Energy in Buildings and Communities Programme

International Energy Agency

Evaluation of the impact and relevance of different energy related renovation measures on selected Case Studies

(Annex 56)

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March 2017

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

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Authors of Report on Case Studies

David Venus and Karl Höfler, AEE – Institute for Sustainable Technologies, Austria

Authors of Co-benefits parts in the report

Manuela Almeida, Marco Ferreira and Ana Rodrigues, University of Minho – Civil Engineering Department, Guimarães, Portugal

Authors of parametric generic calculations parts in the report

Roman Bolliger and Walter Ott, econcept AG, Switzerland

Authors of chapter "Challenges to reach nearly zero energy and nearly zero emissions"

Ove C. Mørck, Cenergia, Denmark and Iben Østergaard, Technological Institute, Denmark

Authors of Case Studies

David Venus, Karl Höfler, Julia Maydl (AT) Jiří Sedlák, Petr Jelínek, Karel Struhala (CZ), Ove Christen Mørck, Iben Østergaard, Kirsten Engelund Thomsen, Jørgen Rose, Søren Østergaard Jensen (DK), Manuela Almeida, Marco Ferreira, Nelson Brito (PT), Ana Sánchez-Ostiz, Silvia Domingo-Irigoyen (ES), Åke Blomsterberg, Rikard Nilsson (SE)

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www.iea-ebc.org
essu@iea-ebc.org

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 28 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 research and development in a number of areas related to energy. 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: Inhabitant 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 Ventilating Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)

Annex 21: Environmental Performance of Buildings (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multizone Air Flow Modelling (*)
Annex 24: Heat, Air and Moisture Transport in Insulated Envelope Parts (*)
Annex 25: Real time HEVAC 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: Control Strategies for Hybrid Ventilation in New and Retorfitted Office Buildings (HybVent) (*)
Annex 36: Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures (*)
Annex 37: Low Exergy Systems for Heating and Cooling (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Thermal Insulation (*)
Annex 40: Commissioning of buildings HVAC Systems for Improved Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy-Efficient Future Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
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 (NZEBs)
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
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: Optimised Performance of Energy Supply Systems with Energy Principles
Annex 65: Long-Term Performance of Super-Insulation in Building Components & 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: Building Energy Epidemiology
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

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, as described in the Energy Performance of Buildings Directive[1]. However, these standards are mainly focused on new buildings neglecting, most of the time, the existing ones that represent the least efficient, the largest consumers and the largest share of the building stock.

The IEA EBC Annex 56 project «Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation» intends to develop a new methodology for cost-effective renovation of existing buildings, using the right balance between the energy conservation and efficiency measures on one side and the measures and technologies that promote the use of renewable energy on the other side. It aims to provide a calculation basis for future standards, which aims at maximizing effects on reducing carbon emissions and primary energy use in building renovation. The project pays special attention to cost-effective energy related renovation of existing residential buildings and low-tech office buildings (without air conditioning systems). Apart from including operational energy use, also the impact of including embodied energy is investigated in the project.

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.

To promote energy efficient buildings, with low energy consumption and energy generation on-site, innovative renovation projects are needed that can act as forerunners and inspiration but also serve as best practice examples for the expert audience and the general public.

Within this project six different Case Studies from six European countries were compiled and analyzed (see Table 1). The Case Studies are both residential and non-residential buildings, which serve as model projects for renovations in each individual country. The specific aim of the case study activity of this project is to provide significant and useful feedback from practice on a scientific basis.

1 Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

Table 1: Overview of the investigated Case Studies

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	2,845 m²
Czech Republic			Kamínky 5, Brno	Elementary School	1987	2009 – 2010	9,909 m²
Denmark			Traneparken, Hvalsø	Multi-family Building	1969	2011-2012	5,293 m³
Portugal			Neighborhood RDL, Porto	Two-family Building	1953	2012	123 m²
Spain			Lourdes Neighborhood, Tudela	Multi-family Building	1970	2011	1,474 m²
Sweden			Backa röd, Gothenburg	Multi-family Building	1971	2009	1,357 m²

The assessment of the Case Studies was performed according to the methodology developed within this project[2], including Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and the evaluation of the co-benefits. Main issues are primary energy use and related carbon emissions of such buildings as well as the costs incurred by investments in energy related renovation measures and in building use during the estimated life cycle period, including also the embodied energy of the materials added to improve the energy efficiency of the building.

The impacts of the different renovation packages are illustrated with the help of graphs depicting primary energy use or carbon emissions on the x-axis and costs on the y-axis. Primary energy use, carbon emissions and costs are considered on a yearly and per m² basis. The principle of these graphs is shown in the following Figure 1.

2 see Ott, W. et al. (2015): "Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)", see http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf

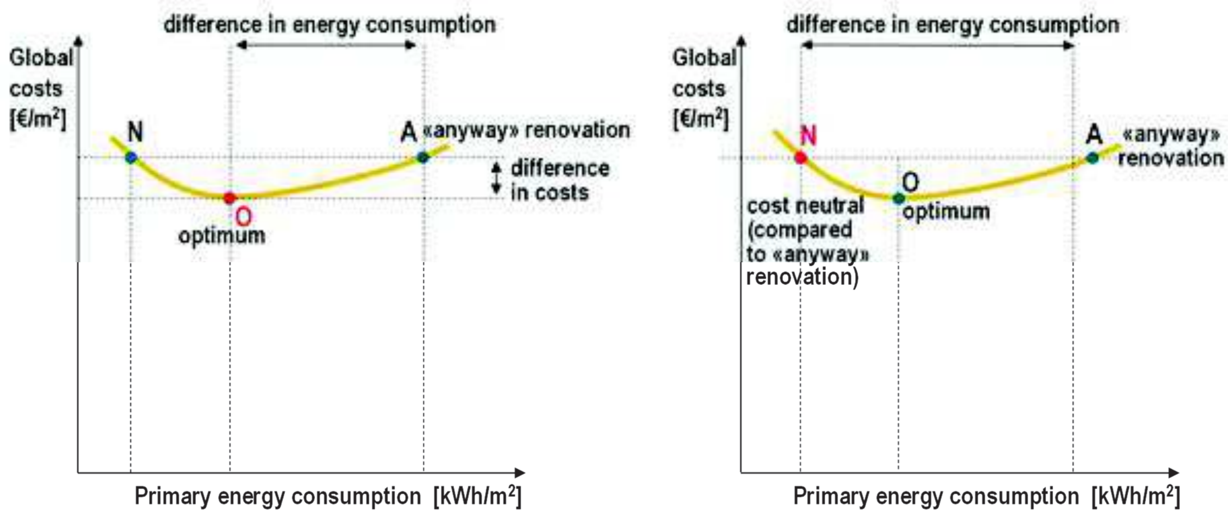


Figure 1: Global cost curve after renovation, starting from the reference case A («anyway renovation») towards renovation options with less primary energy use than in the case of the anyway renovation. Costs comprise annual capital costs, energy costs, as well as operation and maintenance costs. O represents the cost optimal renovation option. N represents the cost neutral renovation option with the highest reduction of primary energy. Renovation options on this curve between A and N are all cost-effective. (BPIE 2010, p. 15, supplemented by econcept).

Objectives

The main objectives of this work are:

- To test the theoretically developed methodology with practical experiences within realized renovations in order to identify possible inconsistencies and providing feedback to refine the methodology;
- To reach an in-depth understanding of the performance of some selected case studies in order to increase the general understanding of the performance of technologies when applied in practice;
- To understand barriers and constraints for high performance renovations by a thorough analysis of case studies and feedback from practice in order to identify and show measures on how to overcome them;
- To support decision-makers and experts with profound, science based information (as a result of thoroughly analyzed case-studies) for their future decisions;
- To show successful renovation projects in order to motivate decision-makers and stimulate the market towards more ambitious renovations.

Parametric calculations

In addition to the actual renovation carried out for the individual projects each Case Study also describes and tests several alternative renovation packages with sets of measures regarding:

- **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
- **Energy sources for heating, cooling and domestic hot water production**
- **RES (renewable energy sources) generation on-site** – measures for the renewable energy generation on-site, e.g. solar thermal installation or photovoltaic modules

The renovation measures range from minimum and average renovation measures to high performance, comprehensive measures. The definition of the investigated packages was up to each country and was performed according to what is feasible in each country. Therefore the investigated packages differ from country to country and many differences between the building standards and the climates in each country exist too. Variations of different energy sources for heating and domestic hot water were also considered to evaluate the influence of the energy source on the total results.

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, establishing also the limit of the cost-effectiveness.

The reference case should include only renovation measures which have to be carried out anyway. Therefore this reference case can also be named “anyway renovation”. Renovation measures included in this package could be the repainting of windows or outside walls or a roof sealing.

As previously mentioned, the assessment of all renovation packages was performed according to the methodology developed within this project, including Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and the co-benefits. Main issues are primary energy use and related carbon emissions of such buildings, including the energy demand for heating, domestic hot water and electricity, as well as also the embodied energy of the materials added to improve the energy efficiency of the building.

This report gives an overview of the defined renovation packages and the calculation results of the six Case Studies. The main results of the investigations are presented on the next pages. The analyzed parameters were the carbon emissions, referring to greenhouse gases, expressed in kgCO_2-eq, the total Primary Energy, which represents the total primary energy used, including the non-renewable part as well as the renewable part, expressed in kWh and the Life Cycle Costs, including investment costs, maintenance costs and energy costs, expressed in EUR.

Carbon emissions reductions

Figure 2 shows the carbon emissions reduction potentials of the six Case Studies. The reduction potentials are shown as absolute values (yellow columns) and as relative reduction potentials (orange columns). The filled parts of the columns represent the minimum reduction, which can be achieved independently of the chosen renovation package (henceforth called "minimum reduction"). The arrows indicate the ranges between the lowest and the highest possible reduction potentials. The hatched columns stand for the lowest carbon emissions which can be achieved by the renovation packages.

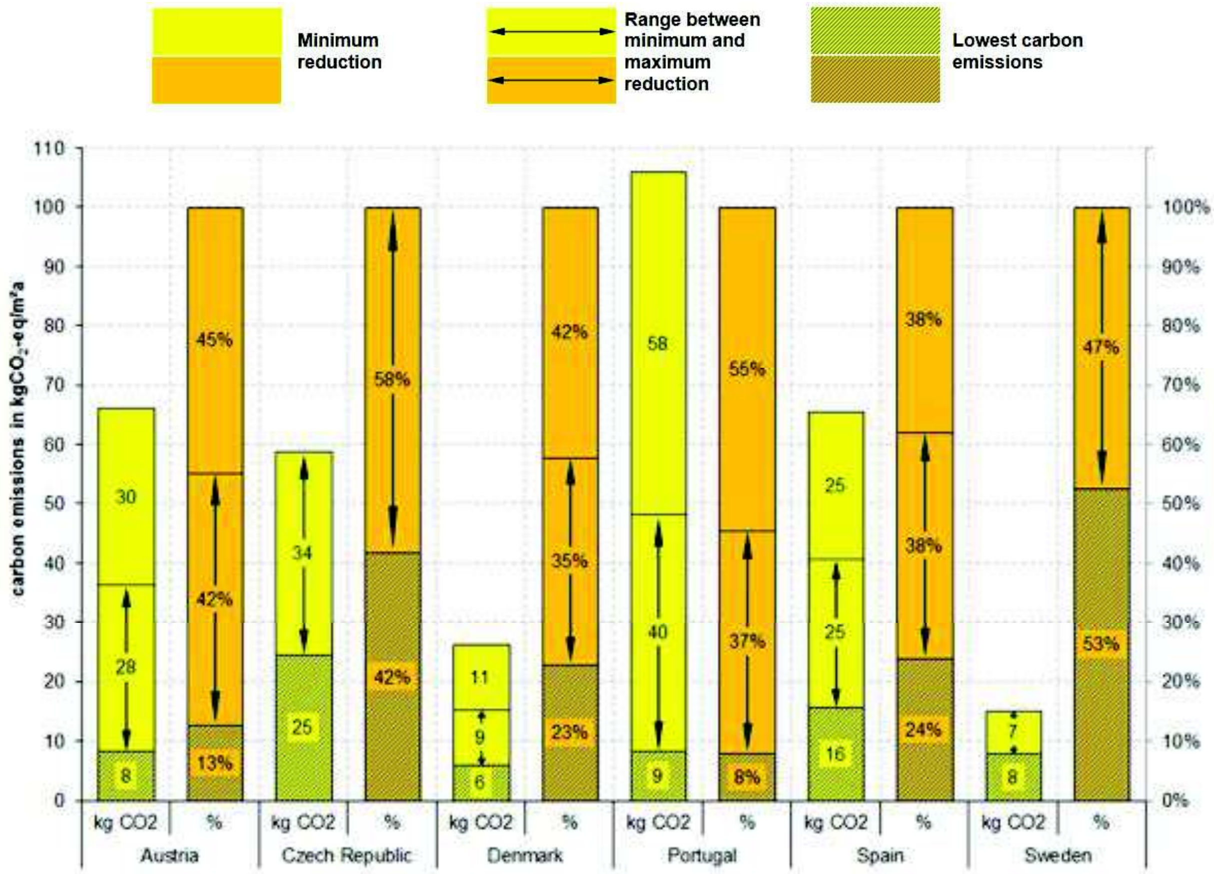


Figure 2: Carbon emissions reduction potential of the six Case Studies. The absolute (yellow columns) and the relative reduction potentials (orange columns) are presented as minimum reduction and also as range between the minimum and maximum reduction, compared with the anyway renovation of each building. The hatched columns represent the lowest possible carbon emissions.

The chart shows that the Portuguese Case Study achieves the highest minimum reduction of all investigated buildings with a value of 58 $kgCO_2$-eq/m²a and also the highest possible savings with 98 $kgCO_2$-eq/m²a, which is a reduction of 92% compared to the reference case. To achieve this high relative reduction a combination of both, improving the energy performance of the building envelope and the change of the energy source for heating and domestic hot water production is necessary.

The Danish Case Study shows the smallest absolute reduction potential with values between 11 $kgCO_2$-eq/m²a and 20 $kgCO_2$-eq/m²a. The reason for that low absolute reduction is the quite low carbon emissions of the reference case, which is similarly true also in Sweden. However looking at the relative reduction potential the values are high and range between 42% and 77% reduction, which is a result of the energy related renovation measures on the building envelope.

In the Spanish Case Study similar results are achieved as in Austria. The absolute savings potential ranges between 25 $kgCO_2$-eq/m²a and 50 $kgCO_2$-eq/m²a which is a reduction of 38% to 76% compared to the reference case. In the Austrian and the Spanish case the high carbon emissions of the reference case lead to those high reductions.

For the Swedish and the Czech Case Studies no minimum reduction is given due to the fact that some of the investigated renovation packages lead to an increase of the carbon emissions, compared to the reference case. That means the reduction potentials range between 0 $kgCO_2$-eq/m²a and 34 $kgCO_2$-eq/m²a (Czech Republic) respectively 7 $kgCO_2$-eq/m²a (Sweden). Compared to the reference case these are reductions of up to 58% in the Czech case and up to 47% in the Swedish case.

In addition to the carbon emissions reductions the analysis of the corresponding Life Cycle Costs is shown in Figure 3. The chart demonstrates the possible LCC reductions, when bringing the carbon emissions to the lowest value. This means for each Case Study the LCC of the renovation package with the lowest annual carbon emissions was compared to the LCC of the individual reference cases. The filled columns represent the LCC reductions, the hatched columns represent the LCC of the renovation package with the lowest carbon emissions.

The analysis shows that the LCC can be reduced from 2 EUR/m²a in the Austrian Case Study up to 17 EUR/m²a in the Portuguese Case Study (in the Danish and Swedish Case Studies no reduction of the LCC is given, therefore no value is shown for these two countries in Figure 3). In relative values these are reductions of 6% in Austria and 22% in Portugal. The reasons for the low reduction in Austria are the quite low LCC of the reference case and much more important the high investment costs of the executed renovation due to the prefabricated façade and the large photovoltaic and solar thermal installations. Therefore the LCC of the Austrian Case Study are higher than they would be without the prefabrication and the RES generation on-site.

In Czech Republic and Spain the relative reductions are even higher than in Portugal. In the Czech Case Study the relative reduction is 46% and in the Spanish Case Study 39%, always compared to the reference cases.

In the Danish and the Swedish case, the reference case corresponds to the cost optimal solution. The investigated energy renovations decrease the carbon emissions and primary energy use, but are not profitable for the building owners. In the Danish Case Study the reason for this is that the energy demand and the LCC of the existing building are already quite low. The Danish and Swedish buildings nevertheless underwent an extensive energy renovation because the façades were worn down and the external concrete walls were weakened by deterioration. The obtained co-benefits were also an argument for the extensive energy renovation. The costs weren´t the driving force of the renovation, instead attractive flats in a safe and green environment was the main focus. The Swedish renovation was a pilot project to gain knowledge on prerequisites, problems and solutions regarding technology, economy and the experience of the residents from a major renovation.

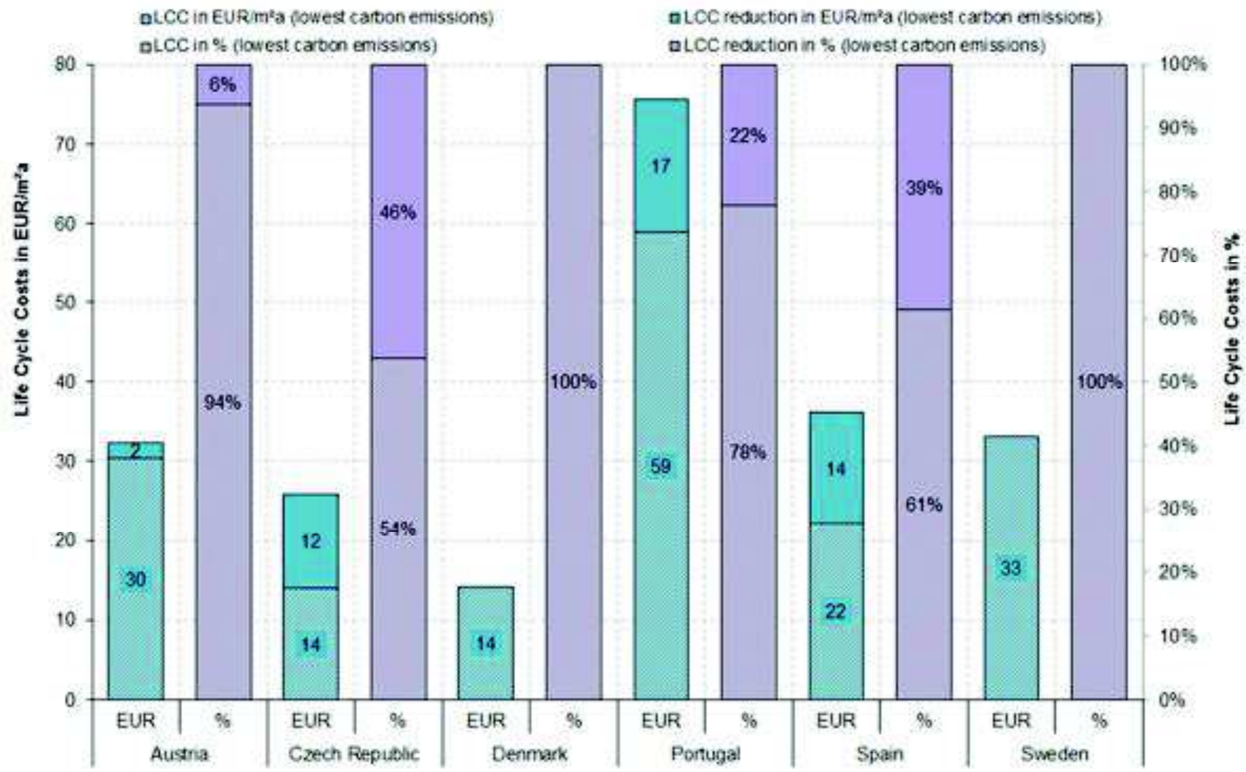


Figure 3: Life Cycle Cost reduction potentials of the six Case Studies. The absolute reduction potential (blue column) and the relative reduction potential (purple column) are presented as values between the reference case and the renovation package which achieves the highest carbon emissions reductions.

Total Primary Energy reductions

Similar to the analysis of the carbon emissions reduction potentials in Figure 2, the total Primary Energy reduction potentials of the six Case Studies are shown in Figure 4. Again the absolute values (yellow columns) and the relative reduction potentials (orange columns) are presented for each Case Study. The filled parts of the columns represent the reduction, which can be at least achieved, independently of the chosen renovation package (here, too, called "minimum reduction"). The arrows indicate the ranges between the lowest and the highest possible reduction potentials. The top of each column stands for the highest possible total Primary Energy reduction. The hatched columns stand for the lowest total Primary Energy which can be achieved by the renovation packages.

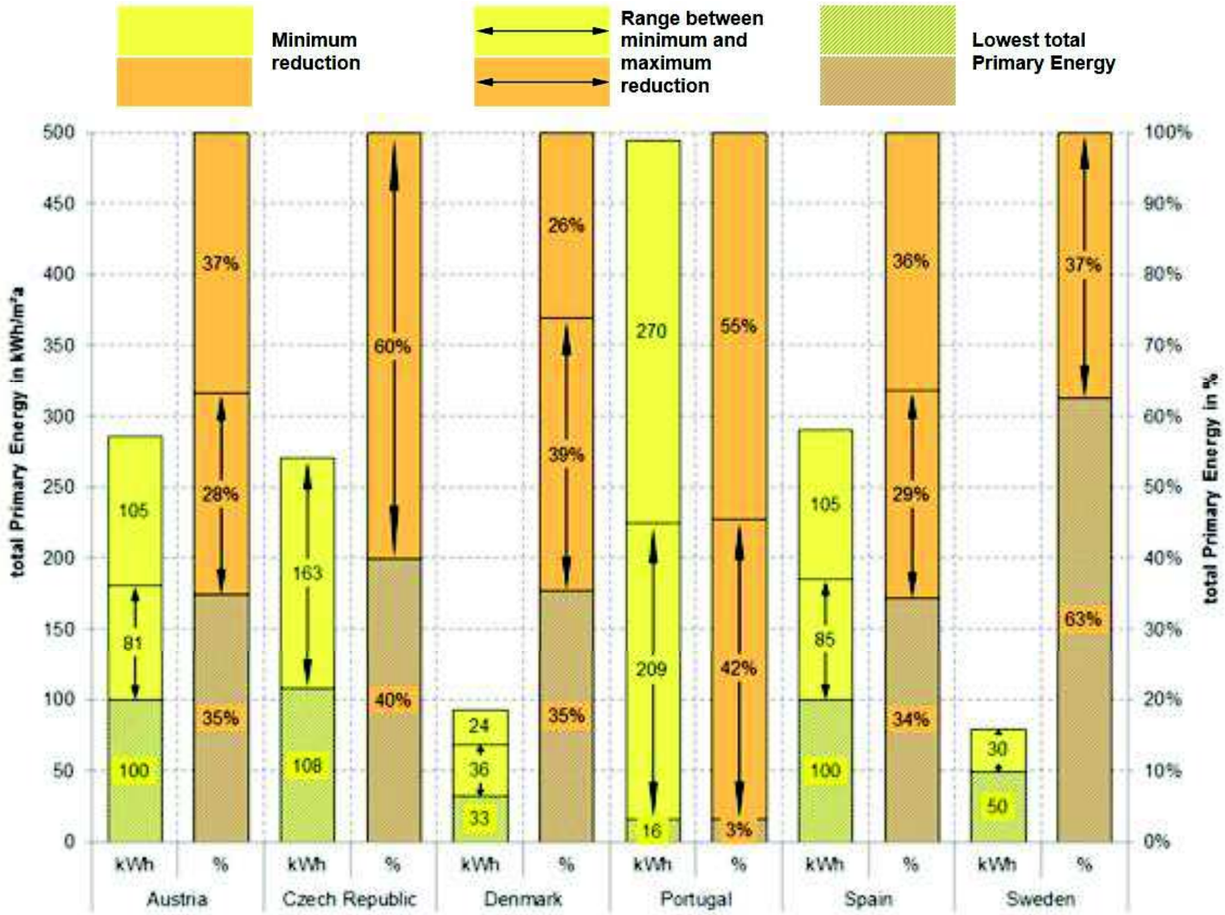


Figure 4: Total Primary Energy reduction potential of the six Case Studies. The absolute (yellow columns) and the relative reduction potentials (orange columns) are presented as minimum reduction and also as range between the minimum and maximum reduction, compared with the anyway renovation of each building. The hatched columns represent the lowest possible total Primary Energy.

The chart shows that the Portuguese Case Study achieves the highest reduction potentials (of all investigated buildings) with at least 270 kWh/m²a up to 479 kWh/m²a. In relative numbers this is a reduction of 55% to 97% compared to the Portuguese reference case. The reasons for this significant reduction potential are the very high total Primary Energy of the reference case and the combination of the thermal insulation of the building envelope and the switch of the energy source to a multi-split air conditioner for heating and cooling and solar thermal panels backed up by electric heater for DHW. The highest reductions are possible when improving the thermal envelope and changing to heat pump supply.

The results in Austria and Spain are again quite similar. The absolute reduction potentials range between 105 kWh/m²a and 186 kWh/m²a in Austria, in Spain between 105 kWh/m²a and 190 kWh/m²a. In relative terms in Austria and Spain reductions between 36% and 65%, compared to the individual reference cases, can be achieved.

65% reduction can be also achieved in the Danish Case Study, even if the absolute reductions are smaller (between 24 kWh/m²a and 60 kWh/m²a) due to the lower total Primary Energy demand of the Danish reference case.

For the Swedish and the Czech Case Studies no minimum reduction is given due to the fact that some of the investigated renovation packages lead to an increase of the Primary Energy, compared to the reference case. Therefore the reduction potentials range between 0 kWh/m²a and 163 kWh/m²a (Czech Republic) and 30 kWh/m²a (Sweden). Compared to the reference cases these are reductions of up to 60% in the Czech case and up to 37% in the Swedish case. This also means that in the Czech and Swedish Case Studies high relative reductions of the total Primary Energy are possible but the investigation showed that the renovation measures can also lead to an increase of the total Primary Energy and therefore not always to a reduction.

Figure 5 shows the LCC reduction potentials when reducing the total Primary Energy to the minimum. For each Case Study the LCC of the specific renovation package, which achieves the lowest total Primary Energy, was compared to the individual reference cases. The reductions are shown as absolute values in EUR/m²a and also as relative reductions (in %).

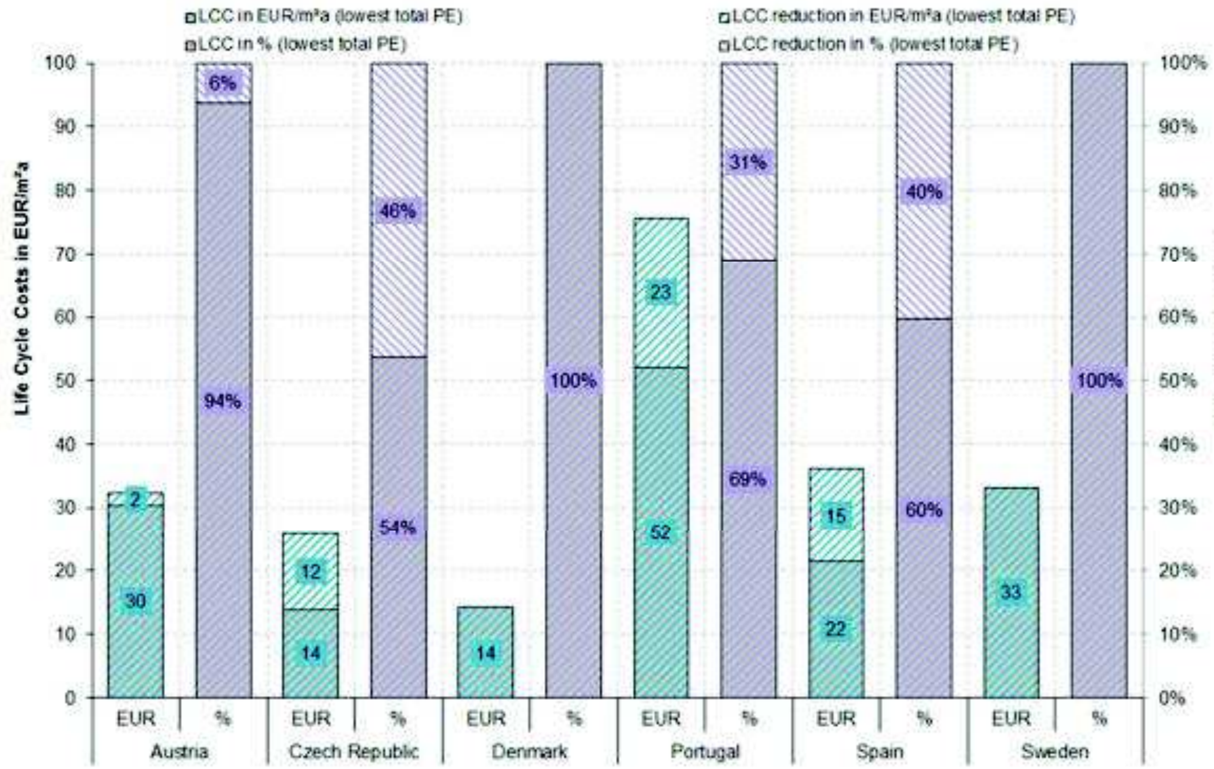


Figure 5: Life Cycle Costs reduction potentials of the six Case Studies. The absolute reduction potentials (blue columns) and the relative reduction potentials (purple columns) are presented as values between the reference case and the renovation package which achieves the lowest total Primary Energy.

The analysis shows that the LCC can be reduced from 2 EUR/m²a in the Austrian Case Study up to 23 EUR/m²a in the Portuguese Case Study (again no values for the Danish and the Swedish Case Studies because for these two buildings no reductions of the LCC were given). In relative value these are reductions of 6% in Austria to 31% in Portugal. The reasons for the low reduction in Austria are the quite low LCC of the reference case and much more important the high investment costs of the executed renovation package v3, due to the prefabricated façade and the photovoltaic and solar thermal installations.

Reducing the total Primary Energy in the Czech Case Study to the lowest possible level also reduces the Life Cycle Costs considerably. The absolute reduction is quite small at a first glance, with a value of 12 EUR/m²a, but compared to the LCC of the reference case the relative reduction is 46%. Reasons for this reduction are the combination of the thermal insulation of the building envelope and the switch to gas heating. In general all investigated renovation packages with heating and domestic hot water production based on natural gas achieve similar LCC results and savings. The photovoltaic installation could further reduce the Life Cycle Costs.

Investigation and confirmation of hypotheses

Based on the defined renovation packages deeper analyses of the influence of the different renovation measures on the Life Cycle Costs, carbon emissions and total Primary Energy were performed. The goal was to test the coherence between renovation measures on the building envelope, the switch of the energy source from non-renewable sources to renewable sources as well as combinations of both.

For each of the residential buildings of the Case Studies the hypotheses investigated also for the generic calculations in this project were tested[3]. The hypotheses are:

1. **The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.**
2. **A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.**
3. **A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.**
4. **Synergies are achieved when a switch to RES is combined with energy efficiency measures.**
5. **To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.**

At this point the confirmation of the hypotheses for the Case Studies is summarized and shown in following Table 2, with following key: ✓ means that the hypothesis is confirmed, ✗ means that the hypothesis is not confirmed. Symbols in parenthesis or separated by a slash indicate that the hypothesis is only partly confirmed / not confirmed.

3 For the Case Study from the Czech Republic, the small number of renovation packages that was available didn't allow the test of the hypotheses.

Table 2: Results for the investigated hypotheses for the five residential buildings of the Case Studies

Hypothesis	Austria	Denmark	Portugal	Spain	Sweden
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.	✓	✓	(✓)	✗	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.	✓	✓	✓	(✓)	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.	✓	(✓)	✓	✓	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures.	✓	✗	✓	✓	✓/✗
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓	✓	(✓)	✓/✗	✓

The hypothesis ***"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements."*** could be completely confirmed for Austria and Denmark and partially for Portugal. In Portugal this hypothesis was only confirmed for the renovation measures roof and wall but not for the remaining measures on the building envelope. For the Spanish and the Swedish Case Study this hypothesis was not confirmed.

The hypothesis ***"A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements."*** was confirmed in all five countries, with limitations in the Spanish Case Study where the hypothesis was confirmed for the switch to district heating with 75% biomass or to biomass heating system, yet not for a switch to heat pump.

The hypothesis ***"A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level."*** is completely confirmed for the Austrian, the Portuguese and the Spanish Case Study and confirmed with limitations in Denmark and Sweden. In the Danish Case Study for example the reference case or simply a switch to a different heating system, without energy efficiency measures, is the cost optimum renovation. All investigated energy related renovation measures lead to an increase of the annual Life Cycle Costs. In the Swedish case, the cost-optimum was not changed by a combination of energy efficiency measures with RES measures. However, it can to be noted that in the case of an oil heating system, renovation measures beyond the cost optimum are similarly cost-effective as the cost optimum, whereas for district heating and the RES based heating systems investigated, additional renovation measures on the building envelope beyond the cost optimum make the renovation significantly less cost-effective.

The hypothesis ***"Synergies are achieved when a switch to RES is combined with energy efficiency measures."*** is confirmed in Austria, Portugal and Spain. In Denmark this hypothesis is disproved. The results showed that it is more cost efficient to use district heating or heat pump and not carrying out further energy related renovation measures on the building envelope. In Sweden the hypothesis can be partly confirmed for the insulation of the exterior wall in combination with the change to district heating based on RES. The hypothesis however is disproved for all remaining renovation measures in combination with district heating based on RES and also for all combinations with a pellets heating system.

The hypothesis ***"To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone."*** is completely confirmed in Austria, Denmark and Sweden. In Portugal and Spain limitations exist. The Spanish Case Study shows a confirmation for the district heating system with 75% biomass and the biomass heating system, yet not for a heat pump. In Portugal it is in general difficult to answer this hypothesis. In fact it cannot clearly be answered. It is more likely to be confirmed but a hundred per cent confirmation is not possible.

Main findings from the generic parametric calculations[4]

In all investigated generic buildings investigated there is a cost optimum, with lower costs than those of an «anyway renovation». Costs are rising for measures going beyond the cost optimum, but many or sometimes all of the measures considered in the assessment are still cost-effective, i.e. lower than the cost of the anyway renovation.

With respect to the energy performance of energy related building renovation measures and the balance between renewable energy deployment and energy efficiency measures, the five main hypotheses have also been investigated. Within this context, some tentative conclusions are made referring to renewable energy sources (RES) in general. However, it is important to note that only specific RES systems were taken into account in the generic calculations. For example the role of solar thermal or small wind turbines has not been investigated and not all types of renewable energy systems were investigated for all reference buildings. In the case of the countries Austria, Denmark, Spain and Sweden, geothermal heat pumps and wood pellet heating systems have been investigated as RES systems; in the case of Portugal an air-water heat pump and its combination with PV were investigated as RES systems. The related findings obtained

4 Taken from the report: "Investigation based on calculations with generic buildings and case studies" (Bolliger and Ott, 2015)

from the parametric calculations with the investigated generic buildings are summarized in the following Table 3.

Table 3: Results for the investigated hypotheses for the generic multi-family buildings

Hypothesis	Austria	Denmark	Portugal	Spain	Sweden
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.	✓	✓	✓	✓	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.	✓	✓	✓	✓	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.	(✓)	(✓)	✓	✓	✗
Synergies are achieved when a switch to RES is combined with energy efficiency measures.	✓	✓	✓	✓	✓
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓	✓	✓	✓	✓

The comparison of the results of the Case Studies (Table 2) with the results of the generic buildings (Table 3) shows good correlation.

Small deviations could be found:

- in Austria for the hypothesis **"A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level"**
- in Portugal for the hypotheses **"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements."** and **"To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone."**
- in Spain for the hypotheses **"A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements."** and **"To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone."**

- in Sweden for the hypothesis **“Synergies are achieved when a switch to RES is combined with energy efficiency measures.”**

In the mentioned cases the named hypotheses could be fully confirmed in the generic buildings but only confirmed with limitations in the real Case Studies (exception: in Austria it´s vice versa).

For some hypotheses however, no correlation between the Case Studies and the generic buildings is given:

- in Denmark the hypothesis **“Synergies are achieved when a switch to RES is combined with energy efficiency measures.”** was confirmed in the generic building but not confirmed in the Case Study
- in Spain the hypothesis **“The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.”** was confirmed in the generic building but not in the Case Study
- in Sweden the hypothesis **“A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.”** was partly confirmed in the Case Study but not in the generic building.

Co-benefits

Several notions are used to refer to the benefits that arise from building renovation with energy efficiency and carbon emissions reduction. In this project, the main focus is on energy, carbon emissions and costs, consequently the reduction of energy use, carbon emissions and costs are direct benefits. Though all the benefits that arise from a renovation project besides these direct benefits can be included in the notion of co-benefits, only co-benefits deriving from energy and carbon emissions related renovation measures are considered in this project.

The co-benefits that arise from energy and carbon emissions related building renovation can be independent from energy, carbon emissions and costs (e.g. less exterior noise), or can be a consequence of these (e.g. less risk of exposure to future energy price increases), and the benefits can impact at private level (e.g. increased user comfort) or/and at society level (e.g. impact on climate change or air pollution).

In this context, the notion of co-benefits refers to all benefits (positive or negative) resulting from renovation measures related to energy and carbon emissions optimized building renovation, besides or as a consequence of energy efficiency increment, carbon emissions reduction or costs reduction.

For each Case Study the co-benefits, derived from energy related renovation measures were analyzed based on the parametric calculations following the developed methodology and also, for some of the Case Studies, interviews performed among the residents of the buildings.

Following conclusions can be drawn from this analysis:

- At the building level, in the renovation of existing buildings, energy efficiency measures, when compared to measures for the use of renewable energy sources, are the main source of co-benefits, particularly those improving the building quality (reduction of problems with building physics, increase of useful building areas and improved safety against intrusion) and the resident physical wellbeing (increased thermal and acoustic comfort, increased use of daylighting and better indoor air quality).
- To maximize the co-benefits from energy related building renovation, it is more relevant to improve more elements of the building envelope in combination than to significantly improve single elements. As an example, the improvement of a façade with additional 20 cm of insulation instead of improving it with 10 cm of insulation will be much less relevant (from the perspective of co-benefits) than to supplement the improvement of the façade with 10 cm of insulation with the replacement of windows.
- Depending on the original condition of the building, improving all the elements of the building envelope usually means going beyond cost optimality (once the improvement of certain elements may not be cost effective in a comprehensive package of measures). Although, the difference in global costs is usually not relevant and packages of measures remain cost-effective when compared to “anyway renovation”. Furthermore, improving all the elements of the building envelope is usually the way to achieve the maximization of the added value from the co-benefits.
- At the building level, measures for the use of renewable energy sources usually have the co-benefits of reducing the exposure to energy price fluctuations. Residents with systems based on renewables (with the exception of systems based on wood pellets) are more comfortable regarding future variations on the energy prices once they are less dependent on energy from the market. Regarding their implementation, many renewable energy systems present a challenge for their integration on existing buildings. Some of these systems (e.g. photovoltaic or solar thermal) often present a challenge for their integration in the architectural characteristics of the existing buildings, while others (e.g. geothermal heat pump) present technical and often also financial challenges to be implemented. On the other hand, other systems (e.g. air/air or air/water heat pumps or wood pellets burner) are much easier to implement than most of the high efficiency measures and may allow reducing the depth of the interventions on the building envelope.

Challenges to reach nearly zero energy and nearly zero emissions

Besides the technical solutions, which are necessary to reach cost effective nearly zero energy buildings after renovation, including high reductions of carbon emissions and total Primary Energy, it is important to know the challenges that occur when trying to reach this goal and also the measures that can be taken to overcome them.

Therefore participants from following countries have been asked 13 questions on this topic: Austria, Czech Republic, Denmark, Finland, Norway, Portugal, Spain, Sweden, Switzerland and The Netherlands.

The questions asked in the interviews were divided into four main categories: information issues, technical issues, ownership issues and economic issues.

The evaluation of the barriers to reach nearly zero energy buildings can be summarized as follows:

One barrier is relevant for all countries, which is the information asymmetry of differing opinions expressed by professionals.

In 9 out of ten countries it was considered to be a barrier that there is a:

- Lack of examples and inspiration
- Lack of economic incentives or uncertainty about the incentives
- Lack of economic knowledge

In 7-8 countries the following were considered to be barriers:

- Incomplete information from the Energy Performance Certificate of Buildings
- Lack of knowledge about possibilities, potential benefits and added values
- Lack of well proven systems, total solutions and information about these
- Lack of clear requirements
- The structure of ownership (private, public, owner, tenant)
- Running costs and investment costs are separated
- Too high investment costs
- Uncertainty about the savings and calculations of saving potential

In 5-6 countries the following was considered to be a barrier:

- Building owners are not allowed to increase rent to pay for energy renovation investments (i.e. the building owner pays for the tenant´s benefits)

Recommendations

The investigations of the six Case Studies and the interviews in ten European countries allow making recommendations for cost effective renovations towards nearly zero energy and emissions in future. In the next paragraphs these recommendations are presented corresponding to their sources (parametric calculations, co-benefits analyses and interviews):

Parametric calculations

A switch to renewable energy sources reduces the carbon emissions more significantly than energy efficiency measures on one or more envelope elements. When the goal is to achieve high carbon emissions reductions, it is more cost effective to switch to renewable energy sources and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.

Synergies can be achieved when a switch to renewable energy sources is combined with energy saving measures on the building envelope.

In general, the combination of energy efficiency measures on the building envelope with measures for the use of renewable energy sources does not significantly change the cost optimal efficiency level.

Whether or not the number of building elements renovated is more important for the energy performance of the building than the efficiency level (insulation thickness) of each particular element has to be checked individually. For some buildings this might be the case, for others however not. This can depend on national standards, prices, weather conditions and other factors.

Energy efficiency measures, when compared with measures associated with the use of renewable energy sources, are the main source of co-benefits at building level.

To maximize the co-benefits associated with energy related building renovation, it is more effective to improve the performance of all the elements of the building envelope than to significantly improve the performance of just one element.

Depending on the original condition of the building, improving the performance of all the elements of the building envelope usually means going beyond cost optimality, but it is still cost-effective when compared to the “anyway renovation”, i.e. a renovation scenario where energy performance is not improved.

The calculation results within the Case Studies have shown that high carbon emissions and Primary Energy reductions are possible, where the corresponding renovation packages are also cost effective, which means that the Life Cycle Costs of the renovation packages are lower than the Life Cycle Costs of the reference case.

However, results have also shown that not all investigated renovation measures bring a reduction of carbon emissions, primary energy and/or Life Cycle Costs. Moreover higher values, compared to the reference case, were calculated in some Case Studies. Therefore a detailed look at different possible renovation measures, including the calculation of the Life Cycle Costs and the Life Cycle Assessment are necessary.

It also has to be mentioned that the assumptions made in the Life Cycle Cost calculation and the Life Cycle Assessment are very important and can influence the results a lot. Therefore these assumptions have to be well-considered and if possible a sensitivity analysis of the most important parameters should be carried out. It is advisable to consult an expert with profound knowledge in the field of Life Cycle Cost calculations and Life Cycle Assessments.

Interviews

Missing good examples for successful renovations are often the biggest barriers for renovations towards nearly zero energy and emissions. The investigated Case Studies are such good examples, but more are needed. This means that national initiatives have to be launched to promote these kinds of building renovations. One of these initiatives could be the financial support or funding programs via direct funding or via research projects. Research projects would bring the additional benefit that new, innovative measures could be tested and evaluated, which in turn would increase the technical knowledge of the building professionals and also of the building owners.

Such a campaign could also counter the lack of economic incentives or uncertainty about the incentives. This means that by launching economic incentives building owners will receive support in financing nearly zero energy and emissions buildings. This will give building professionals the opportunity to realize good building renovations without constantly having the investment costs in mind.

A further important step towards cost effective building renovations is the consideration of the whole building life cycle. That means the Life Cycle Costs of the renovation packages should be regarded over the life cycle of the building and the building element. The investment costs should not be taken as main decision criterion.

If the building owner is faced with the problem of not being allowed to increase the rent to pay for energy renovation measures, it is advisable to go for the cost optimal renovation.

Co-benefits

It is important to look at the carbon emissions and/or Primary Energy of different possible renovation measures over the whole building life cycle. The investigations should include different scenarios, to find the scope of cost effective renovation packages of measures. Within the scope of cost effective renovation scenarios, costs and co-benefits should be considered to find the solution that adds more value to the renovated building. All investigated renovation measures and packages should be compared to a reference situation, where only measures are included that have to be carried out anyway ("anyway renovation").

Table of content

Abbreviations

Abbreviations	Meaning
AT	Austria
BITS	Building integrated technical systems
CO_2-eq	Carbon dioxide equivalent
CZ	Czech Republic
DH	District heating
DHW	Domestic hot water
DK	Denmark
Eff	Heat recovery efficiency of the mechanical ventilation system
EPS	Expanded polystyrene insulation
ES	Spain
GHFA	Gross heated floor area
HP	Heat pump
HVAC	Heating, ventilation, air conditioning
kWh	Kilowatt hours
kWp	Kilowatt peak
LCC	Life Cycle Costs
LCA	Life Cycle Assessment
MVHR	Mechanical Ventilation with Heat Recovery
PE	Primary Energy
PT	Portugal
PV	Photovoltaic (cell)
RES	Renewable energy sources
SE	Sweden
SFP	Specific fan power in $kW/(m^3/s)$
U-value	Thermal transmittance of a building element in W/m^2K
WP	Wood pellets
XPS	Extruded polystyrene insulation

1. Introduction

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, as described in the Energy Performance of Buildings Directive[5]. However, these standards are mainly focused on new buildings neglecting, 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 the existing buildings stock. Renovations attempting to reach these standards often result in very expensive measures and complex procedures, hardly accepted by any owners or promoters.

The IEA-EBC Annex 56 project «Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation» intends to develop a new methodology for cost-effective renovation of existing buildings, using the right balance between the energy conservation and efficiency measures on one side and the measures and technologies that promote the use of renewable energy on the other side. It aims to provide a calculation basis for future standards, which aims at maximizing effects on reducing carbon emissions and primary energy use in building renovation. The project pays special attention to cost-effective energy related renovation of existing residential buildings and low-tech office buildings (without air conditioning systems). Apart from including operational energy use, also the impact of including embodied energy is investigated in the project.

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 than energy conservation and efficiency measures. In existing buildings, the most cost effective renovation solution is often a combination of energy efficiency measures and measures for utilizing renewable energy. Hence, it is relevant to understand the potential of energy conservation and efficiency measures (initially often less expensive measures) and from which point the use of renewables become more economical considering the local context.

To promote energy efficient buildings, with low energy consumption and energy generation on-site, innovative buildings are needed that act as forerunner and also serve as best practice examples for the expert audience and the general public.

Within this project, the gathering of case studies is one of the activities undertaken to reach the overall project objectives because it is a recognized fact that the process of decision-making has to be strongly supported by successful renovations, where comprehensive energy and

5 Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

environmental measures have been realized, i.e. with experiences and lessons learned from practice.

The assessment of the Case Studies was performed according to the methodology developed within this project[6], including Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and the co-benefits. Main issues are primary energy use and related carbon emissions of such buildings as well as the costs incurred by investments in energy related renovation measures and in building use during the estimated life cycle period. Included is also the embodied energy of the materials added to improve the energy efficiency of the building.

6 Ott, W. et al. (2015): "Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)", see http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf

2. Scope

The specific mission of the case study activity in this project is to provide significant feedback from practice on a scientific basis. The main objectives of this work are:

- To understand barriers and constraints for high performance renovations by a thorough analysis of case studies and feedback from practice in order to identify and show measures on how to overcome them;
- To test the theoretically developed methodology in this project with practical experiences within realized renovations in order to identify possible inconsistencies and providing feedback to refine the methodology;
- To reach an in-depth understanding of the performance of some selected case studies in order to increase the general understanding of the performance of technologies when applied in practice;
- To support decision-makers and experts with profound, science based information (as a result of thoroughly analyzed case-studies) for their future decisions;
- To show successful renovation projects in order to motivate decision-makers and stimulate the market towards more ambitious renovations.

Within the “Case Studies”, a deeper analysis was performed in order to evaluate the impact and relevance of different renovation measures and strategies within the project objectives and also testing the methodology of this project.

Within the international cooperation seven Case Studies were analyzed deeper. Six of them are presented in this report as well as the major challenges, findings and conclusions of these best practice examples. The seventh Case Study is the demonstration project “Montarroio” in Portugal, which is an ancient building upgrade within an UNESCO World Heritage context from 1845. Due to the rareness of this building and the investigated renovation measures it is hardly comparable to the other six Case Studies. Furthermore the renovation of the building is not finished yet. For these reasons the Case Study “Montarroio” not included in the findings and conclusion in chapter 5. Nevertheless it is also a remarkable renovation project, even though it is still in the planning stage. Therefore this Case Study can be found with the other country papers in the appendix of this report.

The report is separated in several chapters. Chapter 3 shows first of all an overview of the different Case Studies, gathered and analyzed within this project. Chapter 4 includes the framework conditions for the analysis of the six buildings. The description of the defined renovation packages, the reference case in each country and the main results and conclusions can be found in chapter 5. In chapter 6 the identified challenges are explained together with suggested future research and finally chapter 7 presents recommendations for future renovations. The appendix of this report includes each country paper on the Case Studies.

3. Overview of Case Studies

Table 4 on the next page shows an overview of the six analyzed Case Studies in Austria, Czech Republic, Denmark, Portugal, Spain and Sweden. The evaluated buildings are all 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 9,900 m². These building characteristics, together with the country-specific influencing factors, ensure a quite broad overview and application of the methodology for the investigation of the cost effective energy and carbon emission optimized renovation based on Life Cycle Costs and Life Cycle Assessment.

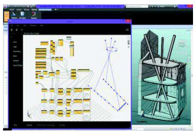
All six Case Studies have been renovated in the past years and the main reasons for the renovations were maintenance, improvement of standard and the energy efficiency of the building. Furthermore this means that the performed calculations and analyses in chapter 5 serve mainly as comparisons between the actual renovation carried out and theoretical renovation packages, which would also have been possible to apply. In this case the investigations in this report do not support the real planning of the building renovations.

A seventh Case Study is undergoing renovation in 2015: located within an UNESCO World Heritage context in Coimbra, Portugal, and thus subjected to very stringent regulations, the final solution is still being negotiated. The Case Study "Montarroio" is a single-family house that aims to demonstrate alternative ways to include ancient buildings as active players in energy efficiency and sustainable practices, with a special focus on the importance of a good initial assessment. Due to the uniqueness of this building and the investigated renovation measures it is hardly comparable to the other six Case Studies and therefore not included in the findings and conclusions in chapter 5. Nevertheless it is also a remarkable renovation project, even though it is still in the planning stage, which should be presented. Therefore this special Case Study can be found with the other country papers in the appendix of this report.

Following Table 4 shows some impressions of the Case Studies before and after the renovation together with some relevant information about the buildings. More information on the Case Studies can be obtained from:

- Individual Case Studies chapters (pages referenced in the first column of Table 4) including a short description of the investigated renovation packages and the reference renovations, the results and the conclusions of the calculations.
- Descriptions of the Case Studies in the country papers in the appendices.

Table 4: Overview of the analyzed Case Studies

Country	Before	After	Site	Building type	Year(s) of construction	Year(s) of renovation	GHFA[7]
Austria (page 37)			Johann-Böhmstraße, Kapfenberg	Multi-family building	1960 – 1961	2012 – 2014	2,845 m^2
Czech Republic (page 81)			Kamínky 5, Brno	Elementary School	1987	2009 – 2010	9,909 m^2
Denmark (page 46)			Traneparken, Hvalsø	Multi-family Building	1969	2011-2012	5,293 m^3
Portugal (page 55)			Neighborhood RDL, Porto	Two-family Building	1953	2012	123 m^2
Portugal (app. 7)			Montarroio, Coimbra	Single family in UNESCO context	14^{th} - 16^{th} century (late medieval)	(2015) ongoing	36 m^2
Spain (page 64)			Lourdes Neighborhood, Tudela	Multi-family Building	1970	2011	1,474 m^2
Sweden (page 73)			Backa röd, Gothenburg	Multi-family Building	1971	2009	1,357 m^2

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

4. Evaluation framework

4.1. Objectives of the analysis

For each of the renovation packages and measures the Life Cycle Cost (LCC) calculation and the Life Cycle Assessment (LCA) were performed according to the developed methodology of this project. The detailed analysis of the LCC regarding investment costs and annual costs were included and the Life Cycle Impact of each renovation package was evaluated according to its total final energy use, the total carbon emissions, the Non-Renewable Primary Energy (NRPE) and the total Primary Energy (PE).

In the following chapter the focus is on the presentation of the most important results, further information on the LCC and LCA results can be found in the individual Case Study papers in the appendix.

For each Case Study the goal was to find out:

- Which carbon emissions and total Primary Energy reductions are possible and still cost effective?
- Characterization of the influence of the renovation measures of the building envelope on the carbon emissions, total PE and LCC results.
- Characterization of the influence of the choice of the energy source for heating and domestic hot water production on the carbon emissions, total PE and LCC results.
- Characterization of the influence of the energy generation on-site on the carbon emissions, total PE and LCC results.

Further conclusions were drawn from the calculation results of each Case Study to answer the hypotheses defined in this project. These hypotheses are:

1. **The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.**
2. **A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.**
3. **A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.**
4. **Synergies are achieved when a switch to RES is combined with energy efficiency measures.**
5. **To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.**

4.2. Definition of renovation packages and reference case

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 methodology developed in this project, including Life Cycle Cost (LCC) and Life Cycle Assessment (LCA)[8]. After, the several renovation packages have also been analyzed considering the co-benefits that potentially result from the combination of the selected renovation measures.

The focus of this project is on residential and non-residential buildings without complex HVAC systems. The main focus areas of the studies are primary energy use and carbon emissions as well as the costs incurred by energy related renovation measures.

For the Case Studies each partner could define 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 production (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. This reference represents the starting point on the global cost curve and 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 and that do not improve the energy performance of the building. Therefore this reference case can also be named as “anyway renovation”. Renovation measures in this package could be for example repainting of windows or 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 consecutively “renovation package v1”, “renovation package v2” and “renovation package v3”, where v3 represents the actual renovation carried out for the particular building.

More detailed information about the different renovation measures of each country can be found in the findings and conclusion in following sections and pages. A description of the existing building and additional information to the actual renovation carried out can be found in the individual country papers in the appendix:

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8 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

Residential buildings

- Austria: chapter 5.1.1 on page 37
- Denmark: chapter 5.2.1 on page 46
- Portugal: chapter 5.3.1 on page 55
- Spain: chapter 5.4.1 on page 64
- Sweden: chapter 5.5.1 on page 73

Non-residential building

- Czech Republic: chapter 5.6.1 on page 81

In these 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. 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) generation on-site** – measures for the renewable energy generation on-site, e.g. solar thermal installation, photovoltaic modules, renewable district heating…

4.3. Co-benefits in the Case Studies

In the reviewed literature, several notions are used to refer to the benefits that arise from building renovation with energy efficiency and carbon emissions reduction. In this project, the main focus is on energy, carbon emissions and costs and consequently, the reduction of energy use, carbon emissions and costs are direct benefits. All the benefits that arise from a renovation project besides these direct benefits are included in the notion of co-benefits. Only co-benefits deriving from energy and carbon emissions related renovation measures are considered (e.g. the change of the interior floor of a dwelling from carpet to a wooden floor might be a measure that improves the indoor air quality but has no impact on the operational energy or carbon emissions).

The co-benefits that arise from energy and carbon emissions related building renovation can be independent from energy, carbon emissions and costs (e.g. less exterior noise), or can be a consequence of these (e.g. less risk of exposure to future energy price increases), and the benefits can impact at private level (e.g. increased user comfort) or/and at society level (e.g. impact on climate change or air pollution).

In this context, the notion of co-benefits refers to all benefits (positive or negative) resulting from renovation measures related to energy and carbon emissions optimized building renovation, besides or as a consequence of energy efficiency increment, carbon emissions reduction or costs reduction.

The co-benefits resulting from renovation measures related to energy and carbon emissions, besides or as a consequence of energy efficiency increment, carbon emissions reduction or costs reduction is a quite embracing concept, including numerous effects at different levels of economy and society. Therefore, it is useful to identify and classify these co-benefits according to underlying principles helping to better understand their nature.

The first distinction that needs to be made regards the different perspectives of the different target groups. For the policy makers, a societal or macroeconomic perspective is required in order to show how policies that are implemented for the reduction of energy and emissions in the building sector may be used to reach other objectives such as economic and social development, sustainability and equity. From the perspective of building owners and promoters, the economic value of a building and the value added by energy related renovation measures, are the most relevant indicators and, therefore, the co-benefits that can potentially increase the willingness to pay for the building present a private perspective.

The focus in this report is only on the private benefits that arise due to the different energy related renovation measures. Table 5 gives an overview of the identified co-benefits.

Table 5: Typology of private benefits of cost effective energy related renovation measures

Category	Co-benefit	Description
Building quality	**Building physics**	Less condensation, humidity and mould problems
	Ease of use and control by user	Ease of use and control of the renovated building by the users (automatic thermostat controls, easier filter changes, faster hot water delivery, etc.)
	Aesthetics and architectural integration	Aesthetic improvement of the renovated building (often depending on the building identity) as one of the main reasons for building renovation
	Useful building areas	Increase of the useful area (taking advantage of the balconies by glazing or enlarging the existing ones) or decrease of useful area (like the case of applying interior insulation or new BITS)
	Safety (intrusion and accidents)	Replacement of building elements with new elements at the latest standards, providing fewer risks such as accidents, fire or intrusion.
Economic	**Reduced exposure to energy price fluctuations**	Reduced exposure to energy price fluctuations gives the user a feeling of control and increased certainty to be able to keep the needed level of comfort.
User wellbeing	**Thermal comfort**	Higher thermal comfort due to better room temperatures, higher radiant temperature, lesser temperature differences, air drafts and air humidity.
	Natural lighting and contact with the outside	More day lighting, involving visual contact with the outside living environment (improved mood, morale, lower fatigue, reduced eyestrain).
	Indoor Air quality	Better indoor air quality (less gases, particulates, microbial contaminants that can induce adverse health conditions) better health and higher comfort
	Internal and external noise	Higher noise insulation but increased risk of higher annoyance due to internal noise after the reduction of external noise level
	Pride, prestige, reputation	Enhanced pride and prestige, an improved sense of environmental responsibility or enhanced peace of mind due to energy related measures
	Ease of installation and reduced annoyance	Ease of installation can be used as a parameter to find the package of measures that aggregates the maximum of benefits

For each Case Study the co-benefits, derived from energy related renovation measures, are presented together with the calculation results. The co-benefits analysis is based on the parametric calculations following the developed methodology and also, for some of the Case Studies, interviews performed among the residents of the buildings.

The co-benefits were analyzed for selected renovation packages, where positive effects or improvements were marked with a green triangle (▲) and negative effects or impairments with a red triangle (▼). The number of triangles stands for the magnitude of positive or negative effects. If a renovation measure leads to both, positive and negative effects, green and red triangles are used at once.

4.4. PE and carbon emissions conversion factors of the six countries

Table 6 and Table 7 show an overview of the different conversion factors used in each country in the Life Cycle Assessment. In Table 6 the conversion factors to calculate the $kgCO_2$-eq emissions based on the final energy use of the building and in Table 7 the conversion factors to calculate the total Primary Energy, also based on the final energy demand of the building are presented. The references are indicated in the footnotes. "-" means that this conversion factor was not used in the calculations of the specific country.

Table 6: Carbon emissions conversion factors in $kgCO_2$-eq/kWh_{final}

Country	Austria[9]	Czech Republic[12]	Denmark[10]	Portugal[11]	Spain[12]	Sweden
Oil	0.302	-	0.331	-	0.294	0.295[12]
Natural gas	0.252	0.238	0.251	0.262	0.237	0.238[12]
Wood / biomass	0.052	-	-	0.045	0.012	-
District heating	0.050	0.087	0.202	-	0.114	0.080[13]
Electricity	0.322	0.924	0.413	0.691	0.594	0.100[12]

Table 7: Total Primary Energy conversion factors kWh_{prim}/kWh_{final}

Country	Austria[9]	Czech Republic[12]	Denmark[14]	Portugal[11]	Spain[12]	Sweden
Oil	1.13	-	1.28	-	1.20	1.21[12]
Natural gas	1.20	1.13	1.19	1.24	1.10	1.13[12]
Wood / biomass	1.19	-	-	1.34	1.14	-
District heating	1.60	1.56	0.69	-	1.64	0.30[13]
Electricity	1.83	3.73	1.78	3.22	3.40	2.96[12]

9 Reference: GEMIS 4.8

10 Reference: Danish Energy Agency - 2015

11 Reference: LCI Ecoinvent v2.2

12 Reference: Eco-bat 4.0

13 Reference: Göteborg Energi 2013

14 Reference: DGNB - DGNB-DK

5. Findings and Conclusions

Residential Buildings

5.1. Case Study "Kapfenberg", Austria

5.1.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope	Painting of the outside walls	80 mm EPS insulation of the façade	240 mm EPS insulation of the façade	Insulation of the façade with prefabricated timber modules and a total insulation of 240 mm
		200 mm EPS insulation of the roof	300 mm EPS insulation of the roof	300 mm EPS insulation of the roof
	Painting and repair of wooden frame windows	New double-glazed windows with an external shading device	New triple-glazed windows with an external shading device	New triple-glazed windows with an external shading device (already integrated in the prefabricated façade modules)
BITS (Building Integrated Technical Systems)	New central heating and domestic hot water production	New central heating and domestic hot water production	New central heating and domestic hot water production	New central heating and domestic hot water production
			New mechanical ventilation system with heat recovery (SFP = 1.62, Eff.= 65%)	New mechanical ventilation system with heat recovery (SFP = 1.62, Eff.= 65%)
Investigated energy sources for heating and domestic hot water	Oil	Oil	Oil	
		Natural gas	Natural gas	
		Wood	Wood	
		District heating based on renewables	District heating based on renewables	District heating based on renewables
RES (renewable energy generation on-site)	None	None	None	144 m² solar thermal system for heating and DHW production
				92 kWp PV system for electricity generation on-site

Based on these renovation packages different additional combinations of the individual renovation measures were tested to answer the defined hypotheses. Following combinations of renovation measures (marked with M1, M2,...) were tested:

Renovation package	Description
Ref	In the reference case, the wall and the windows are repainted and the pitched roof is refurbished. These measures do not improve the energy performance of the building.
M1	80 EPS mm insulation of the façade
M2	240 mm EPS insulation of the façade
M3	M2 + 200 mm EPS insulation of the roof
M4	M2 + 300 mm EPS insulation of the roof
M5	M4 + solar thermal installation
M6	M5 + new double-glazed windows (U-value 1.4 W/m²K)
M7	M5 + new triple-glazed windows (U-value 1.0 W/m²K)
M8	M7 + mechanical ventilation system with heat recovery
M9	M8 + photovoltaic installation

To test the influence of different energy sources for heating and DHW production (RES and non-RES) on the results the defined renovation measures M1 to M9 were also tested with various energy systems. These were:

- Oil (reference case)
- Natural gas
- District heating
- Wood pellets
- Air-water heat pump
- Geo-thermal heat pump

The results of the several calculations can be found in following chapter 5.1.2.

5.1.2. *Results*

Figure 6 shows the calculation results of the Austrian Case Study "Kapfenberg". On the left side the comparison of the Life Cycle Costs with the carbon emissions, on the right side the comparison with the total Primary Energy.

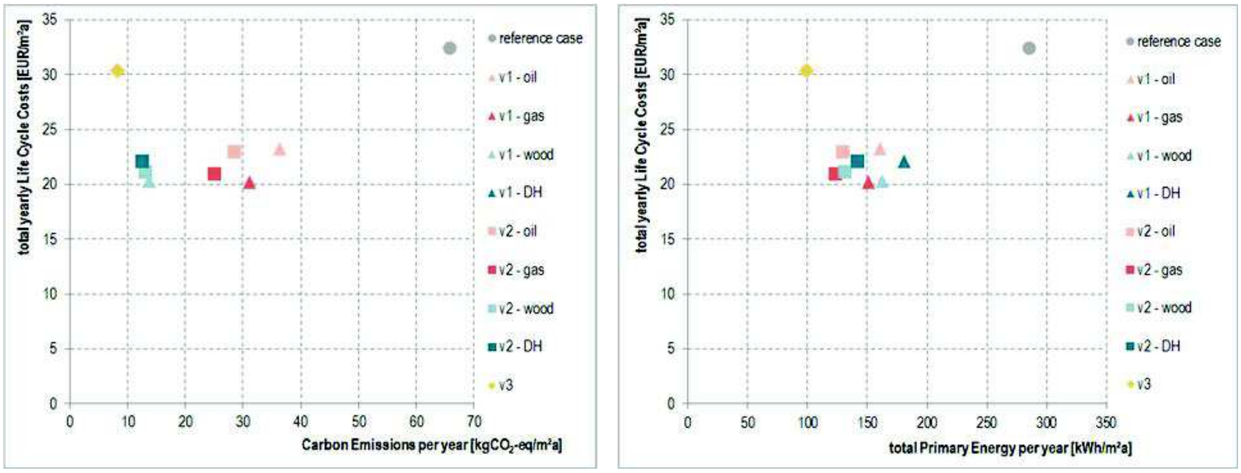


Figure 6: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study "Kapfenberg", Austria

The results show that all investigated renovation packages are cost effective. This means that the annual specific LCC of each renovation package are lower than the LCC of the reference case.

The lowest carbon emissions are achieved by the executed renovation package v3 with heating and domestic hot water production based on district heating including renewable energy generation on-site by solar thermal and photovoltaic installations. This renovation package has annual carbon emissions of about 8 $kgCO_2$-eq/m²a, which is a reduction of nearly 60 $kgCO_2$-eq/m²a or 85%, compared to the reference case.

The lowest total PE is also achieved by renovation package v3. This renovation package achieves a total Primary Energy of 100 kWh/m²a. This is a reduction of nearly 190 kWh/m²a or 65% compared to the reference case.

The cost optimal solution for the Austrian Case Study would be renovation package v1 with heating and DHW production based on natural gas. The cost optimal solution achieves carbon emissions of 31 $kgCO_2$-eq/m²a, total Primary Energy of 152 kWh/m²a and annual LCC of 20.19 EUR/m²a. But in reality this renovation package was no option. The goal of the renovation was to realize a demonstration building which should achieve 80% reduction of the heating energy demand of the existing building, cover at least 80% of the final energy demand of the renovated building by renewable energy sources and reduce the CO_2 emissions by 80% compared to the existing building. The costs were in fact not the most important criterion.

To have a more detailed understanding of the influence of the different renovation measures on the total results, additional analyses of the different energy related renovation measures were performed. On that account the Life Cycle Costs, the carbon emissions and the total Primary Energy were calculated for the renovation measures M1 to M9 (as described on page 38). The following charts show the comparison of cost effectiveness of energy efficiency renovation measures for the Austrian Case Study for the different heating systems, including also renewable energy generation on-site through solar thermal and photovoltaic installations. The reference shown as a grey dot refers to a situation with renovation measures on the building envelope without improving energy-efficiency levels and the installation of a new oil heating system.

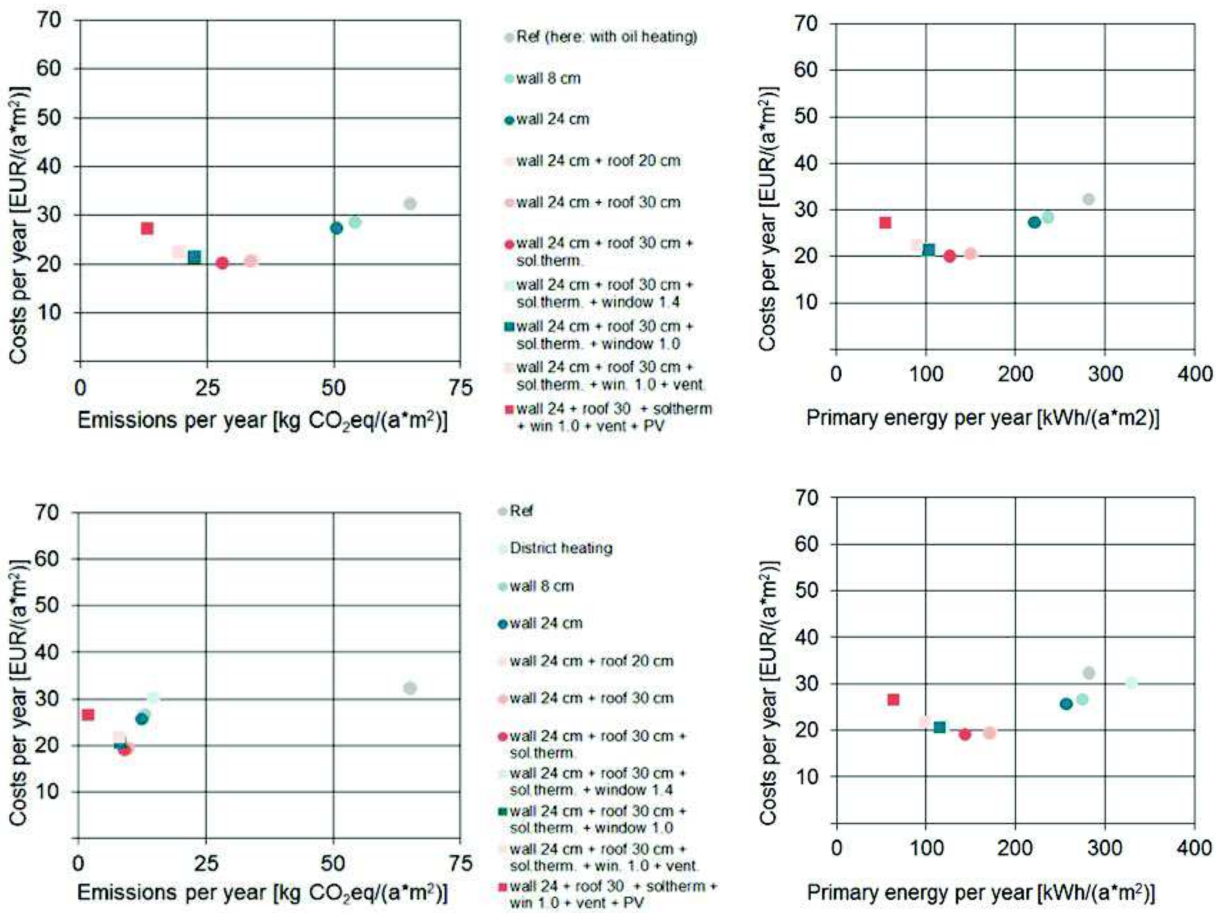


Figure 7: Comparison of cost effectiveness of energy efficiency renovation measures for the Austrian Case Study for the heating systems: oil heating (top) and district heating (bottom), as well as related impacts on carbon emissions and primary energy use

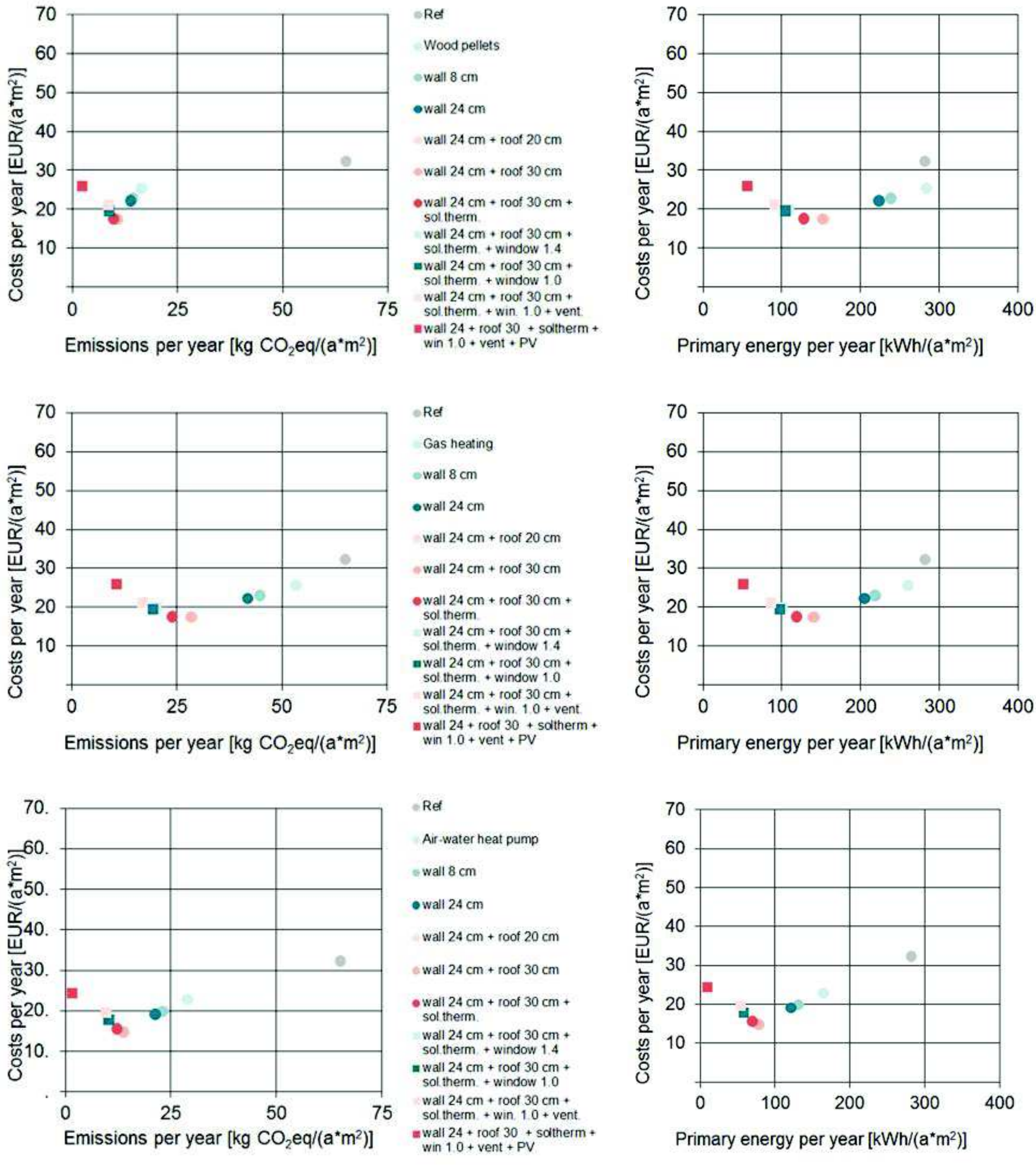


Figure 8: Comparison of cost effectiveness of energy efficiency renovation measures for the Austrian Case Study for the heating systems: wood pellets (top), gas heating (middle) and air-water heat pump (bottom), as well as related impacts on carbon emissions and primary energy use

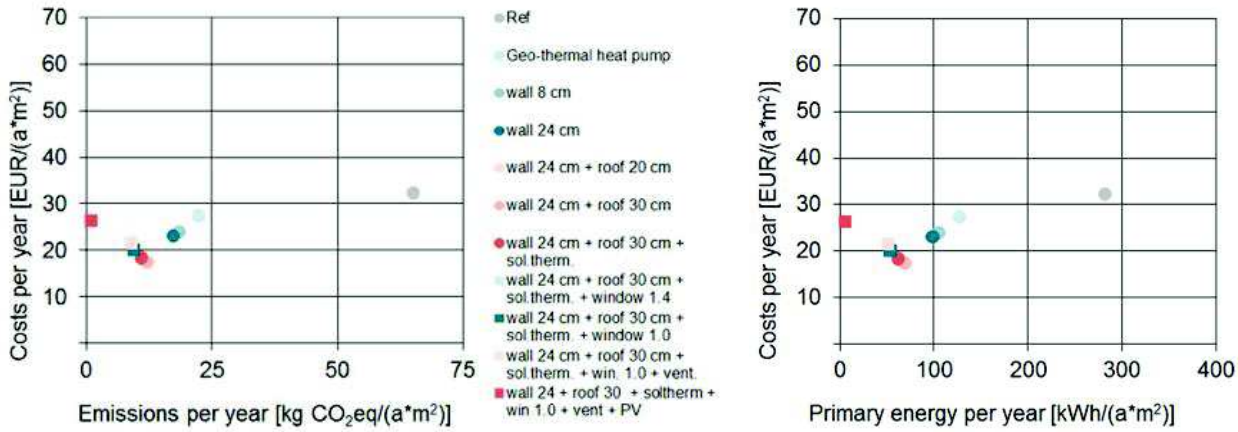


Figure 9: Comparison of cost effectiveness of energy efficiency renovation measures for the Austrian Case Study for a geo-thermal heat pump system, as well as related impacts on carbon emissions and primary energy use

Following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems. In each of these graphs, three different curves are shown, representing the application of the different renovation packages on the building envelope in combination with the installation of different heating systems. Each dot in the curves represents the application of a particular renovation package. The points with the highest emissions or highest primary energy use for each energy source represent the anyway renovation. As more measures are added to the renovation packages, carbon emissions and primary energy use decrease.

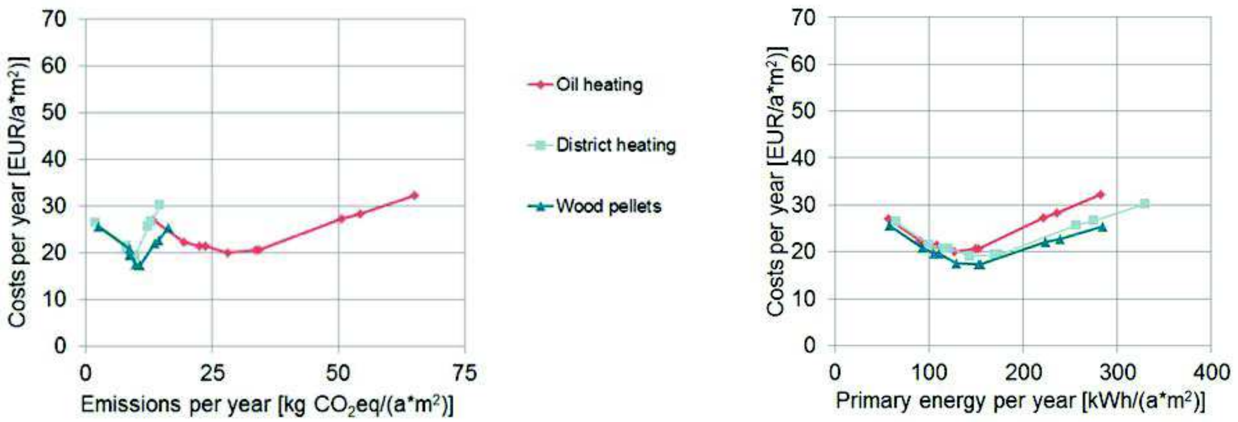


Figure 10: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Austrian Case Study (part I)

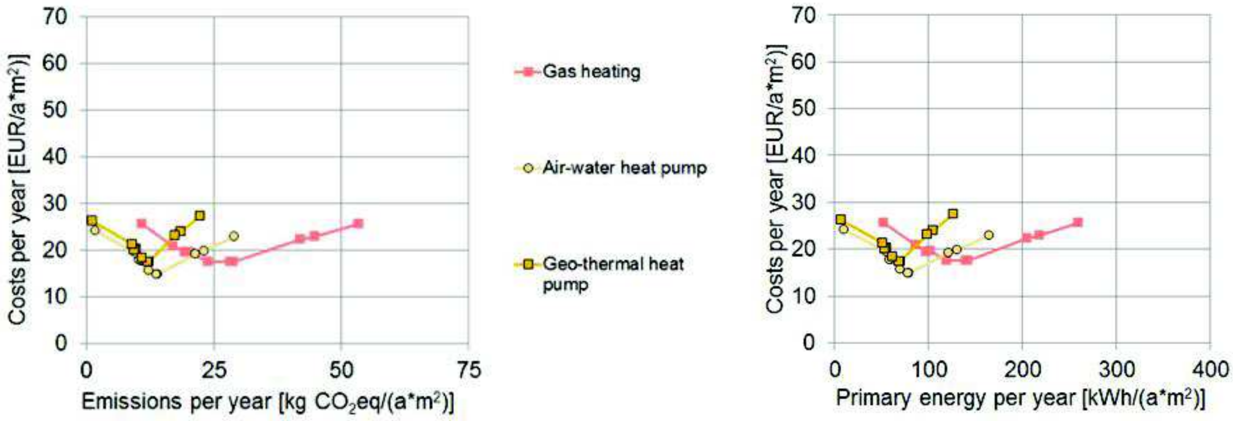


Figure 11: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Austrian Case Study (part II)

5.1.3. Co-benefits

Some interviews were done with the residents considering the building renovation rather or very important due to the several problems and difficulties felt before the renovation, namely the moist, cold, low fresh air, too small areas and discomfort. All the residents of the building had to leave their dwelling for nearly one year because the building renovation was performed in 2 construction phases and also the dwellings inside the building were renovated and modified. That means people living in a dwelling of the 1st construction phase moved to a dwelling in the 2nd construction phase and after finishing the 1st construction phase they moved back.

After the renovation the residents consider the dwelling convenient, large, dry and warm. Less consistent opinions were collected regarding the noise, natural light and air quality. 1/3 of the respondents considered that the dwelling became noisy. Regarding the natural light, 31% of the respondents considered it dark and regarding the air quality 62% of the respondents considered not having enough fresh air in the dwelling.

Although 85% of the respondents have declared that the expectations with the building renovation have been rather or totally satisfied, about 1/3 have identified some relevant problems, namely disturbance through construction works, less daylight and too low indoor temperature.

Table 8 on the next page presents the co-benefits for some of the investigated renovation packages, namely: the reference case, the cost optimal scenario (M3 + air-water heat pump), the best energy performance scenario which is very close to zero (M9 + geothermal heat pump) and the least cost scenario using the geothermal heat pump (M3 + geothermal heat pump).

When analyzing the packages of measures beyond the cost optimal, it is possible to understand that some of these packages present co-benefits that may justify the extra costs that result from the cost benefit calculations that only considers energy related costs.

Based on Table 8, M9 + Geo HP present more co-benefits than the other renovation packages. The mechanical ventilation with heat recovery improves the air quality and the change of windows allows reducing the disturbance from external noise and the security against intrusions. The geothermal heat pump, due to its high efficiency leads to reduced exposure to energy price fluctuations, but on the other hand its installation is not an easy task. In all of the scenarios, the intervention on the façades affects positively the aesthetics, but this benefit is also present in the reference scenario, so it is not a co-benefit that derives from energy related renovation measures.

The use of renewable energy system such as the solar thermal panels and the photovoltaic system as well as the mechanical ventilation with heat recovery, allows reducing significantly the exposure to energy price fluctuation and also increase the notion of pride and prestige related with the building.

Comparing the cost optimal scenario (M3 + air heat pump), with the scenario with the best energy performance (M9 + geothermal heat pump) yearly costs per m2 increase €11. On the other hand, the air quality is improved, the building becomes more protected from external noise and against intrusions, residents are less exposed to energy price fluctuations and experience an increased sense of pride and prestige related to their renovated building.

Table 8: Identification of co-benefits in several renovation packages in the Austrian Case Study

Building elements	Reference	M3 + Air. HP	M3 + Geo. HP	M9 + Geo HP
Façade	Maintenance	24cm of insulation	24cm of insulation	24 cm insulation
Roof	Maintenance	20 cm of insulation	20 cm of insulation	30cm insulation
Floor	Maintenance	Maintenance	Maintenance	Maintenance
Windows	Maintenance	Maintenance	Maintenance	Windows (U=1)
Ventilation	Natural	Natural	Natural	Mech + heat recov.
Heating system	Oil heating	Air Heat Pump	Geo Heat pump	Geo Heat pump
DHW system	Oil heating	Air Heat pump	Geo Heat pump	Geo Heat pump
RES	None	None	None	Solar thermal + PV
Co-benefits				
Aesthetics	▲	▲	▲	▲
Pride/prestige	▲	▲	▲	▲▲
Thermal comfort		▲▲▲	▲▲▲	▲▲▲
Building physics		▲▲	▲▲	▲▲
Internal noise		▼	▼	▼
Price fluctuation		▲▲	▲▲	▲▲▲
Ease of installation		▲▲	▲▼	▲▼
Air Quality		▲	▲	▲▲▲
External noise				▲▲▲
Safety				▲▲
Additional costs [EUR/m^2a]	16	Cost optimal	2	11

5.1.4. Conclusions

For the analyzed parameters carbon emissions, total Primary Energy and the Life Cycle Costs the following conclusions can be drawn:

- All investigated renovation measures are cost effective, which means that the LCC are lower than the LCC of the reference case.
- The highest carbon emissions are found in the reference case. That means that all renovation measures on the building envelope and the variation of the energy sources for heating and DHW production can reduce the carbon emissions.
- The highest total Primary Energy is achieved by the anyway renovation in combination with district heating. Again all investigated renovation packages on the building envelope lead to a reduction of the total PE.
- In order to reduce carbon emissions and total Primary Energy further it is more efficient to concentrate on several building elements than only on one element.
- For natural gas heating and the heat pump systems it could be investigated that only the change of the heating system, without including any further measures on the building envelope, can reduce the carbon emission and the total Primary Energy.
- Renovation measure M9, which represents the most improved building envelope including also renewable energy generation on-site through solar thermal and photovoltaic systems, achieves the lowest carbon emissions and also the lowest Primary Energy values.
- The renewable energy sources (district heating, heat pump systems and wood pellets) achieve the lowest carbon emissions, the heat pump systems the lowest Primary Energy.

Based on the additional calculation results the hypotheses were tested. Table 9 shows the investigated hypotheses for the Austrian Case Study.

Table 9: Results for the investigated hypotheses for the Case Study "Kapfenberg" in Austria

Hypothesis	Results from Case Study "Kapfenberg", Austria
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level	✓
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓

For the Austrian Case Study all five hypotheses could be confirmed.

5.2. Case Study "Traneparken", Denmark

5.2.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope	Maintenance of the outer skin of the external walls	100 mm insulation of the façade	No insulation of the façade	211 mm insulation of the façade
	New roofing	450 mm insulation of the roof	450 mm insulation of the roof	250 mm insulation of the roof
	Painting and repair of wooden frame windows	New triple-glazed windows (energy glass)	New triple-glazed windows (energy glass)	New triple-glazed windows (energy glass)
BITS (Building Integrated Technical Systems)	Renewal of the heating and domestic hot water system	Renewal of the heating and domestic hot water system	Renewal of the heating and domestic hot water system	Renewal of the heating and domestic hot water system
		New mechanical ventilation system with heat recovery (SFP = 1.2, Eff.= 90%)	New mechanical ventilation system with heat recovery (SFP = 1.2, Eff.= 90%)	New mechanical ventilation system with heat recovery (SFP = 1.4, Eff.= 80%)
Investigated energy sources for heating and domestic hot water		Oil	Oil	
		Natural gas	Natural gas	
	District heating based renewables with a share of 53%	District heating based renewables with a share of 53%	District heating based renewables with a share of 53%	District heating based renewables with a share of 53%
RES (renewable energy generation on-site)	None	33 kWp photovoltaic system for the electricity generation on-site	132 kWp photovoltaic system for the electricity generation on-site	33 kWp photovoltaic system for the electricity generation on-site

Note: 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 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 $kgCO_2\text{-eq}/kWh_{final}$ respectively 1.78 kWh_{prim}/kWh_{final} (see also Table 6 and Table 7 in chapter 4.4 on page 36).

Based on these renovation packages, again different additional combinations of the individual renovation measures were tested to answer the defined hypotheses.

Following combinations of renovation measures (marked with M1, M2,...) were tested:

Renovation package	Description
Ref	In the reference case, the outer skin of the external walls was maintained and the wooden frame windows were painted and repaired. New roofing was also included but none of these measures improves the energy performance of the building.
M1	150 mm insulation of the roof
M2	300 mm insulation of the roof
M3	M2 + 100 mm insulation of the façade
M4	M2 + 200 mm insulation of the façade
M5	M4 + new triple-glazed windows
M6	M5 + mechanical ventilation SFP 1.4, Eff=80%
M7	M5 + mechanical ventilation SFP 1.2, Eff=90%

In addition to the different renovation measures on the building envelope and the ventilation system again different energy sources for heating and DHW production were tested, including also photovoltaic energy generation on-site. The investigated energy systems were:

- Oil heating
- Heat pump
- District heating (53% renewable)
- District heating (53% renewable) + 32 kWp photovoltaic system
- District heating (53% renewable) + 132 kWp photovoltaic system

For each of these renovation measures and packages Life Cycle Costs, carbon emissions and Primary Energy were calculated. The results are presented in chapter 5.2.2.

5.2.2. Results

Figure 12 shows the calculation results of the Case Study "Traneparken" in Denmark. On the left side the Life Cycle Costs are plotted in comparison with the carbon emissions and on the right side with the total Primary Energy of the building.

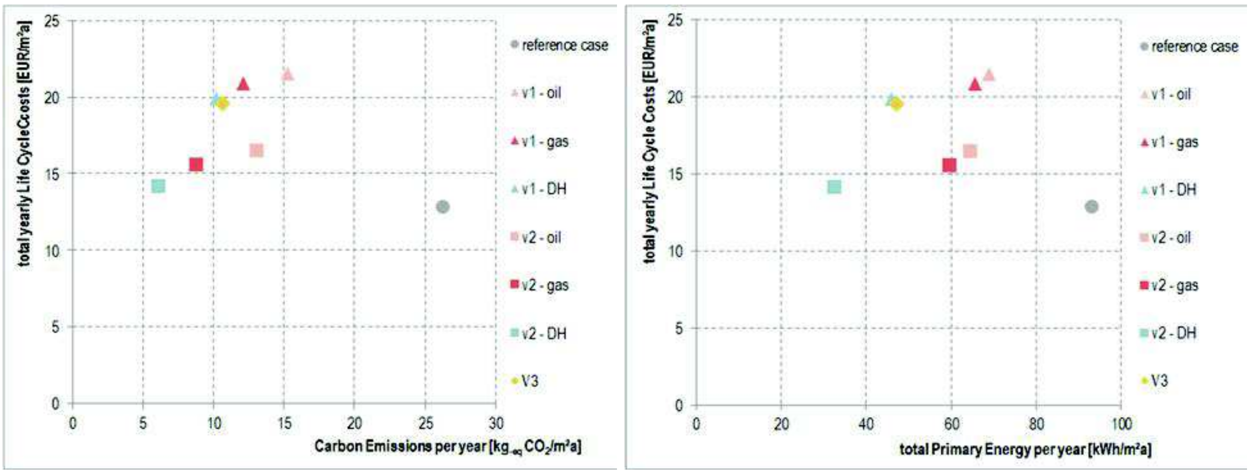


Figure 12: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study "Traneparken", Denmark

The results show that none of the defined and investigated renovation packages is cost effective. In other words, the annual LCC of each renovation package are higher than the LCC of the reference case, which means that the reference case is the cost optimum renovation. A possible reason for that might be that the existing building is already insulated and the additional insulation measures can reduce the carbon emissions and the total Primary Energy but increase the annual Life Cycle Costs.

The lowest carbon emissions are achieved by renovation package v2 with heating and domestic hot water production based on district heating and additionally adding a large PV system. This renovation package achieves carbon emissions of 6.2 $kgCO_2$-eq/m²a. The reference case achieves carbon emissions of 26.4 $kgCO_2$-eq/m²a. Renovation package v2 can therefore save up to 20.2 $kgCO_2$-eq/m²a or 77% of the carbon emissions compared to the reference case.

Renovation package v2 with heating and domestic hot water production based on district heating also achieves the lowest total Primary Energy, with a value of about 33 kWh/m²a. This is, compared to the reference case, a reduction of 61 kWh/m²a or 65%.

The actual renovation carried out (renovation package v3) achieves carbon emissions of 10.7 $kgCO_2$-eq/m²a, a total Primary Energy of 47 kWh/m²a and annual Life Cycle Costs of 19.54 EUR/m²a. Compared to the reference case this is a reduction of 15.7 $kgCO_2$-eq/m²a respectively 60% (carbon emission) and of 46 kWh/m²a respectively 50% (total Primary Energy).

This particular renovation package was chosen, despite it is not the cost optimal solution, due to following reasons: the goal was to renovate the buildings because they were worn down and the external concrete walls were weakened by deterioration. At the same time external balconies were added to improve the flats. The overall intention was to:

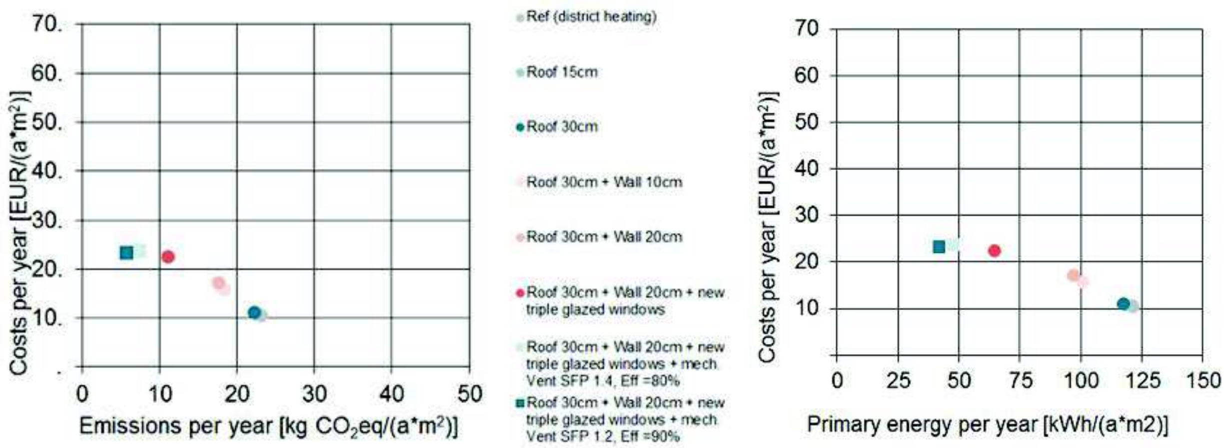
- Renovate worn down parts of the buildings
- Improve the indoor climate
- Improve flats with external balconies
- Improve outdoor areas
- Reduce energy consumption (insulation of constructions, new windows/doors, mechanical ventilation with heat recovery)

The apparent needs - necessary repair of external walls and replacement of windows - were used as an opportunity to drastically improve the insulation of the walls and to choose triple-glazed low energy windows. Thereby a far more sustainable solution was achieved.

Looking at the results it is obvious that not installing any external wall insulation in v2 results in lower Life Cycle Costs than in renovation package v1 and v3. Even when in v2 a much larger PV system is installed, the LCC are still lower. It is interesting to see that installation of a larger photovoltaic system seems to be able to out-balance the expensive exterior wall insulation, especially if the generated energy from the photovoltaic system can be allocated to the building and in this way reduce the annual energy consumption. Nevertheless it has to be mentioned that the insulation of the exterior walls was not an option but a must. The walls were worn down and the comfort in the building was suffering severely due to their state.

The comparison of cost effectiveness of energy efficiency renovation measures for the Danish Case Study for different heating systems (oil heating, district heating and heat pump) and related impacts on carbon emissions and primary energy use is shown in Figure 13 and Figure 14 show.

Figure 15 shows the influence of the different heating systems, including also different photovoltaic energy generation on-site, on the reference case with no additional energy related renovation measures.



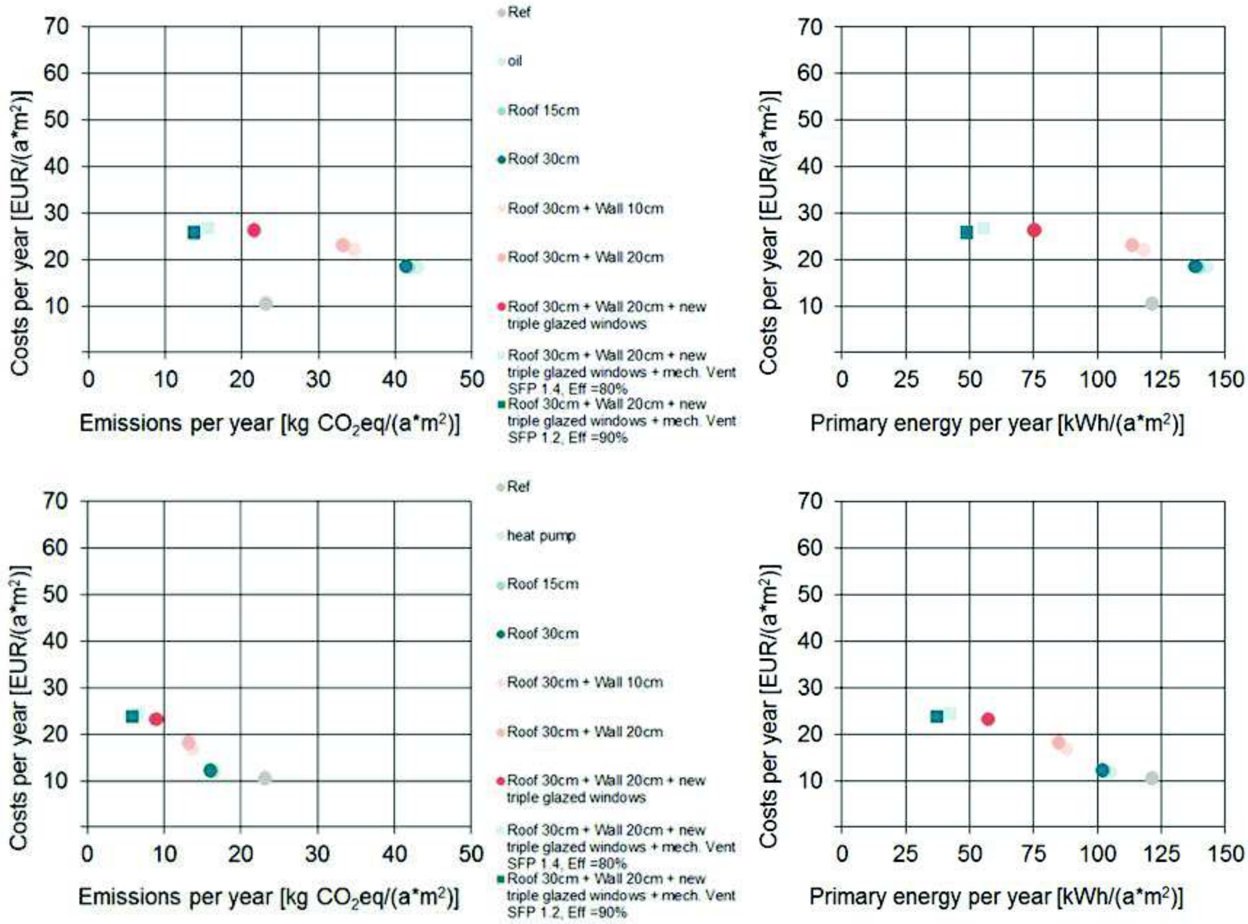


Figure 13: Comparison of cost effectiveness of energy efficiency renovation measures for the Danish Case Study for district heating (top), oil heating (middle) and heat pump (bottom), as well as related impacts on carbon emissions and primary energy use

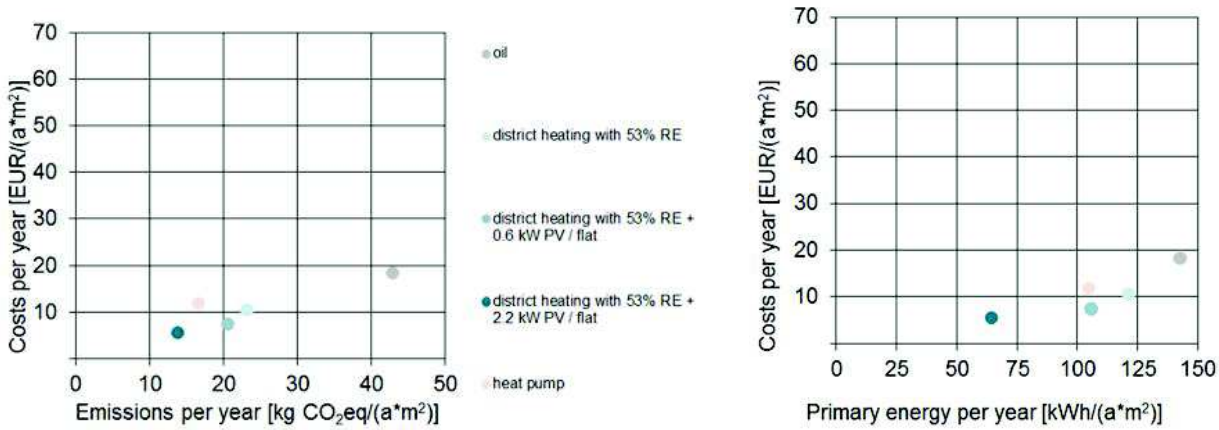


Figure 14: Comparison of cost effectiveness of energy efficiency renovation measures for the Danish Case Study for the different heating systems, including renewable energy generation on-site by the photovoltaic installation, only reference case

Figure 15 summarizes the cost curves for different renovation packages on the building envelope with different heating systems. In the graph, three different curves are shown, representing the application of the different renovation packages on the building envelope in combination with the installation of different heating systems. Each dot in the curves represents the application of a particular renovation package.

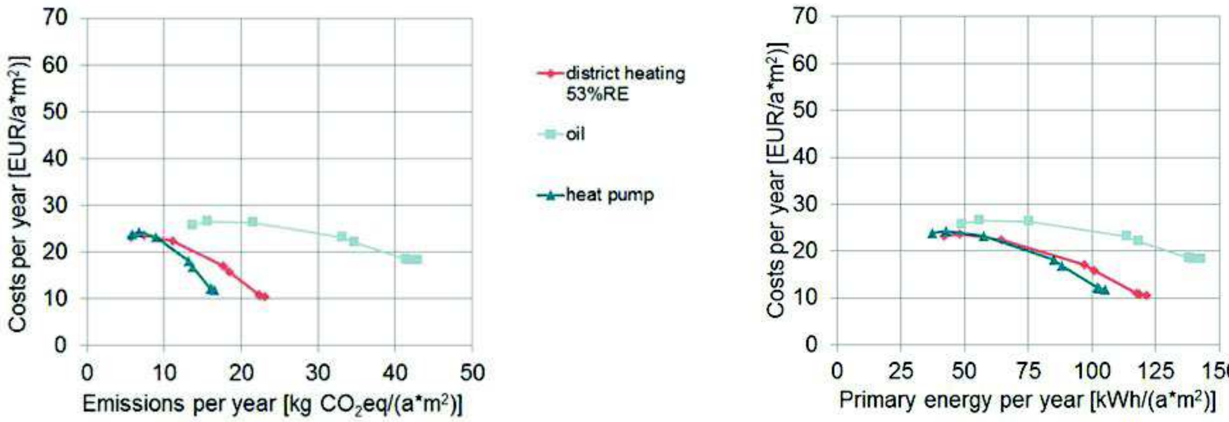


Figure 15: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Danish Case Study

5.2.3. *Co-benefits*

Before renovation, the buildings seemed rather grey and boring and had problems with façades, windows and roofs. The indoor climate was unacceptable and the energy consumption was very high.

Table 10 shows the co-benefits of four renovation packages: the cost optimal solution, a renovation package using a heat pump instead of district heating, renovation package M4 which improves the energy performance of the façade and the roof, and the scenario that leads to the best energy performance (M7 + Heat Pump).

Table 10: Identification of co-benefits in several renovation packages in the Danish Case Study

Building elements	Reference	Reference + HP	M4 + DH	M7 + HP
Façade	Maintenance	Maintenance	20 cm insulation	20 cm insulation
Roof	Maintenance	Maintenance	30cm insulation	30cm insulation
Floor	Maintenance	Maintenance	Maintenance	Maintenance
Windows	Maintenance	Maintenance	Maintenance	Triple Glazed
Ventilation	Maintenance	Maintenance	Maintenance	Mech + heat recov.
Heating system	District heating	Heat pump	District heating	Heat pump
DHW system	District heating	Heat pump	District heating	Heat pump
RES	53% RES	None	None	None
Co-benefits				
Aesthetics	▲	▲	▲	▲
Pride/prestige	▲▲	▲▲	▲▲	▲▲
Thermal comfort			▲▲▲	▲▲▲
Building physics			▲▲	▲▲
Internal noise			▼	▼
Price fluctuation		▲	▲	▲▲▲
Air Quality				▲
External noise				▲▲
Safety				▲
Additional costs [EUR/m^2a]	Cost optimal	1	7	13

Looking at the table, the last two renovation packages which improve the buildings envelope, present some advantages that can play an important role in the final decision. From an economical perspective the difference in the global cost to the cost optimal solution is definitely given but the improvements in the thermal comfort and reduction in the problems related to the building physics are interesting additional benefits. There is a negative co-benefit related to the increase of the insulation on the buildings envelope which is the internal noise from adjacent dwellings that becomes noticeable when the external noise is reduced.

The exposure to the energy price fluctuation decreases significantly in the last renovation package, which also presents the co-benefits of further reducing the external noise and improve safety against intrusions, related with the replacement of windows.

5.2.4. Conclusions

The analysis of the Danish Case Study “Traneparken” allows following conclusions:

- The lowest Life Cycle Costs are achieved by the reference case. That means that none of the investigated renovation measures is cost effective. A reason for this might be the already included façade insulation of the existing building.
- The lowest carbon emissions are achieved by renovation measure M7, which includes the most improved thermal envelope and very efficient mechanical ventilation with heat recovery, together with district heating and similar also with heat pump.
- The lowest Primary Energy is achieved by renovation measure M7 together with the heat pump system.
- If only measures on the wall and the roof are included, together with an oil heating system, the carbon emissions increase. All other investigated renovation measures can reduce the carbon emissions compared to the reference case.
- All investigated renovation measures can reduce the Primary Energy, compared to the reference case. The exception is, if an oil heating is used and only the roof is insulated. This combination increases the total Primary Energy.
- It´s more efficient to concentrate on several building elements than only on one element to reduce the carbon emissions and the total Primary Energy.
- The on-site energy generation by the photovoltaic system reduces carbon emissions, total PE and also LCC compared to the reference case but also compared to the option without the PV installation.

Based on these conclusions the hypotheses for the Danish Case Study were tested (Table 11).

Table 11: Results for the investigated hypotheses for the Case Study "Traneparken" in Denmark. ✓ thereby means that the hypothesis is confirmed, ✗ indicates a not-confirmed hypothesis. (✓) means that the hypothesis is confirmed, but with restrictions

Hypothesis	Results from Case Study “Traneparken”, Denmark
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level	(✓)*
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✗**
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓**

* In this particular case the reference case is the cost optimum renovation. All investigated energy related renovation measures lead to an increase of the annual Life Cycle Costs.

** If the initial situation includes oil heating and the switch to district heating or heat pump is performed.

For the Danish Case Study four of the five hypotheses could be confirmed. Not confirmed is the hypothesis *"Synergies are achieved when a switch to RES is combined with energy efficiency measures"*. This could be explained as follows: starting with anyway renovation and an oil heating system it is more cost efficient to change only the heating system, to district heating or heat pump, and not carrying out further energy related renovation measures on the building envelope. The reduction of carbon emissions and Primary Energy due to the improved building envelope is quite small compared to the change of the energy source. Additionally the LCC increase due to these energy related renovation measures on the building envelope and therefore it is not efficient to combine the switch to RES with the energy efficiency measures on the building envelope.

5.3. Case Study "Rainha Dona Leonor neighborhood ", Portugal

5.3.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope	Maintenance of the outside walls	100 mm EPS insulation of the façade	80 mm cork board insulation of the façade	60 mm EPS insulation of the façade
	Maintenance of the roof	140 mm rock wool insulation of the roof	80 mm cork board insulation of the roof	50 mm XPS insulation of the roof
		80 mm rock wool insulation of the floor	80 mm cork board insulation of the floor	No insulation of the floor
	Maintenance of the existing windows	Maintenance of the existing windows	New double-glazed windows	New double-glazed windows
BITS (Building Integrated Technical Systems)	Renewal of the existing electrical heating and domestic hot water systems HVAC system for cooling	Replacement of the heating and domestic hot water system	Replacement of the heating and domestic hot water system	Replacement of the heating and domestic hot water system
Investigated energy sources for heating and domestic hot water	Electricity (electric heater)	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	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	HVAC (multi-split air conditioned for heating and cooling and solar thermal panels backed up by electric heater for DHW)
RES (renewable energy generation on-site)	None	3.8 m² solar thermal panels for DHW 3.7 kWp photovoltaic panels to support the heat pump	3.8 m² solar thermal panels for DHW 3.7 kWp photovoltaic panels to support the heat pump	3.8 m² solar thermal panels for DHW

The chosen renovation scenario (renovation package v3) 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.

Based on these renovation packages v1, v2 and v3 different additional combinations of the individual renovation measures were tested to confirm the defined hypotheses:

Renovation package	Description
Ref	In the reference case, the walls, the roof and the windows are maintained. These measures do not improve the energy performance of the building.
M1	80 mm rock wool insulation of the roof
M2	80 mm cork board insulation of the roof
M3	140 mm rock wool insulation of the roof
M4	M3 + 60 mm EPS insulation of the façade
M5	M3 + 80 mm cork board insulation of the façade
M6	M3 + 100 mm EPS insulation of the façade
M7	M6 + 80 mm rock wool insulation of the floor
M8	M6 + 80 mm cork board insulation of the floor
M9	M8 + new double-glazed windows

The renovation measures M1 to M9 were tested with following combinations of building integrated technical systems for heating, cooling and DHW:

- Electric heater
- Natural gas
- HVAC + electric heater
- HVAC + electric heater + solar thermal
- Heat pump + PV
- Biomass

The results of these investigations are presented in following chapter 5.3.2.

5.3.2. Results

The calculation results in Figure 16 show on the left side the comparison of the Life Cycle Costs with the carbon emissions and on the right side the comparison of the LCC with the total Primary Energy.

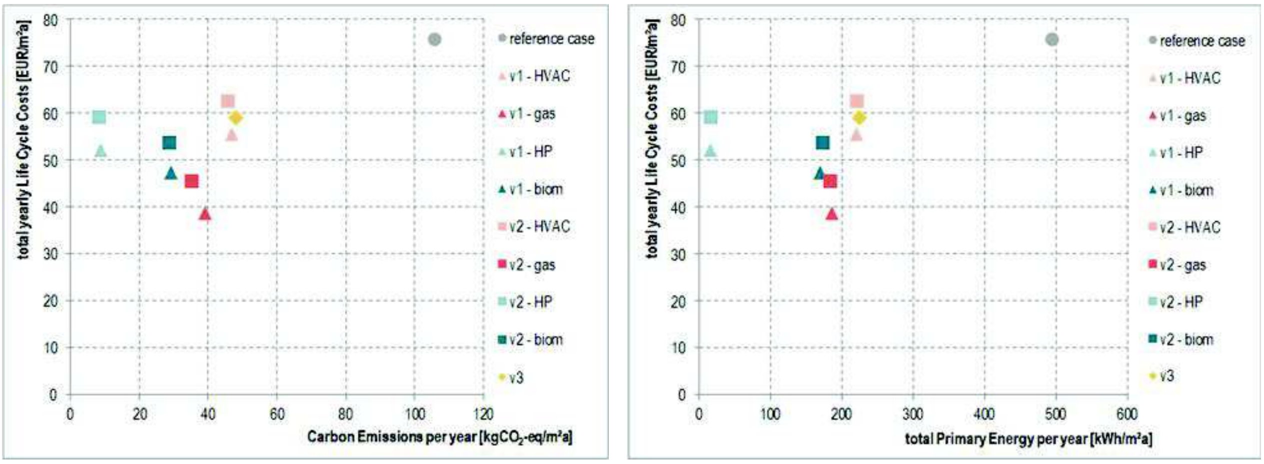


Figure 16: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study “Rainha Dona Leonor neighborhood”, Portugal

The charts show that all investigated renovation packages are cost effective. That means the annual specific LCC of each renovation package are lower than the LCC of the reference case.

The lowest carbon emissions are achieved by renovation package v2 with heating (the energy efficiency measures on the building envelope allowed to avoid the need of a cooling system) and domestic hot water production based on a heat pump, which is supported with a photovoltaic system. The carbon emissions of this system are 8.5 $kgCO_2$-eq/m²a. This is a reduction of more than 97 $kgCO_2$-eq/m² or 92% compared to the reference case, which achieves carbon emissions of 106 $kgCO_2$-eq/m²a.

The lowest total PE is achieved by renovation package v1 with heating and domestic hot water based on a heat pump. With a value of 16 kWh/m²a this renovation package can reduce the total PE, compared to the reference case, by 479 kWh/m²a or 97%. The difference between the renovation package achieving the lowest carbon emissions (renovation package v2) and the one achieving the lowest PE (renovation package v1) is due to the insulation material used in renovation package v2 (cork), which has lower carbon emissions but a significant PE from the biomass used in the fabrication process.

The cost optimal solution for the Portuguese Case Study is renovation package v1 with heating and domestic hot water production based on natural gas. This cost optimal solution achieves carbon emissions of 39.4 $kgCO_2$-eq/m²a, a total PE of 186 kWh/m²a and LCC of 38.78 EUR/m²a.

In relation to the most ambitious, the gap to the cost optimal solution is:

- Carbon Emissions: with additional annual LCC of 20.07 EUR/m²a the carbon emissions could be reduced from 39.37 $kgCO_2$-eq/m²a (cost optimal solution) to 8.50 $kgCO_2$-eq/m²a (lowest carbon emissions). That means with 52% higher LCC the carbon emissions could be reduced by 78%.
- PE: with additional annual LCC of 13.34 EUR/m²a the total PE could be reduced from 186 kWh/m²a (cost optimal solution) to 16 kWh/m²a (lowest total PE). 26% higher LCC would therefore result in a 91% lower total PE.

To have a more detailed understanding of the influence of the different renovation measures on the calculation results of the Portuguese Case Study, the influence of improving the thermal quality of the building envelope, the modification of the energy source for heating and domestic hot water and the use of renewable energy generated on-site was analyzed and is presented on the following pages.

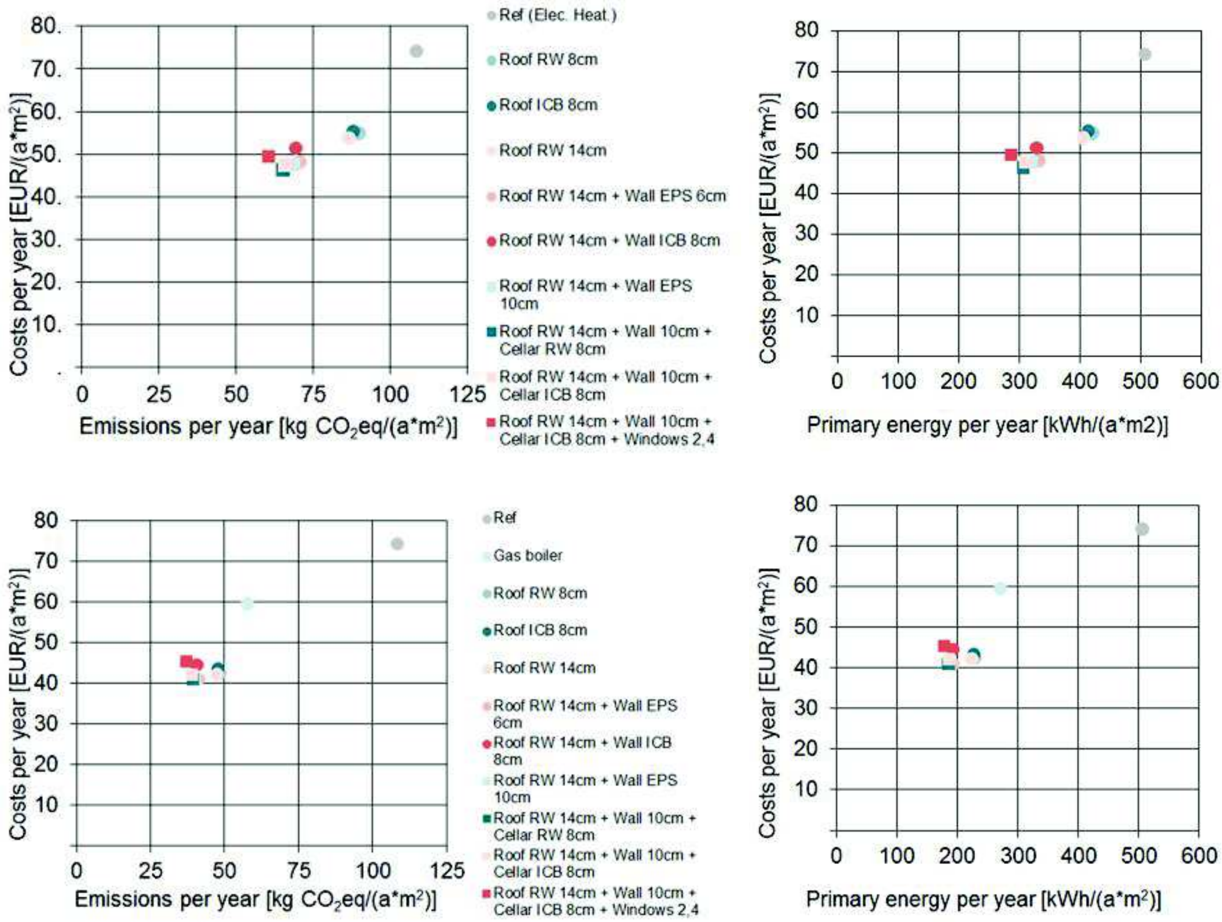


Figure 17: Comparison of cost effectiveness of energy efficiency renovation measures for the Portuguese Case Study for the BITS: electric heater (top) and gas boiler (bottom), as well as related impacts on carbon emissions and primary energy use

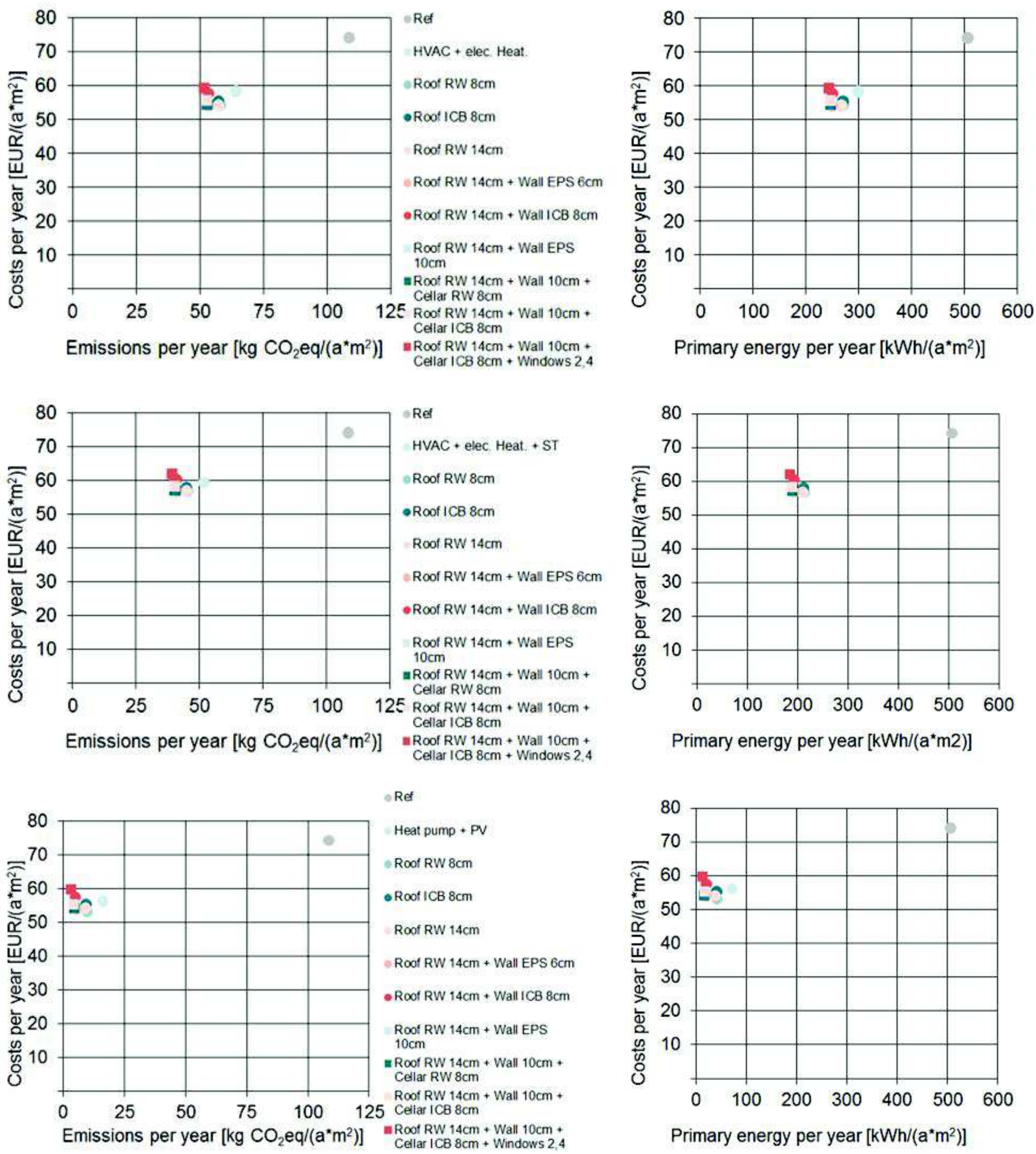


Figure 18: Comparison of cost effectiveness of energy efficiency renovation measures for the Portuguese Case Study for the BITS: HVAC + electric heater (top), HVAC + electric heater + solar thermal (middle) and heat pump + photovoltaic (bottom), as well as related impacts on carbon emissions and primary energy use

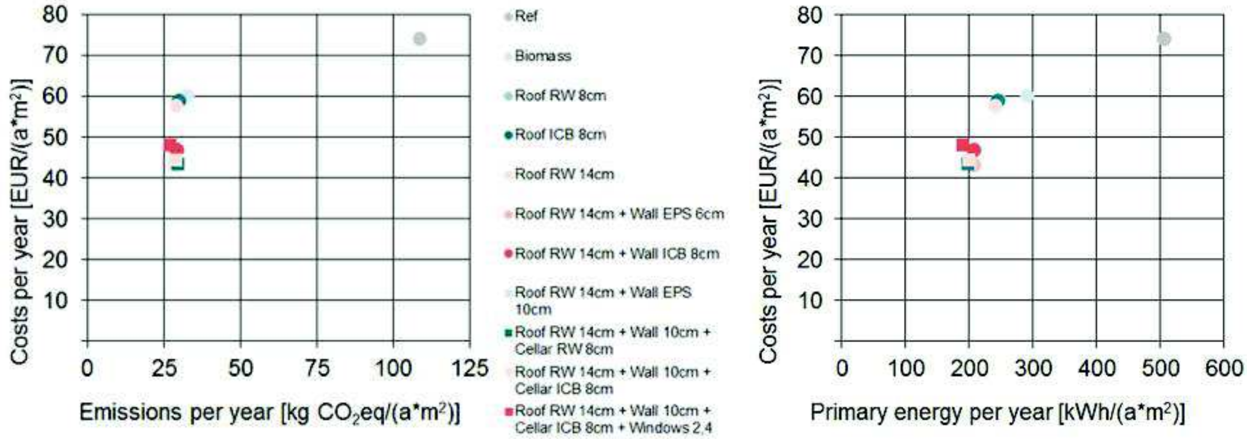


Figure 19: Comparison of cost effectiveness of energy efficiency renovation measures for the Portuguese Case Study for a biomass system, as well as related impacts on carbon emissions and primary energy use

Following Figure 20 summarizes the cost curves for different renovation packages on the building envelope with different BITS.

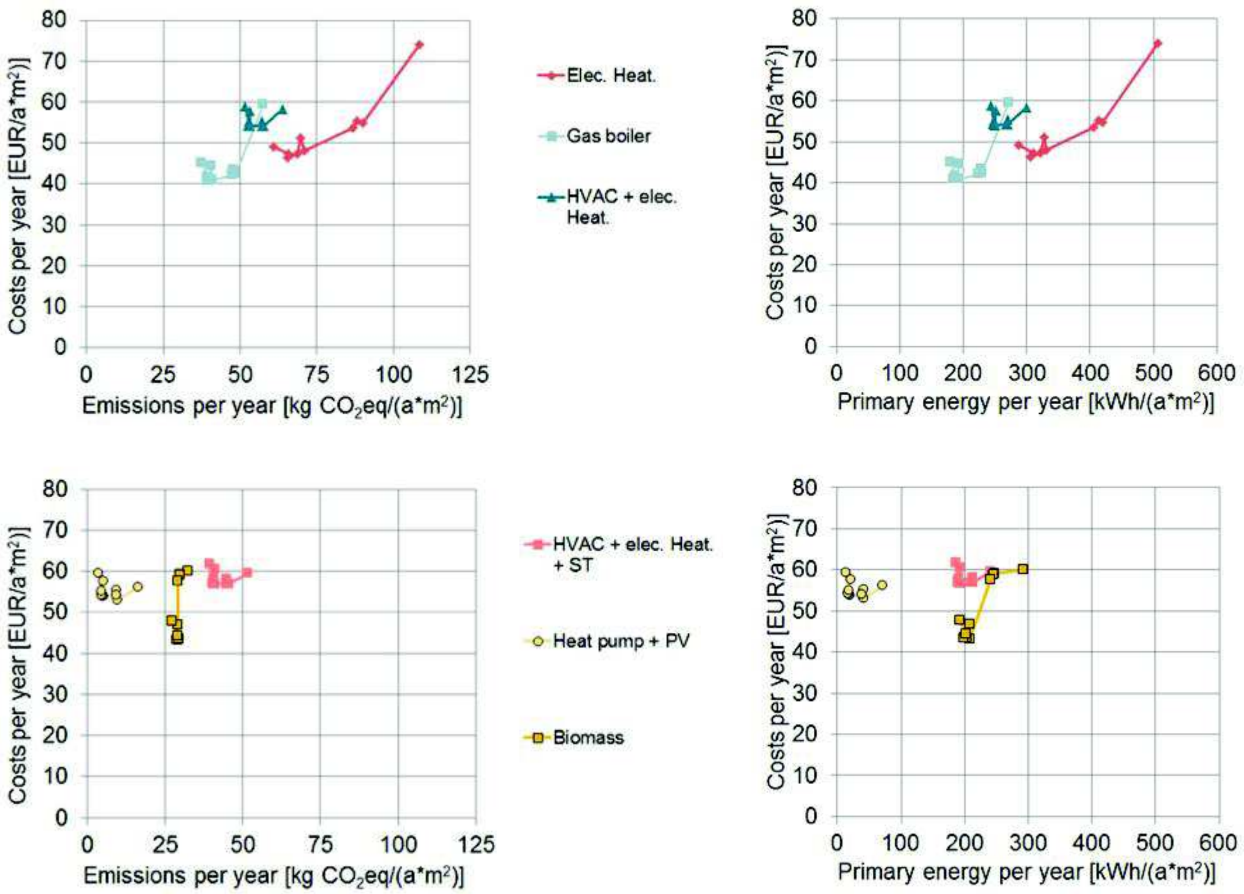


Figure 20: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different BITS and related impacts on carbon emissions and primary energy use for the Portuguese Case Study

5.3.3. Co-benefits

To synthetize the co-benefits analysis, 3 different renovation packages were compared to the cost optimal solution, namely the reference case, the chosen renovation and the best energy performance solution (M9 wit heat pump and photovoltaic panels). The results are presented in Table 12.

Table 12: Identification of co-benefits in several renovation packages in the Portuguese Case Study

Building elements	Reference	Chosen R.	M7 + GB	M9 + HP + PV
Façade	Maintenance	6 cm of RW	10 cm of EPS	10 cm of EPS
Roof	Maintenance	8 cm of RW	14 cm of RW	14 cm of RW
Floor	Maintenance	5 cm of RW	Maintenance	8 cm ICB
Windows	Maintenance	New windows U 2.4	Maintenance	New windows U 2.4
Heating system	Electric heater	Electric heater	Gas boiler	Heat pump + PV
DHW system	Gas boiler	Electric heater + ST	Gas boiler	Heat pump + PV
Co-benefits				
Aesthetics	▲	▲	▲	▲ ▼
Pride/prestige	▲ ▲	▲ ▲	▲ ▲	▲ ▲
Thermal comfort		▲ ▲ ▲	▲ ▲ ▲	▲ ▲ ▲
Building physics		▲ ▲	▲ ▲	▲ ▲
Internal noise		▼	▼	▼
Price fluctuation		▲ ▲	▲ ▲	▲ ▲ ▲
Air Quality		▲	▲	▲
External noise		▲		▲
Safety		▲		▲
Additional costs [EUR/m²a]	33	12	Cost optimal	13

Regarding the aesthetics/architectural integration, the positive co-benefit is also present in the reference case, so it cannot be accounted as a co-benefit deriving from energy related measures. In fact, in the best energy performance package, the existence of photovoltaic panels may be a problem due to the required dimensions and the characteristics of the buildings.

In the implemented renovation package, the introduction of new frames with double glazing present the co-benefit of safety and also of reduced external noise. However, in the interviews performed among the residents, these positive co-benefits have never been mentioned. In fact, once the neighbourhood is located in a very quiet area, nor noise or safety were an issue before the renovation. So the potential co-benefits from the improved window were not felt. Therefore, the relevance of these co-benefits is reduced when compared with the same measure in other case studies.

In the reduction of the exposure to the energy price fluctuation, the best energy performance package is the most independent one, due to the renewable energy production.

The analysis of the interviews to the respondents have also made visible that wrong design might have a huge influence in residents perception. In this case, internal shading and larger windows had negative impact in thermal comfort, natural lighting, building physics, and in the case of internal shading also creating problems with functionality and useful living areas.

5.3.4. Conclusions

For the analyzed parameters carbon emissions, total Primary Energy and Life Cycle Costs following conclusions can be drawn:

- The reference case achieves the highest carbon emissions, the highest Primary Energy values and also the highest LCC for the particular heating systems.
- The lowest carbon emissions and also the lowest Primary Energy values are achieved by the heat pump + PV combination.
- The change of the energy source reduces carbon emissions and total Primary Energy more significantly than the renovation measures on the building envelope.
- The influence of the renovation measures on the building envelope on the carbon emissions and the total Primary Energy reductions is depending on the BITS.
- The cost optimal package of energy efficiency measures does not change significantly with the different BITS combinations. On the other hand, with the use of the most efficient BITS, namely the HVAC and the heat pump, some energy efficiency measures, if compared with the use of those BITS without energy efficiency measures, are not cost effective.

Following Table 13 shows the investigated hypotheses for the Portuguese Case Study.

Table 13: Results for the investigated hypotheses for the Case Study “Rainha Dona Leonor neighborhood“ in Portugal. ✓ means that the hypothesis is confirmed. Symbols in parenthesis indicate that the hypotheses are only partly confirmed.

Hypothesis	Results from Case Study “Rainha Dona Leonor neighborhood”, Portugal
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements	(✓)*
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level	✓
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	(✓)**

* This hypothesis can be confirmed for the renovation measures roof and wall but not for the remaining measures, due to the small number of variants tested for those remaining measures.

** This hypothesis cannot clearly be answered. For the majority of the measures in this case study this is true. Only measures with a gas heating system is a contender.

For the Portuguese Case Study three hypotheses can absolutely be confirmed. The confirmation of the remaining hypotheses is more difficult and not completely possible. So for example the hypothesis: *"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements"* can only be confirmed for the renovation measures roof and wall. This means that it is more efficient to renovate the roof and the wall instead of concentrating only on the roof. Improving also the floor and changing the windows in this case doesn´t lead to major reductions in carbon emissions and Primary Energy. Instead these measures lead to an increase of the annual Life Cycle Costs compared to the situation where only insulation on the roof and the walls is considered.

5.4. Case Study "Lourdes Neighborhood", Spain

5.4.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope	Maintenance of the existing façade	40 mm EPS insulation of the façade	220 mm EPS insulation of the façade	60 mm EPS insulation of the façade
	Maintenance of the existing roof	40 mm XPS insulation of the roof	240 mm XPS insulation of the roof	60 mm XPS insulation of the roof
	No renovation measure regarding the floor	40 mm mineral wool insulation of the floor	240 mm mineral wool insulation of the floor	100 mm mineral wool insulation of the floor
	Maintenance of the old single-glazed windows	New double-glazed windows	New double-glazed windows	New double-glazed windows in addition to the existing single-glazed and sliding aluminum frame
BITS (Building Integrated Technical Systems)	New central heating system for heating and domestic hot water production	New central heating system for heating and domestic hot water production	New central heating system for heating and domestic hot water production	Renewal of the district heating system
			New mechanical ventilation system with heat recovery which can be also used to pre-cool the air (SFP = 1.5, Eff.= 75%)	
Investigated energy sources for heating and domestic hot water	Oil	Oil	Oil	
		Natural gas	Natural gas	
		Air-water heat pump	Air-water heat pump	
		District heating based on renewables (75%) and on natural gas (25%).	District heating based on renewables (75%) and on natural gas (25%).	District heating based on renewables (75%) and on natural gas (25%).
RES (renewable energy generation on-site)	None	None	26 m² solar thermal system for DHW production	
				11 kWp photovoltaic system for the electricity generation on-site

Note: For the scenario comparison, in renovation package v3 prefabrication and on-site photovoltaic system, that covers 50% of the electricity demand of the building, were included but not performed in reality.

Also for the Spanish Case Studies additional combinations of the individual renovation measures were defined and calculated. Again these additional measures were based on the previously described renovation packages v1, v2 and v3. In this case following combinations of renovation measures (marked with M1, M2,...) were tested:

Renovation package	Description
Ref	The reference case includes the maintenance of the existing façade, the existing roof and the old single-glazed windows.
M1	40 mm insulation of the façade
M2	60 mm insulation of the façade
M3	220 mm insulation of the façade
M4	M3 + 40 mm insulation of the roof
M5	M3 + 60 mm insulation of the roof
M6	M3 + 240 mm insulation of the roof
M7	M6 + 40 mm insulation of the floor
M8	M6 + 100 mm insulation of the floor
M9	M6 + 240 mm insulation of the floor
M10	M9 + new double-glazed windows

Also different heating systems were tested. Thereby renewable and non-renewable energy sources were calculated, including also renewable energy generation on-site by solar thermal and photovoltaic installations:

- Oil
- Natural gas
- Natural gas + solar thermal (26 m²)
- Electricity
- District heating (75% biomass)
- District heating (75% biomass) + solar thermal (26 m²)
- District heating (75% biomass) + solar thermal (26 m²) + photovoltaic (11 kWp)
- Heat pump
- Biomass

5.4.2. Results

The calculation results of the Spanish Case Study “Lourdes Neighborhood” can be seen in Figure 21. The chart shows on the left side the comparison of the Life Cycle Costs with the carbon emissions and on the right side the comparison of the LCC with the total Primary Energy.

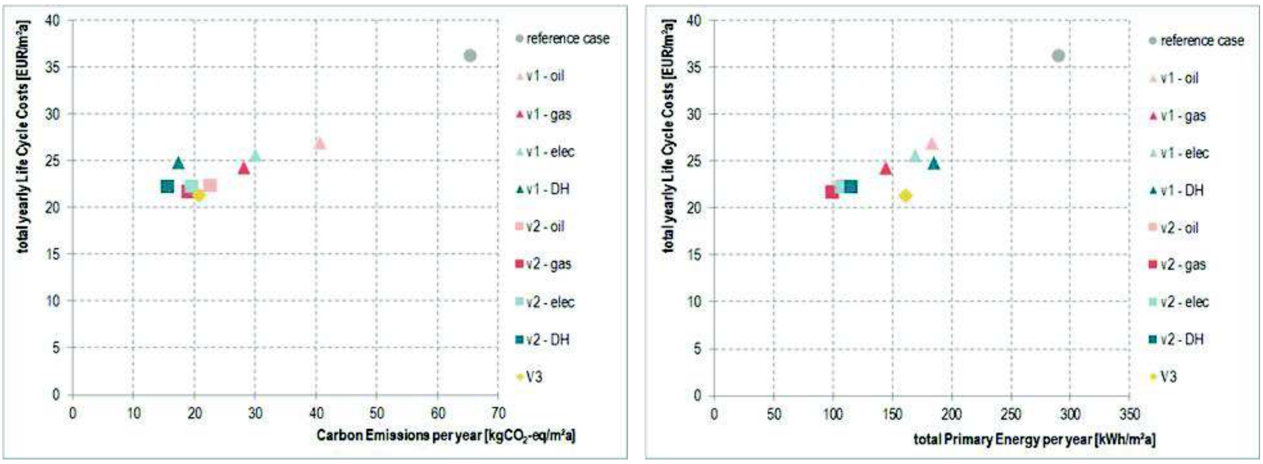


Figure 21: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study “Lourdes Neighborhood”, Spain

As visible in Figure 21 all investigated renovation packages are cost effective. That means the annual specific LCC of each renovation package are lower than the LCC of the reference case.

The lowest carbon emissions are achieved by renovation package v2 with district heating as main energy source for heating and domestic hot water production. For the DHW production also a solar thermal installation was considered. The carbon emissions of this renovation package are 15.7 $kgCO_2$-eq/m²a. The reference case achieves carbon emissions of 65.5 $kgCO_2$-eq/m²a. This means renovation package v2 with district heating and solar thermal installation can reduce the annual carbon emissions by 49.8 $kgCO_2$-eq/m²a respectively 76%.

The lowest total PE is achieved by renovation package v2 with natural gas as main energy source for heating and domestic hot water production. Again a solar thermal installation is considered in this case to support the DHW production. The total PE of this renovation package is 100 kWh/m²a. This is a reduction compared to the reference case of 190 kWh/m²a or 66%.

The cost optimal solution for the Case Study “Lourdes Neigborhood” in Spain is the actual renovation carried out (renovation package v3) considering that DHW is also supplied by the district heating and an additional PV installation is added. The cost optimal solution achieves carbon emissions of 20.9 $kgCO_2$-eq/m²a, a total PE of 162 kWh/m²a and annual LCC of 21.26 EUR/m²a.

The comparison of the cost optimal solution with the most ambitious renovation shows:

- Carbon Emissions: with additional annual LCC of 0.88 EUR/m²a the carbon emissions could be reduced from 20.9 kgCO_2-eq/m²a (cost optimal solution) to 15.7 kgCO_2-eq/m²a (lowest carbon emissions). That means an increase of the LCC by 4%, which is higher than the LCC of the cost optimal solution, the carbon emissions could be reduced by 25%.
- PE: with additional annual LCC of 0.26 EUR/m²a the total PE could be reduced from 162 kWh/m²a (cost optimal solution) to 100 kWh/m²a (lowest total PE). 1% higher annual LCC compared with the cost optimal solution would reduce the total PE by 38%.

To test the separate influence of the different renovation measures on the building envelope and the different heating systems, the cost effectiveness of the energy efficiency measures is analyzed for the Spanish Case Study in Figure 22, Figure 23 and Figure 24.

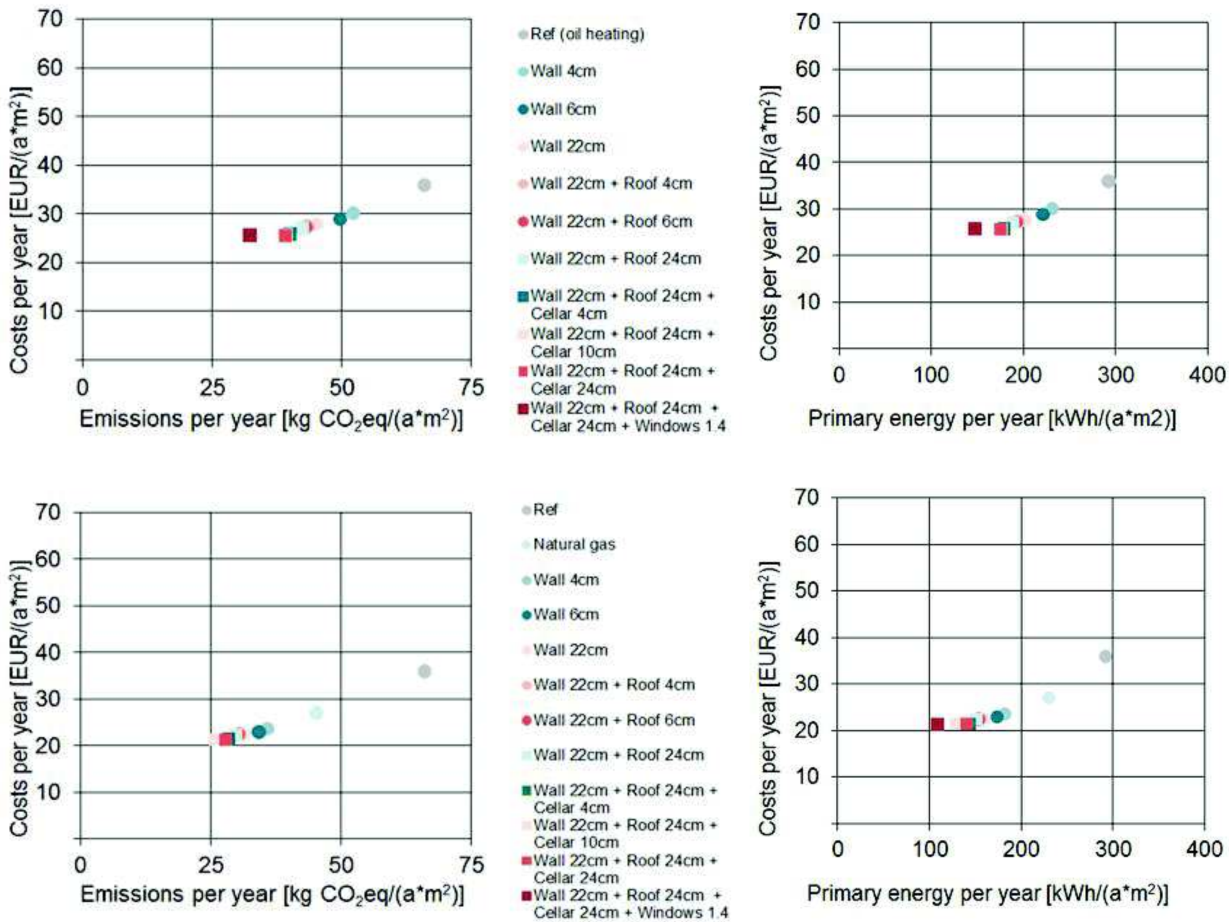


Figure 22: Comparison of cost effectiveness of energy efficiency renovation measures for the Spanish Case Study for the heating systems: oil heating (top) and natural gas (bottom), as well as related impacts on carbon emissions and primary energy use

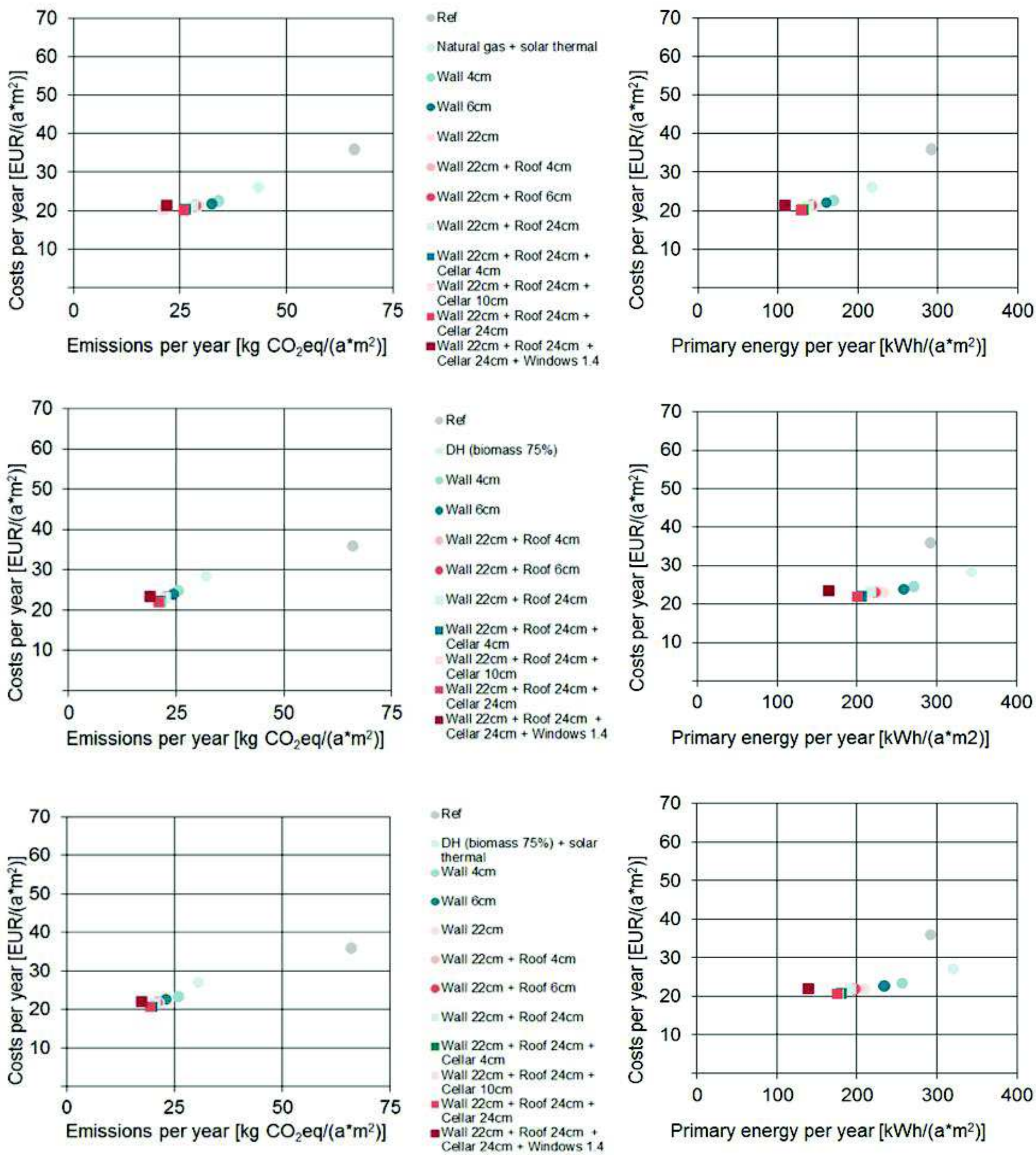


Figure 23: Comparison of cost effectiveness of energy efficiency renovation measures for the Spanish Case Study for the heating systems: natural gas + solar thermal (top), district heating (middle) and district heating + solar thermal (bottom), as well as related impacts on carbon emissions and primary energy use

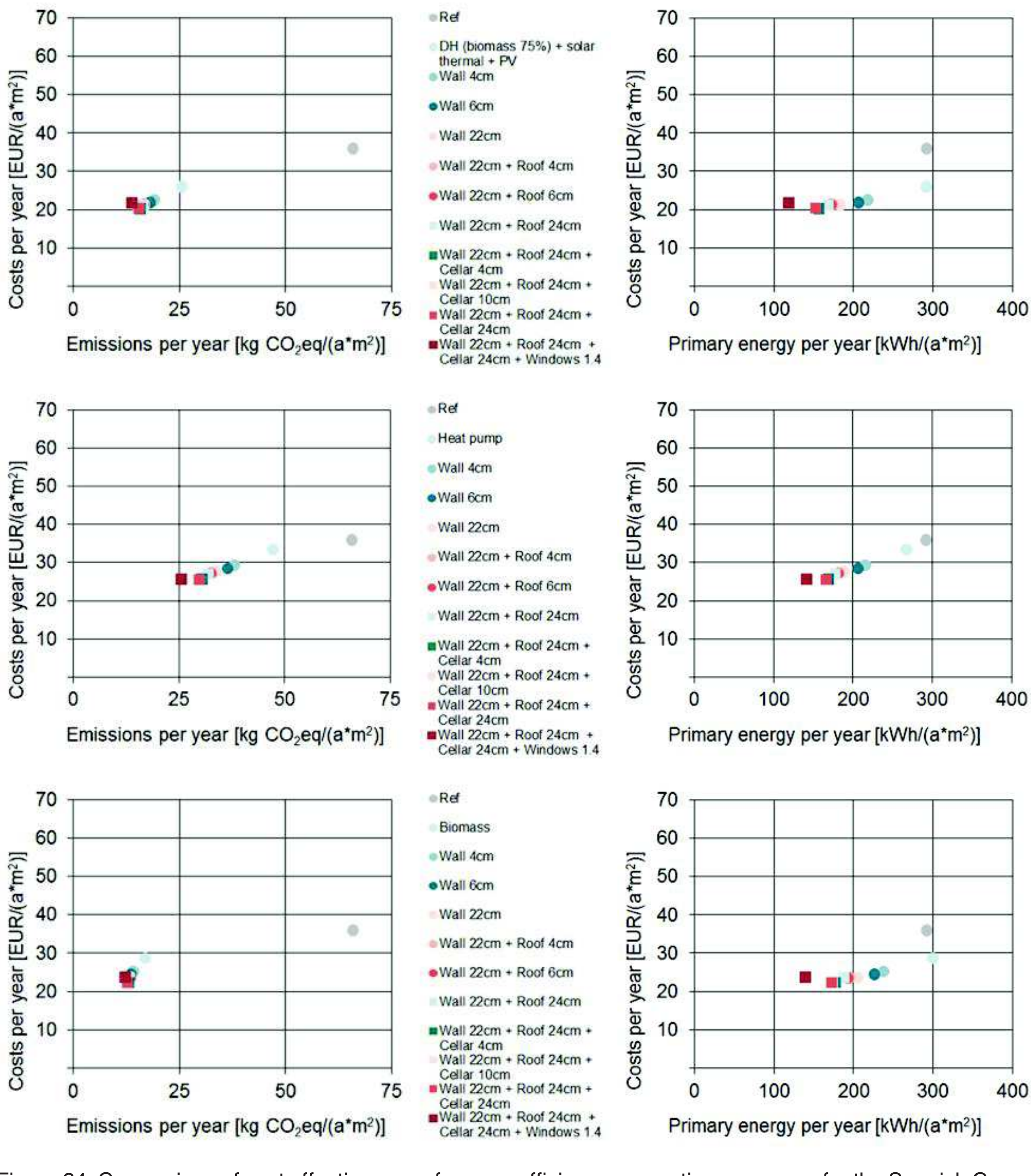


Figure 24: Comparison of cost effectiveness of energy efficiency renovation measures for the Spanish Case Study for the heating systems: district heating + solar thermal + photovoltaic (top), heat pump (middle) and biomass (bottom), as well as related impacts on carbon emissions and primary energy use

The cost curves for the different renovation packages on the building envelope with different heating systems are summarized in Figure 25. In each of these graphs, four different curves are shown, representing the application of the different renovation packages on the building envelope in combination with the installation of different heating systems. Each dot in the curves represents the application of a particular renovation package.

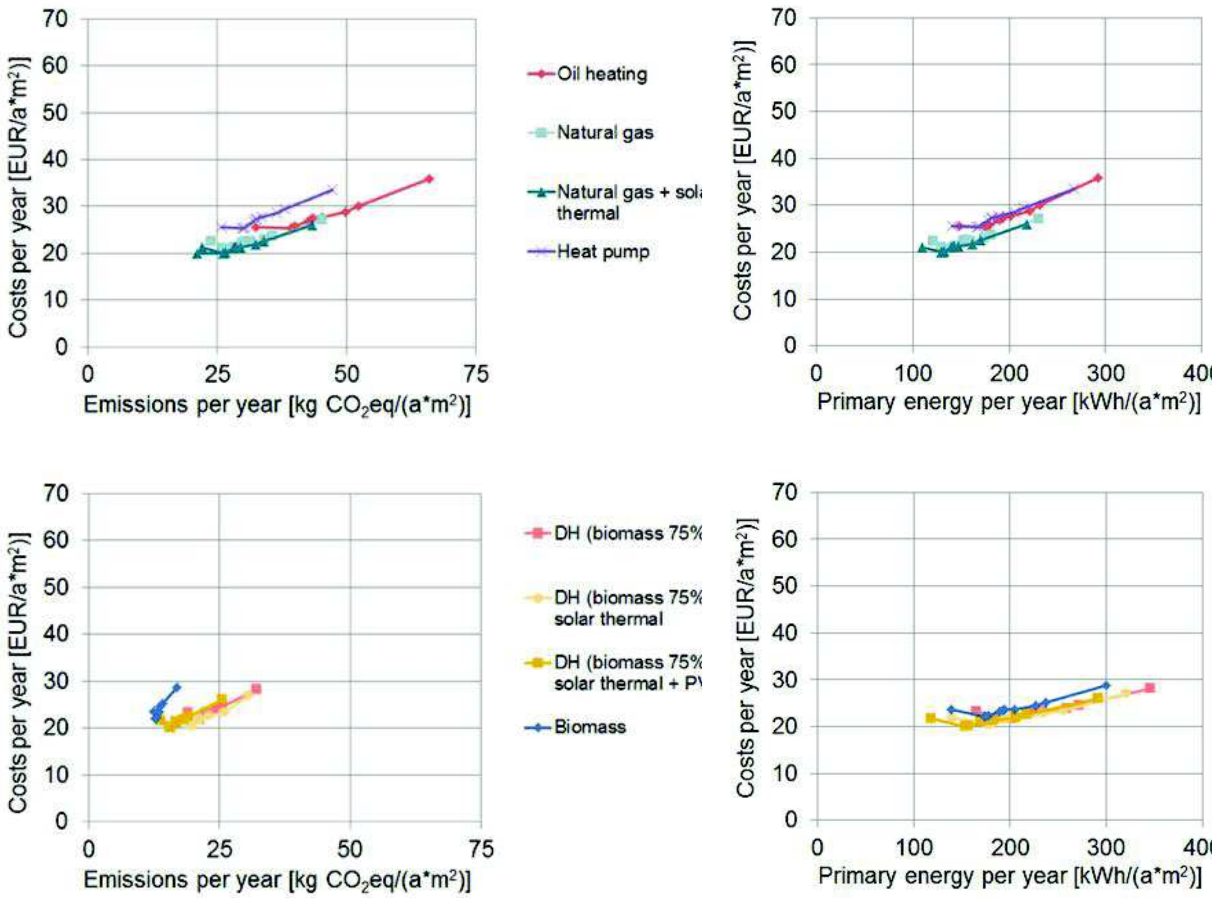


Figure 25: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Spanish Case Study

5.4.3. *Co-benefits*

Table 14 presents the co-benefits for some of the renovation packages, namely the reference case, the cost optimal solution (M9 with gas boiler backed by solar thermal), the solution with the best energy performance (M10 with gas boiler backed by solar thermal) and the chosen renovation package.

Despite presenting higher global costs and worse energy performance than the other two packages improving the energy performance, the chosen renovation package presents more positive co-benefits than the cost optimal and similar benefits to the scenario with the best energy performance. This evaluation derives from the fact that the cost optimal scenario doesn't include the change of the windows while the chosen renovation and the scenario with the best energy performance include improvements in all the building envelope elements.

Table 14: Identification of co-benefits in several renovation packages in the Spanish Case Study

Building elements	Reference	Chosen Renov.	M9 + GB + ST	M10 + GB + ST
Façade	Maintenance	6 cm of XPS	22 cm of XPS	22 cm of XPS
Roof	Maintenance	6 cm of XPS	24 cm of XPS	24 cm of XPS
Floor	Maintenance	10 cm of RW	24 cm of RW	24 cm of RW
Windows	Maintenance	New windows U 1.8	Maintenance	New windows U 1.4
Heating system	Collec. Oil boiler	DH biomass + gas	Gas boiler	Gas boiler
DHW system	Collec. Oil boiler	Gas boiler	Gas boiler	Gas boiler
Renewables	None	None	Solar thermal	Solar thermal
Co-benefits				
Aesthetics	▲	▲	▲	▲
Pride/prestige	▲▲	▲▲	▲▲	▲▲
Thermal comfort		▲▲	▲▲▲	▲▲▲
Building physics		▲▲	▲▲	▲▲
Internal noise		▼	▼	▼
Price fluctuation		▲▲	▲▲	▲▲
Air Quality		▲	▲	▲
External noise		▲▲		▲▲
Safety		▲▲		▲▲
Additional costs [EUR/m²a]	16	1.4	Cost optimal	1.2

5.4.4. *Conclusions*

For the analyzed parameters carbon emissions, total Primary Energy and Life Cycle Costs the following conclusions can be drawn:

- The reference case achieves the highest Life Cycle Costs and highest carbon emissions.
- The highest Primary Energy is achieved, when only the heating system is changed to district heating based on 75% biomass and no further energy related measures are carried out.
- The lowest carbon emissions are achieved by renovation measure M10, which represents the most improved building envelope, together with a biomass heating system.
- The lowest total Primary Energy is also achieved by renovation measure M10 but in this case a natural gas heating system together with a solar thermal installation leads to these low total PE values.
- The calculation results show that it is more effective to reduce the carbon emissions if several building elements are renovated instead of concentrating only on one element. The exception is if the renovation measures on the building envelope are combined with a biomass heating systems. In this case the investigated efficiency measures on the envelope don´t have a big influence on the carbon emissions. The impact of switching from oil to biomass is much larger.
- Only changing the heating system (without improving the thermal properties of the building envelope) reduces the carbon emissions but not automatically the Primary Energy. In the case of district heating, district heating + solar thermal and biomass this measure leads to an increase of the total Primary Energy.

- Carbon emission and total Primary Energy reductions in consequence of renewable energy generation on-site by the solar thermal and photovoltaic installations are given but are quite small. Nevertheless the on-site generation leads also to a reduction of the Life Cycle Costs compared to the system without generation on-site.

Following Table 15 shows the investigated hypotheses for the Spanish Case Study.

Table 15: Results for the investigated hypotheses for the Case Study "Lourdes Neighborhood" in Spain. ✓ means that the hypothesis is confirmed, ✗ means that the hypothesis is not confirmed. Symbols in parenthesis or separated by a slash indicate that the hypothesis is only partly confirmed / not confirmed.

Hypothesis	Results from Case Study "Lourdes Neighborhood", Spain
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	(✓)*
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level	✓
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓/✗*

* Confirmation for district heating with 75% biomass of for biomass heating system possible, yet not for heat pump.

For the Spanish Case Study two of the five hypotheses can be completely confirmed. The hypothesis *"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements"* is disproved, as for example the 22 cm wall insulation achieves similar good results as the same measure plus adding insulation on the roof. That means carrying out additional measures doesn´t lead to major carbon emissions and total Primary Energy reductions.

The hypotheses *"A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements"* and *"To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone."* cannot completely be confirmed. The hypotheses are true for biomass based heating systems but not for heat pump.

5.5. Case Study “Backa röd”, Sweden

5.5.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope	Maintenance of the façade	100 mm additional insulation of the façade	195 mm additional insulation of the façade	195 mm additional insulation of the façade
		100 mm additional insulation of the roof	300 mm additional insulation of the roof	300 mm additional insulation of the roof
		100 mm additional insulation of the base wall and 100 mm expanded clay added in the crawl space	195 mm additional insulation of the base wall and 500 mm expanded clay added in the crawl space	195 mm additional insulation of the base wall and 500 mm expanded clay added in the crawl space
		New triple-glazed windows (U-value 1.7 W/m²K)	New triple-glazed windows (U-value 0.9 W/m²K)	New triple-glazed windows (U-value 0.9 W/m²K)
BITS (Building Integrated Technical Systems)	New district heating substation, for heating and new recirculation for domestic hot water installed	New radiators New individual metering and invoicing of domestic hot water	New radiators New individual metering and invoicing of domestic hot water	New radiators New individual metering and invoicing of domestic hot water
		New balanced mechanical ventilation system with heat recovery (Eff.= 50%)		New balanced mechanical ventilation system with rotary heat exchangers (Eff.= 75%)
		New building automation system		New building automation system
			New low-energy lighting	New low-energy lighting
Investigated energy sources for heating and domestic hot water		Oil	Oil	
		Natural gas	Natural gas	
		Electricity	Electricity	
	District heating partly (81%) based on renewables	District heating partly based on renewables	District heating partly based on renewables	District heating partly (81%) based on renewables
RES (renewable energy generation on-site)	None	None	None	None

Following combinations of renovation measures (marked with M1, M2,...) were defined and tested to answer the defined hypotheses in detail. In addition to the investigated renovation measures in the renovation packages v1, v2 and v3 in M11 a photovoltaic installation was included to test also the influence of a renewable energy generation on-site on the total results.

Renovation package	Description
Ref	In the reference case, the existing façade is maintained. No further energy related renovation measures are considered.
M1	100 mm insulation of façade
M2	195 mm insulation of façade
M3	M2 + 100 mm insulation of the roof
M4	M2 + 300 mm insulation of the roof
M5	M4 + 100 mm insulation of the floor
M6	M4 + 195 mm insulation of the floor
M7	M6 + new windows (U-value 1.7 W/m²K)
M8	M6 + new windows (U-value 0.9 W/m²K)
fasc	M8 + mechanical ventilation with heat recovery
M10	M9 + building automation and low-energy lighting
M11	M10 + photovoltaic installation

The renovation measures M1 to M11 were also tested with different heating systems:

- Oil
- Pellets
- District heating partly (81%) based on renewables
- District heating based on 100 % RES

Again, carbon emissions, total Primary Energy and Life Cycle Costs of the different combinations of renovation measures on the building envelope and of the Building Integrated Technical Systems were tested. The results of the Swedish Case Study “Backa röd” are presented in following chapter 5.5.2.

5.5.2. Results

Figure 26 shows the calculation results. On the left side the comparison of the Life Cycle Costs with the carbon emissions, on the right side the comparison with the total Primary Energy.

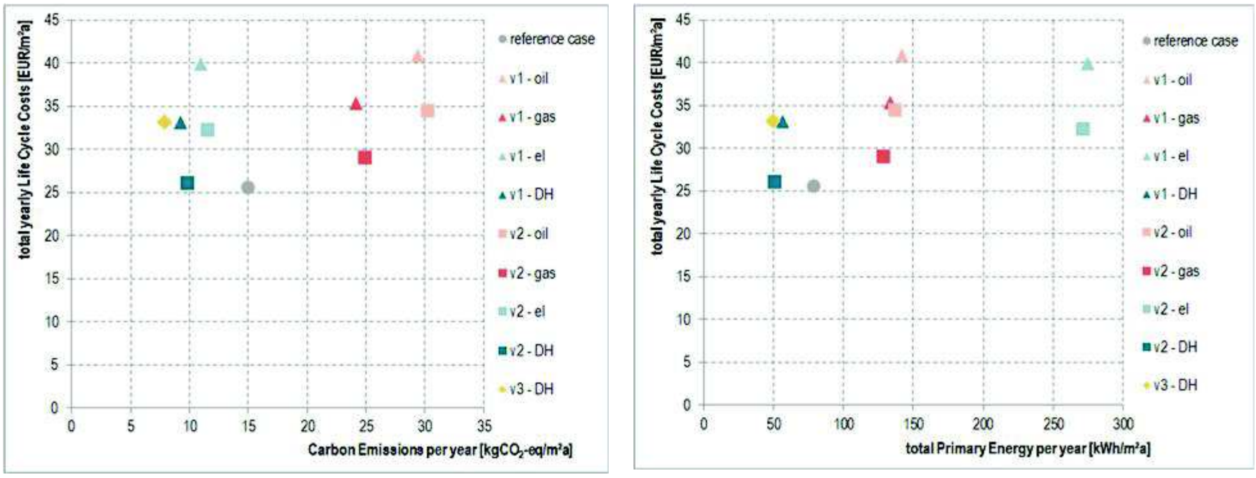


Figure 26: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study “Backa röd”, Sweden

The results show that if the carbon emissions are the main parameter, the renovation packages v2 with heating and domestic hot water production based on electricity, the renovation packages v1 and v2 based on district heating and the actual renovation carried out, renovation package v3, achieve carbon emissions reductions, but are not cost effective. However, the annual costs of renovation package v2 based on district heating are almost the same as for the reference case.

The renovation packages v1 and v2 with heating and DHW production based on natural gas and based on oil achieve higher carbon emissions than the reference case.

The increased carbon emissions can be explained by the higher conversion factor of oil compared to the conversion factor of the partly renewable district heating. The district heating is to 81 % based on renewable energy and 19 % fossil fuels according to Göteborg Energy, which explains the low carbon emission and the low primary energy.

Nevertheless it has to be mentioned that all investigated renovation packages have higher LCC than the reference case. This means that although carbon emissions reduction could be achieved, carrying out these renovation measures would not be cost effective.

If the total PE is regarded as the main parameter the renovation packages v1 and v2 with district heating and the actual renovation carried out (renovation package v3) achieve a reduction of the total PE. The total PE of all other renovation packages is higher than the reference case.

The lowest carbon emissions are achieved by the executed renovation package v3 with a value of 8 kgCO_2-eq/m²a. This is a reduction compared to the reference case by 7 kgCO_2-eq/m²a respectively 47%. In comparison with the highest carbon emissions, which are achieved by renovation package v2 with an oil based heating and domestic hot water production, this is a reduction of 74%.

The lowest total PE is achieved by renovation package v3 with heating and domestic hot water based on district heating. The total PE of this renovation package is 50 kWh/m²a and therefore 30 kWh/m²a or 37% lower than the total PE of the reference case. Compared to the highest total PE, which is achieved by the renovation package v1 with heating and DHW production based on electricity, it is a reduction of 225 kWh/m²a or 82%.

The cost optimal solution is, as mentioned before, the reference case with annual LCC of about 26 EUR/m²a.

The following charts in Figure 27 and Figure 28 show the comparison of the different energy efficiency renovation measures for the Swedish Case Study for conventional district heating, which is partly based on renewables, district heating completely based on renewable energy sources, oil heating and pellets burner (top down), and related impacts on carbon emissions and primary energy use. The reference shown as a grey dot refers to a situation with district heating partly based on renewables.

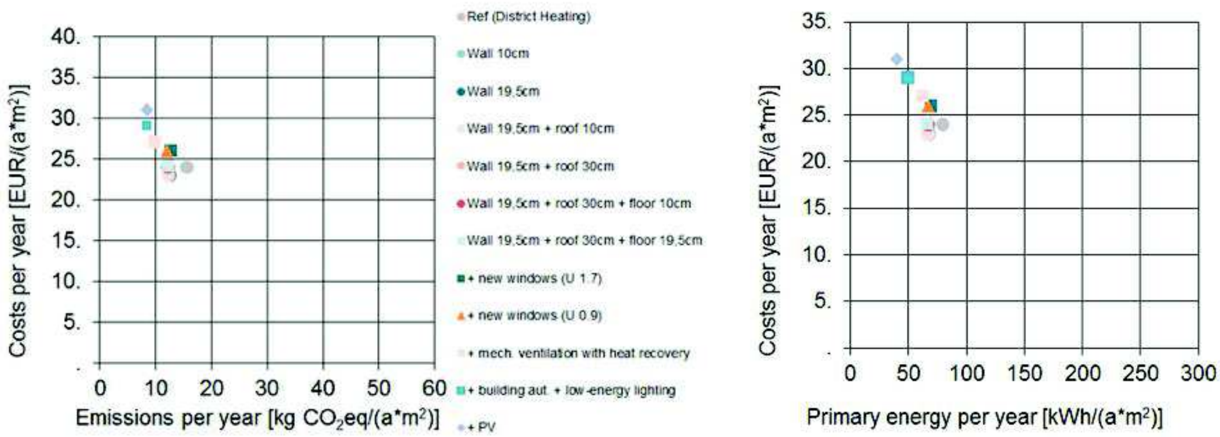


Figure 27: Comparison of cost effectiveness of energy efficiency renovation measures for the Swedish Case Study for district heating (partly based on renewable energy sources), as well as related impacts on carbon emissions and primary energy use.

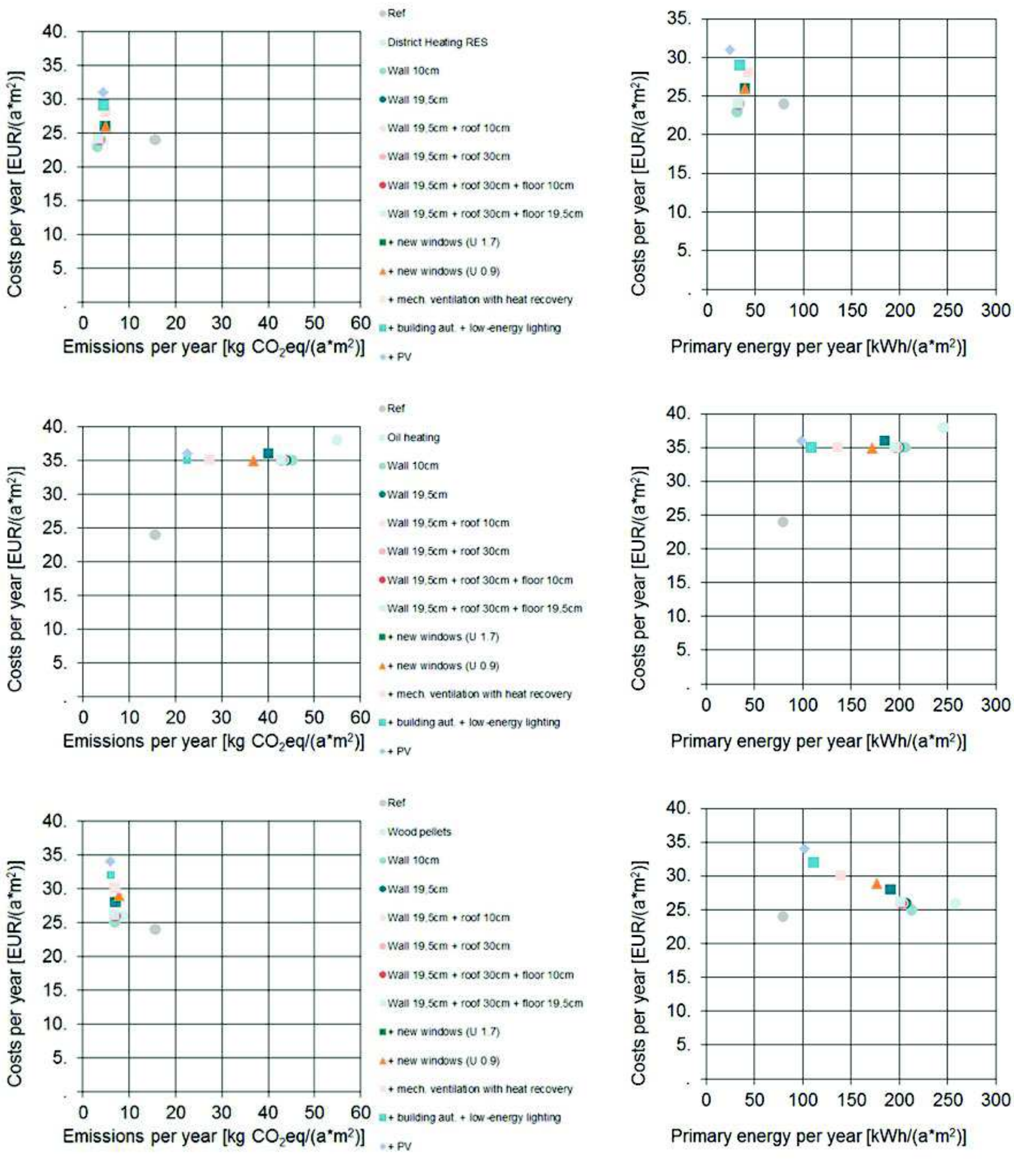


Figure 28: Comparison of cost effectiveness of energy efficiency renovation measures for the Swedish Case Study for district heating based on renewable energy sources (top), oil heating (middle) and pellets burner (bottom), as well as related impacts on carbon emissions and primary energy use

Figure 29 summarizes the cost curves for the different renovation measures on the building envelope with different heating systems. The four different curves represent the application of the different renovation measures on the building envelope in combination with the installation of different heating systems. Each dot in the curves represents the application of a particular renovation package. The point with the highest emissions or highest primary energy use for each energy source represents the anyway renovation. As more measures are added to the renovation packages, carbon emissions and primary energy use decrease.

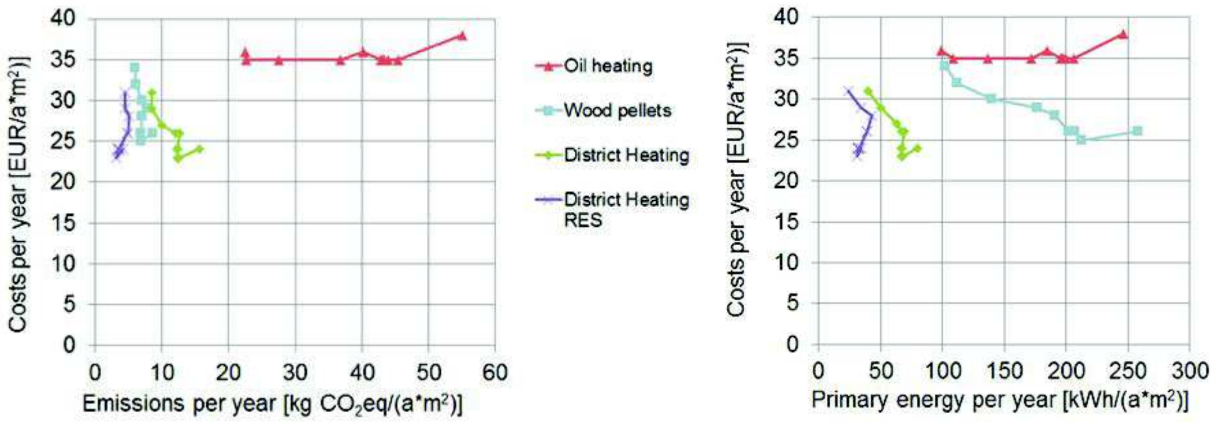


Figure 29: Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Swedish Case Study

5.5.3. Co-benefits

The façades were damaged by carbonation and were in need of renovation. The building was leaky, through the façade and between the apartments. Draught occurred from the infill walls at the balcony and cold floors were caused by thermal bridges from the balconies.

For the co-benefits analysis the cost optimal solution (renovation package M1 + district heating for heating and domestic hot water production) was compared to the solution that leads to best energy performance (renovation package M11 + district heating + photovoltaic installation on-site) and also with M11 combined with wood pellets. The identified co-benefits are visible in Table 16.

Analyzing Table 16 it is noticeable that the packages of measures improving significantly the building envelope present several co-benefits related with the building quality such as improved thermal comfort, reduced problems related to building physics, reduced external noise and improved safety against intrusion. However, this come with increased global cost when compared to the cost optimal package, an increase of 8 to 11 €/m²a. On the other hand, the use of district heating, particularly if mainly based on renewables, is the main origin of financial benefits and economic co-benefits, namely the reduction of the exposure to energy price fluctuations.

Table 16: Identification of co-benefits in several renovation packages in the Swedish Case Study

Building elements	Reference	M1 + DH	M11 + WP + PV	M11 + DH (RES) + PV
Façade	Maintenance	19.5 cm of RW	19.5 cm of RW	19.5 cm of RW
Roof	Maintenance	Maintenance	50 cm of RW	50 cm of RW
Floor	Maintenance	Maintenance	19.5 cm of RW	19.5 cm of RW
Windows	Maintenance	Maintenance	3x glazing U=0.9	3x glazing U=0.9
Ventilation	Natural	Natural	Mech. + heat recov	Mech. + heat recov
Heating system	District heating	District Heating	Wood pellets	RES District heating
DHW system	District heating	District Heating	Wood pellets	RES District heating
RES	None	None	PV	PV
Co-benefits				
Aesthetics	▲	▲	▲ ▼	▲ ▼
Pride/prestige	▲	▲	▲ ▲	▲ ▲
Thermal comfort		▲ ▲	▲ ▲ ▲	▲ ▲ ▲
Building physics		▲	▲ ▲	▲ ▲
Internal noise			▼	▼
Price fluctuation		▲	▼	▲ ▲
Air Quality			▲	▲
External noise			▲ ▲	▲ ▲
Safety			▲ ▲	▲ ▲
Additional costs [EUR/m²a]	1	Cost optimal	11	8

5.5.4. Conclusions

Summarized the following conclusions can be drawn for the analyzed parameters:

- Only changing the heating system from conventional district heating to district heating based on renewables, without improving the building envelope, is not a cost effective measure but reduces carbon emissions and total Primary Energy.
- The oil heating achieves higher (and also highest) carbon emissions and total Primary Energy values. Furthermore none of the investigated renovation measures are cost effective, when combined with oil heating or wood pellets.
- The lowest carbon emissions are achieved by the renovation measure which includes the photovoltaic installation, independent of the chosen energy source for heating and DHW. But it has to be mentioned that the influence of the photovoltaic system on the carbon emissions is quite small, as the photovoltaic system only contributes to the operation of fans and pumps. Besides this measure, the lowest carbon emissions are achieved by the renewable district heating combined with the complete renovation package.
- The lowest total Primary Energy is also achieved by the renovation measure which includes the photovoltaic installation, again independent of the chosen energy source for heating and DHW. Compared to the carbon emissions the influence of the photovoltaic system on the total PE is bigger. If the photovoltaic installation is not taken into account, the lowest total Primary Energy is also achieved by the renewable district heating in combination with the entire investigated renovation measures.

Following Table 17 shows the investigated hypotheses for the Swedish Case Study.

Table 17: Results for the investigated hypotheses for the Case Study "Backa röd" in Sweden. ✓ means that the hypothesis is confirmed, ✗ means that the hypothesis is not confirmed. Symbols in parenthesis or separated by a slash indicate that the hypothesis is only partly confirmed / not confirmed.

Hypothesis	Results from Case Study "Backa röd", Sweden
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓/✗
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓

For the Swedish Case Study two of the five hypotheses can absolutely be confirmed. Disproved is the hypothesis *"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements"*, where the calculations show that performing additional renovation measures on the building envelope does not result in reduced carbon emissions, total Primary Energy values and Life Cycle Costs. The hypotheses *"A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level"* and *"Synergies are achieved when a switch to RES is combined with energy efficiency measures"* cannot completely be confirmed. The hypothesis mentioned second for example is true for insulation of the exterior wall in combination with the change to district heating based on RES but not confirmed for all remaining renovation measures in combination with district heating based on RES and also for all combinations with a pellets heating system.

5.6. Case Study "Kamínky 5", Czech Republic

5.6.1. Investigated renovation packages

	Reference case	Renovation package v1	Renovation package v2	Renovation package v3
Building envelope		Addition of 60 to 90 mm EPS, XPS and mineral wool insulation on the façade	Addition of 60 to 290 mm EPS, XPS and mineral wool insulation on the façade	Addition of 60 to 160 mm EPS, XPS and mineral wool insulation on the façade
		Addition of 90 mm EPS insulation on the roof	Addition of 300 mm EPS insulation on the roof	Addition of 180 mm EPS insulation on the roof
		Addition of up to 130 mm EPS and mineral wool insulation to the ceiling under the first floor	Addition of up to 380 mm EPS and mineral wool insulation to the ceiling under the first floor	Addition of up to 240 mm mineral wool insulation to the ceiling under the first floor
	New double- and triple glazed windows	New double- and triple-glazed windows	New triple-glazed windows	New double- and triple-glazed windows
BITS (Building Integrated Technical Systems)	New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers	New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers	New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers	New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers
	Renovation of the heat exchanger connected to the district heating	New heating system including new storage tank for DHW	New heating system including new storage tank for DHW	New heating system including new storage tank for DHW
Investigated energy sources for heating and domestic hot water	District heating based on natural gas	District heating based on natural gas Natural gas Electricity	District heating based on natural gas Natural gas Electricity	District heating based on natural gas Natural gas Electricity
RES (renewable energy generation on-site)	None	Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site	Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site	Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site

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 renovation package v1, renovation packages v2-DH, v2-gas and v2-elec as well as in all variants of v3.

Remaining variants of renovation package v2 (v2-DH+PV, v2-gas+PV and v2-elec+PV) model “direct” incorporation of the photovoltaic – generated electricity covers 50 % of DHW energy consumption and the rest is used for lighting, common appliances, etc.

5.6.2. Results

The calculation results of the Czech Case Study “Kamínky 5” are shown in Figure 30. The chart on the left side shows the comparison of the Life Cycle Costs with the carbon emissions, the right side shows the comparison of the Life Cycle Costs with the total Primary Energy.

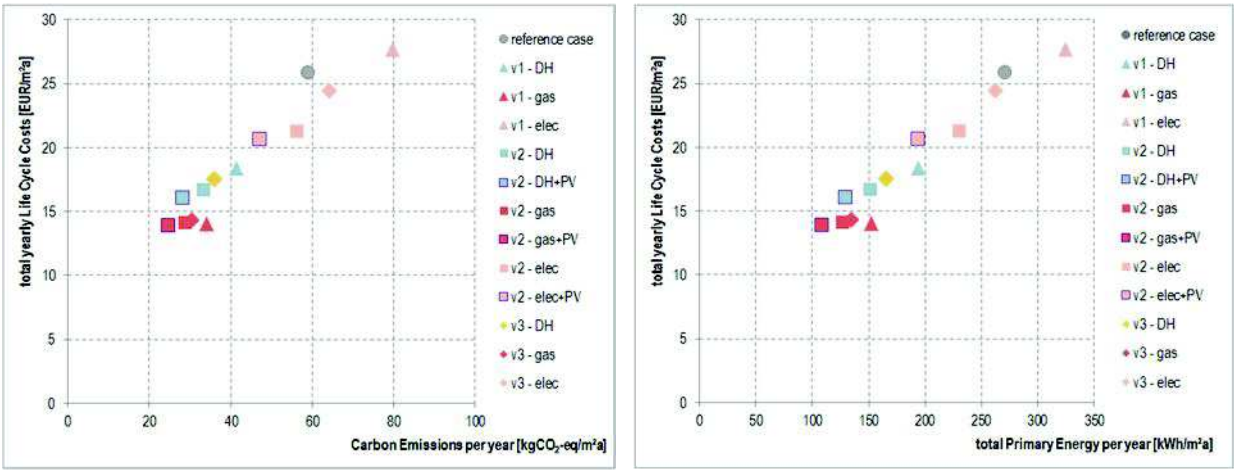


Figure 30: Life Cycle Costs in comparison with carbon emissions (left chart) and total Primary Energy (right chart) of the Case Study “Kamínky 5”, Czech Republic

The results in Figure 30 show that almost all renovation packages v1, v2 and v3 are cost effective. Only the renovation package v1 with heating and DHW production based on electricity achieves higher Life Cycle Costs than the reference case.

The lowest carbon emissions are achieved by renovation package v2, with heating and DHW production based on natural gas, including also the photovoltaic installation owned by the school[15]. This renovation package achieves annual carbon emissions of 25 kgCO_2-eq/m²a, which is a reduction of more than 34 kgCO_2-eq/m²a or 58% compared to the reference case.

15 In this case the generated electricity is used to cover the electricity demand of the school building.

The executed renovation package v3 with district heating achieves annual carbon emissions of 36 kgCO_2-eq/m²a. This is a reduction of almost 23 kgCO2-eq/m²a or 39% compared to the reference case.

The lowest total PE is also achieved by renovation package v2 with natural gas based heating and DHW production, including again the photovoltaic installation for on-site energy generation. This package achieves a total PE of 109 kWh/m²a, which is a reduction of 162 kWh/m²a or 60% compared to the reference case.

The executed renovation achieves a total PE value of 166 kWh/m²a. This is a reduction, compared to the reference case, of 105 kWh/m² or 39%.

The cost optimal solution of all investigated renovation packages is also renovation package v2 based on natural gas for heating and DHW supported by a photovoltaic installation for the energy generation on-site. The annual LCC of this renovation package are 13.89 EUR/m²a. This is a reduction of 12 EUR/m²a or 46% compared to the reference case.

The executed renovation achieves annual Life Cycle Costs of 17.48 EUR/m²a. This value represents a reduction of 8.41 EUR/m²a, which is a reduction of 32% compared to the reference case.

The executed renovation met the expectations, even though the ex-post assessment presented above shows that there were more cost-efficient ways of improving the school‘s energy consumption and environmental impacts. Other variants were dismissed due to increased costs or time requirements during the design process.

Especially time was the limiting factor for the renovation. It was not possible to provide alternative spaces for the school. Thus most of the indoor construction works had to be done during summer holiday, when the school was closed. This meant approximately two months of working time. For example the cost optimum renovation package presented in this assessment uses gas heating. The installation of the gas boiler would have required modifications of the whole heating system. These modifications would have required modifications of floor covers, floors structures and also of other structures of the building. This scale of work would have either required much more time than available two months or increase the unnecessarily increase the construction costs.

Influence of improving the energy performance of the building envelope:

To test the influence of the energy performance of the building envelope on the total results the reference case is compared to the renovation packages v1, v2 and v3, in each case equipped with district heating and the same BITS. In this case only the influence of improving the thermal envelope can be investigated.

Figure 31 shows the comparison of the four different renovation scenarios for district heating, and related impacts on carbon emissions and Primary energy use.

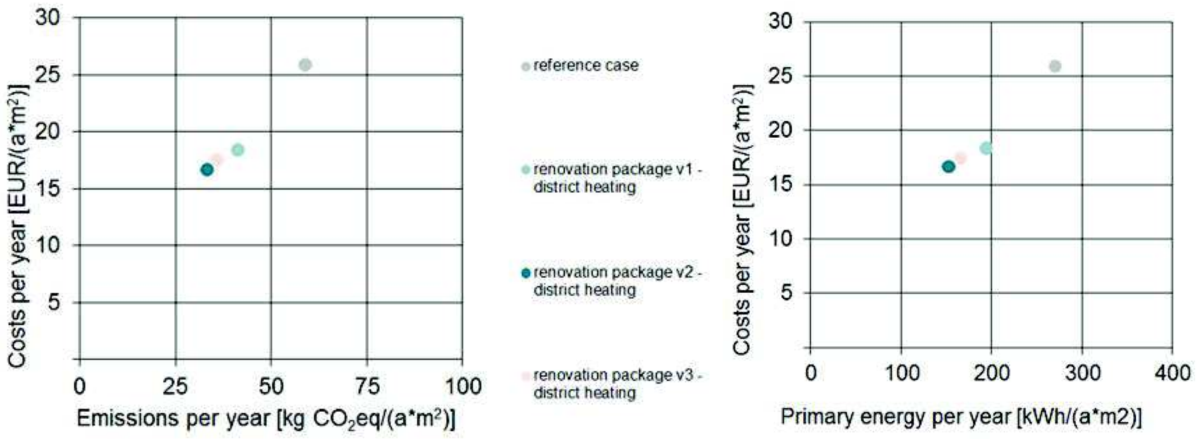


Figure 31: Comparison of four different renovation scenarios, all equipped with district heating, for the Czech Case Study, to investigate the influence of the thermal quality of the building envelope on the annual Life Cycle Costs, carbon emissions and Primary Energy

Influence of modifying the energy source for heating and domestic hot water

For each of the three thermal standards (renovation package v1, v2 and v3) district heating, natural gas and electricity were tested to investigate the influence of the choice of the heating system on the total results of Life Cycle Costs, carbon emissions and total Primary Energy.

The results of this investigation are visible in Figure 32 and Figure 33.

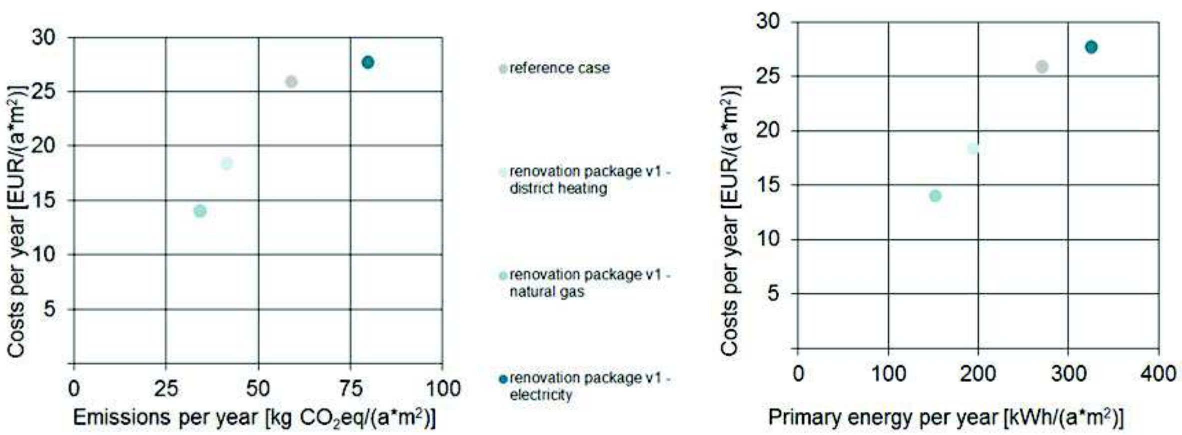


Figure 32: Comparison of district heating, natural gas and electricity for the renovation package v1 of the Czech Case Study to investigate their influence on the annual Cycle Costs, carbon emissions and total Primary Energy

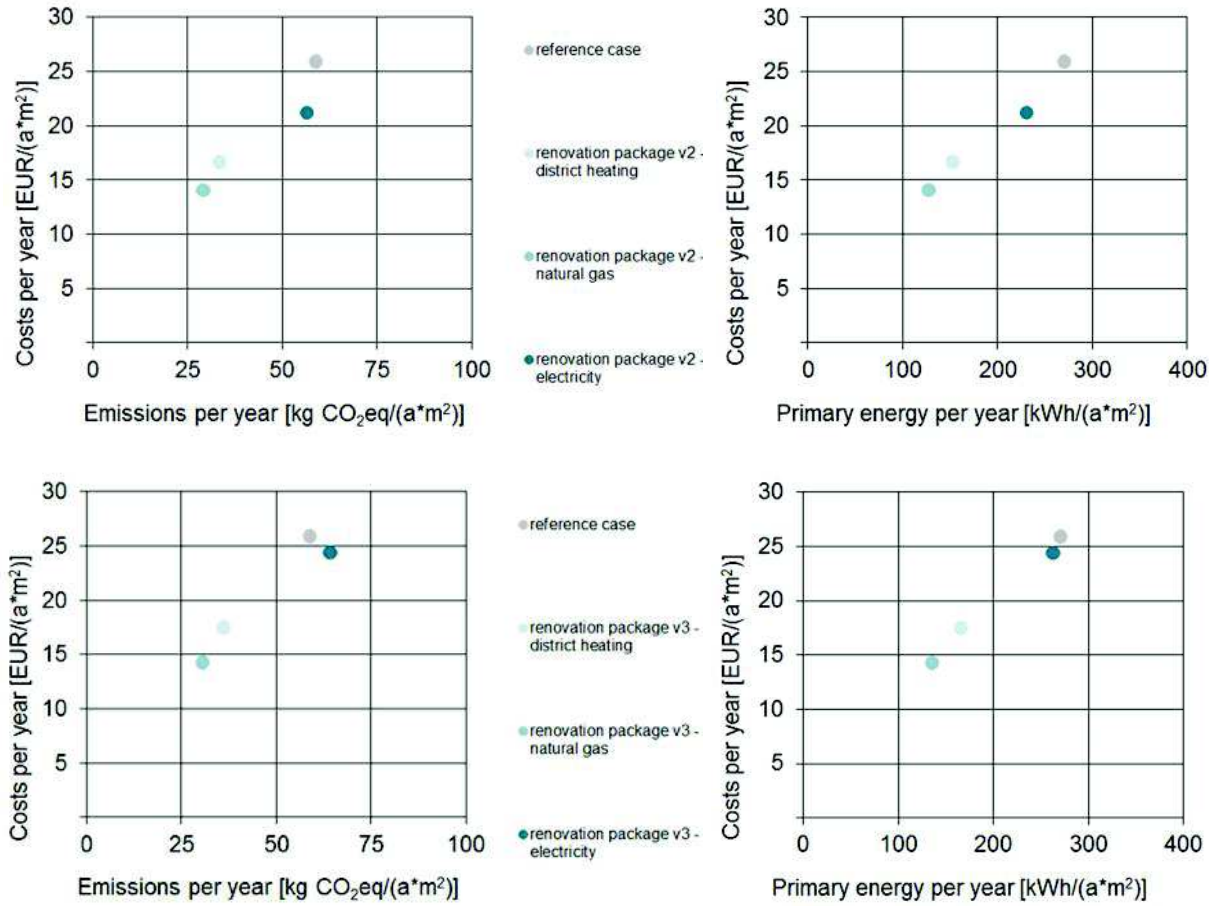


Figure 33: Comparison of district heating, natural gas and electricity for the renovation packages v2 (top) and v3 (bottom) of the Czech Case Study to investigate their influence on the annual Cycle Costs, carbon emissions and total Primary Energy

Influence of renewable energy generation on-site

In the Czech Case Study a photovoltaic installation is considered to generate renewable energy on-site. To investigate the influence of this PV system on the total results, the renovation package v2 was tested with three different energy sources, district heating, natural gas and electricity, both with and without the additional energy generation by the photovoltaic installation. Figure 34 shows the results of these calculations.

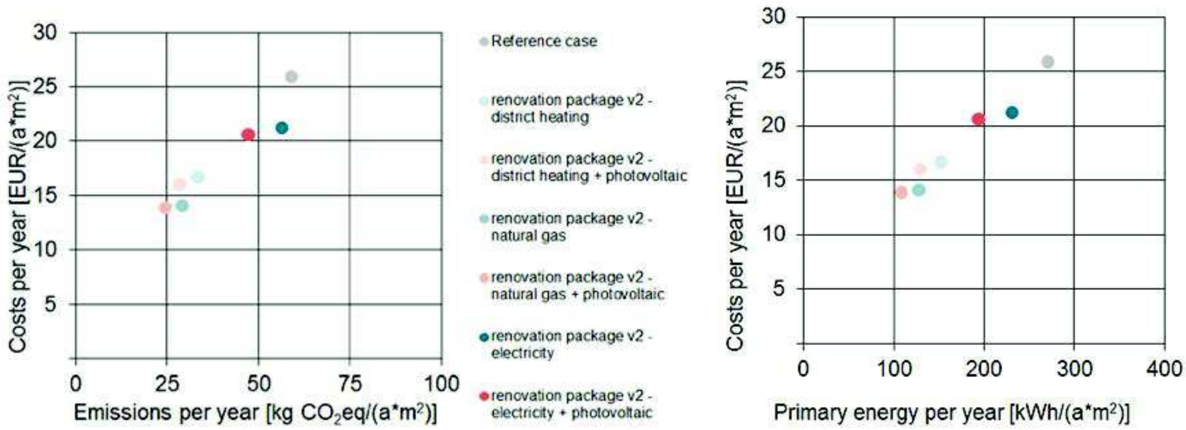


Figure 34: Influence of the photovoltaic energy generation on-site, tested with three different energy sources for heating and DHW (district heating, natural gas and electricity) for the renovation package v2

5.6.3. Conclusions

For the analyzed parameters carbon emissions, total Primary Energy and Life Cycle Costs following conclusions can be drawn:

- Improving the thermal quality of the building envelope reduces the annual carbon emissions, total Primary Energy and Life Cycle Costs. The lowest values are achieved by the renovation package v2, which represents the most improved thermal envelope.
- The highest carbon emissions, total PE and LCC are achieved by the electric heating systems. A modification of the energy source for heating and domestic hot water can reduce the values. Higher reductions are possible if the change is to natural gas heating compared to district heating. The reductions are higher the lower the thermal quality of the building envelope is. That means renovation package v1 achieves the highest reductions and renovation package v2 the lowest.
- The renewable energy generation on-site can reduce carbon emissions and total Primary Energy by about 15%, independent of the used energy source for heating and domestic hot water production. The reduction of the LCC is quite small (within a range of 1-4%) but existing.

For the Czech school building the hypotheses could not be answered based on the existing data and are therefore not shown at this point. The small number of renovation packages that was available didn't allow the test of the hypotheses.

5.7. Overall Results

This chapter includes some overall results to the investigations of each Case Study in the previous chapters. In chapter 5.7.1 the focus is on the carbon emissions results. For each Case Study the calculated carbon emissions are presented and the reduction potentials are shown. Chapter 0 includes the results for the total Primary Energy and chapter 5.7.3 includes a summary of the Life Cycle Costs of each Case Study. In the last part the investigated hypotheses are summarized (see chapter 5.7.4).

5.7.1. Carbon emissions

Figure 35 shows the calculated annual carbon emissions of the six Case Studies. The carbon emissions of the reference cases (light green columns) are compared to the lowest carbon emissions of investigated renovation packages v1, v2 and v3 (dark green columns). The range between the lowest and the highest carbon emissions among all analyzed renovation packages is also highlighted by the arrow.

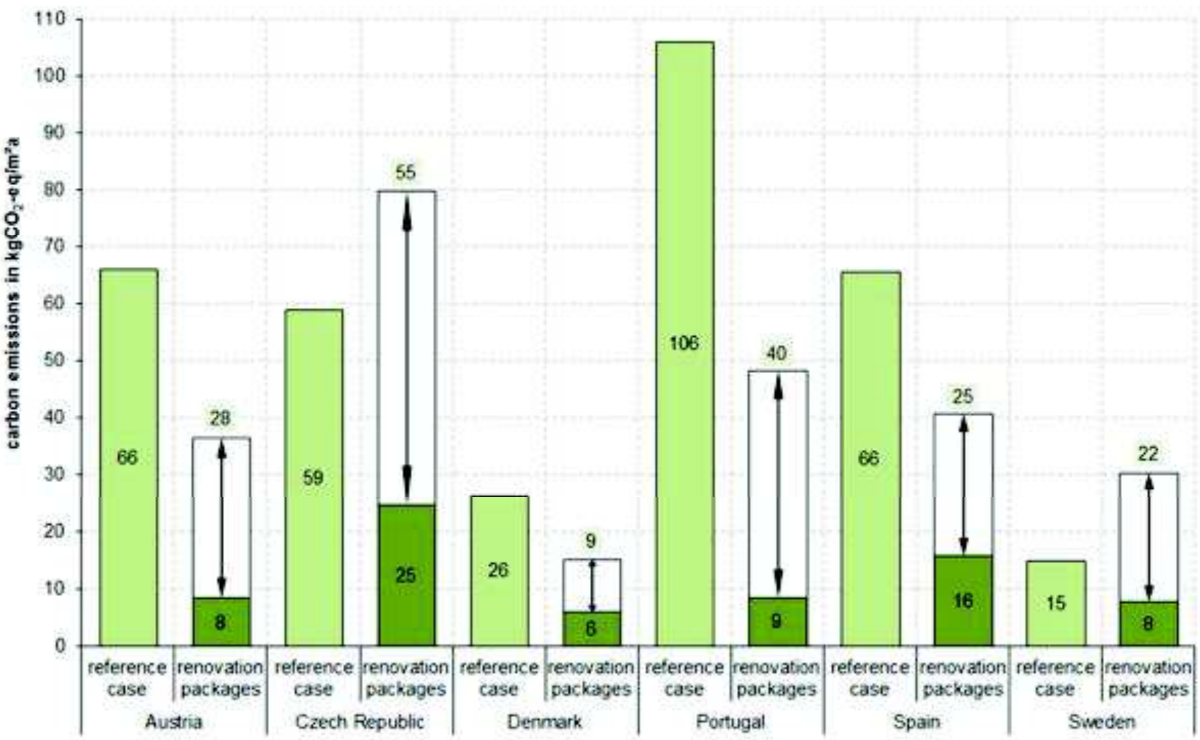


Figure 35: Carbon emissions of the six Case Studies. The carbon emissions of the reference cases are compared to the carbon emissions of the investigated renovation packages, shown as lowest value and as range between the lowest and the highest carbon emissions.

The calculation results show that the Portuguese Case Study achieves the highest carbon emissions in the reference case with 106 $kgCO_2$-eq/m²a. The lowest carbon emissions in the reference case are achieved in the Swedish Case Study with 15 $kgCO_2$-eq/m²a. The reasons for these low carbon emissions of the reference case might be the energy source for heating and domestic hot water, which is district heating based on 81% renewable energy sources. This situation is very common in Sweden.

The lowest carbon emissions of the investigated renovation packages are achieved in the Danish Case Study with 6 $kgCO_2$-eq/m²a. The main reasons for this low value are the chosen energy source for heating and domestic hot water (district heating) and the large photovoltaic installation which is included in this specific renovation package.

The results showed that in four of the six buildings carbon emissions reductions are always given, independently of the chosen measures. This can be seen by the comparison of the highest value of the renovation packages with the reference cases. For the Czech Case Study and the Swedish Case Study this statement is not true. In the Czech Republic the reference case uses district heating based on natural gas for heating and domestic hot water supply. If the energy source is changed to electricity, the carbon emissions increase, although renovation measures on the building envelope are included too (see results for renovation package v3 in Figure 33). Therefore the measures on the envelope cannot compensate the worse conversion factor of electricity compared to district heating.

The same situation is given in the Swedish Case Study. As mentioned before the reference case uses district heating, which is largely, 81%, based on renewables. If the energy source is changed to oil or natural gas the carbon emissions increase, again although energy related renovation measures on the building envelope are included.

Figure 36 shows the carbon emissions reduction potentials of the six Case Studies. The reduction potentials are shown as absolute values (yellow columns) and as relative reduction potentials (orange columns). Again the range between the lowest and the highest reduction potential is highlighted.

The chart shows that the Portuguese Case Study achieves the highest minimum reduction of all investigated buildings with a value of 58 $kgCO_2$-eq/m²a and also the highest possible savings with 98 kgCO2-eq/m²a, which is a reduction of 92% compared to the reference case. To achieve this high relative reduction a combination of both, improving the energy performance of the building envelope and the change of the energy source for heating and domestic hot water production is necessary.

The Danish Case Study shows the smallest absolute reduction potential with values between 11 $kgCO_2$-eq/m²a and 20 $kgCO_2$-eq/m²a. The reason for that low absolute reduction is the quite low carbon emissions of the reference case (see also Figure 35), which is similarly true also in Sweden. However looking at the relative reduction potential the values are high and range between 42% and 77% reduction, which is a result of the energy related renovation measures on the building envelope.

In the Spanish Case Study similar results are achieved as in Austria. The absolute savings potential ranges between 25 $kgCO_2$-eq/m²a and 50 $kgCO_2$-eq/m²a which is a reduction of 38% to 76% compared to the reference case. In both cases the high carbon emissions of the reference cases lead to those high reductions of the investigated renovation packages.

For the Swedish and the Czech Case Studies no minimum reduction is given (see description of Figure 35). That means the reduction potentials range between 0 $kgCO_2$-eq/m²a and 34 $kgCO_2$-eq/m²a (Czech Republic) respectively 7 $kgCO_2$-eq/m²a (Sweden). Compared to the reference cases these are reductions of up to 58% in the Czech case and up to 47% in the Swedish case.

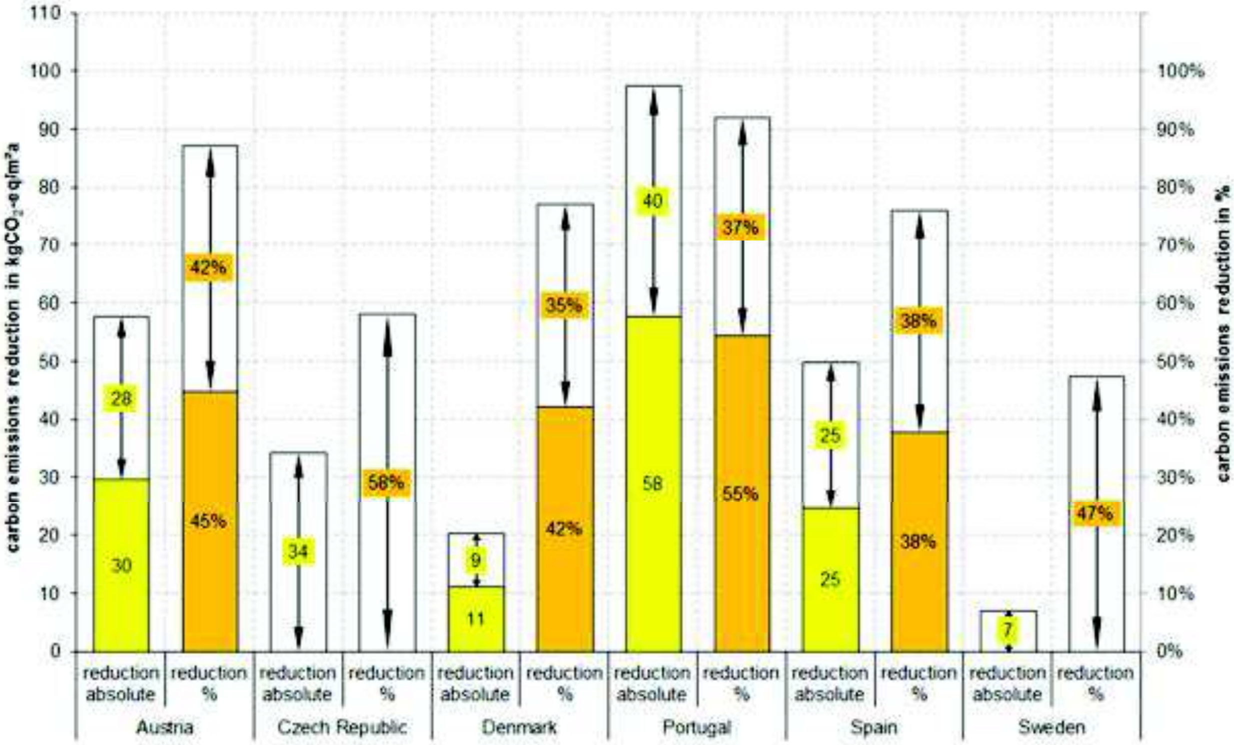


Figure 36: Carbon emissions reduction potential of the six Case Studies. The absolute (yellow columns) and the relative reduction potentials (orange columns) are presented as minimum reduction and also as range between the minimum and maximum reduction.

A comparison of the Life Cycle Costs of the reference cases (light red columns) and those renovation packages which achieve the lowest carbon emissions (dark red columns) are shown in Figure 37. The chart shows that almost all renovation packages, which achieve the lowest carbon emissions, are also cost effective. That means that the LCC of these renovation packages are lower than the LCC of the reference cases. The exceptions are the Danish and the Swedish Case Study, where all investigated renovation packages lead to an increase of the annual LCC (see descriptions in chapter 5.2 (Denmark) and chapter 5.5 (Sweden)).

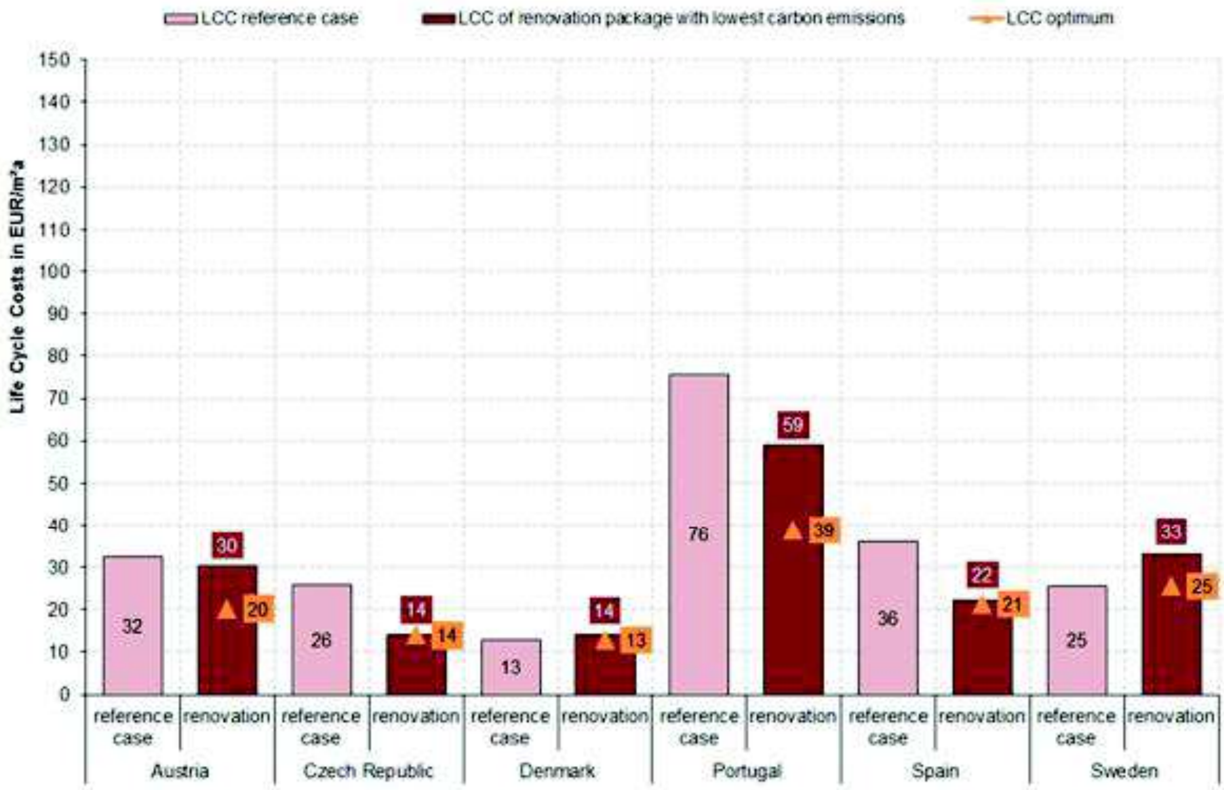


Figure 37: Life Cycle Costs of the six Case Studies. The LCC of the reference cases are compared to the LCC of those renovation packages, which achieve the lowest carbon emissions. Additionally the LCC optimum for each Case Study was marked.

A further analysis of the Life Cycle Costs is shown in Figure 38. The chart demonstrates the possible Life Cycle Cost reductions, when bringing the carbon emissions to the lowest value. That means for each Case Study the LCC of the renovation package with the lowest annual carbon emissions was compared to the LCC of the individual reference cases.

The analysis shows that the LCC can be reduced from 2 EUR/m²a in the Austrian Case Study up to 17 EUR/m²a in the Portuguese Case Study (in the Danish and Swedish Case Studies no reduction of the LCC is given, therefore no value is shown for these two countries in Figure 38). In relative value these are reductions of 6% in Austria to 22% in Portugal. The reasons for the low reduction in Austria are the quite low LCC of the reference case and much more important the high investment costs of the executed renovation package v3, which achieves the lowest carbon emissions, due to the prefabricated façade and the large photovoltaic and solar thermal installations. Therefore the LCC are higher than they would be without the prefabrication and the on-site energy generation.

In Czech Republic and Spain the relative reductions are even higher than in Portugal. In the Czech Case Study the relative reduction is 46% and in the Spanish Case Study 39%, always compared to the reference cases.

The conclusion of the evaluation of the carbon emissions and the corresponding Life Cycle Costs is that high carbon emissions reductions are possible which are cost effective and lead to a high reduction of the Life Cycle Costs. However these case studies, one per country, on which the conclusion is based, might not always be completely representative for the individual country.

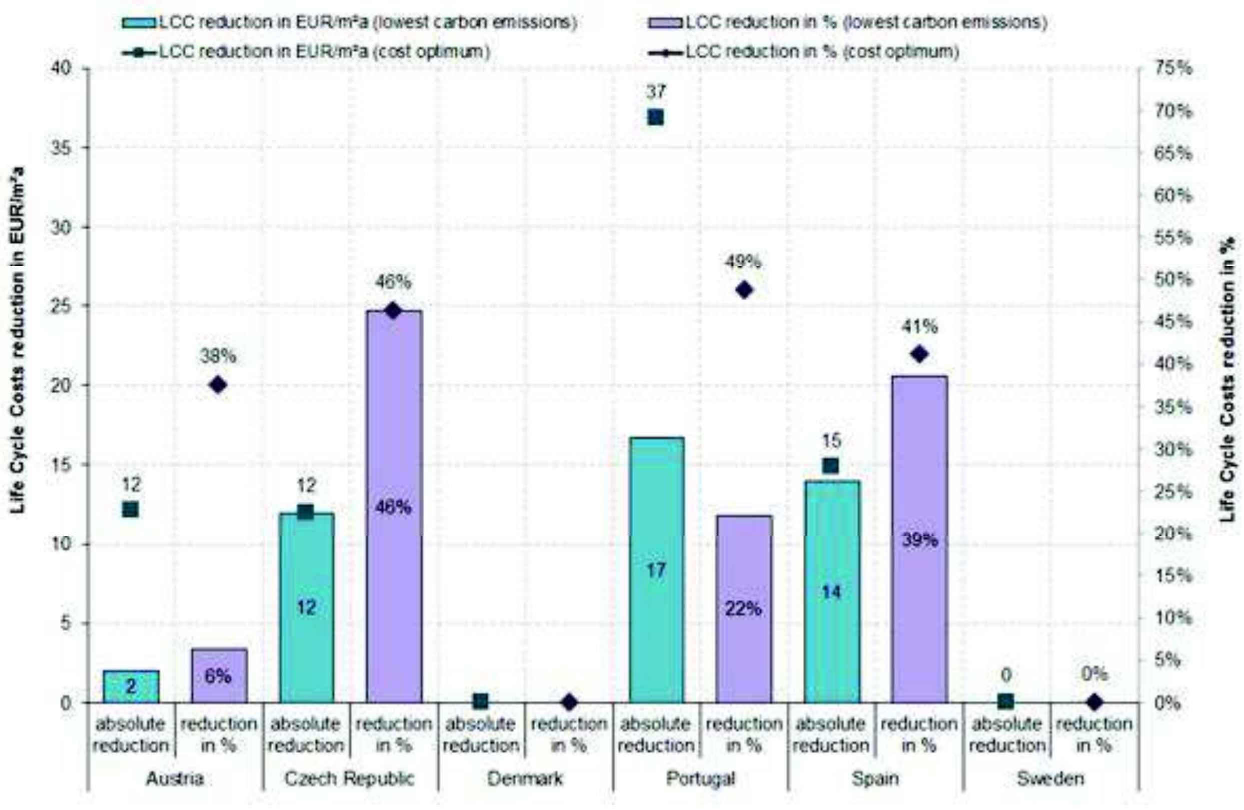


Figure 38: Life Cycle Costs reduction potentials of the six Case Studies. The absolute reduction potential (blue column) and the relative reduction potential (purple column) are presented as values between the reference case and the renovation package which achieves the lowest carbon emissions. Additionally the reduction potentials of the LCC optimum, compared to the reference cases, were marked.

5.7.2. *Total Primary Energy*

Figure 39 shows the calculated total Primary Energy of the six Case Studies. The total Primary Energy of the reference cases (light blue columns) are compared to the lowest total PE of the investigated renovation packages (dark blue columns). The range between the lowest and the highest Primary Energy is highlighted and estimated.

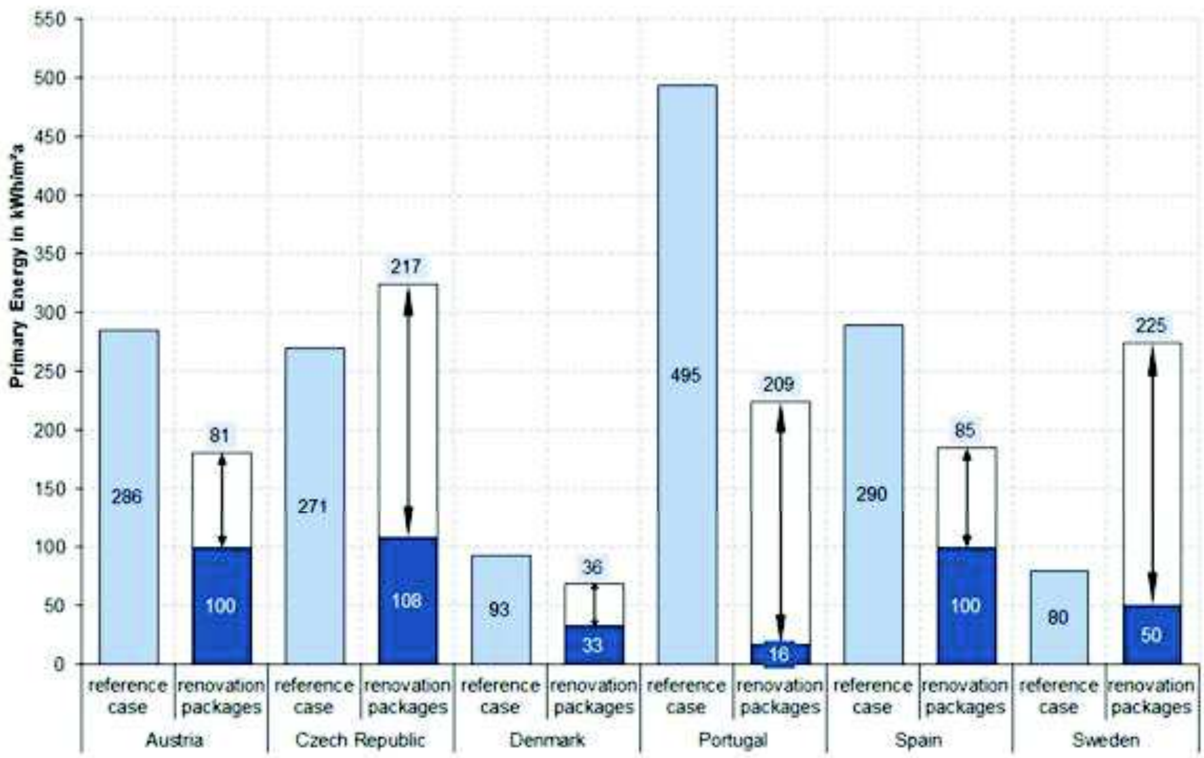


Figure 39: Total Primary Energy of the six Case Studies. The total Primary Energy values of the reference cases are compared to the total Primary Energy values of the investigated renovation packages, shown as lowest value and as range between the lowest and the highest value.

The calculation results show that the Portuguese Case Study achieves the highest total Primary Energy in the reference case with 495 kWh/m²a. The lowest total Primary Energy of all reference cases is achieved in the Swedish Case Study with 80 kWh/m²a. This value is more than six times lower than the total PE of the Portuguese reference case. The main reason for this low value is the high share of renewable energy sources in the considered district heating.

The lowest total Primary Energy after renovation is achieved in the Portuguese Case Study with a value of 16 kWh/m²a. The main reason for this low value is the switch to heat pump, which is supported by a photovoltaic installation on-site (similar to carbon emissions reduction in chapter 5.7.1).

The investigation of the energy related renovation measures in the six Case Studies showed that, similar to the carbon emissions, in four of the six buildings total Primary Energy reductions are always given, independent of the chosen measures. For the Czech Case Study and the Swedish

Case Study this statement is not true. In the Czech case the reference case uses district heating based on natural gas for heating and domestic hot water supply of the building. If the energy source is changed to electricity the total Primary energy values increase, although renovation measures on the building envelope are included (see also description of Figure 35).

The same situation is given in the Swedish Case Study. As mentioned before the reference case uses district heating, which is (largely) based on renewables. If the energy source is changed to oil, natural gas or electricity the total Primary Energy increases, again although energy related renovation measures on the building envelope are included.

Figure 40 shows the total Primary Energy reduction potentials of the six investigated Case Studies, the absolute values (yellow columns) and also the relative (orange columns).

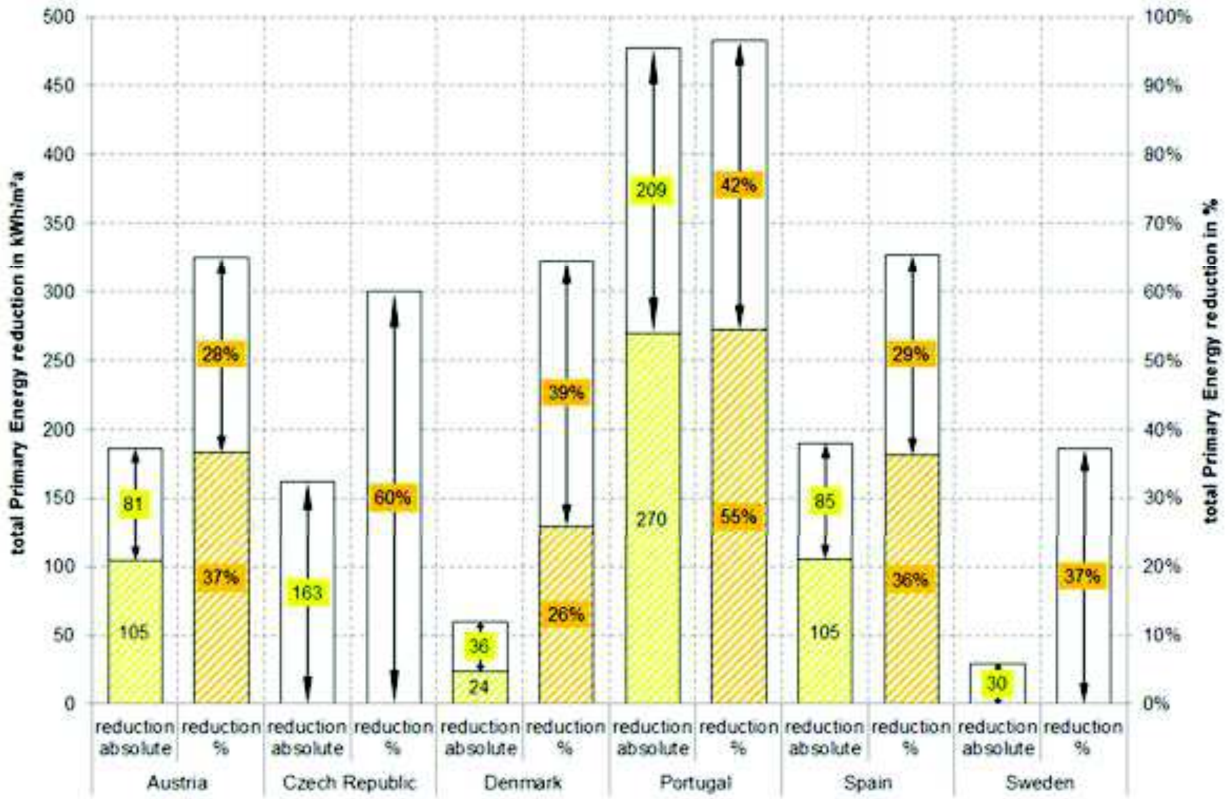


Figure 40: Total Primary Energy reduction potential of the six Case Studies. The absolute (yellow columns) and the relative reduction potentials (orange columns) are presented as minimum reduction and also as range between the minimum and maximum reduction.

The chart shows that the Portuguese Case Study achieves the highest reduction potentials (of all investigated buildings) with the minimum of 270 kWh/m²a and up to 479 kWh/m²a. In relative numbers this represents reductions between 55% and 97%, compared to the Portuguese reference case. The reasons for this high reduction potential are the very high total Primary Energy of the reference case and the combination of the thermal insulation of the building envelope and the switch of the energy source to a multi-split air conditioned heating and cooling system. The highest reductions are possible when improving the thermal envelope and changing to heat pump supply.

The results in Austria and Spain are quite similar. The absolute reduction potentials range between 105 kWh/m²a and 186 kWh/m²a in Austria, in Spain between 105 kWh/m²a and 190 kWh/m²a. In relative terms in Austria and Spain reductions between 36% and 65%, compared to the individual reference cases, can be achieved.

65% reduction can be also achieved in the Danish Case Study, even if the absolute reductions are smaller (between 24 kWh/m²a and 60 kWh/m²a) due to the lower total Primary Energy demand of the Danish reference case.

For the Swedish and the Czech Case Studies no minimum reduction is given (similar to carbon emissions in previous chapter). That means the reduction potentials range between 0 kWh/m²a and 163 kWh/m²a (Czech Republic) respectively 30 kWh/m²a (Sweden). Compared to the reference cases these are reductions of up to 60% in the Czech case and up to 37% in the Swedish case. This also means that in the Czech and Swedish case high relative reductions of the total Primary Energy are possible but the investigated renovation measures can also lead to an increase of the total Primary Energy (see figures in sections 5.5.2 and 5.6.2).

Figure 41 shows similar to Figure 37 the comparison of the Life Cycle Costs of the reference cases (light red columns) and of those renovation packages which achieve the lowest total Primary Energy (dark red columns). The chart shows that almost all renovation packages, which achieve the lowest total Primary Energy in each particular Case Study, are also cost effective. That means that the LCC of these renovation packages are lower than the LCC of the reference cases. The exceptions are again the Danish Case Study and the Swedish Case Study, where all investigated renovation packages lead to an increase of the annual LCC (see section 5.2.2 (Denmark) and section 5.5.2 (Sweden)).

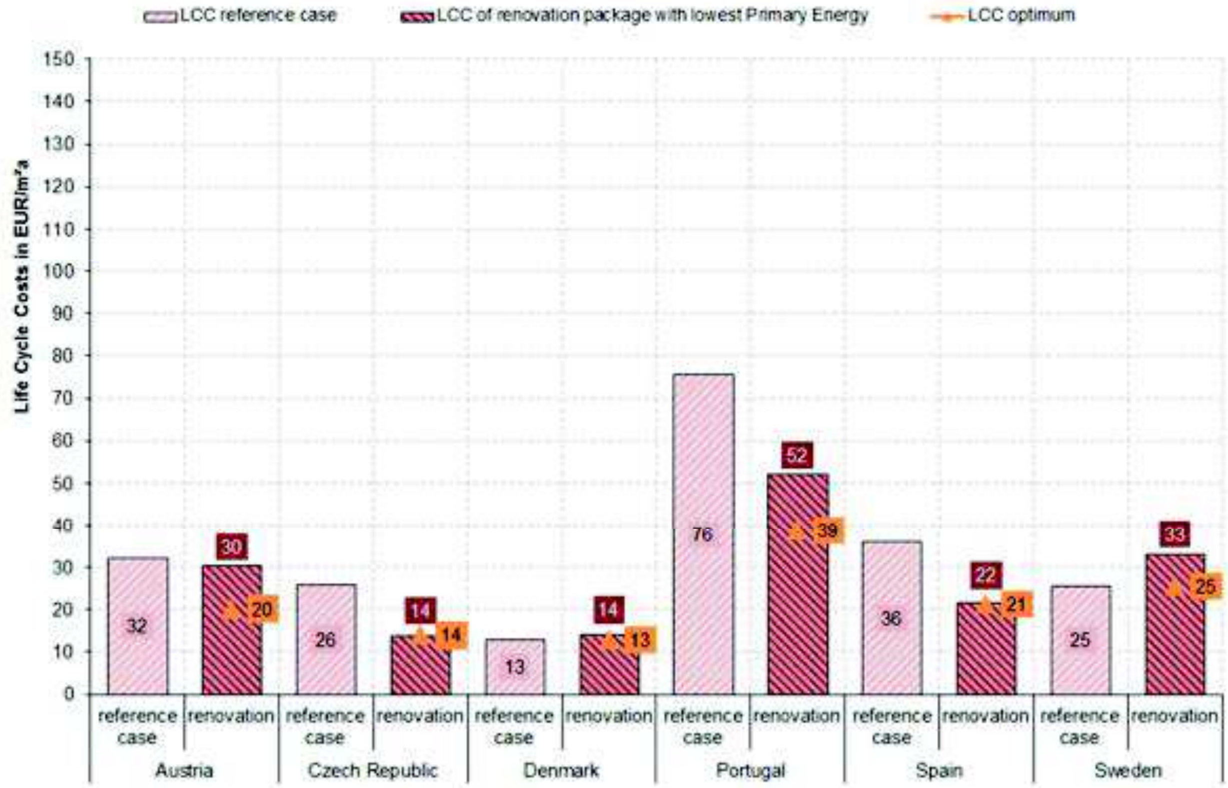


Figure 41: Life Cycle Costs of the six Case Studies. The LCC of the reference cases are compared to the LCC of the renovation packages, which achieve the lowest total Primary Energy. Additionally the LCC optimum for each Case Study was marked.

Figure 42 shows the LCC reduction potentials when reducing the total Primary Energy to the minimum. For each Case Study the LCC of the specific renovation package, which achieves the lowest total Primary Energy, was compared to the individual reference cases. The reductions are shown as absolute values in EUR/m²a and also in relative reductions (in %).

The analysis shows that the LCC can be reduced from 2 EUR/m²a in the Austrian Case Study up to 23 EUR/m²a in the Portuguese Case Study (again no values for the Danish and the Swedish Case Studies because for these two buildings no reductions of the LCC were given). In relative value these are reductions of 6% in Austria to 31% in Portugal. The reasons for the low reduction in Austria are the quite low LCC of the reference case and much more important the high investment costs of the executed renovation package v3, which achieves the lowest total Primary Energy, due to the prefabricated façade and the photovoltaic and solar thermal installations.

Reducing the total Primary Energy in the Czech Case Study to the lowest possible level also reduces the Life Cycle Costs considerably. The absolute reduction is quite small at a first glance, with a value of 12 EUR/m²a, but compared to the LCC of the reference case the relative reduction is 46%. Reasons for this reduction are the combination of the thermal insulation of the building envelope and the switch to gas heating. In general all investigated renovation packages with heating and domestic hot water production based on natural gas achieve similar LCC results and savings. The photovoltaic installation could further reduce the Life Cycle Costs.

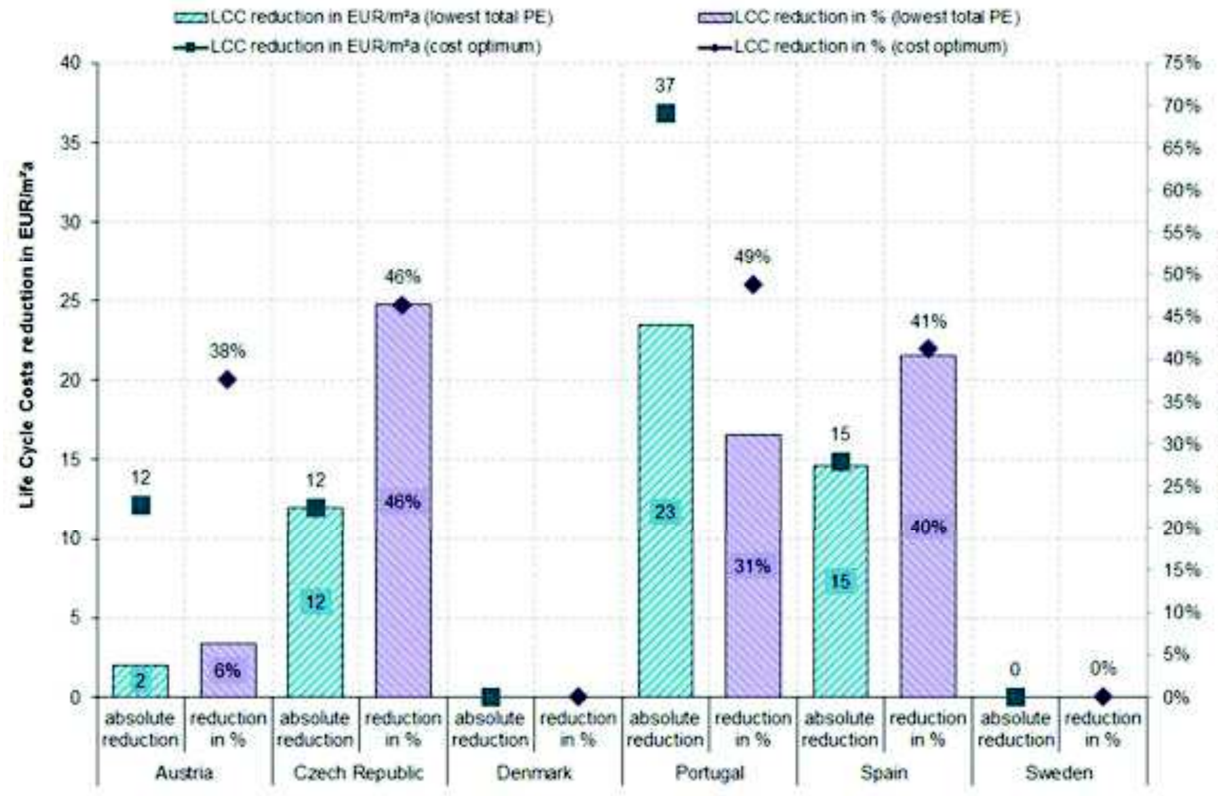


Figure 42: Life Cycle Costs reduction potentials of the six Case Studies. The absolute reduction potentials (blue columns) and the relative reduction potentials (purple columns) are presented as values between the reference case and the renovation package which achieves the lowest total Primary Energy. Additionally the reduction potentials of the LCC optimum, compared to the reference cases, were marked.

5.7.3. *Life Cycle Costs vs. Carbon emission and Primary Energy*

This chapter focuses only on the Life Cycle Costs and the comparison of the cost curves of each country. Interestingly the measures in the studied cases seem to group together so that each case dominates different parts of the graphs. However, it is not known if this is due to country specific conditions or case specific conditions. This becomes apparent in Figure 43, which shows the comparison of the annual Life Cycle Costs with the carbon emissions of all countries on the left side and with the total Primary Energy of all countries on the right side. Each country is marked in a separate color without identifying the individual renovation packages.

Each mark represents one of the investigated renovation packages (reference case, v1, v2, v3) including also different energy sources for heating and DHW.

The analysis of the data in Figure 43 shows that the Portuguese Case Study achieves the highest annual costs of all countries. The LCC range between 39 EUR/m²a (cost optimum) and almost 76 EUR/m²a. Even the cost optimal renovation package has higher LCC than almost all defined renovation packages of the other countries. The investigated renovation packages in Austria, Czech Republic, Denmark and Spain achieve similar LCC, which range between 15 EUR/m²a and 30 EUR/m²a. The LCC range therefore is quite small. The absolute lowest LCC were achieved in the reference case of the Danish Case Study with a value of 12.79 EUR/m²a.

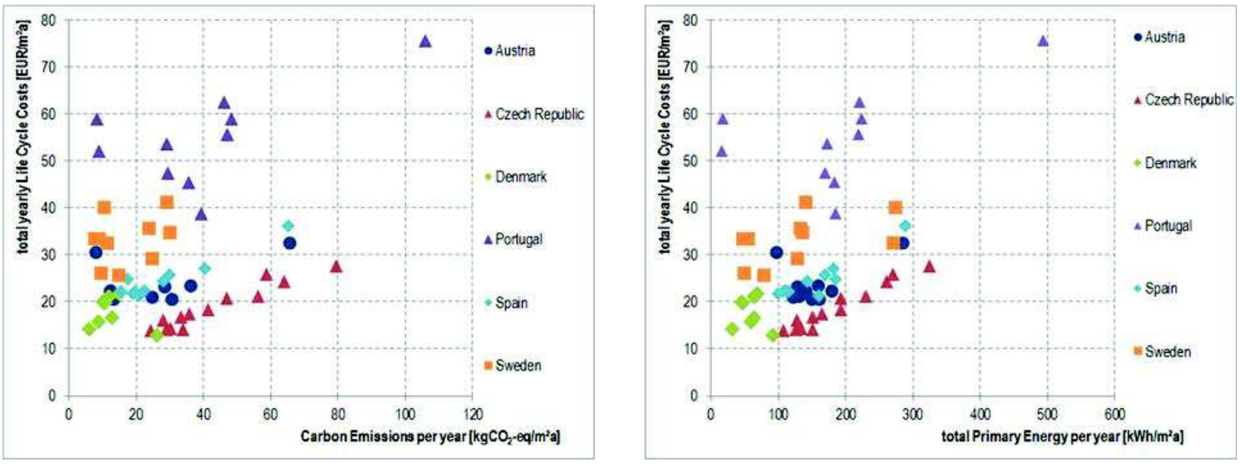


Figure 43: Comparison of Life Cycle Costs, carbon emissions (left side) and total Primary Energy (right side) of all investigated Case Studies

The conclusion of this analysis is that the values can differ from country to country and therefore it is not possible to compare the six Case Studies directly. The differences can be explained for example by differences in building costs, energy costs, climates, building and HVAC technology. Furthermore these factors can also differ from project to project within a country. Especially if the fact is considered that the investigated buildings represent pretty much unique building renovations and therefore are hardly comparable to most other buildings in the six countries.

More information to the differences between the countries and the comparison of the Case Studies with generic buildings can be found in the report “Investigation based on calculations with generic buildings and case studies" (Bolliger and Ott, 2015), which can be downloaded from the IEA EBC Annex 56 website (see: http://www.iea-annex56.org/index.aspx)

5.7.4. *Overview of investigated hypothesis for the five residential Case Studies*

The five investigated hypotheses were tested for each residential building of the Case Studies and presented in the previous chapters. For the Case Study from the Czech Republic, the small number of renovation packages that was available didn't allow the test of the hypotheses. Therefore the analysis in this chapter includes only the five residential Case Studies.

Based on the defined renovation packages deeper analyses of the influence of the different renovation measures on the Life Cycle Costs, carbon emissions and total Primary Energy were performed.

The goal was to test the coherence between renovation measures on the building envelope, the switch of the energy source from non-renewable sources to RES as well as their combinations.

At this point the confirmation of the hypotheses is summarized and shown in following Table 18.

Table 18: Results for the investigated hypotheses for the five residential buildings of the Case Studies. ✓ means that the hypothesis is confirmed, ✗ means that the hypothesis is not confirmed. Symbols in parenthesis or separated by a slash indicate that the hypothesis is only partly confirmed / not confirmed.

Hypothesis	Austria	Denmark	Portugal	Spain	Sweden
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.	✓	✓	(✓)	✗	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.	✓	✓	✓	(✓)	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.	✓	(✓)	✓	✓	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures.	✓	✗	✓	✓	✓/✗
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓	✓	(✓)	✓/✗	✓

The hypothesis ***"The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements."*** could be completely confirmed for Austria and Denmark and partially for Portugal. In Portugal this hypothesis was only confirmed for the renovation measures roof and wall but not for the remaining measures on the building envelope. For the Spanish and the Swedish Case Study this hypothesis was not confirmed.

The hypothesis ***"A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements."*** was confirmed in all five countries, with limitations in the Spanish Case Study where the hypothesis was confirmed for the switch to district heating with 75% biomass or to a biomass heating system, yet not for a switch to heat pump.

The hypothesis ***"A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level."*** is completely confirmed for the Austrian, the Portuguese and the Spanish Case Study and confirmed with limitations in Denmark and Sweden. In the Danish Case Study for example the reference case or simply a switch to a different heating system, without energy efficiency measures, is the cost optimum renovation. All investigated energy related renovation measures lead to an increase of the annual Life Cycle Costs. In the Swedish case, the cost-optimum was not changed by a combination of energy efficiency measures with RES measures. However, it can to be noted that in the case of an oil heating system, renovation measures beyond the cost optimum are similarly cost-effective as the cost optimum, whereas for district heating and the RES based heating systems investigated, additional renovation measures on the building envelope beyond the cost optimum make the renovation significantly less cost-effective.

The hypothesis ***"Synergies are achieved when a switch to RES is combined with energy efficiency measures."*** is confirmed in Austria, Portugal and Spain. In Denmark this hypothesis is disproved. The results showed that it is more cost efficient to use district heating or heat pump and not carrying out further energy related renovation measures on the building envelope. In Sweden the hypothesis can be partly confirmed for the insulation of the exterior wall in combination with the change to district heating based on RES. The hypothesis however is disproved for all remaining renovation measures in combination with district heating based on RES and also for all combinations with a pellets heating system.

The hypothesis ***"To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone."*** is completely confirmed in Austria, Denmark and Sweden. In Portugal and Spain limitations exist. The Spanish Case Study shows a confirmation for the district heating system with 75% biomass and the biomass heating system, yet not for a heat pump. In Portugal it is in general difficult to answer this hypothesis. In fact it cannot clearly be answered. It is more likely to be confirmed but a hundred per cent confirmation is not possible.

5.7.5. *Comparison of the results with the generic parametric calculations*[16]

In all investigated generic buildings investigated there is a cost optimum, with lower costs than those of an «anyway renovation». Costs are rising for measures going beyond the cost optimum, but many or sometimes all of the measures considered in the assessment are still cost-effective, i.e. lower than the cost of the anyway renovation.

With respect to the energy performance of energy related building renovation measures and the balance between renewable energy deployment and energy efficiency measures, the five main hypotheses have also been investigated. Within this context, some tentative conclusions are made referring to renewable energy sources (RES) in general. However, it is important to note that only specific RES systems were taken into account in the generic calculations. For example the role of solar thermal or small wind turbines has not been investigated and not all types of renewable energy systems were investigated for all reference buildings. In the case of the countries Austria, Denmark, Spain and Sweden, geothermal heat pumps and wood pellet heating systems have been investigated as RES systems; in the case of Portugal an air-water heat pump and its combination with PV were investigated as RES systems. The related findings obtained from the parametric calculations with the investigated generic buildings are summarized in the following Table 19.

Table 19: Results for the investigated hypotheses for the generic multi-family buildings

Hypothesis	Austria	Denmark	Portugal	Spain	Sweden
The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.	✓	✓	✓	✓	✗
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.	✓	✓	✓	✓	✓
A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.	(✓)	(✓)	✓	✓	✗
Synergies are achieved when a switch to RES is combined with energy efficiency measures.	✓	✓	✓	✓	✓
To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.	✓	✓	✓	✓	✓

16 Taken from the report: ""Investigation based on calculations with generic buildings and case studies" (Bolliger and Ott, 2015)

The comparison of the results of the Case Studies (Table 18) with the results of the generic buildings (Table 19) shows good correlation.

Small deviations could be found:

- in Austria for the hypothesis **“A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level”**
- in Portugal for the hypotheses **“The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.”** and **“To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.”**
- in Spain for the hypotheses **“A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements.”** and **“To achieve high emission reductions, it is more cost effective to switch to RES and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.”**
- in Sweden for the hypothesis **“Synergies are achieved when a switch to RES is combined with energy efficiency measures.”**

In the mentioned cases the named hypotheses could be fully confirmed in the generic buildings but only confirmed with limitations in the real Case Studies (exception: in Austria it´s vice versa).

For some hypotheses however, no correlation between the Case Studies and the generic buildings is given:

- in Denmark the hypothesis **“Synergies are achieved when a switch to RES is combined with energy efficiency measures.”** was confirmed in the generic building but not confirmed in the Case Study
- in Spain the hypothesis **“The energy performance of the building depends more on how many building elements are renovated than on the energy efficiency level of individual building elements.”** was confirmed in the generic building but not in the Case Study
- in Sweden the hypothesis **“A combination of energy efficiency measures with RES measures does not change significantly the cost optimal efficiency level.”** was partly confirmed in the Case Study but not in the generic building.

6. Challenges to reach nearly zero energy and nearly zero emissions

Besides the technical solutions, which are necessary to reach cost effective nearly zero energy buildings after renovation, including high reductions of carbon emissions and total Primary Energy, it is important to know the challenges that occur when trying to reach this goal and also the measures that can be taken to overcome them.

Therefore participants from the six countries that have provided a Case Study have been asked 13 general questions to this topic, which were not directly related to the Case Studies. Beyond these six countries, representatives from four more countries have been asked to extend the survey and the results. This means representatives from following countries have been interviewed: Austria, Denmark, Czech Republic, Portugal, Spain, Sweden, Finland, The Netherlands, Norway and Switzerland.

The questions asked in the interviews were divided into four main categories:

- **information issues** (information asymmetry, information from Energy Declaration of Buildings, lack of requirements, lack of knowledge, lack of examples,…)
- **technical issues** (lack of well proven systems, total solutions and information)
- **ownership issues** (structure of ownership, rent increase, running costs vs. investment costs)
- **economic issues** (lack economic knowledge, uncertainties about saving potentials, high investment costs, lack of economic incentives)

Each partner was asked to answer questions to above-named issues with yes (Y), if the barrier is relevant in their country, or with no (N), if there is no relevance of the barrier in the specific country.

The investigated questions in each of these four categories and the evaluation results to each of the categories and questions are presented below.

A) Information Issues:

- *Information asymmetry – differing opinions expressed by professionals*
- *Incomplete information from the Energy Declaration of Buildings*
- *Lack of clear requirements*
- *Lack of knowledge about possibilities, potential benefits and added values*
- *Lack of examples and inspiration*

Table 20: Evaluation results of the INFORMATION issues in the 13 countries

A) Information issues	AT	CZ	DK	PT	ES	SE	CH	FI	NE	NO	Total yes	Total no
Information asymmetry – differing opinions expressed by professionals - is this a relevant barrier in your country?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	10	0
Incomplete information from the Energy Declaration of Buildings - Is this a relevant barrier in your country?	Y	Y	Y	Y	Y	Y	-	N	N	Y	7	2
Lack of clear requirements – is that a relevant barrier?	N	N	N/Y	Y	Y	Y	N	Y	Y	Y	7	4
Lack of knowledge about possibilities, potential benefits and added values	Y	Y	N/Y	Y	N	Y	Y	Y	N	Y	8	3
Lack of examples and inspiration	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	9	1

The results show that all ten countries have experienced differing opinions given by professionals, for instance dealing with extra insulation. This information asymmetry between investors and professionals often leads to suboptimal solutions, especially if the professional person is a craftsman without a general approach and corresponding know-how regarding building renovation.

7 of the countries have answered that inadequate information from the Energy Declaration of Buildings is a barrier, often the buildings don´t even have an Energy Declaration at all.

7 of the countries consider the lack of requirements as a barrier, whereas 2 countries do not consider it as a barrier (Denmark has answered as well yes as no). In Portugal for example, there are no requirements imposed to the building if the total value of the renovation works is less than 25% of the value of the building. If it exceeds this value, compliance with rules for new buildings is needed. There is no strong control over this frontier. In Spain, the situation is also quite similar. When the use of the building changes or 25% of the envelope is modified the building has to comply with some limits in energy demand; in other cases, only the components that are modified

have to comply with the requisites for new buildings. And there are always some criteria that avoid implementing the rules.

7 countries consider the lack of knowledge about possibilities, potential benefits and added values as a barrier, whereas 2 countries do not consider it a problem (Denmark has answered as well as yes as no). In Norway for example, the public building owner wants to realize a renovation project on passive house level but does not know that he has to find qualified planners. The planners are chosen based on a competition on price and availability. Special qualifications are not demanded.

The lack of examples and inspiration is relevant in all countries except for Finland. This means that very often good examples of advanced building renovations do not exist, and if they exist they are often not fully and impartially evaluated.

B) Technical Issues:

- *Lack of well proven systems, total solutions & information about these*

Table 21: Evaluation results of the TECHNICAL issues in the 13 countries

B) Technical issues	AT	CZ	DK	PT	ES	SE	CH	FI	NE	NO	Total yes	Total no
Lack of well proven systems, total solutions & information about these	Y	Y	Y	Y	Y	Y	N	N	N	Y	7	3

The lack of well proven systems, total solutions and information about these is relevant for 70% of the countries.

In Portugal for example, systems and solutions to renovate Portuguese buildings to high energy performance are known and available, but they aren´t generally used in integrated solutions. In Austria and the Czech Republic the missing or inadequate national climatic data and the lack of independent technical and pricing control of project for public building are the biggest obstacles in this point.

In Switzerland there are quite many well established solutions for building renovations available. The problem is much more lacking overall analyses and strategic planning of renovation activities for the next 10-20 years, slow know-how diffusion into the renovation practice and craftsmen who favor traditional solutions.

C) Ownership Issues:

- *The structure of ownership, (private, public, owner, tenants)*
- *Building owners not allowed to increase rent to pay for energy renovation investments (building owners pay, tenants benefits)*
- *Running costs and investment costs are two different "boxes"*

Table 22: Evaluation results of the OWNERSHIP issues in the 13 countries

C) Ownership issues	AT	CZ	DK	PT	ES	SE	CH	FI	NE	NO	Total yes	Total no
The structure of ownership, (private, public, owner, tenants)	Y	Y	Y	Y	Y	Y	Y	N	Y	-	8	1
Building owners not allowed to increase rent to pay for energy renovation investments (building owners pay, tenants benefits)	N	N	Y	Y	Y	Y	Y	N	N	N	5	5
Running costs and investment costs are two different "boxes"	Y	Y	Y	Y	N	Y	Y	N	Y	Y	8	2

Eight countries consider ownership issues a problem, one does not and one has neither answered yes nor no. The owner/tenant problem, for example, is very relevant in Switzerland with >60% tenants and with a tenancy law which is basically cost based and requires in the case of renovation that only the share of renovation costs which improves the basic quality of the building may give reasons for an increase of rents. A further problem in Switzerland is the age of the private owners of tenements. About 60% of private owners of tenements are older than 60 years, potentially risk averse and less inclined to large investments.

On the other hand in half of the countries it is a problem that building owners are not allowed to increase rent to pay for energy renovation investments. In Sweden for example, a rent increase in an apartment building usually has to be negotiated with the Swedish Union of Tenants and usually the rent cannot be increased as a result of energy efficiency measures only.

In 8 out of 10 countries it is a problem that running costs and investment costs are two different "boxes".

D) Economic Issues:

- *Lack of economic knowledge*
- *Uncertainty about the savings and calculations of saving potential*
- *Investment costs too high*
- *Lack of economic incentives or uncertainty about the incentives*

Table 23: Evaluation results of the ECONOMIC issues in the 13 countries

D) Economic issues	AT	CZ	DK	PT	ES	SE	CH	FI	NE	NO	Total yes	Total no
Lack of economic knowledge	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	9	1
Uncertainty about the savings and calculations of saving potential	N	Y	Y	Y	Y	Y	N	Y	N	Y	7	3
Investment costs too high	Y	N	Y	Y	Y	Y	Y	Y	N	Y	8	2
Lack of economic incentives or uncertainty about the incentives	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	9	1

The lack of economic knowledge is a barrier in 90% of the countries. In Norway, for example, the economic knowledge would have to be integrated with building knowledge and used in a more holistic way. In Sweden, there is partly lacking know-how. Even professional investors calculate with a surprisingly short payback period. One reason is lacking know-how of renovation measures and performance of renovation measures. A second reason is the attempt to reduce risks because of risk aversion or because of the difficulty to predict longer future time periods. This would typically be necessary for renovation investments having life cycles of 15-40 years.

The uncertainty about the savings and calculations of savings potentials is also a barrier in 7 of the 10 countries as well as the too high investment costs which are a barrier in 80% of the countries. In Norway for example, the investment costs are high with relative low energy prices. Also the planning costs and the maintenance costs for building equipment are high.

The lack of economic incentives or uncertainty about the initiatives is a barrier in 9 countries. Only Finland does not consider this as a problem, in Switzerland on the other hand this is a severe problem.

Conclusions

The evaluation of the barriers to reach nearly zero energy buildings can be summarized as, in average 7 out of 10 of the countries consider the mentioned barriers as relevant.

One barrier is relevant for all countries, which is the information asymmetry of differing opinions expressed by professionals.

In 9 out of ten countries it was considered to be a barrier that there is a:

- Lack of examples and inspiration
- Lack of economic incentives or uncertainty about the incentives
- Lack of economic knowledge

In 7-8 countries the following were considered to be barriers:

- Incomplete information from the Energy Performance Certificate of Buildings
- Lack of knowledge about possibilities, potential benefits and added values
- Lack of well proven systems, total solutions and information about these
- Lack of clear requirements
- The structure of ownership (private, public, owner, tenant)
- Running costs and investment costs are two different “boxes”
- Investment costs too high
- Uncertainty about the savings and calculations of saving potential

In 5-6 countries the following was considered to be a barrier:

- Building owners are not allowed to increase rent to pay for energy renovation investments (i.e. the building owner pays for the tenant´s benefits)

7. Conclusions and recommendations

The investigations of the six Case Studies and the interviews in ten European countries allow making recommendations for cost effective renovations towards nearly zero energy and emissions in future. In the next paragraphs these recommendations are presented corresponding to their sources (parametrical analyses of LCC and LCA, co-benefits analyses and interviews):

Parametric calculations

A switch to renewable energy sources reduces the carbon emissions more significantly than energy efficiency measures on one or more envelope elements. When the goal is to achieve high carbon emissions reductions, it is more cost effective to switch to renewable energy sources and carry out less far-reaching renovations on the building envelope than to focus on energy efficiency measures alone.

Synergies can be achieved when a switch to renewable energy sources is combined with energy saving measures on the building envelope.

In general, the combination of energy efficiency measures on the building envelope with measures for the use of renewable energy sources does not significantly change the cost optimal efficiency level.

Whether or not the number of building elements renovated is more important for the energy performance of the building than the efficiency level (insulation thickness) of each particular element has to be checked individually. For some buildings this might be the case, for others however not. This can depend on national standards, prices, weather conditions and other factors.

Energy efficiency measures, when compared with measures associated with the use of renewable energy sources, are the main source of co-benefits at building level.

To maximize the co-benefits associated with energy related building renovation, it is more effective to improve the performance of all the elements of the building envelope than to significantly improve the performance of just one element.

Depending on the original condition of the building, improving the performance of all the elements of the building envelope usually means going beyond cost optimality, but it is still cost-effective when compared to the “anyway renovation”, i.e. a renovation scenario where energy performance is not improved.

The calculation results within the Case Studies have shown that high carbon emissions and Primary Energy reductions are possible, where the corresponding renovation packages are also cost effective, which means that the Life Cycle Costs of the renovation packages are lower than the Life Cycle Costs of the reference case.

However, results have also shown that not all investigated renovation measures bring a reduction of carbon emissions, primary energy and/or Life Cycle Costs. Moreover higher values, compared to the reference case, were calculated in some Case Studies. Therefore a detailed look at different possible renovation measures, including the calculation of the Life Cycle Costs and the Life Cycle Assessment are necessary.

It also has to be mentioned that the assumptions made in the Life Cycle Cost calculation and the Life Cycle Assessment are very important and can influence the results a lot. Therefore these assumptions have to be well-considered and if possible a sensitivity analysis of the most important parameters should be carried out. It is advisable to consult an expert with profound knowledge in the field of Life Cycle Cost calculations and Life Cycle Assessments.

Interviews

Missing good examples for successful renovations are often the biggest barriers for renovations towards nearly zero energy and emissions. The investigated Case Studies are such good examples, but more are needed. This means that national initiatives have to be launched to promote these kinds of building renovations. One of these initiatives could be the financial support or funding programs via direct funding or via research projects. Research projects would bring the additional benefit that new, innovative measures could be tested and evaluated, which in turn would increase the technical knowledge of the building professionals and also of the building owners.

Such a campaign could also counter the lack of economic incentives or uncertainty about the incentives. This means that by launching economic incentives building owners will receive support in financing nearly zero energy and emissions buildings. This will give building professionals the opportunity to realize good building renovations without constantly having the investment costs in mind.

A further important step towards cost effective building renovations is the consideration of the whole building life cycle. That means the Life Cycle Costs of the renovation packages should be regarded over the life cycle of the building and the building element. The investment costs should not be taken as main decision criterion.

If the building owner is faced with the problem of not being allowed to increase the rent to pay for energy renovation measures, it is advisable to go for the cost optimal renovation.

Co-benefits

It is important to look at the carbon emissions and/or Primary Energy of different possible renovation measures over the whole building life cycle. The investigations should include different scenarios, to find the scope of cost effective renovation packages of measures. Within the scope of cost effective renovation scenarios, costs and co-benefits should be considered to find the solution that adds more value to the renovated building. All investigated renovation measures and packages should be compared to a reference situation, where only measures are included that have to be carried out anyway (“anyway renovation”).

Appendices

Appendix 1: Case Study “Kapfenberg”, Austria

Appendix 2: Case Study “Kamínky 5”, Czech Republic

Appendix 3: Case Study “Traneparken”, Denmark

Appendix 4: Case Study “Rainha Dona Leonor neighbourhood”, Portugal

Appendix 5: Case Study “Lourdes Neighborhood”, Spain

Appendix 6: Case Study “Backa röd”, Sweden

Appendix 7: Case Study “Montarroio”, Portugal