Energy in Buildings and Communities Programme

International Energy Agency

Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)

Investigation based on parametric calculations with generic buildings and case studies

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March 2017

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

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 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: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)

Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (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
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 (RAP-RETRO)
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: LowEx Communities - Optimised Performance of Energy Supply Systems with Energy Principles
Annex 65: Long-Term Performance of Super-Insulation in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behaviour in Buildings
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in low Energy Buildings
Annex 70: Building Energy Epidemiology
Annex 71: Building energy performance assessment based on in-situ measurements
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 (*)

Management summary

Introduction

Buildings are responsible for a major share of energy use and carbon emissions. Accordingly, reduction of energy use and carbon emissions in buildings is an important field of activity for climate change mitigation.

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.

The present report is one of several reports prepared within the framework of this project.

Objectives

The objectives of the work documented in this report are:

– To test the methodology developed within Annex 56 by assessing different packages of energy related renovation measures for typical, generic single-family and multi-family buildings from the countries participating in Annex 56, more specifically:

– To assess energy related renovation measures regarding costs, primary energy use and carbon emissions

– To determine the range of cost-effective and cost-optimal energy related renovation measures

– To determine cost-effective combinations of energy efficiency measures and renewable energy based measures as well as related synergies and trade-offs

– To compare results obtained from calculations with generic buildings with calculations from case studies

– Derive recommendations for target setting by policy makers and for energy and carbon emissions related renovation strategies by owners or investors.

Methodology for parametric assessments of generic buildings

Parametric calculations of the impacts for generic residential buildings:

The exploration and assessment of the impacts of renovation measures on cost, primary energy use and carbon emissions is done with parametric calculations for generic reference buildings for the countries participating in Subtask A of Annex 56 (Ott et al. 2015). The parametric assessment follows the methodology described in the methodology report of Annex 56. The impacts of 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 per year and per m^2 basis. The principle of these graphs is shown in the following figure:

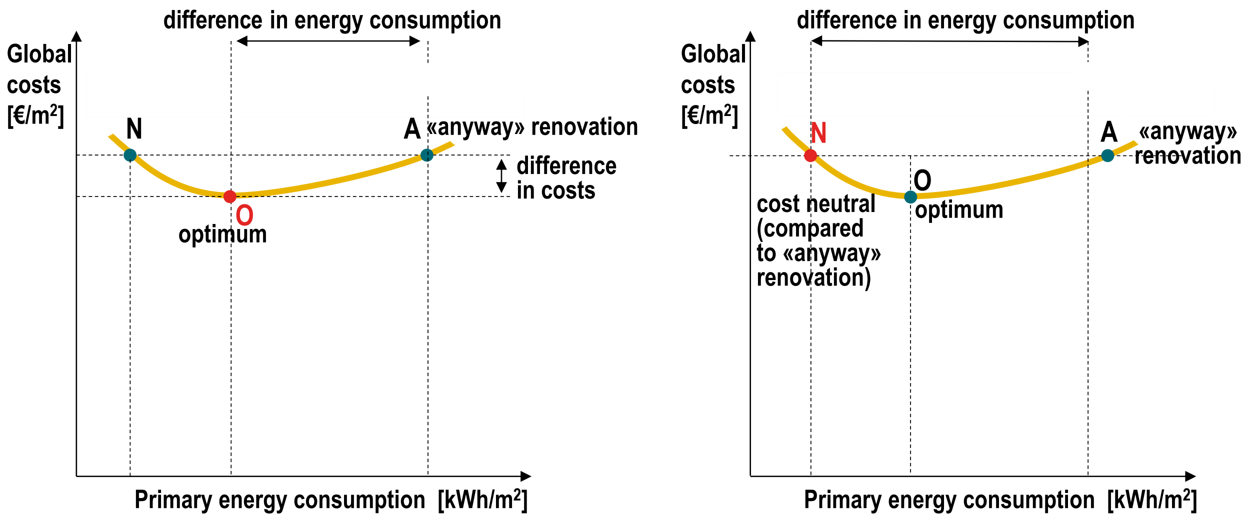


Figure 1 Global cost curve after renovation, starting from the reference case **A** («anyway renovation») towards renovation options with less primary energy use than in the case of the anyway renovation. Costs comprise annual capital costs, energy costs, as well as operation and maintenance costs. **O** 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).

The methodology of Annex 56 is applied to generic single-family and multi-family residential buildings from Austria, Denmark, Italy Norway, Portugal, Spain, Sweden and Switzerland which are typical for the corresponding building stock in those countries. With parametric calculations the impacts of ten different packages of renovation measures on the building envelope on primary energy use, carbon emissions and costs is determined for three different heating systems respectively. Additionally, the impact of the inclusion of embodied energy use is evaluated for the generic Swiss single-family building and the impacts of ventilation with heat recovery is assessed for the generic Swedish and Swiss single-family and multi-family buildings.

To have more information on the impacts of deployment of further renewable energy options, the installation of PV combined with an air/water heat pump is assessed for the generic buildings from Portugal.

Impacts of the renovation packages are assessed by comparison with the impacts of a hypothetical «anyway renovation» case. This reference case comprises measures which would have to be carried out anyway just to restore the functionality of the building without improving the energy performance, e.g. repairs or repainting of a wall, or making a roof waterproof again. In the reference case, the «anyway» measures are associated with costs, which favours the cost-effectiveness of renovation measures. To have a level playing field and to ensure that the comparison of the «anyway renovation» with different options for energy related renovations is correct, it is assumed in all renovation packages and also in the reference case that the existing heating system is replaced. Herewith, both the reference case and the cases with energy related renovation measures have a new heating system with comparable life expectancies.

Assessed energy related renovation measures:
The following types of renovation measures on the building envelope were taken into account on varying levels of energy efficiency levels for all the countries investigated (AT, DK, IT, NO, PT, ES, SE, CH):

— Insulation of wall
— Insulation of roof
— insulation of cellar ceiling
— New energy efficient windows.

The following heating systems were considered:

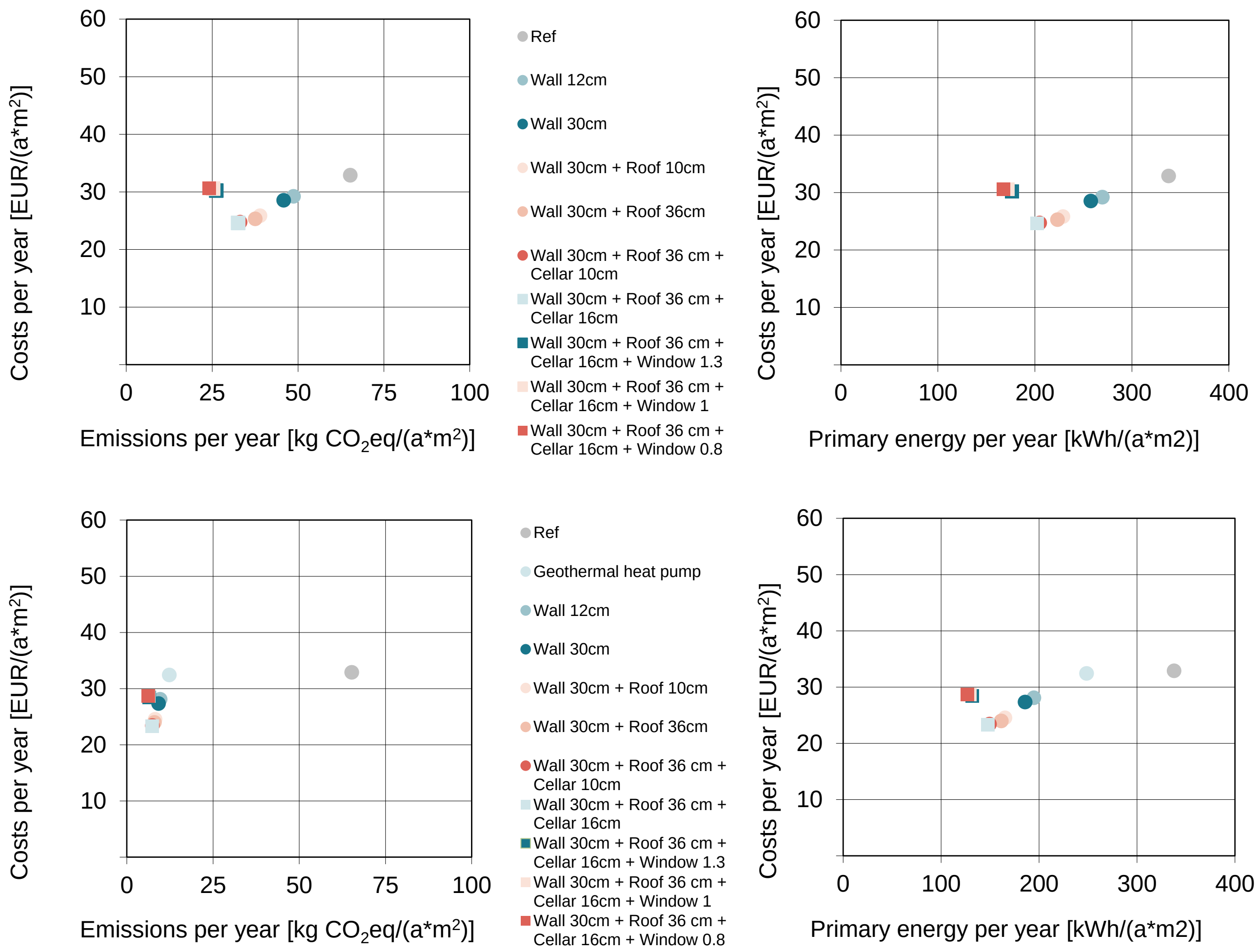
— Oil (AT, DK, CH)
— Natural gas (IT, PT, ES)
— Direct electric heating (NO)
— District heating (SE)
— Wood pellets (AT, DK, ES, SE, CH)
— Wood logs (NO)
— Ground source heat pump (AT, DK, IT, ES, SE, CH,)
— Air source heat pump (IT, NO, PT)
— Air source heat pump combined with a photovoltaic system (PT).

Effects of installing a ventilation system with heat recovery were investigated in two countries (SE, CH). Effects of cooling were investigated in three countries (IT, PT, ES).

All calculations are performed in real terms, applying a real interest rate of 3% per year and energy prices referring to assumed average prices over the next 40 years. By default, a 30% real energy price increase was assumed for the period of 40 years, compared to energy prices of 2010 in the specific country. Accordingly, assumed oil prices varied between the different countries between 0.10 and 0.25 EUR/kWh, electricity prices between 0.16 and 0.33 EUR/kWh. Climate data, lifetimes, primary energy and emission factors applied are country specific. Cost assessment is performed dynamically, discounting future costs and benefits with the annuity method. Country specific cost levels are considered within the assessments. The generic buildings defined are roughly representative for buildings constructed up to 1975-1980, which have not undergone a major energy related renovation yet.

A detailed example of results from the assessments by parametric calculations

The results of the parametric calculations for the Swiss multi-family building are presented subsequently as an example of the results generated by the calculations for generic single-family and multi-family residential buildings. First separate graphs are shown for illustrating impacts on emissions, primary energy use and costs of various combinations of energy efficiency measures, distinguishing according to the heating system (Figure 2). A summary of these curves is then shown in Figure 3.



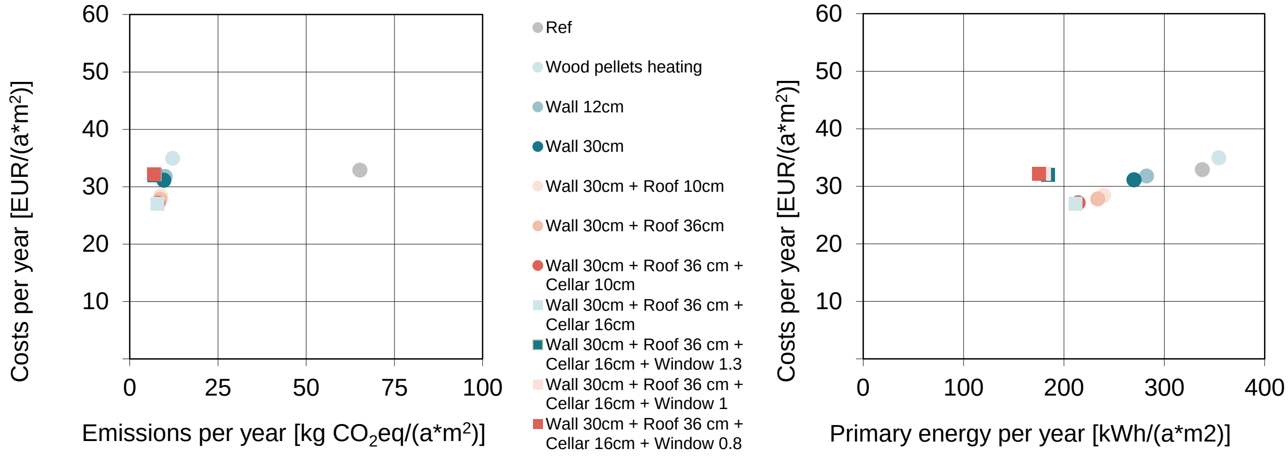


Figure 2 Multi-family building in **Switzerland**: Cost-effectiveness of energy efficiency renovation measures for different heating systems: **Oil heating** (top), **geothermal heat pump** (middle) and **wood pellets** (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the existing oil heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

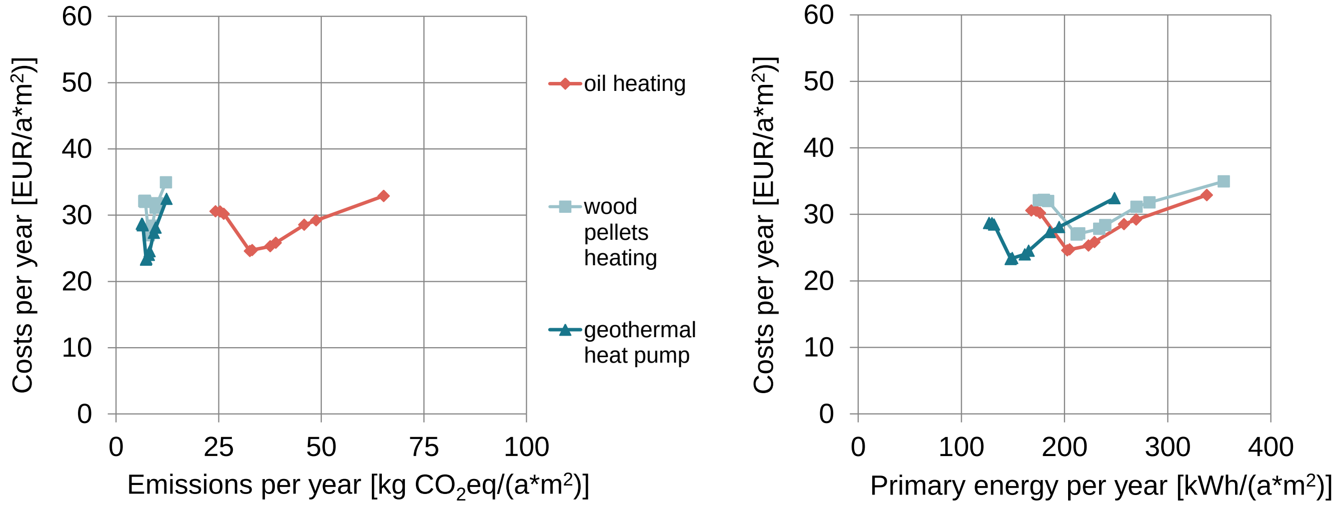


Figure 3 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Switzerland**, for a **multi-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

A summary of graphs resulting from the assessments by parametric calculations for countries investigated

The following graphs summarize the results of the generic calculations carried out with the generic reference buildings investigated, apart from the detailed example shown above.

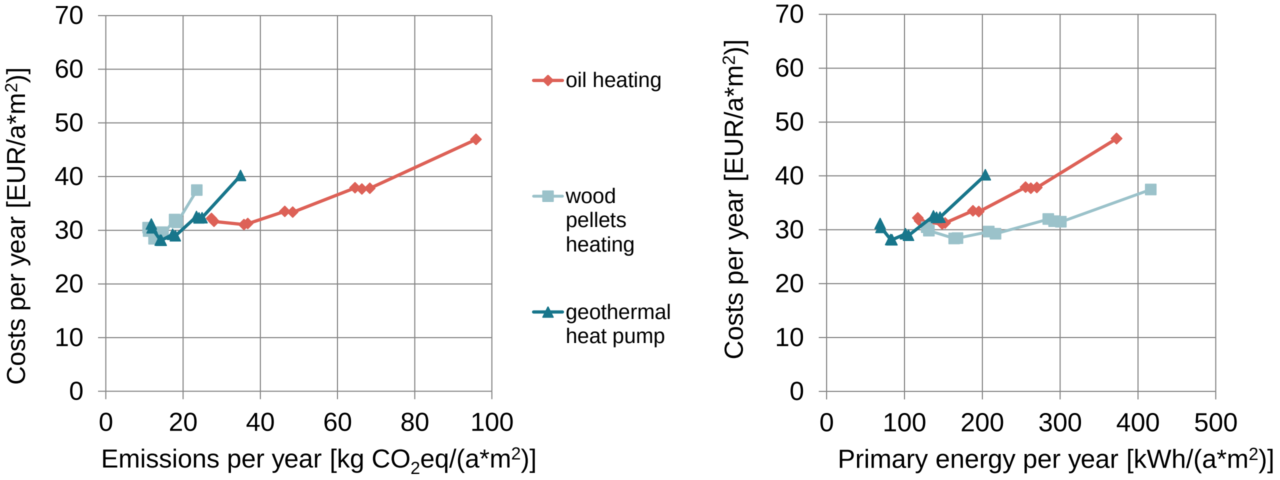


Figure 4 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Austria**, for a **single-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

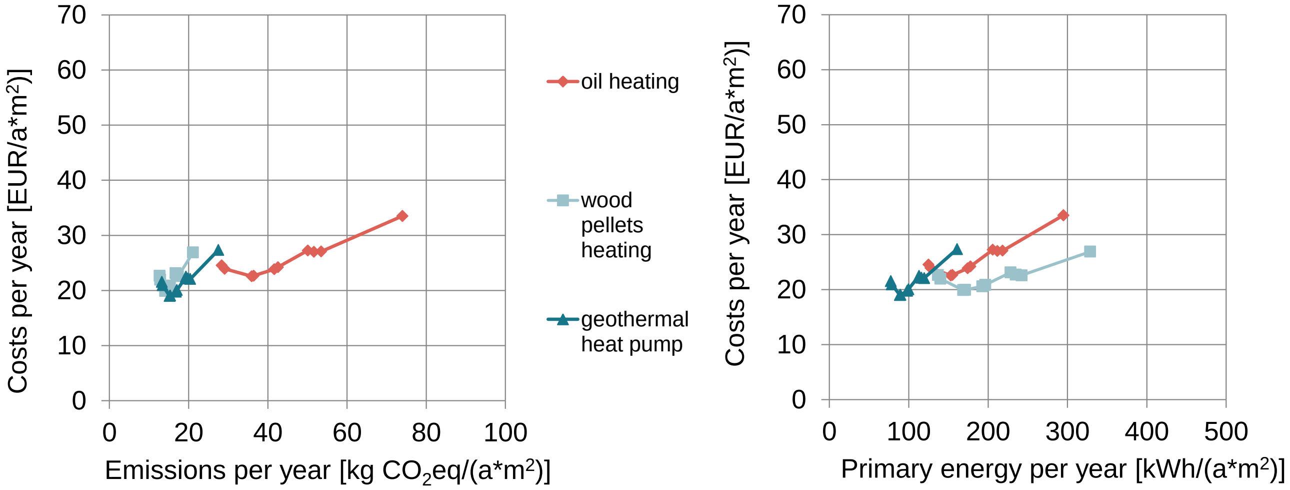


Figure 5 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Austria**, for a **multi-family building**. The reference case is the point on the oil heating curve

with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

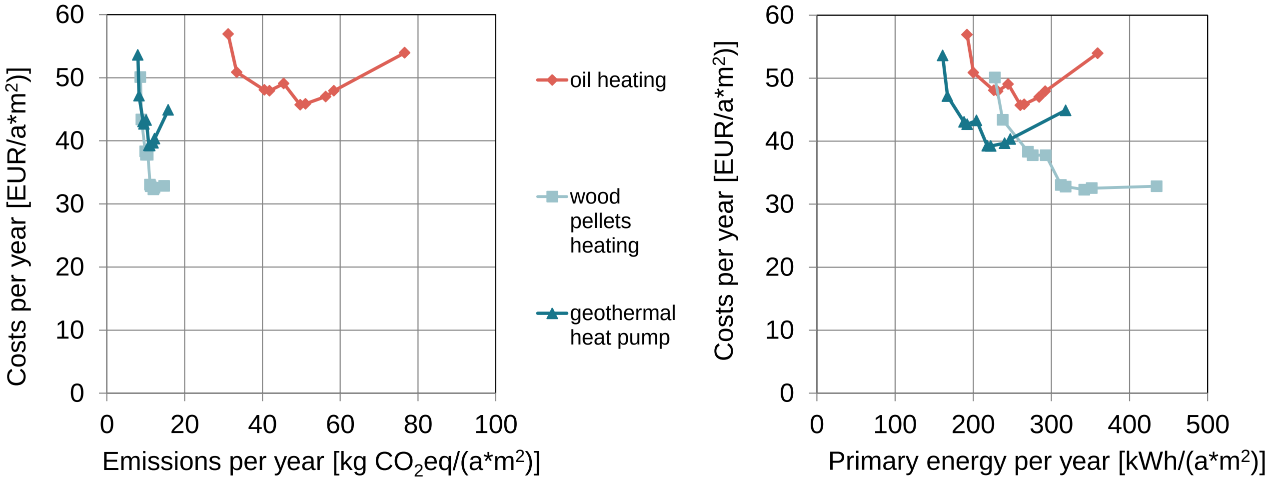


Figure 6 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Denmark**, for a **single-family building**, The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

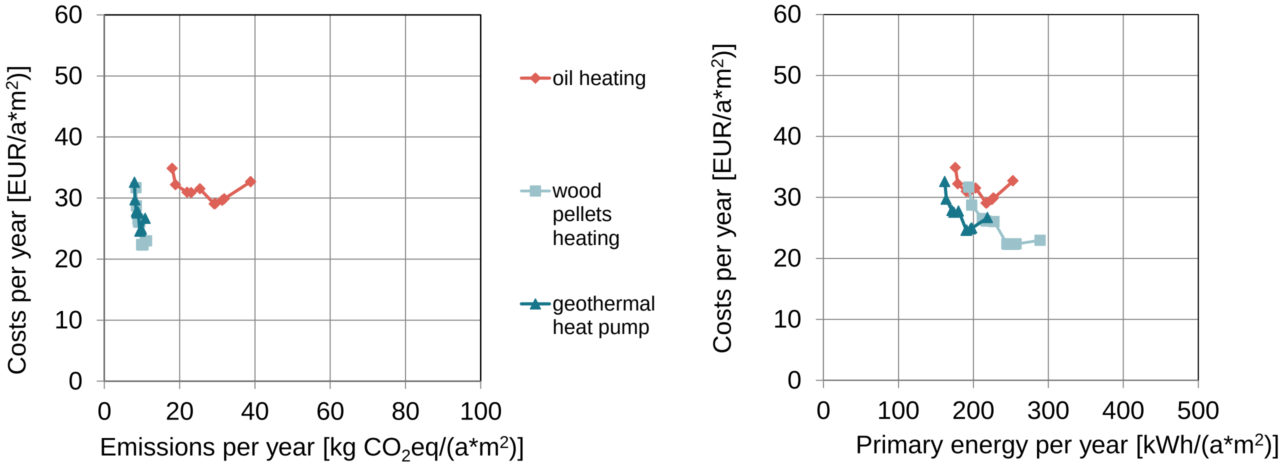


Figure 7 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Denmark**, for a **multi-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

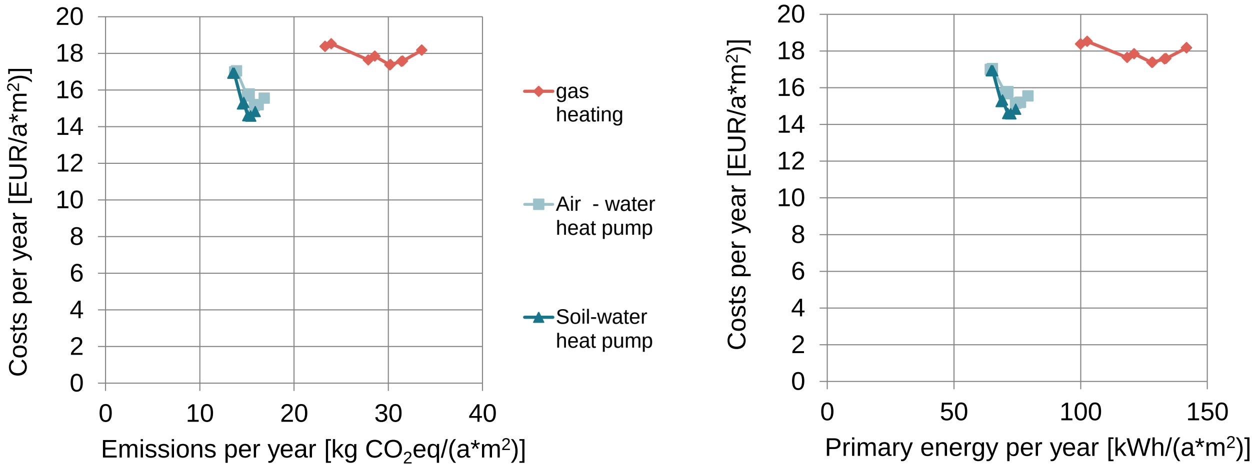


Figure 8 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Italy**, for a **multi-family building**. The reference case is the point on the gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

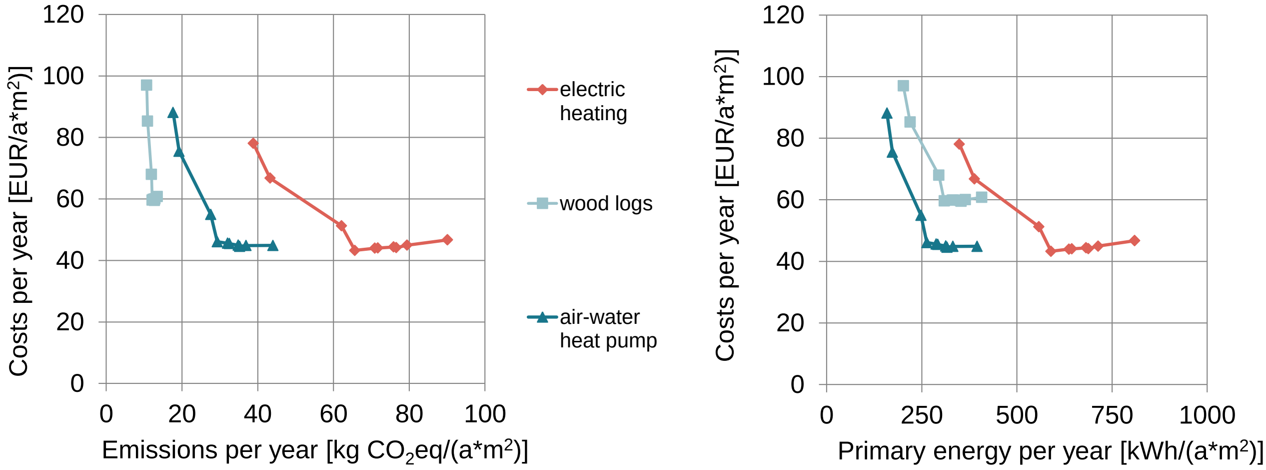


Figure 9 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Norway**, for a **single-family building**. The graphs are calculated with the residual electricity mix based on taking into account in addition also the import and export of guarantees of origin.

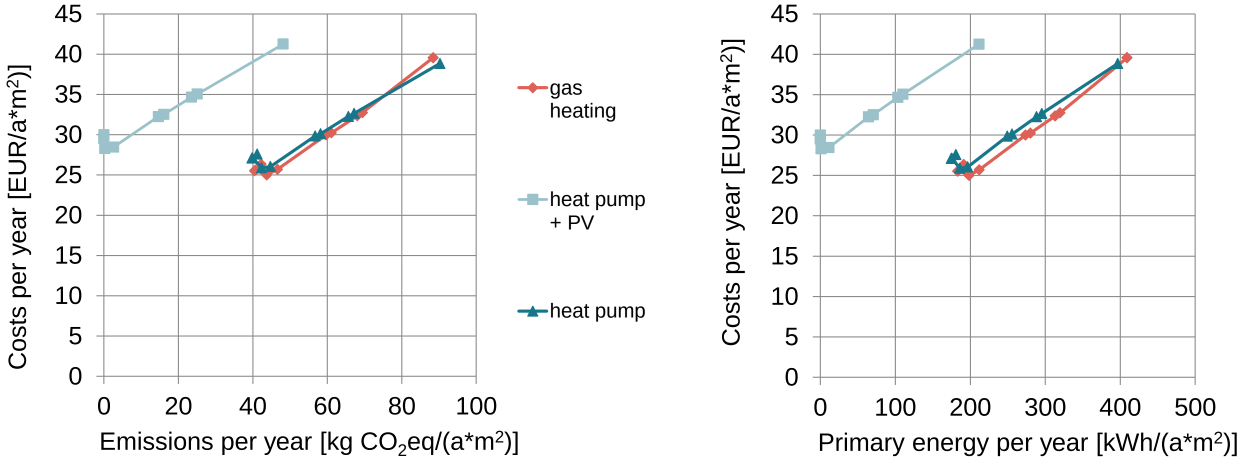


Figure 10 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Portugal**, for a **single-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

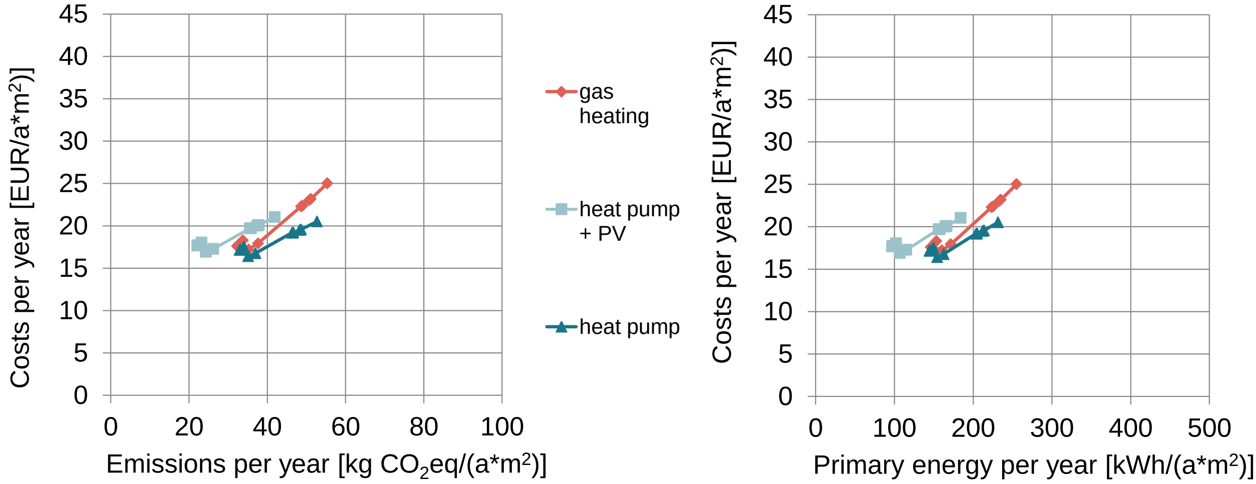


Figure 11 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Portugal**, for a **multi-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

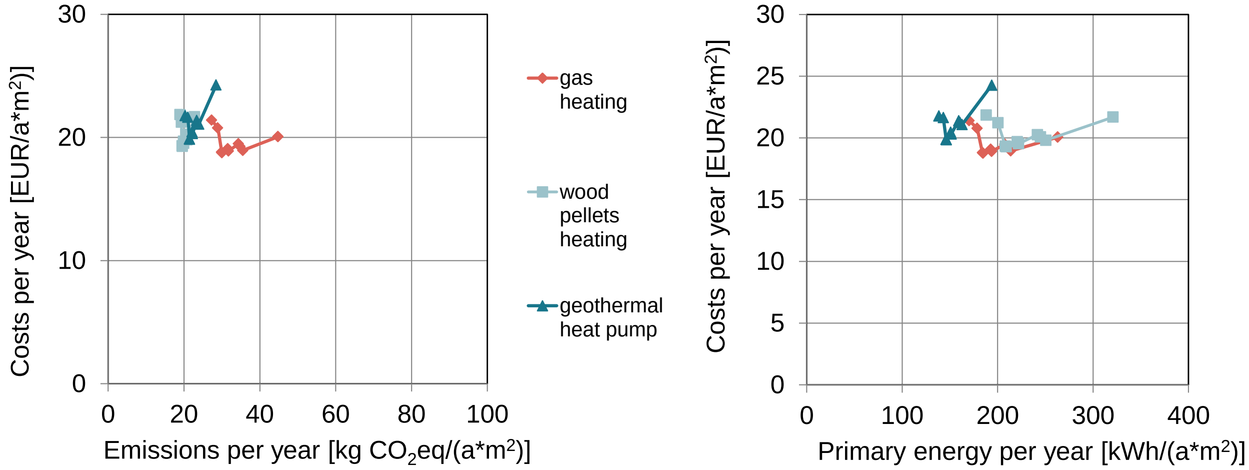


Figure 12 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Spain**, for a **multi-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

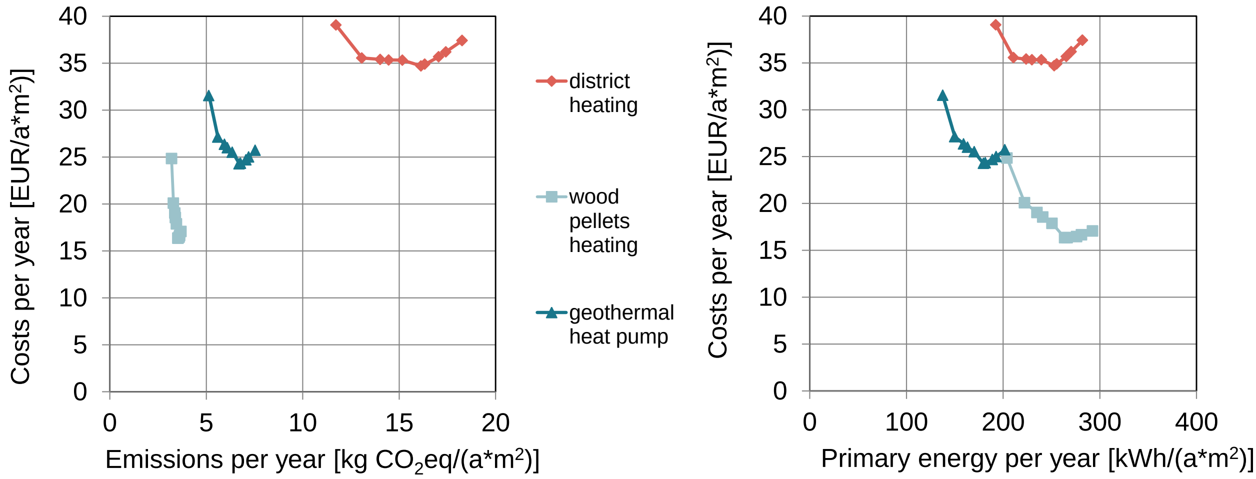


Figure 13 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Sweden**, for a **single-family building**. The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

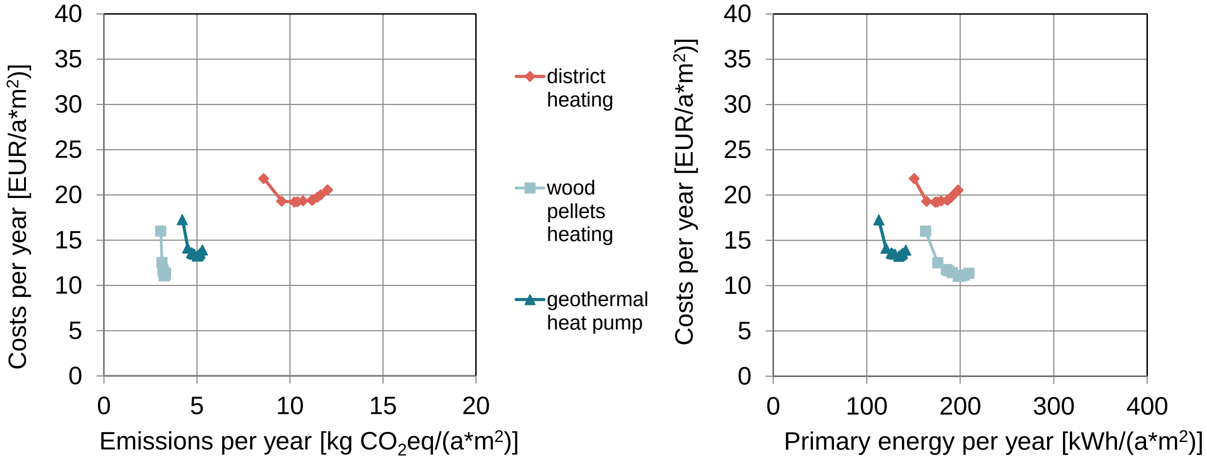


Figure 14 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Sweden**, for a **multi-family building**, The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

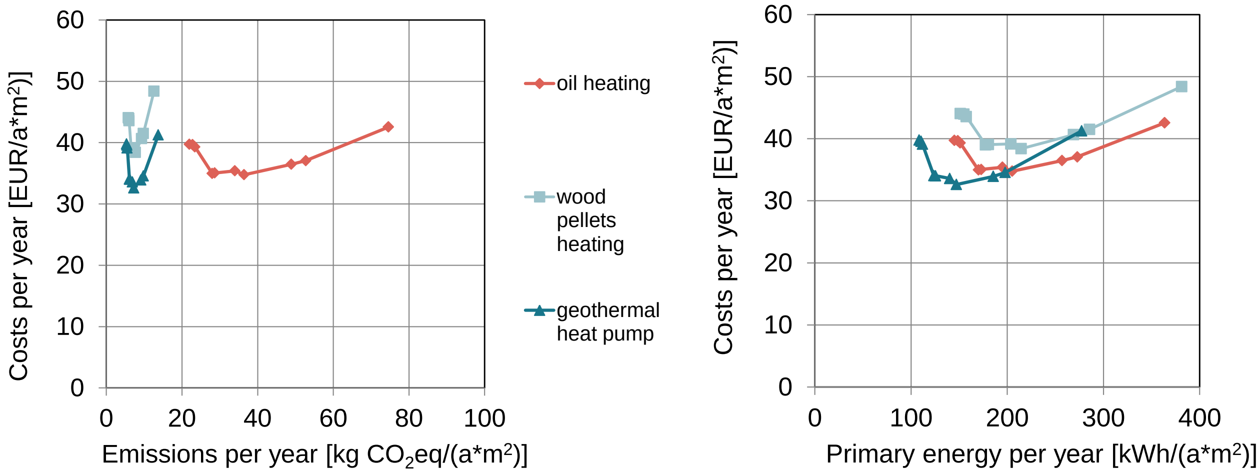


Figure 15 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Switzerland**, for a **single-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Main findings from the generic parametric calculations

Cost-effectiveness

The shape of the cost curves for the investigated generic buildings varies strongly, due to specific characteristics of each building and the national framework conditions. In all 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.

Energy performance and balance between renewable energy deployment and energy efficiency measures

With respect to the energy performance of energy related building renovation measures and the balance between renewable energy deployment and energy efficiency measures, five main hypotheses have been formulated and 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 (AT), Denmark (DK), Spain (ES), Sweden (SE), and Switzerland (CH), geothermal heat pumps and wood pellet heating systems have been investigated as RES systems; in the case of Norway (NO) an air-water heat pump and wood logs; and in the case of Portugal (PT) only 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:

Table 1 Summary of findings for testing the hypotheses in the generic calculations with reference buildings from different European countries. Only selected types of systems using renewable energy sources (RES) were taken into account. **SFB** refers to single-family buildings, **MFB** to multi-family buildings. Countries are abbreviated with their two-letter code: Austria: AT, Denmark: DK, Italy: IT, Norway: NO, Portugal: PT, Spain: ES, Sweden: SE, and Switzerland: CH. In Norway «**Mix1**» refers to an electricity mix based on national production as well as on imports and exports. «**Mix2**» refers to an electricity mix, which in addition also takes into account the trade in guarantees of origin / green certificates.

✓ means that the hypothesis is confirmed.

X means that the hypothesis is not confirmed.

Symbols in parenthesis indicate that the hypothesis is only partly confirmed / not confirmed.

Hypothesis	**SFB AT**	**MFB AT**	**SFB DK**	**MFB DK**	**MFB IT**	**SFB NO Mix1**	**SFB NO Mix2**	**SFB PT**	**MFB PT**	**MFB ES**	**SFB SE**	**MFB SE**	**SFB CH**	**MFB CH**
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	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	✓	✓
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level	(X)	(✓)	(✓)	(✓)	✓	✓	✓	✓	✓	✓	(✓)	X	✓	✓
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 primarily on energy efficiency measures alone	✓	✓	✓	✓	✓	X	✓	X	✓	✓	✓	✓	✓	✓

Based on this overview, the following main observations can be made for the different hypotheses:

Hypothesis 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». Energy performance refers here to primary energy use. The hypothesis is confirmed to a large extent in different country contexts, both for single-family buildings and for multi-family buildings.

Hypothesis 2 «A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements»:
The hypothesis is confirmed for all reference buildings investigated for several types of heat pumps and wood based systems investigated as RES systems, with the exception of Norway.

Hypothesis 3 «A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level»:
This hypothesis is confirmed for a large share of the generic buildings examined. In many cases, the cost-optimal renovation package is the same for different heating system (even though absolute costs of the corresponding optima might differ).

Hypothesis 4 «Synergies are achieved if a switch to RES is combined with energy efficiency measures».
Synergies are understood to occur when energy efficiency measures are cost-effective in combination with a switch of the heating system to a renewable energy system. This hypothesis is confirmed without exception for all reference buildings investigated.

Hypothesis 5 «To achieve high emissions reductions, it is more cost-effective to switch to RES and carry out less far-reaching renovation measures on the building envelope than to focus on energy efficiency measures alone»:
This hypothesis is fully confirmed for most generic buildings investigated. Exceptions are the case of the building in Norway and the single-family building in Portugal.

The assessment also showed that while energy efficiency measures simultaneously reduce primary energy use and carbon emissions in similar proportions, renewable energy measures reduce carbon emissions more strongly than they reduce primary energy use. The implications of this and of the findings regarding the investigated hypotheses are discussed in the conclusions, see further below.

Multi-family buildings

For multi-family buildings, the following hypothesis has been investigated: *«Synergies between RES measures and energy efficiency measures are larger than in single-family buildings.»* Comparisons are made between the effects of different renovation packages in single-family buildings and multi-family buildings from Austria, Denmark, Portugal, Sweden, and Switzerland. The hypothesis is only partially confirmed. This can be explained by the fact that there may be two opposite effects: on the one hand, installed heating systems in multi-family buildings tend to be larger. This offers more opportunities for synergies due to energy efficiency measures: cost savings obtained by a reduction of the peak capacity of the heating system, made possible by lowering the energy need of the building, are more significant for larger systems. However, at the same time the specific energy need per m^2 is smaller in multi-family buildings than in single-family buildings. This in turn means that energy use is already relatively lower, and that a change from a conventional heating system to a RES based system may bring relatively less additional benefits.

Effects of ventilation system

Concerning the effects of ventilations systems, the following hypothesis has been investigated: *«The installation of a ventilation system with heat recovery has effects on the energy performance comparable with measures on other building elements»*. This hypothesis has been investigated for generic single-family and multi-family buildings in Sweden and Switzerland. The hypothesis has been confirmed. The results show that the installation of a ventilation system with heat recovery is an effective measure to reduce both emissions and primary energy use.

Effects of embodied energy

The effects of embodied energy/emissions has been investigated with a generic single-family building in Switzerland. The most far-reaching measures are found to be a bit less favourable in terms of reduction of primary energy use when taking into account the additional energy use because of the embodied energy. This is particularly evident for energy efficient windows. A geothermal heat pump has more embodied energy than a conventional oil heating system, as energy is also needed to drill the borehole. The difference compared is nevertheless rather small.

In the case study in Sweden, embodied energy and embodied emissions were also taken into account. For renovation measures with new windows it was observed that in case of district heating systems largely or entirely based on renewable energies, primary energy use and carbon emissions rather increase than decrease , while in the case of an oil heating system the positive effects that the new windows with a higher energy performance have on reducing emissions/primary energy use outweighs the emissions/energy due to the use of materials. In the case of a wood heating system, a negative effect of new windows was observed with respect to carbon emissions, yet not with respect to primary energy use.

The topic of embodied energy is investigated in more detail in a separate report within Annex 56.

Effects of cooling

Generic calculations taking into account cooling for generic buildings in Italy, Portugal and Spain have shown that with increasing levels of insulation, the energy need for heating decreases, whereas the energy need for cooling increases. This is due to the property of well-insulated buildings to trap internal heat gains more effectively than low-insulated buildings: whereas this is a desired property for reducing heating needs, in summer time this contributes to over-heating and related cooling needs. Shutters to protect against solar radiation are an important measure to reduce related negative effects.

Taking into account cooling needs, with or without shutters, does not favour a different renovation package than without taking into account cooling needs in the generic example investigated.

Taking into account cooling, may have an effect, however, on the choice of the heating system. Heat pump systems exist which can both provide both heating and cooling. There is accordingly a potential for synergies by using the same energy system for both with this type of system. When taking into account the energy need for cooling, a heat pump solution becomes more attractive in comparison with a situation in which cooling is not taken into account.

The following conclusions can be drawn from the investigated effects of taking into account cooling needs:

— The higher the solar irradiance, the more trade-offs exist concerning the effects of building insulation on heating needs and cooling needs, as the effect that additional insulation increases cooling needs gets stronger.
— The higher the temperature, the more synergies exist concerning the effects of building insulation on heating needs and cooling needs, as the effect that additional insulation decreases cooling needs gets stronger.
— In Southern Europe, there are in general more trade-offs than synergies concerning the effects of building insulation on heating needs and cooling needs.
— Shutters can reduce the energy need for cooling significantly.
— Taking into account cooling does not change the cost-optimal package of energy-efficiency renovation measures on the building envelope.

Taking into account cooling needs favours a heat-pump solution as an energy system which can provide both heating and cooling under certain conditions.**Main findings from the parametric calculations in case studies**

Overall, the case studies confirm to a large extent the results obtained from the generic calculations – at the same time, they show that in individual cases, it is also possible to obtain different or even opposite results. This illustrates the limitations for conclusions which can be drawn from generic calculations – for a given renovation situation, each building needs to be examined separately, as case-specific conditions may lead to differing results than generic calculations have given.

Only selected types of systems using renewable energy sources (RES) were taken into account: In the case of the building "Kapfenberg" in Austria: geothermal heat pump, aerothermal heat pump and wood pellets; in the case of "Traneparken" in Denmark: a district heating system with a share of 53% renewable energies and a heat pump; in the case of "Rainha Dona Leonor neighbourhood" in Portugal: a biomass system and a heat pump in combination with PV; in the case of “Lourdes Neighbourhood“ in Spain: a heat pump, district heating with 75% biomass, or 100% biomass; in the case of Backa röd” in Sweden: pellets heating or district heating with RES.

The following table summarizes the results of the parametric calculations in case studies for investigating the five previously mentioned hypotheses related to energy performance and the balance between renewable energy and energy efficiency measures:

Table 2 Summary of findings for testing the hypotheses in the case studies from different European countries: Austria (AT), Denmark (DK), Portugal (PT), Spain (ES), and Sweden (SE). Only selected types of systems using renewable energy sources (RES) were taken into account. ✓ means that the hypothesis is confirmed. X 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	Kapfen-berg, AT	Trane-parken, DK	Rainha Dona Leonor, PT	Lourdes, ES	Backa röd, SE
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	✓	✓	(✓)	X	X
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 cost-optimal efficiency level	✓	(✓)	✓	✓	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓	X	✓	✓	✓/X
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 primarily on energy efficiency measures alone.	✓	✓	(✓)	✓/X	✓

The results of the case studies are described in more detail in a separate report developed of Annex 56 (Venus et al. 2015).

Sensitivities in parametric calculations

The findings are specific to the reference buildings and context situations investigated. The fact that these reference buildings represent typical situations in different countries and take into account different framework conditions strengthens the conclusions derived. Nevertheless, the results remain sensitive to several assumptions. Key parameters are in particular:

Future energy prices: Energy prices play an important role for the cost-effectiveness of renovation measures and for a switch to renewable energy sources: The higher the fossil energy prices, the more cost-effective renovation measures on the building envelope or a switch to renewable energy sources become. Furthermore, the higher the energy prices, the more cost-effective becomes a switch to renewable energy sources compared to a conventional heating system, which usually has lower investment costs, but higher energy costs. In addition, changes in prices of some energy carriers relative to others may favour certain technologies, e.g. lower electricity prices make it more attractive to cover heating needs with heat pump solutions. It is challenging to predict future energy price developments. What matters from a life-cycle perspective are long-term price and cost developments. A decline in fossil fuel reserves and an ambitious climate policy (e.g. with a carbon emission tax) are factors which tend to increase fossil fuel energy prices in the future, while technological progress tends to reduce future renewable and non-renewable energy prices as well as the cost of energy conservation measures. It also needs to be taken into account that (national) energy prices for consumers partly include charges and taxes which are independent of energy price developments on the global markets, reducing thereby the relative volatility of energy prices for consumers. The sensitivity calculations which were carried out confirm that the assumptions on future development of energy prices matter.

Initial energy performance of building envelope: The energy performance of the buildings prior to renovation has an important impact on the additional benefits of building renovation and its cost-effectiveness. Higher energy performance of a building before renovation reduces the economic viability of additional measures because of a worse cost/benefit ratio and lower additional benefits in terms of reduction of carbon emissions or primary energy compared to the situation before renovation.

Climate: It can be expected that in colder climates, energy efficiency renovation measures on the building become more cost-effective, as the temperature difference between inside and outside is higher. In warm or hot climates there can be trade-offs between architectural design, increasing energy performance of the building envelope and cooling needs. Such architectural design may concern for example window area, orientation of windows, or heat storage capacities.

Service lifetimes: With longer lifetimes of renovation measures for given investment costs, measures increasing the energy performance of the building become more cost-effective.

Interest rate: It can be expected that the higher the interest rate for capital costs, the less cost-effective are investments to improve the energy efficiency of the building or a switch to a renewable energy system since they have typically higher investment costs and lower energy costs.

Conclusions

The parametric calculations carried out with generic reference buildings and case studies have shown that there is in general a large potential for cost-effective building renovations which reduce carbon emissions and primary energy use significantly. These results have been obtained based on assuming a moderate real interest rate of 3% and an increase in energy prices by 30% compared to prices of 2010.

It was found that the scope of renovation measures is larger, when the focus is put on cost-effectiveness rather than on cost-optimality. The difference is that cost-optimality focuses on the most cost-effective solution in absolute terms, whereas cost-effectiveness puts any renovation package into relation to a reference case. Costs of the reference case correspond to the energy costs and operational costs occurring in the initial situation combined with investment costs to carry out a number of hypothetical "anyway measures" that would have to be carried out anyway, just to restore the building elements' functionality, without improving the building's energy performance. It is therefore more appropriate to take cost-effectiveness as a benchmark, instead of cost-optimality.

Even when the range of cost-effective renovation options is implemented, however, this often does not lead to nearly zero energy use in renovated buildings. The situation is different from new buildings, where the additional investment costs for reaching nearly zero energy building standards are relatively small compared to the energy savings that can be achieved. Particularly for existing buildings, where previously already some insulation had been made, additional renovation measures to increase the energy efficiency level of the building are often not cost-effective, because of diminishing marginal energy savings with additional insulation.

Yet apart from reaching a nearly zero energy level, there is another important objective that can often be reached cost-effectively in building renovation: nearly zero carbon emissions. With the help of renewable energy measures, this objective can often be reached cost-effectively, even if a nearly zero energy level is not cost-effective for a building renovation.

From a point of view of policy objectives, it can be argued that reducing carbon emissions is anyway more important than reducing primary energy use in building renovation. Climate change is one of the major challenges of this century. At EU level, ambitious targets for reducing greenhouse gas emissions have been formulated. The EU's goal is to reduce greenhouse gas emissions in the EU by 80% - 95% by the year 2050 compared to 1990. As other sectors causing greenhouse gas emissions such as air traffic or agriculture can reduce their emissions only with difficulty, an overall 80%-95% reduction in greenhouse gas emissions can only be achieved if in the building sector, essentially a 100% reduction of greenhouse gas emissions is pursued.

Traditionally, primary energy use has been used as proxy for carbon emissions: The traditional thinking is that reducing primary energy use is synonymous to reducing carbon emissions. This is, however, only the case as long as the heating system is a conventional heating system operating at least in part with fossil fuels. Renewable energy measures allow to reduce carbon emissions significantly by switching the energy carrier, without reducing primary energy use as strongly.

Consequently, putting a focus on reducing carbon emissions and on the use of renewable energies in building renovation could have an important advantage: This could allow to reduce carbon emissions further, beyond the level that can be reached when reducing primary energy use by energy efficiency measures within the limits of cost-effectiveness while keeping a conventional heating system.

Putting an additional focus on reducing carbon emissions in building renovation does not mean that reduction of energy need, primary energy targets or energy efficiency measures don't have to play an important role anymore in building renovation. On the contrary, they continue to be of high importance, for various reasons:

— Energy efficiency measures increase thermal comfort and have also other co-benefits (see separate report in Annex 56 on co-benefits, Ferreira et al. 2015).
— Energy efficiency measures are often necessary to ensure sufficient thermal quality of the building envelope and to prevent damages resulting from problems with building physics
— Carrying out energy efficiency measures is often cost-effective when carried out in combination with a switch to renewable energy.
— If the electricity mix is already to a large extent CO_2-free, because of high shares of renewable energy or nuclear energy, only energy efficiency measures can ensure that electricity use in buildings is reduced.
— Biomass is a form of renewable energy, yet a limited resource. Only by applying energy efficiency targets, apart from emission targets, can it be ensured that energy use in buildings with a biomass heating is also minimized to allow a maximum number of buildings to make use of this resource.
— The availability of renewable energies other than biomass, such as solar energy or wind energy, depends on the season.
— If a large number of heat pumps using geothermal or hydrothermal resources are located close to each other, they may reduce the efficiency of each other, by overexploiting the heat source and thereby lowering the temperature of the heat source. Again, energy efficiency targets and related measures ensure that the available resources can be used by a maximum number of buildings.

— Energy efficiency measures usually bring a long-lasting impact, independent of future changes of the heating system, whereas renewable energy measures such as a switch to a renewable energy system may be reversed the next time the heating system is replaced

Therefore, when the case is made for setting a new target of reaching nearly zero emissions in existing buildings by making increased use of renewable energies, this is not meant to substitute, and rather to supplement existing energy targets.

An important reservation needs to be made, though, which could speak in favour of softening energy efficiency targets at least in some cases to some extent, because of the importance of making increased use of renewable energies. This is subsequently explained:

One of the central questions investigated with the parametric assessments is the balance between energy efficiency measures and measures based on renewable energy. It has been found that in most of the cases, when a switch from a conventional heating system to wood pellets or a heat pump is made, this does not have an impact on the question which package of energy efficiency measures is most cost efficient. Reasons are on the one hand that also with a renewable energy system, cost savings can be achieved by using less energy, even if energy costs are usually smaller for renewable energy systems than for conventional energy carriers. On the other hand, synergies can be achieved if the timing is right between energy efficiency measures and renewable energy measures, as lower energy need of the building allows to install smaller sized heating systems; in addition, heat pumps benefit from increased efficiency, if energy efficiency measures allow to lower the supply temperature of the heat distribution system. Consequently, in many cases there are no trade-offs between renewable energy measures and energy efficiency measures; it is often not necessary to differentiate the cost-optimality of energy efficiency measures with respect to different heating systems. However, in some cases results are also found showing that there are cases where the mix of energy efficiency measures which is necessary to reach the cost optimum is changed by a switch to wood pellets or heat pump. Situations may arise in which requirements set by standards to achieve a certain energy efficiency level in building renovation are only cost-effective with conventional heating systems, yet not with renewable energies; this could be counterproductive for reducing emissions.

Consequently, care needs to be taken to ensure that building codes are not counterproductive for reducing carbon emissions. Several options exist how this may be taken into account in standard making. A first possibility is to differentiate energy efficiency standards according to the type of heating system. This could mean that to be able to continue using conventional energy carriers in a certain building, a higher level of energy efficiency standards would have to be reached than if the building is only heated with renewable energy. A second possibility could be to introduce two types of energy efficiency standards, one regulating overall primary energy use or energy need (per m^2 and year), while the other regulating non-renewable primary energy use or carbon emissions (per m^2 and year) of a building. The standard regulating overall primary energy use or energy need could be made less strict than the standard for non-renewable primary energy use or carbon emissions. Thereby potential obstacles to switch to renewable energies can be reduced, while efficiency requirements are kept also for buildings heated with renewable energies. The standards related to non-renewable primary energy use or carbon emissions could be made stronger to set additional efficiency requirements for buildings which are not heated with renewable energies. They could encourage or even force a change to renewable energies. A third possibility could be to introduce an exception clause into standards which could provide that if it can be proved that a certain energy efficiency measure is not cost-effective in combination with a switch to a renewable energy system, there is only an obligation to carry out the related energy efficiency measures to the extent they are cost-effective. To manage procedures related to such a solution might be challenging; this could be assisted by defining precisely the framework parameters to be applied in related cost-effectiveness calculations and by providing templates for carrying out such calculations.

The concepts of reduction of carbon emissions and reduction of primary energy use could potentially be reconciled and merged by putting a focus only on reducing non-renewable primary energy use. This would mean that for renewable energy and for the share of renewable energy in the electricity mix non-renewable primary energy factors of close to 0 are used.

However, the concept of emission targets is potentially more easily understandable and can be distinguished more easily from the currently existing energy targets. Furthermore, in some countries, standards do not refer to the energy consumption of the building taking into account the energy carrier of the heating system, but to the energy need, calculated only on the basis of the building envelope, without taking into account the type of heating system. Therefore, it may be more appropriate to introduce the concept of "nearly zero-emission targets" for building renovation.

A point which was not a central topic in this project, yet which is of importance and merits further clarification is the question whether it makes more sense to use renewable energies in decentralized systems or in centralized district heating systems. There are several reasons why it can be more efficient to use renewable energies centrally in district heating systems rather than in decentralized systems, although depending on the renewable energy source and the circumstances of the district heating system also the opposite may be the case.

Apart from the above mentioned questions concerning the balance between renewable energies and energy efficiency measures in building renovation, further conclusions can be drawn from the results obtained:

The investigations of different renovation packages show that in order to improve a building's energy performance, it is important to improve energy performance of all elements of the envelope. For each single building element, there are distinctly decreasing marginal benefits of additional insulation. However, within the limits possible, it is recommendable to set ambitious energy efficiency standards also for single building elements, since once some insulation measures are carried out, it is usually not cost-effective anymore to add insulation at a later point of time. The marginal cost-/benefit ratio is unfavourable then. This can lead to a lock in-effect, trapping building owners by preceding investment decisions such that subsequent measures to get closer to the nearly zero energy and emissions targets have an unfavourable cost/benefit ratio.

The impact of embodied energy use and embodied emissions of renovation measures has been found to be smaller than for new building construction, yet it plays a role for high efficiency buildings and for heating systems based on renewable energies or district heating. The calculations carried out indicate that whereas in general taking into account energy and emissions in the materials in building renovation has a low impact on the primary energy use or carbon emissions, this may change for high efficiency buildings and for buildings heated with renewable energy or district heating with a low carbon emission factor. In particular high efficiency windows may sometimes require more additional energy for their construction than what they additionally save during their time of service. When the heating system is based on renewable energy or district heating with waste heat and renewable energies, the effects of embodied emissions are becoming more important, because the emission reductions obtained with additional insulation are smaller.

The evaluations carried out have also shown that renovation projects are often limited by case-specific constraints and interdependencies and do not comprise a complete set of measures on the building envelope and on the energy system. The reasons are in particular financial constraints and non-synchronism of renovation needs of the energy related building elements at stake. What is recommendable in a given situation can only be answered on a case-by-case basis, by assessing different packages of renovation measures needed which take into account immediate renovation needs, financial resources and at least midterm planning of upcoming renovation needs.

Recommendations

Based on the results obtained and the conclusions drawn, the following recommendations are made:

Recommendation 1: Setting new targets to reduce carbon emissions from buildings, supplementing existing energy targets

For building renovation, there is currently no requirement in the EPBD to cover the remaining energy need by renewable energy. However, to reduce the carbon emissions of existing buildings beyond the cost-optimal level of energy efficiency measures, renewable energies have an important function. In building renovation, energy standards based on cost-optimal energy efficiency levels will not allow meeting nearly zero energy targets. Taking costs into consideration, cost-optimality is often achieved at levels far from nearly zero energy levels. To reduce carbon emissions further from there, it is often more cost-effective to use renewable energy sources than to strive for reducing energy need of buildings by further increasing the energy performance of the building envelope. In this situation it is appropriate to increase the relevance of carbon emissions reduction goals by establishing carbon emissions targets for existing buildings. Taking into account the importance of reducing carbon emissions in the building sector, and not just energy use, may lead to a "nearly zero-emission" concept for building renovation, while energy efficiency measures continue to be required to the extent they are cost-effective in such a nearly zero-emission solution.

More specifically, the following recommendations are formulated:

— **For building owners**: In addition to carrying out energy efficiency improvements in building renovation, it makes sense to consider reaching nearly-zero emissions in existing buildings, to make an important contribution to protect the climate.

— **For policy makers**: It is advisable to introduce a target to reach nearly zero carbon emissions in existing buildings undergoing a major renovation, complementing existing energy efficiency requirements. If this is not cost-effective, for example because the heating system would not have to be replaced anyway in the near future, exceptions can be made. For buildings connected to a district heating system, it is possible to reach the goal of nearly zero carbon emissions collectively by transforming the energy source of the district heating system.

Recommendation 2: Switching heating systems to renewable energies

In terms of single measures, the most significant measure to reduce carbon emissions from energy use in buildings is often a switch of the heating system to renewable energies. It is also in many cases a cost-effective measure. Apart from the introduction of nearly zero-emission targets for existing buildings, as explained above, additional measures to ensure a switching of the heating systems to renewable energies makes sense.

More specifically, the following recommendations are formulated:

— **For building owners**: Before a conventional heating system is replaced by one with the same energy carrier, it is advisable to take into consideration a switch of the heating system to renewable energy; in many cases, this is ecologically and economically attractive over a life-cycle perspective. For buildings connected to a district heating system, it is advisable to take into account the current energy mix of the district heating system and the possibility that a switch to renewable energies may occur in the future for the entire district heating system.

— **For policy makers**: It is adequate to make a switch to renewable energies mandatory when a heating system is replaced, similarly to energy improvements of the building envelope. Exemptions may still be granted from such a rule, if the building owner can show that such a measure would not be cost-effective from a life-cycle perspective. Exemptions could also be made if a building is connected to a district heating system which either already has a high share of renewable energy or for which a plan exists to switch it to renewable energies.

Recommendation 3: Making use of synergies between renewable energy measures and energy efficiency measures

The moment when a heating system needs to be replaced, is an ideal moment to carry out a major renovation involving both the heating system and one or more elements of the building envelope. The following recommendations are formulated:

— **For building owners**: The replacement of the heating system is an excellent opportunity to carry out renovation measures on the building envelope as well, creating synergies. If carried out together, the investments in the building envelope result in savings on the investment costs for the heating system, because the more energy efficient a building is, the smaller can be the dimension of the heating system. Furthermore, several measures of the building envelope are preferably combined. It is necessary to look in each case separately, to what extent it makes sense to postpone or schedule earlier than necessary renovation measures of some building envelopes, in order to make use of such synergies.

— **For policy makers**: It is recommendable that standards and other policy measures, for example subsidies, create incentives to combine renovation measures on the building envelope with a replacement of the heating system, in order to make sure that reductions in energy use and emissions are achieved most efficiently. Exceptions could be made for buildings connected to a district heating system, which already has a high share of renewable energy or for which a switch of the district heating system to renewable energy sources is planned.

Recommendation 4: Orientation towards cost-effectiveness rather than cost-optimality to achieve a sufficiently sustainable development of the building stock

The EU's EPBD focuses on cost-optimal measures. Since in building renovation cost-optimal solutions won't result in nearly zero energy buildings, it is indispensable to go a step further and tap the full potential of cost-effective energy related renovation measures with respect to a reference case.

More specifically, the following recommendations are formulated:

— **For building owners**: To obtain the largest possible impact from building renovation in terms of contributing to the reduction of carbon emissions or primary energy use, it is advisable to carry out the most far-reaching energy related renovation package which is still cost-effective compared to the reference case, rather than to limit oneself to the cost-optimal renovation package. Taking into account co-benefits may extend the renovation measures which are considered to be cost-effective even further.

— **For policy makers**: It is recommendable that standards do not limit themselves to make an energy performance level mandatory up to the cost-optimal level, but to make also further measures mandatory as long as they are cost-effective with respect to a reference case.

Recommendation 5: Making use of opportunities when renovations are made "anyway"

The following specific recommendations are formulated:

— **For building owners**: Whenever a renovation of an element of the building envelope needs to be carried out anyway, this is a good opportunity to improve the energy performance of that building envelope element, and to improve also other building envelope elements.

— **For policy makers**: It makes sense that standards for achieving improvements in energy performance focus on situations when one or more building elements are anyway in need of renovation.

Recommendation 6: Taking into account the complexity of building renovation in standards, targets, policies, and strategies

The following specific recommendations are formulated:

— **For building owners**: The complexity of building renovation and the large investments needed require the development of long-term strategies for maintenance, energy improvements and carbon emissions improvements for each building, taking their specific situation into account. It is advisable to develop either a strategy towards a major renovation or a strategy to renovate the building in steps over the years. In the latter case, the measures which are undertaken in one step ideally already include the preparation of further renovations in the future.

— **For policy makers**: To achieve large reductions of energy use and carbon emissions in existing buildings most cost-effectively, it is important that standards, targets and policies take into account the complexity of building renovation while seeking for least-cost solutions and least-cost paths. Flexibility is needed to give renovation strategies a chance to enable the transformation of the building stock towards low energy use and nearly zero emissions. This includes the flexibility to reach these targets in steps over time.

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Abbreviations

Table 3 List of frequently used abbreviations

AT	Austria
BITS	Building integrated technical systems
CH	Switzerland
DHW	Domestic Hot Water
DK	Denmark
EN	European Norm
EPBD	Energy Performance of Buildings Directive
ES	Spain
HP	Heat pump
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
IT	Italy
kWh	Kilowatthours: 1 kWh = 3.6 MJ
λ	Lambda-Value (value for the insulating capacity of a material)
LCA	Life cycle analysis/assessment
LCI	Life cycle impact
LCIA	Life cycle impact analysis
MFB	Multi-family building
MJ	Megajoule; 1 kWh = 3.6 MJ
NO	Norway
NZEB	Nearly zero energy building or nearly zero emissions building
PT	Portugal
PV	Photovoltaics
Ref	Reference
RES	Renewable energy sources
SE	Sweden
SFB	Single family building
STA	Annex 56 Subtask A (Methodology, parametric calculations, LCIA, co-benefits)
STB	Annex 56 Subtask B (Tools)
STC	Annex 56 Subtask C (Case Studies)
STD	Annex 56 Subtask D (User Acceptance and Dissemination)
U-value	Thermal transmittance of a building element

1. Introduction

There is evidence that extrapolating current trends in energy supply and use will not allow to meet existing goals to mitigate carbon emissions and to reduce non-renewable fossil fuel consumption accordingly. In order to change the looming path, it is crucial to identify existing large and promising reduction potentials.

With a share of more than 40% of the final energy use and some 35% of carbon emissions (BPIE, March 2013, p. 5), the building sector represents the largest energy consuming sector and is considered as «the largest untapped source of cost-effective energy saving and CO_2 reduction potential (at least) within Europe, yet the sector continues to suffer from significant underinvestment» (BPIE, February 2013, p. 5). This holds particularly for the existing building stock, whose energy related improvement is highly relevant for mitigating carbon emissions and energy use, yet it is a challenge to make use of these potentials.

Up to now, the focus on energy and carbon emissions related strategies in the building sector was largely on tapping and developing efficiency potentials of new buildings, and thereby mainly of improving the energy performance of the building envelope and technical building systems: As for example the EU's Directive on the energy performance of buildings (EPBD) and its recast are putting emphasis on the high energy performance of the building envelope, albeit in its two step approach deployment of renewable energy is also addressed but only in a second step (see e.g. Holl M. 2011, p. 17). However, the question may be raised if such standards are primarily adequate for new buildings but might not respond effectively to the numerous technical, functional and economic constraints of existing buildings. It might be that for the energy related renovation of existing buildings the expensive measures and processes resulting are not enough accepted by building users, owners and promoters. In the case of existing buildings it can be observed that opportunities are missed too often to significantly improve energy performance of buildings within building renovation, often because of higher initial costs but often also because of lacking know-how and awareness regarding cost-effectiveness if a life-cycle cost approach is assumed. Hence it is relevant to explore the range of cost-effective renovation measures to increase efficiency and deployment of renewable energy to achieve the best building performance (less energy use, less carbon emissions, overall added value achieved by the renovation) at the lowest effort (investment, life cycle costs, intervention in the building, users' disturbance). Therefore, a new methodology for energy and carbon emissions optimized building renovation is to be developed. It is supposed to become a basis for future standards, to be used by interested private entities and agencies for their renovation decisions as well as by governmental agencies for the policy evaluation as well as for the definition of their strategies, regulations and their implementation.

This situation was the trigger to launch IEA-EBC Annex 56 «Cost-effective energy and carbon emissions optimization in building renovation». In Annex 56 costs are integrated into the assessment and evaluation framework of energy and carbon emissions related building strategies, measures and policies. Particularly for building renovation seeking a least cost path on the one hand and maximum energy and carbon emissions reduction on the other hand, the trade-offs between higher building envelope's efficiency, highly efficient technical building systems and deployment of renewable energy, considering carbon emissions as well as primary energy use are explored. Apart from assessing operational energy use, also the impact of including embodied energy is investigated in the project.

2. Objectives

Annex 56 strives to achieve the following objectives:

- Develop and demonstrate a cost, energy and carbon emissions related assessment and evaluation framework
- Define a methodology for the establishment of cost optimized targets for energy use and carbon emissions in building renovation;
- Clarify the relationship between the emissions and the energy targets and their eventual hierarchy;
- Determine cost-effective combinations of energy efficiency measures and carbon emissions reduction measures;
- Highlight the relevance of co-benefits achieved in the renovation process;
- Develop and/or adapt tools to support the decision makers in accordance with the methodology developed;
- Select exemplary case-studies to encourage decision makers to promote efficient and cost-effective renovations in accordance with the objectives of the project.

These objectives are pursued by the subsequent four Subtasks:

STA Development of the methodology and application of the methodology to assess costs, energy and carbon emissions related impacts of building renovation measures by parametric calculations for generic buildings from countries participating in Annex 56. The methodology has to allow for including the relevant LCIA aspects and the assessment of co-benefits into the overall assessment of cost-effective energy related renovation measures.

STB Tools, guidelines and support for decision makers (building owners, investors, policy makers)

STC Case studies and shining examples

STD User acceptance and dissemination

The objectives of the work documented in this report are more specifically:

- To test the methodology developed within Annex 56 by assessing different packages of energy related renovation measures for typical generic single-family and multi-family buildings from the countries participating in Annex 56.
- To assess energy related renovation measures regarding costs, primary energy use and carbon emissions

– To determine the range of cost-effective and of cost-optimal energy related renovation measures

– To determine cost-effective combinations of energy efficiency measures and renewable energy based measures as well as related synergies and trade-offs

– To compare results obtained from calculations with generic buildings with calculations from case studies

– Derive recommendations for target setting by policy makers and for energy and carbon emissions related renovation strategies by owners or investors.

In this report the findings of an investigation based on calculations with generic buildings and case studies carried out as part of Subtask A are presented. For the case studies, only a summary is presented; more detailed information is is available in a separate report.

The performed calculations apply the methodology developed within the methodology subtask of Annex 56, which is documented in a separate report (Ott et al. 2015). Single-family and multifamily residential buildings from various European countries have been investigated. The parametric calculations were carried out for varying packages of energy related renovation measures to assess impacts of these renovation measures related to costs, energy use and carbon emissions.

3. Methodology for parametric assessments of generic buildings

3.1. Scope of generic calculations

General scope

The generic calculations aim to assess renovation strategies to determine cost-effective combinations of renovation measures which optimize energy and carbon emissions savings. The generic calculations also intend to evaluate the synergies and trade-offs between energy and carbon emissions reduction measures in the case of a building renovation. Whereas the generation of these results serves directly to fulfil the objectives of Annex 56, the generic calculations also have the function of illustrating and testing the methodology. Rather than providing an exhaustive assessment of all building types in all countries involved, calculations have been focused on selected reference buildings and renovation packages. Therefore, they also have the role of serving as a model for further, more refined and more comprehensive calculations. Moreover, the calculations test the methodology for the sake of application in more case studies.

In this report, results of parametric calculations with generic single-family (SFB) or multi-family (MFB) residential reference buildings from Austria, Denmark, Italy, Norway, Portugal, Spain, Sweden and Switzerland are documented. These reference buildings are supposed to be representative for a relevant share of existing residential SFB- and MFB-buildings not having undergone a major energy related renovation yet. Furthermore, summaries of five case studies from Austria, Denmark, Portugal, Spain and Sweden, part of a Subtask C in Annex 56, are put into context with the generic calculations that have been carried out.

The calculations carried out follow the methodology developed within Annex 56 which is described in a separate report (Ott et al. 2015).

Assessed energy use and emissions

Energy use and related carbon emissions comprise operational energy use for space heating, domestic hot water, ventilation, space cooling, auxiliary electricity demand for building integrated technical systems such as fans, pumps, electric valves, control devices, etc., appliances and lighting. Embodied energy use for renovation measures is considered to be part of a comprehensive assessment, even if it is not as important as in the case of new building construction. In the parametric calculations embodied energy use is determined for selected cases.

Energy use and related carbon emissions are determined on the level of primary energy use, applying national primary energy conversion factors and national carbon emission factors taking into account upstream primary energy use for energy carriers and for related emissions.

Costs

Integrating the cost perspective is crucial for finding effective or optimal solutions for far-reaching reductions of energy use and carbon emissions of buildings within building renovation. The methodology developed is based on life cycle costs. Usually a private cost/benefit perspective is assumed, comprising initial investment cost, replacement cost during the remaining lifetime of the building, energy cost including existing energy and CO_2-taxes, maintenance and operational costs. Subsidies for energy related measures are excluded from the assessment of costs and benefits to have an assessment which is undistorted by currently prevailing subsidy programs which might change over time. Private cost perspective is relevant for owners and investors but also for policy makers, to consider the impact of possible policy measures from a private cost perspective which is important for the acceptance of the particular program. Social costs, including external costs and benefits are not included, although it is important that they are considered by policy makers for target setting and for the design of energy and emissions related programs. Cost assessment is performed dynamically, discounting future costs and benefits with the annuity method.

Assessments

Impacts are investigated to learn more about synergies or trade-offs between energy and emissions related renovation measures, in particular between increasing energy efficiency of the building envelope and increasing the use of renewable energies, as well as for exploring the range of cost-optimal and of cost-effective renovation measures (Figure 1).

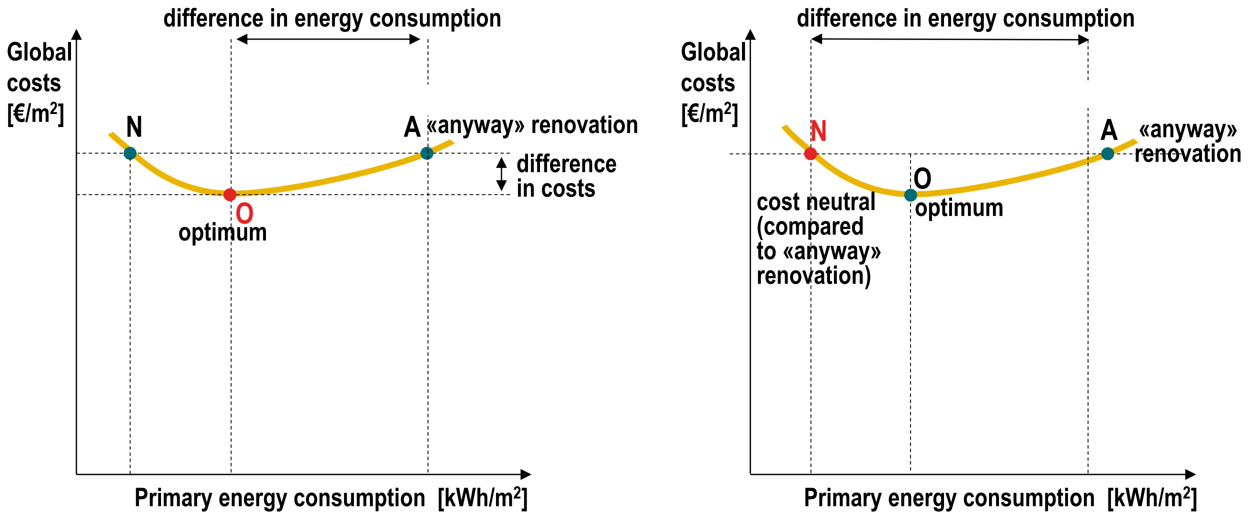


Figure 16 Global cost curve after renovation, starting from the reference case **A** («anyway renovation») towards renovation options with less primary energy use than in the case of the anyway renovation. Costs comprise yearly capital costs, energy costs, as well as operation and maintenance costs. **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 cost-effective. (BPIE 2010, p. 15, supplemented by econcept).

3.2. Calculation procedure and framework conditions

3.2.1. Calculation procedure

The generic calculations follow the methodology developed in Annex 56 and involve in particular the following elements:

- For each country investigated, the framework parameters are determined. These include economic parameters on energy prices, interest rates and exchange rates, emission factors, primary energy factors and climate data.
- For each country investigated, one or more reference buildings, typical for existing and not yet renovated residential buildings for the specific country, are defined, and their properties regarding dimensions and energy performance levels of the building elements are determined.

Costs of «anyway measures» regarding the heating system and the building envelope are determined. These are the costs which would incur to maintain the functionality of the building, without the goal of improving its energy performance. Based on the costs of these measures, combined with energy costs and maintenance costs, the costs for the «anyway renovation» reference case are determined. The costs of energy related renovation packages are compared with this reference case.

Costs and effects of different renovation measures are determined. Individual measures are grouped into renovation packages. Costs and effects on the energy performance of the building are assessed for different renovation packages. A renovation package consists of energy efficiency measures on the building envelope in combination with a replacement of the heating system with an identical conventional system or with a new RES-based heating system. Further energy related measures on the technical building systems can be added to the renovation package. Starting from the reference case, which implies some rehabilitation measures without improving the energy performance (the so called «anyway renovation»), for each reference building usually nine renovation packages are investigated denominated M1 to M9 which have progressive ambition levels related to the resulting energy performance of the building. Renovation packages distinguish themselves both by the number of building elements included in the improvement of energy performance, and in the thickness of the chosen insulation or in the U-value of the chosen window. Furthermore, measures to improve the energy performance of the building by upgrading or installing technical systems such as ventilation with heat recovery or a PV plant are taken into account on a case by case basis. A replacement of the heating system is assumed in all cases, also in the reference case of an anyway renovation. The heat distribution system including the radiators is assumed to remain the same, unless stated otherwise. For each reference building, combinations with three different types of heating systems are considered. The calculation of the energy need of the building is based on a monthly method taking into account energy performance of the building envelope, outdoor climate, target indoor temperature and internal heat gains. Carbon emissions and primary energy use are calculated by taking into account conversion efficiencies of the heating systems and emission factors as well as primary energy factors of the energy carriers including up-stream emissions or energy use. The life-cycle-cost and cost-effectiveness calculations are carried out dynamically with the annuity method and the results are presented as specified per m^2 of heated floor area.

The dimension of the heating system is calculated as the required peak capacity to be able to maintain the target indoor temperature despite heat losses during winter time. The effect of down-sizing new heating systems due to better insulation is taken into account; indirect effects on radiators are not taken into account.

The impact of embodied energy use was investigated for the single family reference building from Switzerland.

In the calculations, no distinction is made between planned (calculated) energetic performance of renovation measures and actually observed energetic performance. In practice, it is sometimes observed that actual energy efficiency performance levels do not reach the target values according to the planning. Such a performance gap may occur because of deviations in the actual construction as compared to the planning, or because of user behaviour, including rebound effects. These aspects are not taken into account in the impact calculations presented here. This may potentially overestimate to a certain degree the cost-effectiveness of renovation measures.

3.2.2. Energy prices

Table 1 shows the energy prices used in the calculations. Prices refer to assumed average prices over the next 40 years. The table contains empty cells, as only data actually used for calculations is indicated. By default, a 30% increase of real energy prices was assumed for the 40-years period compared to prices from 2010, if no official national projections on energy prices were available, which is compatible with the price increases suggested to take into account by the EPBD regulatory framework. A real interest rate of 3% per year is assumed.

Table 4 Assumed average energy prices for households, including taxes, for the period from 2010 to 2050. A 30% increase in prices compared to 2010 is assumed. Energy prices have been estimated only for those combinations of energy carriers and country for which calculations were carried out; for the others, no estimate was made (n.e., not estimated).

Energy carrier	Unit	Austria	Denmark	Italy	Norway	Portugal	Spain	Sweden	Switzerland
Oil	EUR/kWh	0.12	0.15	n.e	n.e	n.e.	n.e.	0.13	0.10
Natural gas	EUR/kWh	n.e.	n.e	0.12	n.e	0.090	0.057	0.12	n.e.
Wood pellets	EUR/kWh	0.080	0.050	n.e	0.10	0.30	0.049	0.040	0.080

Energy carrier	Unit	Austria	Denmark	Italy	Norway	Portugal	Spain	Sweden	Switzerland
Electricity	EUR/kWh	0.21	0.33	0.25	0.16	0.18	0.19	0.25	0.21
District heating	EUR/kWh	n.e	n.e	n.e	n.e	n.e	n.e.	0.10	n.e

3.2.3. Emission factors and primary energy factors

Emission factors and primary energy factors used refer to greenhouse gas emissions or primary energy use of energy carriers consumed including upstream emissions associated with the production, transport and delivery of these energy carriers. Emissions of CH_4 and N_2O are converted into equivalent CO_{2e} emissions, using the UNFCCC global warming potentials of 21 for CH_4 and 310 for N_2O. The respective country mix for electricity is based on the electricity mix and not on the national production mix. The emission factors and primary energy factors used in this project for the countries involved are indicated in Table 5.

Table 5 Greenhouse gas emission factors and primary energy factors used in calculations. Only for those combinations of energy carrier and country the emission factors and primary energy factors are indicated for which calculations were carried out; for the others, no estimate was made (n.e., not estimated). References: Covenant of Mayors (2010), INSPIRE (2013)

Parameter	Unit	Austria	Denmark	Italy	Norway	Portugal	Spain	Sweden	Switzerland
GHG Emission factor									
Oil	kg CO_{2e} / MJ	0.084	0.083	0.077	n.e.	n.e.	n.e.	n.e.	0.083
Natural gas	kg CO_{2e} / MJ	0.070	n.e.	0.092	n.e.	0.066	0.060	n.e.	n.e.
Wood pellets or wood logs	kg CO_{2e} / MJ	0.014	0.010	0.0010	0.010	n.e.	0.010	n.e.	0.010
District heating	kg CO_{2e} / MJ	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	0.020	n.e.
Country mix for electricity	kg CO_{2e} / MJ	0.089	0.081	0.11	0.0040	0.21	0.096	0.027	0.042
Country mix for electricity including trade in certificates	kg CO_{2e} / MJ	n.e.	n.e.	n.e.	0.095	n.e.	n.e.	n.e.	n.e.
Primary non-renewable energy factor									
Oil	-	1.11	1.10	n.e.	n.e.	n.e.	n.e.	n.e.	1.23

Parameter	Unit	Austria	Denmark	Italy	Norway	Portugal	Spain	Sweden	Switzerland
GHG Emission factor									
Natural gas	-	1.19	n.e.	n.e.	n.e.	1.12	1.07	n.e.	n.e.
Wood pellets or wood logs	-	0.15	0.21	n.e.	0.050	n.e.	0.21	n.e.	0.21
District heating		n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Country mix for electricity	-	1.13	1.64	n.e.	0.030	3.28	1.60	n.e.	2.63
Country mix for electricity including trade in certificates	-	n.e.	n.e.	n.e.	2.78	n.e.	n.e.	n.e.	n.e.
Primary energy factor									
Oil	-	1.13	1.10	1.35	n.e.	n.e.	n.e.	n.e.	1.24
Natural gas	-	1.20	n.e.	1.36	n.e.	1.12	1.07	n.e.	n.e.
Wood pellets or wood logs	-	1.19	1.22	1.06	1.06	n.e.	1.25	n.e.	1.22
District heating		n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	1.00	n.e.
Country mix for electricity	-	1.83	1.75	1.86	1.22	3.29	2.35	2.60	3.05
Country mix for electricity including trade in certificates	-	n.e.	n.e.	n.e.	3.10	n.e.	n.e.	n.e.	n.e.

3.2.4. Climate data

The monthly average temperatures and the monthly average global radiation from the directions East, West, South and North for typical locations in the related countries are used as climate data.

3.2.5. Lifetimes

The assumed lifetimes are specific per country and per measure chosen; they are indicated in the related chapters. For the heating system, in general a lifetime of 20 years was assumed.

3.2.6. Calculation tool

To carry out the calculations, a tool developed by the Eracobuild project INSPIRE (Jakob et al. 2014) was used as a starting point, and adapted to fit the needs of the calculations carried out within the framework of Annex 56. Up to ten renovation packages of measures and related reference cases may be represented by the tool in terms of economic and environmental indicators: investment costs and life-cycle costs, total and non-renewable primary energy use, and greenhouse gas emissions. Calculation of energy need follows the principles of EN ISO 13790 and takes into account energy performance of a building envelope, outdoor climate, target indoor temperature, and internal heat gains. Optionally, the life-cycle impact in terms of energy use and greenhouse gas emissions of materials used in the renovation measures can be included. Greenhouse gas emissions and primary energy use are calculated by taking into account conversion efficiencies of the heating systems and emission factors as well as primary energy factors of the energy carriers including up-stream emissions or energy use. The life-cycle-cost and cost-effectiveness calculations are carried out dynamically with the annuity method. In order to compare the annuity of the investment with the increasing savings of energy costs, the savings of energy costs are discounted and converted to an annuity. The calculations are based on real prices, real interest rates and typical lifetimes of the building elements.

3.3. Reference buildings for parametric studies

In Annex 56, the focus is put on residential buildings, both single-family and multi-family houses. The reference buildings serve as the basis for carrying out calculations applying the methodology. Generic reference buildings which are investigated refer to single-family residential buildings with a relatively low energy performance before renovation. Buildings are defined with the purpose to reflect typical buildings of the building stock of the specific country.

For each of the reference buildings, the following parameters are taken into account for calculation of energy use:

- Average building geometry and dimensions: conditioned floor area, area or length of energy related building elements, etc.
- Assumptions on the average use of the buildings: conditioned floor area per person, average hot water consumption per conditioned floor area, presence time of users, set room temperature, etc.
- Average characteristics of energy performance of the buildings and building elements respectively: average U-values for roof, walls, windows, cellar slab; resulting energy need; energy carriers for the heating system, system performance, etc.

The following table summarizes the assumptions made related to the generic reference buildings.

Table 6 Assumed characteristics of single-family reference buildings for Austria, Denmark, Norway, Portugal, Sweden, and Switzerland before renovation. Data sources: TABULA IEE project, BETSI project, Sveby programme

Parameter	Unit	Austria SFB	Denmark SFB	Norway SFB	Portugal SFB	Sweden SFB	Switzer-land SFB
Building period		1958-1968	1960-1969	1961	Before 1960	1961-1975	1960
Gross heated floor area (GHFA)	m^2	242	108	113	80	125	210
Façade area (excl. windows)	m^2	185	90	146	97	111	206
Roof area pitched	m^2	181	130	54	80	-	120
Roof area flat	m^2	-	-	-	-	106	-
Attic floor	m^2	-	108	-	-	-	-
Area of windows to North	m^2	10	5.9	2.0	3.0	7.3	3.3
Area of windows to East	m^2	9.1	1.3	1.7	3.0	3.7	8.3
Area of windows to South	m^2	10	14	14	3.0	7.3	13
Area of windows to West	m^2	9.1	3.2	-	3.0	3.7	8.3
Area of ceiling of cellar	m^2	145	108	51	80	106	80
Average heated gross floor area per person	m^2	60	27	28	37	32	60
Typical indoor temperature (for calculations)	°C	20	20	20	min 20 winter/ max 25 summer	21	20
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/ (a*m^2)	22	31	27	32	25	22
U-value façade	W/(m^2*K)	1.4	0.46	0.50	2.0	0.31	1.0
U-value roof pitched	W/(m^2*K)	0.92	0.39	0.40	2.8	-	0.85
U-value attic floor	W/(m^2*K)	-	-	-	-	-	1.0
U-value roof flat	W/(m^2*K)	-	-	-	-	0.21	1.0

Parameter	Unit	Austria SFB	Denmark SFB	Norway SFB	Portugal SFB	Sweden SFB	Switzer-land SFB
U-value windows	W/(m^2*K)	2.9	2.6	2.7	5.1	2.3	2.7
g-value windows	Factor 0.0 – 1.0	0.76	0.75	0.71	0.85	0.7	0.75
U-value ceiling of cellar	W/(m^2*K)	0.97	1.02	0.50	1.65	0.27	0.90
Energy need hot water	kWh/m^2	14	22	27	29	18	14
Energy need for cooling	kWh/m^2	-	-	-	2.3	-	-

The characteristics of the multi-family reference buildings that were investigated are summarized in the following table:

Table 7 Characteristics of multi-family reference buildings for Austria, Denmark, Portugal, Spain, Sweden, and Switzerland. Data sources: TABULA IEE project, BETSI project, Sveby programme

Parameter	Unit	Austria MFB	Denmark MFB	Italy MFB	Portugal MFB	Spain MFB	Sweden MFB	Switzer land MFB
Building period		1958-1968	1960-1969	1950-1979	Before 1960	1960	1961-1975	1960
Gross heated floor area (GHFA)	m^2	2845	3640	1804	520	1872	1400	730
Façade area (excl. windows)	m^2	2041	1332	1230	542	2049	590	552
Roof area pitched	m^2	-	-	-	130	416	-	-
Roof area flat	m^2	971	-	361	-	-	402	240
Attic floor	m^2	-	910	-	-	-	-	-
Area of windows to North	m^2	220	279	113	26	0	89	32
Area of windows to East	m^2	22	0	113	13	177	1.5	40
Area of windows to South	m^2	243	376	-	26	0	89	47
Area of windows to West	m^2	22	0	-	13	194	1.5	40
Area of ceiling of cellar	m^2	971	910	361	130	312	402	240

Parameter	Unit	Austria MFB	Denmark MFB	Italy MFB	Portugal MFB	Spain MFB	Sweden MFB	Switzer land MFB
Average heated gross floor area per person	m^2	40	35	30	17	40	32	40
Typical indoor temperature (for calculations)	°C	20	20	20	20	19	21	20
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/ ($a*m^2$)	28	44	24	24	49	26	28
U-value façade	W/(m^2* K)	1.2	0.50	1.2	2.0	1.30	0.41	1.0
U-value roof pitched	W/(m^2* K)	-	-	-	2.8	1.8	-	0.85
U-value attic floor	W/(m^2* K)	-	0.40	-	-	-	-	1.0
U-value roof flat	W/(m^2* K)	0.97	-	1.5	-	-	0.20	1.0
U-value windows	W/(m^2* K)	2.6	2.6	4.9	5.1	3.5	2.3	2.7
g-value windows	Factor 0.0 – 1.0	0.76	0.75	0.86	0.85	0.80	0.70	0.75
U-value ceiling of cellar	W/(m^2* K)	0.97	1.50	1.3	1.7	2.0	0.27	0.90
Energy need hot water	kWh/m^2	21	14	17	35	26	23	21
Energy need for cooling	kWh/m^2	-	-	7.6	4.8	-	-	-

3.4. Hypotheses

For the assessment of generic buildings in particular the following hypotheses are made, and their validity is subsequently investigated:

- How many building elements are renovated is more important for the energy performance than the efficiency levels of individual elements: The energy performance of the building after renovation rather depends on how many building elements are renovated than up to what efficiency level single elements are renovated. Energy performance refers here to primary energy use.

- A switch to RES reduces emissions more significantly than the deployment of energy efficiency measures
- 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. Synergies are understood to occur when energy efficiency measures are cost-effective in combination with a switch of the heating system to a renewable energy system.
- 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 installation of a ventilation system with heat recovery has effects on the energy performance comparable with measures on other building elements
- In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger: The rationale for this hypothesis is that multi-family buildings have normally installations with larger capacities, offering therefore more potential for cost reduction, as energy efficiency measures reduce required peak capacities of the heating systems

For the hypothesis related to RES, depending on the country context, different RES systems are investigated. Only RES systems are investigated that can replace the heating system completely, i.e. mostly heat pumps and wood energy systems.

4. Results of parametric assessments of generic buildings

4.1. Cost-effectiveness, carbon emissions and primary energy use of renovation packages with different heating systems

4.1.1. Introduction

In the following chapters, packages of renovation measures are assessed for different reference buildings. The main parameters investigated are costs, carbon emissions and primary energy use. For each of the buildings investigated, first a reference renovation is defined. This renovation comprises measures to restore functionality of the building, yet without improving its energy performance. The reference renovation is then compared to nine different packages of energy related renovation measures. The packages investigated have progressively increasing energy efficiency levels.

The relationship between costs, carbon emissions and primary energy use is shown in two separate graphs. A first graph to show the relationship between costs and carbon emissions, the second for the relationship between costs and primary energy use.

The order of the measures chosen for the increasingly comprehensive renovation packages follows the costs of the measures: economic measures are included first, followed by measures which are more and more costly. Measures with different energy efficiency level for the same building element remain grouped next to each other to better disclose the difference between measures with varying energy efficiency ambition level.

The same set of renovation measures improving energy efficiency is shown for three different heating systems for a given building. A first heating system is chosen to reflect conventional heating systems in the respective country. The two other heating systems are chosen to be based on renewable energies. Thereby we assume that in the case of the reference renovation («anyway renovation») the conventional heating system also has to be renewed and is replaced by a new system of the same type without deliberate energy performance increase (except performance increases by general technological progress).

For Sweden and Switzerland the impact of upgrading an existing ventilation system to a ventilation system with heat recovery is also investigated (see chapter 4.2).

4.1.2. Austria

Single-family building: Renovation packages and related assumptions

For the generic calculations in Austria, the following packages of renovation measures are applied to the building envelope:

Table 8 Description of different packages of renovation measures M1 to M9 and of the reference case for Austria.

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	The wall is insulated with 12 cm of mineral wool.
M2	The wall is insulated with 20 cm of mineral wool.
M3	The wall is insulated with 40 cm of mineral wool.
M4	Additionally to M3, the roof is refurbished including membrane, roof battens, shuttering, gutter and 14 cm of mineral wool insulation.
M5	Additionally to M3, the roof is refurbished including membrane, roof battens, shuttering, gutter and 30 cm of mineral wool insulation.
M6	Additionally to M5, the cellar ceiling is insulated with 8 cm of mineral wool.
M7	Additionally to M5, the cellar ceiling is insulated with 12 cm of mineral wool.
M8	Additionally to M7, the windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.0.
M9	Additionally to M7, the windows are replaced with new windows with a wooden frame and a U-value for the entire window of 0.7.

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 9 Data for different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Austria

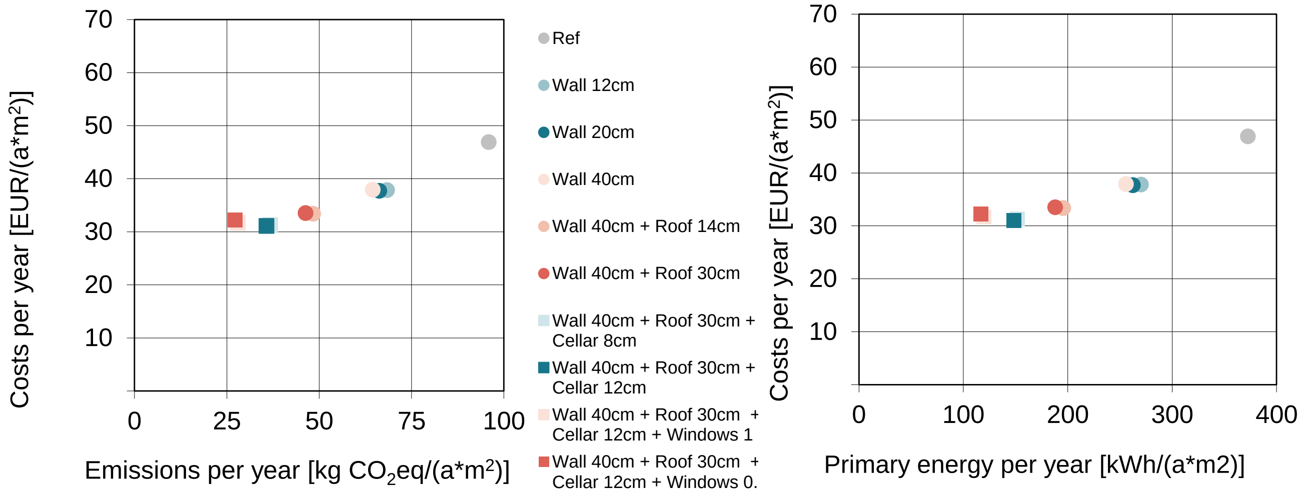
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m2 wall	40	98	120	148	148	148	148	148	148	148
Wall thickness of insulation material	cm	-	12	20	40	40-	40	40	40	40	40

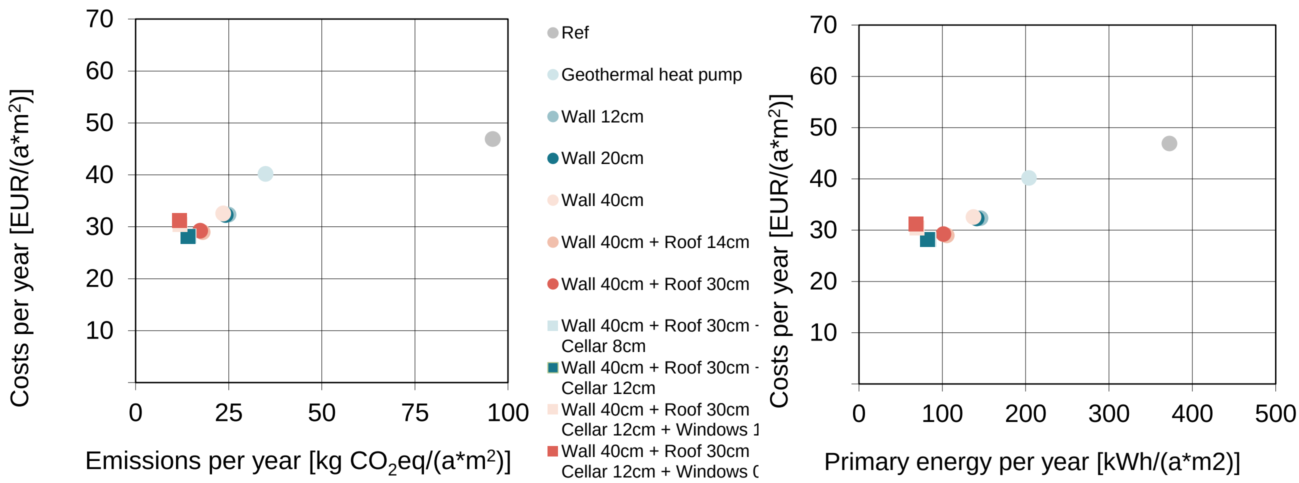
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - ƛ of insulation material	W/mK	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Wall - lifetime of renovation measure	years	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	30	30	30	30	30	30	30	30	559	678
Window - U-Value	W/m2K	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	1	0.7
Window - g-value		0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.63	0.5
Window - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Roof - Costs	EUR/m^2 roof	100	100	100	100	160	190	190	190	190	190
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - ƛ of insulation material	W/mK	-	-	-	-	0.035	0.035	0.035	0.035	0.035	0.035
Roof - lifetime of renovation measure	a	-	-	-	-	40	40	40	40	40	40
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	-	-	60	68	68	68
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	-	8	12	12	12
Cellar ceiling - ƛ of insulation material	W/mK	-	-	-	-	-	-	0.032	0.032	0.032	0.032
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	-	40	40	40	40
Energy need heating	kWh/m^2	243	160	154	148	100	94	65	62	38	36
Peak heating capacity required	kW	21	14	14	14	10	9	7	7	5	5
Conversion efficiency of oil heating system		0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Conversion efficiency of wood pellets heating system		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Conversion efficiency of geo-thermal heat pump		3	3.2	3.2	3.3	3.5	3.6	3.8	3.8	4	4

Single-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:





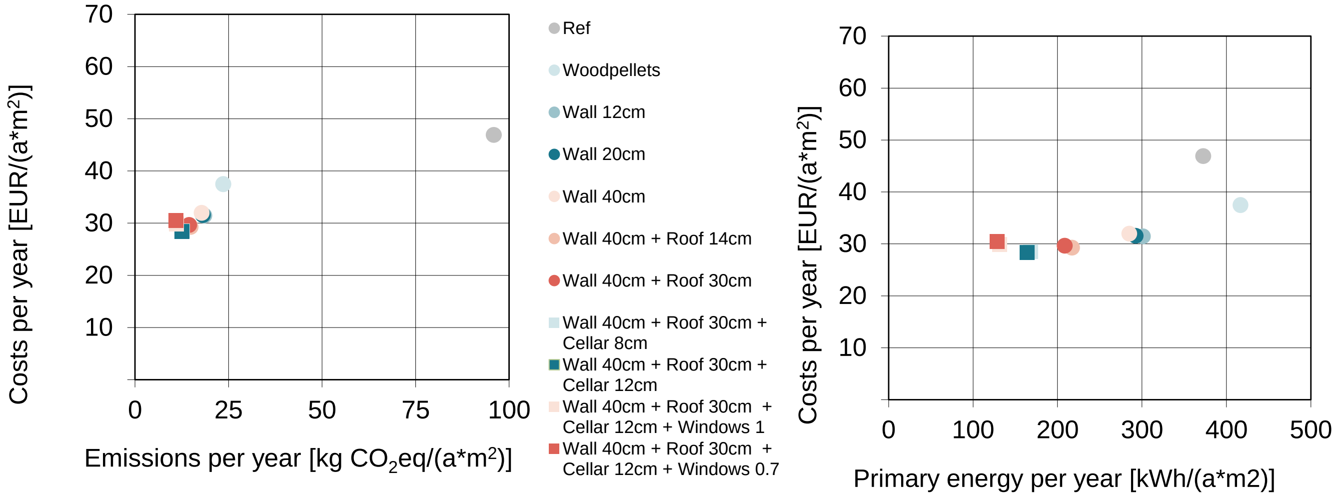


Figure 17 Comparison of cost-effectiveness of energy efficiency renovation measures for a SFB in Austria for <u>different heating systems</u>, oil (top graphs), geothermal heat pump (middle) ,wood pellets (bottom), and related impacts on carbon emissions and primary energy use. The reference shown as a grey dot refers to a situation with a replacement of the oil heating system and rehabilitation measures on the building envelope without improving energy-efficiency levels.

The 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 point with highest emissions or highest primary energy use represents the reference case (Ref). As more measures are added to the renovation packages (M1 – M9), emissions and primary energy use decrease.

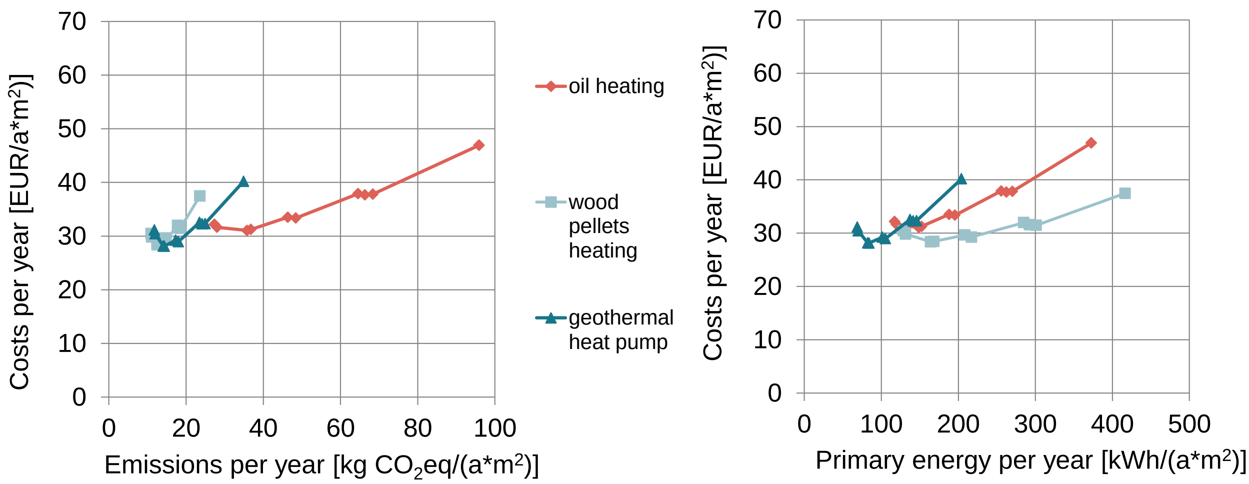


Figure 18 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Austria, for a single-family building The reference case is the point on the oil heating curve

with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Multi-family building: Renovation packages and related assumptions

For the generic calculations in Austria, the same renovation packages are investigated for the multi-family building as for the single-family building:

Table 10 Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Austria.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	40	98	120	148	148	148	148	148	148	148
Wall thickness of insulation material	cm	-	12	20	40	40-	40	40	40	40	40
Wall - ƛ of insulation material	W/mK	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Wall - lifetime of renovation measure	years	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	30	30	30	30	30	30	30	30	559	678
Window - U-Value	W/m^2K	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	1	0.7
Window - g-value		0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.63	0.5
Window - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Roof - Costs	EUR/m^2 roof	100	100	100	100	160	190	190	190	190	190
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - ƛ of insulation material	W/mK	-	-	-	-	0.035	0.035	0.035	0.035	0.035	0.035
Roof - lifetime of renovation measure	a	-	-	-	-	40	40	40	40	40	40
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	-	-	60	68	68	68

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	-	8	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	-	0.032	0.032	0.032	0.032
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	-	40	40	40	40
Energy need for heating	kWh/m^2	159	97	92	87	64	62	46	44	24	22
Peak heating capacity required	kW	175	120	115	111	90	87	72	70	48	44
Conversion efficiency of oil heating system		0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Conversion efficiency of wood pellets heating system		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Conversion efficien-cy of geothermal heat pump		3.2	3.5	3.6	3.6	3.8	3.8	3.9	3.9	4.1	4.1

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:

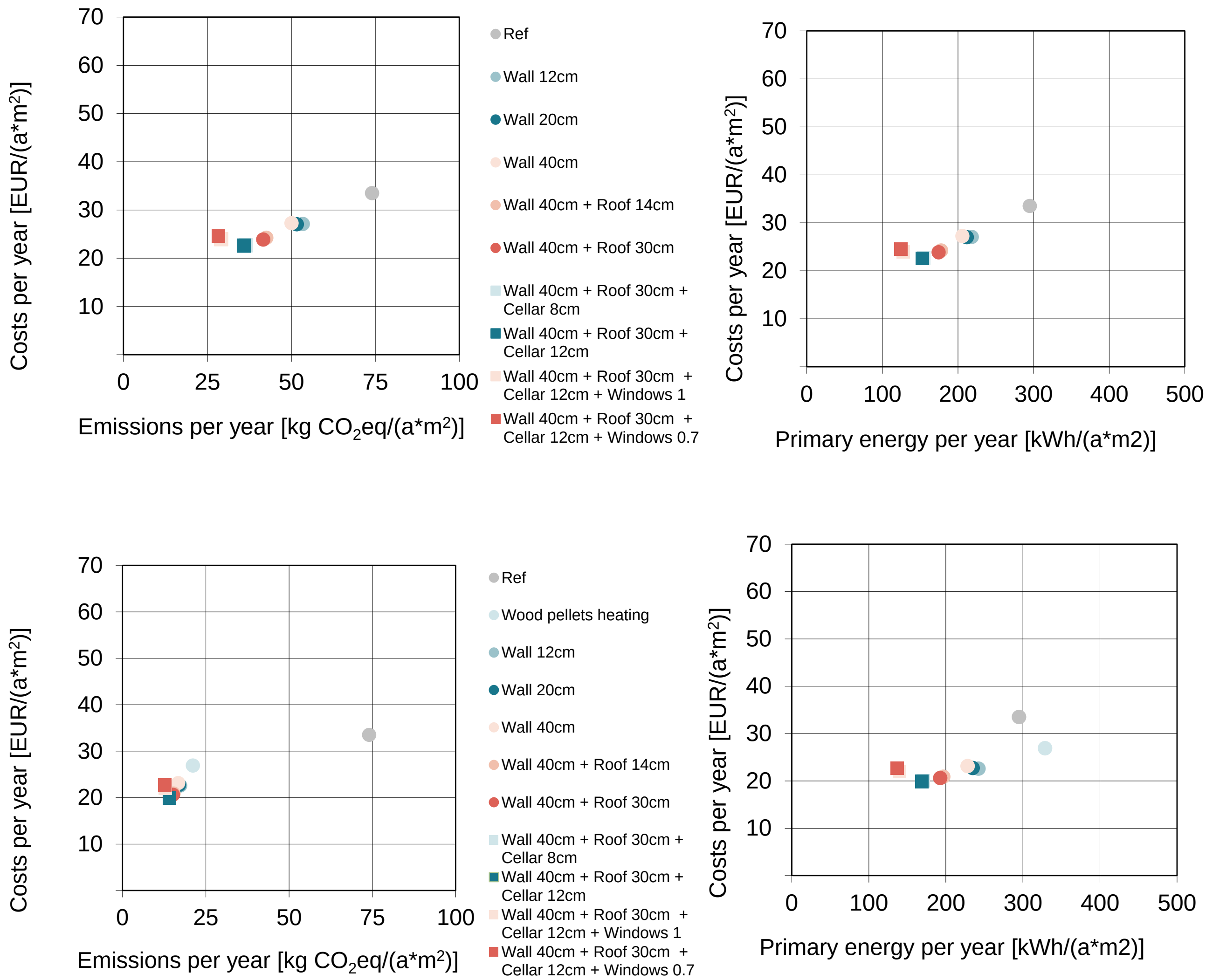


Figure 19 Comparison of cost-effectiveness of energy efficiency renovation measures for a multi-family building in Austria for different heating systems, oil (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the oil heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems.

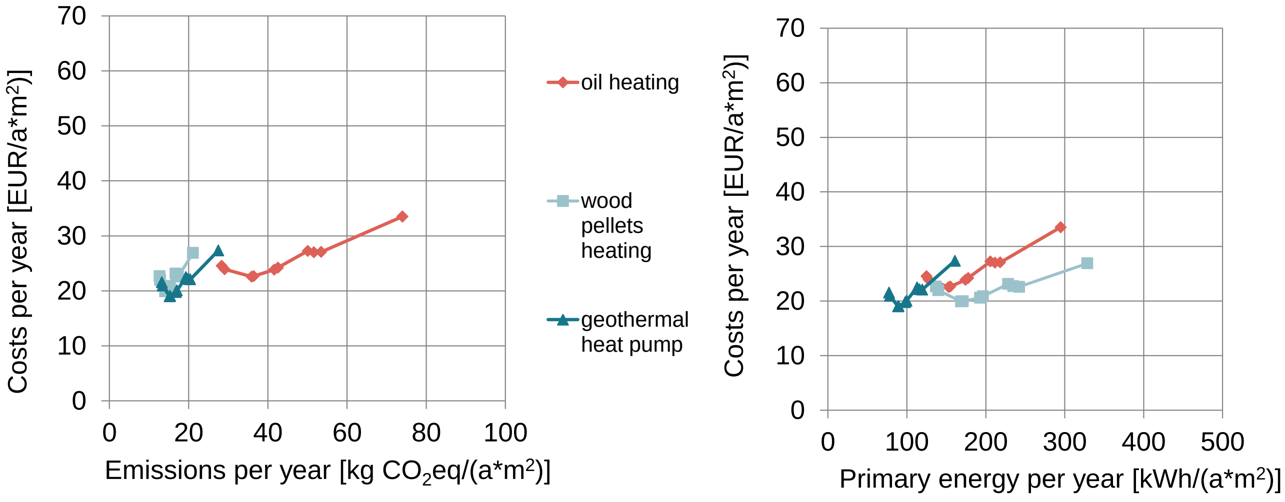


Figure 20 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Austria, for a multi-family building. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Discussion

Single-family building

As can be seen from the graphs, based on the cost data delivered from Austria and the energy price and interest rate assumptions made in this report, many measures investigated are cost-effective in case of the single-family building in Austria. This finding can partly be explained because of the construction period of the reference building. The building investigated as reference building is from 1958 – 1968 and has a relatively low energetic standard before renovation, which increases the savings achieved by energy related renovation. The installation of new windows is not cost-effective.

The results of the calculations with the single-family building in Austria confirm the main hypotheses which are investigated, as summarized in the following table:

Table 11 Results for investigated hypotheses for the single-family reference building in Austria. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Austria.

Hypothesis	Results from SFB in 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 cost-optimal efficiency level	(X)
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.	✓

More specific findings with respect to the different hypotheses:

The first hypothesis is confirmed, as the curves in the graphs demonstrate that renovation packages distinguishing themselves only by the energy efficiency ambition level in one single building element improve energy performance less than renovation packages which distinguish themselves by the number of building elements whose energy performance is improved (more detailed conclusions see chapter 6.1.1., hypothesis 1).

The second hypothesis is confirmed, as both the switch to geothermal heat pump and to wood pellets reduce emissions more strongly than the most ambitious energy efficiency measures while continuing to use oil as energy carrier for heating.

Whereas for the oil heating system the most cost-effective renovation package is M9, for the case of a geothermal heat pump and a wood heating system, the most cost-effective renovation package is M7, without the measures on the windows. The third hypothesis is therefore not confirmed. However, the difference of the cost level between M7 and M9 is small.

Also for the two RES heating systems the energy efficiency measures are cost-effective; the fourth hypothesis is therefore validated in this case.

A switch to a RES system reduces emissions more strongly than the most ambitious energy efficiency measures alone, and this at lower costs. The fifth hypothesis is therefore confirmed for this reference building.

Multi-family building

As for the single-family building, it can be seen that based on the cost data delivered from Austria and the energy price and interest rate assumptions made in this report, many measures investigated are cost-effective in the case of the multi-family building in Austria. The building is from the same construction period 1958 – 1968 as the single-family reference building, with a relatively low energy standard before renovation, offering therefore good opportunities for cost savings due to energy related renovation. The installation of new windows is not cost-effective.

The results of the calculations with the multi-family building in Austria confirm partly the main hypotheses which are investigated, as summarized in the following table:

Table 12 Results for investigated hypotheses for the multi-family reference building in Austria. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Austria.

Hypothesis	Results from MFB in 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 cost-optimal efficiency levels	(✓)
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 same considerations made for the single-family building with respect to the hypotheses investigated also apply for the multi-family building.

Comparison between single-family building and multi-family building

Comparing the graphs for the multi-family buildings with the graphs for the single-family building it can be recognized that specific costs, emissions and primary energy use per m^2 of gross floor area are lower in the case of the Austrian multi-family building compared to the single-family building investigated.

There is no evidence that there are more synergies between energy efficiency measures and RES based measures in multi-family buildings than in single-family buildings. The related hypothesis is therefore not confirmed.

Table 13 Result for the hypothesis related to the comparison of MFB and SFB.

Hypothesis	Results from SFB and MFB in Austria
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger	X

4.1.3. Denmark

Single-family building: Renovation packages and related assumptions

For the generic calculations in Denmark, the following packages of renovation measures are applied to the building envelope:

Table 14 Description of different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Denmark.

Renovation Package	Description
Ref	In the reference case, the joints in the wall are repaired and windows are repainted. These measures do not improve the energy performance of the building.
M1	The cellar ceiling is insulated with 8 cm of rock wool.
M2	The cellar ceiling is insulated with 12 cm of rock wool.
M3	Additionally to M2, the roof part of the building is insulated with 14 cm of granulate on attic floor.
M4	Additionally to M2, the roof part of the building is insulated with 30 cm of granulate on attic floor.
M5	Additionally to M4, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.6.
M6	Additionally to M4, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.
M7	Additionally to M4, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 0.7.
M8	Additionally to M7, the wall is insulated with 12 cm of rock wool batts.
M9	Additionally to M7, the cellar ceiling is insulated with 30 cm of rock wool batts.

The following table describes the characteristics of the different renovation packages that are taken into account.

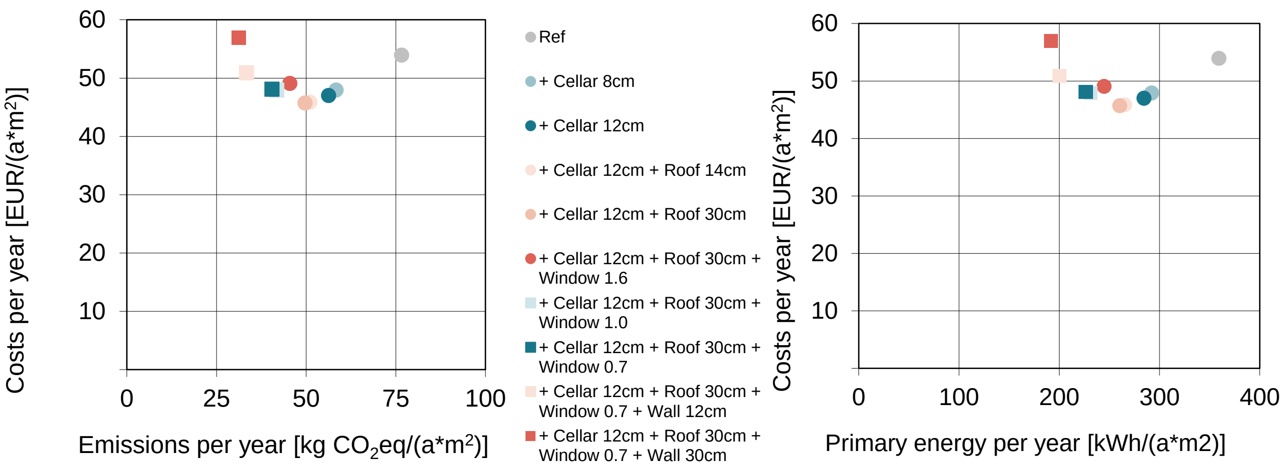
Table 15 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Denmark.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	95	95	95	95	95	95	95	95	272	470
Wall thickness of insulation material	cm	-	-	-	-	-	-	-	-	12	30
Wall – λ insulation material	W/mK	-	-	-	-	-	-	-	-	0.037	0.037
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	10	10	10	10	10	490	550	620	620	620
Window - U-Value	W/m^{2}K	2.6	2.6	2.6	2.6	2.6	1.6	1.0	0.7	0.7	0.7
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.50	0.45	0.38	0.38	0.38
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	-	-	-	34	46	46	46	46	46	46
Roof - thickness of insulation material	cm	-	-	-	14	30	30	30	30	30	30
Roof – λ of insulation material	W/mK	-	-	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Roof - lifetime of renovation measure	a	-	-	-	40	40	40	40	40	40	40
Cellar ceiling - Costs	EUR/m^2 cellar ceiling	-	72	75	75	75	75	75	75	75	75
Cellar ceiling - thickness of insulation material	cm	-	8	12	12	12	12	12	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Cellar ceiling - lifetime of renova-tion measure	a	-	40	40	40	40	40	40	40	40	40

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Energy need for heating	kWh/m^2	196	138	132	115	111	98	86	82	59	52
Peak heating capacity required	kW	7	6	6	5	5	4	4	4	3	3
Conversion efficiency of oil heating system		0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Conversion efficiency of wood pellets heating system		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Conversion efficiency of geo-thermal heat pump		3	3.3	3.3	3.4	3.4	3.5	3.6	3.6	3.8	3.9

Single-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



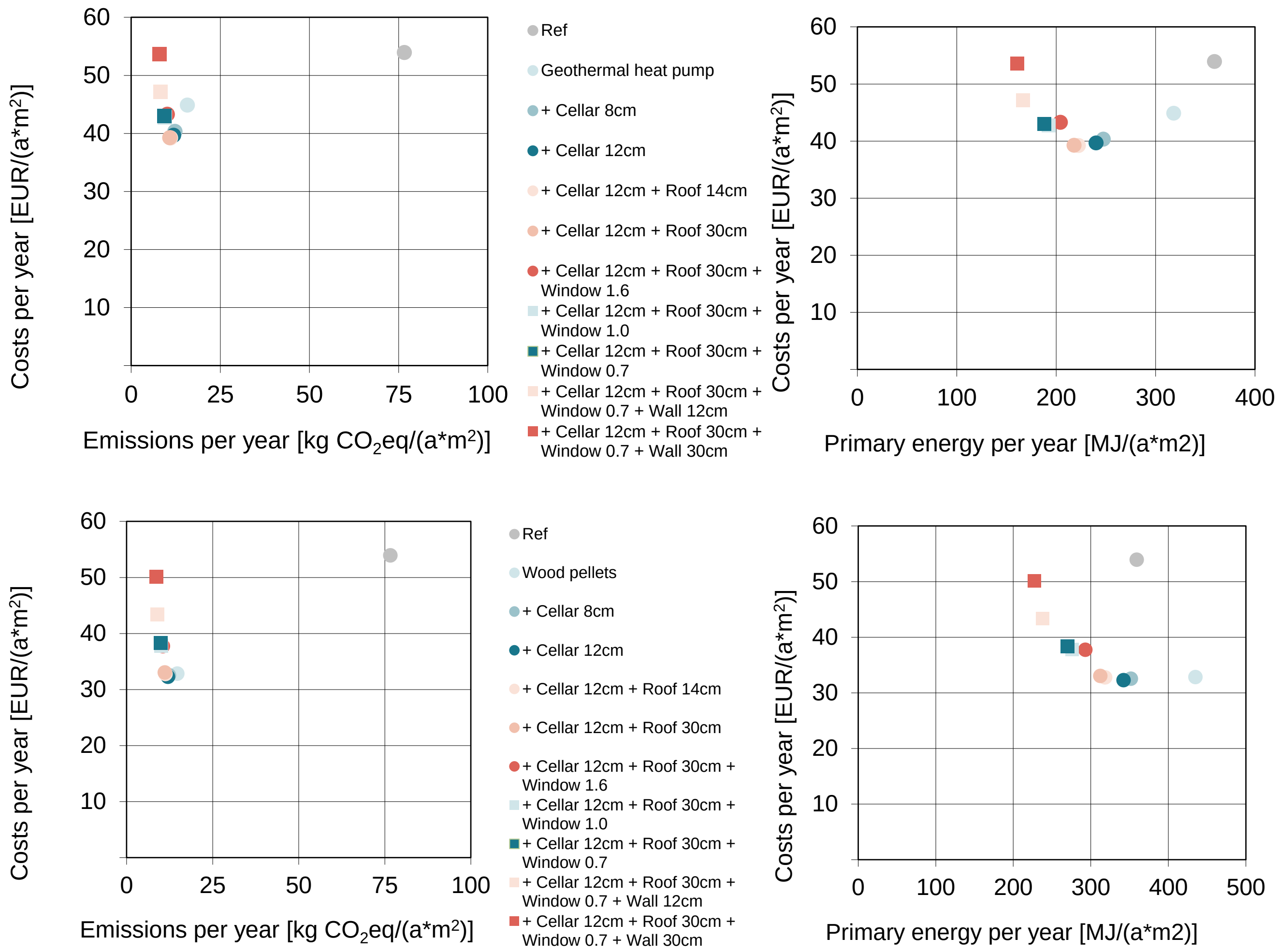


Figure 21 Comparison of cost-effectiveness of energy efficiency renovation measures for single-family building in Denmark for different heating systems, oil (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the oil heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

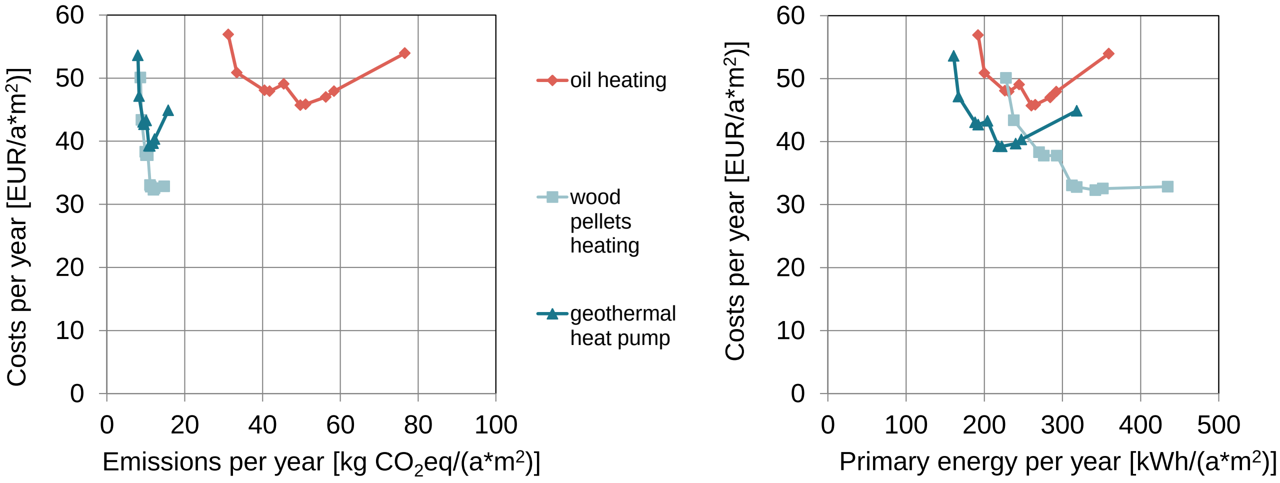


Figure 22 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Denmark, for a single-family building, The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Multi-family building: Renovation packages and related assumptions

Reference measures and renovation measures are identical to the ones for the single family reference building; the difference to the case of the single-family building are the dimensions of the building and related to that the absolute and specific energy need as well as the size of the heating systems.

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 16 Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Denmark.

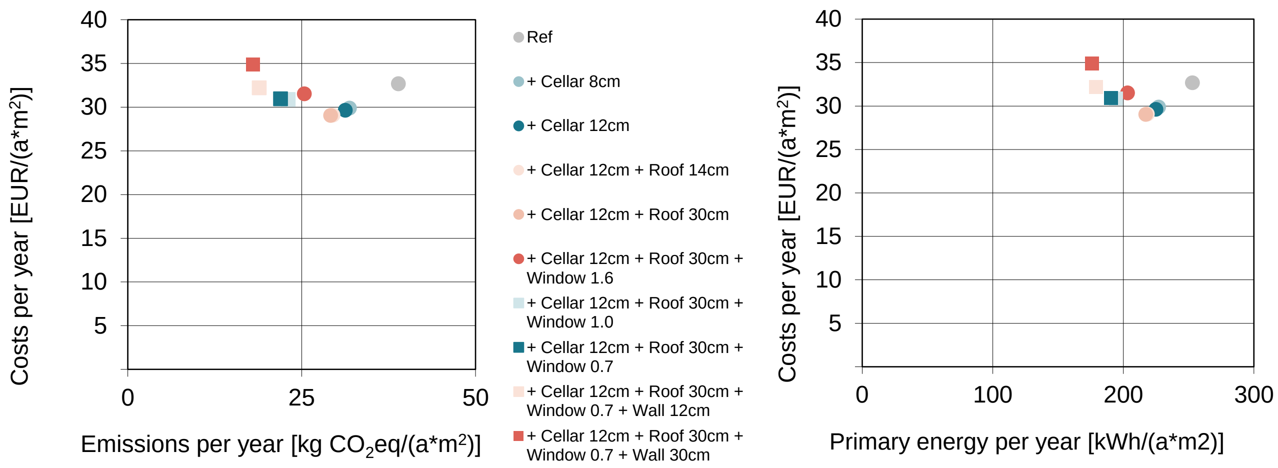
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	95	95	95	95	95	95	95	95	272	470
Wall thickness of insulation material	cm	-	-	-	-	-	-	-	-	12	30
Wall - ƛ insulation material	W/mK	-	-	-	-	-	-	-	-	0.037	0.037

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	10	10	10	10	10	490	550	620	620	620
Window - U-Value	W/m^{2}K	2.6	2.6	2.6	2.6	2.6	1.6	1.0	0.7	0.7	0.7
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.50	0.45	0.38	0.38	0.38
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	-	-	-	34	46	46	46	46	46	46
Roof - thickness of insulation material	cm	-	-	-	14	30	30	30	30	30	30
Roof - λ of insulation material	W/mK	-	-	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Roof - lifetime of renovation measure	a	-	-	-	40	40	40	40	40	40	40
Cellar ceiling - Costs	EUR/m^2 cellar ceiling	-	72	75	75	75	75	75	75	75	75
Cellar ceiling - thickness of insulation material	cm	-	8	12	12	12	12	12	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Cellar ceiling - lifetime of renovation measure	a	-	40	40	40	40	40	40	40	40	40
Energy need for heating	kWh/m^2	82	60	58	52	51	39	32	28	19	16
Peak heating capacity required	kW	134	110	108	102	101	83	72	67	55	52
Conversion efficiency of oil heating system		0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Conversion efficiency of wood pellets heating system		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Conversion efficiency of geothermal heat pump		3.6	3.8	3.8	3.9	3.9	4.0	4.0	4.0	4.1	4.1

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



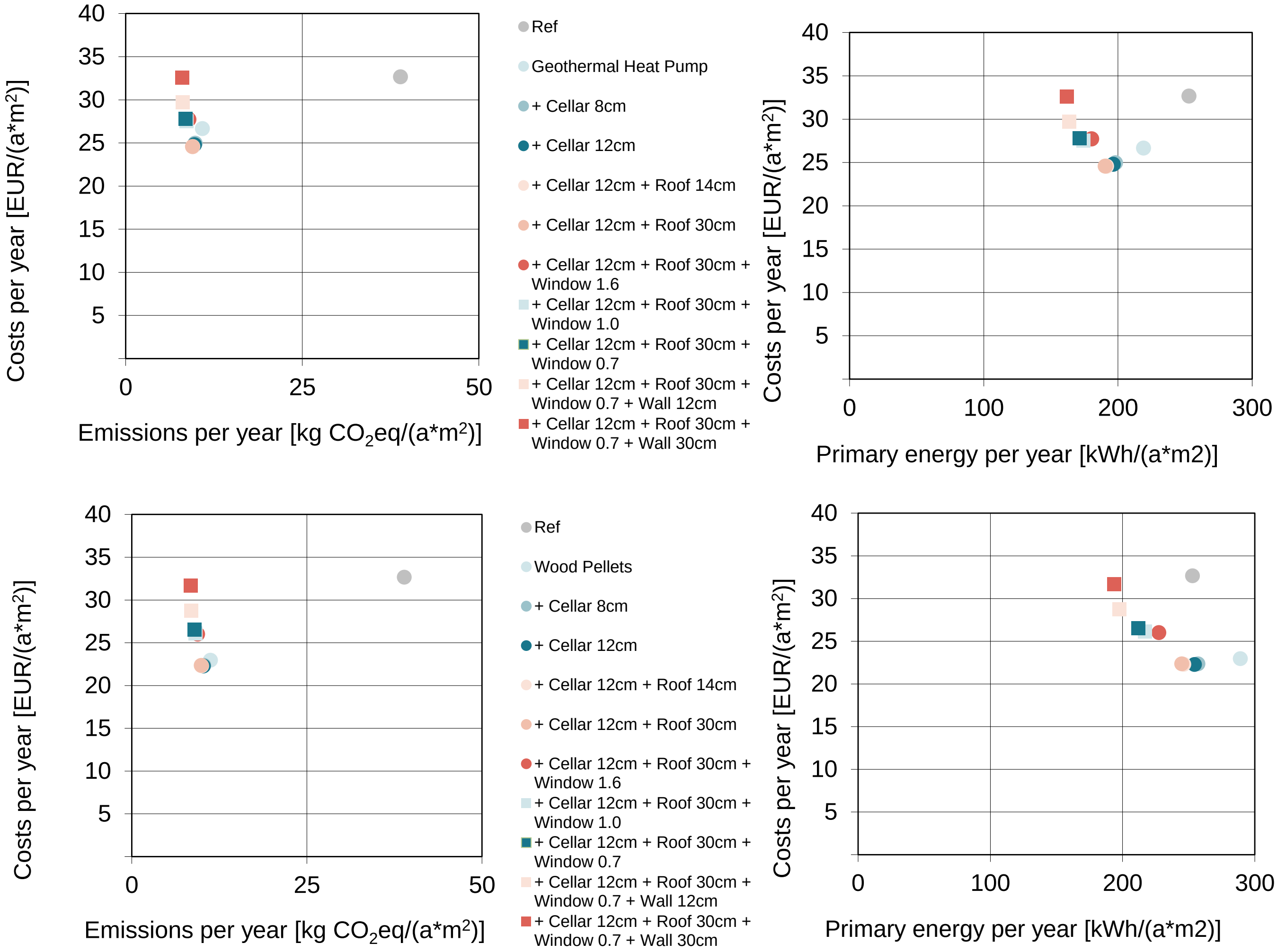


Figure 23 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for multi-family building in Denmark for different heating systems, oil (top graphs), geothermal heat pump (middle), wood pellets (bottom), and related impacts on carbon emissions and primary energy use. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

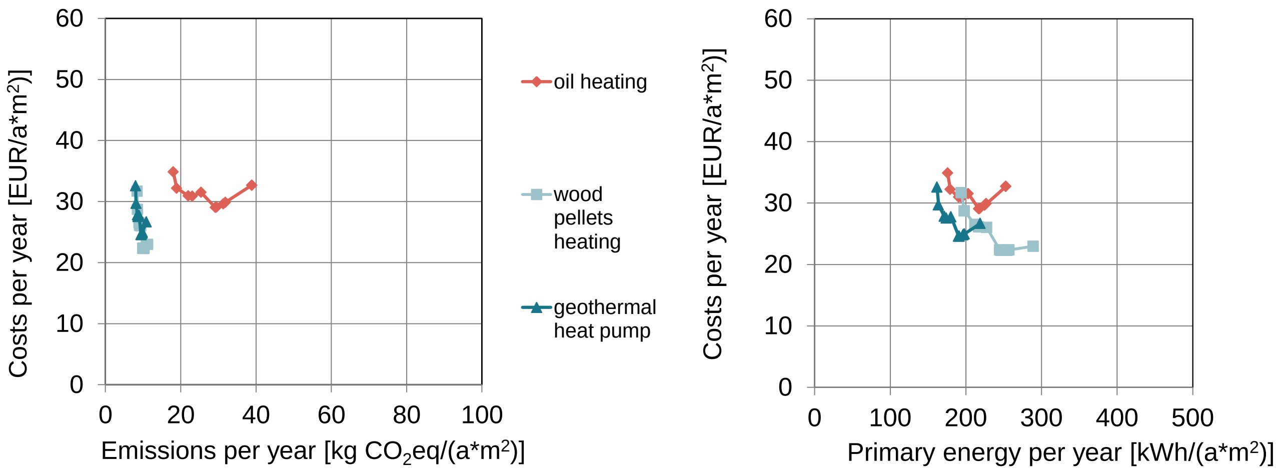


Figure 24 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Denmark, for a multi-family building. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Discussion

Single-family building

The results of the calculations with the single-family building in Denmark confirm the three main hypotheses which are investigated, as summarized in the following table:

Table 17 Results for investigated hypotheses for the single-family reference building in Denmark. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Denmark.

Hypothesis	Results from SFB in Denmark
How many building elements are renovated is more important for the energy performance than efficiency levels of individual 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 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 ambitious renovations on the building envelope than to focus on energy efficiency measures alone.	✓

More specific findings with respect to the different hypotheses:

- The first hypothesis is confirmed, as the curves in the graphs show that renovation packages distinguishing themselves only by the energy efficiency ambition level in one single building element improve energy performance less than renovation packages which distinguish themselves by the number of building elements whose energy performance is improved (more detailed conclusions see chapter 6.1.1., hypothesis 1).
- The second hypothesis is confirmed, as both the switch to the geothermal heat pump and to wood pellets reduce emissions more strongly than the most ambitious energy efficiency measures while continuing to use oil as energy carrier for heating.
- In all combinations with heating systems investigated, renovation package M4 is most cost-optimal except in the case of an oil heating system. With oil heating, renovation package M7 including measures on windows is almost as cost-optimal as M4. For the other heating systems, M7 is significantly less cost-effective. Accordingly, the structure of the optimum changes. The hypothesis is therefore considered to be only partly confirmed.
- Also for the two RES heating systems some energy efficiency measures are cost-effective; the fourth hypothesis is therefore validated in this case.
- A switch to a RES system reduces emissions more strongly than the most ambitious energy efficiency measures, and this at lower costs. The fifth hypothesis is therefore confirmed for this reference building.

Multi-family building

The results of the calculations with the multi-family building in Denmark confirm partly the three main hypotheses which are investigated, as summarized in the following table:

Table 18 Results for investigated hypotheses for the multi-family reference building in Denmark. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Denmark.

Hypothesis	Results from MFB in 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 cost-optimal efficiency levels	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓

Hypothesis	Results from MFB in Denmark
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.	✓

More specific findings with respect to the different hypotheses:

- The first hypothesis is confirmed, as the curves in the graphs show that renovation packages distinguishing themselves only by the energy efficiency ambition level in one single building element improves energy performance less than renovation packages which distinguish themselves by the number of building elements whose energy performance is improved.
- The second hypothesis is confirmed, as both the switch to the geothermal heat pump and to wood pellets reduce emissions more strongly than the most ambitious energy efficiency measures while continuing to use oil as energy carrier for heating.
- Whereas in the case of an oil heating system, renovation package M7 including measures on the windows is almost as cost-optimal as renovation package M4, without measures on the window, for the RES heating systems investigated M7 is by far not cost-effective anymore. The optimum is narrower, focused on M4. Accordingly, with a switch to RES, the cost-optimal energy efficiency levels are changed with a switch to RES. Nevertheless, M4 is the most cost-optimal renovation package for all heating systems. The third hypothesis is therefore considered to be partly confirmed.
- Also for the two RES heating systems some energy efficiency measures are cost-effective; the fourth hypothesis is therefore validated in this case.
- A switch to a RES system reduces emissions more strongly than the most far reaching energy efficiency measures, and at lower costs. The fifth hypothesis is therefore confirmed for this reference building.

Comparison between single-family building and multi-family building

Comparing the graphs for the multi-family buildings and the graphs for the single-family building yields the following observations:

- Specific costs, emissions and primary energy use per m^2 of gross floor area are lower in the case of the Danish multi-family building compared to the single-family building investigated.
- In the case of the multi-family building, there is a more distinct difference in the shape of the impact paths for different heating systems than in the SFB-case: In the multi-family building with a geothermal heat pump, more advanced renovation packages are more

quickly not cost-effective anymore, compared to a situation with an oil heating or a wood pellets heating system.

The hypothesis investigated related to the difference between single-family buildings and multi-family buildings can therefore not be confirmed in the case of the two generic examples investigated in Denmark.

Table 19 Result for hypothesis related to the comparison of multi-family buildings and single-family buildings in Denmark.

Hypothesis	Results from SFB and MFB in Denmark
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger	X

4.1.4. Italy

Multi-family building: Renovation packages and related assumptions

For the generic calculations in Italy, the following packages of renovation measures are applied to the building envelope:

Table 20 Description of different packages of renovation measures M1 to M9 and of the reference case for Italy.

Renovation Package	Description
Ref	In the reference case, for the wall a substitution of deteriorate external plaster is made and the new flat roof gets a new waterproof covering, and the windows are generally repaired and repainted. These measures do not improve the energy performance of the building.
M1	The roof is insulated with 6 cm of EPS
M2	The roof is insulated with 8 cm of EPS
M3	Additionally to M2, the cellar ceiling is insulated with 5 cm EPS
M4	Additionally to M2, the cellar ceiling is insulated with 6 cm EPS
M5	Additionally to M4, new wooden windows are installed with a U-value of 3 W/(m^2 *K).
M6	Additionally to M4, new wooden windows are installed with a U-value of 2.4 W/(m^2 *K).
M7	Additionally to M6, the wall is insulated with 4 cm EPS
M8	Additionally to M6, the wall is insulated with 6 cm EPS

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 21 Data for different packages of renovation measures M1 to M9 and the reference case for a multi-family house in Italy.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8
Wall - Costs	EUR/m^2 wall	50	50	50	50	50	50	50	117	120
Wall thickness of insulation material	cm	-	-	-	-	-	-	-	4	6
Wall – λ insulation material	W/mK	-	-	-	-	-	-	-	-	0.036
Wall - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30
Window - Costs	EUR/m^2 window	81	81	81	81	81	249	255	255	255
Window - U-Value	W/m^{2}K	4.9	4.9	4.9	4.9	4.9	3.0	2.4	2.4	2.4
Window - g-value		0.86	0.86	0.86	0.86	0.86	0.67	0.67	0.67	0.67
Window - lifetime of renovation measure	a	30	30	30	30	30	50	50	50	50
Roof - Costs	EUR/m^2 roof	25	38	41	41	41	41	41	41	41
Roof - thickness of insulation material	cm	-	6	8	8	8	8	8	8	8
Roof – λ of insulation material	W/mK	-	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
Roof - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30
Cellar ceiling - Costs	EUR/m^2 cellar ceiling	-	-	-	23	24	24	24	24	24
Cellar ceiling - thickness of insulation material	cm	-	-	-	5	6	6	6	6	6

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8
Cellar ceiling - ƛ of insulation material	W/mK	-	-	-	0.036	0.036	0.036	0.036	0.036	0.036
Cellar ceiling - lifetime of renova-tion measure	a	-	-	-	30	30	30	30	30	30
Energy need for heating	kWh/m^2	56.4	50.0	49.5	45.9	45.6	40.8	38.7	26.1	24.0
Peak heating capacity required	kW	138	127	126	119	119	107	103	81	77
Conversion efficiency of gas heating system		1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Conversion efficiency of aerothermal heat pump system		4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.3	4.3
Conversion efficiency of geo-thermal heat pump system		4.6	4.6	4.6	4.6	4.6	4.7	4.7	4.8	4.8
Energy need for cooling	kWh/m^2	7.6	7.8	7.8	8.0	8.0	7.2	7.3	7.9	8.1

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:

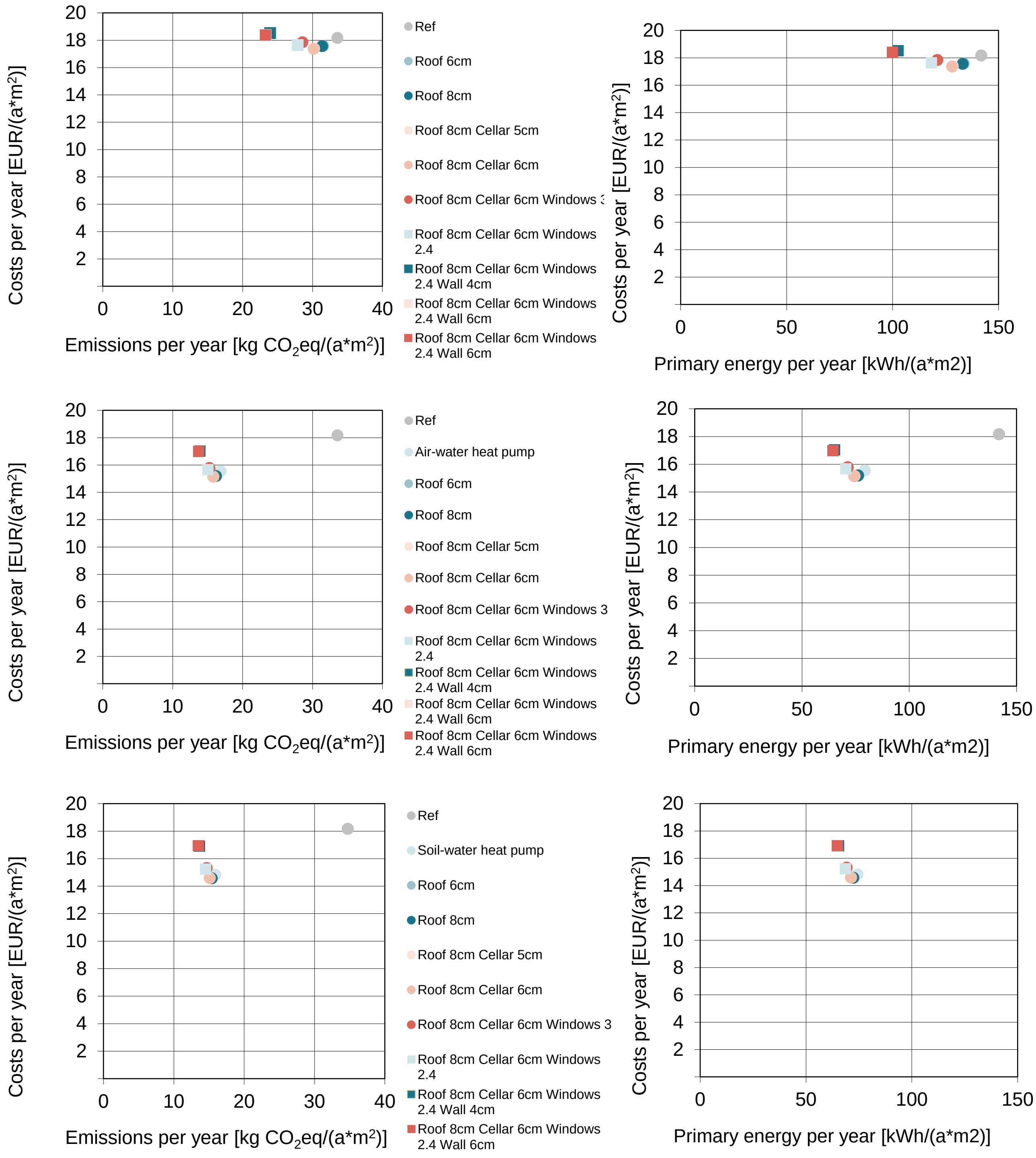


Figure 25 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for multi-family building in Italy for different heating systems, gas (top graphs), air source heat pump (center), ground source heat pump (bottom), and related impacts on carbon emissions and primary energy use. The reference case is the point on the gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

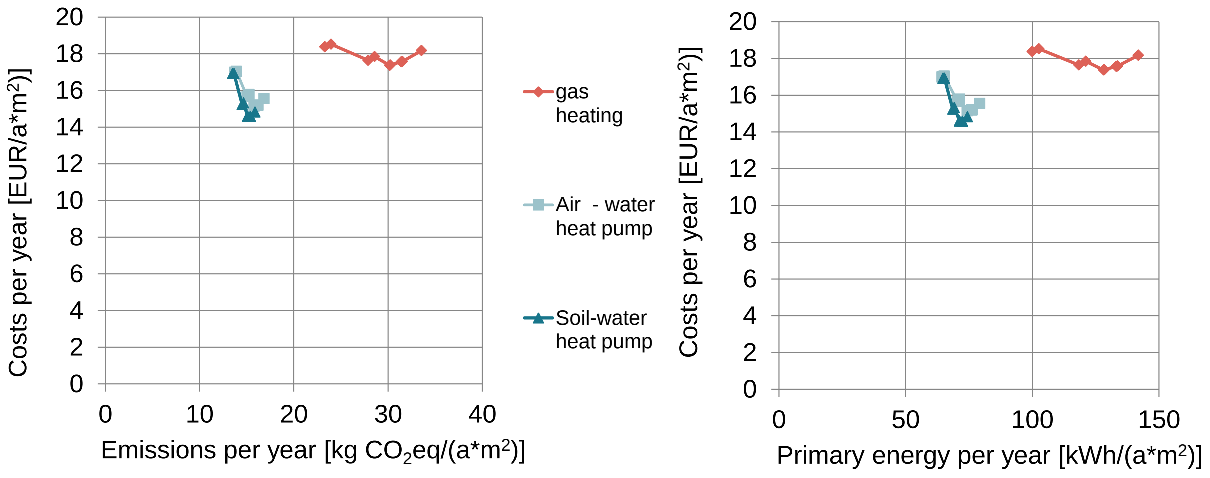


Figure 26 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Italy, for a multi-family building. The reference case is the point on the gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Discussion

The results of the calculations with the multi-family building in Italy confirm the main hypotheses which are investigated, as summarized in the following table:

Table 22 Results for investigated hypotheses for the multi-family reference building in Italy. RES refers here to aerothermal or geothermal heat pump. These are the two RES systems that were investigated in the case of the generic calculations carried out for Italy.

Hypothesis	Results from MFB in Italy
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 cost-optimal efficiency levels	✓
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓

Hypothesis	Results from MFB in Italy
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.	✓

More specific findings with respect to the different hypotheses:

- The first hypothesis is confirmed, as the curves in the graphs show that renovation packages distinguishing themselves only by the energy efficiency ambition level in one single building element improves energy performance less than renovation packages which distinguish themselves by the number of building elements whose energy performance is improved.
- The second hypothesis is confirmed, as both the switch to the aerothermal and the geothermal heat pump reduce emissions more strongly than the most ambitious energy efficiency measures while continuing to use oil as energy carrier for heating.
- With all heating systems, renovation package M4 including measures on the roof and the cellar ceiling the most cost-optimal renovation package. The third hypothesis is thereby confirmed in this case.
- Also for the two RES heating systems investigated some energy efficiency measures are cost-effective; the fourth hypothesis is therefore validated in this case.
- A switch to a RES system reduces emissions more strongly than the most far reaching energy efficiency measures, and at lower costs. The fifth hypothesis is therefore confirmed for this reference building.

4.1.5. Norway

Single-family building: Renovation packages and related assumptions

For the generic calculations in Norway, the following packages of renovation measures are applied to the building envelope:

Table 23 Description of different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Norway.

Renovation Package	Description
Ref	In the reference case, the wall is refurbished and windows are repainted and repaired. Local electric resistance heating is not replaced. These measures do not improve the energy performance of the building.
M1	Windows are replaced with new windows with a wooden frame and a U-value for the entire window

Renovation Package	Description
	of 1.2.
M2	Windows are replaced with new windows with a wooden frame and a U-value for the entire window of 0.8.
M3	Windows are replaced with new windows with a wooden frame and a U-value for the entire window of 0.7.
M4	Additionally to M3, the cellar ceiling is insulated with 8 cm of mineral wool, plasterboard.
M5	Additionally to M3, the cellar ceiling is insulated with 12 cm of mineral wool, plasterboard.
M6	Additionally to M5, the roof is refurbished by insulating the ceiling of the attic floor with 15 cm of mineral wool.
M7	Additionally to M5, the roof is refurbished from the outside with an insulation of 43.5 cm in an airtight construction.
M8	Additionally to M7, the wall is insulated with 15 cm of mineral wool in a ventilated construction.
M9	Additionally to M7, the wall is insulated with 40 cm of mineral wool in a ventilated construction.

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 24 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Norway.

Parameter	Unit	Reference	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	54	54	54	54	54	54	54	54	488	778
Wall - thickness of insulation material	cm	-	-	-	-	-	-	-	-	15	40
Wall - λ of insulation material	W/mK	-	-	-	-	-	-	-	-	0.037	0.037
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	116	495	577	664	664	664	664	664	664	664
Window - U-Value	W/m^2K	2.7	1.2	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Window - g-value		0.71	0.71	0.48	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Window - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Roof - Costs	EUR/m^2 roof	-	-	-	-	-	-	96	408	408	408

Parameter	Unit	Refe-rence	M1	M2	M3	M4	M5	M6	M7	M8	M9
Roof - thickness of insulation material	cm	-	-	-	-	-	-	20	44	44	44
Roof - λ of insulation material	W/mK	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Roof - lifetime of renovation measure	a	-	-	-	50	50	50	50	50	50	50
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	100	120	120	120	120	120
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	8	12	12	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Cellar ceiling - lifetime of renovation measure	a	-	60	60	60	60	60	60	60	60	60
Energy need for heating	kWh/m^2	188	157	149	147	135	133	118	108	54	42
Peak heating capacity required	kW	6	5	5	5	4	4	4	4	2	2
Conversion efficiency of electric heating system		0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Conversion efficiency of air-water heat pump		2.1	2.3	2.3	2.3	2.4	2.4	2.5	2.6	3.1	3.2
Conversion efficiency of wood logs heating		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Single-family building: Results

The outcomes of the calculations for the reference building in Norway depend significantly on the perspective with respect to the electricity mix. Norway has a high share of hydropower in its national production mix. However, a large share of ecological value of this hydropower is traded in the form as «guarantees of origin» or «green certificates» to other European countries, and certificates for electricity from more polluting sources are imported instead. When this would be taken into account, the electricity mix of Norway is significantly less «green». The impacts of the renovation measures on the performance of the building with respect to carbon emissions, primary energy use and costs are therefore shown in two different sets of graphs. In a first set the perspective is based on the national production mix of electricity with imports and exports of electricity itself; in a second set a differing perspective is assumed to include also trading of guarantees of origins / green certificates.

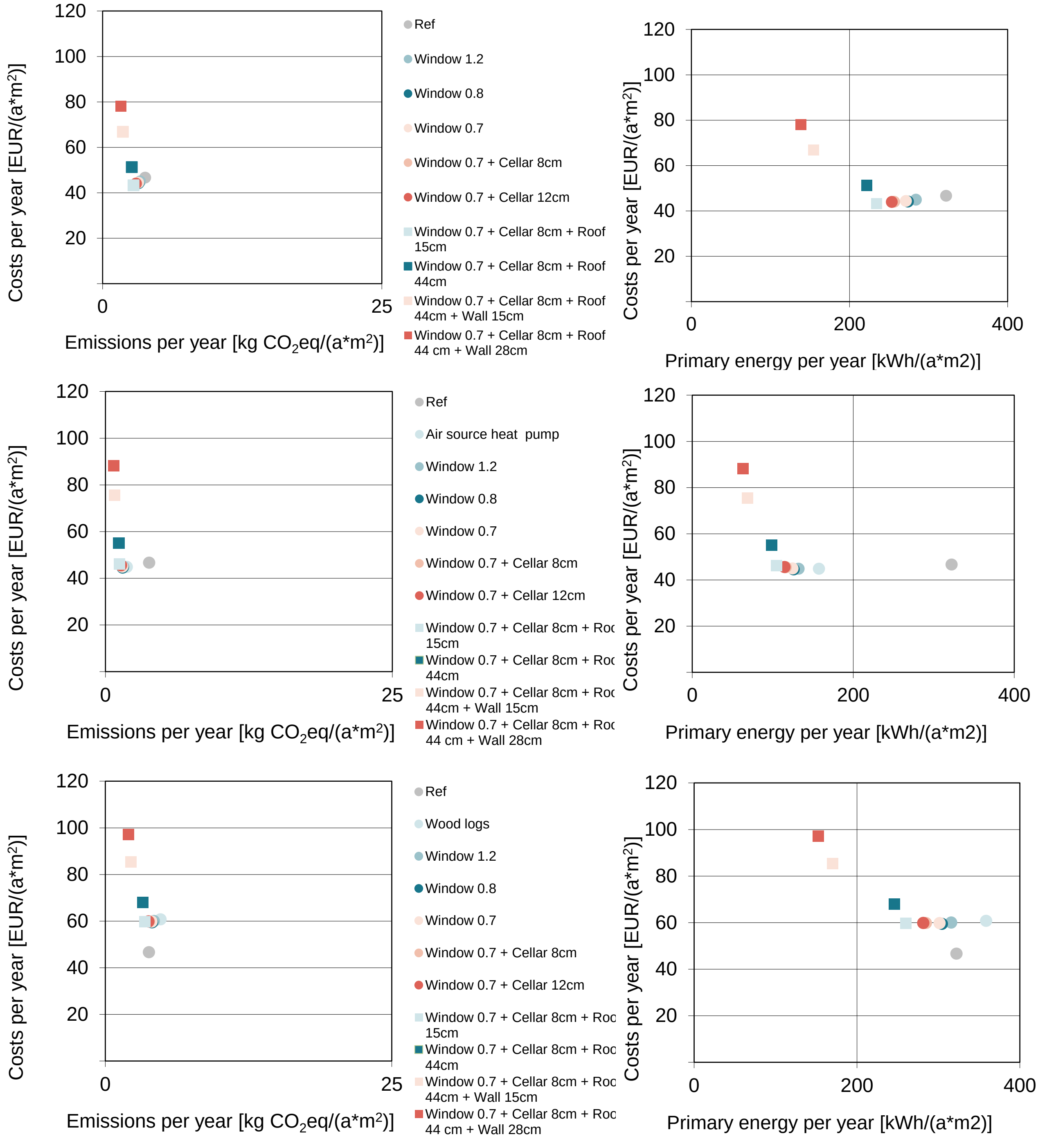


Figure 27 Comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems in single-family building Norway for different heating systems, direct electric heating (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. For determining the impact of electricity on emissions and primary energy use, the **trading of guarantees of origin / green certificates is not taken into account**. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the direct electric heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

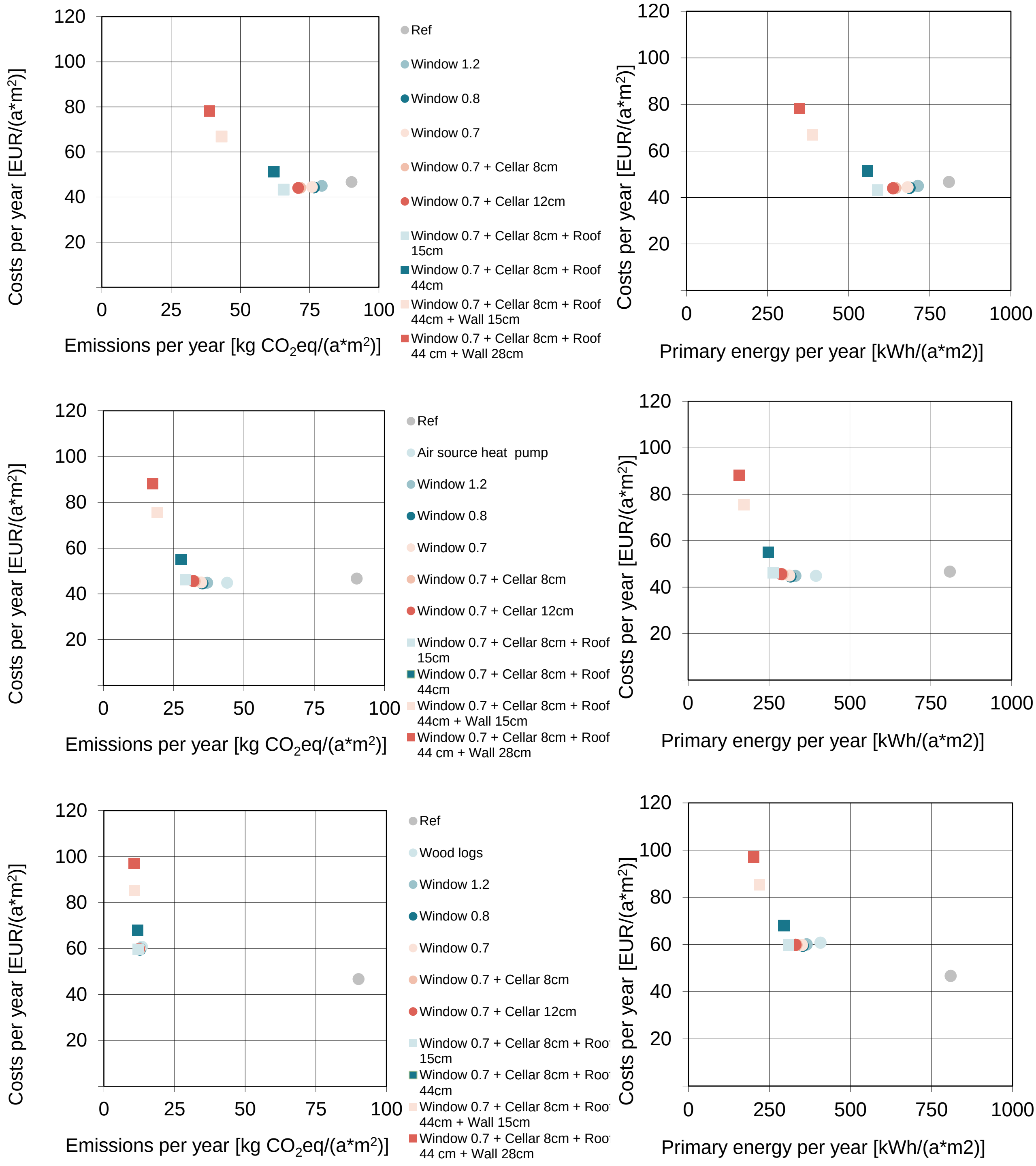


Figure 28 Similar graphs for reference building in Norway as in previous figure, yet for these graphs the residual electricity mix is applied to determine the impact of electricity consumption on emissions and primary energy use. **This electricity mix takes into account imports and exports of guarantees of origin / green certificates**. Note the different scaling of the x-axis compared to the previous set of graphs.

If the national production mix is taken as a basis to calculate the impacts on emissions and primary energy use, a change to a geothermal heat pump or a wood pellets system hardly reduces emissions, which are already low because of the large share of hydropower in the electricity mix. However, if the imports and exports of guarantees of origin / green certificates are taken into account, a change from electricity heating to a heat pump or wood pellets reduces carbon emissions strongly.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

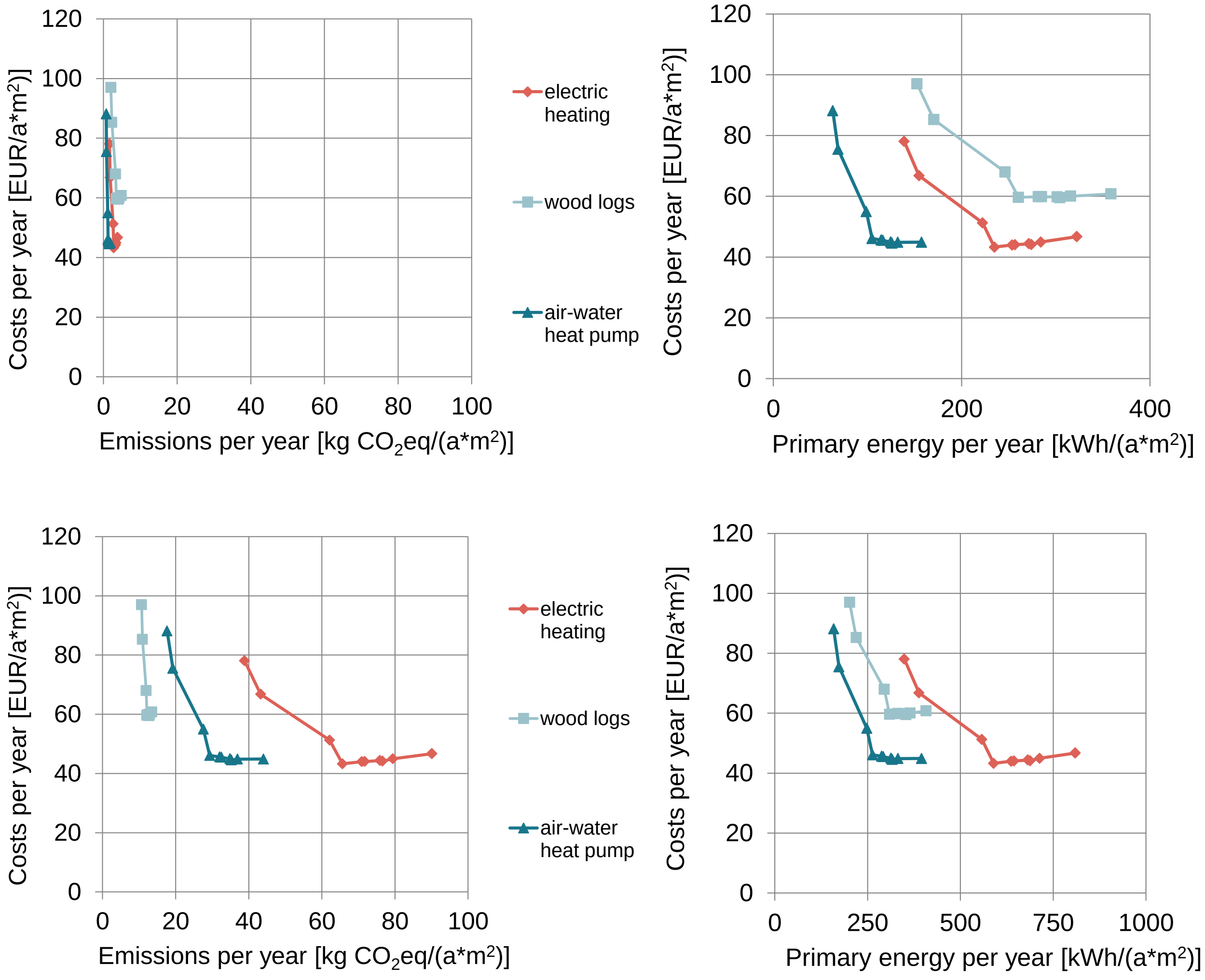


Figure 29 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for a a single-family building in Norway. The upper graphs are calculated with the production electricity mix of Norway as well as imports and exports of electricity; the lower graphs are calculated with the residual electricity mix based on taking into account in addition also the import and export of guarantees of origin.

Discussion

With respect to the different hypotheses investigated, the following conclusions can be made based on the single-family reference building in Norway:

Table 25 Results for investigated hypotheses for reference building from Norway. A distinction is made for two different types of electricity mixes: a production based electricity mix taking into account imports and exports, and an electricity mix which on top of that also takes into account trades with guarantees of origins. RES refers here to an air-water heat pump and wood logs. These are the two RES systems that were investigated in the case of the generic calculations carried out for Norway.

Hypothesis	Results from SFB in Norway – production electricity mix	Results from SFB in Norway – electricity mix taking into account trade with guarantees of origin
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	X	✓
A combination of energy efficiency measures with RES measures does not change significantly 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.	X	✓

More specific findings with respect to the different hypotheses:

- The first hypothesis is confirmed for all building elements. Also costs for the different energy efficiency ambition levels do not vary strongly for different options for a single building element, with the exception of the roof. A reason for this may be that for the roof, different additional renovation costs associated with a high efficiency roof renovation were taken into account, which leads to extra costs for that measure.
- The second hypothesis could not be confirmed in the case of the reference building investigated in Norway, if for the determination of the impact of electricity consumption the production mix with imports and exports, yet without trade of guarantees of origins is used. From that perspective, the electricity mix in Norway is already to a large extent CO_2-free. Accordingly, a change to RES does not lower CO_2-emissions significantly anymore. However, from the perspective of taking into account the trade of guarantees

of origin, the hypothesis can be confirmed.

Independently of the perspective concerning the electricity mix, the switch to a heat pump changes significantly the primary energy use. The switch changes the level of primary energy use to about the same extent as the most ambitious renovation package in terms of energy efficiency measures on the building envelope, yet at significantly lower cost. The switch to the heat pump is also cost-effective compared to the reference case. This is remarkable as it is assumed that a heat distribution system needs to be installed. In the reference case only a decentralized electric heating system is used. The effect of the change to RES on primary energy is different in the case of a switch to wood logs. In that case the impact depends on the perspective with respect to the electricity mix: When the production mix without taking into account the trade in guarantees of origin is considered, a switch to wood logs does not decrease, but increases primary energy consumption. If the trade in guarantees of origin is taken into account, a switch to wood logs decreases primary energy consumption.

- In all investigated combinations with RES measures, renovation package M6 is most cost-effective. The third hypothesis is therefore confirmed in the case of the investigated reference building in Norway. As shown by the results of sensitivity calculations, an important factor leading to this conclusion is that the efficiency of the heat pump system increases with less heat needed due to energy efficiency improvements of the building envelope: as less energy is needed for heating purposes, the difference between the heat source and the necessary temperature in the heating distribution system is lower, which benefits the overall efficiency of the heat pump
- When a switch to a RES system is carried out, some renovation measures continue to be cost neutral or are close to cost-effectiveness. Accordingly, the fourth hypothesis is confirmed.
- If the perspective of the national production mix is chosen, without taking into account the trade of guarantees of origin, high emissions reductions are not possible anymore given the virtually emission-free electricity mix; accordingly, the fifth hypothesis cannot be confirmed in this case. However, if the trade with guarantees of origin is taken into account for the electricity mix, it can be seen that the large emission reductions of far reaching energy efficiency measures can be achieved at lower costs by switching to RES instead.

4.1.6. Portugal

Single-family building: Renovation packages and related assumptions

For the generic calculations in Portugal, the following packages of renovation measures are applied to the building envelope:

Table 26 Description of different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Portugal.

Renovation Package	Description
Ref	In the reference case, the wall is refurbished by high-pressure cleaner, repairing and preparing the surface to apply the new coating system, the pitched roof is repaired by replacing the cover material (clay tiles) and the wood windows are repainted. These measures do not improve the energy performance of the building.
M1	The roof is insulated with 5 cm of XPS.
M2	The roof is insulated with 8 cm of XPS.
M3	Additionally to M2, the cellar ceiling is insulated with 4 cm of XPS.
M4	Additionally to M2, the cellar ceiling is insulated with 5 cm of XPS.
M5	Additionally to M4, the compound wall is refurbished with 4 cm of ETICS – EPS.
M6	Additionally to M4, the compound wall is refurbished with 6 cm of ETICS – EPS.
M7	Additionally to M4, windows are replaced with new windows with a metal frame and a U-value for the entire window of 2.7.
M8	Additionally to M4, windows are replaced with new windows with a metal frame and a U-value for the entire window of 2.5.
M9	Additionally to M4, windows are replaced with new windows with a metal frame and a U-value for the entire window of 2.3.

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 27 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Portugal.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	72	72	72	72	72	83	89	89	89	89
Wall - thickness of insulation material	cm	-	-	-	-	-	4	10	10	10	10
Wall - λ of insulation material	W/mK	-	-	-	-	-	0.036	0.036	0.036	0.036	0.036
Wall - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Window - Costs	EUR/m^2 window	25	25	25	25	25	25	25	251	253	272

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Window - U-Value	W/m^2K	5.1	5.1	5.1	5.1	5.1	5.1	5.1	2.7	2.5	2.3
Window - g-value		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.75	0.75	0.39
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	23	30	33	33	33	33	33	33	33	33
Roof - thickness of insulation material	cm	-	8	14	14	14	14	14	14	14	14
Roof - λ of insulation material	W/mK	-	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
Roof - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	10	16	16	16	16	16	16
Cellar ceiling - thickness of insulation material	cm	-	-	-	4	8	8	8	8	8	8
Cellar ceiling - λ of insulation material	W/mK	-	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
Cellar ceiling - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Energy need for heating	kWh/m^2	218	144	138	111	105	54	43	31	30	37
Peak heating capacity required	kW	19	13	13	11	11	7	6	5	5	5
Conversion efficiency of natural gas heating		0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Conversion efficien-cy of air-water heat pump		2.9	3.2	3.2	3.4	3.4	3.7	3.8	3.9	3.9	3.9
Conversion efficien-cy of air-water heat pump + PV		2.9	3.2	3.2	3.4	3.4	3.7	3.8	3.9	3.9	3.9
Assumed energy need for cooling	kWh/m^2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3

Single-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:

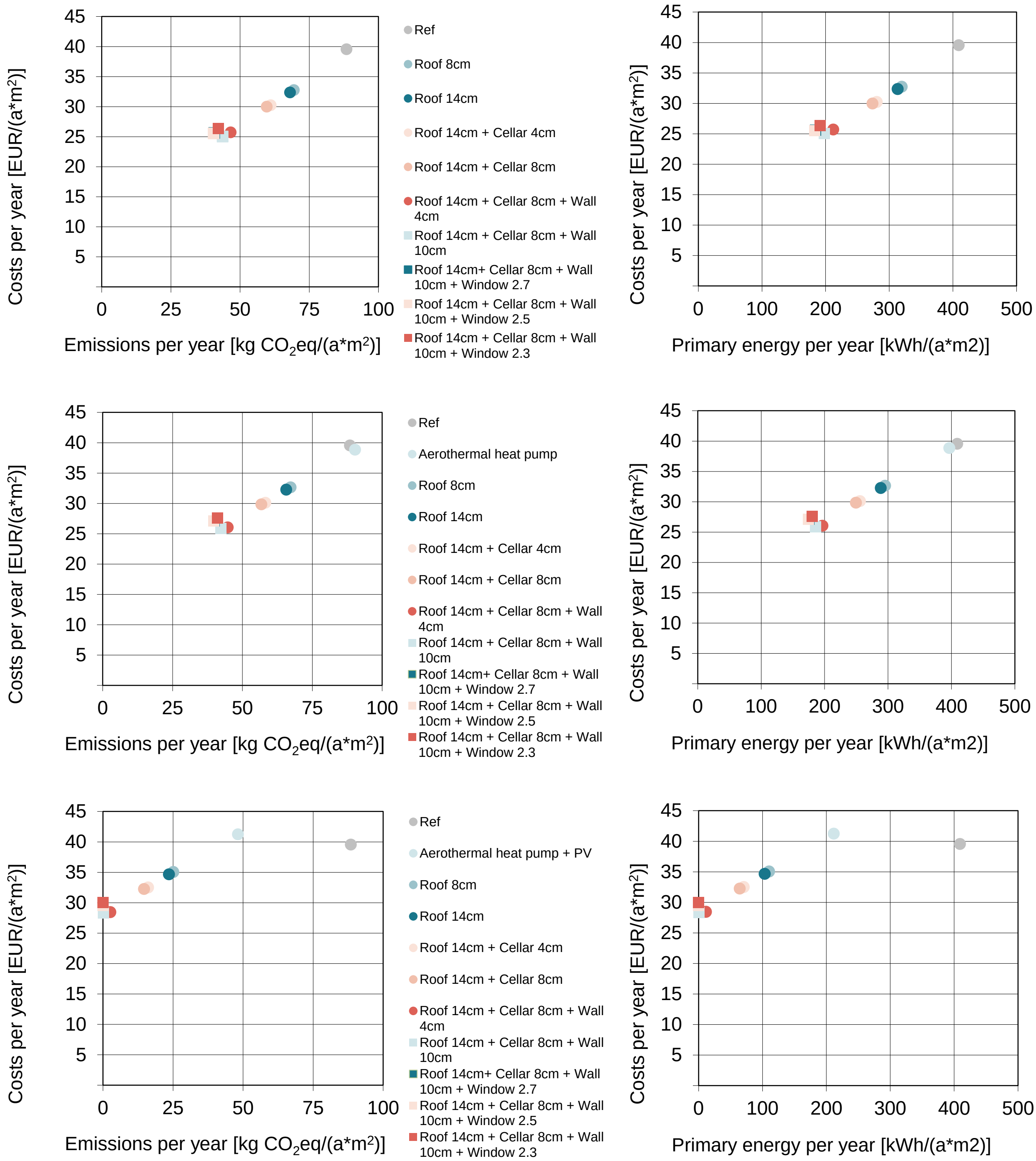


Figure 30 Comparison of cost-effectiveness of energy efficiency renovation measures for a single-family building in Portugal for <u>different heating systems</u>, gas (top graphs), air-water heat pump (middle) and air-water heat pump + PV (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a

situation with a replacement of the gas heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

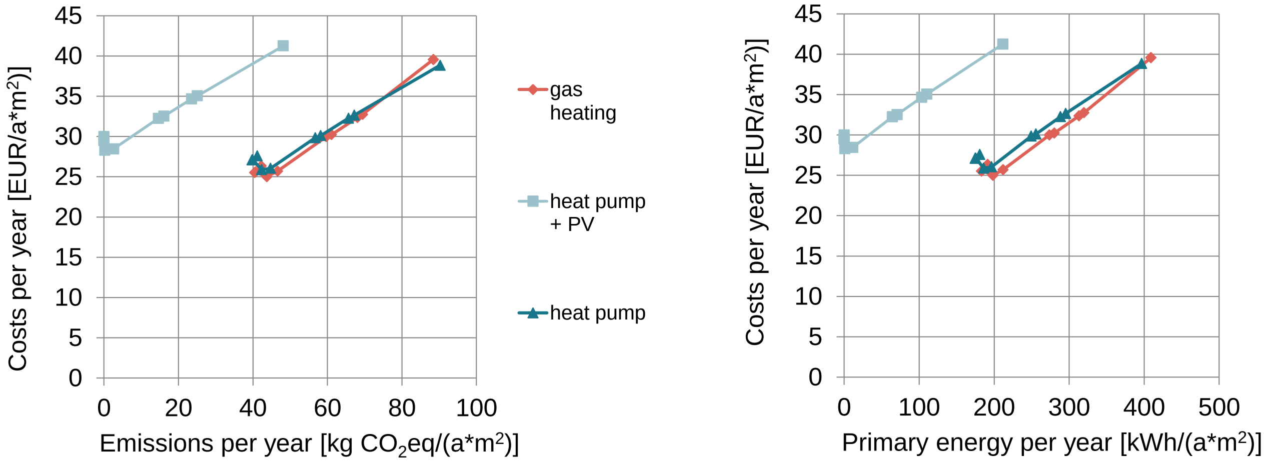


Figure 31 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Portugal, for a single-family building. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Multi-family building: Renovation packages and related assumptions

Reference measures and renovation measures are identical to the ones for the single family reference building; the difference to the case of the single-family building are the dimensions of the building and related to that the absolute and specific energy need as well as the size of the heating systems.

The following table describes the characteristics of the different renovation packages that are taken into account.

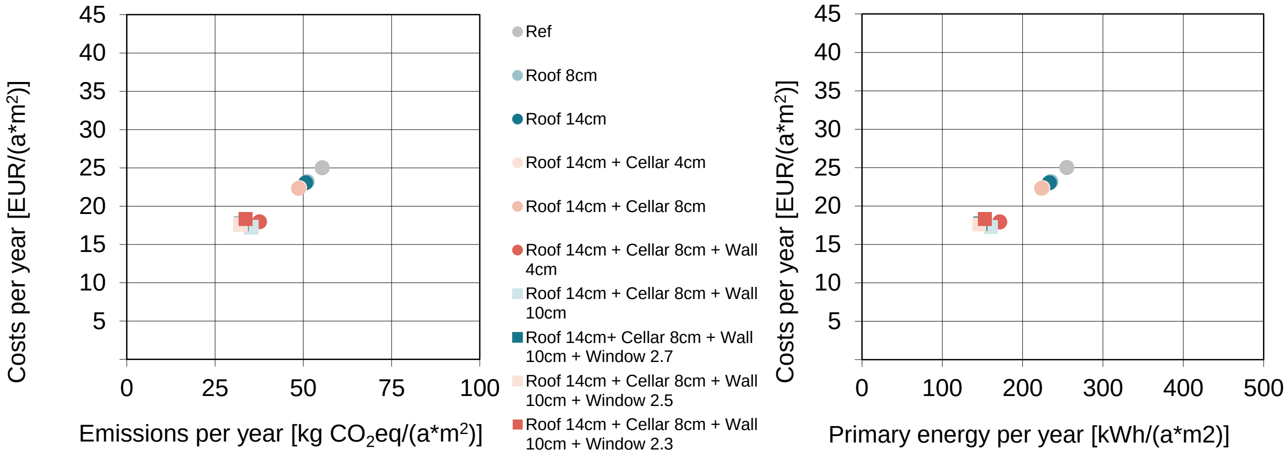
Table 28 Data for different packages of renovation measures M1 to M9 and the reference case for a multi-family house in Portugal.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	72	72	72	72	72	83	89	89	89	89
Wall - thickness of insulation material	cm	-	-	-	-	-	4	10	10	10	10
Wall - λ of insulation material	W/mK	-	-	-	-	-	0.036	0.036	0.036	0.036	0.036
Wall - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Window - Costs	EUR/m^2 window	25	25	25	25	25	25	25	251	253	272
Window - U-Value	W/m^{2}K	5.1	5.1	5.1	5.1	5.1	5.1	5.1	2.7	2.5	2.3
Window - g-value		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.75	0.75	0.39
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	23	30	33	33	33	33	33	33	33	33
Roof - thickness of insulation material	cm	-	8	14	14	14	14	14	14	14	14
Roof - λ of insulation material	W/mK	-	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
Roof - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	10	16	16	16	16	16	16
Cellar ceiling - thickness of insulation material	cm	-	-	-	4	8	8	8	8	8	8
Cellar ceiling - λ of insulation material	W/mK	-	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Cellar ceiling - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Energy need for heating	kWh/m^2	103	87	85	78	77	34	25	14	13	19
Peak heating capacity required	kW	68	60	59	56	55	35	30	23	22	22
Conversion efficiency of natural gas heating		0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Conversion efficiency of air-water heat pump		3.4	3.5	3.5	3.6	3.6	3.9	3.9	4	4	4
Conversion efficiency of air-water heat pump + PV		3.4	3.5	3.5	3.6	3.6	3.9	3.9	4	4	4
Assumed energy need for cooling	kWh/m^2	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



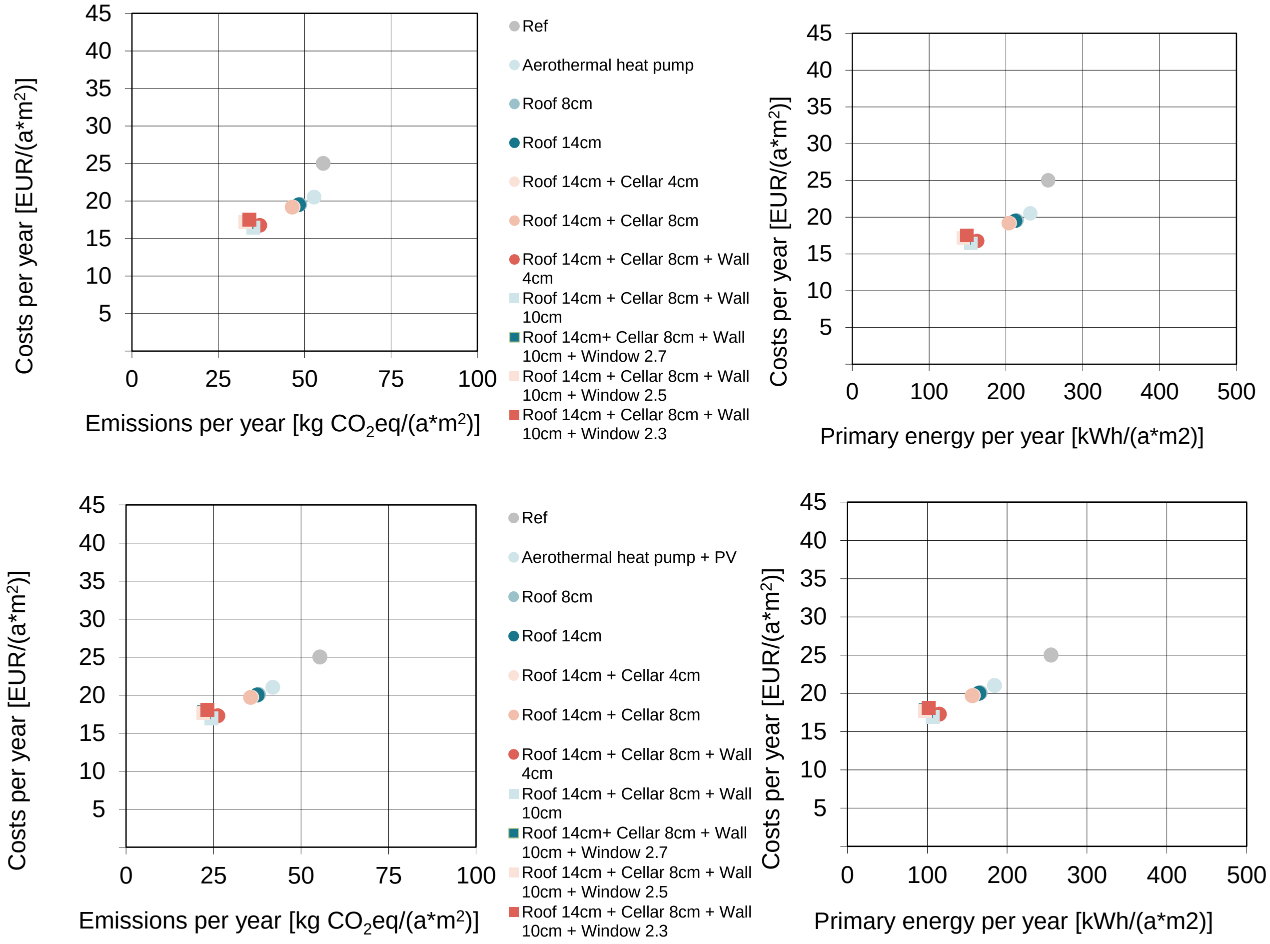


Figure 32 Comparison of cost-effectiveness of energy efficiency renovation measures for multi-family building in Portugal for different heating systems, natural gas (top graphs), air-water heat pump (middle) and air-water heat pump + PV (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the gas heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems.

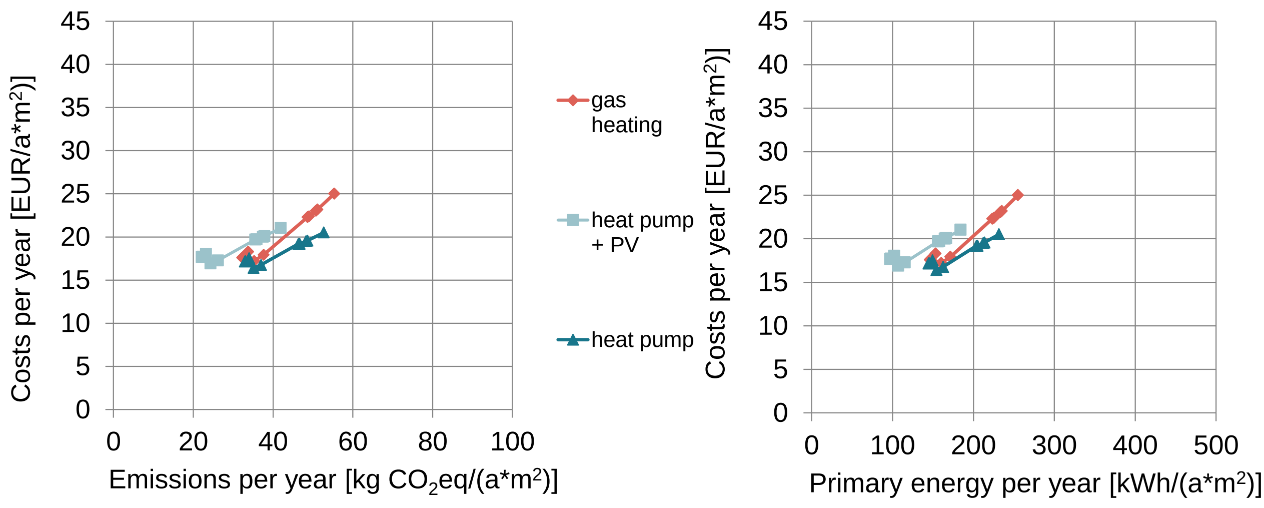


Figure 33 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Portugal, for a multi-family building. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Discussion

Single-family building

It can be seen that most of the energy efficiency measures on the building envelope are cost-effective in the generic calculations with the reference building. This is mostly due to the fact that the difference of costs between «anyway renovations» and energy related renovations is rather small.

Contrary to generic calculations with reference buildings in other countries, a change to a heat pump in the reference building investigated in Portugal reduces emissions only by a small amount. Also primary energy use is reduced only to a small extent by switching the heating system to heat pump. This can be explained by the relatively high emission factor and primary energy factor of the electricity mix in Portugal in comparison with other countries. Furthermore, here an air-water-heat pump was assumed, and not a ground source heat pump, which has a higher efficiency. However, the switch to a heat pump can be recognized to be an important step to reduce emissions and primary energy use significantly in combination with on-site PV electricity production. By installing a PV system, the impacts of electricity use can be reduced to a large extent. Note that here the net effect of the grid-connected PV system was looked at, i.e. on site electricity production is assumed to replace electricity use with an average greenhouse gas emission factor and an average primary energy factor in the grid by the total of amount of electricity produced.

For the generic calculations for the reference buildings in Portugal, a switch to RES heating is therefore assumed to comprise both a switch to heat pump and the installation of a PV system.

Taking into account these explanations, the results of the calculations with the single-family building in Portugal confirm most of the main hypotheses which are investigated, as summarized in the following table. The last hypothesis could not be confirmed, as the switch to heat pump and PV is not advantageous in terms of costs for the case of the single-family building. Costs are not significantly higher, though, for the case of switching to heat pump and PV as compared to the reference case with natural gas.

Table 29 Results for investigated hypotheses for the single-family reference building in Portugal. Here, a switch to RES means the installation of a heat pump in combination with a PV system.

Hypothesis	Results from SFB in 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 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.	X

Multi-family building

In the case of the multi-family building, most renovation measures are cost-effective. This can be explained by the same reasons as for the single-family building, i.e. the small difference between costs of «anyway renovation» as compared to energy related renovations.

All the hypotheses can be confirmed for the calculations with the multi-family building in Portugal. This is also the case for the last hypothesis, which was not confirmed in the case of the single-family building in Portugal.

Table 30 Results for investigated hypotheses for the single-family reference building in Portugal. RES refers here to an air-water heat pump combined with a PV system. Because of a relatively high carbon emission factor and a relatively high primary energy factor of the electricity mix, a heat pump alone, without combination with PV, does not reduce significantly emissions or primary energy compared to natural gas.

Hypothesis	Results from SFB in 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 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.	✓

Comparison between the single-family building and the multi-family building

Comparing the graphs for the multi-family buildings and the graphs for the single-family building yields the following observations:

- Specific costs, emissions and primary energy use per m^2 of gross floor area are lower in the case of the multi-family building in Portugal compared to the single-family building investigated. This can be explained by a higher ratio of volume to surface in the case of the single-family building.
- In the case of the multi-family building, the switch to a heat pump in combination with a PV system is more cost-effective than in the case of a single-family building. This can explained as follows: A heat pump is a more cost-effective solution in a multi-family building compared to a single-family building, because of economies of scale and because of a higher efficiency of the heat pump in a multi-family building due to lower specific energy need, since it is possible to have a lower temperature of the heat distributing system.
- The impact of switching to heat pump and PV on emissions and primary energy reductions is less pronounced in the case of the multi-family building: This is because it has been assumed that the PV system has the same size in both cases.

The hypothesis investigated related to the difference between single-family buildings and multi-family buildings can therefore be confirmed in the case of the two generic examples investigated in Portugal.

Table 31 Result for hypothesis related to the comparison of multi-family buildings and single-family buildings in Portugal. Here, a switch to RES means the installation of a heat pump in combination with a PV system.

Hypothesis	Results from SFB and MFB in Denmark
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger	✓

4.1.7. Spain

Multi-family building: Renovation packages and related assumptions

For the generic calculations with a multi-family building in Spain, the following packages of renovation measures are applied to the building envelope:

Table 32 Description of different packages of renovation measures M1 to M9 and of the reference case for Spain.

Renovation Package	Description
Ref	In the reference case, on the wall a cement mortar repair is carried out and the pitched roof is refurbished. These measures do not improve the energy performance of the building.
M1	The wall is insulated with 12 cm of a cement / glass wool composite material.
M2	The wall is insulated with 20 cm of a cement / glass wool composite material.
M3	The wall is insulated with 30 cm of a cement / glass wool composite material.
M4	Additionally to M3, the thermal barrier to the roof is improved with an indoor refurbishment of the ceiling with a thickness of 14 cm.
M5	Additionally to M3, the thermal barrier to the roof is improved with an indoor refurbishment of the ceiling with a thickness of 20 cm.
M6	Additionally to M5, the cellar ceiling is insulated with a layer of a thickness of 8 cm.
M7	Additionally to M5, the cellar ceiling is insulated with a layer of a thickness 12 cm.
M8	Additionally to M7, the windows are replaced with new windows with a PVC frame and a U-value for the entire window of 2.7.
M9	Additionally to M7, the windows are replaced with new windows with a metal frame and a U-value for the entire window of 1.0.

The following table describes the characteristics of the different renovation packages that are taken into account.

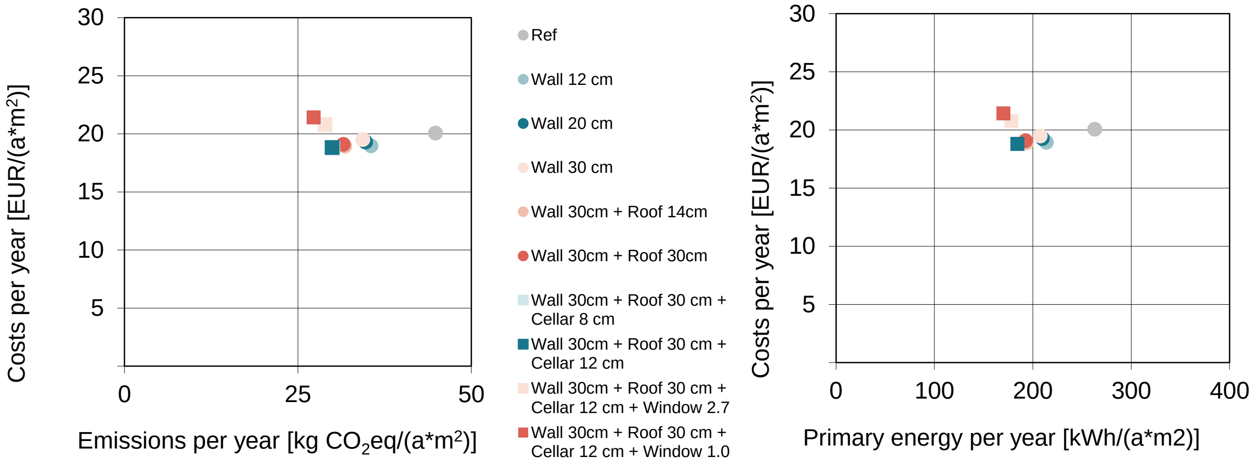
Table 33: Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Spain.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	35	72	85	93	93	93	93	93	93	93
Wall - thickness of insulation material	cm	-	12	20	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.038	0.038	0.038	0.038	0.038	00038	0.038	0.038	0.038
Wall - lifetime of renovation measure	years	50	50	50	50	50	50	50	50	50	50
Window - Costs	EUR/m^2 window	-	-	-	-	-	-	-	-	300	450
Window - U-Value	W/m^{2}K	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	2.7	1
Window - g-value		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.75
Window - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Roof - Costs	EUR/m^2 roof	85	85	85	85	114	142	142	142	142	142
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - λ of insulation material	W/mK	-	-	-	-	0.038	0.038	0.038	0.038	0.038	0.038
Roof - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	-	-	27	40	40	40
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	-	8	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	-	0.038	0.038	0.038	0.038
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	-	50	50	50	50
Energy need for heating	kWh/m^2	93	45	41	39	25	24	16	16	10	2

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Peak heating capacity required	kW	159	101	96	94	76	75	64	63	55	38
Conversion efficiency of gas heating		1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Conversion efficiency of geothermal HP		3.8	4.1	4.1	4.2	4.2	4.2	4.3	4.3	4.3	4.3
Conversion efficiency of wood pellets heating		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



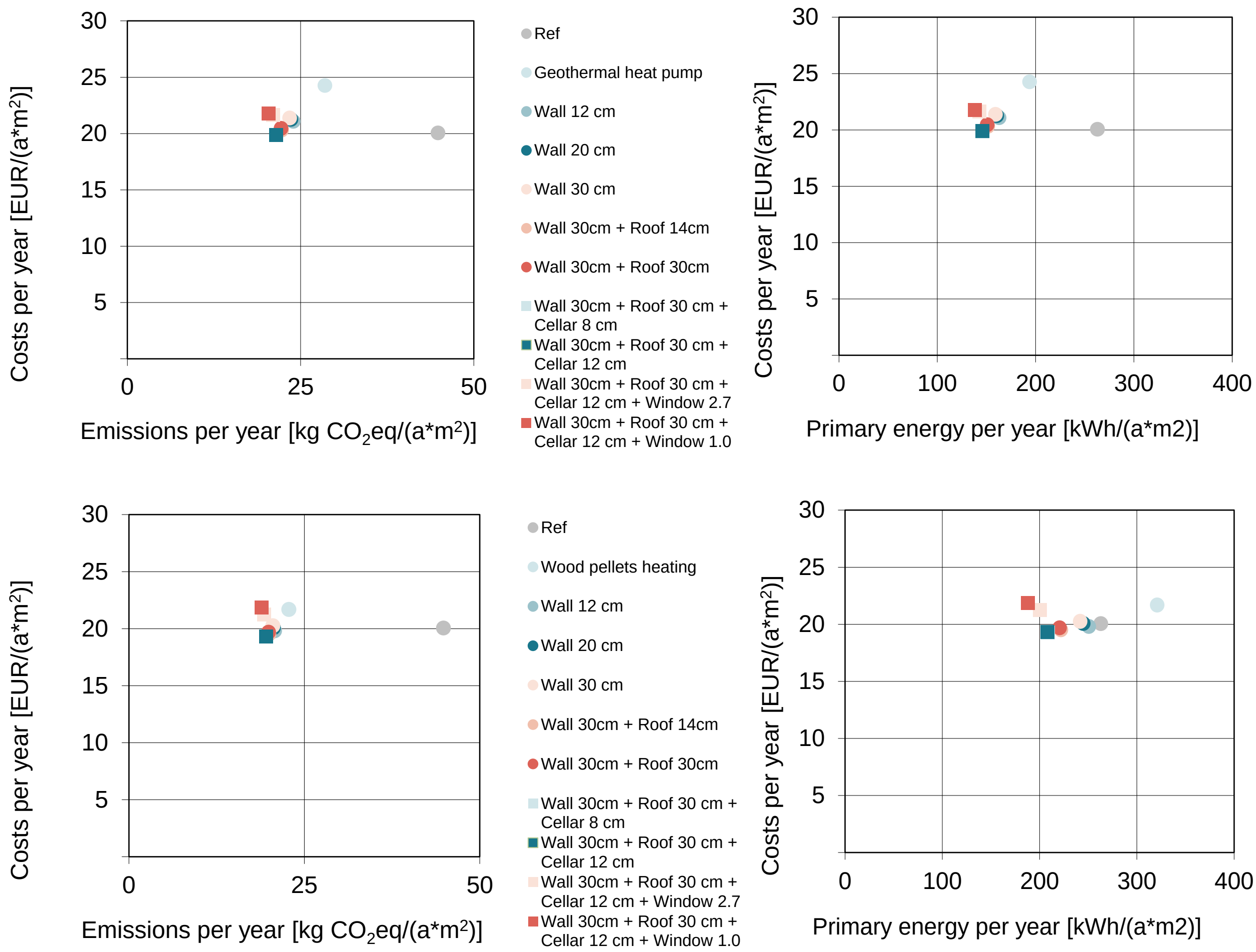


Figure 34 Comparison of cost-effectiveness of energy efficiency renovation measures for a multi-family building in Spain for <u>different heating systems</u>, gas (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the gas heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

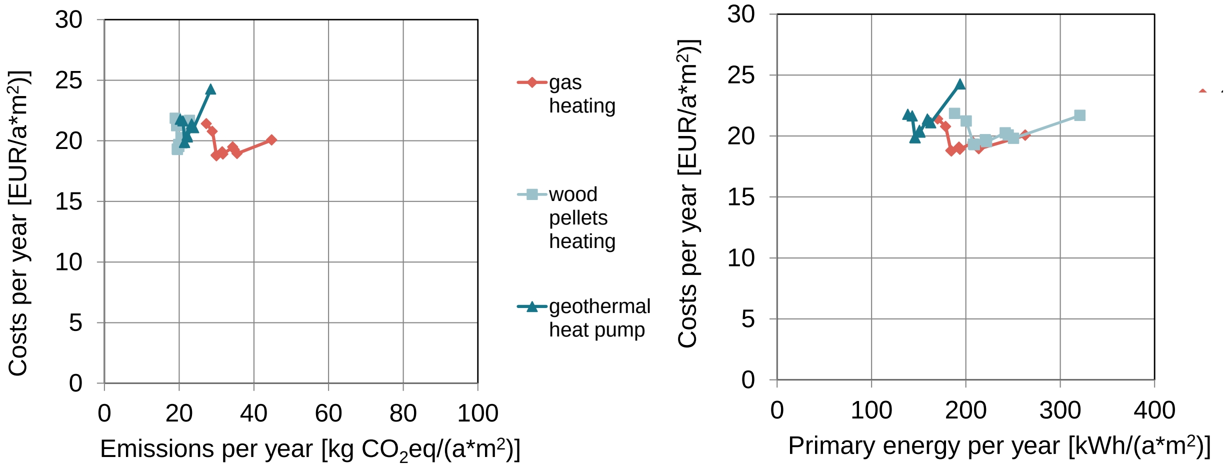


Figure 35 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Spain, for a multi-family building. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

For the calculations with the reference building investigated, the following results are found in particular:

The results show that the renovations of the wall, the roof and of the cellar ceiling are cost-effective measures. The replacement of the windows with new windows is not a cost-effective measure. Impacts are similar for different renovation packages which include the same set of building elements affected by the renovation and which differ from each other only in the energetic ambition level for a single building element.

The change to a RES based heating system changes emissions more strongly than energy efficiency improvements on the building envelope. A switch to a geothermal heat pump reduces primary energy use significantly. A switch to a wood pellets system increases primary energy use compared to the gas heating reference case, though. The most cost-effective solution is to install again a gas heating system. A change to a RES system is not cost-effective. However, when combined with energy efficiency measures, the cost differences to the cost-optimal solution with a natural gas heating system become small.

For all heating systems, renovation package M7 is the most-optimal from the packages investigated.

Discussion

The results of the calculations with the multi-family building in Spain confirm the main hypotheses which are investigated, as summarized in the following table:

Table 34 Results for investigated hypotheses for the multi-family reference building in Spain. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Spain.

Hypothesis	Results from MFB in 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 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.	✓

More specific findings with respect to the different hypotheses:

- The number of building elements energetically improved in the renovation process has a bigger influence on costs and environmental impact than the different ambition levels investigated for single building elements. The first hypothesis is therefore confirmed by the calculations for this reference building (more detailed conclusions see chapter 6.1.1., hypothesis 1).
- When the heating system continues to be natural gas, even the most ambitious energy efficiency measures do not reduce emissions as strongly as if a switch to RES is made. The second hypothesis is therefore clearly confirmed.
- As for all heating systems investigated renovation package M7 is the most cost-effective, the third hypothesis is confirmed.
- If switching to renewable energy, some energy efficiency measures are cost-effective. In case of the geothermal heat pump, energy efficiency measures become even more cost-effective in relative terms than in case of a continued use of natural gas for heating. The forth hypothesis is therefore confirmed.
- For very ambitious energy efficiency measures on the building envelope, while continuing to use a gas heating system, costs go beyond the cost optimum level with a switch to RES. The fifth hypothesis is therefore confirmed.

Generally, energy need for the reference building in Spain is relatively low in comparison with generic examples from other countries: The climate in Spain is relatively warm and the reference building is a relatively large multi-family building, having therefore a low surface area to floor area ratio.

What is not taken fully into account is the fact that with increasing energy efficiency levels, the energy need for heating becomes so low that it might become possible to have no heating system at all (perhaps with ventilation with heat recovery)

The lifetimes chosen of the building elements are relatively long, which favours renovation measures.

For windows, no costs are assumed to occur in the reference case (which is not in line with the methodology applied here, which assumes for the sake of an appropriate comparison, that the window is replaced also in the anyway renovation (e.g. because of being at the end of its life span), but not with the objective to improve energy efficiency of the window). Therefore, the energy efficiency related costs of the windows are overestimated, which makes energetic measures on the windows look less cost-effective.

4.1.8. Sweden

Single-family building: Renovation packages and related assumptions

For the generic calculations with a single-family building in Sweden, the following packages of renovation measures are applied to the building envelope:

Table 35 Description of different packages of renovation measures M1 to M9 and of the reference case for Sweden.

Renovation Package	Description
Ref	In the reference case, the wall, the flat roof, and the windows are refurbished (for windows: repainting and repairing only). These measures do not improve the energy performance of the building.
M1	The wall is insulated with 6 cm of mineral wool
M2	The wall is insulated with 16 cm of mineral wool
M3	The wall is insulated with 30 cm of mineral wool
M4	Additionally to M3, the flat roof is insulated with 14 cm of mineral wool
M5	Additionally to M3, the flat roof is insulated with 30 cm of mineral wool
M6	Additionally to M5, the cellar ceiling is insulated with 8 cm of mineral wool
M7	Additionally to M5, the cellar ceiling is insulated with 12 cm of mineral wool

Renovation Package	Description
M8	Additionally to M7, the windows are replaced with a new standard window which as a U-value for the entire window of 1.8.
M9	Additionally to M7, the windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.0.

The following table describes the characteristics of the different renovation packages that are taken into account.

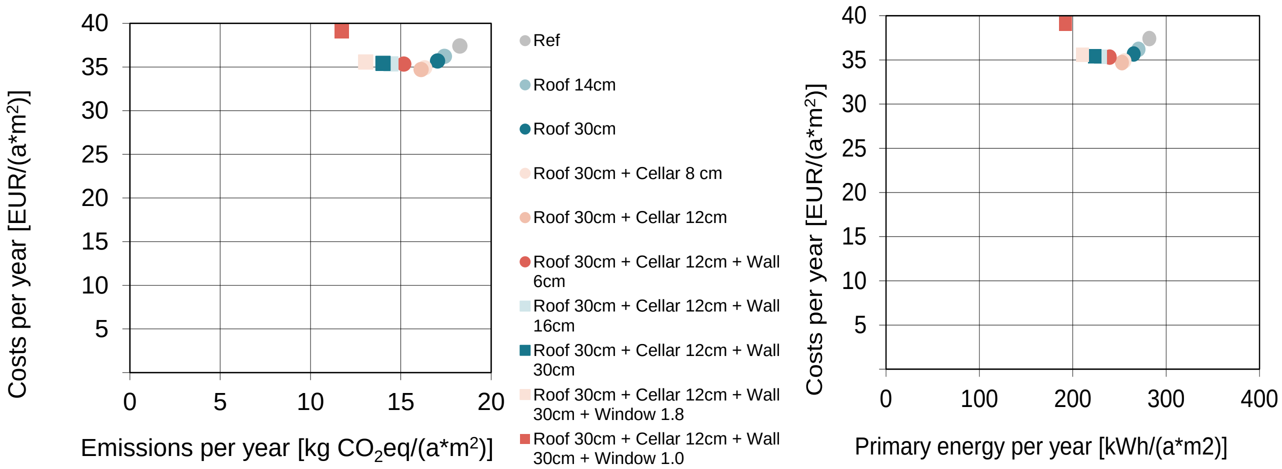
Table 36 Data for different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Sweden.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2	42	100	130	150	150	150	150	150	150	150
Wall - thickness of insulation material	cm	-	6	16	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	years	50	50	50	50	50	50	50	50	50	50
Window - Costs	EUR/m^2 window	9	9	9	9	9	9	9	9	178	784
Window - U-Value	W/m^2K	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	1.8	1
Window - g-value		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	22	22	22	22	61	75	75	75	75	75
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - λ of insulation material	W/mK	-	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04
Roof - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	-	-	7	10	10	10
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	-	8	12	12	12

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	-	0.038	0.038	0.038	0.038
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	-	50	50	50	50
Energy need for heating	kWh/m^2	135	125	117	112	103	99	91	89	79	65
Peak heating capacity required	kW	5	5	5	4	4	4	4	4	3	3
Conversion efficiency of district heating		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Conversion efficiency of geothermal HP		3.3	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.6	3.7
Conversion efficiency wood pellets heating		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

Single-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



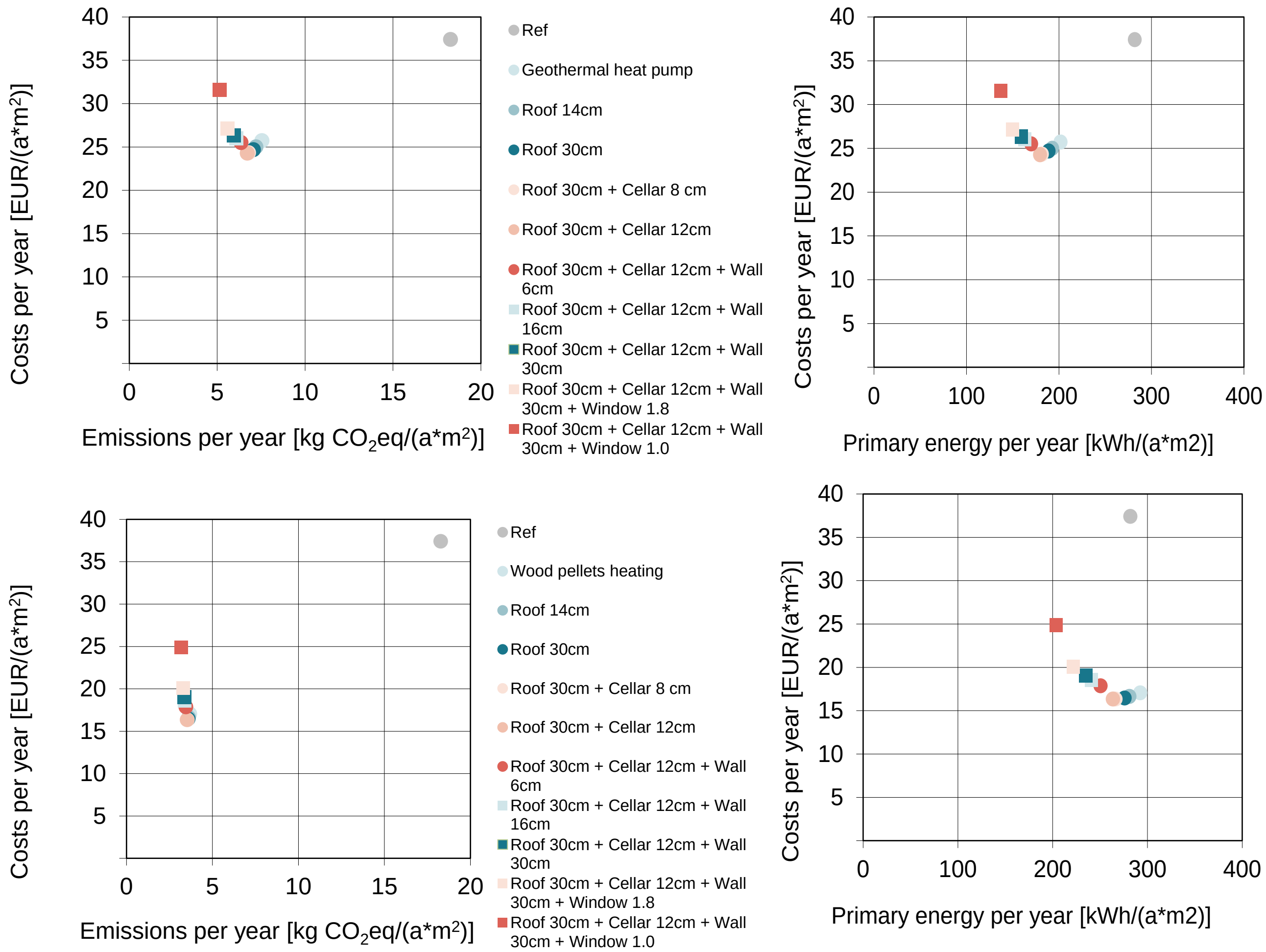


Figure 36 Comparison of cost-effectiveness of energy efficiency renovation measures for a single-family building in Sweden for different heating systems, district heating (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the district heating substation and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

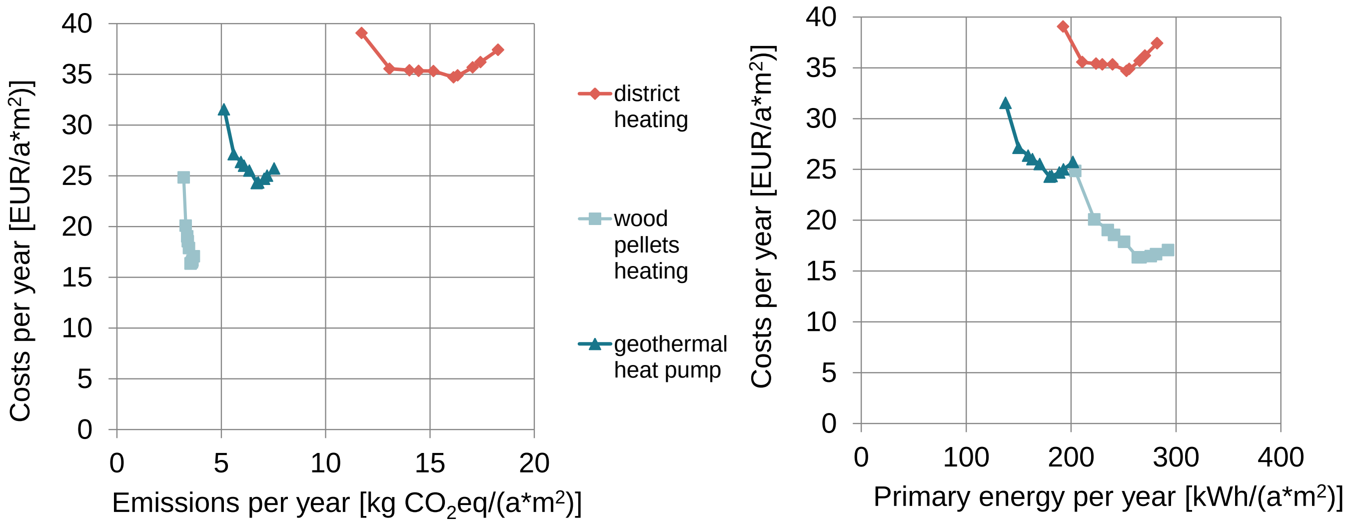


Figure 37 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Sweden, for a single-family building. The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

For the calculations with the reference building investigated, the following results are noted in particular:

The results show that in the case of this reference building and the assumption of a district heating system, the renovation of the roof and of the cellar ceiling are cost-effective measures for all energy efficiency ambition levels investigated. Measures on the wall with 6 cm, 16 cm or 30 cm of insulation, as well as the replacement with new standard windows with a U-value of 1.8 W/(m^2*K) are approximately cost-neutral. The high efficiency window with a U-value of 1.0 W/(m^2*K) is not cost-effective anymore. The most cost-effective renovation packages are M3 and M4.

If a change to geothermal heat pump is considered, renovations on the building envelope are less cost-effective in comparison with a situation in which only the heating system is replaced. Whereas the cost-optimum is still with renovation packages M3 and M4, further renovation measures are clearly less cost-effective. All measures on the envelope are still cost-effective in combination with a switch to the geothermal heat pump if compared to the reference situation with a replacement of the oil heating system with the same energy system without energy efficiency improvements on the building envelope.

For a change to a wood pellets system, the situation is similar to the change to a geothermal heat pump with respect to the cost-effectiveness of the different renovation packages, yet more pronounced. Renovation packages up to M4 are cost-effective, with an optimum at M4; beyond that, energy efficiency measures are not cost-effective any more.

The change to a RES based heating system reduces emissions more strongly than energy efficiency improvements on the building envelope. With respect to the primary energy use, a change to a RES system leads to significant reductions as well for a geothermal heat pump, but not for a wood pellets system, where primary energy use increases slightly compared to the reference case. The most cost-effective solution is to switch to a wood pellets system while carrying energy efficiency measures only for the roof and the cellar ceiling. This solution would lead to strong emissions reductions and also to less non-renewable primary energy use; total primary energy use, as indicated in the graph, would decrease only slightly.

For all heating systems, renovation package M4 is among the cost-optimal packages, considering the packages investigated.

Multi-family building: Renovation packages and related assumptions

For the generic calculations with a multi-family building in Sweden, the investigated renovation packages are the same as for the Swedish single-family building.

The following table describes the characteristics of the different renovation packages that are taken into account.

Table 37 Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Sweden.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	42	100	130	150	150	150	150	150	150	150
Wall - thickness of insulation material	cm	-	6	16	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	years	50	50	50	50	50	50	50	50	50	50
Window - Costs	EUR/m^2 window	9	9	9	9	9	9	9	9	178	784
Window - U-Value	W/m^2K	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	1.8	1
Window - g-value		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6
Window - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Roof - Costs	EUR/m^2 roof	22	22	22	22	61	75	75	75	75	75
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - λ of insulation material	W/mK	-	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04
Roof - lifetime of renovation measure	a	50	50	50	50	50	50	50	50	50	50
Cellar ceiling - Costs	EUR/m^2 ceiling	-	-	-	-	-	-	7	10	10	10
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	-	8	12	12	12
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	-	0.038	0.038	0.038	0.038
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	-	50	50	50	50
Energy need for heating	kWh/m^2	68	63	60	58	54	52	49	49	41	31
Peak heating capacity required	kW	34	32	31	30	29	28	27	27	42	20
Conversion efficiency of district heating		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Conversion efficiency of geothermal heat pump		3.7	3.7	3.7	3.7	3.7	3.8	3.8	3.8	3.9	3.9
Conversion efficiency of wood pellets heating		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:

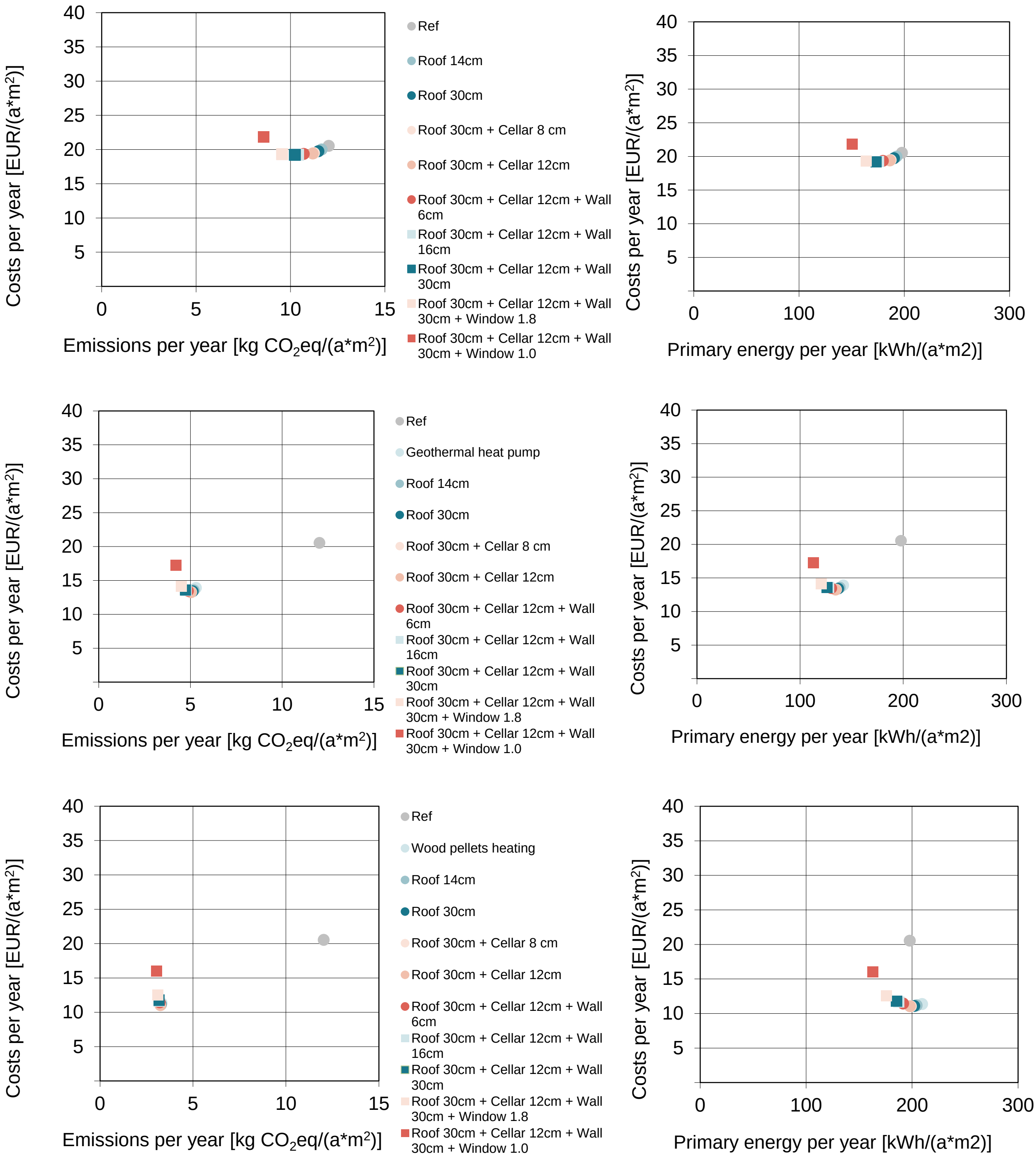


Figure 38 Comparison of cost-effectiveness of energy efficiency renovation measures for a multi-family building in Sweden different heating systems, district heating system (top graphs), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the district heating substation, and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems. For the sake of comparison, the graphs for the single-family building from Sweden are shown subsequently.

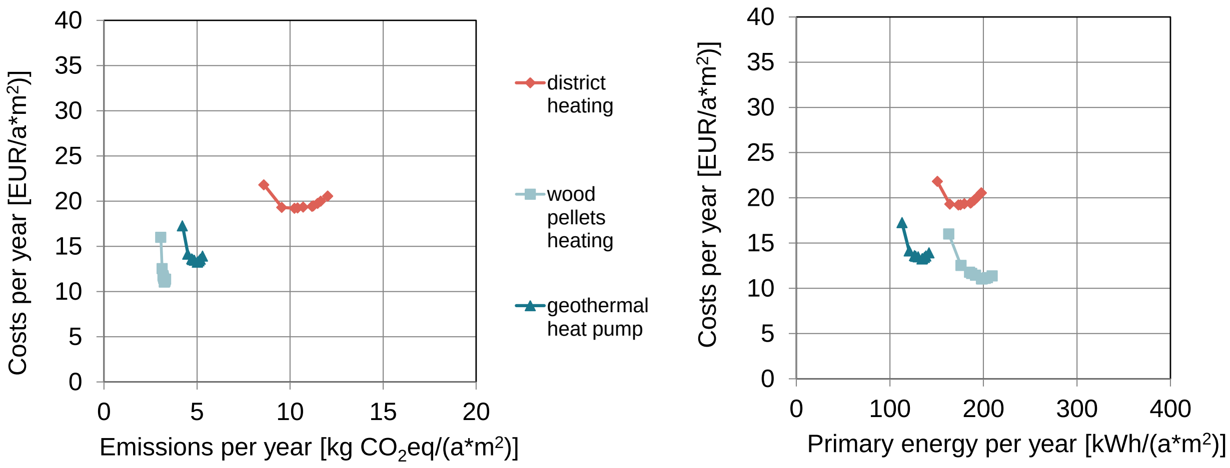


Figure 39 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Sweden, for a multi-family building, The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

For the calculations with the reference building investigated, the following results are found:

The shape of the cost curves for the multi-family building is similar as for the single-family building investigated. However, in the case of the multi-family building the specific costs and the specific emissions as well as the specific primary energy use are smaller than in the single-family building. A change to renewable energy is cost-effective for all renovation measures on the building envelope and reduces emissions more strongly than any measure on the building envelope. When switching to renewable energy, costs, emissions and primary energy use change less strongly than in the case of the single-family building.

In the case of the multi-family building energy efficiency measures on the building envelope are in relative terms more cost-effective compared to the single-family building. Having a geothermal heat pump heating, all considered renovation options on the building envelope are cost-neutral, except the high-efficiency windows (renovation package M9). For the wood pellets heating system, the difference in terms of cost-effectiveness between a simple change to a wood pellets heating system and the combination with energy efficiency measures on the building envelope becomes significantly smaller, making all considered renovation options on the building envelope nearly cost-neutral, except the energy related renovation of the windows (renovation packages M8 and M9).

Discussion

Single-family building

The results of the calculations with the single-family building in Sweden confirm partly the main hypotheses which are investigated, as summarized in the following table:

Table 38 Results for investigated hypotheses for the single-family reference building in Sweden. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Sweden.

Hypothesis	Results from SFB in Sweden	Comments
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	X	Confirmed for cellar ceiling and roof; not confirmed for windows and wall
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 cost-optimal efficiency level	(✓)	The optimum remains the same; further renovation measures become less cost-effective in case of a switch to RES, though
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 wall with measures ranging over a relatively large range of insulation (from 6 cm to 30 cm), the change on the environmental impact is relatively strong and of similar magnitude as of including the roof or the cellar ceiling in the renovation. For the windows, there is a similarly large difference of environmental impact between windows of a U-value of 1.8 and 1.0 W/(m^2*K). For the cellar ceiling the differences in cost-effectiveness for different insulations levels are small, yet also the differences in the thicknesses of insulation distinguished are small (8 cm and 12 cm). For the roof, the differences are small, even if the thickness of the insulation material is doubled (from 14 cm to 30 cm). The first hypothesis is therefore partly not supported.

The second hypothesis is clearly confirmed for the geothermal heat pump and the wood pellets heating system. A switch to these heating systems reduces emissions more strongly than carrying out energy efficiency measures on the building envelope and replacing the heating system with a conventional heating system of the same type.

The third hypothesis is confirmed for all heating systems. However, further renovation measures become less cost-effective in case of a switch to RES. The hypothesis is therefore considered to be only partly confirmed.

The fourth hypothesis is confirmed, as for both the switch to a geothermal heat pump and the switch to a wood pellets system, some renovation measures on the building envelope continue to be cost-effective.

The fifth hypothesis is clearly confirmed, as with the switch to RES, even the most far-reaching renovation package on the building envelope is more cost-effective than the most cost-effective renovation package without switching to RES.

Most renovation packages on the building envelope considered are cost-effective for the case of a conventional heating system. The lifetimes chosen are relatively long, which favours renovation measures.

The low price for wood pellets is the reason for wood pellets being the most cost-effective solution.

Multi-family building

The results of the calculations with the multi-family building in Sweden confirm partly the main hypotheses which are investigated, as summarized in the following table.

Table 39 Results for investigated hypotheses for the multi-family reference building in Sweden. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Sweden.

Hypothesis	Results from MFB in Sweden	Comments
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	X	Confirmed for cellar ceiling and roof; not confirmed for windows and wall
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 cost-optimal efficiency level	X	More energy efficiency measures are cost-effective in case of a conventional heating system.
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.	✓	

Comparison between single-family building and multi-family building

The results about the validation of the hypotheses are similar as for the single-family building from Sweden, with the following differences:

- The cost optimum is no longer the same regardless of the type of heating system chosen. In case of a switch to a RES system, less energy efficiency measures are cost-effective. The differences are not large, as the curves are relatively flat
- Energy efficiency measures in combination with a renewable RES heating system become nevertheless more cost-effective in the case of the multi-family building compared to the single-family building

The differences between the costs, environmental impacts and energy impacts of different renovation packages is in general smaller in case of a multi-family building than in case of a single-family building

The fact that costs, emissions and primary energy use are smaller for the multi-family building as compared to the single-family building can be explained by the smaller ratio of exterior surface to volume in the multi-family building.

The fact that energy efficiency measures in combination with a RES heating system become more cost-effective in the case of the multi-family building compared to the single-family building can be explained by the fact that in multi-family buildings the heating systems are larger, and therefore also the effects of a reduction of the size of the heating system if in combination with energy efficiency measures reducing energy need.

The hypothesis that in multi-family buildings, the synergies between RES measures and energy efficiency measures are larger, is confirmed.

Table 40 Results for investigated hypothesis related to comparison of multi-family buildings and single-family buildings in Sweden

Hypothesis	Results from SFB and MFB in Sweden
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger	✓

4.1.9. Switzerland

Single-family building: Renovation packages and related assumptions

For the generic calculations in Switzerland, the following packages of renovation measures are applied to the building envelope:

Table 41 Description of different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Switzerland.

Renovation Package	Description
Ref	In the reference case, the plastering of the wall is restored, the wall is repainted, and the roof is refurbished, yet all those measures do not improve the energy performance of the building.
M1	The wall is insulated with 12 cm of rock wool.
M2	The wall is insulated with 30 cm of rock wool.
M3	Additionally to M2, the roof is insulated with 12 cm of rock wool.
M4	Additionally to M2, the roof is insulated with 36 cm of rock wool.
M5	Additionally to M4, the cellar ceiling is insulated with 10 cm of rock wool.
M6	Additionally to M4, the cellar ceiling is insulated with 16 cm of rock wool.
M7	Additionally to M6, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.3.
M8	Additionally to M6, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 1.
M9	Additionally to M6, windows are replaced with new windows with a wooden frame and a U-value for the entire window of 0.8.

The following table describes the characteristics of the different renovation packages that are taken into account.

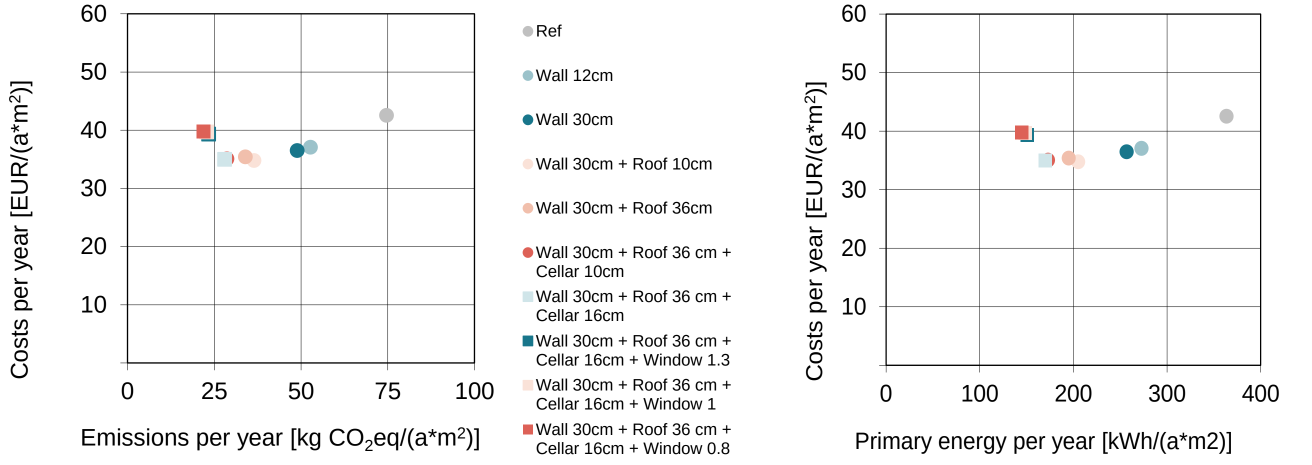
Table 42 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Switzerland. Sources: Lifetimes of building elements: AHB 2009, SIA 2004, Bund Technischer Experten (BTE) 2008, Bundesministeriums für Verkehr, Bau- und Wohnungswesen (BVBW) 2001, SIA 2010. The energy need is calculated based on the input parameters for the different building envelope elements taking into account both the original U-values of the buildings and the changes due to the renovation.

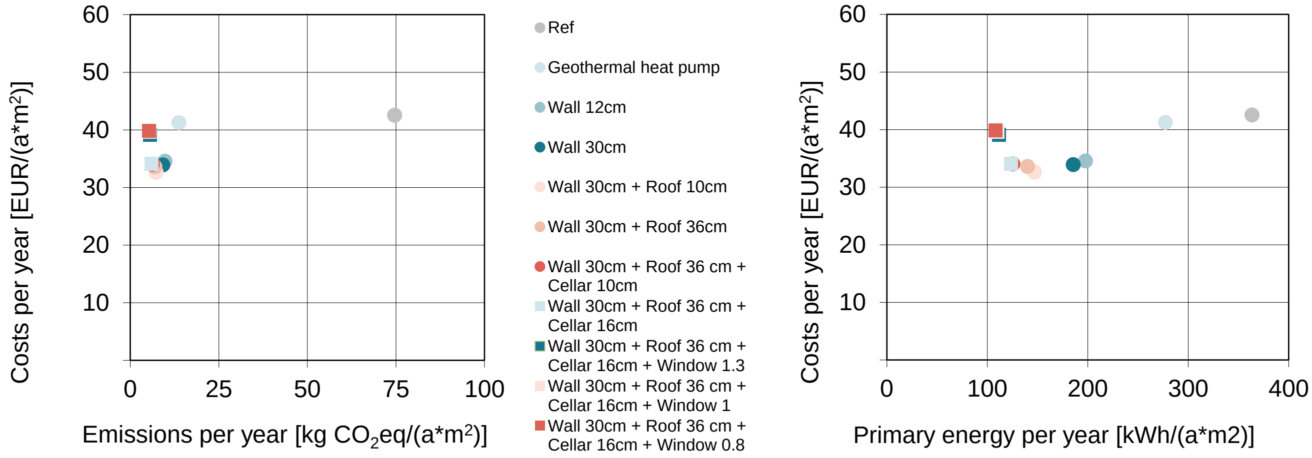
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	62	142	167	167	167	167	167	167	167	167
Wall - thickness of insulation material	cm	-	12	30	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Window - Costs	EUR/m^2 window	33	33	33	33	33	33	33	763	832	875
Window - U-Value	W/m^2K	2.7	2.7	2.7	2.7	2.7	2.7	2.7	1.3	1	0.8
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.55	0.45	0.45
Window - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	63	63	63	183	233	233	233	233	233	233
Roof - thickness of insulation material	cm	-	-	-	12	36	36	36	36	36	36
Roof - λ of insulation material	W/mK	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Roof - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Cellar ceiling - Costs	EUR/m^2 cellar ceiling	-	-	-	-	-	87	96	96	96	96
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	10	16	16	16	16
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04
Cellar ceiling - lifetime of renovation measure	a	-	-	-	-	-	40	40	40	40	40
Energy need for heating	kWh/m^2	207	135	123	82	74	57	54	39	38	35
Peak heating capacity required	kW	15	11	10	7	7	6	6	4	4	4
Conversion efficiency of oil heating system		0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Conversion efficiency of geothermal heat pump		3.0	3.4	3.4	3.7	3.7	3.9	3.9	4.0	4.0	4.0
Conversion efficiency of wood pellets heating		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Single-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:





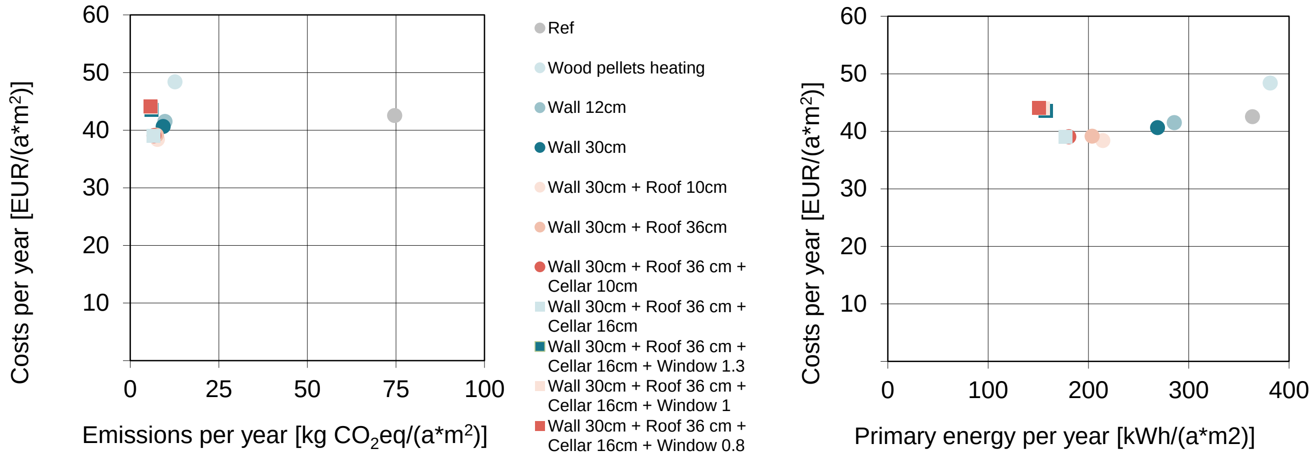


Figure 40 Single-family building Switzerland: Comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems, oil (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the oil heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

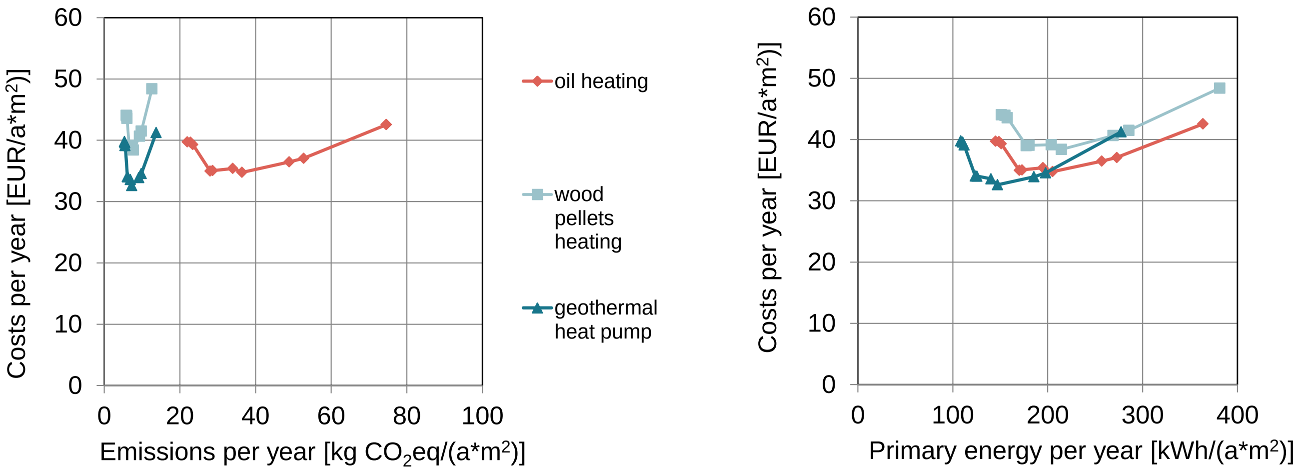


Figure 41 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for a single-family building. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Multi-family building: Renovation packages and related assumptions

For the generic calculations with a multi-family building in Switzerland, the investigated renovation packages are the same as for the single-family building.

The following table describes the characteristics of the different renovation packages that are taken into account.

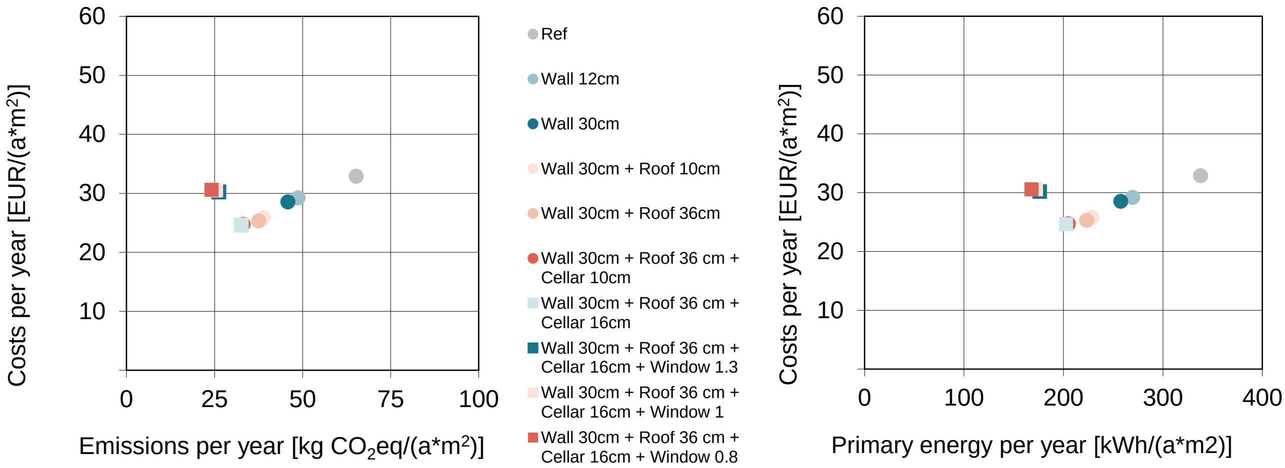
Table 43 Data for different packages of renovation measures M1 to M9 and the reference case for a multi-family building in Switzerland. Sources: Lifetimes of building elements: AHB 2009, SIA 2004, Bund Technischer Experten (BTE) 2008, Bundesministeriums für Verkehr, Bau- und Wohnungswesen (BVBW) 2001, SIA 2010. The energy need is calculated based on the input parameters for the different building envelope elements taking into account both the original U-values of the buildings and the changes due to the renovation.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	58	128	140	140	140	140	140	140	140	140
Wall - thickness of insulation material	cm	-	12	30	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	33	33	33	33	33	33	33	763	832	875
Window - U-Value	W/m^2K	2.7	2.7	2.7	2.7	2.7	2.7	2.7	1.3	1	0.8
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.55	0.45	0.45
Window - lifetime of renovation measure	a	-	30	30	30	30	30	30	30	30	30
Roof - Costs	EUR/m^2 roof	58	58	58	146	188	188	188	188	188	188
Roof - thickness of insulation material	cm	-	-	-	12	36	36	36	36	36	36
Roof - λ of insulation material	W/mK	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Roof - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Cellar ceiling - Costs	EUR/m^2 cellar ceiling	-	-	-	-	-	87	93	93	93	93
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	10	16	16	16	16
Cellar ceiling - λ of insulation material	W/mK	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04
Cellar ceiling - lifetime	a	-	-	-	-	-	40	40	40	40	40

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
of renovation measure											
Energy need for heating	kWh/m^2	158	107	99	77	73	58	57	32	27	23
Peak heating capacity required	kW	45	33	31	26	25	22	21	15	14	13
Conversion efficiency of oil heating system		0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Conversion efficiency of geothermal heat pump		3.2	3.5	3.5	3.7	3.7	3.8	3.8	4	4.1	4.1
Conversion efficiency of wood pellets heating		0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Multi-family building: Results

The resulting impacts on the performance of the building with respect to carbon emissions, primary energy use and costs are shown in the following graphs:



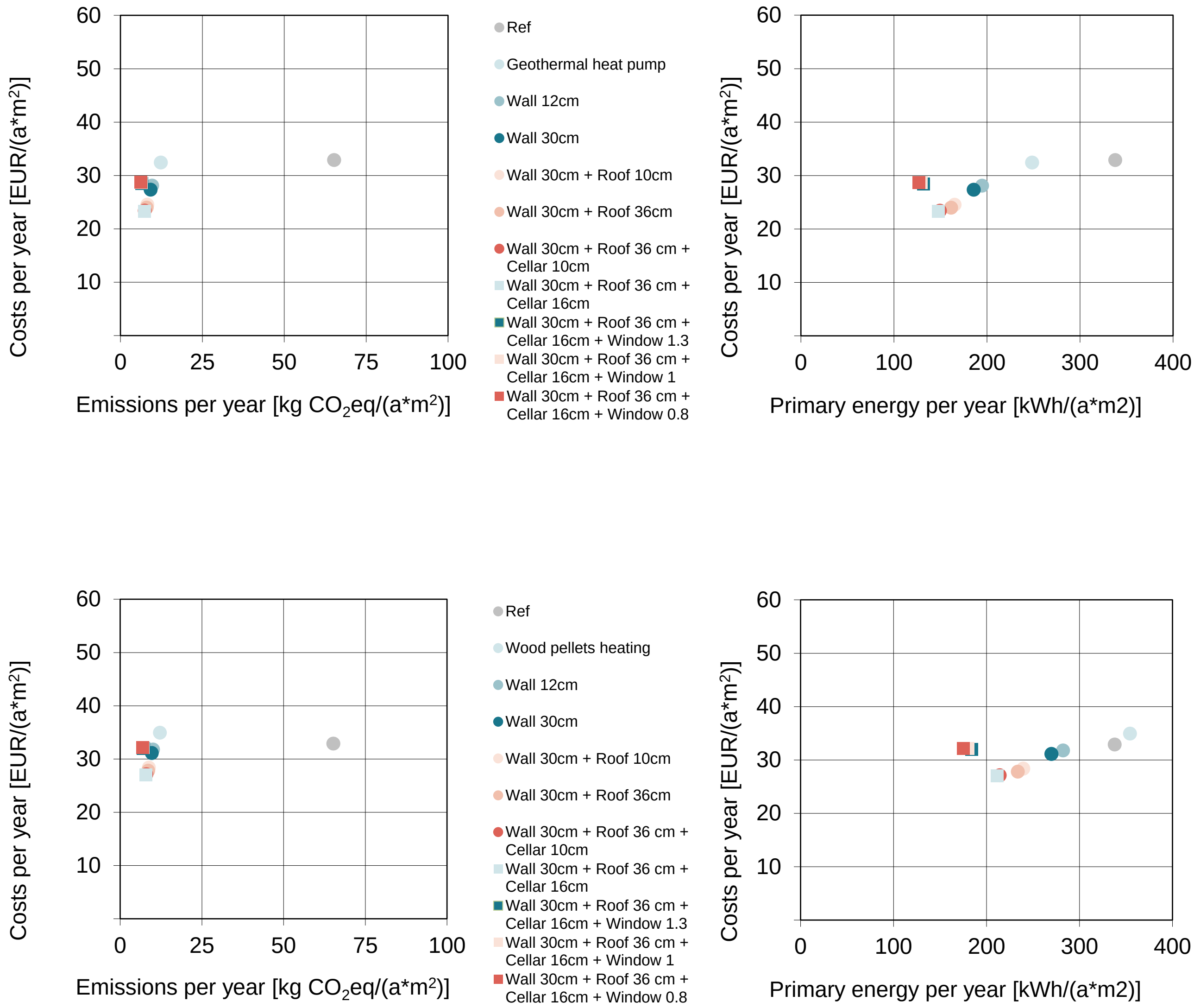


Figure 42 Multi-family building Switzerland: Comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems, oil (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the oil heating system and rehabilitation measures of the building envelope without improving energy-efficiency levels.

The following graphs summarize the cost curves for different renovation packages on the building envelope with different heating systems:

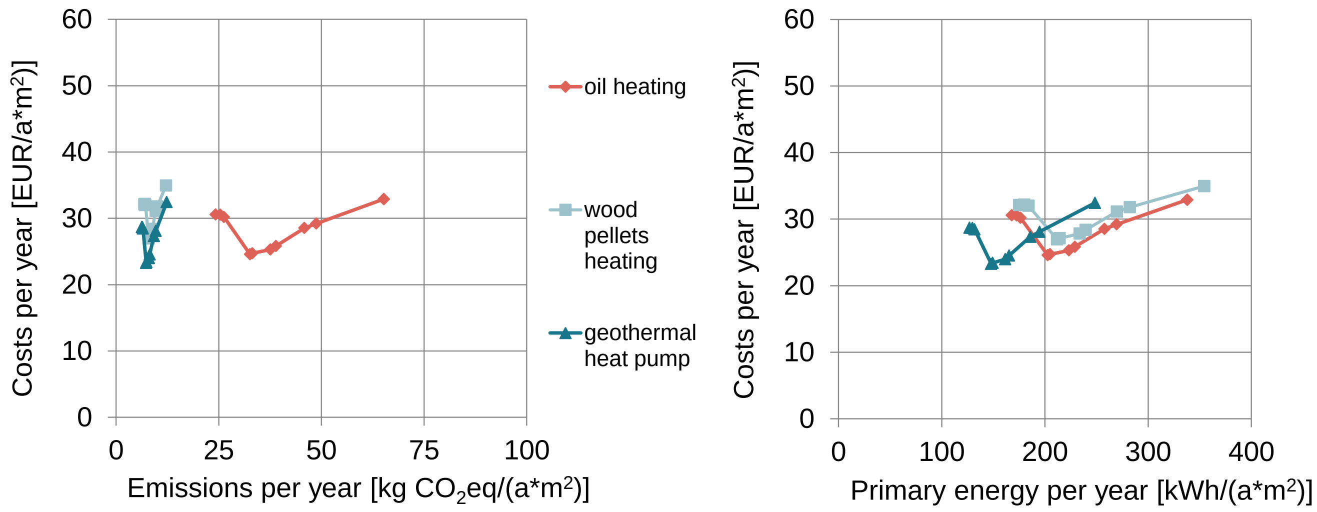


Figure 43 Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for a multi-family building The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

Discussion

Single-family building

The results of the calculations with the single-family building in confirm the main hypotheses which are investigated, as summarized in the following table:

Table 44 Results for investigated hypotheses for the single-family reference building in Switzerland. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Switzerland.

Hypothesis	**Results from SFB in Switzerland**
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 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.	✓

Multi-family building

The results of the calculations for the multi-family building in Switzerland confirm the main hypotheses which are investigated, as summarized in the following table:

Table 45 Results for investigated hypotheses for the multi-family reference building in Switzerland. RES refers here to geothermal heat pump and wood pellets. These are the two RES systems that were investigated in the case of the generic calculations carried out for Switzerland.

Hypothesis	Results from MFB in Switzerland
How many building elements are renovated is more important for the energy performance than efficiency levels of individual 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 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.	✓

Comparison between single-family building and multi-family building

The results of the calculations with the multi-family building and the single-family building confirm for one RES system the hypothesis that in multi-family buildings, the synergies between RES measures and energy efficiency measures are larger. In the case of a switch to a geothermal heat pump, it can be seen that whereas in the single-family building, measures related to the insulation of the cellar ceiling are not cost-effective, they are in the case of the multi-family building. Whereas differences in specific costs can explain this partially, the main contribution for explaining this observation are likely to be the different ratios of building envelope to floor area.

Table 46 Result for investigated hypothesis related to the comparison of multi-family buildings and single-family buildings.

Hypothesis	Results from SFB and MFB in Switzerland
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger	✓

4.2. Ventilation

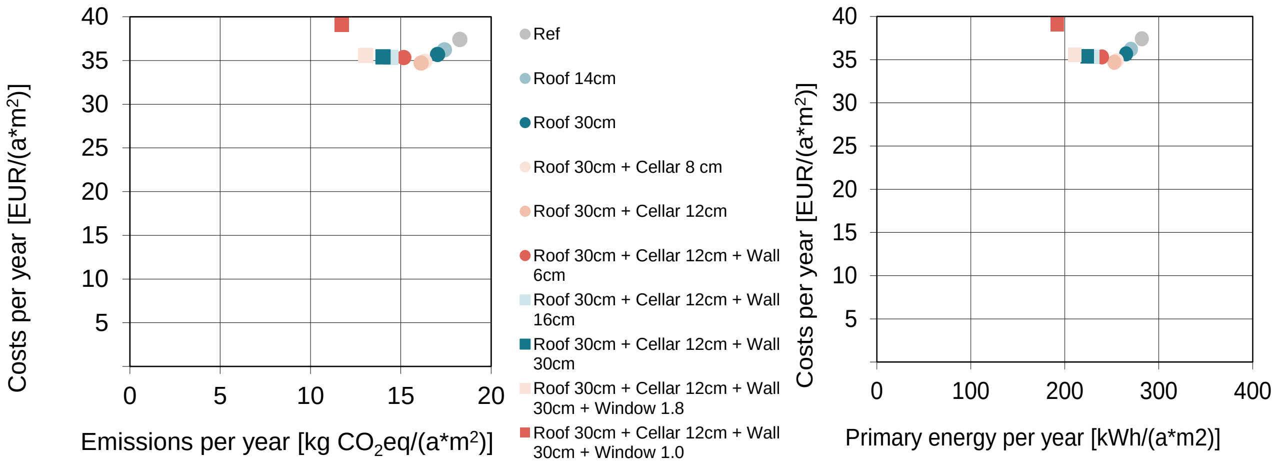
4.2.1. Upgrading of the ventilation system in Sweden

For the reference buildings in Sweden, the impact of upgrading an existing ventilation system to a ventilation system with heat recovery is investigated. The starting point is a mechanical exhaust only ventilation, which is upgraded to mechanical supply and exhaust ventilation with heat recovery. The air flow is assumed to be 1.02 m^3 per m^2 gross heated floor area and per hour for the single-family building and 1.06 m^3 per m^2 gross heated floor area and per hour for the multi-family building.

Table 47 Parameters for the ventilation system in Sweden in a single-family building (SFB) and in a multi-family building (MFB).

Parameter	Unit	SFB	MFB
Investment costs for upgrading of ventilation system	EUR	2'200	14'600
Electricity demand for ventilation per year	kWh/m^2	2.2	2.2
Temperature adjustment factor to take into account the reduction of heat losses	-	0.3	0.3

Both in single-family buildings and multi-family buildings, the installation of a mechanical supply and exhaust ventilation is found to be a cost-effective measure reducing significantly both carbon emissions and primary energy use. The following figures illustrate this finding.



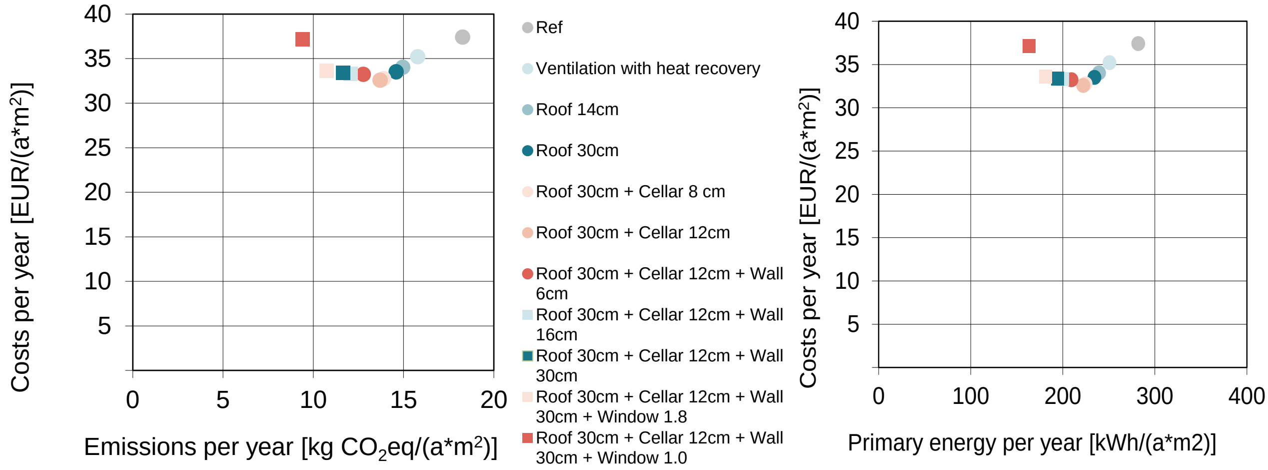


Figure 44 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost-effectiveness and environmental impacts of different renovation packages in a single-family building in Sweden. The graphs above show renovation measures without improving the energy performance of the existing ventilation system; the graphs below show renovation packages with an upgrade of the ventilation system. The reference case is indicated with a grey dot.

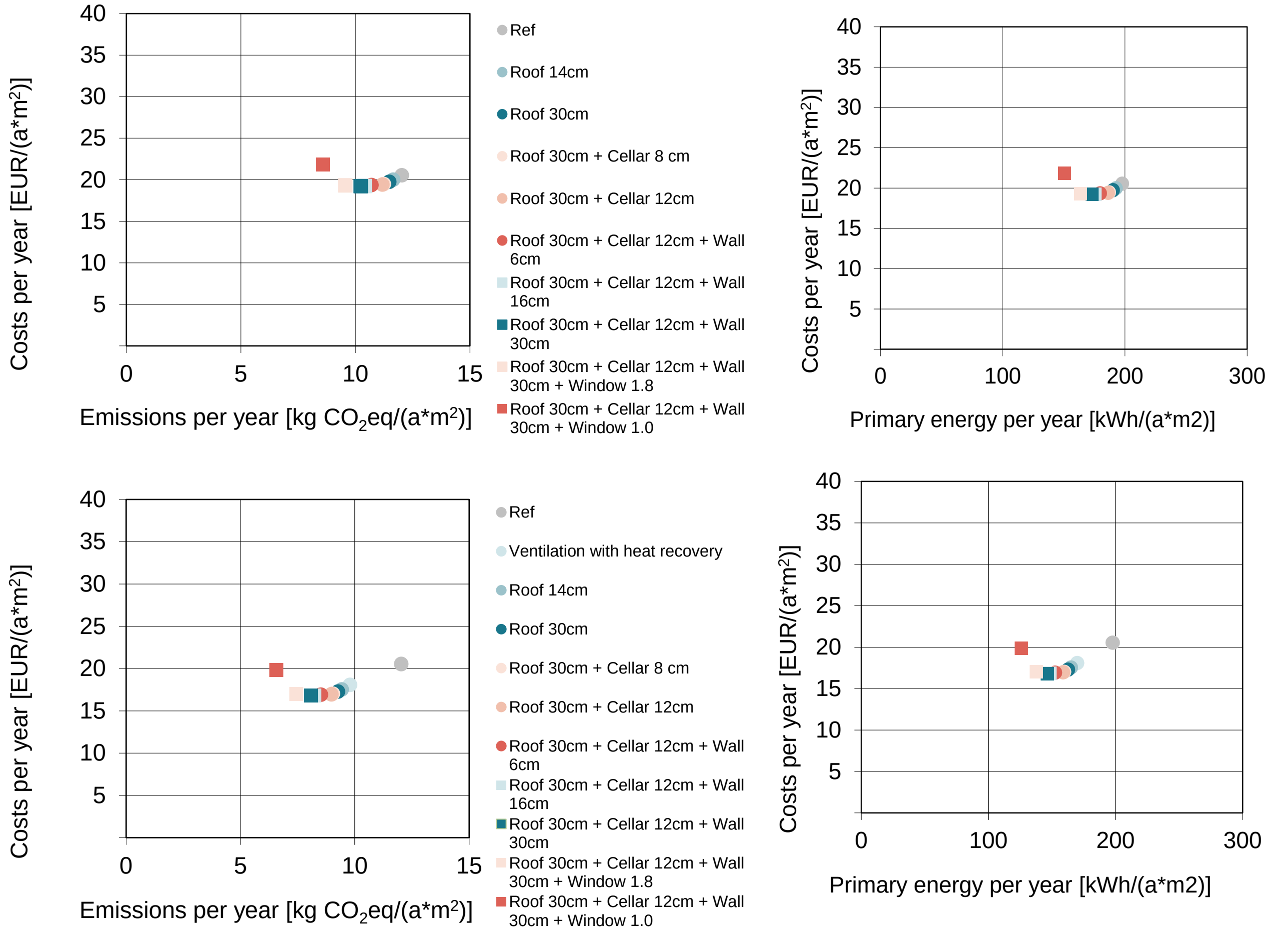


Figure 45 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost-effectiveness and environmental impacts of different renovation packages in a multi-family building in Sweden. The graphs above show renovation measures without improving the energy performance of the existing ventilation system; the graphs below show renovation packages with an upgrade of the ventilation system. The reference case is indicated with a grey dot.

4.2.2. *Upgrading of the ventilation system in Switzerland*

For the reference buildings in Switzerland, the impact of adding measures on ventilation have been investigated as well. The installation of a ventilation system with heat recovery is assumed. In the reference case, no ventilation system is installed. In order to see the impact of adding a ventilation system more clearly, in the reference a relatively large air flow rate of 1.8 m^3 per m^2 gross heated floor area and per hour is assumed for the multi-family building and 1.5 m^3 per m^2 gross heated floor area and per hour for the single-family building. The following table provides information about the characteristics of the ventilation system installed:

Table 48 Parameters for the ventilation system in Switzerland in a single-family building (SFB) and in a multi-family building (MFB).

Parameter	**Unit**	**SFB**	**MFB**
Investment costs of ventilation system	EUR	14’230	85’400
Electricity demand for ventilation per year	kWh/m^2	2.2	2.2
Temperature adjustment factor to take into account the reduction of heat losses	-	0.4	0.3

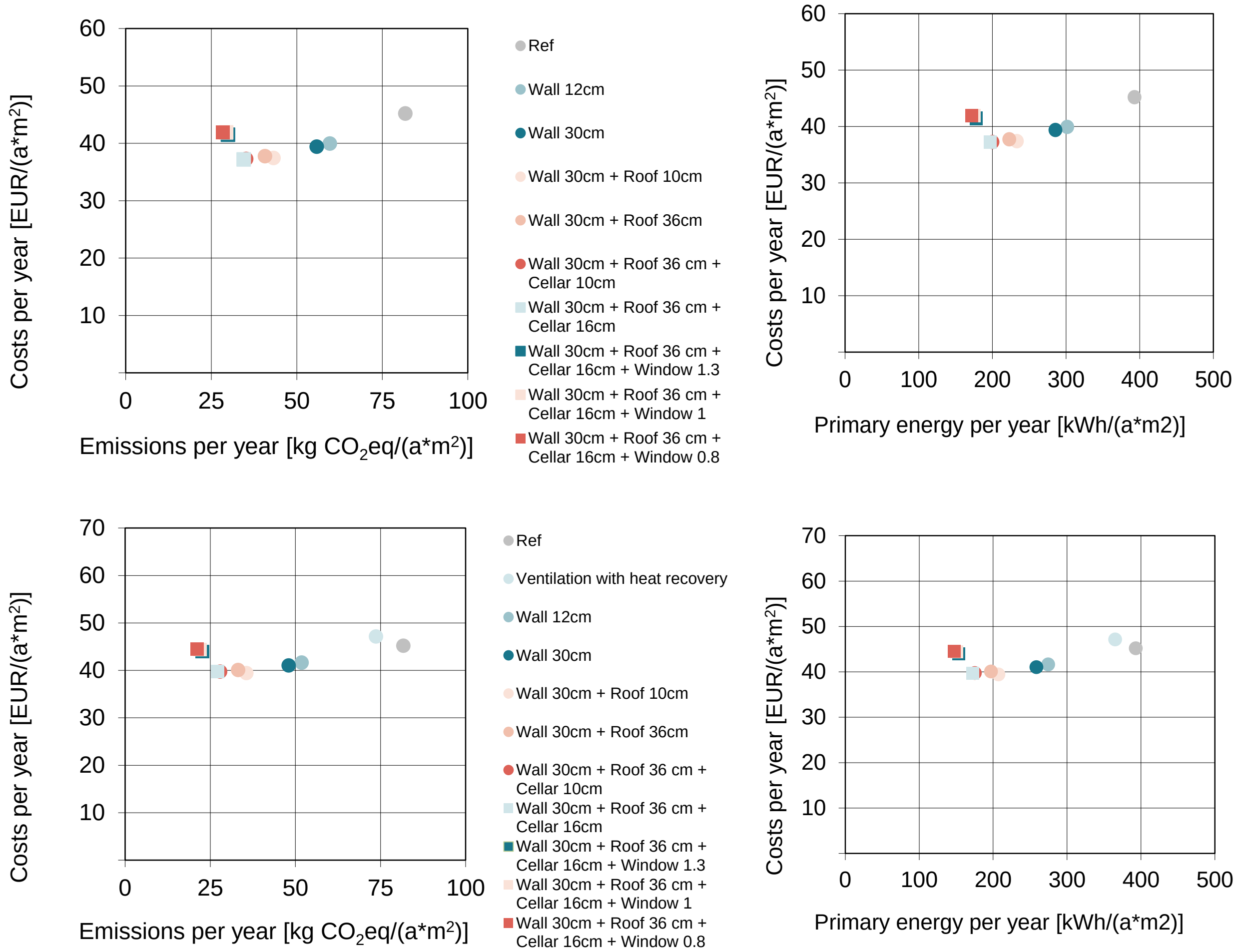


Figure 46 Effect of adding a ventilation system with heat recovery on cost-effectiveness and environmental impacts of different renovation packages in a single-family building in Switzerland, assuming an oil heating system. The graphs above show renovation measures without existing ventilation system; the graphs below show renovation packages with the inclusion of a ventilation system. The reference case is indicated with a grey dot. An oil heating system is assumed.

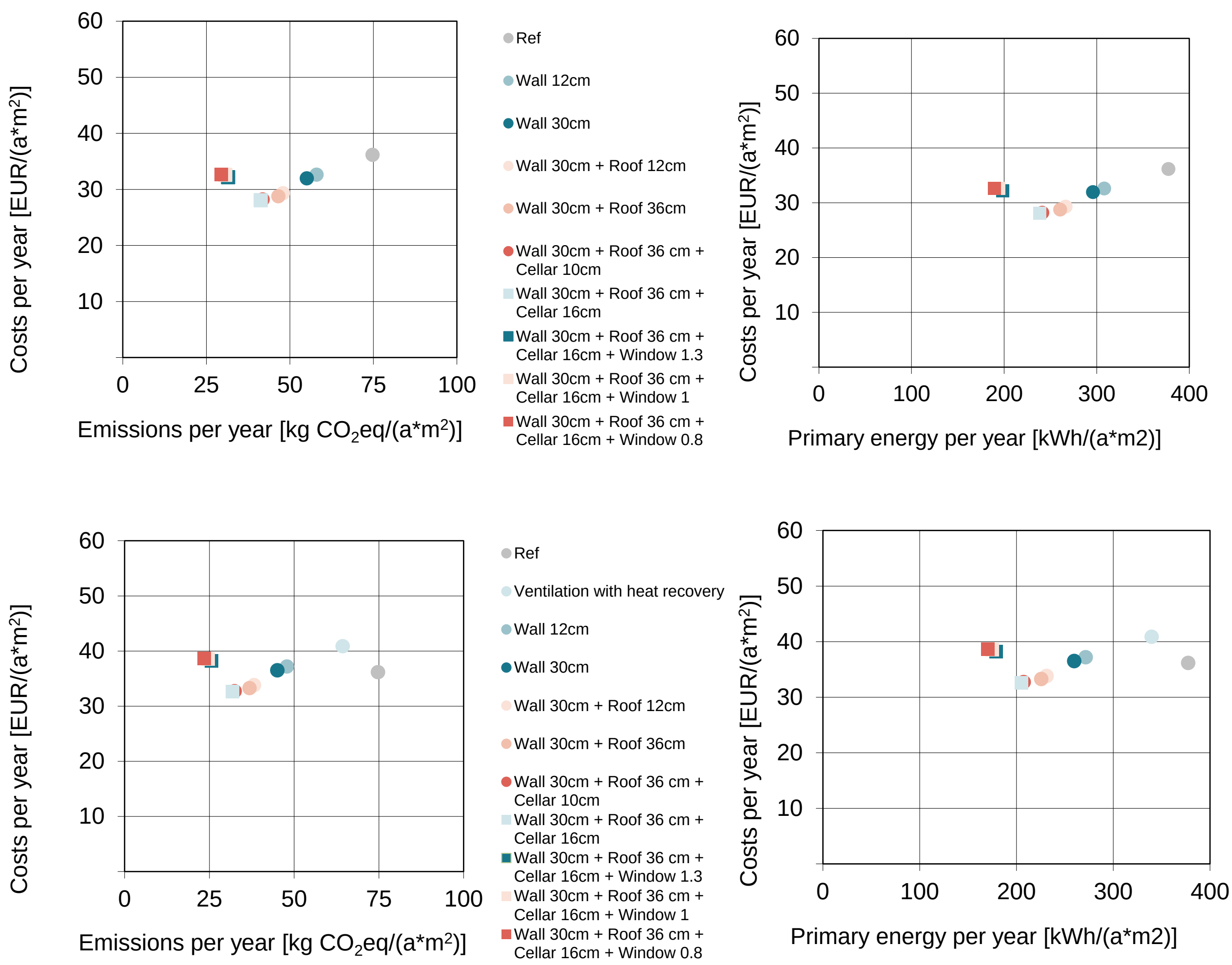


Figure 47 Effect of adding a ventilation system with heat recovery on cost-effectiveness and environmental impacts of different renovation packages in a multi-family building in Switzerland. The graphs above show renovation measures without an existing ventilation system; the graphs below show renovation packages with the inclusion of a ventilation system. The reference case is indicated with a grey dot. An oil heating system is assumed.

4.2.3. Discussion of the impacts of upgrading the ventilation system

The installation of a ventilation system with heat recovery is an effective measure to reduce both emissions and primary energy use. The hypothesis that the installation of a ventilation system with heat recovery has comparable effects on the energy performance as measures on other building elements is confirmed.

Table 49 Results for the investigated hypothesis for the multi-family and single family reference buildings in Sweden and in Switzerland.

Hypothesis	Results from SFB in Sweden	Results from MFB in Sweden	Results from SFB in Switzerland	Results from MFB in Switzerland
The installation of a ventilation system with heat recovery has effects on the energy performance comparable with measures on other building elements	✓	✓	✓	✓

In Sweden, the impact is bigger in relative terms than in Switzerland, which can be explained by the larger average difference between indoor and outdoor temperature. In Sweden, the upgrade to a ventilation system with heat recovery is cost-effective; in Switzerland, it is a rather expensive investment and not cost-effective. It is important to underline here, that in Sweden simply the ventilation is added with heat recovery, reusing ducts etc., whereas in Switzerland the installation of a whole new system is assumed. The latter is naturally much more expensive. The investment costs for an upgrade to a ventilation system with heat recovery in the single-family building in Sweden are rather low and can achieved only in special circumstances, without additional costs for air ducts. High costs of installing ventilation with heat recovery in renovated buildings in Switzerland can be explained with the often complicated situation relevant for installing ventilation in existing buildings. Therefore, the range of initial costs of ventilation systems is quite large, allowing for lower costs in advantageous cases.

4.3. Embodied energy

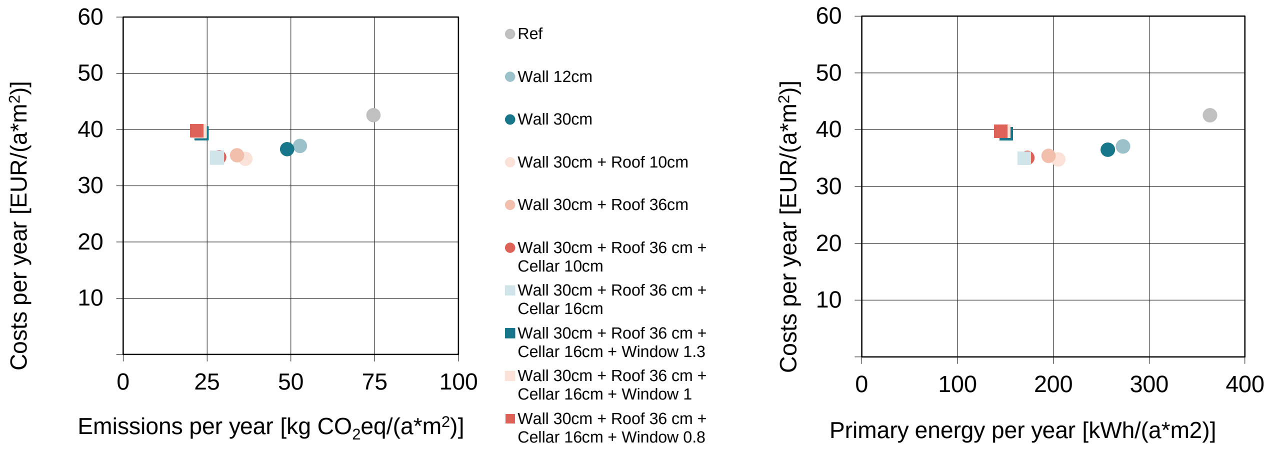
For the single-family reference building from Switzerland, calculations have been carried out to investigate the impact of taking into account the embodied energy in the materials for the renovation measures. The different renovation packages M1 to M9 are explained in chapter 4.1.9. The impact is divided by the number of years of the expected service life of the related building elements. The following table provides an overview on the impacts.

Table 50 Energy in materials for various renovation packages for a single-family building in Switzerland; renovation packages on the envelope M1 to M9 also include a change of the heating system.

Type of heating system	Unit	New heating system only	M1	M2	M3	M4	M5	M6	M7	M8	M9
Oil heating	kWh/(a*m^2)	0.53	2.1	3.9	5.4	8.6	9.1	9.5	12	12	12.5
Geothermal heat pump	kWh/(a*m^2)	6.1	6.0	7.5	8.3	11	12	12	15	15	15
Wood pellets	kWh/(a*m^2)	2.3	3.7	5.5	7.0	10	11	11	14	14	14

The results of the calculations for energy in materials and related emissions are shown in the following graphs:

Energy in materials not included



Energy in materials included

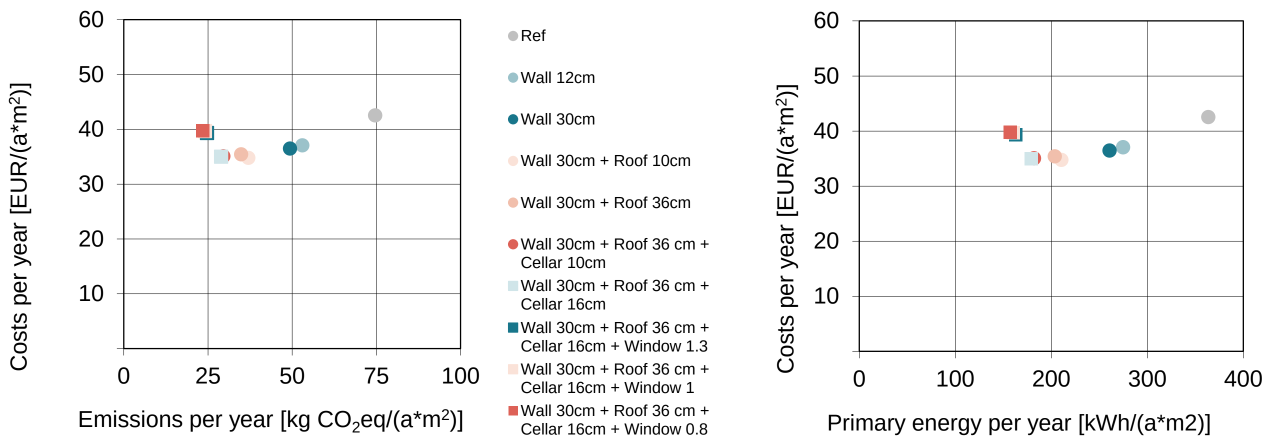
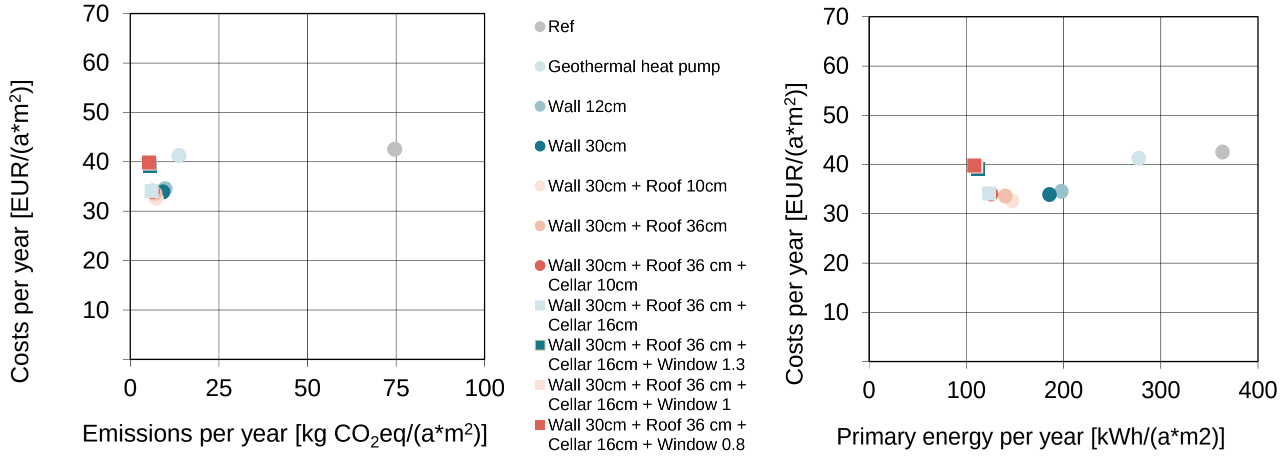


Figure 48 Comparison of calculations for a single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including the renewal of an **oil heating system**. The reference case (grey dot) is virtually the same whether embodied energy is included or not, because embodied energy use of the activities in the reference case is so small.

Energy in materials not included



Energy in materials included

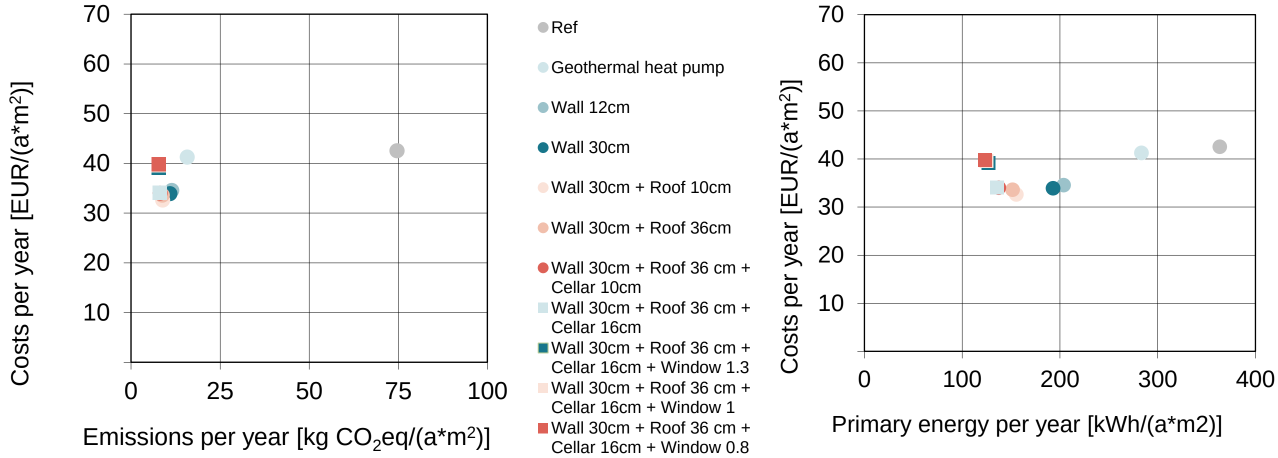
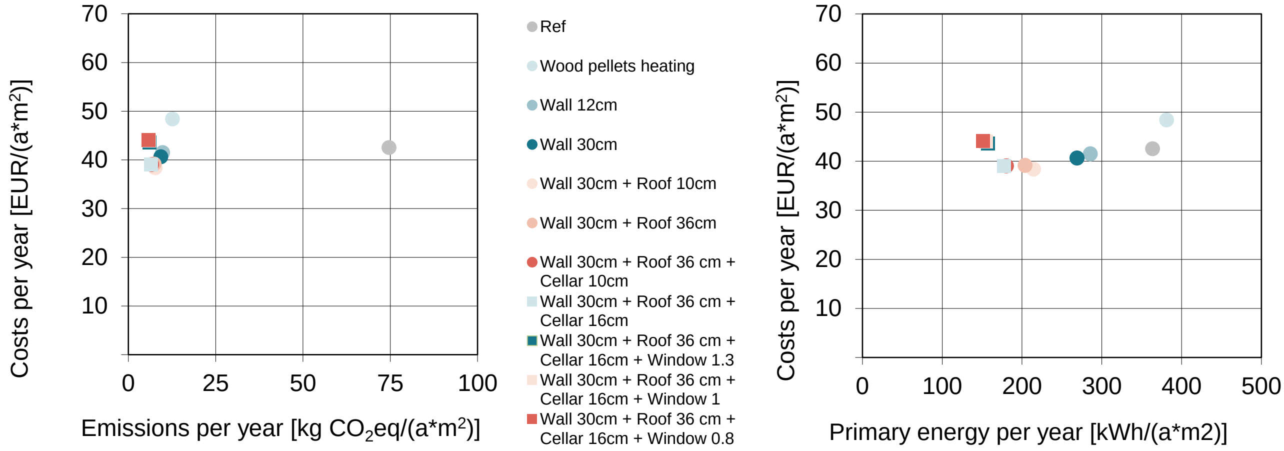


Figure 49 Comparison of calculations for a single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including a switch to a **geothermal heat pump**. The reference case (grey dot) is virtually the same whether embodied energy is included or not, because embodied energy use of the activities in the reference case is so small.

Energy in materials not included



Energy in materials included

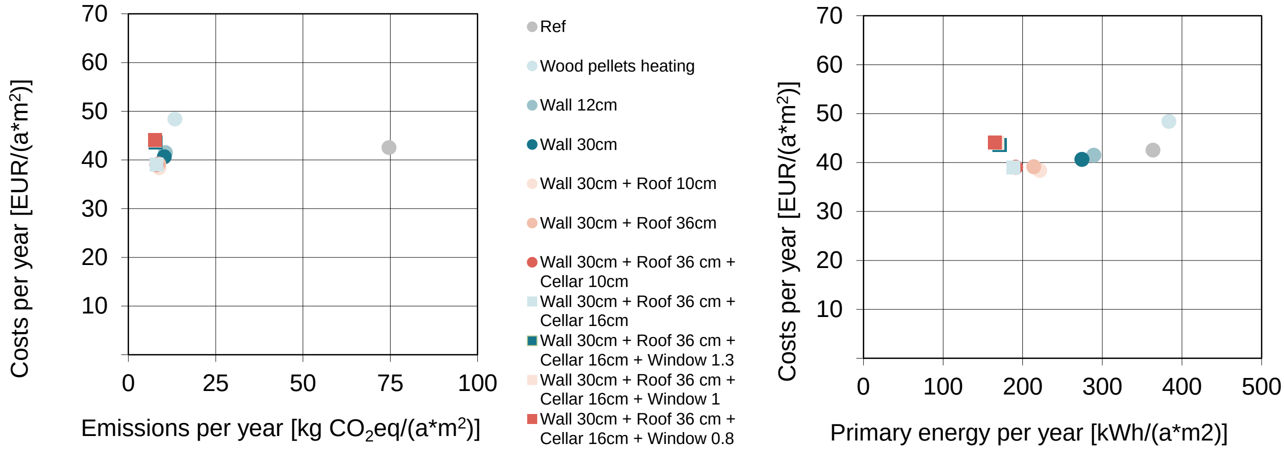


Figure 50 Comparison of calculations for a single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including a switch to a **wood pellet heating system**. The reference case (grey dot) is virtually the same whether embodied energy is included or not, because embodied energy use of the activities in the reference case is so small.

The most far-reaching measures are a bit less favourable in terms of reduction of carbon emissions or primary energy use when taking into account the additional carbon emissions or energy use in the material. This is particularly visible for the windows.

Embodied energy use of the geothermal heat pump is higher, since energy is also needed to drill the borehole. Nevertheless, the difference compared to an oil heating or a wood pellet heating system is small, in comparison with the other effects of the renovation measures. The calculations carried out so far indicate that the advantages of switching to a renewable energy system remain, even if the use of embodied energy is taken into account.

4.4. Cooling

4.4.1. Questions investigated

To examine the impact of cooling need on cost-effective energy and carbon emissions optimization in building renovation, the following questions were investigated:

— How do solar radiation and outside temperature interact with energy efficiency levels of buildings for determining the cooling needs?

— What is the impact of shutters on reducing cooling needs and potential trade-offs between energy efficiency measures and cooling needs?

— What is the impact of taking into account cooling on determining the optimal envelope renovation package?

— What is the impact of taking into account cooling on the choice of the heating system?

4.4.2. Results for Portugal

The following figures show the energy need for heating and cooling for the generic multi-family reference building from Portugal, as defined in chapter 3.3. Note that the cooling need is relatively low, because of a low ratio of window surface to gross floor area. It can be observed that the more insulation is applied, increasing from renovation package E1 to renovation package E10, the energy need for heating decreases, while the energy need for cooling increases. In renovation package E10, energy need for heating increases and energy need for cooling decreases, because of the lower g-value of the new window. Renovation packages E1 to E10 are described in chapter 4.1.6 on generic calculations for Portugal.

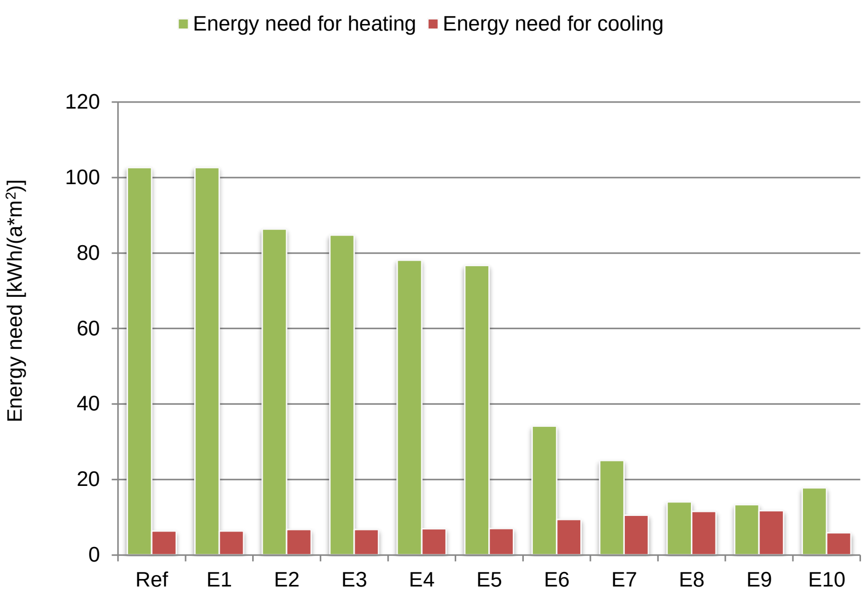


Figure 51 Energy need for heating and cooling for the generic multi-family reference building in Portugal.

In the figure above, the underlying temperature levels for the outside air are in the range between 11.3 °C (January) and 22.9 °C (August).

In a hypothetical situation in which an average temperature of 30 °C in July is assumed (as illustrated in the following figure), it can be observed that in such a case a different effect would be observed: cooling need decreases in such a case as does heating need when more insulation is added.

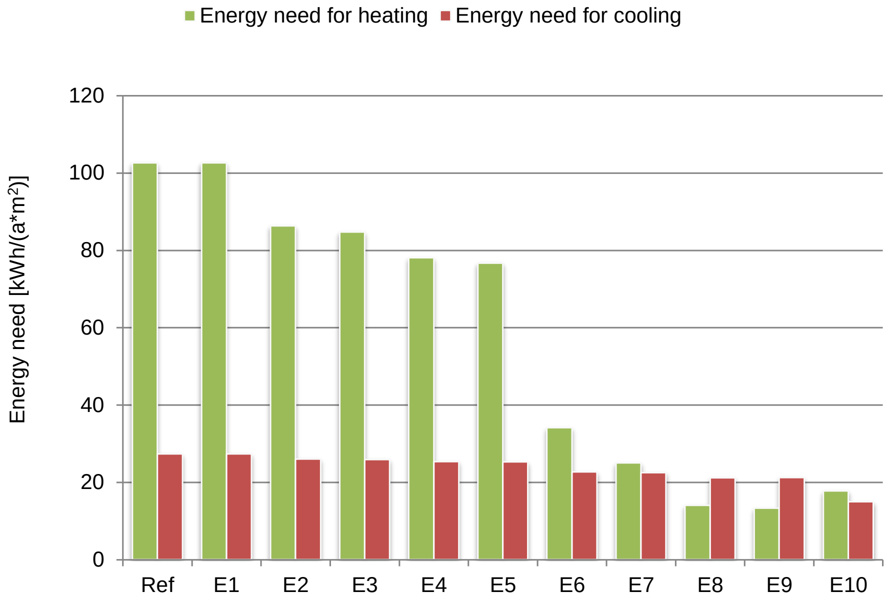


Figure 52 Energy need per year for heating and cooling for the generic reference building in Portugal, with a hypothethical average temperature of 30 °C in July.

In the situation with actual average temperatures, when the application of shutters for the windows is assumed, with a shading effect and a time of use of the shutters resulting in an overall reduction of irradiation by approximately 50%, the increase in energy need for cooling with increasing efficiency levels is less pronounced, in comparison to a situation without shutters (Figure 51), as illustrated in the following figure.

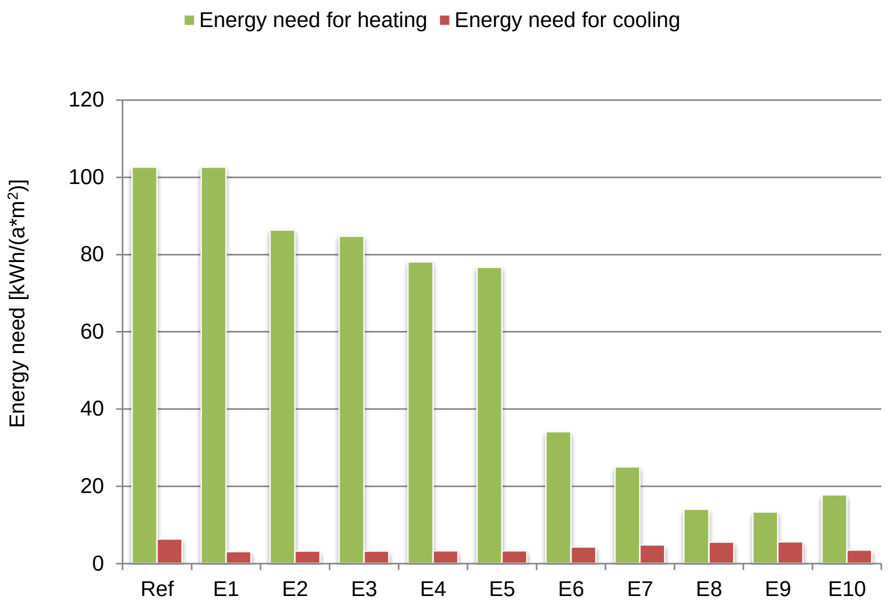
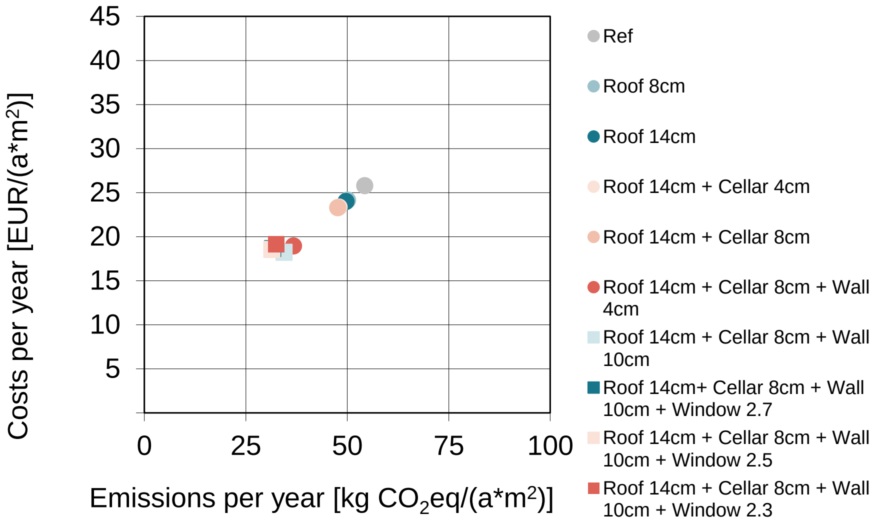


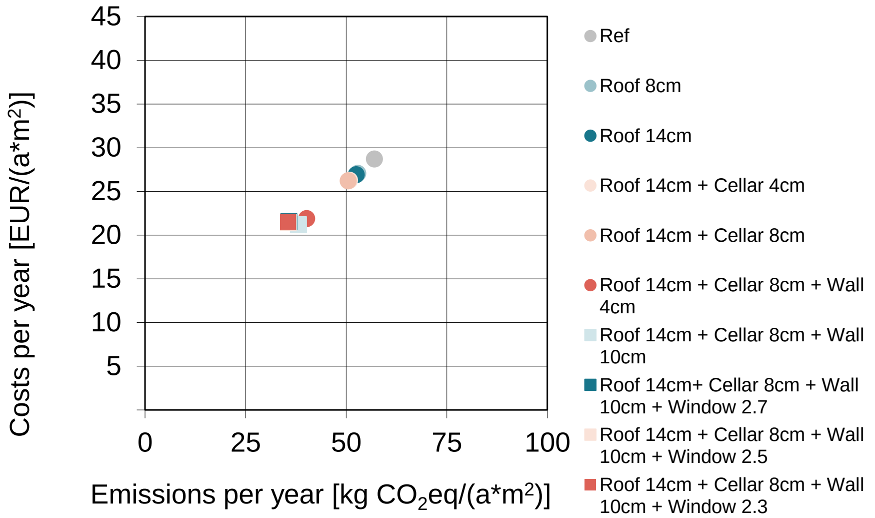
Figure 53 Energy need per year for heating and cooling for the generic reference building in Portugal, taking into account the use of shutters.

When the emissions/costs plots are compared in the case of the reference building in Portugal with and without taking into account cooling, it can be observed that the most cost-effective renovation package in the situation without cooling remains the most cost-effective also when cooling is taken into account. This is shown in the following figures.

Without taking into account cooling



Taking into account cooling, without shutters



Taking into account cooling, with shutters

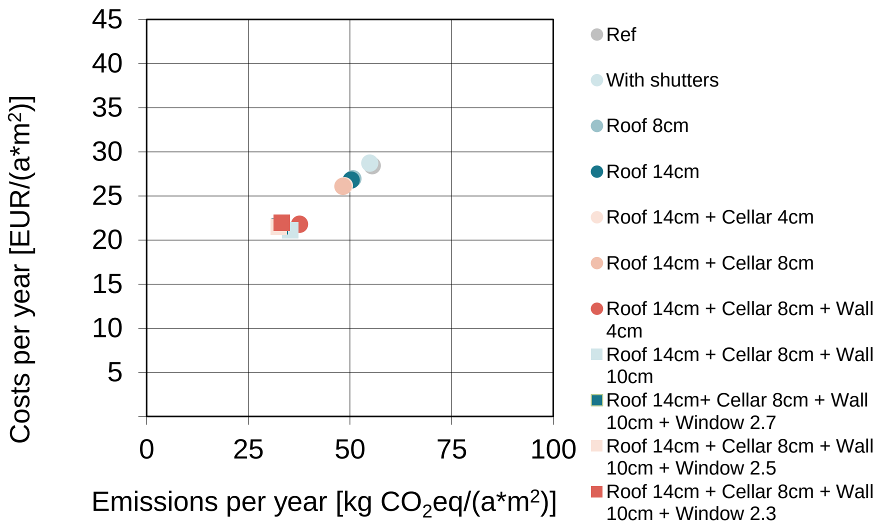


Figure 54 Comparison of emissions/cost curves for the generic building in Portugal without taking into account cooling (top) and with taking into account cooling (lower two figures). The latter case is differentiated in a situation without use of shutters (center), and with use of shutters (bottom).

In all of the cases shown in the figures above, the renovation package including measures on the roof, the cellar and the wall is the most cost-effective. Taking into account cooling needs, with or without shutters, does not favour a different renovation package than without taking into account cooling needs in the generic example investigated.

4.4.3. Results for Italy

The following figures show the energy need for heating and cooling for the generic multi-family reference building in Italy, as defined in chapter 3.3. It can be observed that the more insulation is applied, increasing from renovation package E1 to renovation package E10, the energy need for heating decreases, while the energy need for cooling increases. There is, however, a reduction of cooling need when comparing renovation package E6 to renovation package E5. The reason is the lower g-value of the new windows. Renovation packages E1 to E10 are described in chapter 4.1.4 on generic calculations for Italy.

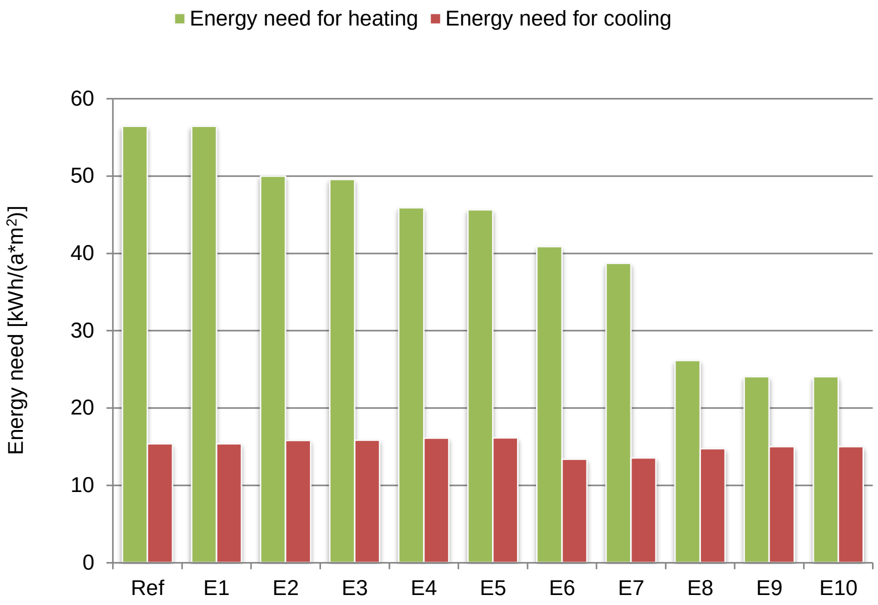


Figure 55 Energy need per year for heating and cooling for the generic reference building in Italy.

When the application of shutters is assumed, the increase in energy need for cooling with increasing efficiency levels is less pronounced, in comparison to a situation without shutters, as illustrated in the following figure. For taking into account the effect of shutters, it is assumed that solar energy transmittance of the glazing coupled with external venetian blinds as shading device result in a reduction factor of 0.15, and that the fraction of the time during which the solar shading is in use corresponds to 70%, which results in an overall shading reduction factor of 0.4.

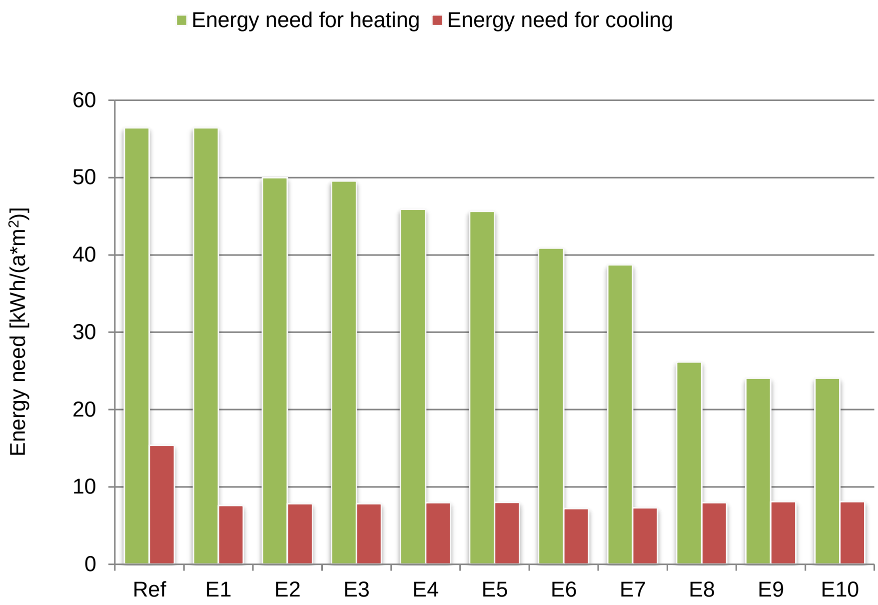
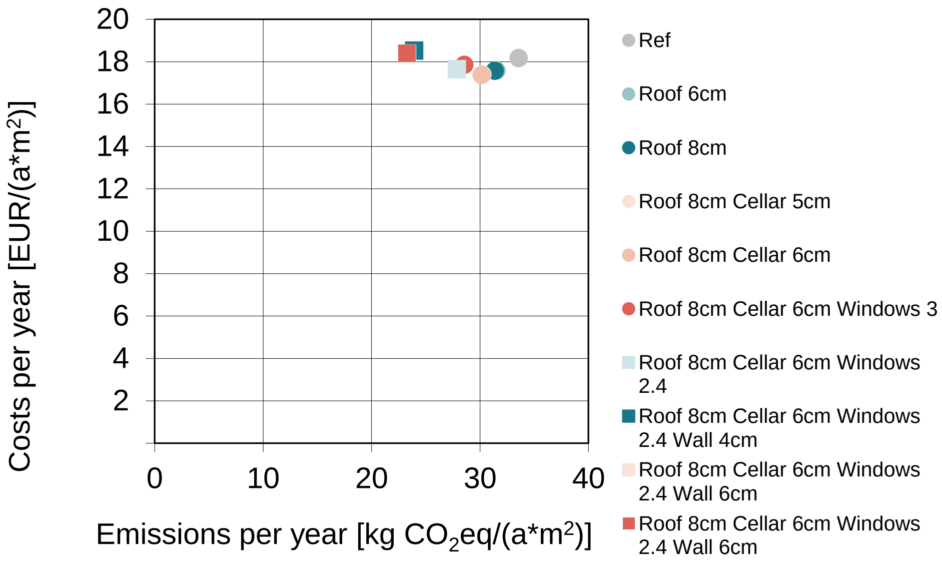


Figure 56 Energy need per year for heating and cooling for the generic reference building in Italy, taking into account the use of shutters.

When the emissions/cost plots are compared in the case of the reference building in Italy with and without taking into account cooling, it can be observed that the most cost-effective renovation package in the situation without cooling remains the most cost-effective also when cooling is taken into account. This observation is the same for a situation with shutters or without shutters. This is shown in the following figures. When taking into account cooling, only a situation with shutters is taken into account.

Renovation packages with gas heating, excluding cooling



Taking into account cooling, with shutters

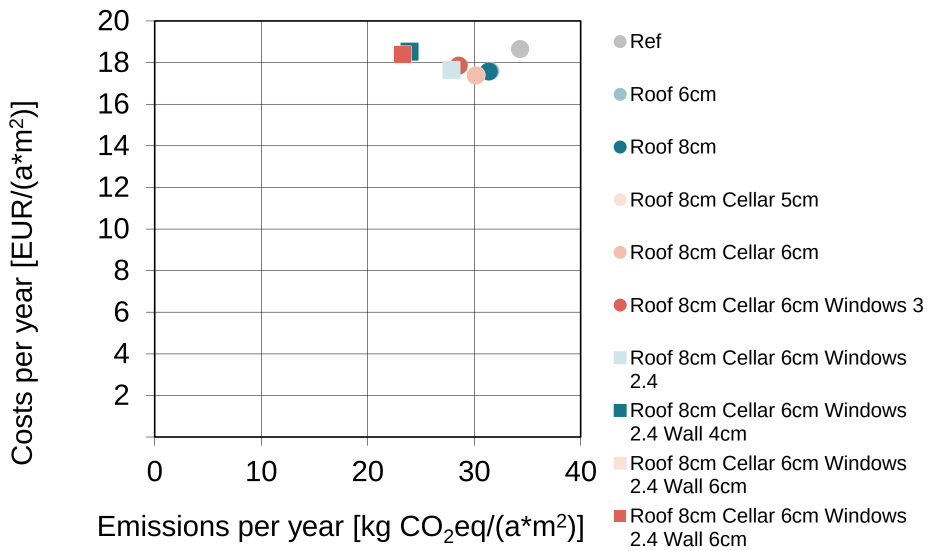


Figure 57 Comparison of emissions/cost curves for the generic building in Italy without taking into account cooling (top) and with taking into account cooling (lower figure). When cooling is taken into account, the use of shutters is assumed. For the related calculations, no costs have been taken into account for the shutters or the cooling system; it is assumed they are already part of the building.

In both of the cases shown in the figures above, the renovation package including measures on the roof and the cellar ceiling is the most cost-effective.

4.4.4. Results for Spain

The following figures show the energy need for heating and cooling for the generic multi-family reference building in Spain, as defined in chapter 3.3. It can be observed that the more insulation is applied, increasing from renovation package E1 to renovation package E10, the energy need for heating decreases, while the energy need for cooling increases. Renovation packages E1 to E10 are described in chapter 4.1.7 on generic calculations for Spain.

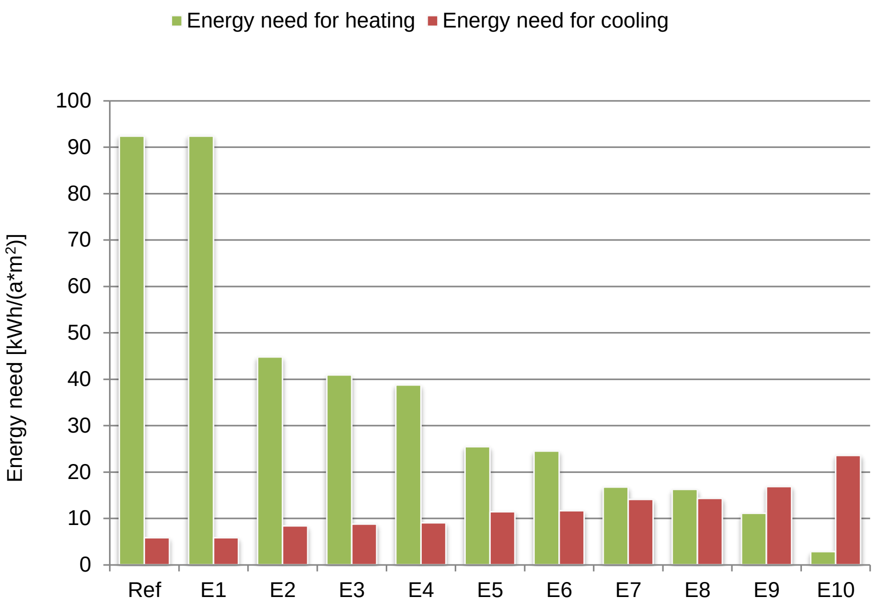


Figure 58 Energy need per year for heating and cooling for the generic reference building in Spain.

When the application of shutters is assumed, with a shading effect and a time of us use of the shutters resulting in an overall reduction of irradiation by approximately 50%, the increase in energy need for cooling with increasing efficiency levels is less pronounced, in comparison to a situation without shutters, as illustrated in the following figure.

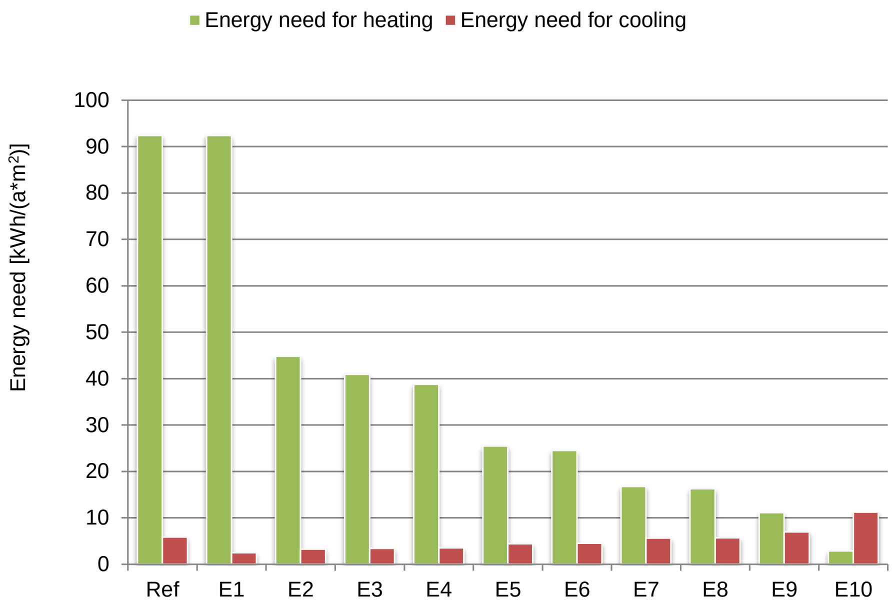
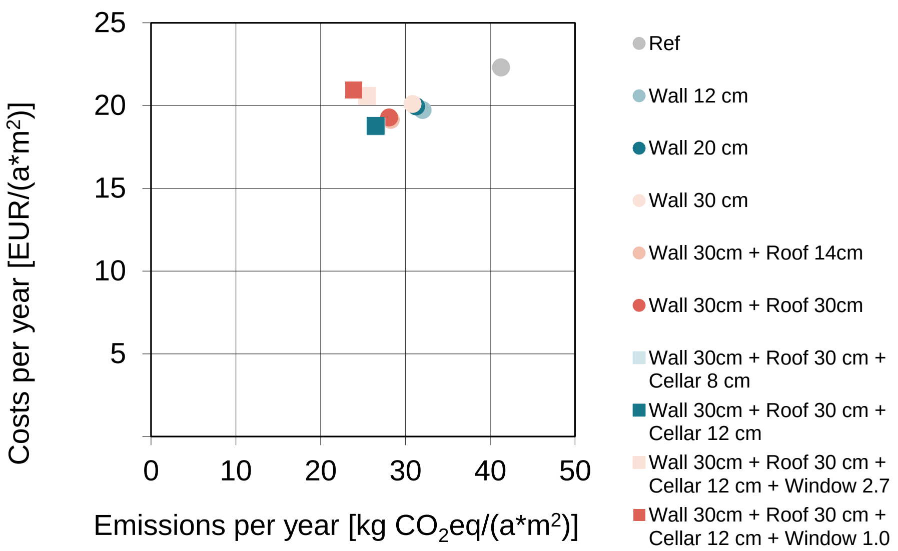


Figure 59 Energy need per year for heating and cooling for the generic reference building in Spain, taking into account the use of shutters.

When the emissions/cost plots are compared in the case of the reference building in Spain with and without taking into account cooling, it can be observed that the most cost-effective renovation package in the situation without cooling remains the most cost-effective also when cooling is taken into account. This observation is the same for a situation with shutters or without shutters. This is shown in the following figures. When taking into account cooling, only a situation with shutters is taken into account.

Renovation packages with gas heating, excluding cooling



Taking into account cooling, with shutters

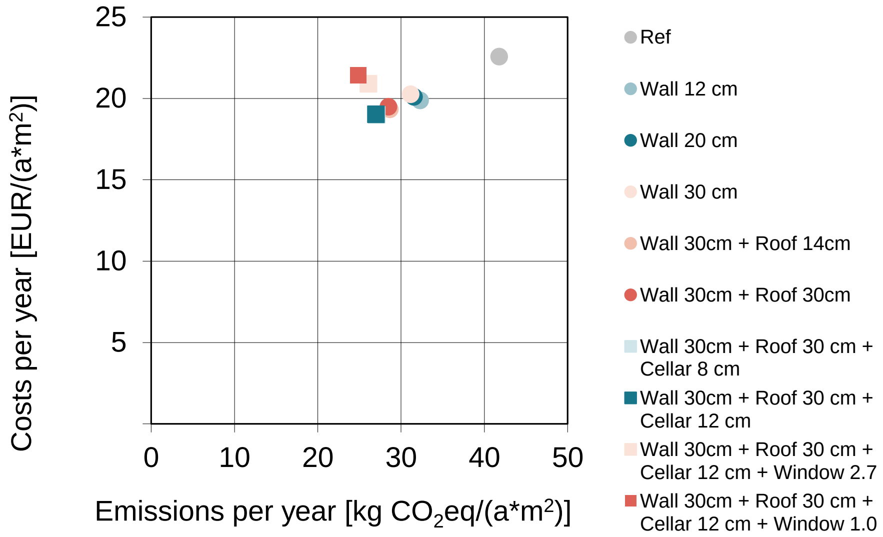


Figure 60 Comparison of emissions/cost curves for the generic building in Spain without taking into account cooling (top) and with taking into account cooling (lower figure). When cooling is taken into account, the use of shutters is assumed. For the related calculations, no costs have been taken into account for the shutters or the instalation of a cooling system; it is assumed they are already part of the building.

In both of the cases shown in the figures above, the renovation package including measures on the wall, the roof and cellar is the most cost-effective.

4.5. Sensitivities

For the calculation with a multi-family reference building in Switzerland, results are shown for different steps of the calculation, in order to provide additional insight on the influence of different parameters.

The following graph shows as a starting point the cost curves for the generic single-family building in Switzerland, as defined in chapter 3.3.

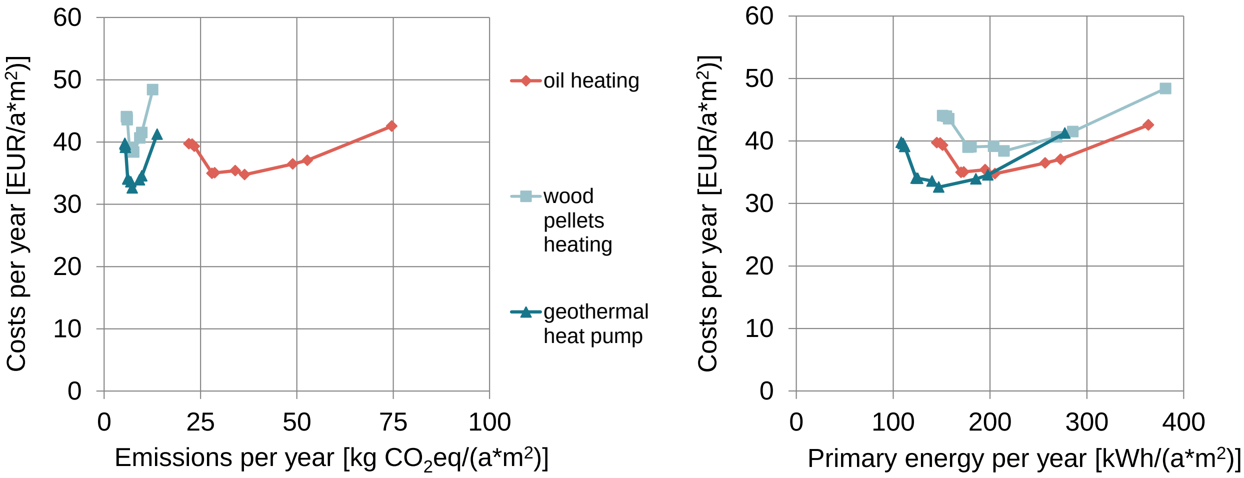


Figure 61 Aggregated comparison of different renovation packages for the single-family reference building in Switzerland

Effect of change of building dimensions from a single-family building to a multi-family building

The following graphs illustrate a change of building dimensions from SFB to MFB, while leaving the other parameters the same, for the primary energy / cost graph.

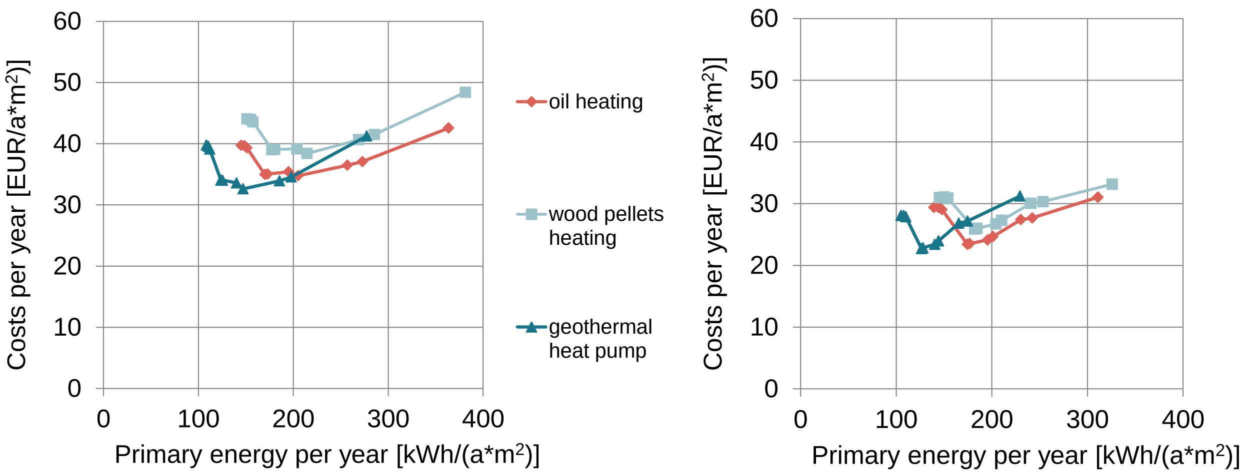


Figure 62 Effect of building dimensions on different renovation packages; left-hand side: single-family reference building in Switzerland; right-hand side: multi-family building.

Specific costs per m² are lowered because of the change in building dimensions. This is due to a higher ratio of volume to exterior surface in multi-family building, saving specific energy costs. Specific primary energy use and carbon emissions per m² decrease as well, in particular for less far-reaching building renovations.

Effects of changes of building dimensions and of conditioned floor area per person from a single-family building to a multi-family building

A change in building dimensions is not the only difference between single-family buildings and multi-family buildings. The following illustrates the difference between the generic single-family building and the multi-family building taking into account the smaller number of conditioned floor area per person typical for multi-family buildings, and related increases in domestic hot water and electricity consumption per m².

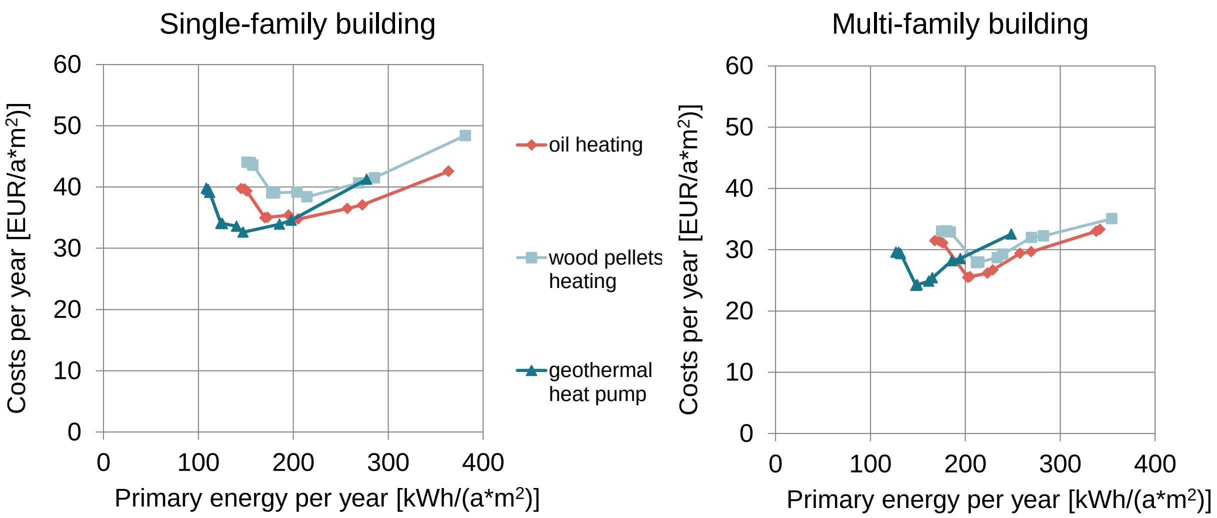


Figure 63 Effect of a change from a single-family building (left) to a multi-family building (right), illustrated for the Swiss reference buidlings. Apart from building dimensions also condiditioned floor area per person and related changes in the use of domestic hot water and electricity consumption per m² are taken into account.

While specific costs per m² are, overall, lower in a multi-family building, the effects of using less conditioned floor area per person leads to a decrease in primary energy use only for low efficiency standards. In buildings with a well insulated thermal envelope, primary energy use is higher in a multi-family building than in a single-family building.

Effect of differentiation of specific investment costs of renovation measures for single-family buildings and multi-family buildings

For multi-family buildings, the specific investment costs for a building element as expressed per m² of renovated surface area of that building element are usually lower than for a single-family building, because of economies of scale. The following table summarizes the different cost data taken into account for the single-family building and the multi-family building.

Table 51 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family building and a multi-family building in Switzerland.

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - thickness of insulation material	cm	-	12	30	30	30	30	30	30	30	30
Wall – Costs for Single-Family Building	EUR/m^2 wall	62	142	167	167	167	167	167	167	167	167
Wall – Costs for Multi-Family Building	EUR/m^2 wall	58	128	140	140	140	140	140	140	140	140
Window - U-Value	W/m^{2}K	2.7	2.7	2.7	2.7	2.7	2.7	2.7	1.3	1.0	0.8
Window – Costs for Single-Family Building	EUR/m^2 window	33	33	33	33	33	33	33	763	832	875
Window – Costs for Multi-Family Building	EUR/m^2 window	33	33	33	33	33	33	33	763	832	875
Roof - thickness of insulation material	cm	-	-	-	12	36	36	36	36	36	36
Roof – Costs for Single-Family Building	EUR/m^2 roof	63	63	63	183	233	233	233	233	233	233
Roof – Costs for Multi-Family Building	EUR/m^2 roof	58	58	58	146	188	188	188	188	188	188
Cellar ceiling - thickness of insulation material	cm	-	-	-	-	-	10	16	16	16	16
Cellar ceiling – Costs for Single-Family Building	EUR/m2 cellar ceiling	-	-	-	-	-	87	96	96	96	96
Cellar ceiling – Costs for Multi-Family Building	EUR/m^2 cellar ceiling	-	-	-	-	-	87	93	93	93	93

The following graphs illustrate the related effects, by including changes to the specific costs of measures for the MFB:

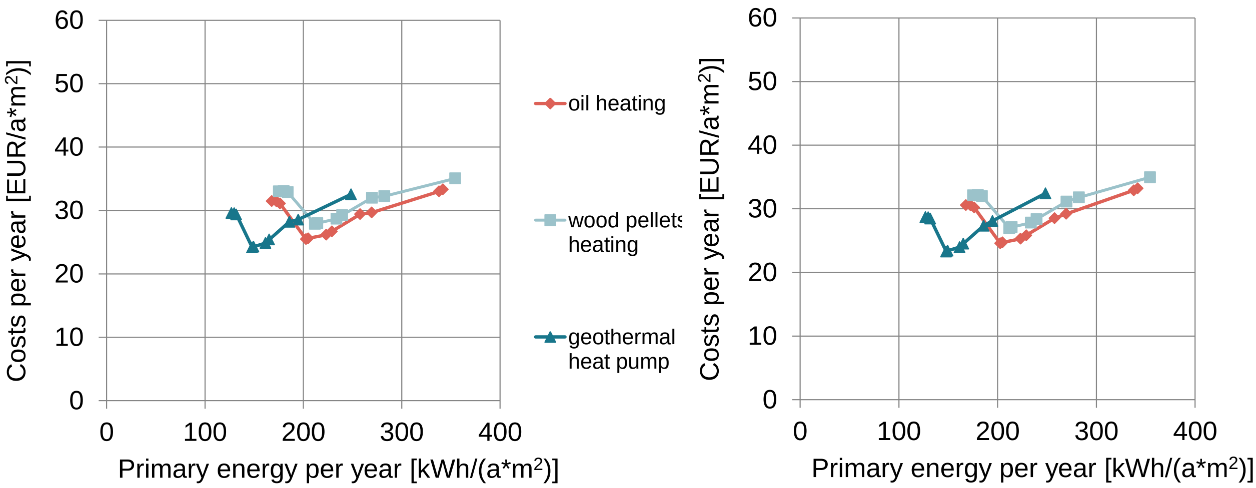


Figure 64 Energy performance and cost-effectiveness for multi-family building in Switzerland taking into account lower specific costs for renovation measures in multi-family buildings than in single-family buildings

Compared to the change in building dimensions, the change in specific costs has little effect on the position of the curves. Specific costs per m^2 are only lowered to a relatively small extent due to economies of scale of renovation measures in multi-family buildings.

Effect on investment costs for the heating system due to energy efficiency measures reducing the energy need of the building

In the following graph, the results of the calculations are shown when the size of the heating system is assumed to be constant, irrespective of the reductions of energy need due to energy efficiency measures. The investment costs for the new heating systems are not lowered in the related calculations if the building is more insulated. This corresponds to a situation in which first the heating system is replaced and the renovation measures on the building envelope are only carried out afterwards, compared to a situation where renovation measures on the building envelope are carried out prior to or combined with the installation of a new heating system.

In the other calculations, the size of the peak capacity of the heating system is adapted according to the lower heating energy need: The lower the energy need of the building because of energy efficiency measures on the building envelope, the lower the required peak capacity of the heating system, and the lower related size of the heating system. The significance of this effect can be seen by comparing the following graphs:

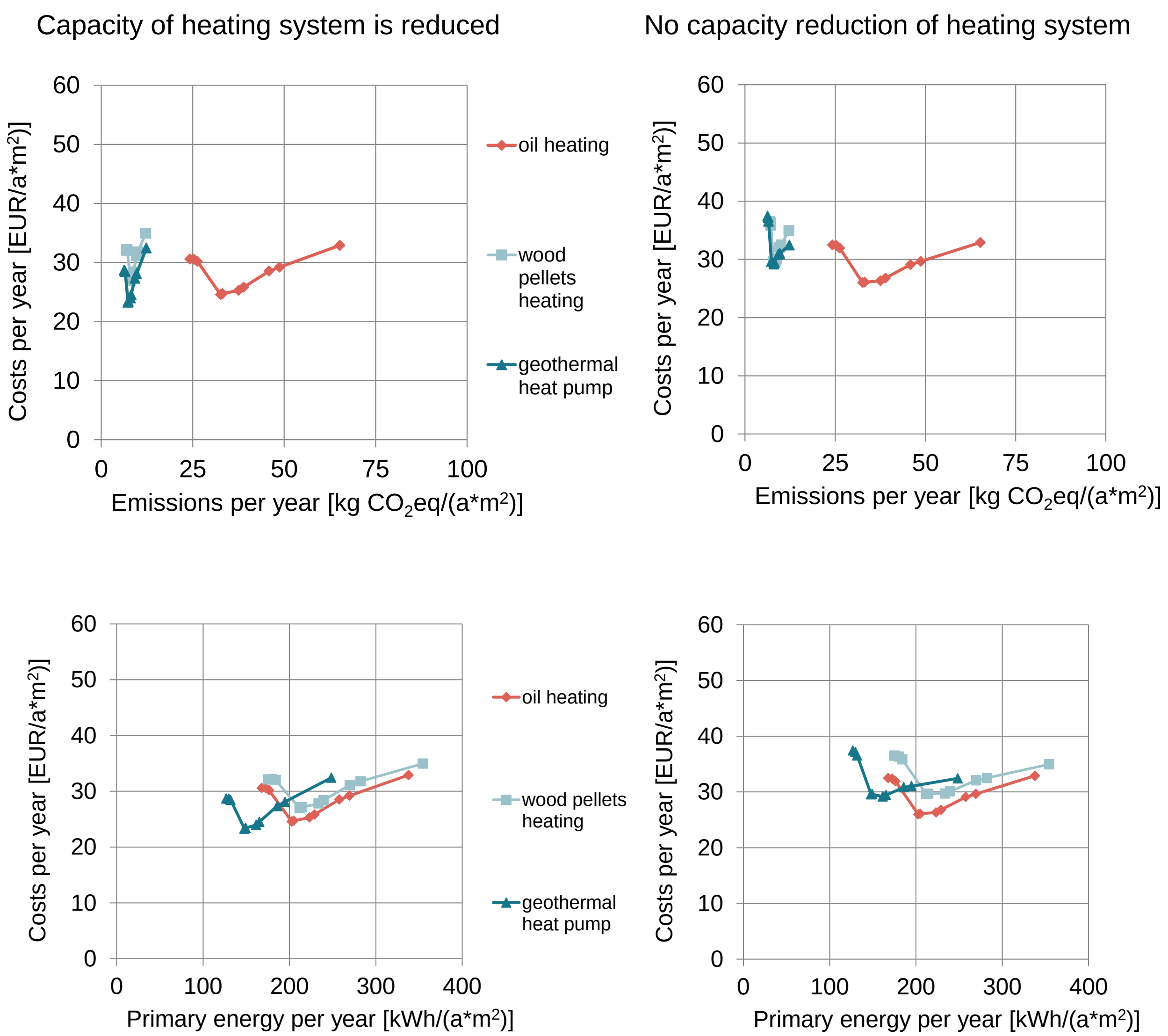


Figure 65 Energy performance and cost-effectiveness for a multi-family building in Switzerland, with (left-hand side) and without (right-hand side) any reduction of the peak capacity of the heating system for more far reaching energy efficiency measures

The effect of not including the possible reduction of the size of the heating system due to energy efficiency measures is three-fold:

1. Far-advanced energy efficiency measures including the installation of new windows are significantly less cost-effective for all heating systems investigated, particularly for the two based on renewable energies
2. Whereas a change from the oil heating to a geothermal heat pump is still cost-effective, the most cost-effective of the investigated renovation packages includes an oil-heating system.

3. For a heating system based on geothermal heat pump, the cost-optimal renovation does no longer include measures on the cellar ceiling.

From these observations, it can be concluded:

The reduction of peak capacity for heating systems if energy efficiency measures are carried out, is an important factor for creating synergies. It influences significantly the cost-effectiveness of RES-based solutions. Only if the change to a renewable energy system is combined with energy efficiency measures, can the cost-optimal solution be found. In the cost optimum which includes synergies between the investigated renewable energy sources and energy efficiency measures, carbon emissions and primary energy use are reduced significantly more strongly, than if a cost optimum is sought without change of the heating system.

Effect of varying energy prices

The following graphs document the effects of changes in the assumptions on energy prices. Instead of the standard price scenario of Table 1 which starts from current energy prices and assumes a price increase of 30% for the upcoming 40 years, a low price scenario (Figure 66) and a high price scenario (Figure 67) are assumed. In the low price scenario oil and wood pellets prices are assumed to be 0.07 EUR/kWh and electricity prices are assumed to be 0.16 EUR/kWh on average, whereas in normal calculations the related values are 0.1 EUR/kWh and 0.2 EUR/kWh, respectively. In the high price scenario, oil and wood pellets prices are assumed to be 0.13 EUR/kWh and electricity prices are assumed to be 0.24 EUR/kWh on average.

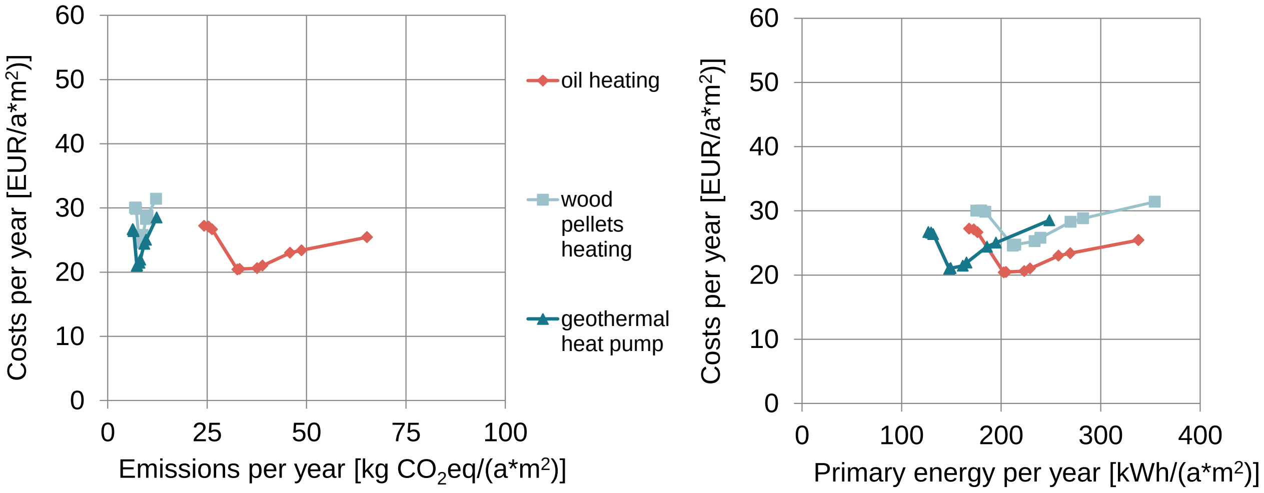


Figure 66 Low energy price scenario: Energy performance and cost-effectiveness for the multi-family building in Switzerland

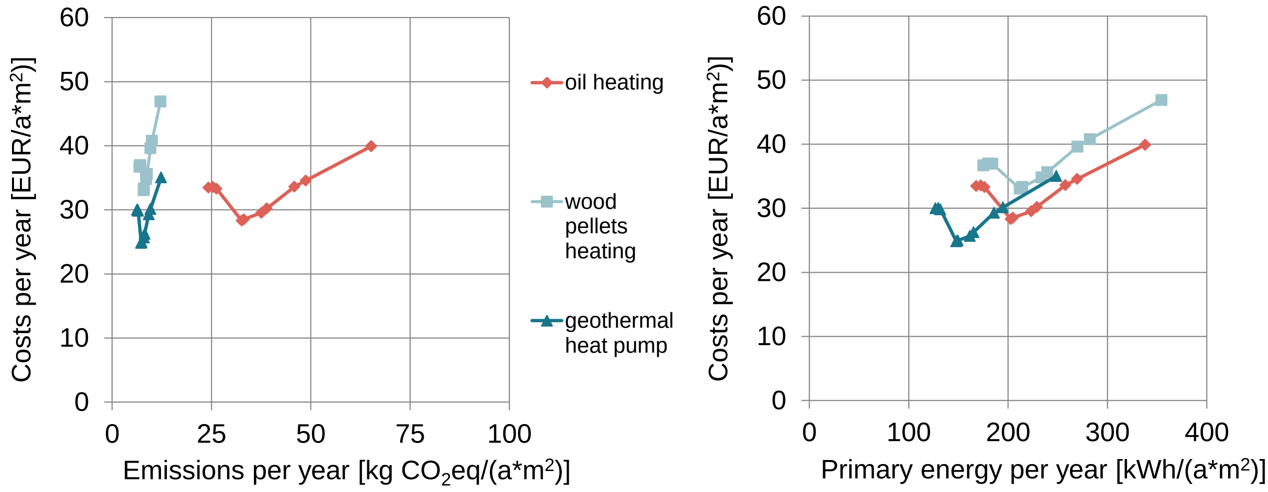


Figure 67 High energy price scenario: Energy performance and cost-effectiveness for multi-family building in Switzerland

Figure 66 and Figure 67 illustrate the fact that energy prices matter a lot for resulting life-cycle costs and hence for economic viability of energy related renovation measures. Renovation package M6 is still the most cost-effective renovation package in both the low price scenario and the high price scenario. However, comparing with the reference case with an oil heating system, in the case of low energy prices, renovation packages M7-M9 are not cost-effective anymore, independent of the heating system chosen. Therefore, it is crucial to think about future energy price development and to integrate resulting expectations into the economic assessment of renovation options.

Regarding the relative attractiveness of different heating systems, the following can be observed:

Assuming lower energy prices, a change to a geothermal heat pump system, when combined with no or few measures on the building envelope, is less cost-effective than installing a new oil based system. If more energy efficiency measures are carried out, however, a change to a geothermal heat pump becomes equally or even more cost-effective compared to related renovation packages with an oil based heating system.

When assuming higher energy prices, a change to a geothermal heat pump is more cost-effective, for all renovation packages on the building envelope.

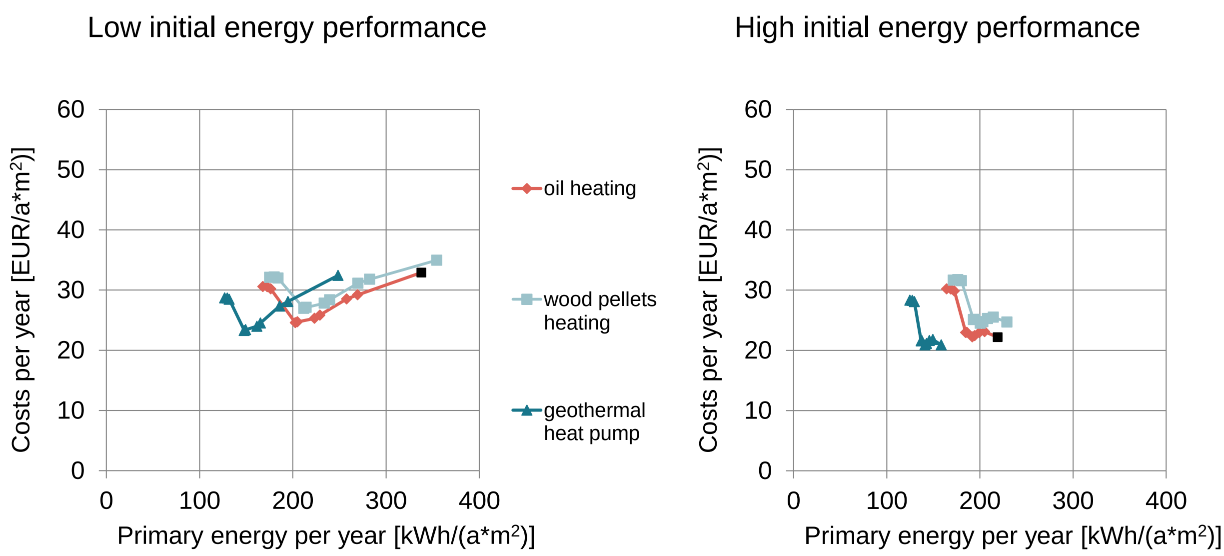
Influence of initial energy performance of building envelope on economic viability of energy related measures

The initial energy performance of a building before renovation has an influence on the cost-effectiveness of energy related measures as well as on their impact on primary energy use and carbon emissions. The higher the initial energy performance of the building is, the less are the achievable reductions of primary energy use and carbon emissions. Since marginal benefits of additional insulation are distinctly decreasing it is less cost-effective or might even be not cost-effective anymore to increase energy performance of the building in the case of moderate to high initial energy performance of the building.

This is illustrated with the following graphs of the investigated generic Swiss multi-family building (see Figure 68).

In the case of a low initial energy performance of the multi-family building investigated (left side of Figure 68), all measures are cost-effective, resulting annual costs are lower than in the reference case of the anyway renovation. Renovation package M6 is the cost-optimal package for a building with low initial energy performance. This holds also if the oil heating system is substituted by a geothermal heat pump system or by a wood pellets system. Beyond the cost optimum, renovation packages M7 to M9, which include new windows, yield further reductions in primary energy use and carbon emissions which are still cost-effective compared to the reference case of the anyway renovation. Replacement of the oil heating system by a geothermal heat pump reduces costs and allows for further reductions of energy and carbon emissions with the measures M1 - M9.

In the case of high initial energy performance of the multi-family building investigated (right hand side of Figure 68), renovation measures do not lead to more cost-effective solutions; they are more or less cost-neutral, or, if new windows are included, not cost-effective. A switch to a geothermal heat pump is cost-effective, a switch to a wood pellet system is not cost-effective, as in the case of a low initial energy performance.



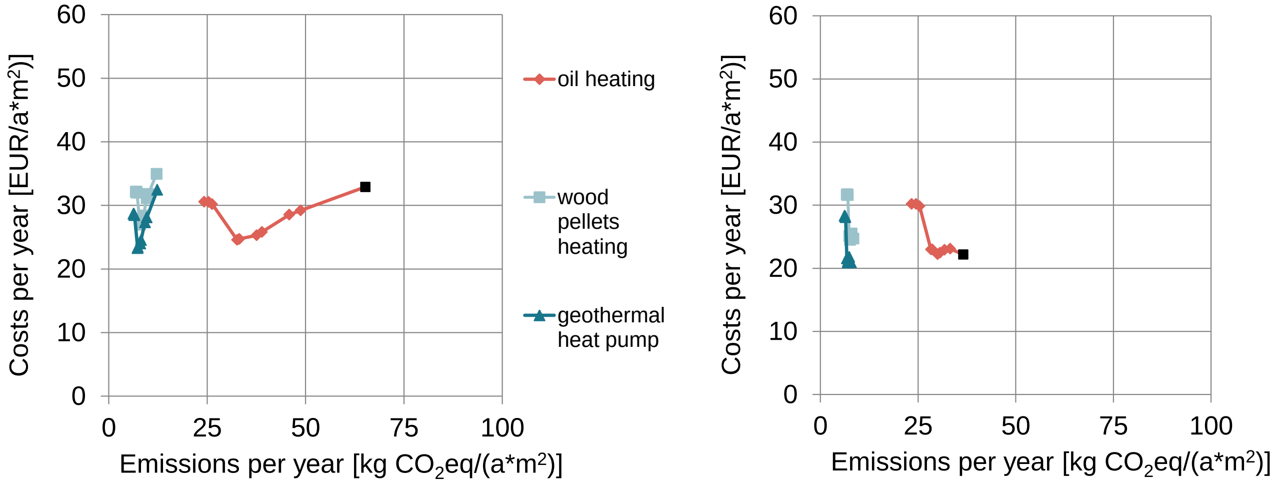


Figure 68 Energy performance and cost-effectiveness for a multi-family building in Switzerland with a *low initial energy performance* (left side) and a *high initial energy performance* (right side). Annual life-cycle costs and resulting primary energy use are indicated in the figures on the top and carbon emissions are indicated in the bottom figures. The reference scenario is an "anyway" renovation, including the replacement of the oil heating system with a heating system of the same type (black square dot).

If the multi-family building has a higher initial energy performance before renovation (right side of Figure 68), only the insulation of the cellar ceiling (M5 and M6) and of the roof (M3 and M4) are still cost-effective compared to the reference case with the anyway renovation. The better insulation of the walls and the roof are only slightly or nearly cost-effective since the walls and the roof have already some initial insulation. Better windows with lower U-values are definitively not cost-effective any more. Cost-optimal renovation option is still M6, especially if combined with a geothermal heat pump.

4.6. Summary table

The results of the generic calculations regarding the impacts of different renovation packages in the reference buildings investigated are summarized in the following table.

Table 52 Summary of impacts on carbon emissions and primary energy use of different renovation packages in the reference buildings investigated

Country	Building type	Heating system	Carbon emissions ($kg\ CO_{2e}$ / m^2 a)		Specific Primary energy use (kWh/m^2 a)	
			No energy efficiency measures	Max. energy efficiency measures	No energy efficiency measures	Max. energy efficiency measures
Austria	SFB	Oil	96	27	373	117

Country	Building type	Heating system	Carbon emissions ($kg\ CO_{2e} / m^2\ a$)		Specific Primary energy use ($kWh/m^2\ a$)	
			No energy efficiency measures	Max. energy efficiency measures	No energy efficiency measures	Max. energy efficiency measures
		Wood pellets	24	11	417	129
		Geothermal heat pump	35	12	204	69
	MFB	Oil	74	28	295	125
		Wood pellets	21	13	329	137
		Geothermal heat pump	28	13	161	77
Denmark	SFB	Oil heating	77	31	359	192
		Wood pellets	15	8.6	435	228
		Geothermal heat pump	16	8.0	318	161
	MFB	Oil heating	39	18	253	176
		Wood pellets	11	8.4	289	194
		Geothermal heat pump	11	8.0	219	162
Italy	MFB	Gas heating	34	23	142	100
		Aerothermal heat pump	17	14	79	64
		Geothermal heat pump	16	14	74	65
Norway	SFB – el. mix1	Electric heating	3.8	1.6	322	139
		Wood logs	4.8	2.0	359	153
		Air source heat pump	1.9	0.74	157	63
	SFB – el. mix2	Electric heating	90	39	809	349
		Wood logs	13	11	407	201
		Air source heat pump	44	18	395	158
Portugal	SFB	Gas heating	88	40	409	183
		Air source heat	90	40	397	175

Country	Building type	Heating system	Carbon emissions ($kg CO_{2e} / m^2 a$)		Specific Primary energy use ($kWh/m^2 a$)	
			No energy efficiency measures	Max. energy efficiency measures	No energy efficiency measures	Max. energy efficiency measures
		pump				
		Air source heat pump + PV	48	0	212	0
	MFB	Gas heating	55	32	255	146
		Air source heat pump	53	33	232	145
		Air source heat pump + PV	42	22	184	97
Spain	MFB	Gas heating	45	27	263	170
		Wood pellets	23	19	321	188
		Geothermal heat pump	29	20	194	138
Sweden	SFB	District heating	20	13	293	204
		Wood pellets	5.0	4.5	304	215
		Geothermal heat pump	12	8.0	237	161
	MFB	District heating	13	10	209	162
		Wood pellets	4.7	4.5	221	175
		Geothermal heat pump	8.3	6.6	166	133
Switzerland	SFB	Oil heating	75	22	364	145
		Wood pellets	13	5.8	381	151
		Geothermal heat pump	14	5.4	277	108
	MFB	Oil heating	65	24	338	168
		Wood pellets	13	6.8	354	175
		Geothermal heat pump	12	6	249	127

5. Calculations based on case studies

5.1. Introduction

The aim of the evaluating case studies in this context is to investigate the methodology developed in Annex 56 in concrete cases. A separate report of Annex 56 describes the results obtained in detail (Venus et al. 2015). Here, only a part of the results are indicated, with a specific focus of investigating the hypotheses that were also investigated with the generic calculations. In particular, the actually implemented renovation package is not described here; only some of the calculation results based on concrete measures which were found to be possible in the related case studies, with case-specific values on energy performance and costs, are shown here.

The following table summarizes the characteristics of the buildings from the case studies, as used in calculations:

Table 53 Characteristics of buildings investigated in case studies as used in calculations

Parameter	Unit	Kapfen-berg, Austria	Trane-parken, Denmark	Rainha Dona Leonor, Portugal	Lourdes, Spain	Backa röd, Sweden
Building year / period		1961	1960ies	1953	1970	1971
Gross heated floor area (GHFA)	m^2	2845	1754	123	1474	1357
Façade area (excl. windows)	m^2	1463	822	117	1247	821
Roof area pitched	m^2	-	-	74	361	-
Roof area flat	m^2	711	-	-	-	305
Attic floor	m^2	-	585	-	-	55
Area of windows to North	m^2	6	78	-	73	39
Area of windows to East	m^2	169	116	14	13	39
Area of windows to South	m^2	6	78	-	74	45
Area of windows to West	m^2	173	116	3	11	54
Area of ceiling of cellar	m^2	711	585	-	323	360
U-value façade	$W/(m^2*K)$	0.87	0.67	1.38/1.69	1.89	0.31
U-value roof pitched	$W/(m^2*K)$	-	-	2.62	1.25	-
U-value attic floor	$W/(m^2*K)$	-	0.2	-	-	0.14
U-value roof flat	$W/(m^2*K)$	2	-	-	-	0.14

Parameter	Unit	Kapfen-berg, Austria	Trane-parken, Denmark	Rainha Dona Leonor, Portugal	Lourdes, Spain	Backa röd, Sweden
U-value windows	$W/(m^2*K)$	2.5	2.4	3.4	5.2	2.40
g-value windows	Factor	0.65	0,65	0.85	0.85	0.76
U-value ceiling of cellar	$W/(m^2*K)$	0.39	0.4	-	1.47	0.40

5.2. Case study in Austria

5.2.1. Building

The building chosen for the case study in Austria is a residential building which was built between 1960 and 1961. It is a typical building from the 1960's made of prefabricated sandwich concrete elements without any additional insulation. The renovation concept which was implemented was an ambitious renovation, reducing primary energy use and CO_2 emissions by 80%. It included the installation of prefabricated façade elements as an innovative renovation concept. Energy efficiency measures were combined with the use of a renewable energy based district heating system.

Fig. 3: Images of the building investigated in the case study in Austria before (left) and after (right) the renovation.

5.2.2. Measures

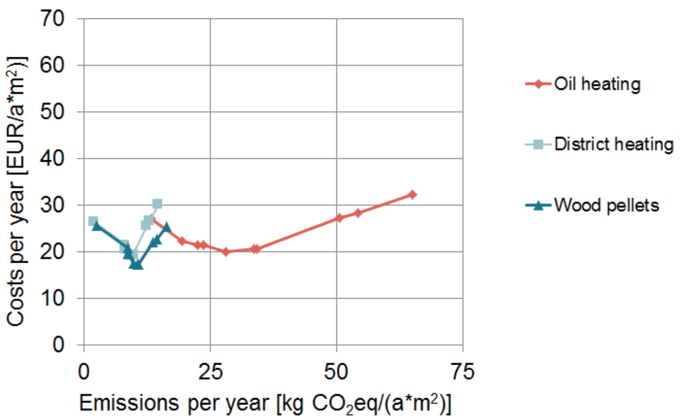
In the following table, different renovation packages are described for which the effects were investigated.

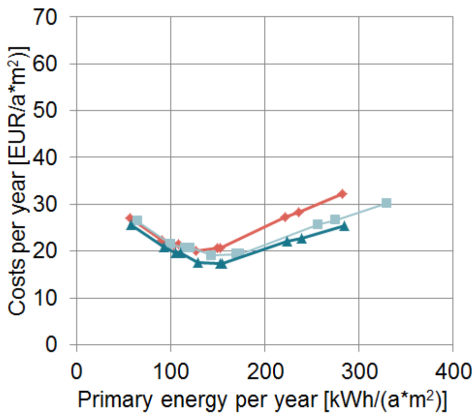
Table 54 Description of different packages of renovation measures M1 to M9 and of the reference case for the case study in Austria.

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

5.2.3. Results

The following graphs illustrate the results of the case study. 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 point on the curve for the oil heating system (red line) with the highest emissions or highest primary energy use represents the reference case. As more measures are added to the renovation packages, carbon emissions and primary energy use decrease.





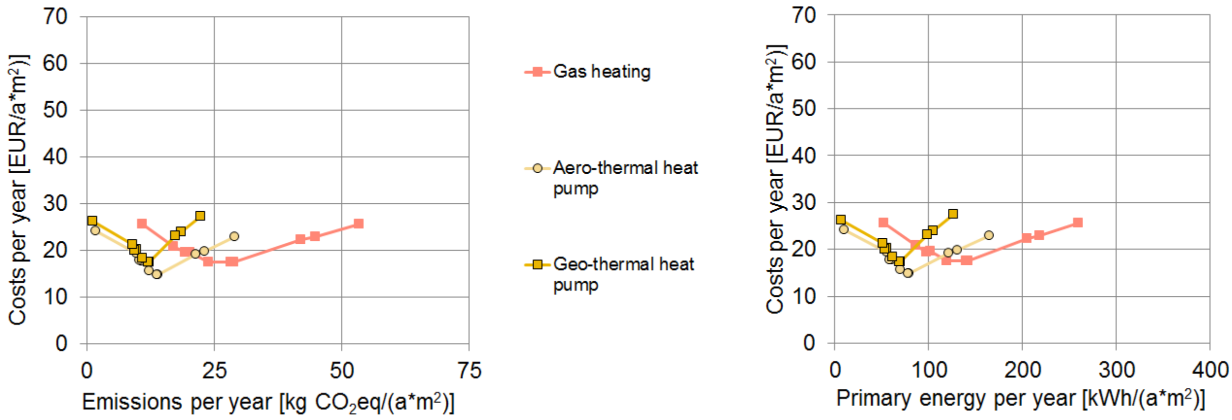


Figure 69: Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Austrian case study

5.2.4. Discussion

With respect to the different hypotheses investigated, the following can be observed (for a summary see the subsequent table):

From the results it can be seen that a variation in the insulation level of a particular building element, e.g. the different insulation thicknesses of the insulation of the wall in renovation packages M1 and M2, has only a relatively small impact in comparison with the inclusion of additional building elements in the building renovation. The first hypothesis is therefore confirmed.

A switch to wood pellets, aerothermal heat pump or geothermal heat pump reduces carbon emissions more strongly than energy efficiency renovation measures. For example, a switch to wood pellets reduces emissions more strongly than energy efficiency measures on the wall, the roof, and the windows combined; a switch to an aerothermal heat pump reduces emissions more strongly than energy efficiency measures on the wall and the roof combined. The second hypothesis is therefore confirmed.

Independent of the choice of the heating system, the renovation package including measures on the roof and the wall is the most cost efficient of the ones investigated. The cost-effectiveness of the solar thermal installation, however, depends on the type of the heating system chosen. While solar thermal is cost-effective in the case of an oil heating system, the measure is slightly not cost-effective in the case of a heat pump. The third hypothesis is therefore confirmed.

Also in the case of a switch to a wood pellet system, a geothermal heat pump or a aerothermal heat pump, energy efficiency measures on the building envelope up to a certain point increase cost-effectiveness. The fourth hypothesis is therefore confirmed.

High emission reductions can be obtained more cost-effectively by combining energy efficiency measures with a switch to a renewable energy system than relying on energy efficiency measures alone. Accordingly, the fifth hypothesis is confirmed.

Overall, the results of the calculations with the case study in Austria confirm the main hypotheses which are investigated, as summarized in the following table:

Table 55 Results for investigated hypotheses for the case study “Kapfenberg“ in Austria. RES refers here to geothermal heat pump, aerothermal heat pump and wood pellets. ✓ means that the hypothesis is confirmed.

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 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.	✓

5.3. Case study in Denmark

5.3.1. Building

For the case study in Denmark Traneparken, was chosen. Traneparken consists of 3 multi-story blocks of flats. Each block has 3 storeys with in all 66 flats. The buildings are typical of the 1960s and made of prefabricated re-enforced sandwich concrete elements with approx. 50 mm insulation material.

Fig. 3: Images of the building investigated in the case study in Denmark before (left) and after (right) the renovation.

5.3.2. Measures

In the following table, different renovation packages are described for which the effects were investigated.

Table 56 Description of different packages of renovation measures M1 to M7 and of the reference case for the case study in Denmark.

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 facade
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%

5.3.3. Results

The following graphs illustrate the results of the case study.

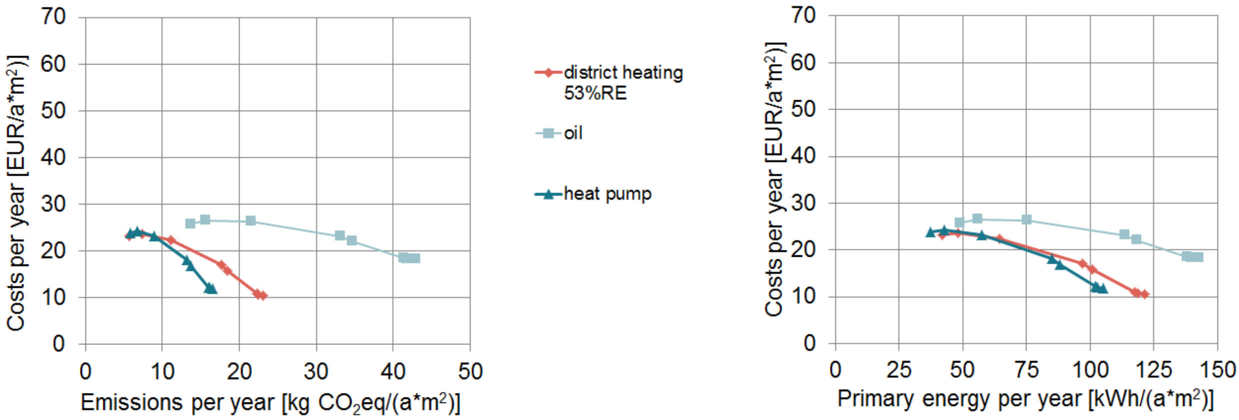


Figure 70: Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Danish case study

5.3.4. Discussion

A particular aspect of this case study is that renovation packages are in general not cost-effective compared to the reference case or simply a switch of the heating system. Probably this is due to an insulation standard of the building which is not low prior to renovation.

With respect to the different hypotheses investigated, the following can be observed (for a summary see the subsequent table):

Whether the insulation thickness added to the roof is 150 mm or 300 mm, whether the insulation added to the wall is 100 mm or 200 mm, only has a relatively small effect on emissions reductions or reductions of primary energy use compared to differences in combining different building elements in the renovation. The first hypothesis is therefore confirmed.

Compared to a situation with an oil heating system, a switch to district heating with a share of 53% renewable energies or a switch to a heat pump system reduces emissions more strongly than energy efficiency measures which include measures on the wall and the roof. In the case of a switch to a heat pump, this reduces emissions even more strongly than energy efficiency measures on the wall, the roof, and the windows. The second hypothesis is therefore confirmed.

As for all heating systems investigated, undertaking no energy efficiency measures is the most cost-effective approach, the third hypothesis is basically confirmed.

Compared to a situation with an oil heating system, it is most-effective just to switch heating system to district heating or heat pump, without further measures on the building envelope. The reduction of carbon emissions and primary energy use due to the improved building envelope is quite small compared to a change of the energy source. The fourth hypothesis is therefore disproved.

In order to achieve far-reaching emission reductions, compared to a situation with an oil heating system it is more cost-effective to switch to district heating or heat pump than and carry out less energy efficiency measures than to focus only on energy efficiency measures. The fifth hypothesis is therefore confirmed.

Overall, for the Danish case study four of the five hypotheses could be confirmed, as summarized in the following table:

Table 57 Results for investigated hypotheses for the case study "Traneparken" in Denmark. RES refers here to a district heating system with a share of renewable energies of 53% and a heat pump. ✓ means that the hypothesis is confirmed. **X** means that the hypothesis is not confirmed. Symbols in parenthesis indicate that the hypothesis is only partly confirmed / not confirmed.

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 cost-optimal efficiency level	(✓)*
Synergies are achieved when a switch to RES is combined with energy efficiency measures	X**
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 a renovation 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.

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

5.4. Case study in Portugal

5.4.1. Building investigated

The building chosen for the case study in Portugal is part of a social housing neighbourhood built in 1953 with several two floor buildings with variations in the area and the number of bedrooms. The building investigated has a dwelling on each floor. Since the entire neighbourhood had never been submitted to significant renovation, none of the buildings had thermal insulation or installed heating or cooling systems and the windows were the original wooden framed with single glazing. The domestic hot water was provided by an electric heater with a storage tank. The main goals of the intervention were to improve the livability of the dwellings and common areas and simultaneously restore consistency and homogeneity of the group of buildings, by subtracting the added forms, restoring the design and shape of the original volumes.

Fig. 3: Images of the building investigated in the case study in Portugal before (left) and after (right) the renovation.

5.4.2. Measures investigated

In the following table, different renovation packages are described for which the effects were investigated.

Table 58 Description of different packages of renovation measures M1 to M9 and of the reference case for the case study in Portugal.

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 facade
M5	M3 + 80 mm cork board insulation of the façade

Renovation Package	Description
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

5.4.3. Results

The following graphs illustrate the results of the case study:

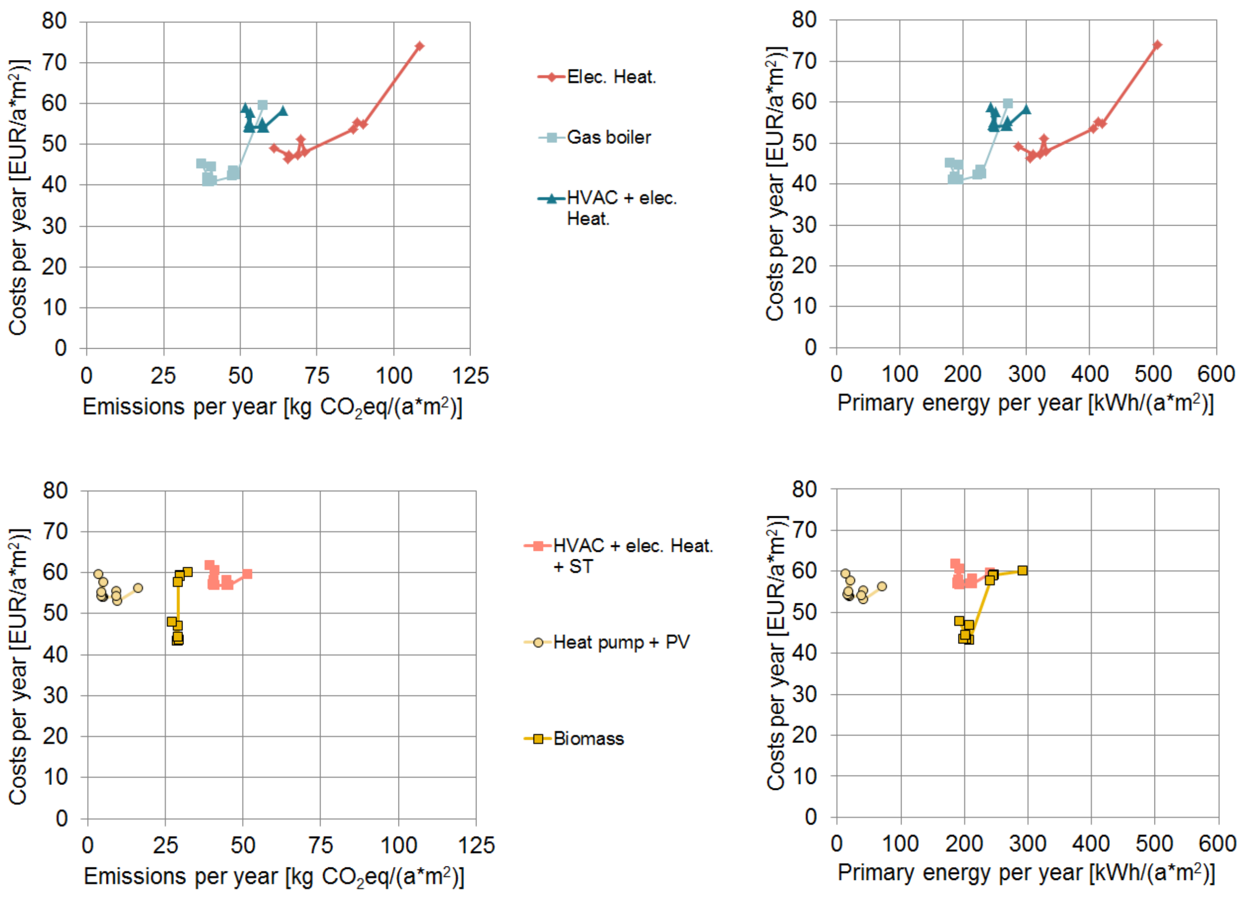


Figure 71: Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Portuguese case study

5.4.4. Discussion

With respect to the different hypotheses investigated, the following can be observed (for a summary see the subsequent table):

Differences in the insulation levels of the roof or the wall only have a small impact on the reduction of carbon emissions or primary energy use, compared to not including any related renovation measure at all. Regarding the cellar ceiling and windows the reduced number of variants that have been tested do not allow to check this hypotheses. The first hypothesis is therefore partly confirmed.

A switch to a biomass system or a system based on heat pumps and PV reduces emissions more strongly than improvements of the building envelope when the heating system is based on electric heating or gas. The second hypothesis is therefore confirmed.

When a heat pump in combination with PV is chosen as heating system, the most cost-effective renovation package is to carry out only an 8 cm insulation on the wall, whereas with a gas heating or an electric heating, the most cost-effective renovation package includes measures on the roof, the wall, and the cellar. This is also the case for a wood heating system. However, as the differences are only small, the third hypothesis is therefore considered to be confirmed. However, the differences in the cost optima are small. Also in the case of a switch to a renewable energy system, some measures on the building envelope are cost-effective. The fourth hypothesis is therefore confirmed.

A switch to heat pump and PV, or a switch to biomass, lead to stronger emission reductions than energy efficiency measures while keeping an electric heating system or a gas heating system. The cost of a solution with heat pump and PV, however, is not lower than the investigated renovation packages of a gas heating or of electric heating. A biomass system is more cost-effective than the investigated renovation packages with electric heating, but less cost-effective than the investigated renovation packages with gas heating. It can be assumed, that to achieve similar emission reductions with a gas heating system or electric heating as when a RES system is chosen, the additional energy efficiency measures would overall result in higher costs than the ones with a renewable energy system. However, from the data gathered with this case study, this cannot be confirmed with certainty. It is therefore only probable that the fifth hypothesis is confirmed, yet from the data this cannot be deduced with certainty.

Overall, for the Portuguese case study the investigated hypotheses can be partially confirmed, as summarized in the following table:

Table 59 Results for investigated hypotheses for the case study “Rainha Dona Leonor neighborhood“ in Portugal. RES refers here to a biomass system and a heat pump in combination with PV. ✓ means that the hypothesis is confirmed. Symbols in parenthesis indicate that the hypothesis is only partly confirmed / not 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 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 cannot clearly be answered. It is more likely to be confirmed, yet the confirmation is not certain.

5.5. Case study in Spain

5.5.1. Building investigated

The building chosen for the case study in Spain is a residential building constructed in 1970 which is part of a big social neighborhood with low quality construction. It is a five story building with a northwest – southeast axis. The building lacks insulation. The existing facade was made of a single hollow brick with 25 cm of width. The floor of the first floor (in contact with unheated spaces) is made of a concrete beam slab with ceramic hollow fillers. The old pitched roof has an unheated space under it and is covered by ceramic tiles. The original wooden windows were nearly all replaced by owners at different times during the last years so their thermal performance differs from window to window.

Fig. 3: Images of the building block investigated in the case study in Spain. In each of the two pictures, the renovated building is on the left side.

5.5.2. Measures investigated

In the following table, different renovation packages are described for which the effects were investigated.

Table 60 Description of different packages of renovation measures M1 to M10 and of the reference case for the case study in Spain.

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 facade
M2	60 mm insulation of façade

Renovation Package	Description
M3	220 mm insulation of facade
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

5.5.3. *Results*

The following graphs illustrate the results of the case study:

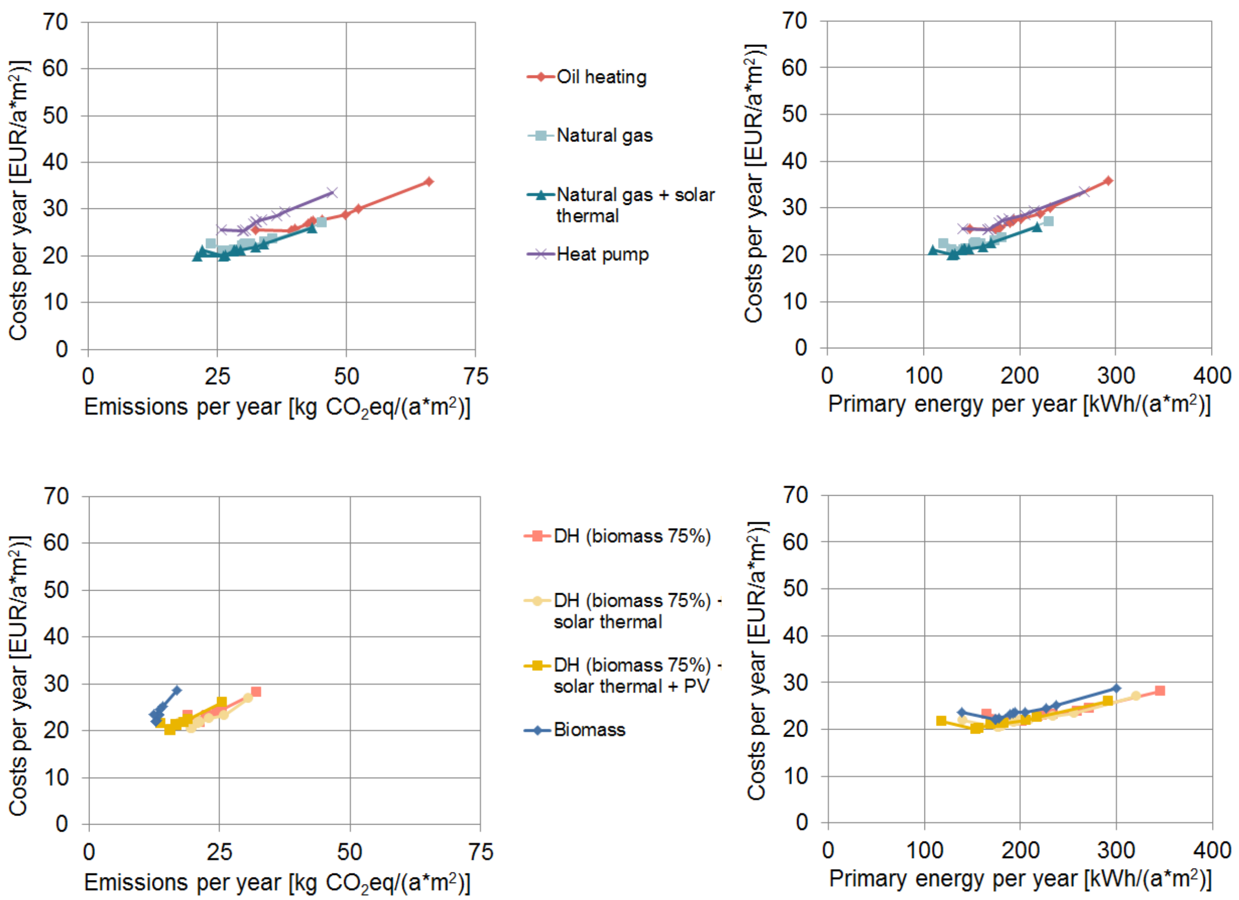


Figure 72: Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Spanish case study

5.5.4. Discussion

With respect to the different hypotheses investigated, the following can be observed (for a summary see the subsequent table):

Varying the energy efficiency levels between different renovation packages has a similar effect as varying the number of building elements included in the renovation. For example, the 22 cm wall insulation achieves similar good results as the same measure plus adding insulation on the roof, whereas it differs more strongly from renovation packages which include only an insulation of the wall of 4 cm or 6 cm. Therefore, the first hypothesis is not confirmed.

A switch to a heat pump leads to a strong reduction of carbon emissions, stronger than any other single energy efficiency measure; however, with an increasing number of efficiency measures, in the case of an oil heating, similar reductions of carbon emissions can be achieved as with a heat pump. Furthermore, a gas heating system causes a similar amount of carbon emissions as a heat pump system for different renovation packages investigated. A stronger reduction of carbon emissions can be achieved, when a switch is made to district heating with a large share of biomass, or directly a biomass heating system. The second hypothesis is therefore confirmed, though not clearly.

For the different heating systems investigated, the renovation package M9 which includes measures on the wall, the roof, and the cellar, is at the cost optimum. For an oil heating system or a gas heating system, the last renovation package, which also includes measures on the window, is just as cost-effective, whereas for a heat pump system, a district heating solution or a biomass system the inclusion of measures on the window is less cost-effective. Nevertheless, the third hypothesis is confirmed.

Also when a switch to a heat pump, a district heating system with 75% biomass, or a biomass system is carried out, are measures on the building envelope cost-effective. The fourth hypothesis is therefore confirmed.

To achieve high emission reductions, it is more cost-effective to carry out energy efficiency measures while heating with a gas heating system, than to carry out energy efficiency measures and switching to a heat pump system. For the district heating system with 75% biomass, however, the situation is different: high emission reductions can be achieved at slightly lower costs than a gas or oil heating system with a large number of efficiency measures. For biomass, the most cost-effective renovation package is just as cost-effective as the gas heating system; however, it has lower carbon emissions, and it can be assumed that emission reductions of the same scope would be more expensive with a gas heating system. The fifth hypothesis is therefore partly confirmed and partly not confirmed.

Overall, for the Spanish case study two of the five hypotheses can be completely confirmed. For two other hypotheses a partial confirmation can be obtained, depending on what is understood by the RES heating system. These hypotheses are confirmed for a district heating system with biomass or a biomass system, yet not for a heat pump. The heat pump solution overall doesn't look such attractive to reduce carbon emissions and increase energy performance. However, it needs to be kept in mind that with a heat pump solution, the energy performance of the building can be further improved by combining it with a PV system to provide greener electricity for the heat pump. The findings are summarized in the following table

Table 61 Results for investigated hypotheses for the case study “Lourdes Neighborhood“ in Spain. RES refers here to heat pump, district heating with 75% biomass, or biomass. ✓ means that the hypothesis is confirmed. **X** 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	X
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 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.	✓/X*

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

5.6. Case study in Sweden

5.6.1. Building investigated

The building chosen for the case study in Sweden located in Gothenburg in the district of Backa röd, which consists of 1,574 apartments in high-rise buildings, low-rise buildings and low tower blocks built in the sixties during the ’million homes’ program. The first building to be energy renovated, is a low tower block with 16 two bedroom apartments and 4 floors. The apartments have good floor plans, with generous and easily furnished rooms. However, the buildings needed to be renovated due to maintenance needs. The buildings are typical for the seventies with a prefabricated concrete structure with sandwich facades panels, a triple layer wall. The facades 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. The buildings are heated by district heating. In each apartment there were radiators under the windows.

Fig. 3: Images of the building investigated in the case study in Sweden before (left) and after (right) the renovation.

5.6.2. Measures investigated

In the following table, different renovation packages are described for which the effects were investigated.

Table 62 Description of different packages of renovation measures M1 to M11 and of the reference case for the case study in Sweden.

Renovation Package	Description
Ref	In the reference case, the existing façade is maintained and the roof is insulated with 200 mm insulation. No further energy related renovation measures are considered.
M1	100 mm insulation of facade
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)

Renovation Package	Description
M8	M6 + new windows (U-value 0.9 W/m²K)
M9	M8 + mechanical ventilation with heat recovery
M10	M9 + building automation and low-energy lighting
M11	M10 + photovoltaic installation

5.6.3. Results

The following graphs illustrate the results of the case study:

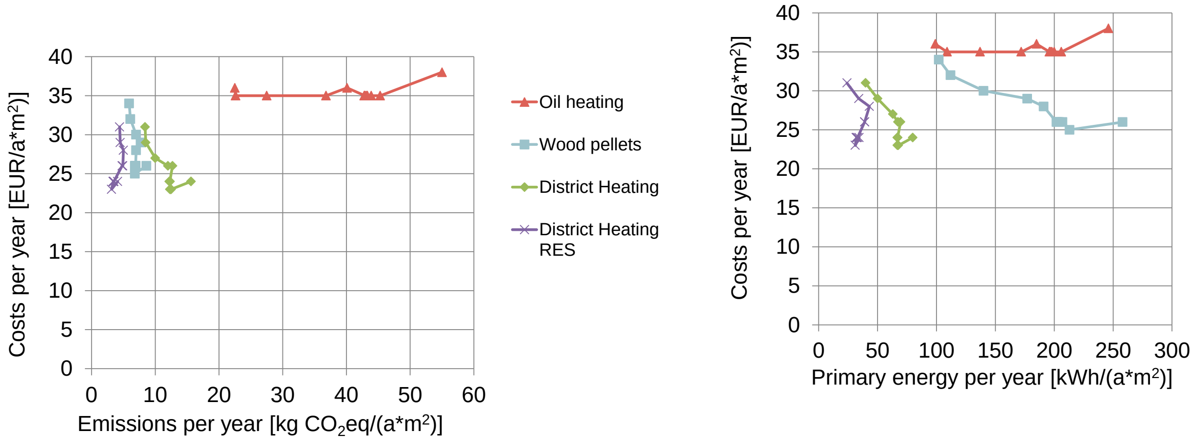


Figure 73: Aggregated comparison of cost-effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use for the Swedish case study. Note: the heating type "District Heating" contains here 81% RES, the heating type "District Heating RES" 100% RES.

5.6.4. Discussion

Three particular findings in the case study from Sweden are the following: First of all, all renovation packages investigated are cost-effective with respect to the reference. Secondly, whereas in the case of an oil heating system, also far-reaching renovation measures on the building envelope are near the cost optimum, in the case of a district heating system or a wood pellets heating system, further renovation measures beyond the insulation of the wall increase costs significantly compared to the cost optimum. Thirdly, in the case of a district heating system, some renovation measures lead to higher emissions and higher primary energy use instead of lowering them.

This latter effect is due to the fact that energy embodied in materials and related emissions are included in the calculations. It occurs if measures on the windows are included in combination with heating provided by a district heating system. For such renovation packages, increases in carbon emissions and primary energy use occur. The district heating in the case study is based on a share of 81% or 100 % renewable energies/waste heat, with particularly low greenhouse gas emission factors and primary energy factors. The effect is particularly pronounced for a district heating system based on 100% renewable energy. In the related case investigated, the more efficient window with U-value of 0.9 W/(m^{2*}K) leads to more carbon emissions than the window with U-value of 1.7 W/(m^{2*}K). Regarding overall primary energy use, both types of new windows increase it approximately equally when taking into account embodied energy. In the investigated case with a district heating system based on 81% renewable energy, the window with a lower U-value of 0.9 W/(m^{2*}K) increases emissions less than the window with U-value of 1.7 W/(m^{2*}K). Taking into account embodied energy, the window with the lower U-value does not change primary energy use; primary energy savings due to lower operational energy use are approximately equal to the embodied energy of the new window in a life cycle perspective. The window with a higher U-value does increase overall primary energy use, though, due to the embodied energy. Such negative effects on overall primary energy use and carbon emissions due to embodied energy/emissions were not observed for an oil heating system. For an oil heating system, the effects that the new windows have on reducing emissions/primary energy use because of reduced heating fuel consumption outweigh embodied energy and related emissions of the materials used. In the case of a wood pellets heating system, the new windows, when taking into account embodied emissions, increase overall carbon emissions, while overall primary energy use, including embodied energy, declines.

With respect to the different hypotheses investigated, the following can be observed (for a summary see the subsequent table):

In the case of an oil heating system, the difference of the energy performance between a window with a U-value of 1.7 W/(m^{2*}K) and a window with a U-value of 0.9 W/(m^{2*}K) is larger than the difference of the energy performance between renovation packages which include different numbers of building elements such as roof or floor insulation. Furthermore, for some heating systems, additional renovation measures increase, rather than decrease primary energy use and emissions. Accordingly, the first hypothesis cannot be confirmed.

A switch from oil heating to pellets heating or district heating reduces emissions more strongly than all energy efficiency measures when still an oil heating is used. The second hypothesis is therefore confirmed.

The cost optimum of the renovation packages investigated is the one which includes only measures on the wall, regardless of the type of heating systems investigated. The third hypothesis is therefore confirmed. It needs to be noted, however, that in the case of an oil heating system, also renovation measures beyond the cost optimum are similarly cost-effective, whereas for the RES based heating systems investigated, additional renovation measures on the building envelope reduce the cost-effectiveness relatively strongly.

Insulation of the exterior wall was found to be cost-effective in combination with a switch to the investigated RES based heating systems, however, for other renovation measures that could not be confirmed. The fourth hypothesis is therefore partly confirmed, and partly not confirmed.

By switching the wood pellets or district heating, high emission reductions can be achieved more cost-effectively than with renovation packages which are still based on a heating system with oil. The fifth hypothesis is therefore confirmed.

Overall, for the Swedish case study two of the five hypotheses were confirmed completely. For the hypothesis *"A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level"*, some reservations are made. 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 not confirmed, and the hypothesis *"Synergies are achieved when a switch to RES is combined with energy efficiency measures"* was partly confirmed and partly not confirmed.

Table 63 Results for investigated hypotheses for the case study "Backa röd" in Sweden. RES refers here to pellets heating or district heating with RES. ✓ means that the hypothesis is confirmed. **X** 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	X
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 cost-optimal efficiency level	(✓)*
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓/X*
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 the case of an oil heating system, also renovation measures beyond the cost optimum are similarly cost-effective, whereas for the RES based heating systems investigated, additional renovation measures on the building envelope reduce the cost-effectiveness relatively strongly

** Only the insulation of the exterior wall was found to be cost-effective in combination with a switch to the investigated RES based heating systems; for other renovation measures that could not be confirmed

6. Discussion

6.1. Discussion of results from generic calculations

6.1.1. Cost-effectiveness and the balance between renewable energy and energy efficiency measures

The shape of the cost curves for the investigated generic buildings varies strongly, due to specific characteristics of each building and the national framework conditions. In all generic buildings investigated there is a cost optimum, with lower costs than those of an «anyway renovation». Costs are rising for measures beyond the cost optimum, but many or sometimes all of the measures considered in the assessment are still cost-effective, i.e. annual costs from a life-cycle-perspective are lower than the cost of the anyway renovation.

Only selected types of systems using renewable energy sources (RES) were taken into account. In the cases of the countries Austria (AT), Denmark (DK), Spain (ES), Sweden (SE), Switzerland (CH), geothermal heat pumps and wood pellets heatings have been investigated as RES systems; in the case of Norway (NO) an air-water heat pump and wood logs; and in the case of Portugal (PT) only an air-water heat pump and its combination with PV were investigated as RES systems.

With respect to the energy performance of energy related building renovation measures and the balance between renewable energies deployment and energy efficiency measures, five main hypotheses have been formulated and investigated. The results based on the calculations for the different reference buildings are summarized in the following table:

Table 64 Summary of findings for testing the hypotheses by assessments of generic reference buildings from different European countries. **«SFB»** refers to single-family building, «**MFB»** refers to multi-family building. Countries are abbreviated with their two-letter code: : Austria: AT, Denmark: DK, Italy: IT, Norway: NO, Portugal: PT, Spain: ES, Sweden: SE and Switzerland: CH. In Norway, «**Mix1**» refers to an electricity mix based on national production as well as on imports and exports. «**Mix2**» refers to an electricity mix, which in addition to that also takes into account the trade in guarantees of origin / green certificates.

✓ means that the hypothesis is confirmed.

X means that the hypothesis is not confirmed.

Symbols in parenthesis indicate that the hypothesis is only partly confirmed / not confirmed.

Hypothesis	**SFB AT**	**MFB AT**	**SFB DK**	**MFB DK**	**MFB IT**	**SFB NO Mix1**	**SFB NO Mix2**	**SFB PT**	**MFB PT**	**MFB ES**	**SFB SE**	**MFB SE**	**SFB CH**	**MFB CH**
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	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	✓	✓
A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level	(X)	(✓)	(✓)	(✓)	✓	✓	✓	✓	✓	✓	(✓)	X	✓	✓
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 primarily on energy	✓	✓	✓	✓	✓	X	✓	X	✓	✓	✓	✓	✓	✓

Hypothesis	SFB AT	MFB AT	SFB DK	MFB DK	MFB IT	SFB NO Mix1	SFB NO Mix2	SFB PT	MFB PT	MFB ES	SFB SE	MFB SE	SFB CH	MFB CH
efficiency measures alone.														

The assessment also showed that while energy efficiency measures simultaneously reduce primary energy use and carbon emissions in similar proportions, renewable energy measures reduce carbon emissions more strongly than they reduce primary energy use.

Based on results from the calculations with the generic reference buildings, the following conclusions can be drawn with respect to the hypotheses investigated. Within this context, some tentative conclusions are made referring to renewable energy sources (RES) in general. However, it needs to be kept in mind that in the generic calculations carried out, only specific RES systems were taken into account. The role of solar thermal or small wind turbines has not been investigated. Moreover, not for all reference buildings all other types of renewable energy systems were looked at.

Hypothesis 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»

The hypothesis is confirmed to a large extent in different country contexts, both in single-family buildings and in multi-family buildings. The findings reflect the fact that the first few cm of insulation added have the highest impact in reducing the U-value of a certain building element, whereas marginal benefits like energy and energy cost savings decrease with further insulation. In the existing building stock, buildings often have several building elements with relatively low efficiency standards. It therefore has a higher impact if several building elements are involved in a building renovation as compared to a focus on a single building element alone. In other words, marginal benefits from improvements in the energy performance of a single building element decrease relatively rapidly.

The confirmation of the hypothesis implies that it is more important to improve significantly the energy performance of as many building elements as possible than to strive for maximum energy performance of particular building elements. However, the findings also provide support for the conclusion that it is advisable to choose a high efficiency level if the energy performance of an element of the building envelope is improved: It is much cheaper to achieve directly a high insulation standard for a certain building element than to insulate and increase the energy performance later, especially because of the lower marginal cost-/benefit-ratio of higher insulation levels, if the building has previously been insulated to some extent already.

The exceptions among the examples assessed are the buildings in Sweden. In the examined reference buildings from Sweden, an increase in the energy efficiency ambition level of measures on the wall have a higher impact on the overall energy performance than the inclusion of renovation measures on other building elements. This could be due to the fact that the temperature differences are higher in Sweden between outside and indoor temperature than in other countries investigated. Another explanation is that the generic reference buildings from Sweden have the lowest initial U-values from the reference buildings investigated.

Hypothesis 2 «A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements »

The hypothesis is confirmed for all reference buildings investigated with the exception of Norway, for several types of heat pumps and wood systems investigated as RES systems. Energy efficiency measures on the building envelope lead to rather incremental improvements, whereas a change to a renewable energy system allows large reductions of carbon emissions at once, if fossil fuels are thereby substituted. This is confirmed also in the case of substitution of average district heating in Sweden. Carbon emissions reductions which can be achieved by RES are in most of the cases higher than the reductions from the cumulated sum of all of the efficiency measures assessed and this at lower costs. For energy related renovation of existing buildings this has a high significance.

It is important to keep in mind that energy efficiency measures on the building envelope are long lasting, while the energy source of the heating system might change. Furthermore, energy efficiency measures have also potentially more important co-benefits for home-owners than a switch to renewable energies.

However, if the emission target is given equal or higher relevance than the primary energy target, these findings may imply that a shift in the energy related renovation strategy for existing buildings is appropriate. The currently prevailingly recommended two step approach for striving for nearly zero energy buildings – insulate first to a maximum and cover only the remaining energy need with renewable energy - has to be challenged for the case of building renovation, as opposed to new building construction. The results of the parametric calculations demonstrate quite clearly that for the measures considered, a strategy which contains the deployment of RES as a central element has advantages. This does not mean that there are no synergies with respect to efficiency improvements on the building envelope (see below), but it means that considering also costs, it is tentatively favourable to switch to a RES as heating system (e.g. heat pumps or wood) and choose preceding renovations on the building envelope at a level which is cost-effective taking into account the switch to RES.

The exception observed in Norway is a bit intriguing and applies only if an electricity mix is used for the calculation without taking into account trading of guarantees of origin. In that case, electricity consumption is associated with almost no emissions, as Norway's electricity production is mostly from hydropower. If an electric heating system is assumed in the reference case, emissions of the building are almost zero, and a switch to RES can therefore not reduce emissions significantly anymore. However, the trading of guarantees of origin has important implications for the electricity mix in Norway. If this is taken into account, switching to RES has a clear advantage in terms of reducing emissions as compared to energy efficiency measures, also in Norway.

The effect of a switch to RES on primary energy use is less clear. Heating systems with wood based fuels tend to have larger primary energy use than conventional heating systems, whereas heat pumps tend to lead to lower primary energy use. If only non-renewable primary energy is considered, however, also a switch to wood energy would reduce primary energy use significantly, though.

Hypothesis 3 «A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level»

This hypothesis is confirmed for a large share of the generic buildings examined. In many cases, the cost-optimal renovation package is the same for different heating systems (even though absolute costs of the corresponding optima might differ). A switch to a heating system using renewable energy sources does not change significantly cost-optimal efficiency level of measures on the building envelope. Nevertheless, the extent to which other measures near the optimum are still cost-effective, may change.

Heating systems based on renewable energies usually have lower annual operational energy costs than conventional heating systems. Hence, if a switch to renewable energies is carried out, it could be expected that the cost-optimal energy efficiency level of the building envelope is already achieved at a lower ambition level. However, the results obtained from the generic calculations with different reference buildings indicate, that if measures reducing energy need are combined with a replacement of the heating system, there are to a large extent synergies and not trade-offs between energy efficiency measures reducing energy need and renewable energy measures. Synergies result if demand side measures reduce peak capacity of the heating system. This reduces costs for renewable energy systems with typically higher initial investment costs than conventional heating systems. For heat pumps, there is an additional synergy between energy efficiency measures and renewable energy measures, as heat pumps work more efficiently if the energy need is lowered by energy efficiency measures allowing for lower supply temperature of the heating distribution systems.

Hypothesis 4 «Synergies are achieved if a switch to RES is combined with energy efficiency measures»

Synergies are understood to occur when there are cost-effective renovation packages including both energy efficiency measures and a switch of the heating system to a renewable energy system. This hypothesis is confirmed without exception for all generic buildings investigated. It is a further indication of synergies that exist between RES and energy efficiency measures, and that cost-effective renovation does not mutually exclude RES based measures and energy efficiency measures. For using synergies it is important that the energy efficiency measures are carried out before the heating system has to be replaced.

Hypothesis 5 «To achieve high emissions 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 is fully confirmed for most generic buildings investigated (except for the case of the building in Norway for the same reasons which led to an exception in Hypothesis 2, and for the single-family building in Portugal). This finding is important. As explained in the comment to hypothesis 2, these findings may lead to reappraising the basic strategies for ambitious energy related renovation of existing buildings. Since costs are a major challenge and barrier for ambitious building renovations, it is crucial to consistently exploit the range of cost minimizations while still ensuring the achievement of ambitious energy savings and carbon emissions mitigation targets. As explained above, this can be a reason for a change in priorities among RES deployment and energy efficiency improvements within building renovation processes.

It needs to be kept in mind that here only selected RES systems were investigated and only greenhouse gas emissions were looked at - wood burning for example can result in a number of other pollutants as well.

6.1.2. Comparison between multi-family buildings and single-family buildings

The following Table 65 summarizes the results for investigating the hypothesis related to the comparison between multi-family buildings and single-family buildings.

The hypothesis is only partially confirmed. This can be explained by the fact that there may be two opposite effects: on the one hand, installed heating systems in multi-family buildings are larger. This offers more opportunities for synergies due to energy efficiency measures: cost savings obtained by a reduction of the peak capacity of the heating system, made possible by lowering overall energy need of the building, are more significant for larger systems. However, at the same time the specific energy need per m^2 is smaller in multi-family buildings than in single-family buildings. This in turn means that energy use is already relatively lower, and that a change from a conventional heating system to a RES based system may bring less additional benefits.

Table 65 Summary of findings for testing the hypothesis related to the comparison of multi-family buildings and single-family buildings.

Hypothesis	Results from SFB and MFB in Austria	Results from SFB and MFB in Denmark	Results from SFB and MFB in Portugal	Results from SFB and MFB in Sweden	Results from SFB and MFB in Switzerland
In multi-family buildings, the synergies between RES measures and energy efficiency measures are larger than in single-family buildings	X	X	✓	✓	✓

6.1.3. *Effects of the ventilation system*

The following table summarizes the results for investigating the hypothesis related to the effects of a ventilation system.

Table 66 Summary of findings for testing the hypothesis related to the effects of a ventilation system.

Hypothesis	Results from SFB in Sweden	Results from MFB in Sweden	Results from SFB in Switzerland	Results from MFB in Switzerland
The installation of a ventilation system with heat recovery has effects on the energy performance comparable with measures on other building elements	✓	✓	✓	✓

The hypothesis that the installation of a ventilation system with heat recovery has comparable effects on the energy performance as measures on other building elements is confirmed. The results show that the installation of a ventilation system with heat recovery is an effective measure to reduce both emissions and energy need.

The two cases assessed for the parametric calculations resulted in additional savings of primary energy use of about – 25 kWh/m^{2}a to – 40 kWh/m^{2}a and a carbon emissions mitigation effect of about – 2 kg CO_2/m^{2}a to – 10 kg CO_2/m^{2}a. Interestingly, these savings are additional and don't reduce saving and mitigation impacts of other energy related renovation measures.

6.1.4. *Effects of embodied energy*

In calculations related to a reference single-family building from Switzerland, the following results were found:

The most far-reaching measures are a bit less favourable in terms of reduction of primary energy use when taking into account additional embodied energy use of the insulation material. This is particularly visible for the windows.

Results obtained from calculations taking into account the embodied energy use of renovation measures therefore indicate that this does have an impact on the environmental performance of high-efficiency insulation measures. The environmental benefit of some specific measures such as high-efficiency windows is reduced or even neutralized by increased use of energy for the production of the related materials. Nevertheless, the impact of embodied energy use in building renovation is rather low; it plays a smaller role than in the construction of new buildings, as relatively few components are added during the renovation process, in comparison with the construction of a new building.

A geothermal heat pump has a higher use of embodied energy, as energy is also needed to drill the borehole. The difference compared to an oil heating system is nevertheless rather small. Overall, the calculations carried out so far indicate that the advantages of switching to a renewable energy system remain, even when the additional use of embodied energy is taken into account. The advantages of changing from a fossil fuel based system to such a renewable energy based system are not significantly changed when embodied energy use is taken into account.

6.1.5. Effects of cooling

With increasing levels of insulation, the energy need for heating decreases, whereas the energy need for cooling increases. This is due to the property of well-insulated buildings to trap internal heat gains more effectively than low-insulated buildings: whereas this is a desired property for reducing heating need, in summer time this contributes to over-heating and related cooling need. The effect of insulation on cooling needs would be different if average outside temperatures were at least for a limited amount of time above the target inside temperature, as illustrated by the hypothetical case of a 30°C average temperature in July. In such a case, the insulation would help to keep the heat outside.

Under actual average temperatures, shutters may reduce the negative effect of insulation on cooling needs. The reason is that shutters effectively block heat gains through irradiance when activated.

When comparing different renovation packages in situations with and without taking into account cooling needs, the following can be observed in the three generic examples investigated: The most cost-effective renovation package in the situation without taking into account cooling, remains the most cost-effective also when cooling is taken into account. This observation is the same for a situation with shutters or without shutters. In other words: Taking into account cooling needs, with or without shutters, does not favour a different renovation package than without taking into account cooling needs in the generic example investigated.

Taking into account cooling, may have an effect, however, on the choice of the heating system. As for heat pump systems exist which can both provide heating and cooling, there is a potential for synergies by using the same energy system for both. When taking into account energy need for cooling, a heat pump solution becomes more attractive in comparison with a situation in which cooling is not taken into account.

Overall, the following conclusions can be drawn from the investigated effects of taking into account cooling needs:

- **The higher the solar irradiance, the more trade-offs** exist concerning the effects of building insulation on heating needs and cooling needs, as the effect that additional insulation increases cooling needs gets stronger**.**
- **The higher the temperature, the more synergies** exist concerning the effects of building insulation on heating needs and cooling needs, as the effect that additional insulation decreases cooling needs gets stronger**.**
- In Southern Europe, there are **in general more trade-offs than synergies** concerning the effects of building insulation on heating needs and cooling needs.
- **Shutters can reduce energy need for cooling** significantly.
- Taking into account **cooling does not change the cost-optimal package** of energy-efficiency renovation measures on the building envelope.
- Taking into account cooling needs **favours a heat-pump solution** as an energy system which can provide both heating and cooling under certain conditions.

6.2. Discussion of results from case studies

6.2.1. Cost-effectiveness and the balance between renewable energy and energy efficiency measures

The following table summarizes the results from the case studies with respect to the hypotheses investigated.

Only selected types of systems using renewable energy sources (RES) were taken into account: In the case of the building "Kapfenberg" in Austria: geothermal heat pump, aerothermal heat pump and wood pellets; in the case of "Traneparken" in Denmark: a district heating system with a share of 53% renewable energies and a heat pump; in the case of "Rainha Dona Leonor neighbourhood" in Portugal: a biomass system and a heat pump in combination with PV; in the case of “Lourdes Neighborhood“ in Spain: a heat pump, district heating system with 75% biomass, or 100% biomass; in the case of Backa röd” in Sweden: pellets heating or district heating with RES.

Table 67 Summary of findings for testing the hypotheses in the case studies from different European countries. Only selected types of systems using renewable energy sources (RES) were taken into account.
✓ means that the hypothesis is confirmed. **X** 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	**“Kapfenberg”, Austria**	**“Trane-parken”, Denmark**	**“Rainha Dona Leonor neighbour-hood“, Portugal**	**“Lourdes Neighbor-hood“, Spain**	**"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	✓	✓	✓/X	X	X
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 cost-optimal efficiency level	✓	(✓)	(X)	✓	(✓)
Synergies are achieved when a switch to RES is combined with energy efficiency measures	✓	X	✓	✓	✓/ X
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 primarily on energy efficiency measures alone.	✓	✓	(✓)	✓/X	✓

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 the deployment of energy efficiency measures”* is confirmed in all five countries, with limitations in the Spanish case study where the hypothesis is 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 and the Spanish case studies and confirmed with some reservations for Denmark and Sweden. In the Danish case study 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. In Portugal different heating systems lead to different cost-optimal efficiency levels, but the differences are small. Therefore this hypothesis is not strongly disproved by the case study from Portugal.

The hypothesis *“Synergies are achieved when a switch to RES is combined with energy efficiency measures”* is confirmed in Austria, Portugal, and Spain. In Sweden, the hypothesis is partly confirmed, and partly not confirmed. In Denmark this hypothesis is disproved. The results of the case study in Denmark showed that 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 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 that the hypothesis is only confirmed for the district heating system with 75% biomass and the biomass heating system, yet not for the heat pump. In Portugal the available data do not allow to answer this hypothesis clearly: based on the available data, it can only be concluded that it is likely that this hypothesis is confirmed also for the case study from Portugal.

6.2.2. Comparison of results from case studies with results from generic calculations

Country comparisons

For each country, generic calculations and case studies can be compared:

Austria

The results of the case study "Kapfenberg" from Austria are relatively similar to the ones of the generic calculations for multi-family buildings in Austria. The shape of the curves as well as the absolute values for costs, carbon emissions and primary energy use are relatively similar.

Denmark

The results of the case study "Traneparken" are different from the results of the generic calculations in Denmark. None of the investigated measures on the building envelope is cost-effective in the case study, whereas in the generic calculations at least the measures on the cellar ceiling and on the roof have been found to be cost-effective. In the case study, the initial energy performance of the roof is higher than in the generic calculations, 0.2 W/m^2K compared to 0.4 W/m^2K, which is an important factor for explaining differences.

Portugal

The results of the case study “Rainha Dona Leonor neighbourhood“ are to some extent similar to the ones of the generic calculations for Portugal. A similarity is that for a gas heating system, many measures are cost-effective, except new windows. Apart from that, there are several differences visible in the graphs. Explanations for that are:

In the case study, different variants of materials for the insulation measures were investigated; cork board based insulation was found to be less cost-effective than EPS or rock wool. In the generic calculation, only one material per building element was investigated. This explains a part of the differences in the graphs. Furthermore, in the case study, a broader scope of heating systems was investigated: Electric heating, HVAC + electric heating, HVAC + electric heating + solar thermal, and a biomass have been examined in the case study, whereas in the generic calculations only a heat pump with or without PV system was taken into account in addition to gas as conventional heating system.

When the impacts of heat pump + PV are compared in the case study and the generic calculations, it can be seen that in the case study, the cost curve has a different shape compared to the generic calculations: Whereas in the generic calculations, renovation packages are increasingly more cost-effective, as more measures are added, the most cost-effective renovation package is reached in the case study more quickly, after which costs increase as more measures are added. It can also be observed that overall, carbon emissions and primary energy use are much lower and costs are higher in the case study. The lower carbon emissions and the lower primary energy use could be explained by a difference in the size of the PV system: If it is larger in relative terms as compared to the generic calculation, then more emissions and primary energy use are compensated through the renewable electricity production with the PV system. A lower cost-effectiveness of energy efficiency measures may be explained by higher initial energy performance of the building in the case study.

Spain

The results of the case study "Lourdes Neighbourhood" shows some similarity with those of the generic calculations for a reference building from Spain. Several measures on the building envelope are cost-effective, for different heating systems examined. The installation of new windows is not cost-effective, both in the generic calculations and in the case study. However, in the case study in general a higher cost-effectiveness of renovation measures could be observed compared to the assumed reference case. Furthermore, in the generic calculations the heat pump examined had a better environmental performance than the heat pump examined in the case study. Costs are in a comparable range. For the gas heating and the biomass heating systems, carbon emissions and primary energy use are in a similar range as well.

Sweden

The results of the case study "Backa röd" show some similarities and also some differences to the generic calculations carried out for Sweden. In the case study and in the generic calculations, the investigated energy efficiency measures are mostly cost-efficient with respect to the reference case. In the case study and in the generic calculations, there is a package of renovation measures to increase energy performance of the building envelope which is cost optimal for all types of heating systems investigated. At the same time, in case of a switch to RES, further renovation measures beyond the cost optimum make the renovation significantly less cost-effective. Apart from these similarities, there are also differences. The curves in the generic calculations and in the case study look rather different for the situation with district heating. It needs to be taken into account that in the case study, also the heating type "district heating" contains a large share of RES. It also needs to be underlined that in the Swedish case study, embodied energy/emissions were included in the assessment. Taking embodied energy into account yields negative effects on overall primary energy use for measures on the windows, when carried out in combination with district heating. This is not the case when such measures are carried out in combination with an oil heating system or a wood heating system, as for both of them higher primary energy factors apply than for the district heating.

In the generic calculations, it was found that mechanical ventilation with heat recovery is a cost-effective solution. In the case study the mechanical ventilation is cost-neutral in case of an oil heating system, while not cost-effective for the other investigated heating systems. Additionally it was foundthat building automation and low-energy lighting are cost-effective measures in case of a combination with an oil heating system, while they are not cost-effective in case of a combination with one of the other heating systems investigated. In the case study, PV was not found to be a cost-effective measure, yet a measure which reduces emissions and primary energy use for all heating systems investigated. These additional measures have not been examined in the generic calculations.

Comparison of hypotheses

Regarding the different hypotheses investigated, results obtained from the generic calculations can be compared as follows to the results of the case studies:

Hypothesis 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

The hypothesis was more clearly confirmed in the generic calculations than in the case studies. A possible explanation is that in the case studies, the initial energy efficiency level of the investigated building elements was less uniform (higher) than in the generic calculations. This could have led to more frequent situations in the case studies in which some measures yield only small incremental benefits, whereas on highly inefficient building elements different levels of insulation thicknesses lead to relatively large differences in overall energy performance.

Hypothesis 2: A switch to RES reduces emissions more significantly than energy efficiency measures on one or more envelope elements

The hypothesis is clearly confirmed in the generic calculations and in the case studies for the RES systems investigated.

Hypothesis 3: A combination of energy efficiency measures with RES measures does not change significantly cost-optimal efficiency level

This hypothesis is confirmed for a large share of both the generic reference buildings examined and the case studies. In the case studies where this hypothesis was not confirmed, the differences were small. A similar observation has been made for the generic calculations. This means that even if in some cases the cost-optimal renovation package in terms of energy efficiency measures is not the same for different heating systems, related differences in cost-effectiveness for a given building can be expected to be small. Nevertheless, it is advisable to take into account that this hypothesis is not always confirmed.

Hypothesis 4: Synergies are achieved when a switch to RES is combined with energy efficiency measures

This hypothesis is confirmed for all reference buildings in the generic calculations and is confirmed in all except one of the case studies. The exception which was found in one case study relates to a specific building in Denmark. An explanation is that this building has a relatively high initial energy performance. Therefore, energy efficiency measures on the building envelope were not cost-effective, for any heating system. The case study in which the hypothesis was not confirmed indicates thereby that, whereas in general it can be expected that this hypothesis is fulfilled, the situation may be different in specific cases with relatively high initial energy performance.

Hypothesis 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 primarily on energy efficiency measures alone.

This hypothesis was confirmed for most reference buildings investigated in the generic calculations as well as to a large extent for the case studies. The findings from the case study in Spain show that the hypothesis may not be confirmed in the case of a switch to a heat pump, if the country's electricity mix is relatively CO_2 intensive and if no further measures are undertaken to generate part of the electricity used from a renewable energy source, such as with photovoltaics.

Overall comparison

Overall, the case studies confirm to a large extent the results obtained from the generic calculations – at the same time, they show that in an individual case it is also possible to obtain different or opposite results. This illustrates the limitations for general conclusions which can be drawn from generic calculations. For a given renovation situation, each building needs to be examined separately, since case-specific conditions may lead to different results than those obtained from generic calculations.

6.3. Sensitivities in parametric calculations

6.3.1. General comments

The findings are specific to the buildings and context situations investigated. The fact that the generic buildings represent typical situations in different countries and take into account different framework conditions strengthens the conclusions derived. Nevertheless, the results remain sensitive to several assumptions, as this has been shown in case studies and calculations on sensitivities for generic buildings. Key parameters are in particular the ones mentioned in the following chapters.

6.3.2. Influence of future energy prices

As shown by sensitivity calculations, energy prices play an important role for the cost-effectiveness of renovation measures and for a switch to renewable energy sources: The higher the energy prices, the more cost-effective renovation measures on the building envelope become. Furthermore, the higher the energy prices, the more cost-effective becomes a switch to renewable energy sources compared to a conventional heating system, which usually has lower investment costs, but higher energy costs. In addition, changes in prices of some energy carriers relative to others may favour certain technologies, e.g. lower electricity prices make it more attractive to cover heating needs with heat pump solutions.

It is challenging to predict future energy price developments. What matters from a life-cycle perspective are long-term price and cost developments. A decline in fossil fuel reserves and an ambitious climate policy (e.g. with a carbon emission tax) are factors which tend to increase fossil fuel energy prices in the future, while technological progress tends to reduce future renewable and non-renewable energy prices as well as the cost of energy conservation measures. It also needs to be taken into account that (national) energy prices for consumers partly include charges and taxes which are independent of energy price developments on the global markets, reducing thereby the relative volatility of energy prices for consumers. The sensitivity calculations which were carried out confirm that the assumptions on future development of energy prices matter.

6.3.3. Influence of initial energy performance of building envelope

The energy performance of the buildings prior to renovation has an important impact on the additional benefits of building renovation and its cost-effectiveness, since marginal benefits of additional insulation and energy performance measures on the building envelope strongly decrease with rising insulation and performance level. Hence, higher energy performance of a building before renovation reduces the economic viability of additional energy related measures because of a worse cost/benefit ratio and lower additional benefits in terms of reduction of carbon emissions or primary energy use compared to the situation before renovation.

6.3.4. Influence of climate, lifetimes of renovation measures and interest rates

Further important parameters which were so far not investigated in detail are climate, lifetimes of renovation measures and the interest rate.

It can be expected that in colder climates, energy efficiency renovation measures on the building become more cost-effective, as the temperature difference between inside and outside is higher. In warm or hot climates there can be trade-offs between architectural design, increasing energy performance of the building envelope and cooling needs. Such architectural design may concern for example the window area, orientation of windows, or heat storage capacities.

With longer lifetimes of renovation measures for given investment costs, measures increasing the energy performance of the building become more cost-effective. If the lifetimes are shorter, improvements of the energy performance are less cost-effective.

Considering the interest rate, it can be expected that the higher the interest rate, the less cost-effective are investments to improve the energy efficiency of the building or a switch to a renewable energy system since they have typically higher investment costs and lower energy costs. A higher interest rate favours energy intensive solutions at the expense of investment and capital cost intensive energy conservation and renewable energy deployment measures.

7. Conclusions and recommendations for cost-effective energy and carbon emissions optimized building renovation

7.1. Conclusions from parametric assessment of renovation solutions

General conclusions

A large unused potential for cost-effective reductions of carbon emissions and primary energy use in buildings exists

The parametric calculations which were carried out for generic reference buildings and case studies have shown that there is in general a large potential for cost-effective building renovations which reduce carbon emissions and primary energy use significantly. Both energy efficiency measures and measures to switch to renewable energies contribute to these objectives. These results have been obtained based on assuming a moderate real interest rate of 3% and an increase in energy prices by 30% compared to prices of 2010.

It was recognized that there is an important difference between cost-effectiveness and cost-optimality. Cost-optimality refers to the most cost-effective renovation package in absolute terms. Cost-effectiveness is related to a reference case. The reference case is understood to refer to the initial situation of the building combined with measures which would hypothetically be necessary "anyway", just to restore the functionality of the building elements, without improving the building's energy performance. With the exception of rare cases in which no measure is cost-effective at all, more measures can be carried out in a building renovation when cost-effectiveness is set as a limit compared to a renovation which focuses only on cost-optimality. In the generic calculations, differences between the cost optimum and the extent to which measures are still cost-effective have been found to be particularly large in Denmark, Sweden, and Switzerland.

It is also important to understand cost-effectiveness from a life-cycle perspective. Building renovation measures do not pay off in a few years, but rather bring economic advantages in the long run. In order to highlight the benefits of building renovation, it is therefore necessary to focus on the long-term perspective, and not just to compare investment costs of renovation measures or to focus on measures with short payback times.

Mix of cost-optimal renovation measures mostly does not depend on the type of heating system, yet exceptions exist

The results obtained from the generic calculations and case studies indicate that in most of the cases, when a switch from a conventional heating system to wood pellets or a heat pump is made, this does not have an impact on the most cost efficient package of energy efficiency measures. Or in other words: The combination of energy efficiency measures which is determined to be cost-optimal when the building has a conventional heating system, is in most of the cases also the cost-optimal combination of renovation measures when a switch to one of the mentioned renewable energy systems is carried out. This does not mean that the cost optimum remains the same in absolute terms, with equal costs, carbon emissions and primary energy use, independent of the choice of the heating system; on the contrary, the cost optima often differ quite strongly for different heating systems. Instead, it means that most often, the selection of the type of energy efficiency measures to reach a cost optimum can be done independently of the type of heating system considered. Consequently, in many cases there are no trade-offs between renewable energy measures and energy efficiency measures; it is often not necessary to differentiate the cost-optimality of energy efficiency measures with respect to different heating systems.

However, in some cases results were also found showing that there are cases where the mix of energy efficiency measures which is necessary to reach the cost optimum is slightly changed by a switch to wood pellets or heat pump.

Heating with renewable energy such as wood pellets heating or heat pumps: The most powerful measure to cost-effectively reduce carbon emissions

Presupposing the assumptions made for the parametric calculations, deployment of renewable energy is often the measure which reduces carbon emissions most significantly. It was observed that a substitution of a conventional heating system based on fossil fuels with a renewable energy system reduces carbon emissions in many cases more significantly than energy efficiency measures on the building envelope, even when they are combined.

Heat pumps and wood heating systems play an important role, since they allow to replace conventional heating systems completely. Solar energy can in principle cover heating needs as well; however, it can do that mostly as a system to cover only a part of the heating needs. Solar energy could substitute other forms of heating completely, but only with large storage capacities. Such large storage capacities can be installed in new buildings, yet hardly in existing buildings. Apart from using solar energy as a source for providing heat with solar collectors, solar energy can also be used to generate electricity. In combination with a heat pump, solar electricity can in turn be used as a source for providing heating or cooling to the building.

The benefits of heat pumps to reduce carbon emissions depend on the electricity mix, as heat pumps require electricity to operate. The benefit of heat pumps is particularly high in countries where the share of renewable energy in the electricity mix is already high. The environmental benefit of heat pumps can be increased by combining it with on-site renewable electricity production, for example with a PV system.

Fully integrating costs in the assessment discloses that in the case of building renovation, deployment of renewable energy is mostly the measure which reduces carbon emissions with the best cost/benefit relation. Exceptions were found in Spain, where gas is more cost-effective because of low gas prices, and in Norway and Switzerland for wood pellets. Sensitivity calculations indicate that lower energy prices favour conventional energy use and efficiency measures from the perspective of the cost-effectiveness, but deployment of wood pellets heating or heat pumps are still the measures with the highest single impact on emissions mitigation from the measures investigated.

Heat pumps often also reduce significantly primary energy use, wood pellets heating reduces only non-renewable primary energy use

A shift to renewable energy use has a high impact on non-renewable energy use, similarly to its impact on reducing carbon emissions. If overall primary energy use is considered, however, the situation is less straightforward. On the one hand, primary energy use of wood pellets heating is higher than the one of conventional heating (except in the Norwegian case for electric heating if Norwegian imports and exports of guarantees of origin of the electricity consumed are taken into account). On the other hand, a change to a heat pump system is the single measure with the highest impact for reducing primary energy use in most of the countries for which generic calculations were carried out.

Conclusions for standard setting and policy making

Bearing in mind the preceding observations and conclusions for building renovation, the following indications for standard setting and policy making can be derived:

Lack of building sector targets focusing on carbon emissions or on non-renewable primary energy

Climate change is one of the major challenges of this century. At EU-level, ambitious targets for reducing greenhouse gas emissions have been formulated. The EU's goal is to reduce greenhouse gas emissions in the EU by 80% - 95% by the year 2050 compared to 1990. This is highly ambitious, considering the vast amount of daily activities which cause greenhouse gas emissions. This overall target means that the target for the building sector needs to be even more ambitious. In the building sector, greenhouse gas emissions can be reduced to zero with today available technology . The situation is different for the transport sector, where the emissions of airplanes can be eliminated only with difficulty, and also the reduction of emissions from cars is faced with challenges such as mileage or availability of filling/charging stations.

Also in agriculture, methane emissions or nitrous oxide emissions can hardly be eliminated to a large extent. This means that an overall 80%-95% reduction of greenhouse gas emissions can only be achieved if in the building sector, essentially a 100% reduction of greenhouse gas emissions is pursued.

The targets set by energy policy and climate policy for the building sector have so far focused on reducing primary energy use in buildings. The main measures to reduce primary energy use are energy efficiency measures on the building's thermal envelope. Energy efficiency measures reduce simultaneously carbon emissions and primary energy use. However, apart from energy efficiency measures, there is also an alternative way how carbon emissions can be lowered, by switching from a conventional, fossil fuel based heating system to a renewable energy source. This switch does not necessarily reduce primary energy use to the same extent as carbon emissions.

A switch to a wood heating system, for example, reduces carbon emissions strongly, whereas primary energy use often does not decrease, but increase. The primary energy in the wood is accounted for in a similar way as the energy in oil or gas, although the effect of using wood energy on carbon emissions is much lower: CO_2 emissions occurring when wood is burnt are compensated by the regrowth of the wood in the area from which the wood was taken out.

To give another example: A switch to a heat pump, does often reduce primary energy use, yet not to the same extent as carbon emissions are reduced. The reason is that the factor which is used to determine the primary energy content of the electricity used to operate the heat pump usually takes into account electricity from renewable sources with a factor of 1 and electricity from nuclear energy with a factor of 3 to 4. Both forms of electricity production cause only a relatively small amount of CO_2 emissions.

This means that by putting a focus on the reduction of primary energy use and not on the reduction of carbon emissions in the building sector, there is a risk that the renewable energies' potentially highly important contribution to eliminate carbon emissions from buildings is systematically underestimated or not adequately taken into account. A solution could be to formulate carbon emissions target for the building sector supplementing existing energy targets.

If the focus on primary energy use is kept, the role of renewable energies for mitigating climate change can be more adequately taken into account if just the non-renewable part of the primary energy use is considered. This would mean that for renewable energy and for the share of renewable energy in the electricity mix primary energy factors of nearly zero are used.

Renewable energy measures often reduce carbon emissions more cost-effectively than energy efficiency measures

Transformation of the existing building stock for meeting the ambitious emission targets has to be carried out at least possible costs to give this transformation a chance. The parametric calculations that have been carried out show that renewable energy measures often reduce carbon emissions more cost-effectively than energy efficiency measures. Acknowledging the large possible contribution of renewable energy based heating systems to reduce emissions at least costs, it is recommended to consider the development of standards to increase the use of renewable energies.

Current building codes may be counterproductive for reducing carbon emissions

The parametric calculations have shown that in many cases, there are synergies between energy efficiency measures and renewable energy based measures and not trade-offs. However, in the calculations some examples were found where the combination of energy efficiency measures on the building envelope to reach a cost optimum is not the same for different heating systems. In such a case, situations may arise in which requirements set by standards to achieve a certain energy efficiency level in building renovation could be counterproductive for reducing emissions. For example, as long as a certain building is heated with natural gas, it could be cost efficient to install new windows to increase the energy efficiency; however, if a switch is made to a heat pump or a wood pellets system, it may be that the installation of these windows is no longer cost-effective, as heat pumps and wood pellets systems often have lower annual energy costs. Requiring to carry out related energy efficiency measures could effectively mean that a continued use of a gas heating is promoted, whereas a switch to a renewable energy system could reduce emissions more significantly.

Furthermore, the calculations carried out were based on the assumption that energy efficiency measures and the switch to a RES-heating system are carried out simultaneously. This is a presupposition that synergies can be used by installing smaller sized heating system due to the reduced energy need because of energy efficiency measures. If this is not the case, because a renewable energy system has already been installed, it can be expected that measures on the building envelope are less cost-effective with such a renewable heating system. This was confirmed in one example of the sensitivity calculations. The cost-effectiveness is improved again only when the heating system needs to be replaced next time and its size can be decreased taking into account the reduced energy need.

Several options exist on how this may be taken into account in standard setting. A first possibility is to differentiate energy efficiency standards according to the type of heating system. This could mean that to be able to continue using conventional energy carriers in a certain building, a higher level of energy efficiency standards would have to be reached than if the building is only heated with renewable energies. Another possibility could be to introduce two types of energy efficiency standards, one regulating overall primary energy use or energy need (per m^2 and year), while the other regulating non-renewable primary energy use or carbon emissions (per m^2 and year) of a building. The standard regulating overall primary energy use or energy need could be made less strict than the standard for non-renewable primary energy use or carbon emissions. Thereby potential obstacles to switch to renewable energies can be reduced, while efficiency requirements are kept also for buildings heated with renewable energies. The standards related to non-renewable primary energy use or carbon emissions could be made stronger to set additional efficiency requirements for buildings which are not heated with renewable energies. They could encourage or even force a change to renewable energies. A third possibility could be to introduce an exception clause into standards which could provide that if it can be proved that a certain energy efficiency measure is not cost-effective in combination with a switch to a renewable energy system, there is only an obligation to carry out the related energy efficiency measures to the extent they are cost-effective. To manage procedures related to such a solution might be challenging; this could be assisted by defining precisely the framework parameters to be applied in related cost-effectiveness calculations and by providing templates for carrying out such calculations.

Whether it makes sense to adapt building standards accordingly, depends, however, also on other reasons which favour carrying out energy efficiency measures (see below).

Improvement of energy performance of the building envelope within building renovation is indispensable and has important co-benefits

Even if energy or carbon emission targets can be reached to some extent by using renewable energies, without making use of energy efficiency measures, there are numerous reasons for carrying out energy efficiency measures during building renovation:

- Energy efficiency measures increase thermal comfort and have also other co-benefits (see separate report in Annex 56 on co-benefits, Ferreira et al. 2015).
- Energy efficiency measures are often necessary to ensure sufficient thermal quality of the building envelope and to prevent damages resulting from problems with building physics
- Carrying out energy efficiency measures is often cost-effective when carried out in combination with a switch to renewable energies. A reduction of the energy use of the building through energy efficiency measures, allows to reduce the capacity of the installed heating system, which increases cost-effectiveness. Synergies are thereby created.
- If the electricity mix is to a large extent CO_2-free because of high shares of renewable energies or nuclear energy, only energy efficiency measures can ensure that electricity use in buildings is reduced.
- Biomass is a limited resource. Biomass can also be used for other purposes than for the heating of buildings. Apart from being used as a resource in production processes or for construction, it can be transformed into liquid fuels for transportation. If biomass is used for heating, it may be advantageous to burn it in large combined heat and power plants rather than in small-scale domestic heating systems. On the one hand, biomass can thereby also be used to generate electricity in winter months, when sunshine and electricity output from PV plants are smaller; on the other hand, local air pollution by particulate matter from

burning biomass is a factor that needs to be taken into account, particularly because related pollution occurs in residential areas. It is easier to control these emissions in larger biomass plants. Furthermore, the sustainability of biomass, exploited in a sustainable way, is an important aspect.

— The availability of renewable energies other than biomass, such as solar energy or wind energy, depends on the season.

— If a large number of heat pumps using geothermal or hydrothermal resources are located close to each other, they may reduce the efficiency of each other, by overexploiting the heat source and thereby lowering the temperature of the heat source. The efficiency of the heat pump decreases when the difference between the temperature of the source and the supply temperature required in the heat distribution system increases. If the energy need of the buildings is reduced, such negative factors are reduced. Furthermore, in some areas the installation of a large number of heat pumps may require grid reinforcements. If the energy need of buildings is reduced, so are the peak capacities required for the heat pumps and related grid reinforcements.

— The lifetime of many RES systems is shorter than the lifetimes of measures on the building envelope. If these RES are then not replaced again with RES systems, the efficiency of the building will be reduced drastically. At this point in time, it is not certain that the RES systems will actually be replaced by new RES systems. In contrast, the energy efficiency measures on the building envelope have a longer lifetime, and their long-term effect is therefore more certain. The lifetime of windows is shorter than that of other building elements, but these will most certainly be replaced with windows of the same or of a higher standard.

Decentralized renewable energy systems vs. centralized renewable energy use in district heating systems

Once it is acknowledged that it makes sense to promote more strongly the use of renewable energies for reducing carbon emissions from buildings, a second question is whether it makes more sense to use them in decentralized systems or in centralized district heating systems. This question was not specifically investigated as a part of this project. However, the question is important, in particular for buildings which are connected to a district heating system and for which a switch to a renewable energy system is under discussion. It is necessary to explore related questions in more detail.

Standards and incentives in the case of a replacement of the heating system

The results found in this study indicate that from a perspective of reducing carbon emissions at least costs, a shift to renewable energy sources makes a large difference. A change to heating with renewable energy such as wood energy or a heat pump can reduce emissions substantially and cost-effectively and this often to a further extent than single energy efficiency measures while keeping the existing energy carrier.

A simple, yet highly effective measure could be, to extend the principle that improvements of the energy performance are mandatory as long as they are cost-effective also to the heating system. This could mean that a new standard is adopted requiring a switch to a renewable energy system in case of a replacement of a conventional heating system, as long as such a switch is cost-effective.

Synergies between renewable energy measures and energy efficiency measures

The moment of replacement of the heating system is a good opportunity to combine a switch to renewable energies with energy efficiency measures on the building envelope: As the energy need of the building is reduced, peak capacity of the heating system can be reduced as well. This is a key driver for making many energy efficiency measures of the building envelope cost-effective in combination with a switch of the heating system. If this opportunity is missed and the dimensions of the heating system are determined without taking into account improvements on the building envelope, subsequent energy related renovation of the building envelope will be less cost-effective and the heating system will be more expensive because of a higher capacity.

For heat pumps, there is an additional factor which strengthens such synergies: The efficiency of the heat pump is higher, if the energy need of the building is reduced, because this means that the supply temperature in the heat distribution system can be kept lower. This is beneficial for the efficiency of the heat pump, because the efficiency increases as the temperature difference between the temperature of the heat source and the supply temperature of the heat distribution system, which the heat pumps needs to overcome, decreases.

Financial resources (financial liquidity) can, however, be the bottleneck for carrying out a shift to a renewable energy system and for improving the energy performance of the building envelope at the same time. Furthermore, often the building envelope doesn't need renovation yet at the point of time the heating system has to be replaced.

Number of building elements involved in building renovation and energy-efficiency levels of individual building elements

From parametric calculations the following conclusions can be derived: In order to improve a building's energy performance, it is important to improve energy performance of all elements of the envelope. For each single building element, there are distinctly decreasing marginal benefits of additional insulation. For example, increasing the thickness of the wall's insulation from 12 cm to 30 cm has often less impact on energy savings than limiting the wall's insulation at 12 cm and adding to the roof an insulation of 10 cm thickness.

But at the same time, it is recommendable to choose ambitious energy efficiency levels to the extent possible or economical, in order to not miss opportunities within building renovation, if the building envelope is energetically improved. Once the insulation measures are carried out, it is usually not cost-effective anymore to add further insulation at a later point of time, because the marginal cost-/benefit ratio is unfavourable then. This would lead to a lock-in effect: the building owners are trapped by preceding investment decisions and would often have to decide for measures with an unfavourable cost-/ benefit ratio if it was required to get closer to the nearly zero energy target.

For stepwise renovation it is recommendable to have a medium to long term plan for the different steps, making sure that insulation added over time are matched to each other and that potential problems arising from adding insulation not at the same time are avoided to the extent possible.

Impact of embodied energy use and embodied emissions of renovation measures is smaller than for new building construction, yet plays a role for high efficiency buildings and for heating systems based on renewable energies or district heating

The calculations carried out indicate that in the case of building renovation in general, taking into account energy and emissions embodied in the renovation materials has a low impact on the primary energy use or carbon emissions. This may change for high efficiency buildings and for buildings heated with renewable energies or district heating with a low carbon emission factor. In particular high efficiency windows may sometimes require more additional energy for their construction than what they additionally save during their time of service. When the heating system is based on renewable energies or district heating with waste heat and renewable energies, the effects of embodied emissions are becoming more important, because the emission reductions obtained with additional insulation are smaller.

Constraints and non-synchronism in building renovation

Renovation projects are often limited by case-specific constraints and interdependencies and do not comprise a complete set of measures on the building envelope and on the energy system. The reasons are in particular financial constraints and non-synchronism of renovation needs of the energy related building elements at stake. What is recommendable in a given situation can only be answered on a case by case basis, by assessing different packages of renovation measures needed which take into account immediate renovation needs, financial resources and at least midterm planning of upcoming renovation needs. There might be situations in which a switch to a renewable energy system is made without improving energy performance of the building envelope if the envelope does not need renovation yet. But the related advantages and disadvantages have to be assessed for the particular situation, taking costs, thermal comfort and possible problems with building physics carefully into account.

7.2. Recommendations for cost-effective energy and carbon emissions optimized building renovation

1. Setting new targets to reduce carbon emissions from buildings, supplementing existing energy targets

The EU's Directive on the energy performance of buildings (EPBD) is the main instrument for reducing energy use and carbon emissions in the building sector at EU level. It regulates how minimum energy targets for new and existing buildings have to be determined by the Member States. Targets for the energy performance of new buildings, existing buildings undergoing major renovation, or the renovation of individual building elements which have a significant impact on the energy performance of the building envelope have to correspond at least to the energy performance level achieved by cost-optimal energy efficiency measures. For building renovation, such targets are only required to the extent they are technically, functionally and economically feasible.

For new buildings, the requirement is to achieve a nearly zero energy level and to cover the remaining nearly zero or very low amount of energy required to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (two step approach). In the EPBD, the emission target is expressed only in a general manner and it is not quantified. Accordingly, resulting regulatory efforts focus primarily on establishing energy targets.

For building renovation, there is currently no requirement in the EPBD to cover the remaining energy need by renewable energies. However, to reduce the carbon emissions of existing buildings beyond the cost-optimal level of energy efficiency measures, renewable energies have an important function. In building renovation, energy standards based on cost-optimal energy efficiency levels will not allow meeting nearly zero energy targets. Taking costs into consideration, cost-optimality is often achieved at levels far from nearly zero energy levels. To further reduce carbon emissions, it is often more cost-effective to use renewable energy sources than to strive for reducing energy need of buildings by further increasing the energy performance of the building envelope. Marginal cost/benefit ratios of renewable energy use are often better than the ones of further increasing energy performance of the building envelope for reaching nearly zero emissions or nearly zero non-renewable energy use. Parametric calculations performed with different packages of energy related renovation measures in eight European countries highlight the relevance of using renewable energy in building renovation if low remaining emissions and non-renewable energy use are aimed for at lowest possible costs.

Emission targets and use of renewable energy sources can be connected. If there was a target on reducing emissions to nearly zero in building renovation, this would normally mean that further measures have to be undertaken to reduce emissions beyond the cost-optimal level of energy efficiency measures, by switching to renewable energies.

In this situation it is appropriate to increase the relevance of carbon emissions reduction goals by establishing carbon emissions targets for existing buildings.

The emission targets for the building stock ideally supplement targets for the energy performance of the building envelope, corresponding to the target setting required e.g. by the EPBD. Energy targets remain highly important, even if additional carbon emission targets are adopted: Carbon emission targets alone do not create incentives to reduce the use of electricity provided by renewable energies or nuclear energy, they do not create incentives either to reduce the use of renewable energy sources which are only available to a limited extent, such as wood. Furthermore, energy targets also ensure sufficient quality of the building envelope and installations, and bring important co-benefits such as good thermal comfort, good indoor air quality. They also help avoid problems with building physics. The reduction of energy use in buildings is a well understood and accepted concept.

An additional emission target makes sense particularly for existing buildings. The nearly zero-energy target for new buildings already ensures a minimization of their carbon emissions. In the case of existing buildings, a nearly zero-emission target complementing the energy targets could ensure that also in these buildings the necessary transformation to a 100% reduction of carbon emissions is achieved.

Theoretically, non-renewable energy targets can be equivalent to emission targets for the purpose of promoting the use of renewable energies in buildings. However, the concept of emission targets is potentially more easily understandable and can be distinguished more easily from the currently existing energy targets. Furthermore, in some countries, standards do not refer to the energy consumption of the building taking into account the energy carrier of the heating system, but to the energy need, calculated only on the basis of the building envelope, without taking into account the type of heating system.

The setting of an emissions related target supplementing existing energy targets would allow overall cost optimization and maximum freedom of choice. It would provide freedom to select the most appropriate energy related measures within building renovation to reach related targets. Energy efficiency requirements of the building envelope are particularly suited up to the cost-optimal levels of the building envelope; beyond that point, it is advantageous to put the focus on nearly zero emissions or nearly zero non-renewable energy use. The choice between energy saving measures, increasing energy efficiency and deployment of renewable energy for a particular building will then depend on the prerequisites of the building, on the framework conditions and on the cost/benefit ratios of possible measures. Use of limited renewable energy sources will depend on their price, which of course increases if wide spread use of such resources increases their scarcity, assuming that their use is restricted to a sustainable level.

In short, taking into account the importance of reducing carbon emissions in the building sector, and not just energy use, may lead to a "nearly zero-emission" concept for building renovation, while energy efficiency measures continue to be required to the extent they are cost-effective in such a nearly zero-emission solution.

Recommendation 1: Setting new targets to reduce carbon emissions from buildings, supplementing existing energy targets

For building owners: In addition to carrying out energy efficiency improvements in building renovation, it makes sense to consider reaching nearly-zero emission in existing buildings, to make an important contribution to protect the climate.

For policy makers: It is advisable to introduce a target to reach nearly zero carbon emissions in existing buildings undergoing a major renovation, complementing existing energy efficiency requirements. If this is not cost-effective, for example because the heating system would not have to be replaced anyway in the near future, exceptions can be made. For buildings connected to a district heating system, it is possible to reach the goal of nearly zero carbon emissions collectively by transforming the energy source of the district heating system. In such cases it is advisable to develop the most favourable strategy in cooperation with building owners.

2. Switching heating systems to renewable energies

In terms of single measures, the most significant measure to reduce carbon emissions from energy use in buildings is often a switch of the heating system to renewable energies. It is also in many cases a cost-effective measure. Whether the measure makes sense ecologically, needs to be evaluated in each case separately. For a switch to heat pumps, the carbon intensity of the national electricity mix is an important factor. For a switch to wood heating, the availability of regional wood resources needs to be considered. Solar energy can add an important contribution in most cases, for providing domestic hot water, heating or cooling, or by improving the electricity mix of a specific building with a PV system. In case of a district heating system, it also needs to be taken into account in each case separately, whether an individual system or a connection to the district heating system is more advantageous.

A switch to renewable energies is also an option to improve the energy performance of a building when regulations on the protection of monuments or other characteristics of a given building limit the range of feasible renovation measures on the building envelope.

Because of its importance for reducing carbon emissions from energy use in buildings, it is recommended to make a switch of the heating system to renewable energies mandatory when a heating system is changed. The measure is similar to existing mandatory requirements related to energy efficiency measures when carrying out a renovation of the building envelope.

However, it is a general principle established in the energy policy of many countries that building owners are not required to undertake renovation measures which are not cost-effective over the economic lifecycle. Therefore, an exception is formulated: If it is shown for a given building that no switch to one of the available renewable energy sources is cost-effective, an exception could be granted from the rule that a switch to renewable energies is mandatory when the heating system is replaced. National administrations could prepare calculation tools, including specific assumptions on the future development of energy prices, to facilitate and to harmonize related demonstrations of lack of cost-effectiveness.

Recommendation 2: Switching heating systems to renewable energies

For building owners: Before a conventional heating system is replaced by one with the same energy carrier, it is advisable to take into consideration a switch of the heating system to renewable energy; in many cases, this is ecologically and economically attractive over a life-cycle perspective. For buildings connected to a district heating system, it is advisable to take into account the current energy mix of the district heating system and the possibility that a switch to renewable energies may occur in the future for the entire district heating system.

For policy makers: It is adequate to make a switch to renewable energies mandatory when a heating system is replaced, similarly to energy improvements of the building envelope. Exemptions may still be granted from such a rule, if the building owner can show that such a measure would not be cost-effective from a life-cycle perspective. Exemptions could also be made if a building is connected to a district heating system which either already has a high share of renewable energy or for which a plan exists to switch it to renewable energies.

3. Making use of synergies between renewable energy measures and energy efficiency measures

The moment when a heating system needs to be replaced, is an ideal moment to carry out a major renovation involving both the heating system and one or more elements of the building envelope. This allows to create synergies between renewable energy measures on the one hand and energy efficiency measures on the other hand. The better the insulation of the building envelope is, the smaller is the required capacity of the heating system. Therefore, additional energy performance related investments on the building envelope lead to reduced investment costs for the heating system. This means that at the time when the replacement of the heating system is made, ideally also measures on the building envelope are carried out.

It makes sense to combine several measures on the building envelope in order to benefit from synergies between them, for example due to sharing planning costs, costs for scaffolds and other costs. Combining several measures on the building envelope also facilitates to avoid potential problems when only one element of a building envelope is energetically improved. For example, when the exterior wall is insulated, the joints of the exterior wall, e.g. the joints between the wall and the roof, between the wall and the windows, or between the wall and the foundation, potentially create thermal bridges that can result in problems with indoor climate or mold. This can be avoided by insulating the joints as well or the joining constructions, which is much easier if the building elements are renovated at the same time. Furthermore, when new windows are installed, the frame needs to take into account a potential increase in the thickness of the wall due to energetic insulation, which is easier to ensure if both building elements are renovated at the same time.

To what extent it makes sense to postpone or schedule earlier than necessary renovation measures of some building envelopes, in order to make use of such synergies, needs to be evaluated in each specific case.

Recommendation 3: Making use of synergies between renewable energy measures and energy efficiency measures

For building owners: The replacement of the heating system is an excellent opportunity to carry out renovation measures on the building envelope as well, creating synergies. If carried out together, the investments in the building envelope result in savings on the investment costs for the heating system, because the more energy efficient a building is, the smaller can be the dimension of the heating system. Furthermore, several measures of the building envelope are preferably combined. It is necessary to look in each case separately, to what extent it makes sense to postpone or schedule earlier than necessary renovation measures of some building envelopes, in order to make use of such synergies.

For policy makers: It is recommendable that standards and other policy measures, for example subsidies, create incentives to combine renovation measures on the building envelope with a replacement of the heating system, in order to make sure that reductions in energy use and emissions are achieved most efficiently. Exceptions could be made for buildings connected to a district heating system, which already has a high share of renewable energy or for which a switch of the district heating system to renewable energy sources is planned.

4. Orientation towards cost-effectiveness rather than cost-optimality to achieve a sufficiently sustainable development of the building stock

The EU's EPBD focuses on cost-optimal measures. Since in building renovation cost-optimal solutions won't result in nearly zero energy buildings, it is indispensable to go a step further and tap the full potential of **cost-effective** energy related renovation measures with respect to a reference case. All renovation packages having lower life cycle costs than the reference case are considered to be cost-effective, even if costs are beyond the minimal costs of the cost-optimal package of renovation measures.

Furthermore, if co-benefits of building renovations are quantified for a given renovation, this further increases the scope of renovation measures which are cost-effective.

Recommendation 4: Orientation towards cost-effectiveness rather than cost-optimality to achieve a sufficiently sustainable development of the building stock

For building owners: To obtain the largest possible impact from building renovation in terms of contributing to the reduction of carbon emissions or primary energy use, it is advisable to carry out the furthest reaching renovation package which is still cost-effective compared to the reference case, rather than to limit oneself to the cost-optimal renovation package. Taking into account co-benefits may extend the renovation measures which are considered to be cost-effective even further.

For policy makers: It is recommendable that standards do not limit themselves to make an energy performance level mandatory up to the cost-optimal level, but to make also further measures mandatory as long as they are cost-effective with respect to a reference case.

5. Making use of opportunities when renovations are needed "anyway"

The need to renovate buildings' envelope or its technical installations represents an excellent opportunity for improving their energy performance. Many energy efficiency measures are profitable when a renovation of the related building elements is needed anyway to restore their functionality. Such measures which would be necessary anyway, are for example repainting or repairing a wall, or making a roof waterproof again. In such a case, the life-cycle costs of a scenario with an energetic improvement of the building performance can be compared with a scenario in which only the functionalities are restored. The actual costs of the energy measures will then only comprise the difference between these two scenarios. If a renovation is not carried out at a time when such a renovation needs to be carried out anyway, the cost-effectiveness of energy related measures will be lower, and it may take another 20-40 years until the opportunity is reappears.

Recommendation 5: Making use of opportunities when renovations are made "anyway"

For building owners: Whenever a renovation of an element of the building envelope or of the building integrated technical systems needs to be carried out anyway, this is a good opportunity to improve the energy performance of that element of the building elements, and to improve also other building envelope elements.

For policy makers: It makes sense that standards for achieving improvements in energy performance focus on situations when one or more building elements are anyway in need of renovation.

6. Taking into account the complexity of building renovation in standards, targets, policies, and strategies

A large number of factors have an influence on determining which measures for a reduction of energy use and carbon emissions mitigation are technically possible and economically viable for the renovation of a given building. The identification of cost-effective solutions yielding far reaching energy or carbon emissions reductions is therefore more complex than for new buildings.

At the same time, the need to identify such least-cost paths and to tailor requirements accordingly is high. At the political level, it is important to demonstrate that the existing targets of energy policy and climate policy are achieved at the lowest cost possible. The building stock has a high relevance for the overall targets on energy savings and carbon emissions mitigation. Whatever the solutions are for building renovation, their effectiveness will determine to a large extent the effectiveness of climate and energy policy as a whole. Furthermore, from the perspective of building owners, only standards, targets and policies directed towards cost-effective solutions are acceptable.

Accordingly, it is important to take into account the complexity of building renovation in the setting of standards, targets and policies and to tailor them with respect to the requirements of the existing building stock.

For individual building owners, it makes sense to take into account the specificities of a given building by developing a long-term strategy how to best improve the energy performance of a given building yielding maximal added value. This may also include stepwise renovation. It could mean for example to start by insulating the roof, insulate the wall and replace the windows in five years, and switch to renewable energies the next time the heating system needs to be replaced in ten years.

Recommendation 6: Taking into account the complexity of building renovation in standards, targets, policies, and strategies

For building owners: The complexity of building renovation and the large investments needed require the development of long-term strategies for maintenance, energy improvements and carbon emissions improvements for each building, taking into account their specific situation. It is advisable to develop either a strategy towards a major renovation or a strategy to renovate the building in steps over the years. In the latter case, the measures which are undertaken in one step ideally already include the preparation of further renovations in the future.

For policy makers: To achieve the large reduction of energy use and carbon emissions in existing buildings most-effectively, it is important that standards, targets and policies take into account the complexity of building renovation while seeking for least cost solutions or for least cost paths. Flexibility is needed to give renovation strategies a chance to enabling the transformation of the building stock towards low energy use and nearly zero emissions. This includes the flexibility to reach these targets in steps over time.

8. Outlook

Midterm and long term targets announced by climate and energy policy are ambitious. The EU has set medium and long term targets to reduce primary energy use and carbon emissions as well as to increase renewable energy generation and renewable energy deployment. Reducing greenhouse gas emissions by 40% below 1990 levels until 2030 was decided in combination with an increase of energy efficiency by 27% compared to projections and a share of renewable energies in the EU's energy consumption of also 27% (European Commission 2011a). Furthermore, the EU has declared to strive for greenhouse gas emission reductions in the range of 80% - 95% below 1990 levels by 2050 (European Council 2014).

Since most of energy use and carbon emissions in the building sector will be caused by the existing building stock, energy performance of currently existing buildings has to be improved significantly in the future. But improving energy performance as well as extending deployment of renewable energy sources is more complex in the case of existing buildings than for new buildings. There are many hindering parameters of existing buildings as well as unfavourable framework and context conditions, which play a more relevant role than in the case of new buildings. The range of technical solutions is more limited, costs are often increased and good solutions are often not straightforward.

Within the framework of the activities in Annex 56 results from calculations with generic buildings and case studies are presented in this report. A contribution was made to explore the related challenges. Recommendations have been given on how the special characteristics of the building stock can better be taken into account in the future.

The challenges remain high. A building stock with significantly higher energy performance and less emissions is needed. Further research will be needed to further explore the related questions and overcome the many existing obstacles.

A particular topic which is interesting to be investigated further is the relationship between transforming existing district heating systems to renewable energies, individual renewable energy systems and possibly new types of district heating systems based on renewable energies.

The results presented in this report can be further developed by pursuing research on input data, by extending the comparisons to more reference buildings for other building types, as well as to energy characteristics, countries or climate zones and by taking into account also other renovation measures which have not been investigated here, for example building automation or energy efficient devices.

The type of calculations carried out, with a focus on investigating synergies and trade-offs between energy efficiency measures and renewable energy based measures, is recommended to be carried out in more detail for different country contexts. It is recommended to consider related results in standard setting by policy makers. For systematic assessments, and also for case-specific evaluations, tools like the INSPIRE tool (Ott et al. 2014) used for this report can play a supporting role and can be further refined, adapted and developed.

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