm], ρ = 520 [kg/m³]

6b. Air, 60mm

7. Softwood (conifers), 27 [mm], ρ = 520 [kg/m³]

8. Terra cotta files, 20 [mm], ρ = 1700 [kg/m³]

This is an inhomogeneous element. The renovated part should be modelled with two different sections:

- 1st section: 4 – 5 – 6b – 7 – 8, covers 90% of the element area
- 2nd section: 4 – 5 – 6a – 7– 8, covers 10% of the element area

8.4. Building integrated technical systems

- **Heating:** heating is provided by an air-water heat pump which covers 100% of the building needs. Heat pump efficiency (annual COP) is 2.03 [-] for heating and power needed is 19.8 [W/m² (heated floor area)] ;
- **Domestic hot water:** DHW is produced by solar thermal collectors and by the air-water heat pump. The solar thermal installation (5 m² of flat plate collectors) yearly covers 65% of the energy needs. The heat pump provides the rest. The DHW power needs for the heat pump is 1.3 [W/m² (heated floor area)] and its annual COP is 2.34 for DHW [-];
- **Heat distribution:** the heat hydraulic distribution network (radiators) is renovated;
- **Photovoltaic systems:** part of the electricity consumption of the building is provided by the on-site PV installation. It comprises 10 m² of monocrystalline panels mounted on the slanted roof (1kWp). It produces 1'288 kWh of electricity yearly. The remaining electricity needs are covered by the grid;
- **Ventilation:** Double flow (AHU) with steel channels, external heated air flow 0.3 m³/(m²h);

- **Sanitary and electrical systems** are not renovated.

8.5. Operational energy consumption

In order to calculate the energy saved and the corresponding environmental impacts reduction due to the energy related renovation measures, Tables 12 and 13 presents the energy needs before and after renovation:

Table 12 Operational energy consumption before renovation

	Energy needs [kWh/an]	Energy carrier	Cover [%]	Efficiency [%]
Heating	29'588	Light fuel oil	100	90
Domestic hot water	1'912	Light fuel oil	100	90
Lighting	1'939	Electricity	100	100
Electrical equipment	920	Electricity	100	100

Table 13 Operational energy consumption after renovation

<table>
<tr><th></th><th>Energy needs [kWh/an]</th><th>Energy carrier</th><th>Cover [%]</th><th>Efficiency [%]</th></tr>
<tr><td>Heating</td><td>7'598</td><td>Electricity</td><td>100</td><td>203</td></tr>
<tr><td rowspan="2">Domestic hot water</td><td rowspan="2">1'912</td><td>Electricity</td><td>35</td><td>234</td></tr>
<tr><td>Solar thermal panels</td><td>65</td><td>-</td></tr>
<tr><td>Lighting</td><td>1'939</td><td>Electricity</td><td>66[1]</td><td>100</td></tr>
<tr><td>Electrical equipment</td><td>920</td><td>Electricity</td><td>30[2]</td><td>100</td></tr>
<tr><td>Ventilation</td><td>740</td><td>Electricity</td><td>100</td><td>100</td></tr>
</table>

1,2 : The PV system covers the rest.

8.6. Primary energy and carbon emissions conversion factors

In order to make the results better comparable, the electricity taken into account in this case study is the low voltage UCTE mix, rather than to take the national low voltage for each country. The following table presents the impact values for UCTE electricity at plug kWh.

Table 14 Primary energy and carbon emissions LCA-based conversion factors used in the inter-comparison exercise (UCTE electricity mix)

	Non-renewable primary energy [MJ/kWh]	Total primary energy [MJ/kWh]	Carbon emissions [kg CO_2-eq/kWh]
Heating	11.95	12.74	0.595

9. Appendix 3: Integrated Performance View (IPV) template

The template of the IPV is presented below for the specific case of a renovated Swiss building with the LCA and LCC results before and after renovation. It has to be noticed that this template can only be used to report a final assessment and is not able to handle a comparison of different renovation scenarios.

Les Charpentiers

Location:	Morges, Switzerland	**Gross floor area (before/after):**	4'280 / 4'836	[m^2]
Construction/Renovation:	1965 / 2010	**Forme factor (after):**	0.71	[-]
Building type:	Multifamiliy house	**Heating / cooling degree day:**	2392/0	[°d]
Building structure:	Reinforced concrete	**More information:**	SFOE report	

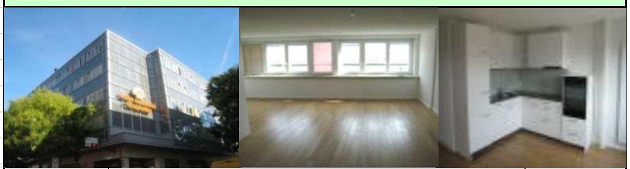
Before renovation			After renovation		
					
Construction elements	**Description (energy related)**	**U-value [W/(m^2 K)]**	**Construction elements**	**Description (energy related)**	**U-value [W/(m^2 K)]**
Roof	Unheated attic	3.5	**Roof**	Mineral wool 160 mm / Mineral wool 300 mm	0.21/ 0.13
Facade	Concret + Plaster	1.2	**Facade**	Concret 200 mm + Mineral wool 180 mm + GAP module	0.17
Glazing/Frame	Double glazing / wood frame	2.9 / 1.3	**Glazing/Frame**	Triple glazing / PVC frame	0.70 / 0.72
Floor	Plaster 50 mm + Mineral wool 20mm + Concret	1.11	**Floor**	Plaster 50 mm + Mineral wool 20mm + Concret	1.11
BITS	**Description**	**Final energy [kWk/(m^2 y)]**	**BITS**	**Description**	**Final energy [kWh/(m^2 y)]**
Heating	Gas boiler	124	**Heating**	Gas boiler 110 kW + CHP 12 kWth and 5 kWel	9.2
DHW	Gas boiler	27.2	**DHW**	Gas boiler 110 kW + CHP 12 kWth and 5 kWel	14.4
Cooling	-	-	**Cooling**	-	-
Auxiliaries	Distribution pumps	1.8	**Auxiliaries**	Distribution pumps	2.3
Lighting	Fluocompact	0.7	**Lighting**	LED	0.4
Ventilation	Air extraction system	0.4	**Ventilation**	Mechanical ventilation heat recovery MVHR	1.7
(Common appl.)	Lift + laundry	1.9	**(Common appl.)**	Lift + laundry	2.3
	Total	**156**		**Total**	**30.3**
Comments	The last attic floor was added in the 80th. On South and East facades were balconies.		**Comments**	The facade's renovation is made of a prefabricated elements (Gap solution) placed in front of the balconies. Thus there is no more thermal bridge and the total gross heated floor area increases of 14%.	

Figure 29 IPV template filled in for the specific case of reporting the building description building before and after renovation: example of “Les Charpentiers”[46]

[46] A building renovation case study from Switzerland presented in the report “Shining Examples of Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)” available online: http://www.iea-annex56.org/Groups/GroupItemID87/BROCHURE_2.pdf

LCCA methodology:	Annex 56 (IEA)	**Annual interest rate:**	3%
Reference study period:	60 years	**Increase energy rate:**	0%
Main data source(s):	Construction companies (LCCA)		

Life cycle cost assessment (LCCA)

Component / Energy consumption				Investment cost		Investment cost [€/m²-GFA]	Annual cost [€/m²-GFA/y] Ref.	Annual cost [€/m²-GFA/y] Renov.
BITS	Heating			793'372	€	164.06		8.37
	DHW			820'023	€	169.57		8.65
	Cooling				€	0.00		0.00
	Auxiliaries				€	0.00		0.00
	Lighting			448'816	€	92.81		4.16
	Ventilation			220'674	€	45.63		3.07
	Common appl.			148'598	€	30.73		2.07
Envelope	Roof	1099	m²	344	€/m²-element	78.18		2.80
	Facade	1235	m²	472	€/m²-element	120.54		5.70
	Win.	699	m²	960	€/m²-element	138.76		5.37
	Floor	169	m²	344	€/m²-element	12.02		0.89
Energy consumption	Heating						12.94	0.96
	DHW						2.83	1.50
	Cooling						-	-
	Electricity (misc.)						0.80	1.20
					Total	**852**	**16.57**	**44.74**

LCIA methodology:	Annex 56 (IEA)
Reference study period:	60 years
Main data source(s):	Ecoinvent v2.2 (LCIA)

Life cycle impact assessment (LCIA)

Material / Energy consumption				Final energy [kWh/(m² y)] Ref.	Final energy Renov.	GWP [kg-eq CO_2/(m² y)] Ref.	GWP Renov.	PE_{NRE} [kWh/(m² y)] Ref.	PE_{NRE} Renov.	PE_{Total} [kWh/(m² y)] Ref.	PE_{Total} Renov.
BITS	Heating						0.09		0.42		0.43
	DHW						0.14		0.65		0.68
	Cooling						-		-		-
	Auxiliaries						-		-		-
	Lighting						-		-		-
	Ventilation						0.27		1.21		1.29
	Common appl.						-		-		-
Envelope	Roof	1099	m²				0.35		1.3		1.4
	Facade	1235	m²				0.39		1.8		3.5
	Win.	699	m²				0.96		4.3		4.5
	Floor	169	m²				0.10		0.4		0.9
Energy consumption	Heating			124	9	29.4	2.2	138.3	10.3	138.8	10.3
	DHW			27	14	6.5	3.4	30.3	16.1	30.4	16.1
	Cooling			-	-	-	-	-	-	-	-
	Electricity (misc.)			4.7	6.6	0.7	1.0	12.4	17.4	14.3	20.2
			Total	**156**	**30**	**37**	**9**	**181**	**54**	**184**	**59**

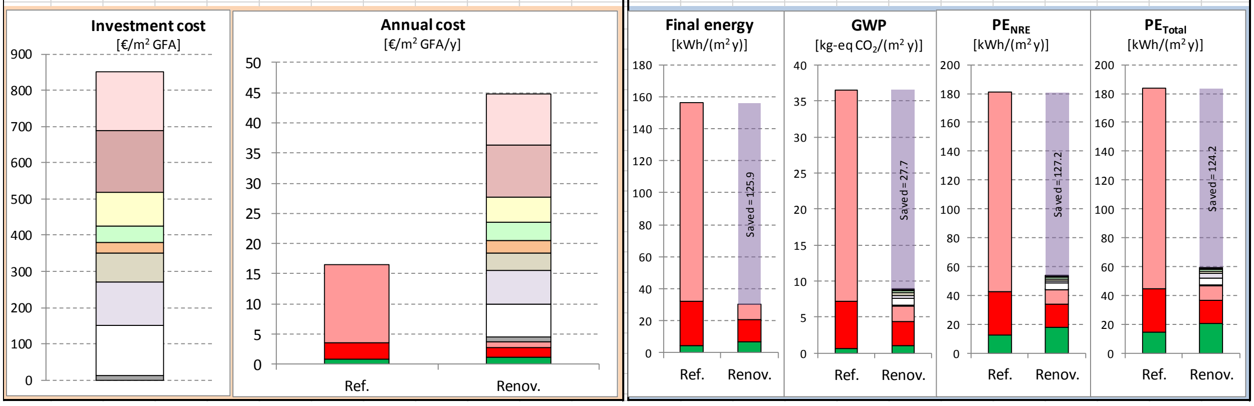


Figure 30 IPV template filled in for the specific case of reporting the LCA and LCC results of a building before and after renovation: example of “Les Charpentiers”[47]

47 A building renovation case study from Switzerland presented in the report “Shining Examples of Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)” available online: http://www.iea-annex56.org/Groups/GroupItemID87/BROCHURE_2.pdf

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