EBC

Energy in Buildings and Communities Programme

International Energy Agency

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

Energy in Buildings and Communities Programme

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

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

Methodology and Assessment of Renovation Measures by Parametric Calculations

Energy in Buildings and Communities Programme

April 2014

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

IEA-EBC project «Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation» intends to develop a calculation basis for future standards, which aim at maximum effects on reducing carbon emissions and primary energy use. Thereby, the project pays special attention to the renovation of existing residential buildings and to cost effective building renovation.

Objectives

The objectives of this report are:

– Methodological guidelines and national framework conditions: Development of a common methodology for the assessment of building renovation with respect to cost, primary energy use, carbon emissions and further benefits of energy related building renovation as well as for the derivation of target values for energy and carbon emissions optimized building renovation;

– Assessment of energy related renovation measures regarding cost, primary energy use and carbon emissions: Test of the methodology by assessing different packages of energy related renovation measures for typical (generic) single-family and multi-family houses from the participating countries. The range for cost effective and for cost optimal energy related renovation measures as well as the trade-offs between measures reducing primary energy use and measures mitigating carbon emissions shall be explored to derive recommendations for target setting (policy makers) and for energy and carbon emissions related renovation strategies (owners, investors).

– Life cycle impact assessment (LCIA) within building renovation: Development of a common LCIA methodology for the assessment of energy related building renovation measures and strategies. The flexible methodology shall allow integrating embodied energy use and related carbon emissions into the cost effective building renovation methodology to be developed in this project.

Scope

Primarily residential buildings (not significantly energetically renovated yet):
The focus of this project is on primary energy use and related carbon emissions of residential buildings and non-technical office buildings (not having air conditioning) being renovated as well as on the cost incurred by the energy related renovation measures.

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 (fans pumps, electric valves, control devices, etc.), built in appliances (like lifts) and lighting (operational energy demand for plug in appliances is not considered). 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 (especially for electricity consumed) taking into account upstream primary energy use for energy carriers and for related emissions.

The impacts of cooling and cooling measures on buildings with cooling needs has not been investigated yet (work in progress, cooling will be evaluated for generic buildings in ES, IT, PT).

Cost:
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 anytime. 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 to consider for the policy makers, especially for target setting and for the design of energy and emissions related programs. Cost assessment is performed dynamically, discounting future costs and benefits (global cost method or the annuity method for the parametric calculations).

Trade-off analyses and optimization of energy and carbon emissions related renovation measures:
The impact assessments are carried out to learn more about the trade-offs between energy and

emissions related renovation measures (i.e. between measures increasing energy efficiency of the building envelope and appliances and the deployment of renewable energy) as well as for exploring the range of cost optimal and of cost effective renovation measures (Figure 1).

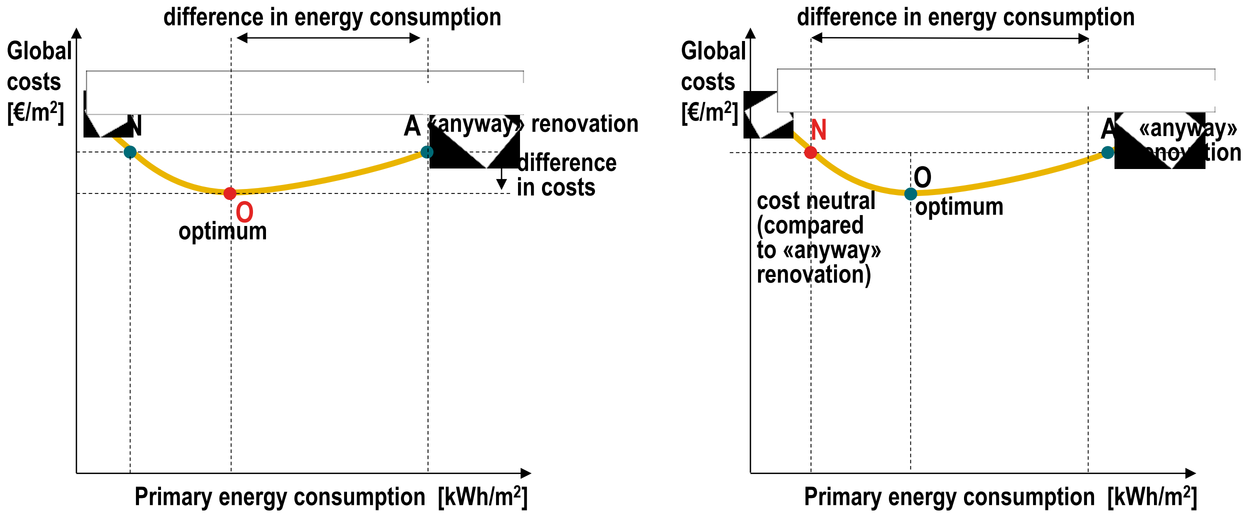

Figure 1 Global cost curve after renovation (yearly costs for interest, energy, operation and maintenance), starting from the reference situation **A** («anyway renovation») towards renovation options yielding less primary energy use than in the case of the anyway renovation. **O** represents the cost optimal renovation option. **N** represents the cost neutral renovation option with the highest reduction of primary energy (BPIE 2010, p. 15, supplemented by econcept).

Assessment of cost effective energy related renovation measures

Parametric calculations of the impacts for generic SFH and MFH buildings:

The exploration and assessment of the impacts of renovation measures (energy efficiency measures as well as deployment or on-site generation of renewable energy) on cost, primary energy use and carbon emissions is done with parametric calculations for a generic single-family house and a multi-family house for each country participating in STA. In the future, these assessments will be complemented with the help of case studies from realized projects (the latter is still work in progress). The generic buildings analysed are typical for the building stock of the specific countries and represent existing buildings not having undergone a major energy related renovation yet. The assessments apply national primary energy factors and carbon emissions conversion factors. These factors represent the actual situation in the participating countries and don't incorporate possible changes of these factors in the future. It is pointed out that these conversion factors are not supposed to be determined politically, but corresponding to the real physical situation of primary energy consumed and related carbon emissions. Applying life cycle impact analysis, the methodology is elaborated to take into account embodied energy use and related carbon emissions caused by energy related renovation measures.

System boundaries:
System boundaries are clearly defined, especially for the sake of correctly allocating impacts of the energy and carbon emissions related part of renovation measures, distinguishing them from business–as-usual renovation measures which are implemented through necessity or choice «anyway». Such «anyway» renovations may be needed to restore the previous functionality and the quality of the building, yet do not improve the energy performance of the building, nor do they deploy renewable energy sources.

Assessed generic buildings and the corresponding reference renovation case:
The methodology was tested with generic single-family and multi-family residential buildings from Austria, Denmark, 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 were determined for three different heating systems respectively. Additionally, the impact of the inclusion of embodied energy use was evaluated for the generic Swiss SFH and the impacts of ventilation with heat recovery were assessed for the generic Swedish and Swiss SFH and MFH. 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 was assessed and demonstrated in for the generic buildings from Portugal. Related impacts are assessed by comparison with the impacts from the «anyway» renovation case. To have a level playing field and to ensure that the comparison of the anyway (or business as usual) renovation with different options for energy related renovations is correct, it is assumed that in the case of an anyway renovation the existing heating system (in most cases an oil or gas heating system, in SE district heating and in NO direct electric heating) is also replaced (by the same kind of heating system). 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 in varying levels of energy efficiency levels for all the countries investigated (AT, DK, NO, PT, ES, SE, CH): Insulation of wall, insulation of roof, insulation of cellar ceiling, and new energy efficient windows. The following heating systems were considered: Oil (AT, DK, CH), natural gas (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, ES, SE, CH), air source heat pump (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).

Results from the assessment by parametric calculations in the case of a generic Swiss multi-family house

The results of the parametric calculations for the Swiss MFH are presented subsequently as an example of the results generated by the calculations for generic SFH and MFH buildings in AT, CH, DK, ES, NO, PT, and SE (Figure 2).

All calculations were 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 next 40 years, compared to energy prices of 2010 in the specific country. Climate data, lifetimes, primary energy and emission factors applied are country specific. The generic buildings defined are roughly representative for buildings constructed up to 1975-1980, which have not undergone a major energy related renovation yet.

Presupposing the assumptions mentioned above, development of yearly costs with increasing number and ambition level of energy related renovation measures is u-shaped for all generic buildings investigated (Figure 3). I.e. in all cases assessed there is a cost optimum, being below the cost of an «anyway» renovation. Cost 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).

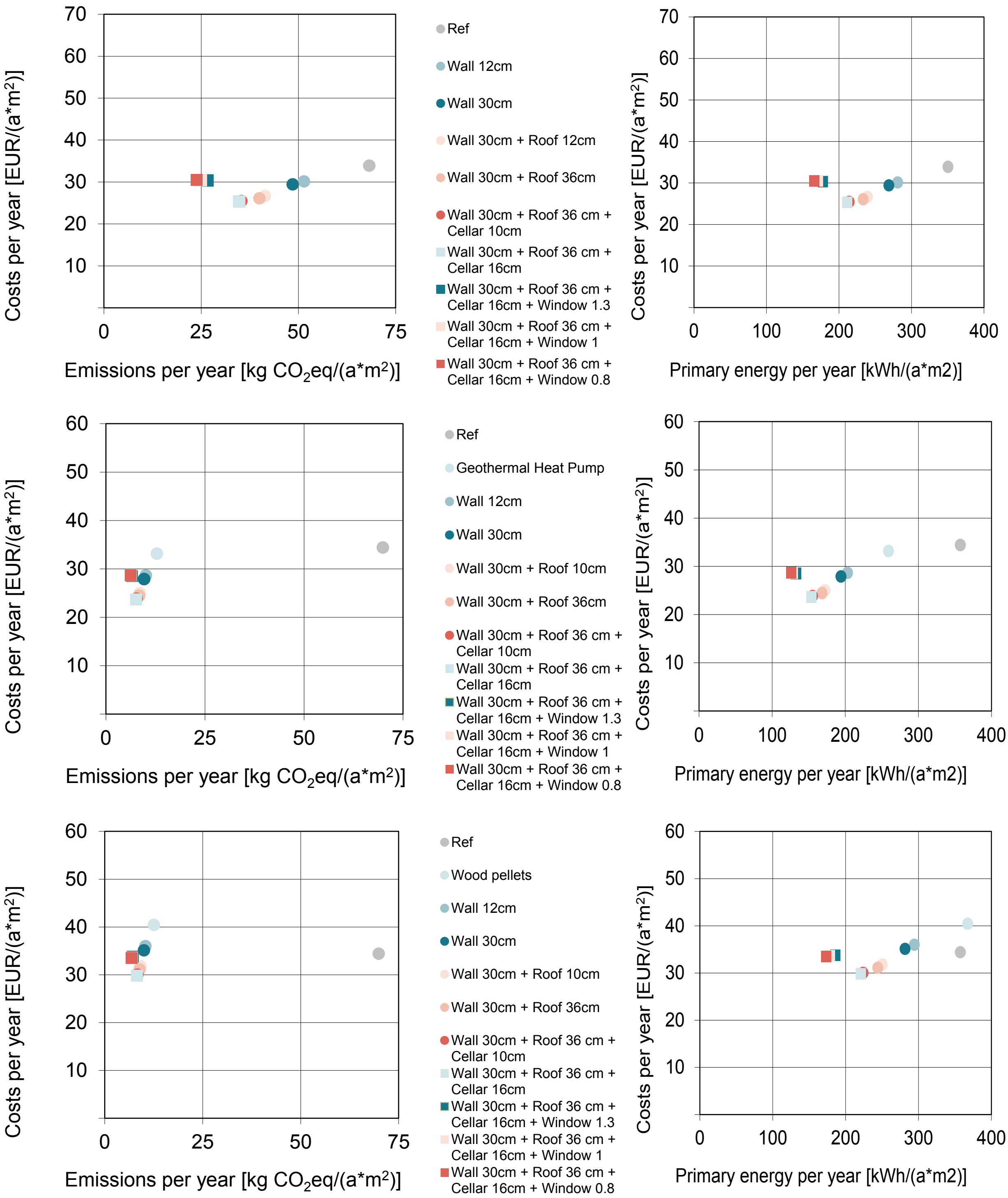

Figure 2 MFH in **Switzerland**: Cost effectiveness of energy efficiency renovation measures for <u>different heating systems</u>: **Oil heating** (top), geothermal heat pump (middle) and **wood pellets** (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs,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

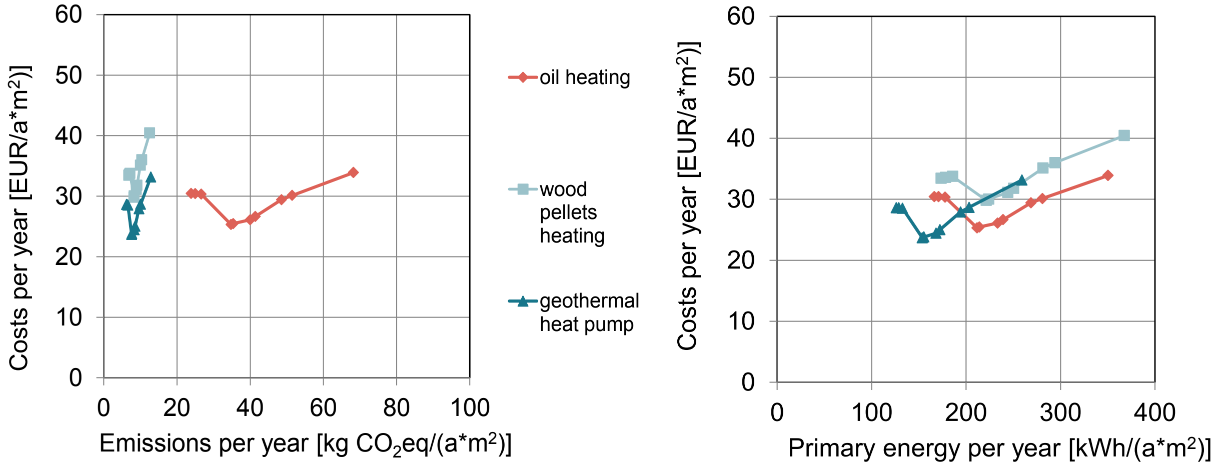

Figure 3 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for multi-family building. The reference case is the point on the oil heating curve with the highest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

Main findings from the parametric calculations and conclusions

Cost optimal mix of energy related renovation measures:

The mix of cost optimal renovation measures mostly does not depend on the type of the heating system: The results obtained from the generic calculations indicate that in most of the cases, a switch to wood pellets or a heat pump has no or hardly any impact on the mix of energy related renovation measures at the cost optimum. Nevertheless, the level of the cost optimum as well as the impact on primary energy use and carbon emissions at the cost optimum depend on the heating system considered. However, the results also show that there are cases where the mix of measures in the cost optimum can be slightly changed by a switch to wood pellets or ground source heat pump. But in the examples assessed the cost optimal packages of renovation measures for different heating systems are either the same or then close together. Assessment of further examples would be necessary to explore this aspect more in depth.

Effect of shift to renewable energy on primary energy use:

Considering primary energy use the shift to renewable energy deployment has a high impact on non-renewable primary energy use but overall primary use may be reduced only in the case of heat pumps, not in the case of wood energy use.

Renewable energy deployment is favourable, costs can be reduced by reducing energy demand of the building first:

The analysis demonstrates a clear case for employing renovation measures which reduce the heat loss of the building envelope first to reduce energy demand such that any renewable energy technologies installed can be lower capacity and therefore lower cost Moreover, it is crucial to ensure sufficient thermal quality of the building envelope and to prevent lack of comfort and damages resulting from problems with building physics by increasing the energy performance of low performing building envelopes.

More relevance on emission targets, supported by supplementing energy targets:
Transformation of the stock of existing buildings towards ambitious emission targets has to be effected in a cost effective way, realizing at the same time best possible value for the building to give this transformation a chance within the renovation of buildings. Acknowledging the large possible contribution of renewable energy based heating systems to emission goals and taking into account the eminent role of costs incurred by energy related renovation measures, it is recommendable to put more focus on ambitious emission targets. Under such circumstances, the requirements on the energy efficiency of the building envelope should not be too strict. Otherwise is might be possible that too much resources are spent for far reaching efficiency measures with an unfavourable ratio of costs related to emissions and energy savings so that more optimal solutions with higher impact are foregone. Nevertheless, energy efficiency measures remain important, for example to ensure thermal comfort and building physics requirements as well as to allow benefits from lower costs for capacity adjusted heating systems.

It is more favourable to improve energy performance of all elements of the envelope than only of one or few – if insulation is carried out, decision for a high standard is beneficial:
Due to distinctly decreasing marginal benefits and increasing marginal costs, it is more beneficial to improve the energy performance of several elements of the building envelope than to costly maximise energy performance of particular elements. However, within the limits possible, it is recommendable to be ambitious, if building envelope is energetically improved, since once the insulation measures are carried out, it is usually not cost effective any more 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.

Switch to renewable energy use combined with a reduction of energy demand of the building yield synergies:
In order to benefit from cost related synergies of improving energy performance of the building envelope combined with a shift to a heating system using renewable energy, it is favourable to combine a switch to a renewable energy system with energy efficiency measures on the building envelope. So the full potential of renewable energy deployment and energy efficiency measures to reduce carbon emissions and primary energy use can be better exploited.

Optimal renovation strategy depends on the particular building, based on a midterm planning of upcoming renovation needs:
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 latter does not need renovation yet. But the pros and cons have to be assessed for the particular situation, taking costs, thermal comfort and possible problems with building physics carefully into account.

Impact of embodied energy use of renovation measures is smaller than is the case of new building construction:
Calculations taking into account the embodied energy use of renovation measures indicate that embodied energy has an impact on the environmental performance of high-efficiency insulation measures. In particular the environmental benefit of high-efficiency windows is reduced or even neutralized by increased use of energy for the production of such windows. 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.

The fact that the reference buildings chosen for parametric calculations 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. In particular, energy prices play an important role related to the cost effectiveness of renovation measures and to a switch to renewable energy sources: The higher conventional 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.

Two important parameters were not investigated in detail:

- Energy performance of the buildings prior to renovation: It 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 use compared to the situation before renovation.
- Climate: In colder climates, energy efficiency measures on the building become more cost effective, as the temperature difference between inside and outside is higher.

Table of content

Abbreviations

Table 1 List of frequently used abbreviations

Abbreviations	Meaning
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
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
λ	Lambda-Value (value for the insulating capacity of a material)
LCI	Life cycle impact
LCIA	Life cycle impact analysis
MFB	Multifamily building
MFH	Multi-family house
MJ	Mega joule; 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
SFH	Single-family house
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
WP	Work Package

1. Introduction

1.1. General context

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. To change the looming path 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 stock of existing buildings, whose energy related improvement is highly relevant for mitigating carbon emissions and energy use, yet it is a challenge to unleash 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 European Energy Performance of Buildings Directive (EPBD) and its recast are very much putting high emphasis on the high energy performance of the building, albeit in its two step approach deployment of renewable energy is also addressed but only in the 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 processes and measures resulting, possibly 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 was 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 a trigger to launch IEA-EBC Annex 56 «Cost effective energy and carbon emissions optimization in building renovation». In Annex 56 efforts are made to integrate costs 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 maximal 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, shall be explored.

1.2. Objectives of IEA-EBC Annex 56 for the development and demonstration of a cost, energy and carbon emissions related assessment and evaluation framework

Annex 56 strives to achieve the following objectives:

- 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 Developing the methodology and applying 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

In this report the findings of **Subtask A**, developing the methodology of Annex 56 and performing calculations for generic buildings in various countries are presented. It is a preliminary report with the aim to deliver inputs for the discussion of new or revised standards in the European Union.

The methodology report from STA presented here comprises the following parts:

- Methodology, calculation procedures, notions, scopes and boundary conditions to be applied within Annex 56:
    - Scopes and perspectives for the assessment: Scope of energy use and carbon emissions investigated, private and societal perspective for the cost and impact assessment;
    - Definition of system boundaries for the assessment of costs, energy use and supplies as well as for carbon emissions taken into consideration and investigated;
    - Definition of concepts, notions and units;
    - Definition of metrics and conversion factors;
    - Definition of calculation procedures;
    - LCIA methodology and LC-impacts to take into account for the assessment of the impacts of energy related building renovation in Annex 56.
- Generic buildings (single-family and multi-family residential buildings) and parametric calculations of varying packages of energy related renovation measures to assess cost, energy use and carbon emissions related impacts of these renovation measures for: Austria, Denmark, Norway, Portugal, Spain, Sweden and Switzerland.
- Preliminary conclusions derived from hitherto existing work

Not all of the work planned within STA is finished yet. The following investigations and corresponding chapters are still work in progress and will be supplemented for the final report in summer 2014:

- Further specification of the integration of cooling into the calculation procedures;
- Sensitivity analyses, assuming different energy prices interest rates, etc.;
- Inclusion of selected impacts from a LCIA of renovation measures into the assessment (embodied energy and related carbon emissions);
- Examples assessing the impacts of ventilation and cooling measures, presented in the generic calculations for Sweden and Switzerland;
- Identification of relevant co-benefits from energy related building renovation and definition of the methods how to integrate these co-benefits into the overall assessment of the renovation measures.

2. Methodology for the assessment and optimization of cost, energy use and carbon emissions

2.1. Introduction

Subsequent methodological guidelines aim at defining and harmonizing scope, notions, system boundaries, approaches, calculation methods and assumptions regarding input values and their future perspectives for evaluating and assessing energy related building renovation activities aiming at cost effective solutions yielding maximum energy and carbon emissions reductions. The methodology outlined draws among other sources from the newest developments within the recast of the Energy Performance of Building Directive (EPBD) of the European Union[1] and methodology development in IEA SHC Task 40/EBC Annex 52 «Towards Net Zero Energy Solar Buildings»[2].

The methodological guidelines address renovation of the residential building stock comprising also office buildings without complex building technologies.

The methodology provides the basis for the assessment and evaluation of energy related renovation options, first and foremost with respect to cost, energy use and carbon emissions. Furthermore, it allows also for a broader approach going beyond cost effective reduction of carbon emissions and energy use by taking into account co-benefits and overall added value achieved in a renovation process. Besides impact indicators for primary energy use, carbon emissions and costs it also provides a methodological framework for integrating at least embodied energy use for renovation measures as part of a lifecycle impact assessment. It is supposed to allow to assume either an individual end-user and investor perspective respectively (financial or microeconomic) or a societal (macroeconomic) perspective. The methodology and resulting

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

[2] See http://www.ecbcs.org/annexes/annex52.htm

fundamentals for renovation standards have to be applicable to different climatic and country specific situations.

2.2. Scope, system boundaries, definitions

2.2.1. Scope of energy use and related carbon emissions subject to the assessment of energy use and carbon emissions related building renovation

For residential buildings and simple office buildings the following components of energy use and related carbon emissions are considered:

- Operational energy use for space heating, space cooling, ventilation (HVAC), domestic hot water heating (DHW) and auxiliary energy use for heating, cooling and DHW (fans, pumps, electric valves, control devices, etc.);
- Operational energy use for lighting;
- Operational energy use of built in appliances:
  - Built in household appliances like stove, washing machine, refrigerator/freezer, tumbler: In some countries they are provided by the owner/landlord and the use is often allocated to the electricity use of the building (at least in a fraction of the apartments or buildings). In other countries they are not built in but provided by the occupants. Their electricity use is a part of the occupant's use.
  - Built in common appliances like lifts, escalators, garage ventilation, etc.

  Since these appliances are built in, it is suggested to include operational energy use of household and common appliances into energy and carbon emissions related assessment.
- Operational energy use of plug in appliances is not included automatically: e.g. see guidelines accompanying Commission Delegated Regulation supplementing EPBD (Directive 2010/31/EU) which proposes that electricity for household appliances and plug loads may be included, but not mandatorily (Official Journal of the EU, 19.4. 2012, p. C 115/8). In many countries, household appliances (like stove, washing machine, refrigerator/freezer, tumbler) are provided by the owner or landlord which suggests that their energy use is included. Moreover, the share of plug in's on energy use of buildings will increase with increasing needs for plug in energy services as well as with decreasing energy use and carbon emissions for heating.

  Hence it is proposed that plug loads may be included into energy and carbon emissions assessment (possibly with the help of default standard energy use and carbon emission values, to at least roughly illustrate their impact and relevance on the assessment).

- Embodied (primary) energy use for building materials, technical equipment and appliances: This share of primary energy use in the building sector is increasing due to the supposed decrease of energy needs for HVAC. For the sake of a comprehensive assessment it is preferable to include embodied energy use into analyses, even if in the case of building renovation embodied energy use is less relevant than in the case of new building construction.

2.2.2. System boundaries and metrics for energy and carbon emissions related building assessment

Figure 4 illustrates the system boundaries for the energy related assessment of renovated buildings and defines the relevant energy flows on the levels of:

- Energy demand of the building, taking into account heat gains and thermal losses;
- Net delivered energy, taking into account energy delivered to the building, on-site energy generation and energy exported to grids;
- Embodied energy used for energy related building renovation (in the case of new buildings it would be embodied energy of new building construction). Embodied energy use equals the cumulated primary energy demand for production, transportation and disposal of building components, appliances, renewable energy generation units and building construction measures within building renovation.

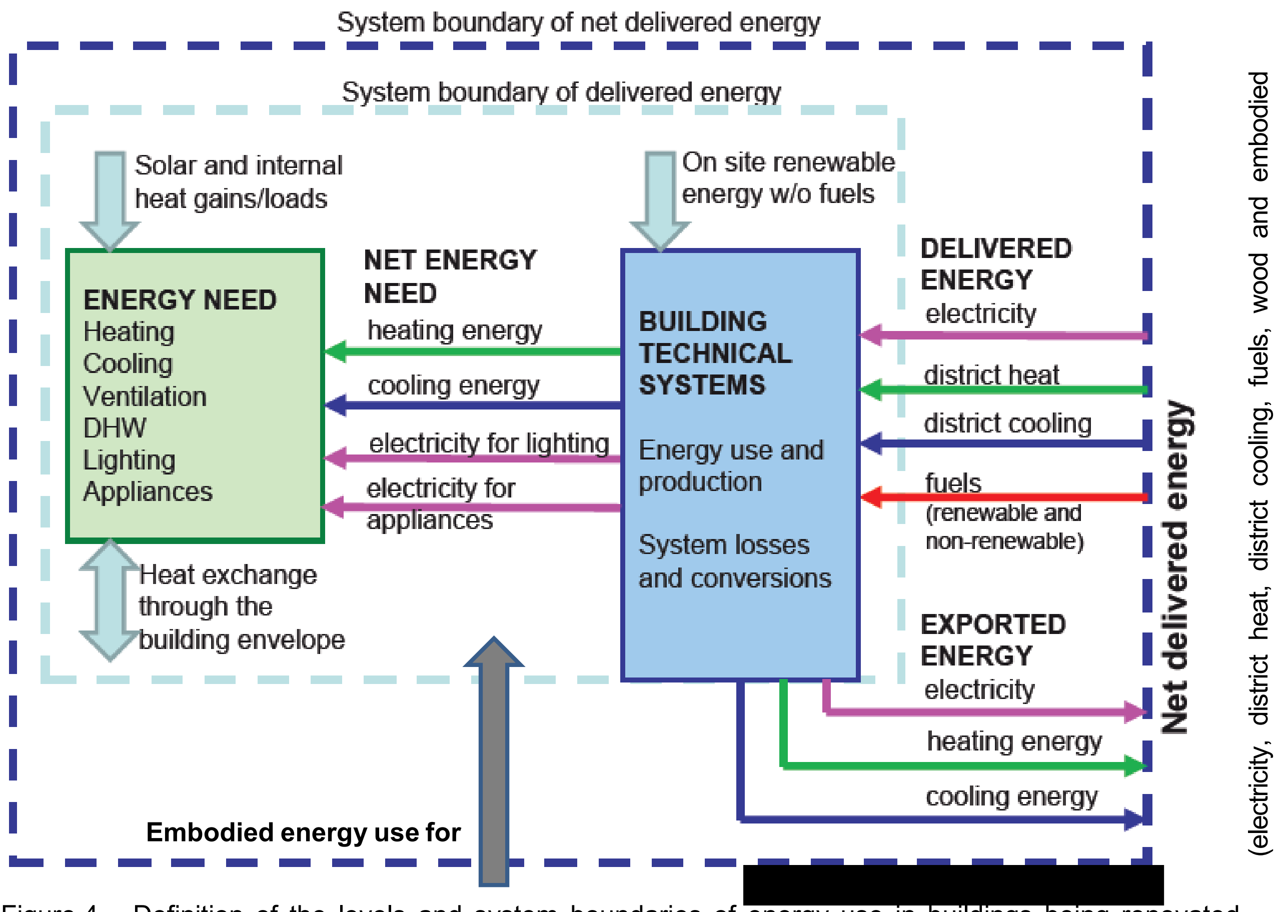


Figure 4 Definition of the levels and system boundaries of energy use in buildings being renovated, including on-site renewable energy generation, passive heat gains, exported energy and embodied energy use for renovation measures (see Kurnitski J., 2011, REHVA Task Force, supplemented by econcept for the case of building renovation)

Primary energy conversion factor for energy carriers:

The conversion from final energy use to **primary energy** use of energy carriers is performed with the help of primary energy conversion factors per energy carrier, which take into account upstream energy use for extraction, processing, transportation and distribution of energy carriers. Primary energy conversion factors have to be determined by a life cycle impact assessment. They vary by country, depending on the share and on the origin of the energy carriers consumed in the particular country and are often determined within LCIA databases for the particular country. In some countries «political» conversion factors or conversion factors defined for specific labels or energy related requirements are employed which differ from the «physical» or «ecological» conversion factors which are determined as previously defined. For the sake of analytical transparency, physical conversion factors should be employed within Annex 56 whenever possible.

Primary energy conversion factor for electricity:

Primary energy conversion factors for electricity depend on the way electricity is generated and on the mix of generation technologies employed and consumed by the end users. For the sake of energy related assessments of building renovation, the national mix of electricity consumed is most appropriate to determine national primary conversion factors for electricity. Only if the mix of electricity consumed is not known, the mix of national electricity production might be used as second best solution, even if this might differ substantially from the mix of electricity effectively consumed, especially in countries with a relevant share of electricity imported where the source of production is not known. Political conversion factors or conversion factors used by particular labels are only second best solutions too. They might be physically not appropriate.

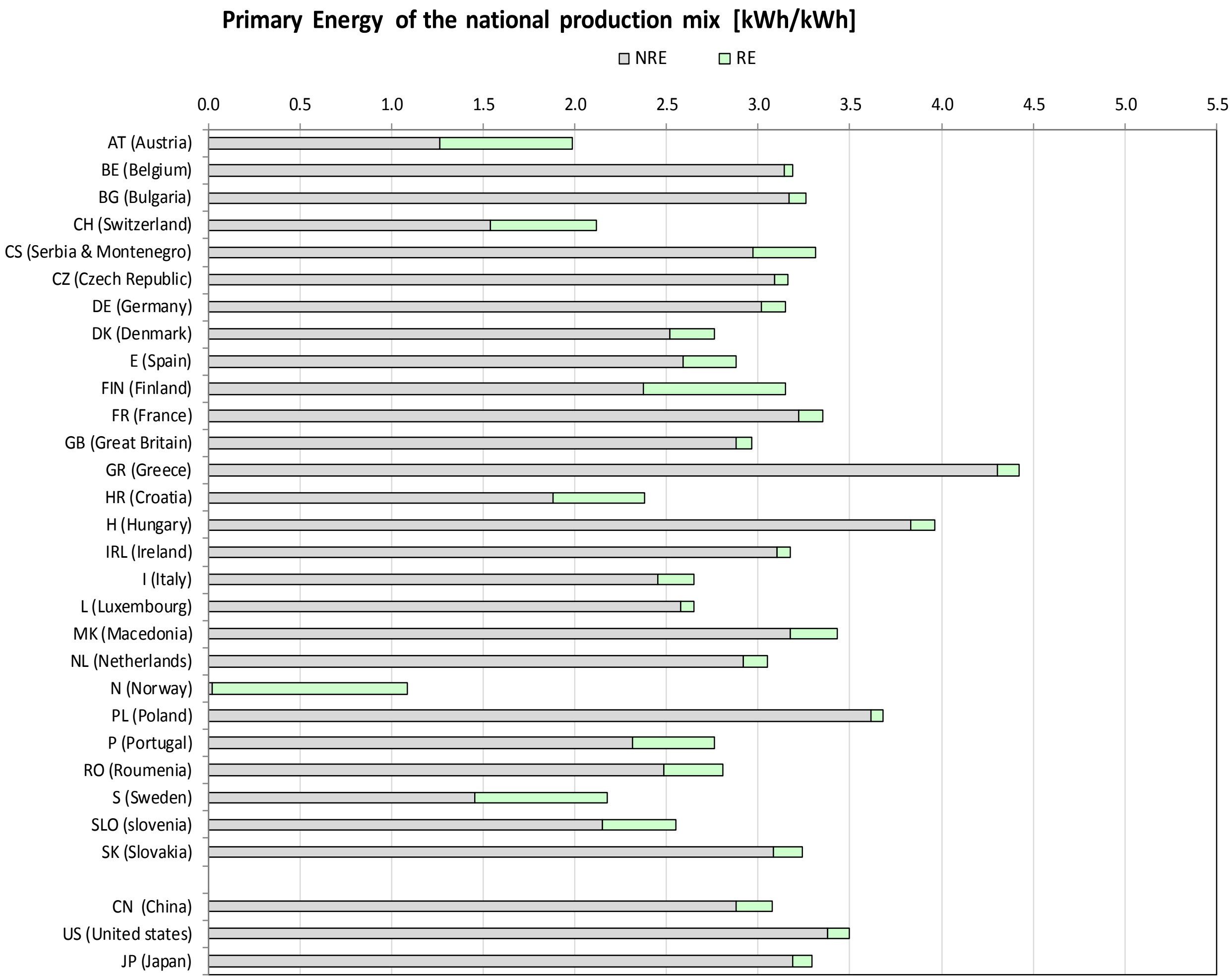


Figure 5 Primary energy/final energy conversion factor of electricity for the **national generation mix** (Ecoinvent v2.2)

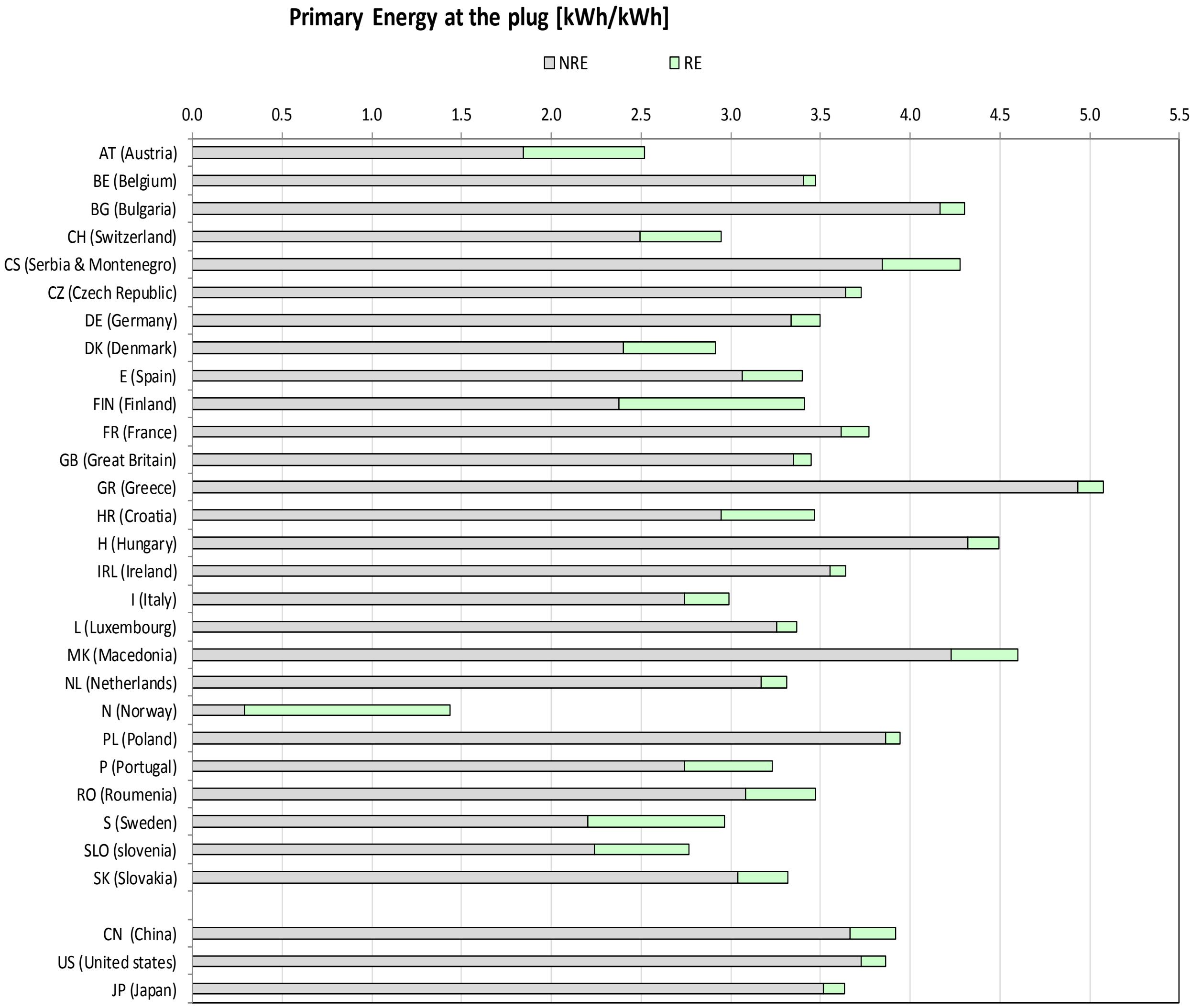


Figure 6 Primary energy/final energy conversion factor of **delivered electricity at the plug of the end users** (Ecoinvent v2.2)

District heating and cooling:

The primary energy conversion factor of district heating and cooling is determined by the input share of the energy carriers to generate district heat or cold and by the corresponding primary energy factors. Additionally, distribution losses and embodied energy use of the heat distribution system have to be included.

System boundaries for on-site energy generation:

Usually the scope and the boundary for on-site generation of renewable energy is the building lot (boundary II in Figure 7), while boundary III allows for the use of off-site produced renewable energy (e.g. biomass) within the building lot. For the boundaries II and III it might be appropriate in certain situations to pool several buildings which have a common heating and/or cooling system to attain (economically) more favourable conditions for renewable energy generation and use. On site generated electricity fully sold to an off-site user or owner of the generation unit is not accounted for in the building assessment.

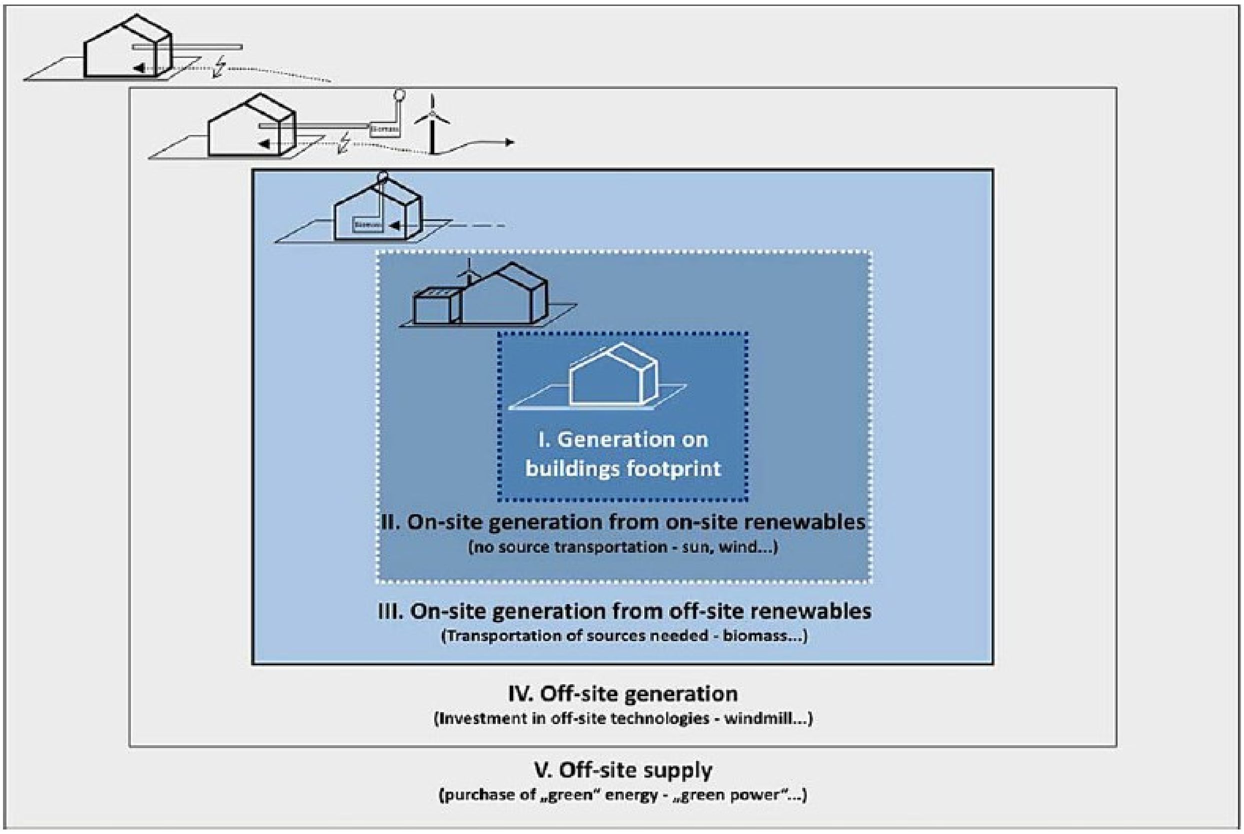


Figure 7 Overview of possible renewable supply options (Marszal A.J. et al. 2011, p. 975)

Carbon emissions of energy related building renovation measures:

The impact of energy related building renovation measures on carbon emissions is determined from the impact of the measures on net delivered energy use plus embodied energy use. For net delivered energy common carbon emission factors for the final energy carriers consumed are applied. Carbon emissions of embodied energy use have to be determined by a LCIA of the corresponding renovation measures, using available LCIA databases (see chapter 2.4). There are two levels of carbon emission conversion factors:

Carbon emission conversion factors according to the Kyoto protocol (CO_{2e});

Country specific carbon emission conversion factors comprising also upstream emissions for the delivery of final energy carriers to the building. As far as available, carbon emission conversion factors comprising upstream emissions of the energy carriers shall be employed in Annex 56.

Carbon emissions from embodied energy use have to be determined by a LCIA of renovation measures

Gross floor area or net floor area?

Units and target values for energy use and carbon emissions are usually expressed in **MJ/m^{2}a** or **kWh/m^{2}a** and **kg CO_2-equivalents per m^2*a (kg CO_{2e}/m^{2}a)**. In certain cases it might be preferable to have additionally "**person**" as unit since DHW and electricity use are rather depending on the number of persons than on m^2 of (conditioned) net or gross floor area.

(Conditioned) gross floor area:
Sum of the covered area of all conditioned floors of a building (including exterior walls). Unconditioned rooms within the conditioned envelope are included too. Unoccupied, unheated basements, attics, garages outside the thermal envelope are excluded.

(Conditioned) net floor area:
Total conditioned floor area inside the building envelope excluding the external and internal walls and vents, shafts, stairs, (unoccupied) attics, basements, garages. The area is not reduced by partition walls or other moveable furnishing.

Figure 8 Illustration of (conditioned) gross floor area and net floor area. Hatched areas: Non conditioned exterior gross and net floor area respectively

For the time being, it is suggested to apply gross floor area as unit for energy and carbon emissions analyses in the building sector. In Europe, this is the usual unit used in the energy and in the construction sector for energy calculations, for building design and for unit cost calculations: From 8 countries, answering to the survey of STC concerning indicators and metrics, 5 use gross floor area (AT, CH, DK, NO and SE (FI is unclear)) and 3 use net floor area (AT (for energy demand), IT, PT). It should be feasible to determine national conversion factors to change between net and gross floor area. If necessary, other units (e.g. per person) might also be used occasionally or for special purposes.

2.3. Calculation of primary energy use and related carbon emissions of residential buildings renovated

Overall primary energy use and carbon emissions are calculated on an annual basis. In general all analyses of emissions, energy use, costs and benefits are supposed to assume a life cycle approach, either based on the life time of the respective building or on the technical or service life time of renovation measures. Life cycle data has to be broken down to the different stages and the various building systems, elements or products and expressed as yearly units during the lifecycle or yearly units per square meter gross or net floor area (see above and chapter 2.4 LCIA and embodied energy).

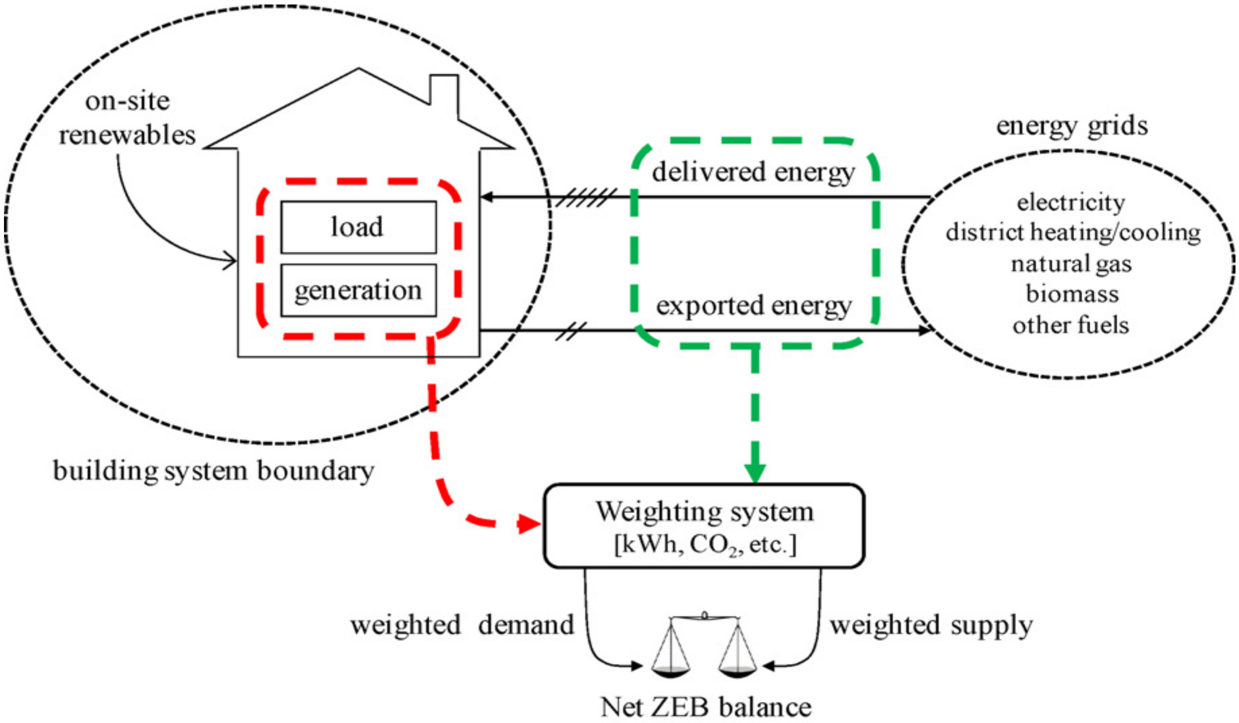
Calculation of primary energy use is widely aligned with the methodology proposed by the EPBD but is extended for the inclusion of primary energy use for components s (embodied energy use, see chapter 2.4; Official Journal of the EU, 19.4. 2012, p. C 115/9):

The calculation of the energy performance of a building before/after renovation starts with the calculation of energy demand for heating and cooling. Then the final energy use for all energy uses is determined, whereupon the primary energy input for all of the energy uses as well as the primary energy use for components and appliances deployed within building renovation is calculated. Carbon emissions related to the renovation measures can be derived from the primary energy use by energy carrier with the help of carbon emissions conversion factors. Usually, the calculation goes from the needs to the source (i.e. from the building's energy and components needs to the primary energy use and related carbon emissions), depending on the national calculation procedures. Electrical systems (such as lighting, ventilation, auxiliary) and thermal systems (heating, cooling, domestic hot water) are considered separately inside the building's boundaries.

Delivered primary energy is determined from delivered energy carriers and components by the use of national primary energy conversion factors and LCIA data for embodied energy used.

Electricity exported from the building site into the grid is converted into primary energy by using either:

- an appropriate conversion factor for grid electricity substituted by the surplus electricity generated on-site or
- primary energy content of embodied energy of on-site generation equipment.



Sartori 2012

Figure 9 Terminology for building related energy use and renewable energy generation (Sartori I. et al. 2012)

Calculation of energy performance according to the guidelines accompanying Commission Regulation (EU) No 244/20121 (Official Journal of the European Union, 16.1. 2012, p. C 115/10, supplemented by econcept):

1. Calculation of the building's net thermal energy demand to fulfil the user's requirements. The energy demand in winter are calculated as energy losses via the envelope and ventilation minus the internal gains (from appliances, lighting systems and occupancy) as well as 'natural' energy gains (passive solar heating, passive on-site cooling, natural ventilation, etc.);
2. Subtraction from (1) of the thermal energy from renewable energy sources (RES) generated and used on-site (e.g. from solar collectors);
3. Calculation of the energy uses for each end-use (space heating and cooling, hot water, lighting, ventilation, appliances) and for each energy carrier (electricity, fuel) taking into account the characteristics (seasonal efficiencies) of generation, distribution, emission and control systems;
4. Subtraction of the electricity from RES, generated and used on-site (e.g. from PV panels), from electricity use;
5. Calculation of the delivered energy for each energy carrier as sum of energy uses (not covered by RES);

6. Calculation of the primary energy associated with the delivered energy, using national conversion factors (conversion factor for national mix of consumed electricity, respectively);
7. Calculation of primary energy associated with energy exported to the market (e.g. generated by RES or co-generators on-site). Here the conversion factor might be different from the one above if not the conversion factor for the national consumption mix but the conversion factor for the national marginal generation technology which is substituted by on-site generation is applied;
8. Calculation of primary: The difference between the two previously calculated amounts: (6) - (7).
9. Calculation of (primary) embodied energy use depending on the materials used for renovation.
10. Calculation of carbon emissions is done with national carbon emissions conversion factors, yearly carbon emissions are expressed as units of CO_2-equivalents (**CO_{2e}**) or units of **CO_{2e}**$/m^2_{\text{floor area.}}$

In accordance with the Kyoto Protocol, carbon emissions shall account for carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, ammonia NH_3, hydrofluorocarbons HFC, perfluorocarbons PFC and sulphur hexafluoride SF_6. Carbon emissions shall be related to **CO_{2e}** by international harmonised conversion factors for non CO_2 carbon emissions.

If embodied energy will be taken into account it comprises use of embodied energy for the relevant building materials and products and as far as possible for equipment and appliances (see chapter 2.4). Emissions and energy use related to the generation and transport of energy carriers are not included in embodied energy use. Instead the emission factors and primary energy factors of the energy carriers take into account upstream processes.

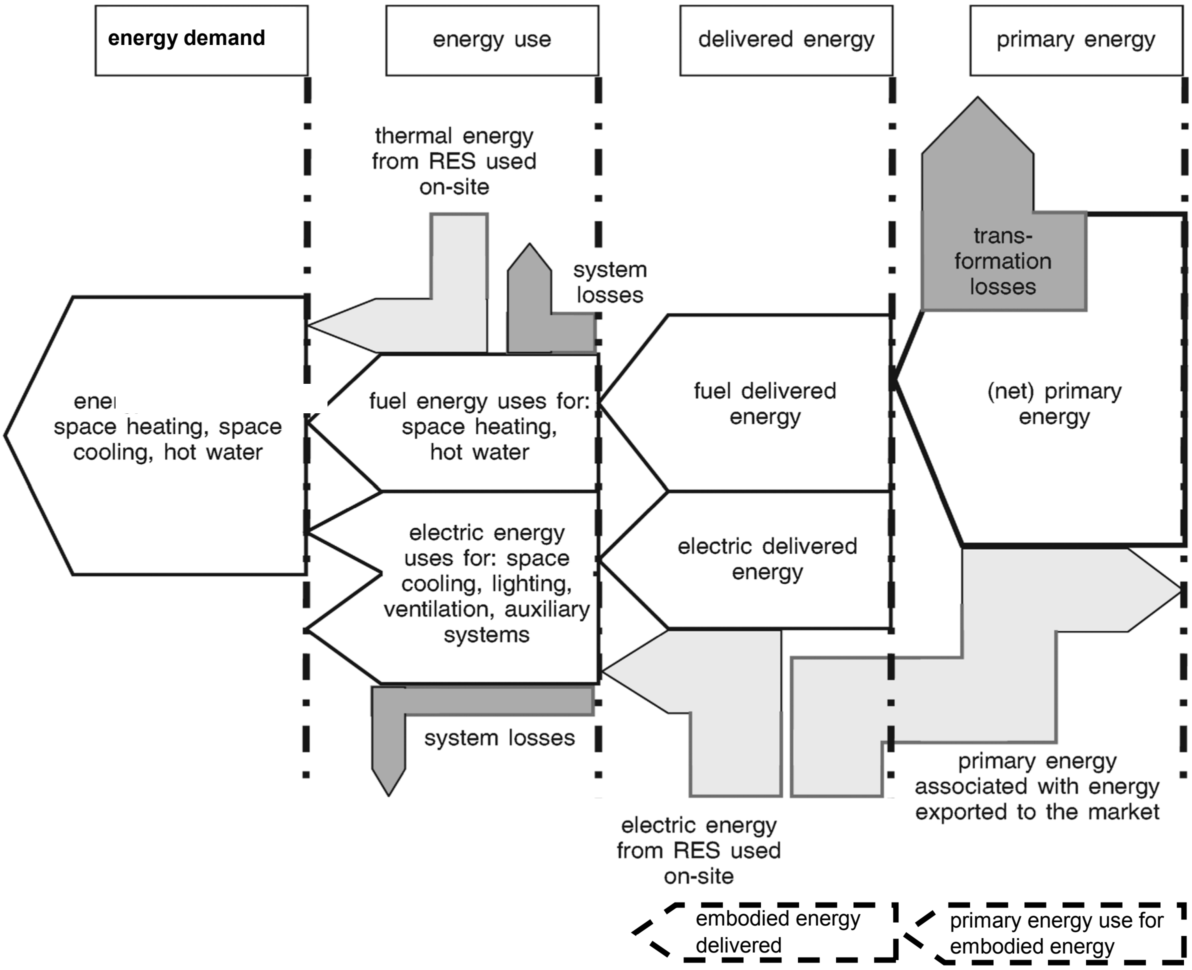


Figure 10 Illustration of the calculation scheme (Official Journal of the EU, 16.1. 2012, p. C 115/11; supplemented by econcept)

2.4. Life cycle Impact Assessment LCIA for energy related building renovation

2.4.1. *Introduction*

The purpose of this document is to present the methodology applied in Annex 56 for assessing the environmental impacts of renovated buildings. The proposed methodology is based on the state of the art of the life cycle impact assessment (LCIA) for buildings. But to stay pragmatic, it includes only processes having a relevant contribution to the total environmental impacts of the renovated building that can be put into practice in a reasonable amount of time and can provide relevant results in order to optimise the LCIA process of renovated buildings.

The methodology subsequently outlined addresses also stakeholders not involved in Annex 56, who would like to know the details of the approach used in Annex 56. The following considerations aim at summarizing the relevant information for LCIA in Annex 56 without going into all of the details but making clear how the necessary calculations have to be performed.

2.4.2. LCIA of energy related renovation measures

The assessment of the performance of a building can be based on several indicators, such as cost, operational energy use, environmental impacts and energy use of building components and materials. Whatever the indicators used, the generic pattern of its time evolution can be schematised as shown in Figure 11.

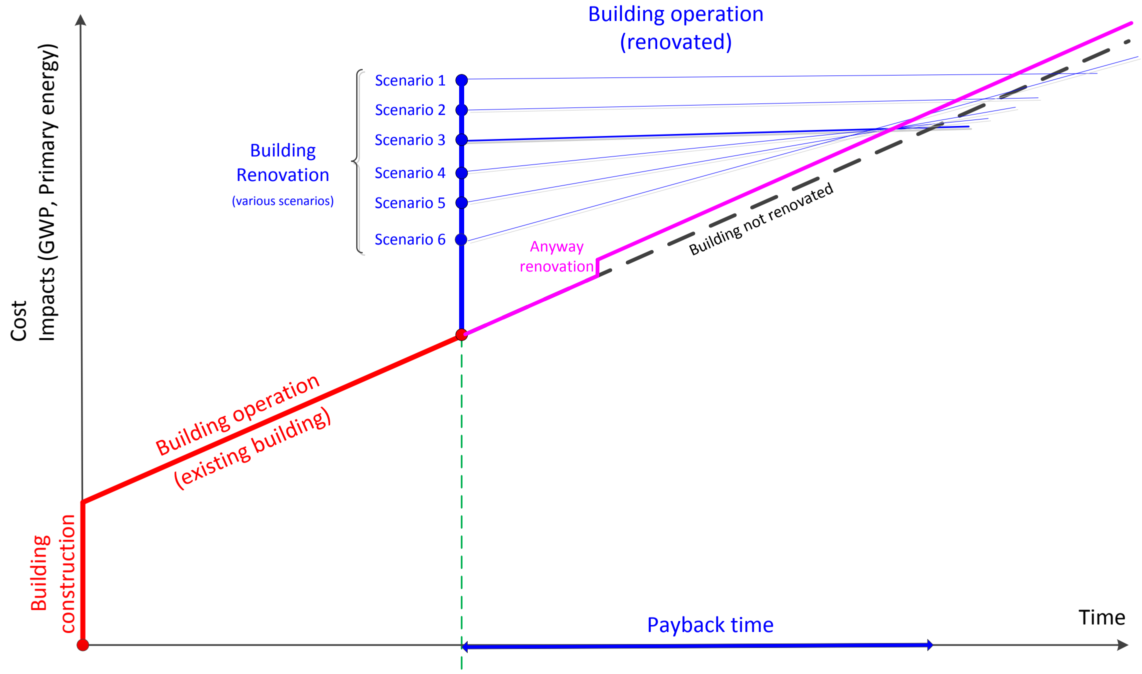


Figure 11 Schematic representation of the effect of energy related renovation measures compared to the existing situation

Building construction generates certain initial impacts and costs. During the building operation, there is a flow of yearly operational impacts and costs, primarily due to the energy use. After carrying out a building renovation, there is a new step-like increase of the impacts and costs due to the refurbishment of building elements and technical systems. The importance of this contribution depends on the implemented renovation scenario. During the building operation after renovation, the flow of yearly impacts and costs mainly due to energy use will also depend on the implemented scenario as shown in Figure 11 (the more complete and ambitious the energy related renovation package the higher is the initial step of impacts due to the renovation and the lower are the impacts of subsequent building operation).

The final goal of the optimisation is to find the scenario with the lowest impacts and costs during the reference study period. The reference case is based on “anyway renovations” (concept described in 2.5.2), which restore the full functionality of the building but do not improve the energy performance of the building.

In Annex 56, the LCIA is used to compare the environmental impacts of energy related renovation measures. Therefore, it will take into account only measures that affect the energy performance of the building (thermal envelope, building integrated technical systems and energy use for on-site production and delivered energy). Renovation measures which are not related to the energy performance of the building (e.g. such as changing the kitchen sinks) are not included into the assessment of the energy related renovation measures.

2.4.3. Existing LCIA methodologies

During the last decade, many LCIA methodologies have been published at national and international levels in order to present solutions to perform building LCIA. These include, for instance, generic approaches such as presented in ISO 14040 and followings (ISO 14040, 2006), ILCD Handbook (European Commission, 2011) or EeBGuide – Products (Wittstock et al., 2012a). There are also more building oriented approaches such as the EN 15978 (EN 15978, 2012) or “EeBGuide –Buildings” (Wittstock et al., 2012b) published recently.

Although these approaches tend to present a methodology as complete as possible, it is generally not fully applicable in practice, because of the lack of information required or the time and resources needed to put it into practice. At national level, some methodologies have been developed.

The aim of the following considerations is not to inventory and to compare all existing methodologies but to present the approach used in Annex 56 to perform the LCIA of existing buildings. The methodology used in Annex 56 is a compromise, taking into account several constrains such as:

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

In the framework of Annex 56, a pragmatic approach has been considered to perform the LCIA of a renovated building. The remaining document presents this methodology in more detail.

2.4.4. *Object of assessment, physical and temporal system boundaries*

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

- Temporal system boundary: It defines the elementary stages which have to be included, occurring during the life cycle of the building;
- Physical system boundary: It defines all materials and energy flows to be included in the calculation.

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

Life cycle of building renovation (temporal system boundary)

Many breakdowns of the building life cycle into the relevant stages have been proposed within the last decade (Citherlet, 2001; EN 15978, 2012; Wittstock et al., 2012b), and similar breakdowns can be used for building renovation. A generic breakdown into elementary stages and the boundaries of the main stages are presented in Figure 12 (see below).

***Materials produc*tion stage**: The boundary of this stage covers the 'cradle to gate' processes for manufacturing the materials used in the construction elements and technical systems. It includes all processes from the raw materials extraction to the final products (brick, insulation panel, boiler, pipes, etc.) at the gate of the manufactory ready to be delivered.

Building construction stage: The boundary of this stage encompasses the transportation of the materials and construction equipments (cranes, scaffolding, etc.) to the building site and all processes needed for the construction/renovation of the building.

Building operation stage: The boundary of this stage comprises the period during which the building is used by occupants, i.e. from the end of building construction or renovation to the demolition of the building. This stage also includes the maintenance, repair and replacement of the construction materials. It also includes energy used by technical systems during the building operation (heating, lighting, domestic hot water production, etc.).

Building end of life stage: This stage covers the end-of-life of the building from the building demolition to the materials elimination. It includes the processes for building decommissioning and waste transport and management (recycled, reused, incinerated or dumped in a landfill).

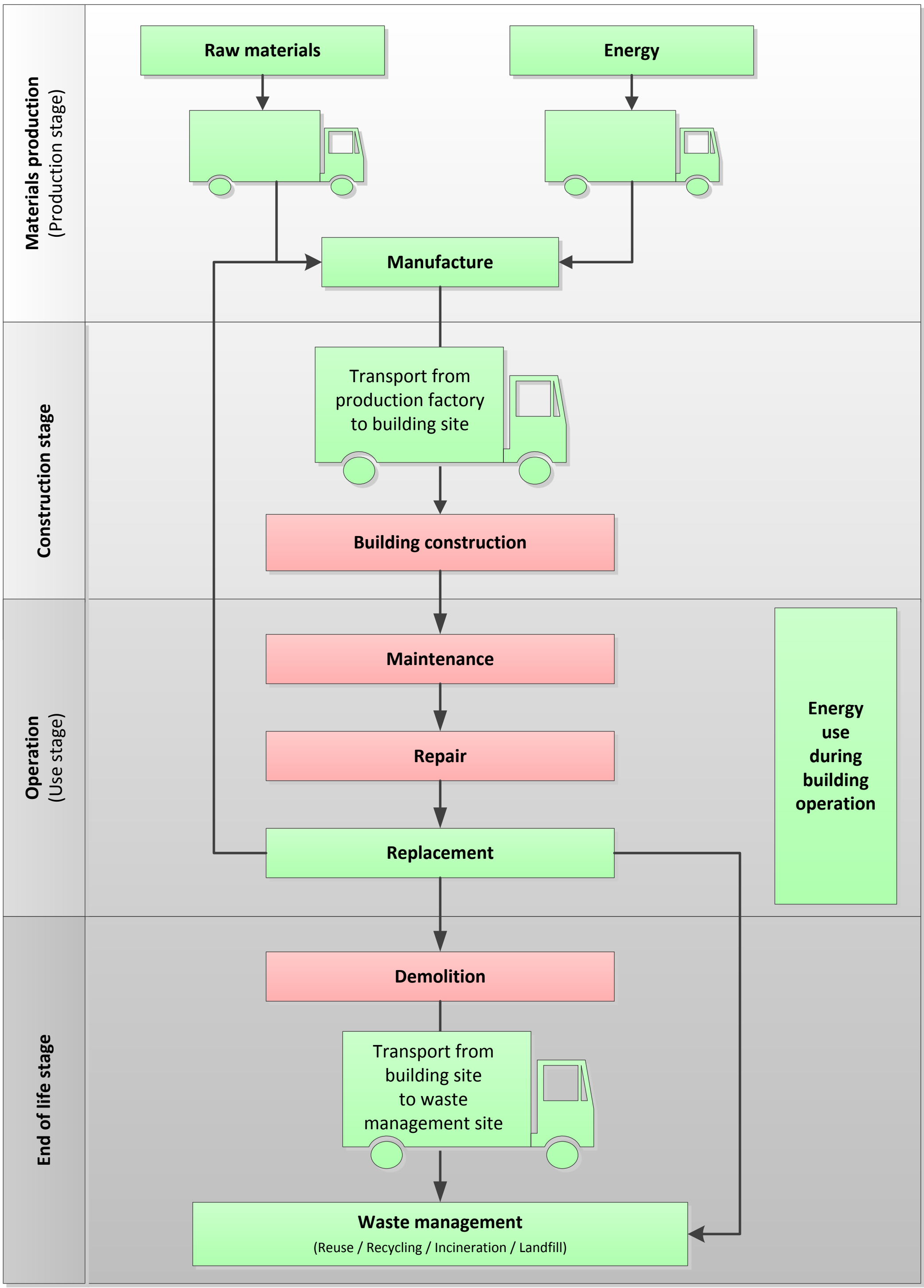


Figure 12 Schematic breakdown of a building's life cycle into elementary stages.

It should be kept in mind that Figure 12 is a generic representation of the complete life cycle of a building, in which each elementary stage may use energy and materials.

Furthermore, not all of the elementary stages contribute to the same extent to life cycle impacts of a building (new or renovated). Negligible impacts should be excluded from the assessment and calculations, even more so if they require information difficult to access.

Life cycle stages used in Annex 56:
In order to facilitate the application of LCIA, the methodology used to assess the effects of energy related renovation measures is pragmatic and takes into account only the relevant stages.

There are several stages that should be definitely taken into account in the LCIA of energy related building renovation and which are mandatory in Annex 56 (green boxes in Figure 12):

Material production, i.e. all stages required for the materials used for energy related renovation measures. It includes the extraction of raw materials, transport and transformation required to have the components ready to be used. For the sake of simplification, these stages are grouped in one stage called «material production».

New materials transportation between the production site and the building site. To calculate the corresponding impacts, it is necessary to know the transportation distance(s) and the mean(s) of transport used for each material. The corresponding data can be either based on known information or on default values based on realistic hypotheses. These data should be reported and documented (type of transport, distance). During this stage, some materials may be lost (damage, broken) and have to be replaced (new production). The replacement of these lost materials can be neglected.

Materials replacement, i.e. the replacement of materials in components (construction elements or BITS) used for energy related renovation measures that will be replaced during the reference study period, due to a short service life.

Energy use during the building operation stage for the reference study period.

Transportation of wasted materials **at the end of the building's life** (materials added during the reference study period for energy related renovation measures). This corresponds to the transport from the building site to the waste management site. To calculate the corresponding impacts, it is necessary to know the transport distance(s) and the mean(s) of transport used for each material. The corresponding data can be either based on known information or on default values based on realistic hypotheses. These data should be reported and documented (type of transport, distance).

Waste management of removed materials (removed energy related renovation measures during the reference study period).

On the opposite, the following stages can be neglected (red boxes in Figure 12) due their marginal contribution:

Maintenance: The maintenance stage includes the processes for maintaining the functional, technical and aesthetic performance of the building fabric and building integrated technical systems (BITS), such as painting work, replacement of filters (ventilation), etc. This stage does not take into account the replacement of a building component that must be changed because it has reached the end of its service life. The replacement impacts are included in the replacement stage (green boxes in Figure 12).

The life cycle impacts from the maintenance stage of energy related renovation measures is insignificant (compared to the total building's LCIA) and therefore can be neglected, contrary to the cost assessment, for which the maintenance must be taken into account.

Repair: Repair of a building element cannot be easily analysed because by definition it happens randomly and there is no reliable information that could help to calculate precisely its contribution. In addition, this contribution happens seldom and therefore, it can be neglected.

Building construction and demolition: These stages take place on the building's construction site. It should be reminded that the construction equipment will be used not only for one building. Therefore, their contribution per building is highly reduced and these stages can be omitted (Khasreen et al., 2009). In addition, energy used on-site during building construction and demolition can be neglected compared to the energy embodied in the construction materials or the energy used during building operation.

In Annex 56, the three previous stages are not mandatory, but if they are included in the calculation, it should be reported.

Physical system boundary

The physical system boundary defines the materials and energy fluxes which must be taken into account for the LCIA. Figure 13 shows a synthetic building model which includes construction elements and building integrated technical systems (BITS). The construction elements consist of one or more materials. The BITS consist of components (boilers, pumps, etc.) which are made of materials. In addition, these components use one or more energy vector.

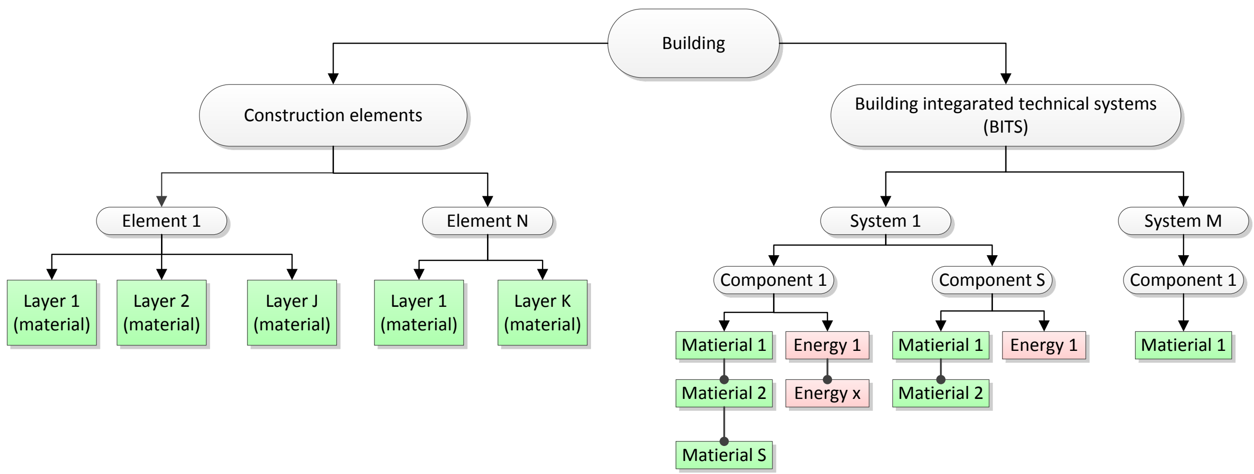


Figure 13 Structure of the building model

In order to perform an LCIA of a renovated building, the two following main contributions should be taken into account:

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

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

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

Components added or replaced for energy related renovation measures for building elements (envelope) and for BITS-components (for more details see Appendix). The stages corresponding to manufacturing, replacement and waste disposal of these components must be included in the calculation. (It should be noticed, that the LCIA is influenced by the service life of the construction materials and of the components of the BITS (this aspect is detailed in the Appendix).

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

2.4.5. System boundaries for operational and embodied energy use of renovated buildings in Annex 56

Operational energy use

Energy use of building operation comprises energy use for several energy services which can be separated into occupants-related energy use and building-related energy use, as shown in Figure 14. Occupant related means that the occupants decide on buying and installing the energy consuming device. Building related means that the building owner decides on installing it, it is in the building the occupant is using. In the case of an owner living in the house or apartment owned, the owner is also the occupant but the corresponding use is still either building related (here the owner-occupant is considered as the investor) or occupant related (here the owner is considered as occupant).

Final decision on how to consider common appliances is not made yet in Annex 56. In many countries the "white appliances" like stove, refrigerator, sometimes freezer, washing machine, tumbler or dryer are built in appliances and therefore building related. But there are countries where the tenants rent an apartment without the "white appliances", which they buy and install by themselves. The system boundaries in Figure 14 still have to be confirmed within Annex 56 in the upcoming meetings. Here we suggest to use the following boundaries which are likely to be confirmed.

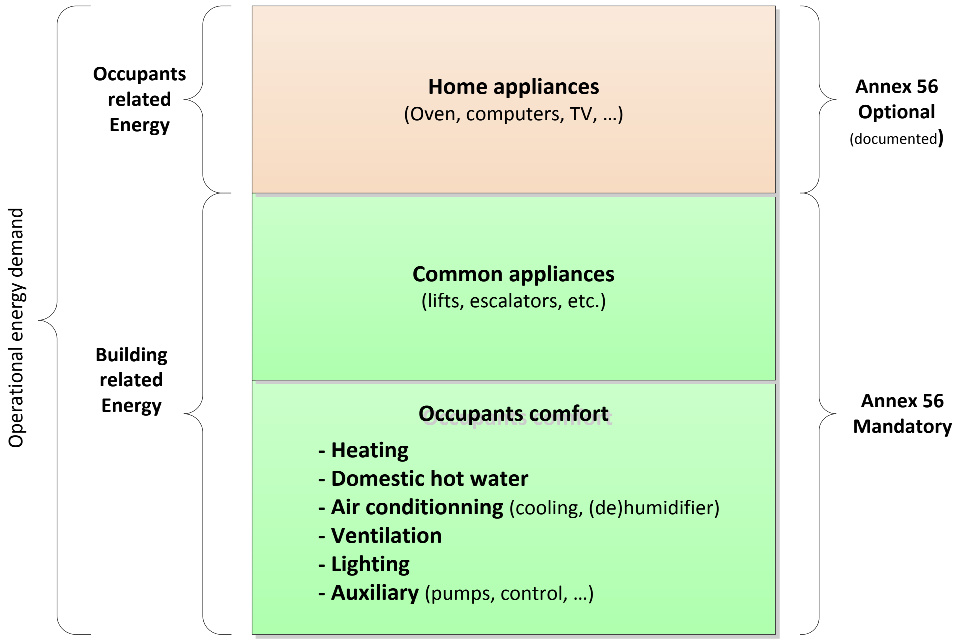


Figure 14 Building system boundary for building energy use in Annex 56

LCIA in Annex 56 comprises mandatorily the following elements of operational energy use:

- Heating
- Domestic hot water (DHW)
- Air conditioning (cooling & (de)humidifier)
- Ventilation
- Lighting
- Auxiliary
- Integration of energy use from home appliances is optional, it might be included if reported and documented.
- Assessment of overall energy use of renovated buildings comprising operational energy use after renovation and embodied energy use of the building's renovation

To summarize, the system boundary to perform an LCIA and to assess overall energy use of a renovated building should include in Annex 56 the following environmental impacts:

- Embodied energy use of the components added for energy related renovation measures of the thermal envelope of the building.
- Embodied energy use of the components added for energy related renovation measures comprising building integrated technical systems (BITS) and on-site energy generation units. If they are a simple replacement of an existing unit or device not improving energy performance or non-renewable energy input and if they are only replaced because the end of the life was reached, embodied energy use is for the retrofit of the building and not an energy related measures).
- Embodied energy use of the components added to provide the same building function before and after renovation: This embodied energy use is not added to the energy use for the energy related renovation measures, since it is energy use incurring anyway by the anyway renovation.
- Operational energy use to provide thermal and lighting comfort for the occupants as well as for the operation of the common appliances after renovation (the latter still has to be discussed). Integration of energy use of home appliances is optional.

Figure 15 shows the energy and components related impacts to take into account in the LCIA and assessment of overall energy use related to a renovated building.

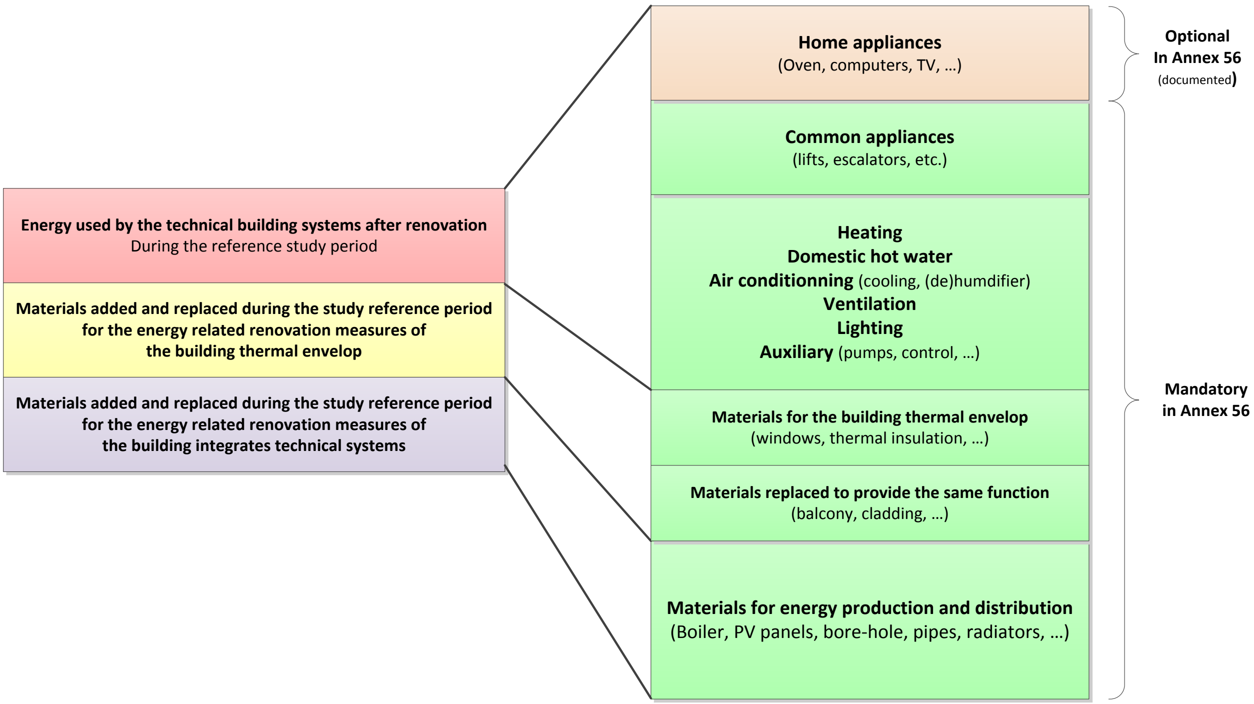


Figure 15 Impacts to be included in the LCIA of renovated buildings in Annex 56

2.5. Cost assessment: Global cost for 60 years

The methodology to correctly calculate energy and carbon emissions related costs of building renovation draws inter alia from EPBD Art. 4, Annex I and Annex III, draft methodology provided by European Commission in 2011 (BPIE 2010; Hermelink A.H. 2009 and Boermans T. et al. 2011).

2.5.1. Scope of cost evaluation

The scope of cost evaluation is based on a **lifecycle cost** approach and comprises:

- Initial global investment expenditures yielding yearly capital costs (interest and amortization) during the life of a building element on a yearly cost base;
- Replacement costs during the life of the building;
- Running costs, including energy costs, possible costs for carbon emissions, costs for auxiliary energy use, operational costs and maintenance costs;
- Lifetime of a building corresponds to the residual expected lifetime at the moment of building renovation or if residual lifetime is unknown it is 60 years (for the sake of analysis).

Definitions for cost evaluation (see Figure 16):

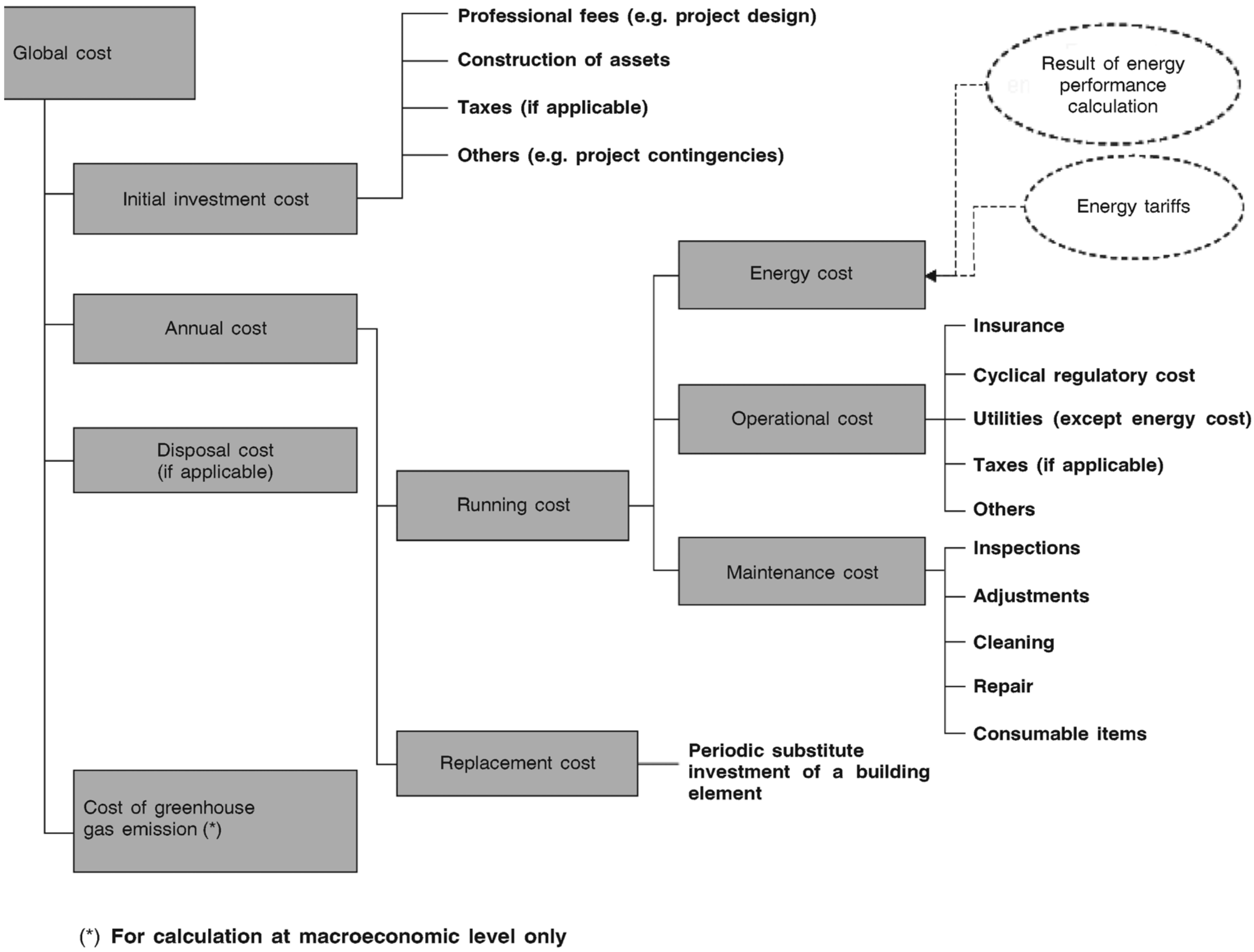


Figure 16 Cost categorization according to the framework methodology of EPBD recast (Official Journal of the EU, 19.4. 2012, p. C 115/16)

The guidelines to the EPBD recast propose the following cost categories (Official Journal of the European Union, 19.4. 2012, p. C 115/16; see Figure 16).

- Global cost mean the sum of the present value of the initial investment costs plus the present value of the sum of running costs (energy, operational and maintenance costs) and replacement costs (referred to the starting year) and possible costs of carbon emissions (as well as possible co-benefits);
- Initial investment costs mean all costs incurred up to the point when the renovated building or the renovated building element is delivered, ready to use. These costs include design, purchase of building elements, connection to suppliers, installation and commissioning processes;
- Energy costs mean annual energy costs including fixed and peak charges for energy as well as national taxes;

- Operational costs mean all costs linked to the operation of the building including annual costs for insurance, utility charges and other standing charges and taxes;
- Maintenance costs mean annual costs for measures for preserving and restoring the desired quality of the building or building element. This includes annual costs for inspection, cleaning, adjustments, repair and consumable items;
- Replacement cost means a substitute investment for a building element or installation (HVAC), according to the estimated economic lifecycle during the calculation period;

Besides the cost perspective there is the value perspective which is for building owners basically even more comprehensive and more relevant. Increased value of building renovation means the increased economic value of the building as a result of to its global quality improvement, especially regarding energy and emission related renovation actions.

2.5.2. Cost assessment of energy and carbon emissions related renovation measures

For assessing cost and economic efficiency of energy and carbon related renovation measures, it is necessary to define a reference situation to properly determine the effects of an energy related renovation on energy use, carbon emission reductions and cost. In principle the assessment is based on a **full cost approach** which is in line with the regulation prescribed by the EPBD recast (see European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, p. 115/16f.). This means that for each assessed renovation measure or package of renovation measures applied to a building, full cost of renovation and cost of subsequent operation of the building (energy costs and energy related maintenance costs) have to be calculated. Since the focus is on the evaluation of energy related renovation measures or packages of renovation measures (and not on the assessment of total renovation costs) for the investor and building user, a reference case has to be determined which comprises all renovation measures except the measures which are specifically energy related. This reference case is called an **«anyway renovation»** and comprises only renovation measures which have to be carried out «anyway» because the end of the technical life of building elements has been achieved or the functionality or service quality of a building element is not sufficient any more)[3]. Therefore, the following cost items may be omitted from the calculation (see : European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, p. 115/16f.):

3 In the case of major renovations, the “reference case” or "anyway renovation case" normally already comprises also energy related renovation measures. In many countries there are regulations, requiring from larger renovation projects to comply with energy related targets (e.g. in Portugal, if the renovation has an investment value above 25% of the building value or in Switzerland, if the investment is larger than 25% of the assurance value of the building or larger than 200'000 CHF). In such cases the reference could be chosen to be a renovation which just complies with existing energy use requirements.

- Costs related to building elements which do not have an influence on the energy performance of the building, for example: cost of floor covering, cost of wall painting, etc. (if the energy performance calculation does not reveal any differences in this respect); EN C 115/16 Official Journal of the European Union 19.4.2012;
- Costs that are the same for all renovation measures assessed for a certain reference building (even if the related building elements have or could have an influence on the energy performance of the building). Since these cost items do not make a difference in the comparison of the renovation measures, it is not required to take them into account. Examples could be cost of scaffolding, demolition cost, etc. – once again under the precondition that no differences in these cost items can be expected for the renovation measures assessed.

For calculating the cost optimality of minimum energy performance requirements, the additional **cost** calculation approach is not suitable for the following reasons (European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, p. 115/17):

- The characteristics of the building have an impact on the results of the assessment of cost optimality;
- The additional cost calculation approach cannot fully reflect the scope of assessed measures: Many energy efficiency measures are to be seen as an integral part of the building design. This is particularly true for measures that are related to ‘passive cooling' approaches, such as the choice of share of window area and the placement of window areas according to the orientation of the building, the activation of thermal mass, the package of measures related to night cooling, etc. The additional cost calculation approach makes it difficult to show inter-linkages between certain building characteristics, e.g. the choice of a certain type of façade requires certain static preconditions; thermo-active building systems for heating and cooling require a certain level of net energy demand, etc. (this holds also for the case of building renovation, albeit to a lesser extent);

The **reference situation** for the evaluation of energy and carbon related renovation costs comprises those building renovation measures which are not carried out with the purpose to reduce energy use and carbon emissions but which are carried out for maintaining the building and its functionality: A renovation with so called «anyway» measures strives for the renewal of building elements or building parts which have arrived at the end of their service life, not deliberately endeavouring for higher energy performance (even if in some cases they may reduce energy use compared to the previous solution, since these «anyway» measures have a better energy performance than the replaced building elements because of general technology and market developments). Building renovation comprising energy related measures is then compared to this reference case.

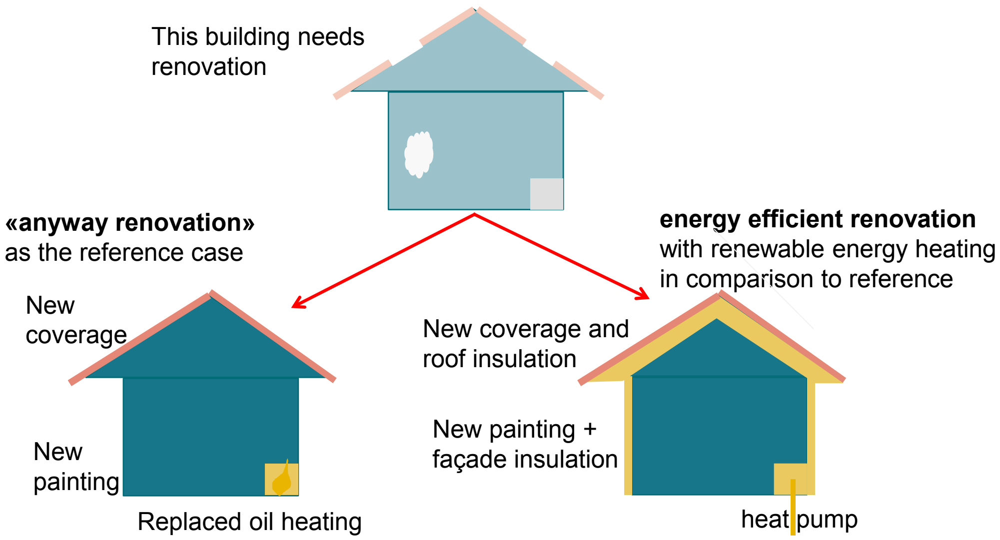


Figure 17 «Anyway renovation» vs. «energy related renovation» in the case of an anyway necessary building renovation due to functional reasons and building elements at the end of their service life.

2.5.3. Different perspectives: Private cost and social cost and benefits

Private cost perspective:

Building owners, investors and sometimes even policy setters assume a private cost perspective, assessing building renovation and operation solutions. It is an individual perspective relying on the prevailing political and economic framework conditions, as for example indirect taxes, subsidies, energy taxes or emission taxes, etc.

Social cost perspective:

Policy setters, government bodies, public companies etc. are supposed to comply with existing political goals and targets as well as private owners and investors endeavouring to be a front runner or shining example. From this perspective, building renovation is to be assessed more comprehensively, taking into account external costs and benefits but not including financing taxes (which aim at raising money for the government) nor subsidies (which do not lower social costs). Energy and emission taxes are taken into account for the private as well as for the social perspective, since they internalize at least partly external costs (for climate change effects, air pollution effects, biodiversity losses, etc.). To integrate into the cost assessment private co-benefits as well as social costs incurred by external effects is a big challenge because quantification and even more monetarization of these effects is usually not available and complex to appraise.

Scope depending cost elements	
Private cost perspective	**Social cost perspective**
Investment costs Initial investment cost Replacement costs	**Investment costs** Initial investment cost Replacement costs
Utilization costs of building Energy costs + energy-/CO_2-taxes Maintenance costs Operational costs	**Utilization costs of building** Energy costs + energy-/CO_2-taxes Maintenance costs Operational costs
Co-benefits: Higher user comfort (temperature, air draft and quality), less problems with building physics, reduction of exterior noise, higher aesthetic value, etc.)	**External costs** (e.g. health damages, building damages, ecological damages due to fossil air pollution) and **benefits** (direct and indirect job creation[4], local economic impacts, less dependence on energy imports)[5]
Indirect taxes and subsidies	---

Figure 18 Cost categories relevant from a private cost perspective and from a societal cost perspective, respectively.

For the global cost assessment, direct cost incurred by investments (capital costs: interest and amortization) and building operation ought to be supplemented by cost or benefits from external effects (social costs) and co-benefits (private benefits). Energy related renovation measures have typically quite different costs and benefits compared to non-energy related anyway renovation measures: Higher capital costs due to higher investments, lower energy costs due to better energy performance, higher co-benefits and lower external costs (see Figure 19).

4 Wei, M.; Patadia, S.; Kammen, D.M. (2009) synthesized 15 job studies, covering renewable energy, energy efficiency, carbon capture and storage and nuclear power with respect to their job creation potential. They found that all non-fossil fuel technologies (energy efficiency, renewable energy and low carbon) create more jobs per unit energy used or saved than coal and natural gas.

5 Job creation studies have to be interpreted carefully. Very often they do not really determine net job creation by energy efficiency and renewable energy taking adequately into account job losses in the economy if financial resources are reallocated for energy efficiency and renewable energy. Studies applying a general computable equilibrium model for Switzerland and assuming a high energy taxing policy to transform the energy sector until 2050 to about 2 tons of CO_2 per capita per year yield high possible reductions of non-renewable energy demand combined with slight job losses (until 2050 -0.7% compared to a business as usual scenario) and slight GDP losses (-0.08% per year until 2050; Ecoplan 2012).

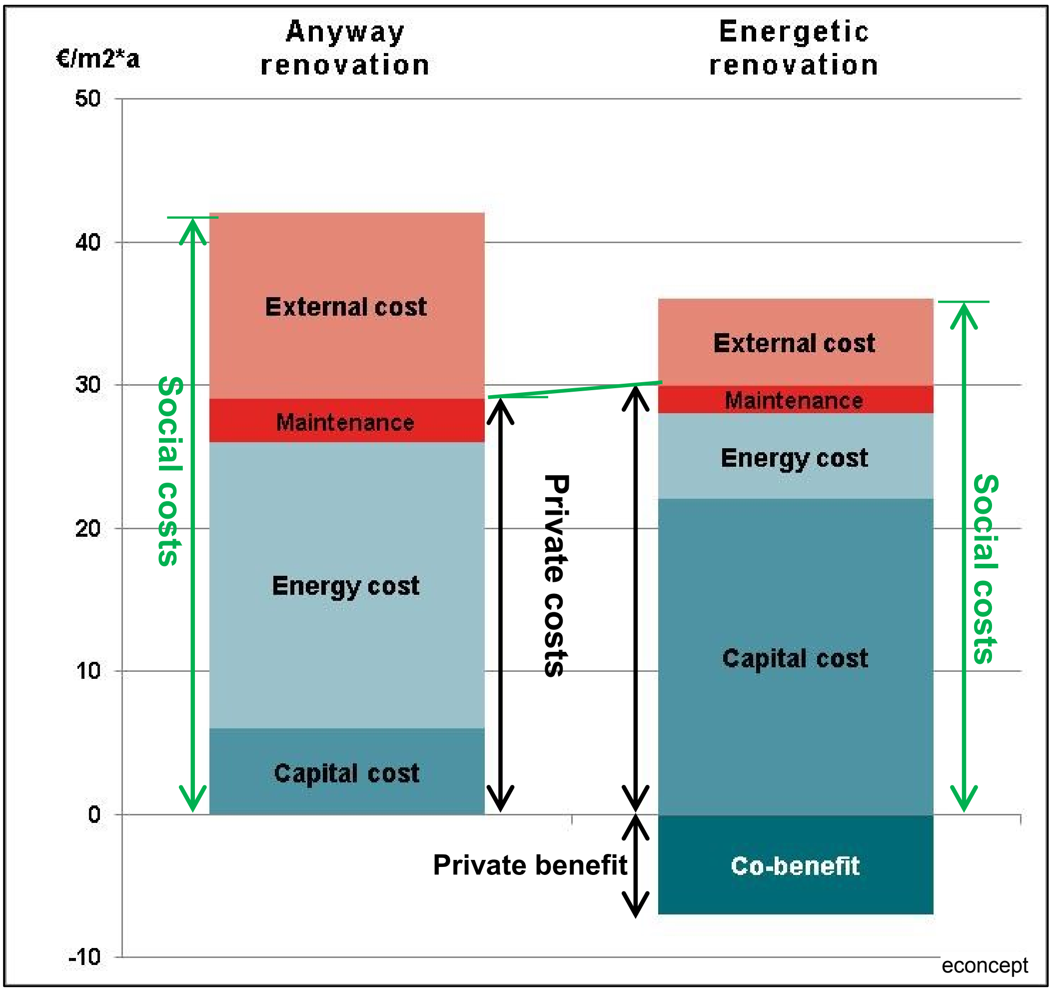


Figure 19 Anyway renovation compared to energy and carbon emission related renovation: Private yearly costs and co-benefits and social yearly costs (including external costs without already internalized financial payments for CO_2-allowances or taxes)

2.5.4. *Cost calculation method: Dynamic cost calculation*

Adequate cost calculation has to be performed dynamically, i.e. future costs and benefits have to be discounted to yield economically correct results. Neither payback methods with typically much too short static payback times nor static cost calculation are adequate for cost calculations of energy conservation measures which have long lifes. According to EN 15459 (Energy performance of buildings – economic evaluation procedure for energy systems in buildings) it is adequate to apply either the ***global cost method*** or the ***annuity method*** for dynamic cost calculation:

By applying the **global cost method**, the present value of all investment costs (initial investment costs and replacement costs) and running costs (energy, operational and maintenance costs) during a predefined calculation period or during the life of the building are determined. Thereby all future costs, cost savings and monetary benefits are discounted and summarized which yields the present value of the corresponding cost and benefit flows during the assessment period. Often buildings or certain building elements have a longer life span than the calculation period assumed. In such cases it is necessary to estimate a residual value for the building or for building elements at the end of the calculation period. To estimate residual values at the end of the calculation period, linear depreciation is applied as proposed by the guidelines for the EPBD recast. Discounted residual values have to be added to the net present value. For the calculation period energy prices and interest rates as well as operational and maintenance costs have to be projected for every year of the evaluation period to be taken into account and discounted properly. This method corresponds with the discounted cash flow method used in the realm of building development and management.

The **annuity method** transforms investment costs into average annualized costs, yielding constant annual costs during the life span of the investment considered. Minimal time horizon is usually the service life of the building element with the longest life expectancy. Yearly energy costs, operational costs and maintenance costs are added to yearly annuity costs of initial investment, yielding constant yearly global costs during the evaluation period. If energy prices as well as yearly operational costs and maintenance costs are not constant during the calculation period, it is necessary to determine and apply an adjustment factor to take into account real future energy price increases or real future cost increases[6].

General average adjustment factor for price or cost increases applying the annuity method:

a *annuity for constant real prices (costs)*

m *general average adjustment factor*

t *time range of cost evaluation*

I *real interest rate*

r *rate of yearly increase of energy prices, maintenance costs or operational costs*

Annuity: $$a = \frac{i*(1+i)^t}{(1+i)^t-1}$$

*If the energy prices or the costs are rising, it is necessary to calculate an average energy price or cost value, which dynamically takes into account the price or cost increases in the period t. This can be done by calculation of an average or medium adjustment factor **m** which has to be multiplied with the energy price or the annual costs at the beginning of period t with prices or costs increasing annually by a rate r (e.g. 0.02 for an annual rate of 2%):*

$$m = \frac{\left(1+\frac{i-r}{1+r}\right)^t-1}{\left(\frac{i-r}{1+r}\right)*\left(1+\frac{i-r}{1+r}\right)^t} * a$$

6 General average adjustment factor for price or cost increases applying the annuity method

Example:

*For a real interest rate **i** = 0.03 (3% per year), price or cost increases **r** of 0.04 (4% per year) during the calculation period **t** of 20 years resulting average price (cost) increase factor **m** is:*

$$m = 1.49.$$

*Hence yearly capital cost **c** for an initial investment **I** are:* $\mathbf{c = a * I}$

*If yearly energy costs **e** are increasing by 4% p.a. and the real interest rate **i** is 3% p.a. the adjusted average annual energy costs $\mathbf{e_a}$ during period t are:* $\mathbf{e_a = e * m}$

The guidelines of EPBD-recast propose to apply the global cost method.

The annuity method may be used for cost calculations within the evaluation of various packages of renovation measures for generic buildings. By using the annuity method, it is not necessary to determine residual values at the end of a preset calculation period for measures which have a longer life than the assumed time horizon of the cost calculation and since it is easy to obtain average yearly costs (or costs/m^2 per year) for measures with differing service life. Furthermore the annuity method assumes that building elements are replaced at the end of their element-specific service life (i.e. corresponding replacement investment is taken into account).

2.6. Cost effective energy and carbon emissions optimization in building renovation

To reduce cost effectively carbon emissions **and** energy use is not a clear cut optimization task but rather a trade-off analysis of costs and benefits of energy related measures versus carbon emissions related employment of renewable energy sources. Trade off analysis can be turned into an optimization task if one target is set for optimization thereby taking into account a boundary condition with respect to the second target dimension. E.g. assuming a zero emission building, prioritising the emission target, carbon emissions would be reduced cost optimally to zero. Simultaneously, the building has to fulfil a boundary condition which is related to the resulting energy demand of the zero emission building, which is supposed to ensure satisfactory thermal comfort and prevent problems with building physics (e.g. mold, thermal bridges).

2.6.1. *Cost optimal vs. cost effective energy and carbon emissions related building renovation*

Cost optimal efficiency measures within a two-step approach to nearly zero energy and/or emissions buildings

In Europe for the time being, the concepts of the recast of the Energy Performance of Building Directive (EPBD) prevail in the discussion on future energy performance standards for buildings. The directive is based on a two-step approach (illustrated in Figure 20) which assumes that the improvement of energy related building performance starts first with cost effective energy related efficiency measures, up to an efficiency level which is cost optimal (see Official Journal of EU from 21.3. 2012 and 19.4. 2012). This cost optimum can be assessed on a private financial level (relevant for building owners, investors and users) or on a societal macro level (relevant for the policy makers). The EU Member States are obliged to implement energy related building performance standards which achieve at least the cost optimal or least cost performance level.

To achieve nearly zero energy or nearly zero emission buildings, either additional efficiency measures or the supply of renewable energy generated on-site can be applied to further reduce carbon emissions and remaining non-renewable energy use which results in the two-step approach, mentioned above and illustrated in Figure 20.

In the case of building renovation, it has to be explored in more detail if the two step approach still holds if a cost perspective is assumed. Moreover it has to be clarified to what extent cost optimal minimum energy performance standards allow achieving the ambitious future targets within energy related building renovation. Widespread stepwise renovation practices may often favour the choice of renewable energy use for the next upcoming renovation step (especially if the heating system has to be replaced). Thereby, carbon emissions and non-renewable primary energy use can already be reduced significantly and cost effectively. This choice might especially be recommendable if the building envelope is not at the end of its service life and does not have to be renewed yet due to functional reasons.

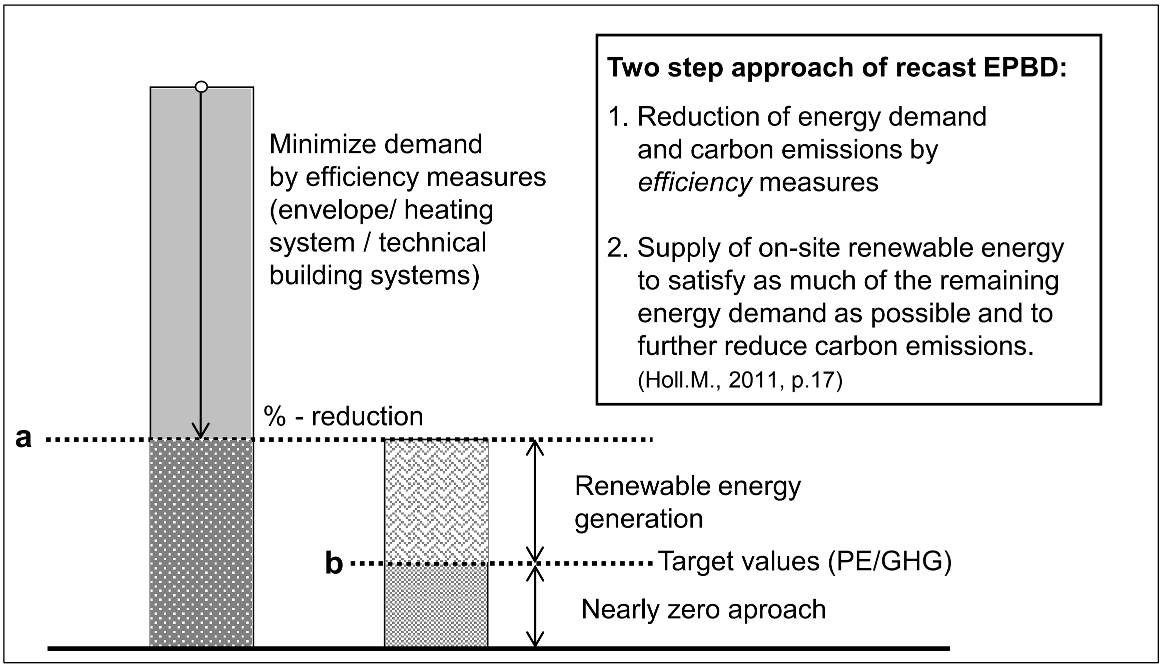


Figure 20 Two-step approach of EPBD recast (Holl M. 2011, p. 17)

Global cost effectiveness approach for building renovation to achieve nearly zero energy and nearly zero emissions buildings

In the case of building renovation cost optimal energy related renovation measures will usually not allow to achieve NZEB's. Therefore, the range of economically viable renovation measures, has to be extended to comprise the evaluation of all renovation measures, being still cost effective.

Figure 21 illustrates the cost effectiveness approach to determine minimal energy and/or emission standards. Minimal requirements depend on the performance level which can be achieved economically viable compared to anyway renovations which represent the reference renovation situation. In Figure 21 resulting primary energy reductions A → N are remarkably higher than in the case of the economic most favourable minimal cost solution O with a primary energy reduction A → O.

Moreover, resulting savings depend on the cost perspective assumed (see subsequent chapter 2.6.2). If a social cost perspective is assumed which comprises also external costs, they will be higher than in the case of a private cost perspective (depending on the degree of internalisation of external cost in the private costs, e.g. by carbon taxes or a emission cap and trade regime).

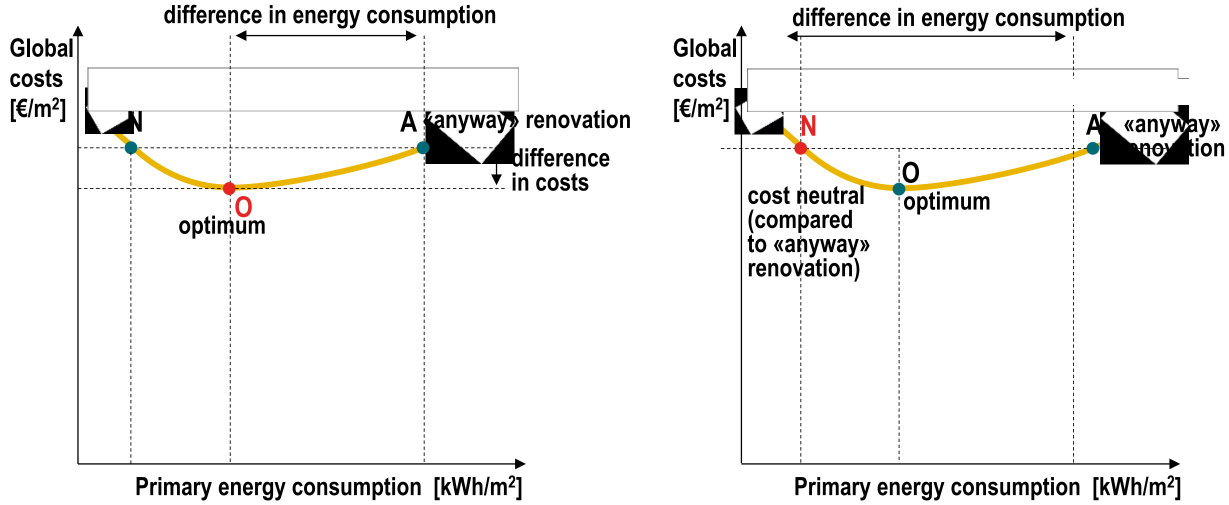


Figure 21 Global cost curve after renovation (yearly costs for interest and amortization of the renovation measures, energy cost, cost for operation and maintenance), starting from the reference situation **A** («anyway» renovation) towards energy related renovation options yielding less primary energy use after renovation than in the case of the anyway renovation. **O** represents the cost optimal renovation option. **N** represents the renovation option with the highest reduction of primary energy still not having higher cost than the anyway renovation (BPIE 2010, p. 15, supplemented by econcept).
Left: **O** = cost optimal reduction and right: **N** = cost neutral reduction

2.6.2. Cost effective optimization of energy use and carbon emissions reduction in the course of building renovation

Market based or normative optimization and standard setting

Market based approach:
The optimization task relies on market prices and costs[7]. It explores the range of renovation measures which are most cost optimal (see EPBD) or which are cost effective and economic viable (as proposed above, see Figure 21). Market based optimization strives for optimal contributions to energy and/or carbon emissions targets which are cost optimal (first step in the EPBD-framework) or cost effective compared to an anyway renovation serving as reference.

Basically it is possible to extend this approach which relies on a private cost perspective by an approach which strives for internalizing (at least partially) external cost into market cost and prices, for example by energy price addings, energy taxes, CO_2- taxes, pollution taxes or costs for emission certificates within a cap and trade system for emissions. At the time being, external costs are not or only partially internalized. Full internalization would lead to higher energy costs

[7] Depending on the prevailing institutional national framework, external cost may be partially internalised in the market prices.

which would foster investment and operational decisions to reduce energy consumption and carbon emissions.

Normative approach:
Within a normative approach, explicit energy and carbon emissions targets are set normatively (motivated politically and/or ecologically). Optimization seeks least cost energy related renovation measures to comply with the targets.

Reduction of energy demand vs. reduction of carbon emissions

The priorities with respect to reduction of primary energy use and carbon emissions reduction are not clearly determined. EPBD suggests priority for building efficiency measures, at least up to a cost optimal package of energy related efficiency measures, thereby clearly reducing energy use. Carbon emissions are reduced too, but the extent of the reduction is depending on the energy carriers deployed to cover energy demand.

Considering current trends in Europe as well as previous strategies in the realm of increased energy performance of buildings and associated resource and climate policy, the topic of reducing energy demand dominated so far the discussions (e.g. recast of EPBD with the concept of "nearly zero energy buildings"). However, this priority may be put into question based on the possibility that there may be cost-effective solutions to reduce carbon emissions significantly in building renovation by making use of renewable energy sources, combined with less far-reaching energy efficiency improvements.

Addressing the relationship between nearly zero energy and nearly zero CO_2-emissions and the EU energy policy in the building sector BPIE (Nov. 2011, p. 24) states: "The intent of the EPBD is clearly to achieve (nearly) zero CO_2 emissions through reductions in energy use, i.e. even if energy was not an issue CO_2-emissions still would be. Therefore it is important to establish how a move towards "nearly zero energy" will affect CO_2-emissions (zero energy will inadvertently result in zero CO_2, however the definition of zero is typically not the "ideal and absolute" zero, but instead a zero over a period of time and a zero that might be a balance of energy production and use)." This insinuates that also within the framework of EPBD, reduction of carbon emissions is most important. BPIE derives a target value for CO_2-emissions for new NZEB of <3 kg CO_2/m^2a for the sake of achieving the long term 2050 targets in the building sector, thereby assuming that existing buildings will have higher emissions in the average. For operational energy use in 2050 Switzerland has target values of 2.5 kg CO_2/m^2a and 5 kg CO_2/m^2a for new and for renovated buildings respectively and for embodied energy use 8.5 and 5 kg CO_2/m^2a for new and for renovated buildings (SIA 2040, 2011).

From a societal perspective, evidence suggests for the time being that the challenge to cope with climate change will possibly be higher than to solve future resource problems in the energy sector (e.g. see BP, «Energy Outlook 2030»; shale gas revolution and new fossil energy reserves due to new drilling technologies in the USA and Europe, etc.). At the same time there are various energy related measures to reduce carbon emissions, which are attractive from a cost perspective, especially in the case of building renovation (marginal cost of efficiency measures increase exponentially with increasing efficiency level and are often higher than (marginal) costs of renewable energy use, which increase less or might sometimes even decrease).

It has to be acknowledged that the country specific background may vary widely among participating countries. It might be relevant for the focus of the future development of standards and for target setting, whether more weight is put on reduction of non-renewable energy use or on reduction of carbon emissions. Besides differing climate conditions the following characteristics of country specific building sectors will be important for future standards and targets in the case of building renovation:

- Overall energy use and level of energy performance of existing building stock
- Current energy sources (potential) and carriers used to meet energy demand of the building stock
- Share of electricity use for heating, cooling and DHW
- National electricity mix (fossil, renewable and nuclear) to cover electricity demand of existing buildings
- National carbon emissions reduction targets and possibly national energy reduction targets
- Prevailing types of construction of buildings, building categories as well as the age of the building stock and of major building types or categories
- Potential of renewable energy sources which are exploitable economic viably

Implications for the definition of low energy and low carbon standards:

- The above considerations suggest to develop a comparative methodology framework which allows for different country specific situations and thereby allows for prioritizing either nearly zero energy related renovations or nearly zero carbon emissions related renovations.
- Reduction of energy use as well as reduction of carbon emissions are both important within building renovation. It has to be decided if they shall be of equal importance and if this importance depends on the particular countries and their context conditions. From a global perspective a slight priority on the carbon emissions mitigation in the building sector appears arguable.

Cost effective optimization of energy use and carbon emissions within building renovation

As outlined above cost effective optimization of carbon emissions reduction and energy use reduction takes place either

- within the range of cost-effective energy and carbon emissions related renovation measures. Thereby, costs will be a major driver for the choice as well as for the evaluation of energy and carbon emissions related renovation measures and packages (market approach)

or

- with respect to a normatively set energy and/or emission target (ecological approach, if the target is derived ecologically, political approach if the target is set politically, whereupon political targets are usually also based on ecological targets or limits)

Normative approach:
If we assume a normative approach, cost optimality means to minimize the costs to achieve preset energy or carbon emissions targets. This will yield minimum cost packages of renovation measures which meet the normatively preset carbon emissions or energy use target.

If an emissions target has to be achieved, thermal comfort and requirements from building physics must be assured. This can be done by additional boundary conditions regarding energy performance of the building and its envelope which have to be taken into account while optimizing cost effective measures. Assuming that this boundary condition is necessary, some kind of two-step approach emerges again, with a first step assuring minimal or cost optimal energetic quality of the building envelope and the second step optimizing contributions to the normatively set target.

Market based approach:
In theory it can be expected that market based solutions yield least cost solutions, reducing energy demand to a level which is cost optimal for the prevailing political and economic context (regulations, energy prices, interest rate, possible energy and carbon taxes, etc.). The focus is on energy since energy has a price and reduction of energy use by costly energy related renovation measures can benefit from lower energy costs. On the other hand, carbon emissions don't have a price or if they have it is usually not adequate, which is the reason why carbon emissions reduction is disregarded on the market.

Market based solutions tend to **cost optimal** solutions which focus on energy demand reduction. If the range of economic viable solutions is extended to **cost effective** solutions, which are beyond the cost optimum but which are still economic viable, the question then arises to what extent further renovation measures shall focus on energy performance of the building or if they rather should focus on the reduction of carbon emissions. Marginal costs of further reducing non-renewable energy demand by energy efficiency measures beyond the cost optimum are often fast increasing and are economically less favourable in reducing non-renewable energy demand and carbon emissions than renewable energy generation on-site or deployment of off-site renewable energy sources.

To optimize among the range of possible measures, costs and benefits of these measures have to be aggregated and compared. This requires the assessment and valuation of resulting effects, especially the valuation of savings of primary energy compared to reductions of carbon emissions. This can be done with approaches established by multi criteria analysis:

Distance to target approach for the valuation of environmental goods and services:
To assess the contribution of 1 t CO_2 emissions reduction per year compared with primary energy savings of 1 MWh per year, existing targets to reduce carbon emissions and primary energy use respectively are taken as objectives to be achieved (if existing). The higher the need for savings or reductions to achieve the respective target the higher the valuation of a unit reduction.

Shadow pricing:
Within shadow pricing, external costs of primary energy use and of carbon emissions are determined and added to the energy costs. If all externalities could be determined and monetized, resulting shadow prices would represent global social costs of resource use and could be used directly for cost optimization. External costs can be estimated directly by valuation of external effects or by determining avoidance costs incurred by meeting a preset energy saving target or a carbon emission target.

Priority on the reduction of carbon emissions:
If we assume that

- meeting global carbon emissions targets has priority,
- the level of cost optimal measures has to be outperformed to meet these targets,
- energy performance of the building, achieved at the cost optimum is sufficient for thermal comfort and building physics reasons
- then optimization is done among renovation measures still cost effective but maximising possible carbon emissions reduction.

Hitherto existing analyses from generic single-family houses and multi-family houses shall be extended to learn more about existing trade-offs, trends of marginal costs for further efficiency oriented and renewable energy supply measures. Later they are supplemented with the identification and assessment of further benefits or co-benefits of building renovation.

2.7. Notes on cooling in residential buildings

2.7.1. Background: Increasing relevance of cooling in residential buildings

Currently, primary energy demand of the existing building stock in the colder northern region of Europe is mainly driven by the heating demand (see Table 2 for the electricity consumption for cooling) while already today the primary energy demand in southern regions of Europe is also affected by the cooling demand. Due to the climate change, the average surface temperatures in Europe are expected to rise in the next years.

Table 2 Breakdown of residential electricity consumption in EU-27 countries in 2007 (Bertoldi et al. 2009) and 2009 (Bertoldi et al. 2012)

EU-27 residential electricity consumption	2007		2009	
	[TWh/a]	[%]	[TWh/a]	[%]
Cold appliances (refrigerators & freezers)	122.0	15%	122.2	14.5%
Washing machines (2007) and drying (2009)	51.0	6%	60.7	7.2%
Dishwashers	21.5	3%	25.3	3.0%
Electric ovens & hobs	60.0	7%	55.6	6.6%
Air-conditioning	**17.0**	**2%**	**39.6**	**4.7%**
Ventilation	**22.0**	**3%**		
Water heaters	68.8	9%	74.1	8.8%
Heating systems/electric boilers	150.0	19%	160.9	19.1%
Lighting	84.0	10%	84.3	10.0%
Television; entertainment	54.0	7%	69.9	8.3%
Set-top boxes	9.3	1%	14.3	1.7%
Computers, office equipments	22.0	3%	60.7	7.2%
External power supplies	15.5	2%		
2007: Home appliances stand-by 2009: Vacuum cleaners and coffee machines	43.0	5%	40.4	4.8%
Others	60.6	8%	34.5	4.1%
Total residential electricity consumption	**800.7**	**100%**	**840.5**	**100%**

Table 2 illustrates that for the time being cooling in residential buildings in Europe has a limited relevance. It is less important than cooling in commercial buildings with more interior heat sources. But this relevance is fast increasing because of rising and more widespread comfort needs and higher temperatures due to climate change (Bertoldi et al, 2012, p. 63f.). Consequently, the next challenge regarding the refurbishment of buildings in Europe is to either prevent cooling or to provide efficiently cooling with the least primary energy demand possible and the lowest additional carbon emissions.

The current refurbishment of the buildings in warmer climate zones of Europe, which targets a reduction of the primary energy demand for heating, also affects the primary energy demand for cooling. Additionally, many house owners in this region will not only refurbish their buildings to meet certain energy standards or reduce the costs for the building operation, but to provide a higher standard of comfort. Contrary to heating, the primary energy demand for cooling of residential buildings in Europe is less monitored. As a result, the cooling demand of buildings in European countries is currently only estimated.

According to the status reports «Electricity Consumption and Efficiency Trends in European Union, Status Report 2009» (Bertoldi and Atanasiu, 2009) and Status Report 2012 (Bertoldi, Hirl, Labanca, 2012), air-conditioning and ventilation only accounted for about 5% and 4.7% respectively of the total power consumption in 2007 and 2009 respectively in the EU-27 households, which is equivalent to approximately 17 + 22 TWh/a 2007 and 39.6 TWh/a in 2009 as shown in Table 2. This is significantly less than the 6% of the total power consumption for air-conditioning in American households in 2009 (IEA 2009).

The cooling demand of residential buildings largely depends on the climate conditions and the cooling standards of the country. The contour map shown in Figure 22 on the left represents the European Cooling Index. 100 represents «average» European climate conditions with average outdoor temperatures just above 10°C, which occurs for example in Strasbourg and Frankfurt (ecoheatcool, work package 2, 2006). This index is based on the climatic conditions of 80 urban locations in Europe only, without considering the effect of building regulations on the cooling demand. According to this index, a large difference exists between the cooling demand of the northern and southern European countries, which is also expressed by the following comment (Ecodesign Lot10, 2008):

"Destination of air-conditioners varies a lot depending on latitudes:

- Northern and central Europe: air-conditioners are mostly installed in offices and light commercial buildings. The market for «renting» portable units is quite significant.
- Southern France and Mediterranean area: installations in private dwellings are also relevant. This explains well the high sale volumes recorded in these countries."

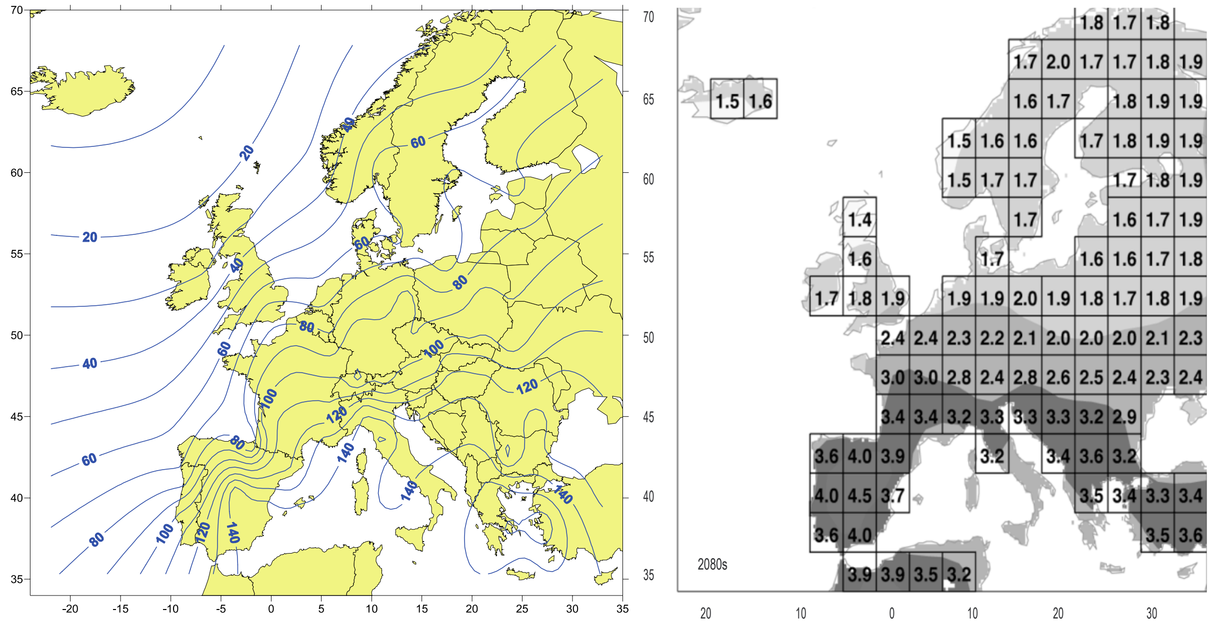


Figure 22 **On the left**: Contour map representing the European Cooling Index that illustrates the large differences of the cooling demand of buildings in Europe. The index is normalised, thus 100 is equal to an average European condition, which occurs for example in Strasbourg and Frankfurt.
On the right: Map with increasing temperatures, presenting a possible scenario of projected temperature changes in Europe for 2080 relative to the average temperatures in the period 1961–1990. According to this scenario, the average surface temperatures are expected to increase in absolute terms more in southern Europe.

2.7.2. Determining the cooling demand of buildings

Standards to determine the cooling demand

The European standard EN ISO 13790 defines methods for calculating the «energy use for space heating and cooling» of buildings. It has been adopted in national standards like the SIA 380.104:2008[8] (Switzerland). The described methods allow determining the sensible heating and cooling demand for the entire building or for each individual area in the building. The EN ISO 13790 describes 3 methods for calculating the annual cooling demand. Typically, the national building codes determine which method applies. The calculation methods are:

- Quasi steady state calculation method per month;
- Simplified dynamic calculation method per hour;
- Detailed dynamic calculation method (i.e. per hour).

8 The DIN V 18599 regulates the EU directive 2002/91/EG in Germany. The standard EN ISO 13791:2012 allows with a simplified method to calculate the room temperature of buildings if the building is not mechanically ventilated.

The quasi steady state calculation method per month results in correct annual results, but individual results per month can contain considerable errors. The simplified dynamic calculation method per hour results in more accurate results per month, but is not validated regarding the hourly results. The detailed dynamic calculation method gives the most accurate results, as the thermal inertia of the building is most realistically reflected (response time due to the thermal capacity of the building). However, this method can be time intense and sumptuous.

The results from the quasi steady state calculation method are sufficient to determine the annual cooling demand, which affect the three indicators primary energy, cost and greenhouse gas emissions. The detailed dynamic calculation method can be applied in addition to determine if the thermal comfort is given in the building at any time. Figure 23 illustrates the calculation steps to determine the cooling demand $Q_{C,nd}$ according to the quasi steady state calculation method, which is applied in the calculation tool for generic examples in Annex 56. The method includes the calculation of:

- The heat transfer by transmission and ventilation of the building zone when heated or cooled to a constant internal temperature;
- The contribution of internal and solar heat gains to the building heat balance;
- The annual energy demand for heating and cooling, to maintain the specified set-point temperatures in the building – latent heat not included;

Besides the necessary input values of climatic data, building use, geometry and construction, the desired interior temperature, a.k.a. set point temperature for cooling($\theta_{int,set,C}$), is an important input value for the calculation. This threshold considerably influences the cooling demand and is defined by the respective national building code(s). The purpose of limiting the room temperature to a certain threshold is to ensure thermal comfort permanently for the majority of occupants/users. However, it is important to realize that this temperature is not an arbitrary number, but notably the result of technological development. Before the invention of cooling devices, higher interior temperatures have been accepted inevitably.

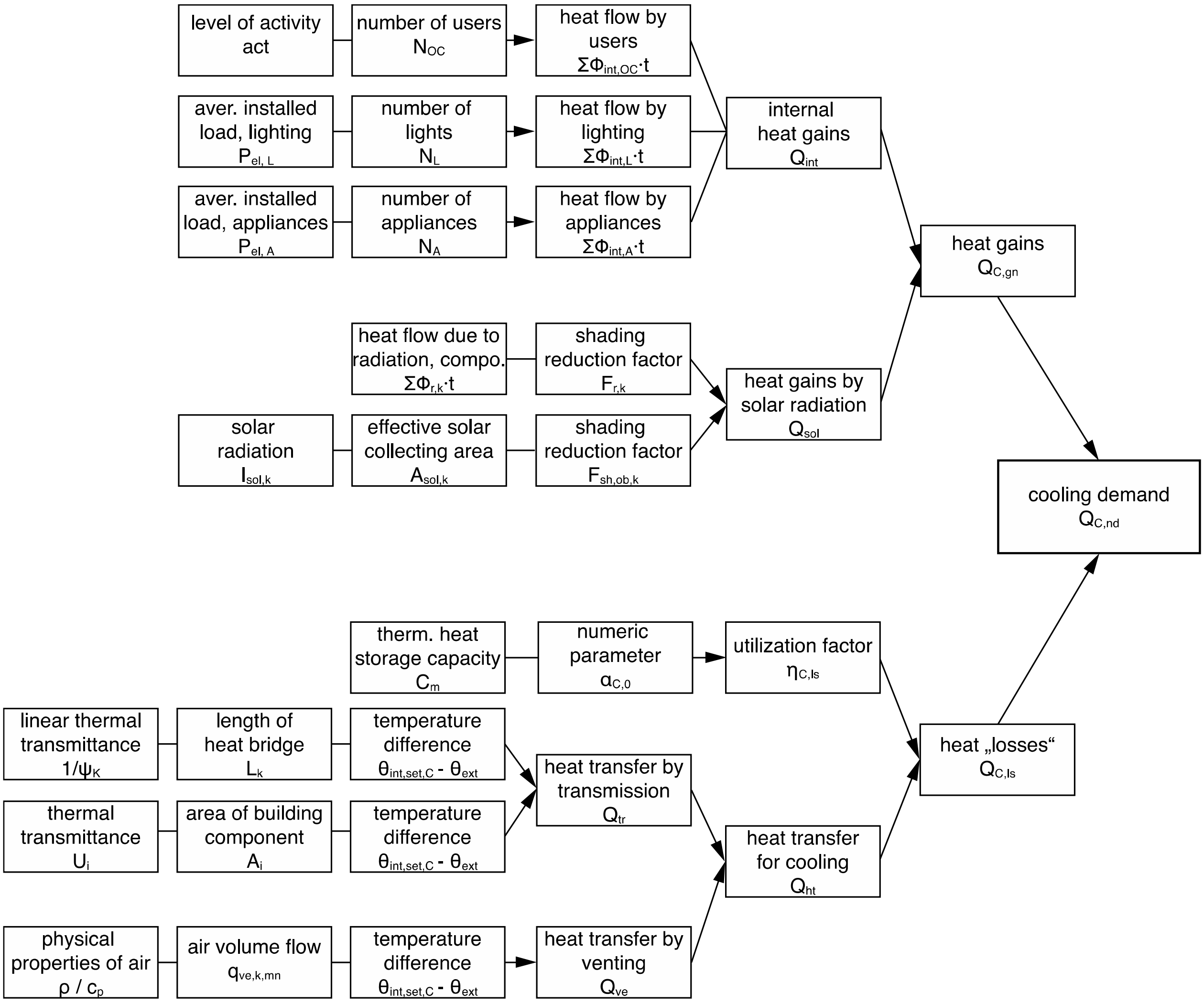


Figure 23 Overview of the relevant determinants to determine the cooling demand according to the quasi steady state calculation method

Today, cooling buildings at the expense of vast consumption of fossil fuels is scrutinized. However, since the power from renewable resources is more costly and also not permanently available (wind or solar power generation is more fluctuating than the instantaneously available power from fossil fuels), a constant set point temperature is questionable. As a result, some national building codes have been revised to allow for an adaptive set point temperature relative to the exterior temperature and seasonal clothing of the building users with more but clearly limited deviations. Besides, accepting a higher set point temperature in general during hot periods affects the number of days, where active cooling is necessary. The national standards define the set temperature depending on the building use. In absence of a regulation, the EN ISO 13790 proposes $\theta_{int,set,C}$ = 26°C °C for residential buildings. The DIN V18599-10 also defines a maximal temperature of 26°C for the interior spaces ($\theta_{int,C,max}$), but also gives a nominal temperature of 25°C ($\theta_{int,C,nominal}$). The Swiss norm 382/1 (SIA 382/1, 2007, p. 28) defines a range for the room temperature, which is between 21.0 – 24.5°C for average exterior daily temperatures up to16°C, between 22.0 – 26.5°C for exterior temperatures above 30°C and a transitional range between external temperatures of 16.0 - 30°C. (See Appendix for the description of the quasi steady state method).

2.7.3. Measures for reducing the cooling demand

Based on the calculation method of the cooling demand presented in the previous chapter, various measures exist for reducing the actual cooling demand. They can be categorized in three groups:

- Passive measures, which require the installation or the replacement of certain permanent building components (see Table 3);
- Active measures, which also require the installation of some devices, but can be adjusted in operation according to the demand (see Table 4)
- Measures with focus on the user behaviour (see Table 5).

The costs for installing or replacing appliances and devices are typically higher than the implementation of methods or control devices to change the user behaviour. Depending on the availability of products, which affect the labour cost, the installation costs can considerably differ between countries. Furthermore, the cost for installing components in a refurbishment project also depends on the specific building. The installation of glazing with low solar energy transmittance for example can also require in certain projects the replacement of the complete window, which is considerably more costly than just replacing the glazing. The impact on the cooling demand also depends highly on the building type and the context. It is difficult to generalize the efficiency of certain measures[9]. Depending on the orientation of the windows, measures on the windows are more or less effective. Because of different construction costs in Europe and different settings of existing buildings, the rating of cost and impact of the following tables is subjective. The table lists various measures, which affect different parameters regarding the calculation method of the cooling demand.

9 For example: The potential for reducing the cooling demand by reducing the solar irradiation compared by reducing the internal heat gains is considerably higher in buildings where the cooling demand is driven by solar heat gains.

Table 3 Passive measures for reducing cooling demand. In the column «Cost», an estimate regarding the costs is given, distinguishing low costs (+), medium costs (++), and high costs (+++). In the column «Impact», an estimate regarding the impact is given, distinguishing low impact (+), medium impact (++), and high impact (+++).

Purpose:	Measures	Affected parameter	Cost	Impact
Reducing Q_{sol}	*Installing fixed sun-blinds, trees etc.*	*This increases the shading reduction factor $F_{sh,ob,k}$.*	+	+++
	Reducing the window size	This reduces the effective collecting area of the surface $A_{sol,k}$.	++	++
	Applying a different external surface material to lower the absorption coefficient	This lowers the absorption coefficient $\alpha_{S,c}$ of the surface $A_{sol,k}$	+	+
	Increasing the thermal resistance of the building envelope	This is equivalent to reducing the thermal transmittance U_c, which reduces the effective collecting area of the surface $A_{sol,k}$	+/+++	+/++
	Installing of solar glazing	This lowers solar energy transmittance g_{gl}	++	++
Reducing Q_{tr}	Increasing the compactness of the building	This reduces relatively the area of the envelope A_i, which subsequently reduces heat transfer coefficient H_x	+/++	+
	Reducing thermal bridges	This is done by reducing the linear thermal bridge l_k, its according linear thermal transmittance ψ_k or the local point thermal transmittance χ_j, which reduce the heat transfer coefficient H_x	+	+
	Increasing the thermal resistance of the envelope	This is equivalent to reducing the thermal transmittance U_c, which reduces heat transfer coefficient H_x	+/ +++	+

Table 4 Active measures for reducing the cooling demand. In the column «Cost», an estimate regarding the costs is given, distinguishing low costs (+), medium costs (++), and high costs (+++). In the column «Impact», an estimate regarding the impact is given, distinguishing low impact (+), medium impact (++), and high impact (+++).

Purpose:	Measures	Affected parameter	Cost	Impact
Reducing Q_{sol}	Installing movable sun-blinds,	This increases the shading reduction factor $F_{sh,ob,k}$.	+	+++
Reducing Q_{ve}	Installing earth tubes, HRV, ERV, passive evaporative cooling etc.	This reduces the supplied exterior temperature θ_e, which reduces the temperature difference to the set point temperatures, $\theta_{int,set,C}$.	++	+
	Installing CO_2 sensors, presence detectors etc.	This reduces the mean volume flow $q_{ve,k,mn}$ by selective venting according to actual demand, which affects the heat transfer coefficient $H_{ve,adj}$	+	++

Purpose:	Measures	Affected parameter	Cost	Impact
Reducing Q_{int}	Installing efficient lighting (bulbs, dimmers and systems)	This reduces the heat flow rate from electrical lighting heat flow rate $\phi_{int,L}$.	-	+
	Reducing the number of light bulbs to a minimum	This reduces the heat flow rate from electrical lighting heat flow rate $\phi_{int,L}$.	-	+
	Installing efficient electrical appliances and production devices	This reduces the heat flow rate from appliances $\phi_{int,A}$ and the heat flow rate from production processes $\phi_{int,proc}$	-/+	+
	Allow for standby and off operation during idling phases	This reduces the heat flow rate from appliances $\phi_{int,A}$, potentially the heat flow rate from production processes $\phi_{int,proc}$	-	+

Table 5 Measures on the user behaviour level. In the column «Cost», an estimate regarding the costs is given, distinguishing low costs (+), medium costs (++), and high costs (+++). In the column «Impact», an estimate regarding the impact is given, distinguishing low impact (+), medium impact (++), and high impact (+++).

Purpose:	Measures	Affected parameter	Cost	Impact
Reducing Q_{int}	Reducing the level of activity (if possible)	This reduces the heat flow rate from occupants $\phi_{int,OC}$		(+)
	Reducing clothing factor to adapt to climate (if possible)	This increases the personal heat flow rate at the skin of the occupants by increasing evaporation and convection		
	Reducing the operation time with presence detectors etc.	This reduces the heat flow rate from electrical lighting $\phi_{int,L}$. Potentially, this also reduces the heat flow rate from appliances $\phi_{int,A}$, from HVAC $\phi_{int,HVAC}$ and from hot water systems $\phi_{int,WA}$.	+	+

2.7.4. *Methods to reduce the energy demand for cooling processes*

Generally, the efficiency of cooling processes is affected by two elements. One is the efficiency of the machine, which is typically rated in classes (like A, A++ etc.). This efficiency is also expressed by the process efficiency η and the Carnot efficiency ς of the respective machine. The other aspect is the efficiency of the process, which highly depends on the temperature lift the machine has to provide (between$T_H - T_C$). Since the set point temperature of the space typically determines the source temperature in the process, the efficiency is more affected by the temperature of the heat sink.

2.7.5. *Decision path for cooling processes*

Generally speaking: the higher the cooling demand and the lower the power of the available heat sinks, the more mechanical cooling is needed. Since this can cause higher installation and operational costs, the balance of energy use and carbon emissions tends to be higher with mechanical cooling systems. Nevertheless, this is not necessarily the case. Under certain conditions mechanical cooling with powerful heat sinks and efficient systems might cause lower primary energy demand and result in less carbon emissions than by further reducing cooling demand. Thus, the expenditures for reducing the cooling demand, as described in chapter 2.7.3, needs to be balanced with the expenditures for efficient cooling processes, as described in chapter 2.7.4.

As discussed in chapter 2.7.3, the cooling methods can be categorized as passive, hybrid or active strategies. Due to the maximum cooling power that each method can provide, the applicable methods cannot be chosen arbitrarily, but depends on the required cooling demand and the context conditions (first and foremost the power of the heat sink). Figure 24 and Figure 25 illustrate decision trees to determine the cooling strategy of a building (based on Plato 1995). Natural cooling power by night considerably depends on the temperature difference between the interior set temperature and the exterior ambient temperature$(\theta_{\mathrm{int,set,C}} - \theta_{\mathrm{e}})$. Further criteria, like air quality, noise and security issues determine if window ventilation is possible. If mechanical ventilation is installed, the air exchange can artificially be increased to increase cooling. Adiabatic cooling is only possible if the temperature difference between the exterior temperature and the wet bulb temperature is big enough$(\theta_{\mathrm{e}} - \theta_{\mathrm{wb}})$. In case that window- or mechanical ventilation is not possible, the supply air can be (pre-)cooled with a heat exchanger connected to a natural heat sink, i.e. lake, river, ground water or ground, or an artificial heat sink as for example for the production of hot water. Due to the installation costs of sophisticated heat sinks, like cooling towers, they are typically only installed for bigger multifamily residential apartment blocks. While the dry cooling towers require night time temperatures below 20°C to be operable, the wet cooling towers require low relative humidity and a lot of potable water for operation. Systems connected to powerful heat sinks can be operated in free cooling mode, which is typically determined by its temperature. In case of a heat sink with low power, air-conditioning systems or hydraulic systems connected to a chiller or reversible heat pump need to be installed to provide cooling (systems operating with Carnot-cycles). This is also necessary if the cooling demand is greater than 250 Wh/(m^2d).

It goes without saying that mixed systems (e.g. evaporation cooling & precooled supply air) are also a possible solution, especially when optimizing processes in terms of efficiency and of economical advantages.

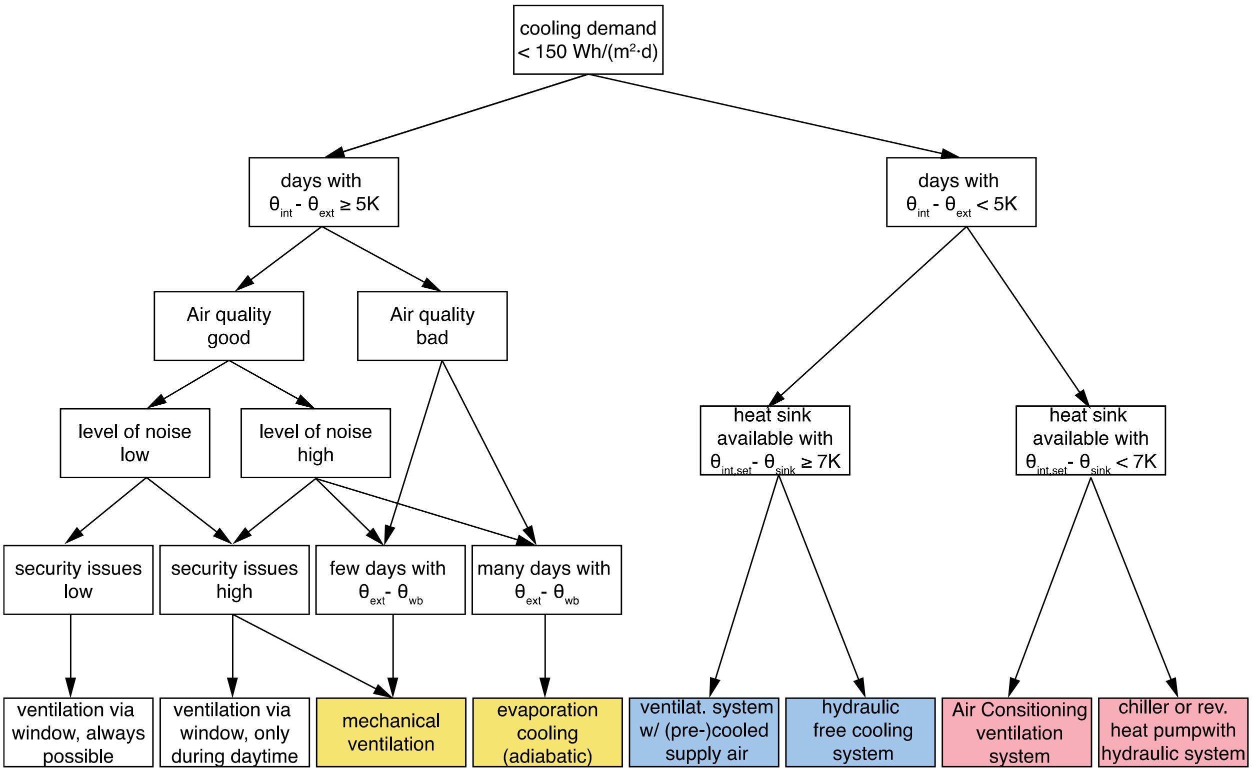


Figure 24 Decision tree to determine possible and reasonable methods to provide cooling for a building with a **cooling demand smaller than 150 Wh/(m²·d)**. The colours indicate the amount of primary energy required to operate the systems (white =without, yellow=low, blue=medium, red=high)

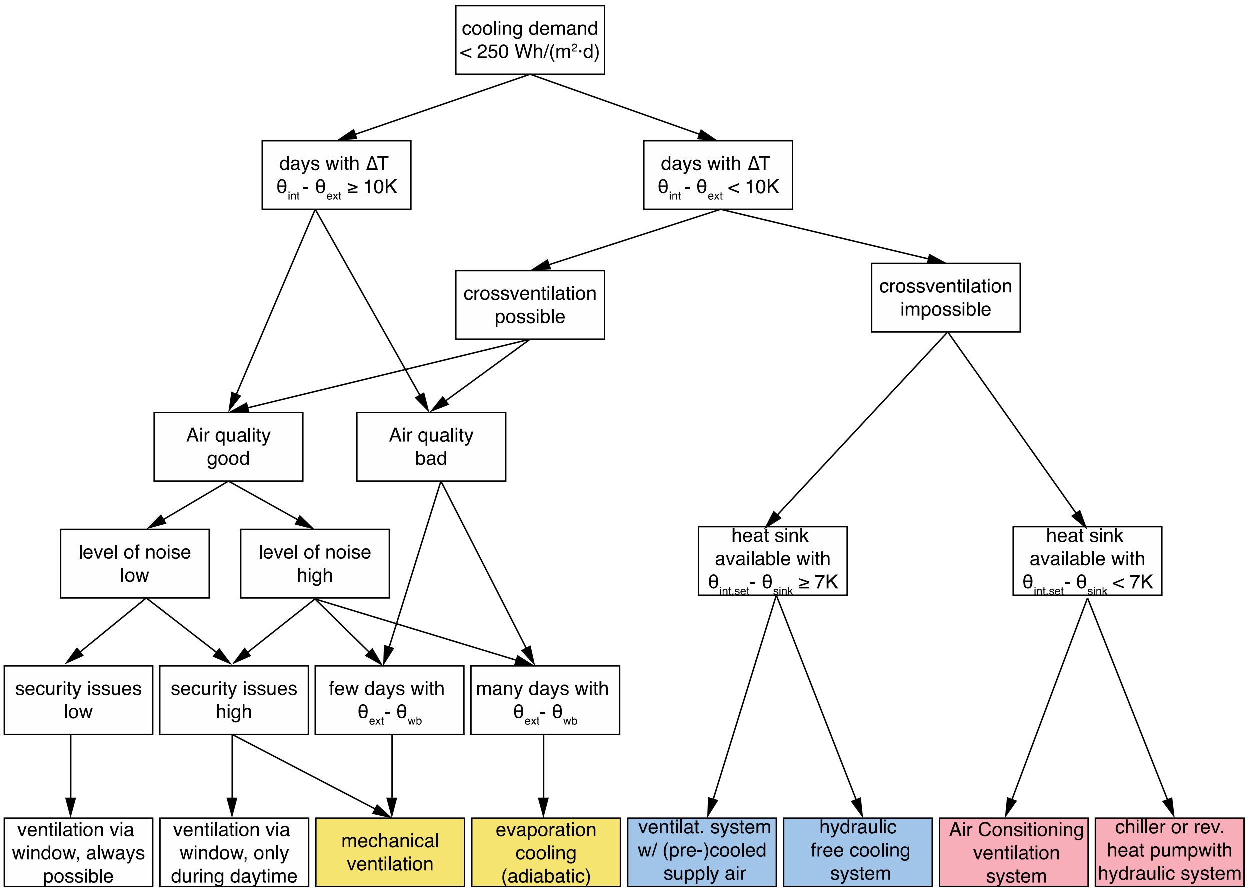


Figure 25 Decision tree to determine the possible and reasonable methods to provide cooling for a building with a **cooling demand smaller than 250 Wh/(m²·d)**. The colours indicate the amount of primary energy required to operate the systems (white =without, yellow=low, blue=medium, red=high)

3. Generic buildings and parametric assessments

3.1. Scope of generic calculations

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 detailed case studies.

In this report, results of parametric calculations with generic single-family (SFH) or multi-family (MFH) residential reference buildings from Austria, Denmark, Norway, Portugal, Spain, Sweden and Switzerland are documented. These reference buildings are supposed to be representative for a relevant share of existing residential SFH- and MFH-buildings not having undergone a major energy related renovation yet.

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 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 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 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 demand of the building takes 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 was investigated for the calculations with one reference building from Switzerland.

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 6 Assumed average energy prices for households, including taxes, for the period from 2010 to 2050. A 30% increase in prices compared to today 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	Norway	Portugal	Spain	Sweden	Switzerland
Oil	EUR/kWh	0.12	0.15	n.e	n.e.	n.e.	0.13	0.1
Natural gas	EUR/kWh	n.e.	n.e	n.e	0.09	0.057	0.12	n.e.
Wood pellets	EUR/kWh	0.08	0.05	0.1	0.3	0.049	0.04	0.08
Electricity	EUR/kWh	0.21	0.33	0.16	0.18	0.19	0.25	0.21
District heating	EUR/kWh	n.e	n.e	n.e	n.e	n.e.	0.104	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 from CH_4 and N_2O are converted into $\mathbf{CO_{2e}}$ 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 7.

Table 7 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	Norway	Portugal	Spain	Sweden	Switzerland
GHG Emission factor								
Oil	kg CO_{2e} / MJ	0.083	0.083	n.e.	n.e.	n.e.	n.e.	0.083
Natural gas	kg CO_{2e} / MJ	n.e.	n.e.	n.e.	0.066	0.06	n.e.	n.e.

Parameter	Unit	Austria	Denmark	Norway	Portugal	Spain	Sweden	Switzerland
GHG Emission factor								
Wood pellets or wood logs	kg CO_{2e} / MJ	0.01	0.01	0.01	n.e.	0.01	n.e.	0.01
District heating	kg CO_{2e} / MJ	n.e.	n.e.	n.e.	n.e.	n.e.	0.02	n.e.
Country mix for electricity	kg CO_{2e} / MJ	0.086	0.081	0.004	0.208	0.096	0.027	0.042
Country mix for electricity including trade in certificates	kg CO_{2e} / MJ	n.e.	n.e.	0.095	n.e.	n.e.	n.e.	n.e.
Primary non-renewable energy factor								
Oil	-	1.23	1.1	n.e.	n.e.	n.e.	n.e.	1.23
Natural gas	-	n.e.	n.e.	n.e.	1.12	1.07	n.e.	n.e.
Wood pellets or wood logs	-	0.21	0.21	0.05	n.e.	0.21	n.e.	0.21
District heating		n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Country mix for electricity	-	1.08	1.64	0.03	3.28	1.6	n.e.	2.63
Country mix for electricity including trade in certificates	-	n.e.	n.e.	2.78	n.e.	n.e.	n.e.	n.e.
Primary energy factor								
Oil	-	1.24	1.1	n.e.	n.e.	n.e.	n.e.	1.24
Natural gas	-	n.e.	n.e.	n.e.	1.12	1.07	n.e.	n.e.
Wood pellets or wood logs	-	1.22	1.22	1.06	n.e.	1.25	n.e.	1.22
District heating		n.e.	n.e.	n.e.	n.e.	n.e.	1	n.e.
Country mix for electricity	-	2.02	1.75	1.22	3.29	2.35	2.6	3.05
Country mix for electricity including trade in certificates	-	n.e.	n.e.	3.1	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 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 demand 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 demand 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 demand:

- 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; energy demand; energy carriers for the heating system, system performance, etc.

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

Table 8 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	Switzerland 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	5.86	2	3	7.3	3.3
Area of windows to East	m^2	9.1	1.3	1.7	3	3.65	8.3
Area of windows to South	m^2	10.0	13.92	13.6	3	7.3	13.2
Area of windows to West	m^2	9.1	3.2		3	3.65	8.3
Area of ceiling of cellar	m^2	145	108	51.1	80	106	80
Average heated gross floor area per person	m^2	60	27	28.3	37	32.3	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	26.5	32	25	22
U-value façade	W/(m^2*K)	1.44	0.46	0.5	2	0.31	1
U-value roof pitched	W/(m^2*K)	0.92	0.386	0.4	2.8	-	0.85

Parameter	Unit	Austria SFB	Denmark SFB	Norway SFB	Portugal SFB	Sweden SFB	Switzerland SFB
U-value attic floor	W/(m²*K)	--	-	-	-	-	1
U-value roof flat	W/(m²*K)	-	-	-	-	0.21	1
U-value windows	W/(m²*K)	2.9	2.6	2.7	5.1	2.3	3
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/(m²*K)	0.97	1.023	0.5	1.65	0.27	0.9
Energy demand hot water	kWh/m²	14	22	26.5	28.7	18	14
Energy demand for cooling	kWh/m²	-	-	-	2.3	-	-

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

Table 9 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	Portugal MFB	Spain MFB	Sweden MFB	Switzerland MFB
Building period		1958-1968	1960-1969	Before 1960	1960	1961-1975	1960
Gross heated floor area (GHFA)	m²	2845	3640	520	1872	1400	730
Façade area (excl. windows)	m²	2041	1332	542	2049	590	552
Roof area pitched	m²	-	-	130	416		
Roof area flat	m²	971	-		-	402	240
Attic floor	m²	-	910		-	-	-
Area of windows to North	m²	220	279	26	0	88.5	31.6
Area of windows to East	m²	22	0	13	177	1.5	39.5
Area of windows to South	m²	243	376	26	0	88.5	47.4
Area of windows to West	m²	22	0	13	194	1.5	39.5
Area of ceiling of cellar	m²	971	910	130	312	402	240

Parameter	Unit	Austria MFB	Denmark MFB	Portugal MFB	Spain MFB	Sweden MFB	Switzerland MFB
Average heated gross floor area per person	m^2	40	35	17	40.3	32.3	40
Typical indoor temperature (for calculations)	°C	20	20	20	19	21	20
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/ (a^*m^2)	28	44	23.5	48.7	26	28
U-value façade	$W/(m^2*K)$	1.21	0.5	2	1.3	0.41	1
U-value roof pitched	$W/(m^2*K)$	-	-	2.8	1.8	-	0.85
U-value attic floor	$W/(m^2*K)$	-	0.4		-	-	1
U-value roof flat	$W/(m^2*K)$	0.97	-		-	0.2	1
U-value windows	$W/(m^2*K)$	2.57	2.55	5.1	3.5	2.3	2.7
g-value windows	Factor 0.0 – 1.0	0.76	0.75	0.85	0.8	0.7	0.75
U-value ceiling of cellar	$W/(m^2*K)$	0.97	1.52	1.65	2.0	0.27	0.9
Energy demand hot water	kWh/m^2	75	14	35.3	25.9	23	75
Energy demand for cooling	kWh/m^2	-	-	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.
- 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

- 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.

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

3.5.1. 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).

3.5.2. *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 10 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.

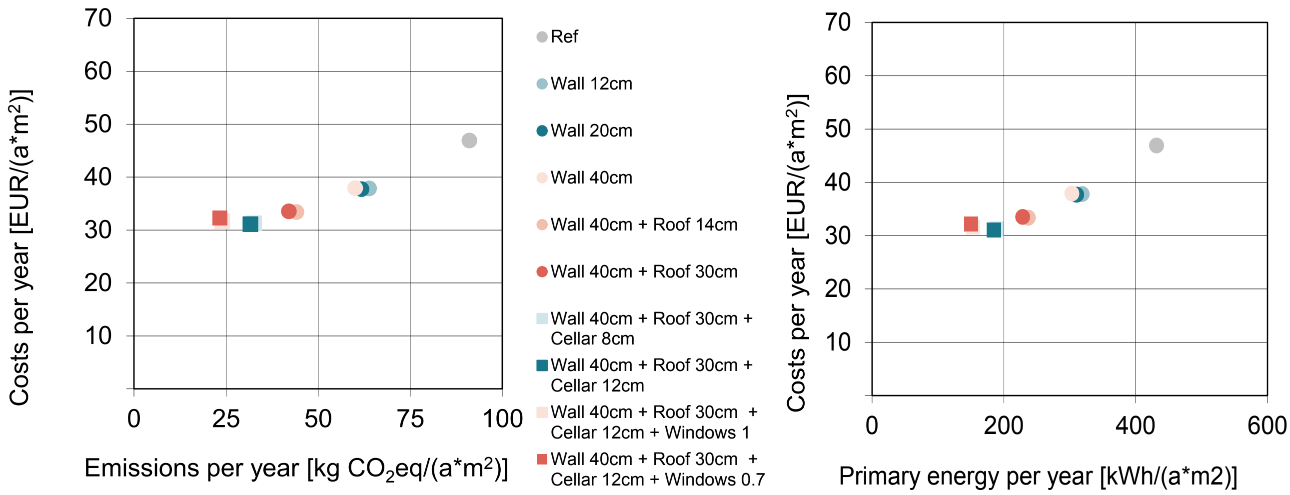
Table 11 Data for different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Austria

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
Wall - λ 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 - λ 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 - 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 demand heating	kWh/m^2	243	160	154	148	100	94	65	62	38	36

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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
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:



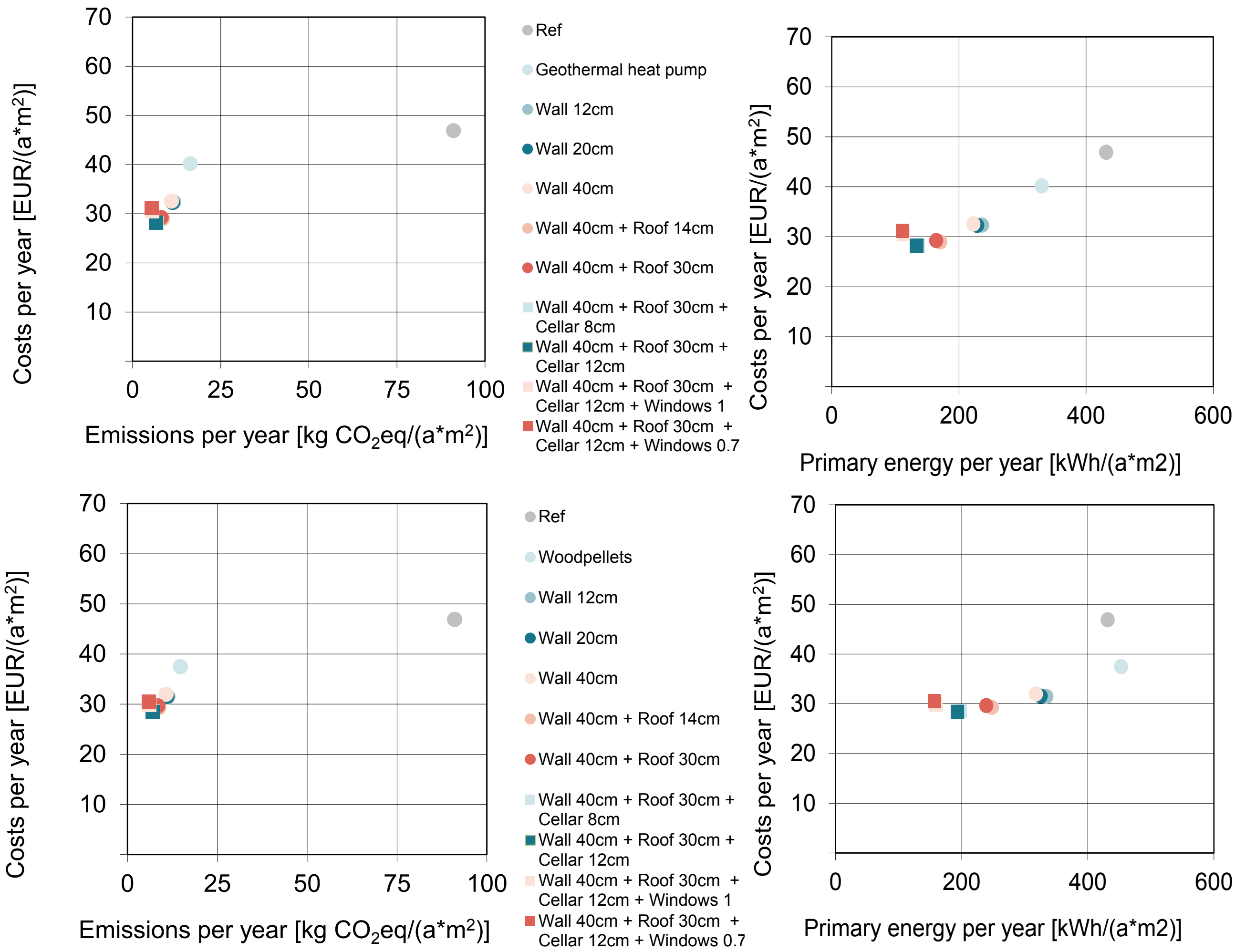


Figure 26 Comparison of cost effectiveness of energy efficiency renovation measures for a SFH in Austria for different heating systems, oil (top), geothermal HP (middle) and wood pellets (bottom), and related impacts on carbon emissions and primary energy use. he reference shown as a grey dot refers 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.

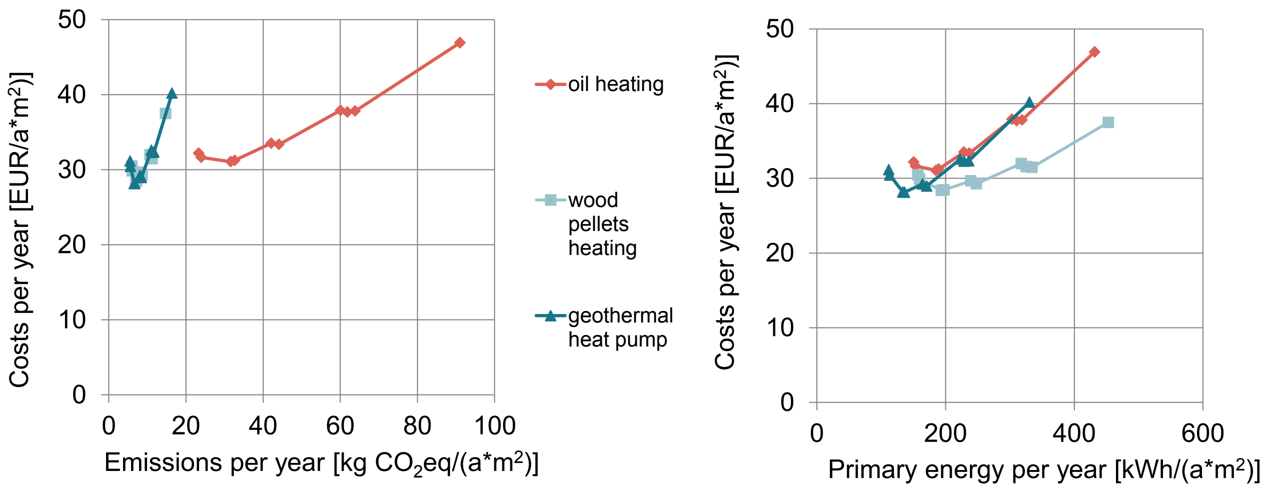


Figure 27 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Austria, for a single-family building. The reference case is the point on the oil heating curve with the highest 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 multi-family building:

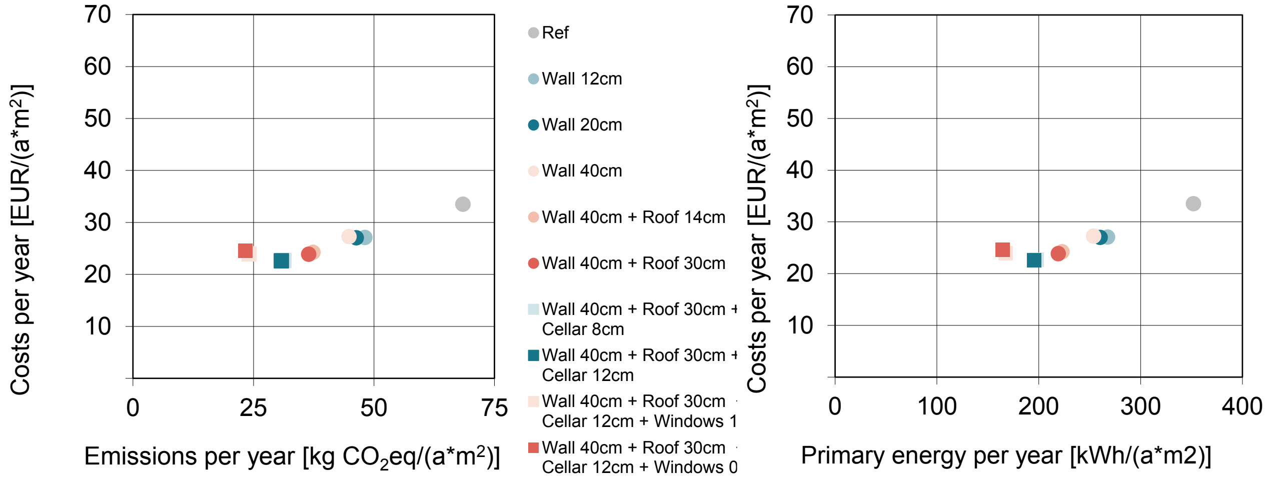
Table 12 Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Austria.

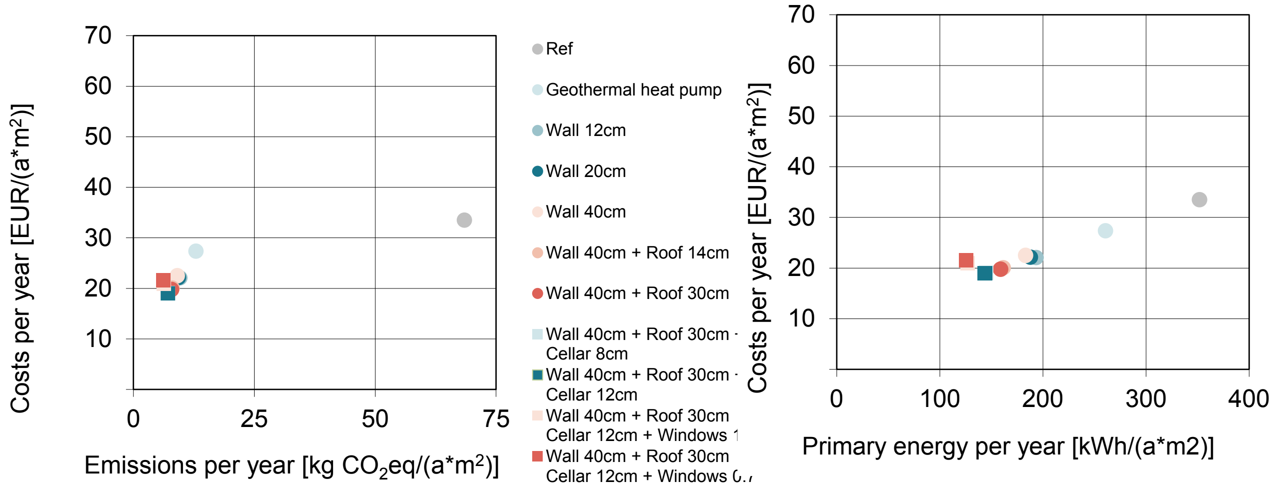
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m² wall	40	98	120	148	148	148	148	148	148	148
Wall thickness of insulation material	cm	-	12	20	40	40-	40	40	40	40	40
Wall - ƛ of insulation material	W/mK	-	0.037	0.037	0.037	0.037	0.037	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/m² 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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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/m² roof	100	100	100	100	160	190	190	190	190	190
Roof - thickness of insulation material	cm	-	-	-	-	14	30	30	30	30	30
Roof - λ 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/m² ceiling	-	-	-	-	-	-	60	68	68	68
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 demand for heating	kWh/m²	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 efficiency 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:





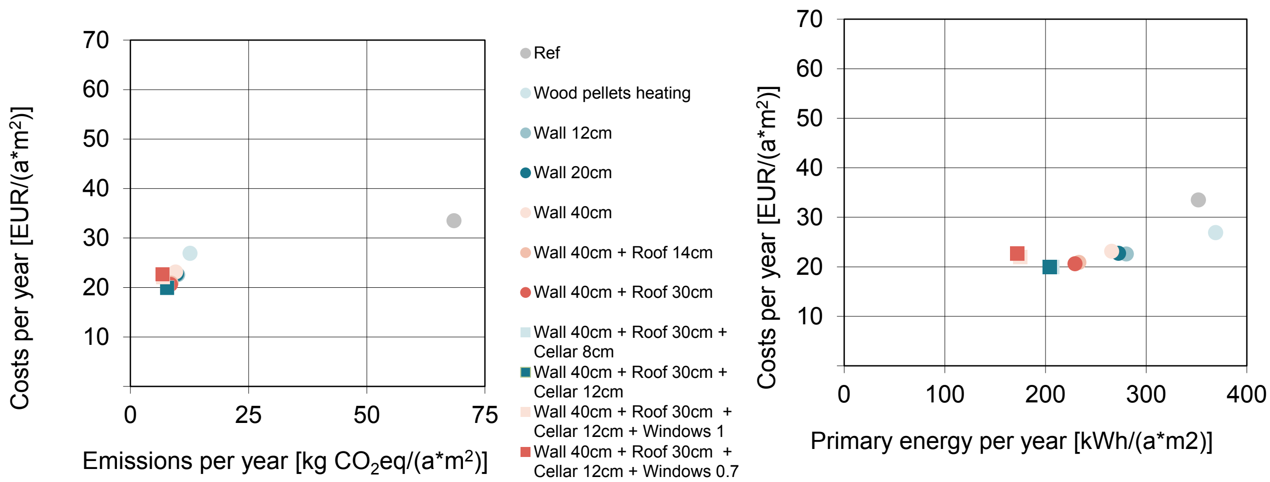


Figure 28 Comparison of cost effectiveness of energy efficiency renovation measures for multi-family building in Austria for different heating systems: oil heating (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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.

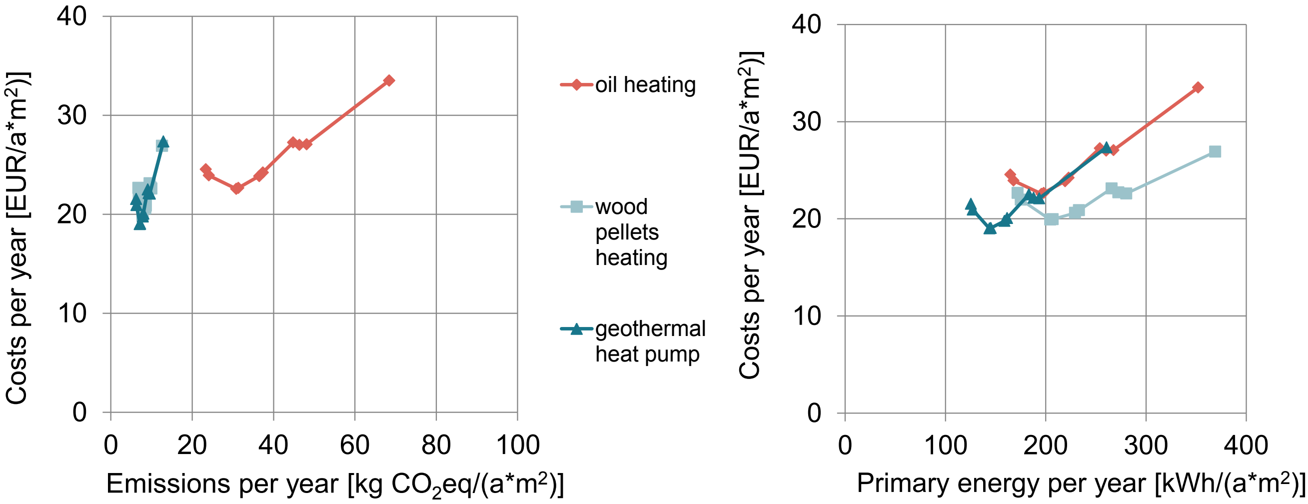


Figure 29 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Austria, for a multi-family building. The reference case is the point on the oil heating curve with the highest 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 the building period 1958 – 1968 and has relatively low energetic standards 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 13 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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 3.10.1., 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 14 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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 ongraphs for the single-family building it can be recognized that specific costs, emissions and primary energy use per m2 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 15 Result for the hypothesis related to the comparison of MFH and SFH.

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

3.5.3. 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 16 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, of granulate on attic floor 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 17 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Denmark.

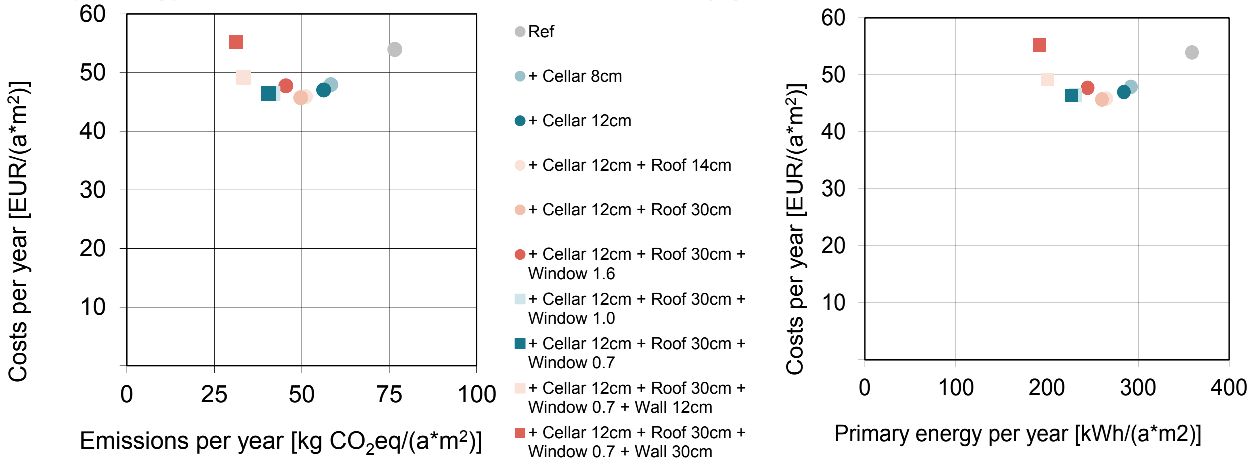
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	95	95	95	95	95	95	95	95	272	470
Wall thickness of insulation material	cm	-	-	-	-	-	-	-	-	12	30
Wall – λ insulation material	W/mK	-	-	-	-	-	-	-	-	0.037	0.037

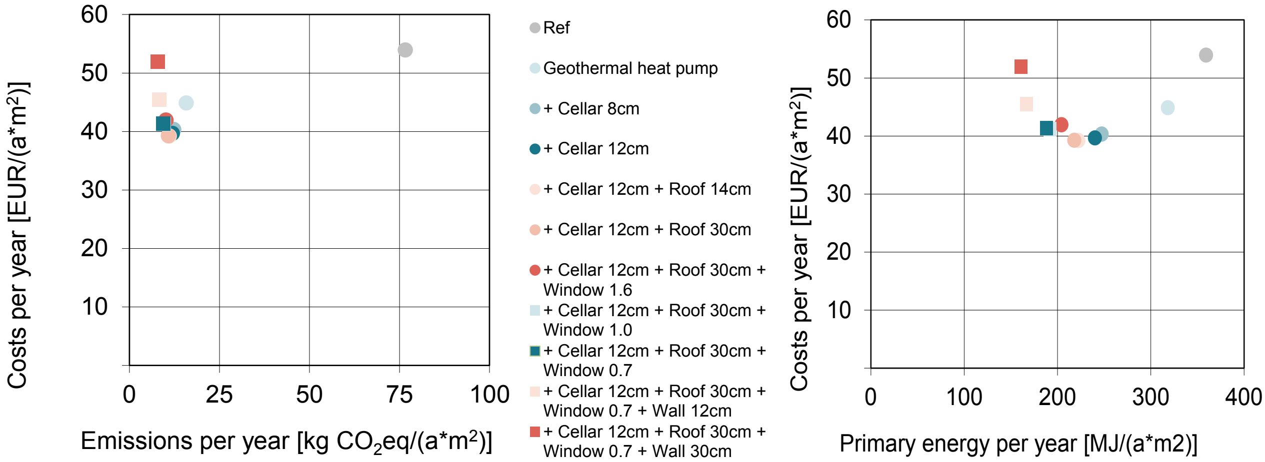
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m² window	10	10	10	10	10	490	550	620	620	620
Window - U-Value	W/m^2K	2.6	2.6	2.6	2.6	2.6	1.6	1	0.7	0.7	0.7
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.5	0.45	0.38	0.38	0.38
Window - lifetime of renovation measure	a	30	30	30	30	30	50	50	50	50	50
Roof - Costs	EUR/m² 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/m² 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 demand for heating	kWh/m²	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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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:





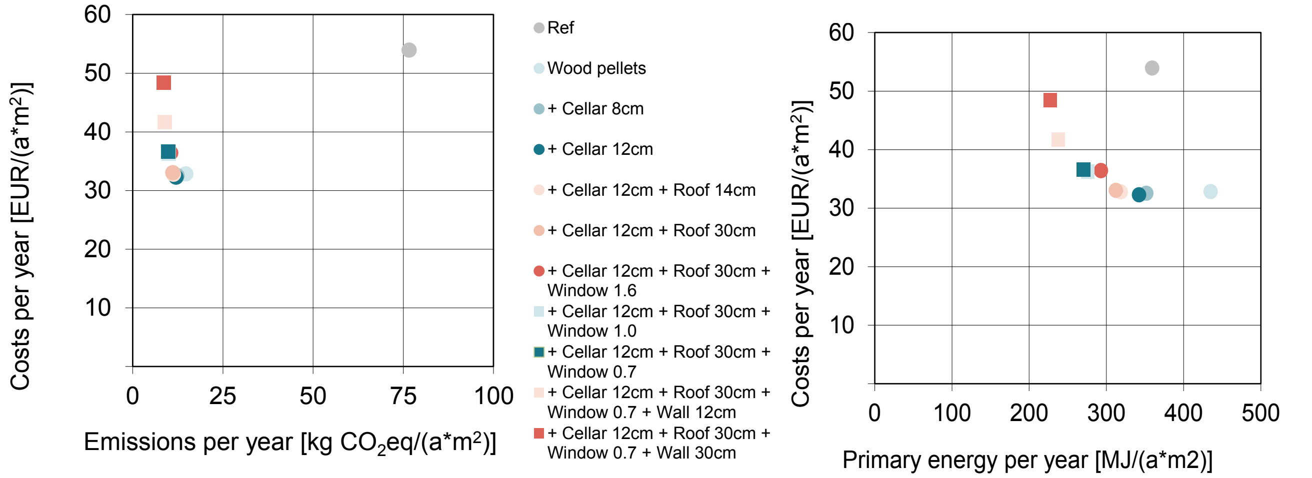


Figure 30 Comparison of cost effectiveness of energy efficiency renovation measures for single-family building in Denmark for <u>different heating systems</u>: oil (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In 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:

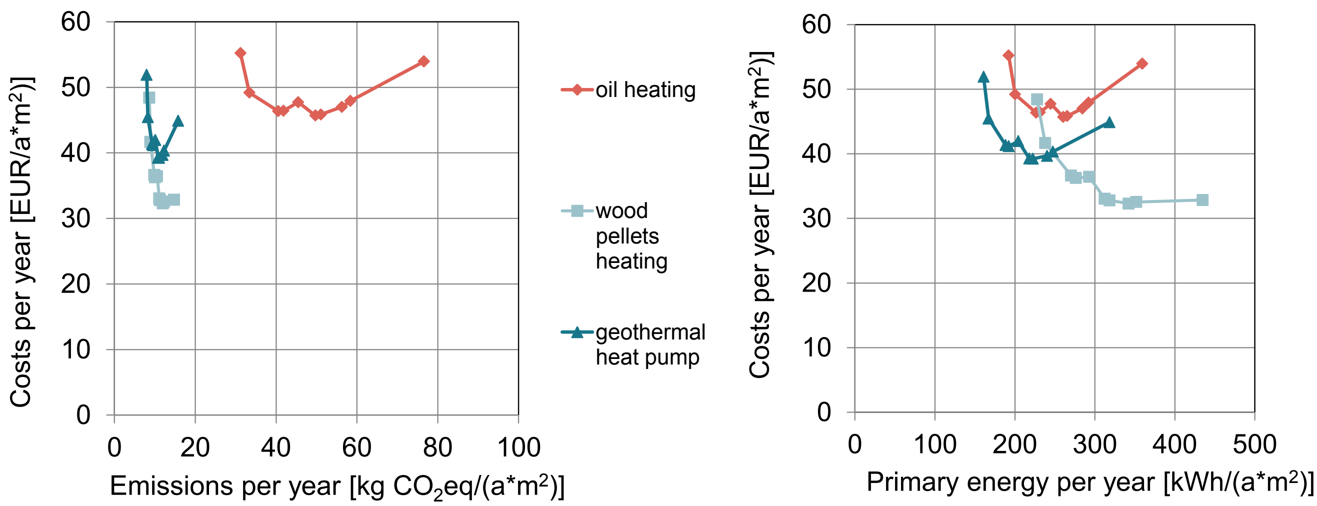


Figure 31 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Denmark, for a single-family building, The reference case is the point on the oil heating curve with the highest 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 demand 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 18 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 - 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	0.7	0.7	0.7
Window - g-value		0.75	0.75	0.75	0.75	0.75	0.5	0.45	0.38	0.38	0.38
Window - lifetime of renovation measure	a	30	30	30	30	30	50	50	50	50	50
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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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 demand 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
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:

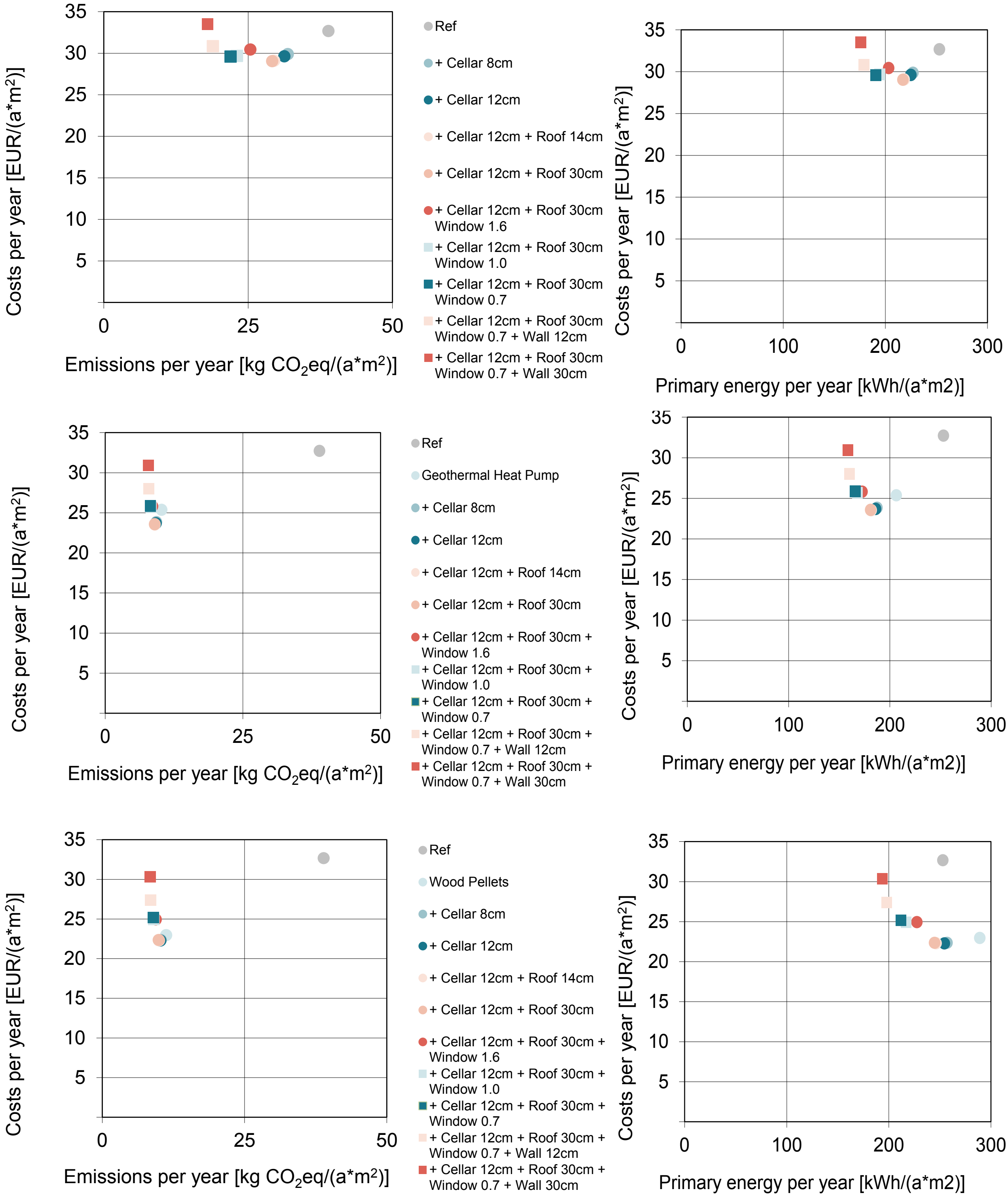


Figure 32 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for multi-family building in Denmark for different heating systems and related impacts on carbon emissions and primary energy use. The reference case is the point on the oil heating curve with the highest emissions/primary 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:

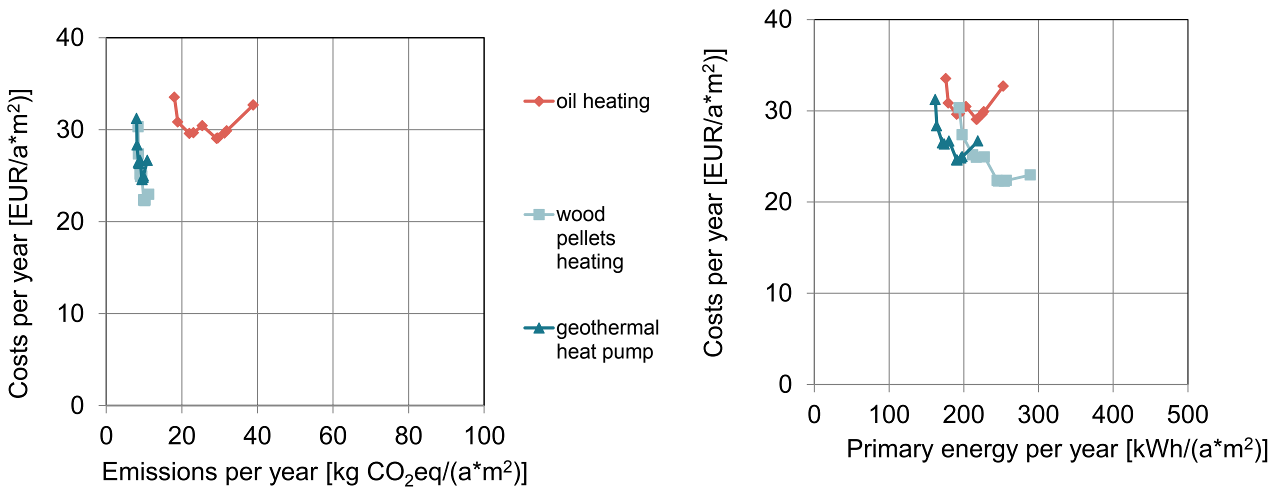


Figure 33 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Denmark, for multi-family building. The reference case is the point on the oil heating curve with the highest 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 19 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	✓
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 3.10.1., 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 20 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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.	✓

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 21 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

3.5.4. *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 22 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 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.

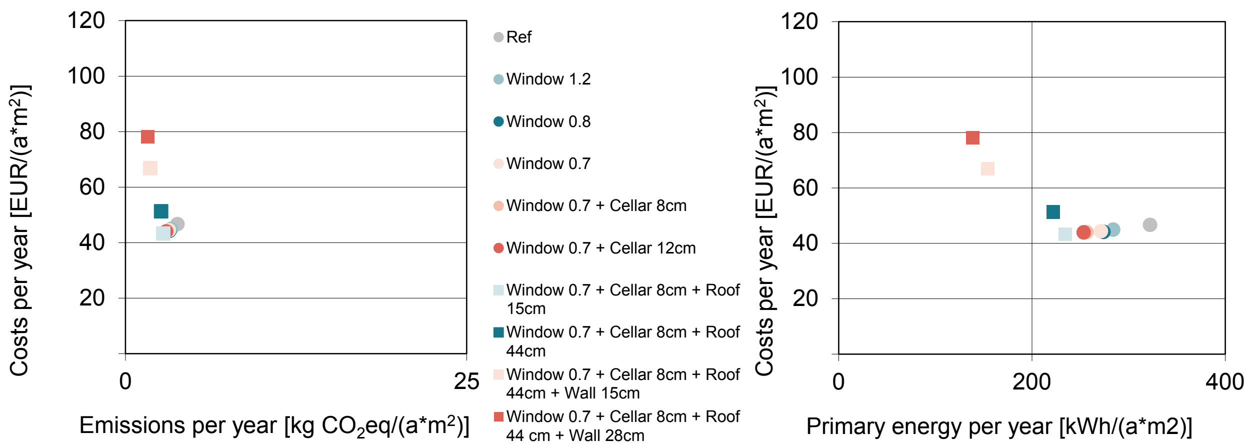
Table 23 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Norway.

Parameter	Unit	Refe-rence	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
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 demand 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

Parameter	Unit	Refe-rence	M1	M2	M3	M4	M5	M6	M7	M8	M9
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.



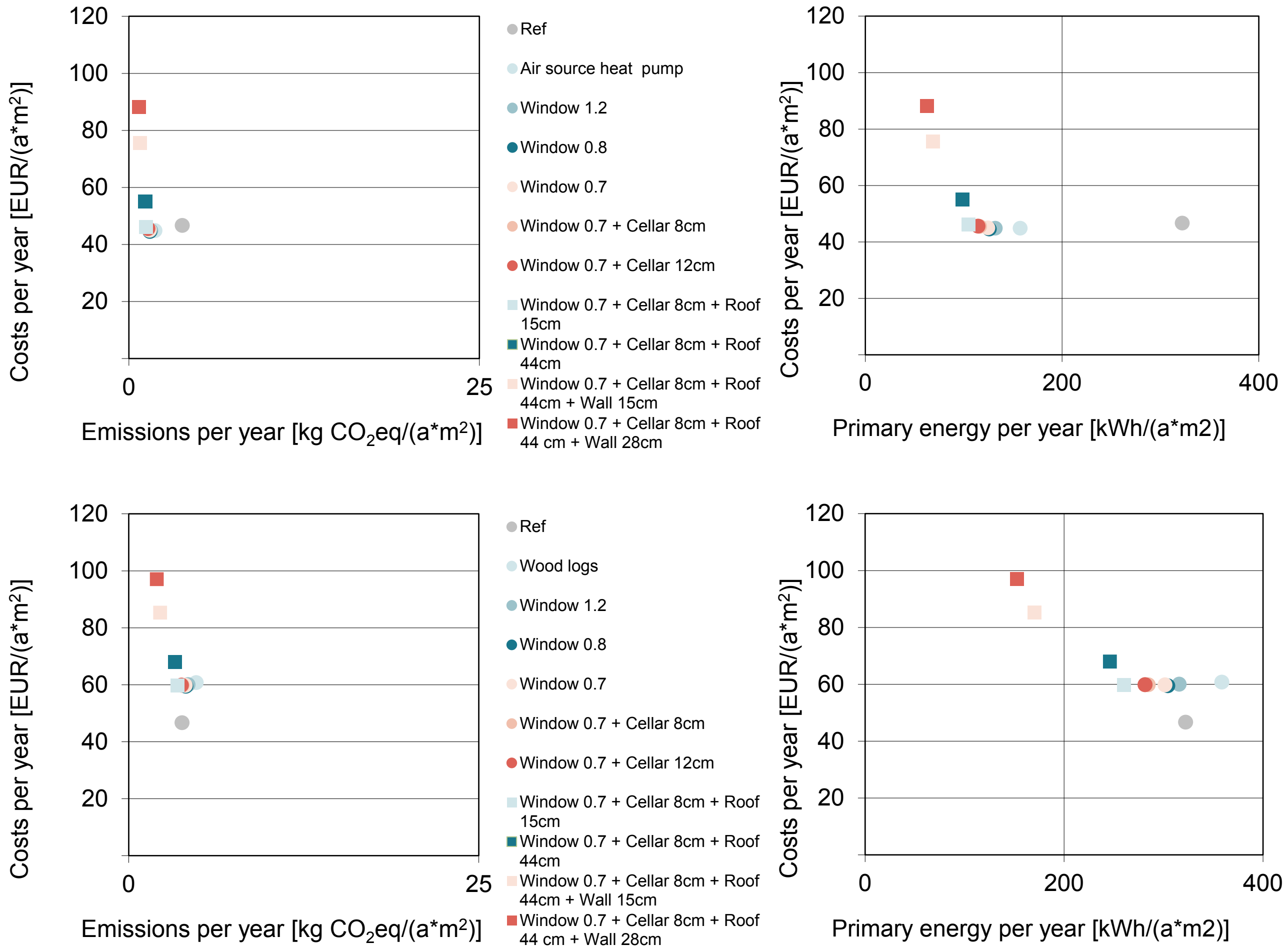


Figure 34 Comparison of cost effectiveness of energy efficiency renovation measures for different heating systems in single-family building Norway for <u>different heating systems</u>: direct electric heating (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on 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.

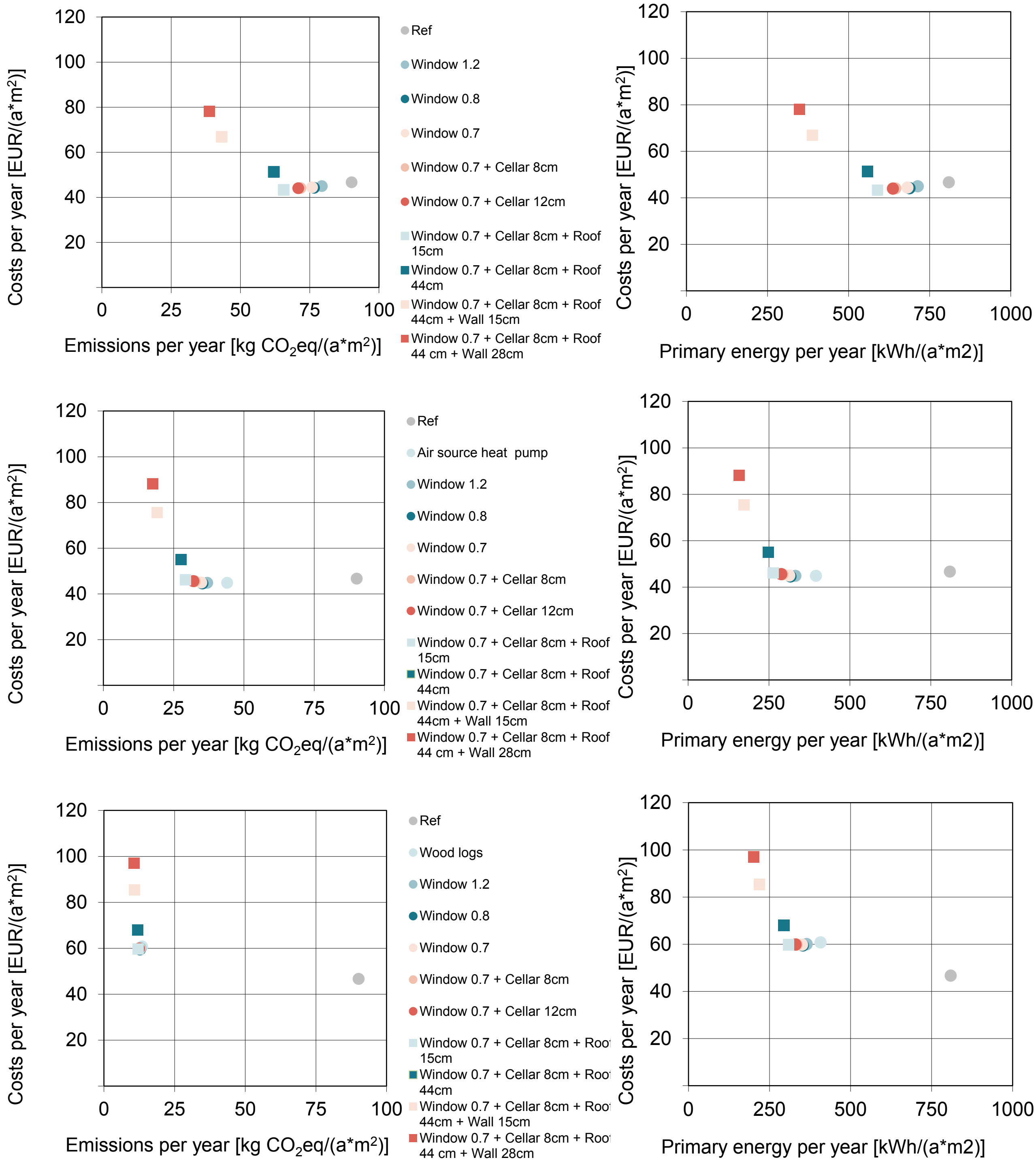


Figure 35 Similar graphs for reference building in Norway as in previous figure, yet for these graphs the residual electricity mix is applied to determine the impact of electricity consumption on emissions and primary energy use. **This electricity mix takes into account imports and exports of guarantees 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:

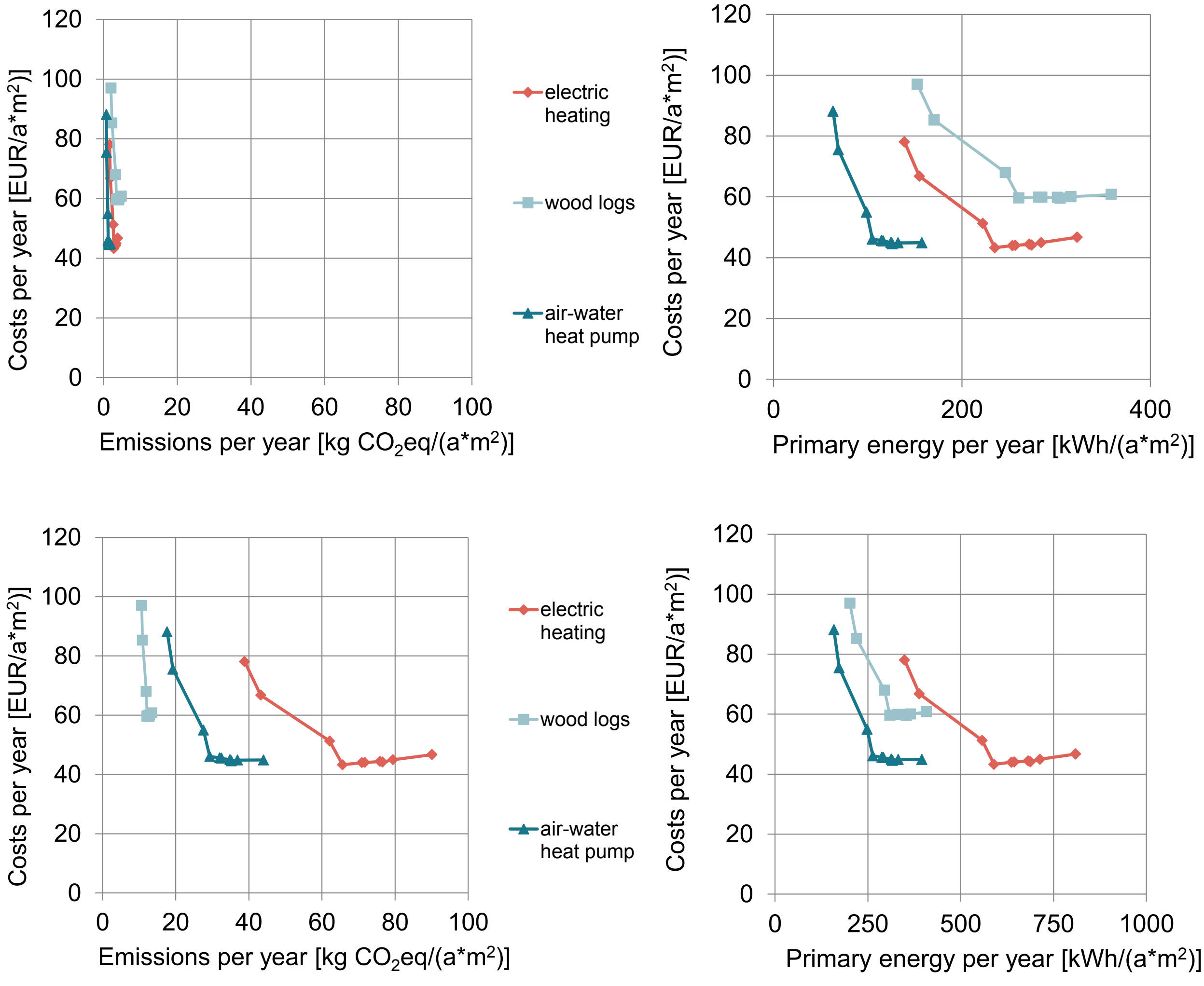


Figure 36 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Norway. The upper graphs are calculated with the production electricity mix of Norway as well as imports and exports 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 24 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	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.

3.5.5. 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 25 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 26 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
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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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 demand for heating	kWh/m^2	228	153	148	120	115	63	51	37	36	35
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 efficiency of air-waterHP		2.9	3.2	3.2	3.4	3.4	3.7	3.8	3.9	3.9	3.9
Conversion efficiency 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

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:

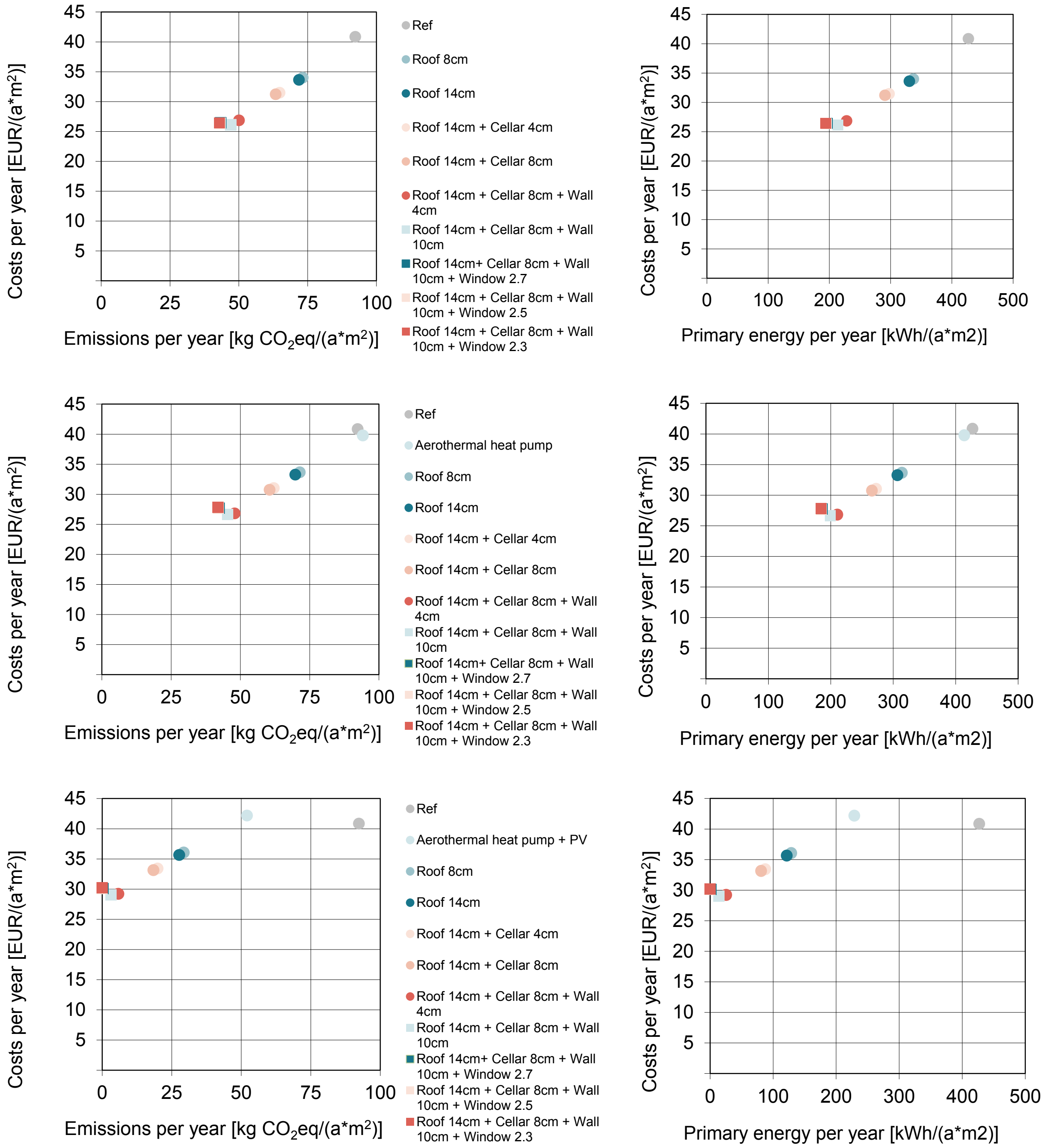


Figure 37 Comparison of cost effectiveness of energy efficiency renovation measures for single-family building in Portugal for <u>different heating systems</u>: natural gas (top), air-water heat pump (middle) and air-water heat pump + PV (bottom), as well as related impacts on carbon emissions and primary 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:

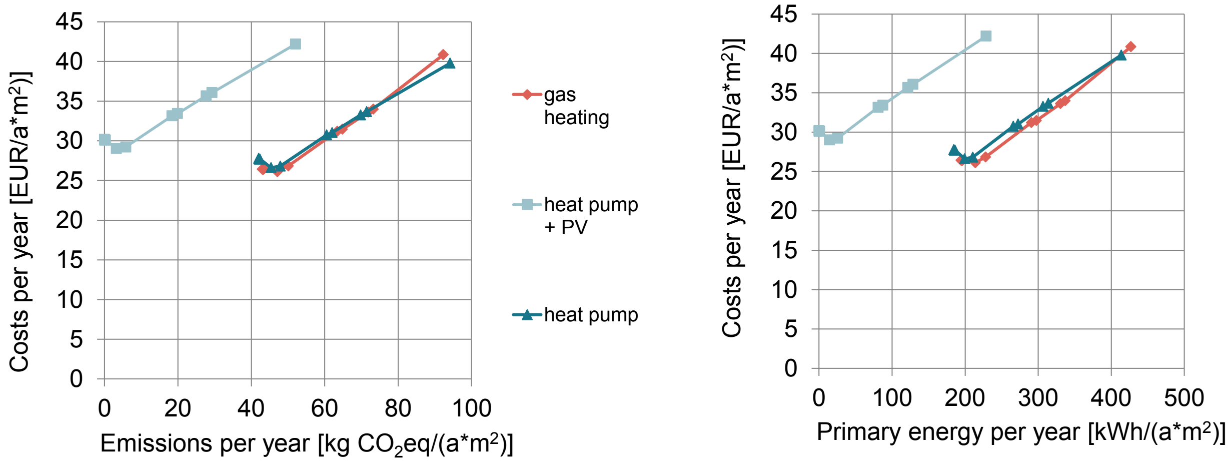


Figure 38 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Portugal, for single-family building. The reference case is the point on the natural gas heating curve with the 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 demand 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 27 Data for different packages of renovation measures M1 to M9 and the reference case for a multi-family house in Portugal.

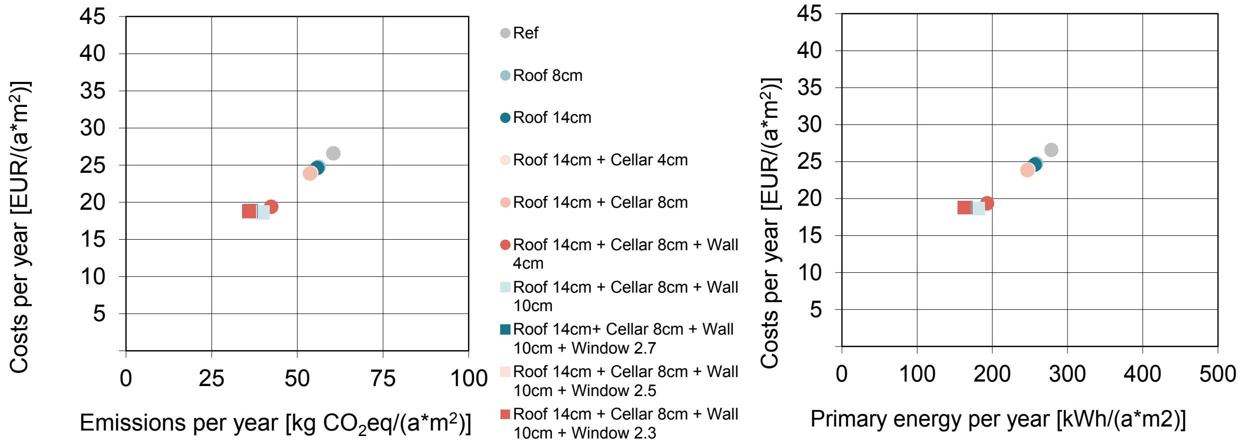
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m² wall	72	72	72	72	72	83	89	89	89	89
Wall - thickness of insulation material	cm	-	-	-	-	-	4	10	10	10	10

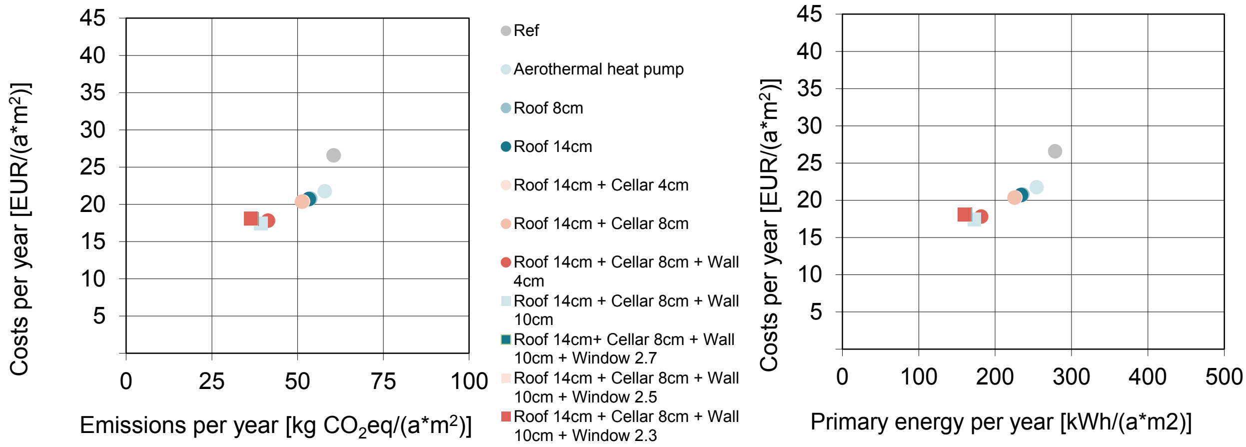
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - λ of insulation material	W/mK	-	-	-	-	-	0.036	0.036	0.036	0.036	0.036
Wall - lifetime of renovation measure	a	30	30	30	30	30	30	30	30	30	30
Window - Costs	EUR/m² window	25	25	25	25	25	25	25	251	253	272
Window - U-Value	W/m²K	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/m² 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/m² 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 demand for heating	kWh/m²	113	96	94	88	86	42	32	18	17	17
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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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

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:





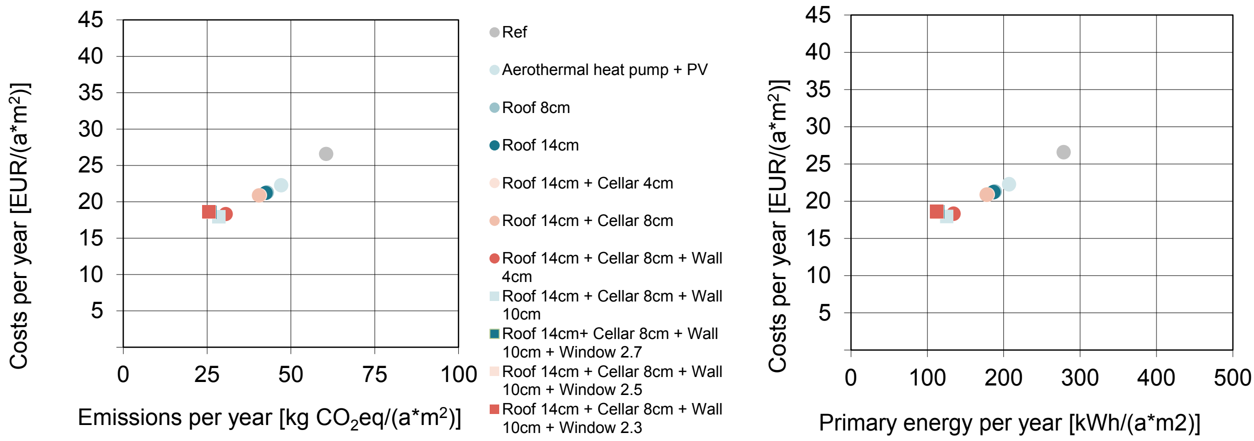


Figure 39 Comparison of cost effectiveness of energy efficiency renovation measures for multi-family building in Portugal for <u>different heating systems</u>: natural gas (top), air-water heat pump (middle) and air-water heat pump + PV (bottom), as well as related impacts on carbon emissions and primary 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.

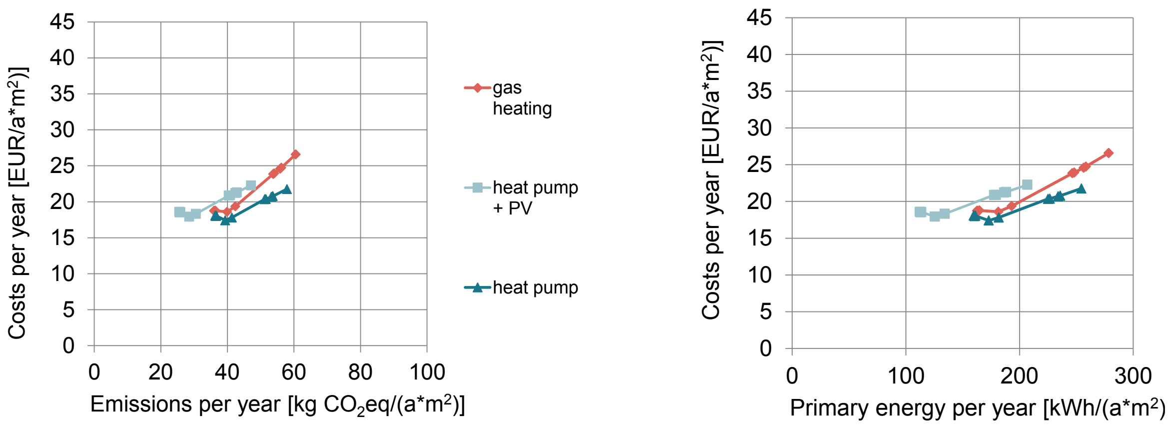


Figure 40 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Portugal, for multi-family building. The reference case is the point on the natural gas heating curve with the 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 28 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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 29 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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

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 demand, 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 30 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	✓

3.5.6. *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 31 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.

Renovation Package	Description
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.

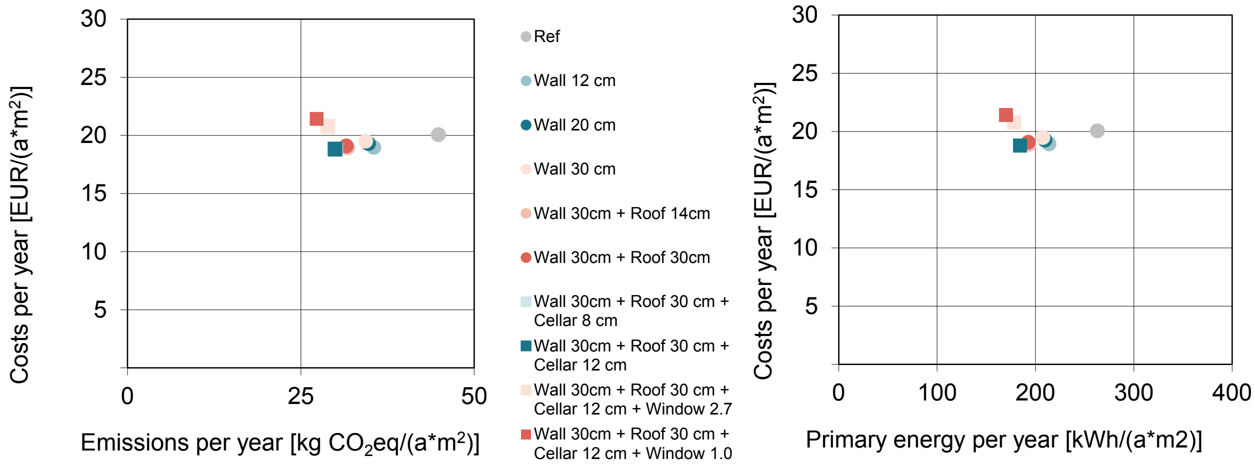
Table 32: Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Spain.

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

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 demand for heating	kWh/m^2	93	45	41	39	25	24	16	16	10	2
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:



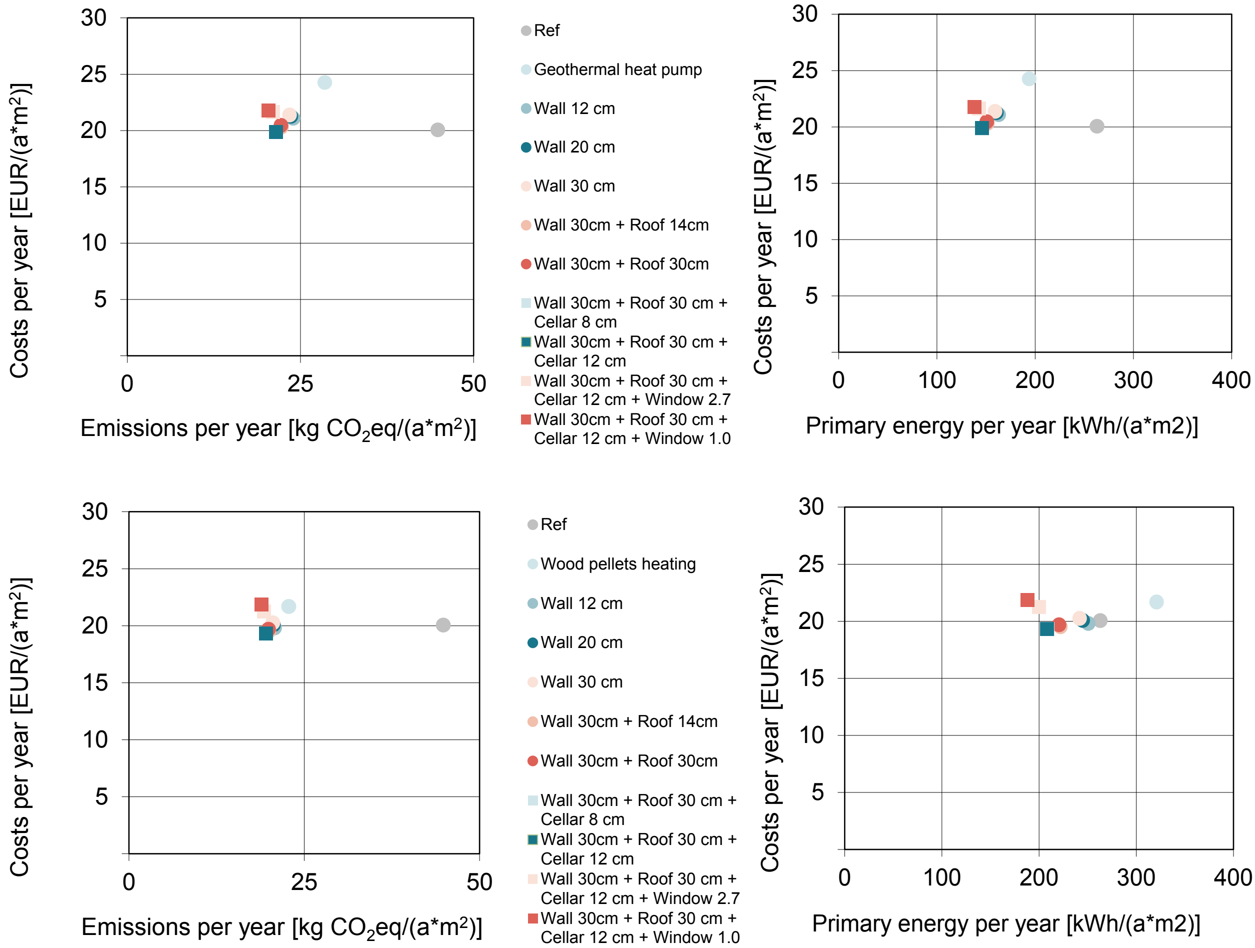


Figure 41 Comparison of cost effectiveness of energy efficiency renovation measures for multi-family building in Spain for <u>different heating systems</u>: natural gas (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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:

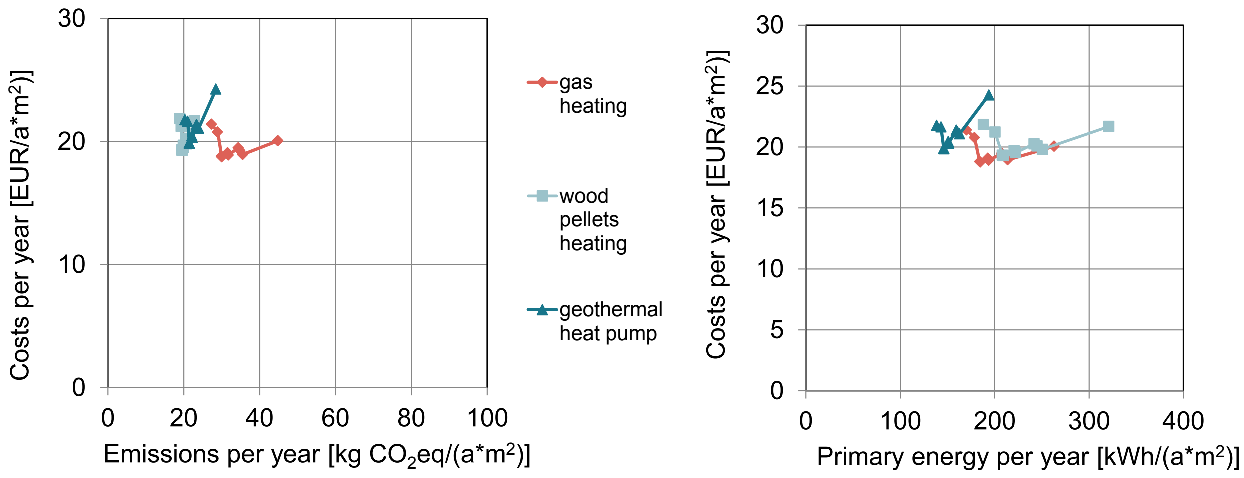


Figure 42 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Spain, for multi-family building. The reference case is the point on the natural gas heating curve with the highest 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 33 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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 3.10.1., 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 energies, 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 demand for the reference building in Spain are 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 demand 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.

3.5.7. 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 34 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
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.

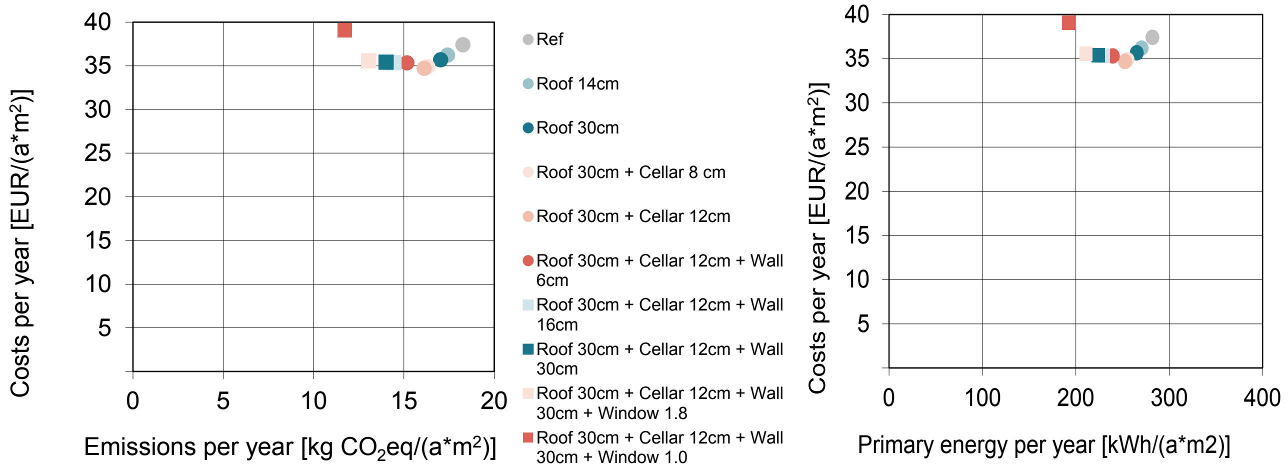
Table 35 Data for different packages of renovation measures M1 to M9 and of the reference case for a single-family house in Sweden.

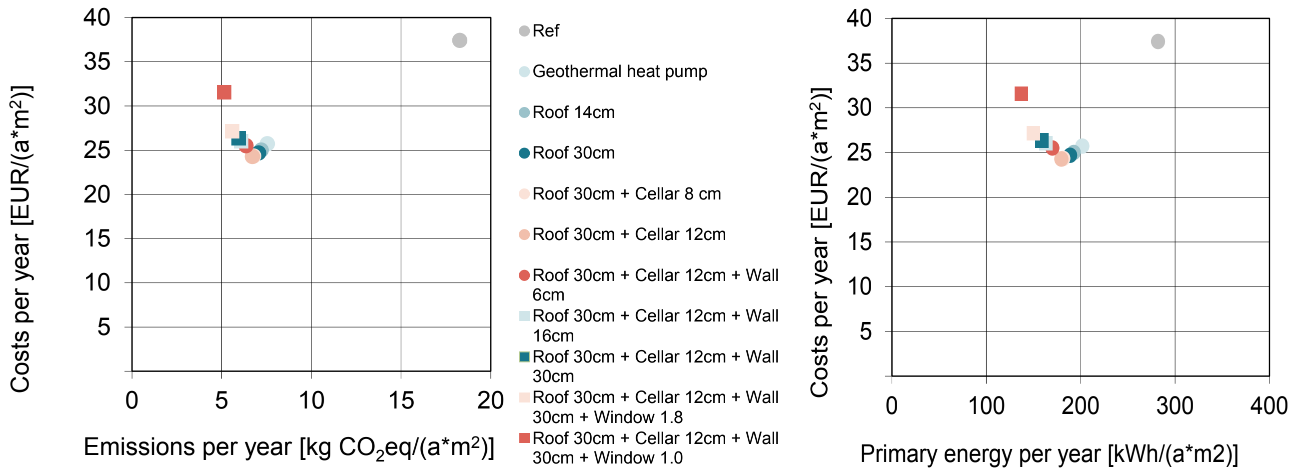
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m²	42	100	130	150	150	150	150	150	150	150
Wall - thickness of insulation material	cm	-	6	16	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	years	50	50	50	50	50	50	50	50	50	50
Window - Costs	EUR/m² window	9	9	9	9	9	9	9	9	178	784
Window - U-Value	W/m²K	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/m² 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/m² 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 demand for heating	kWh/m²	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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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:





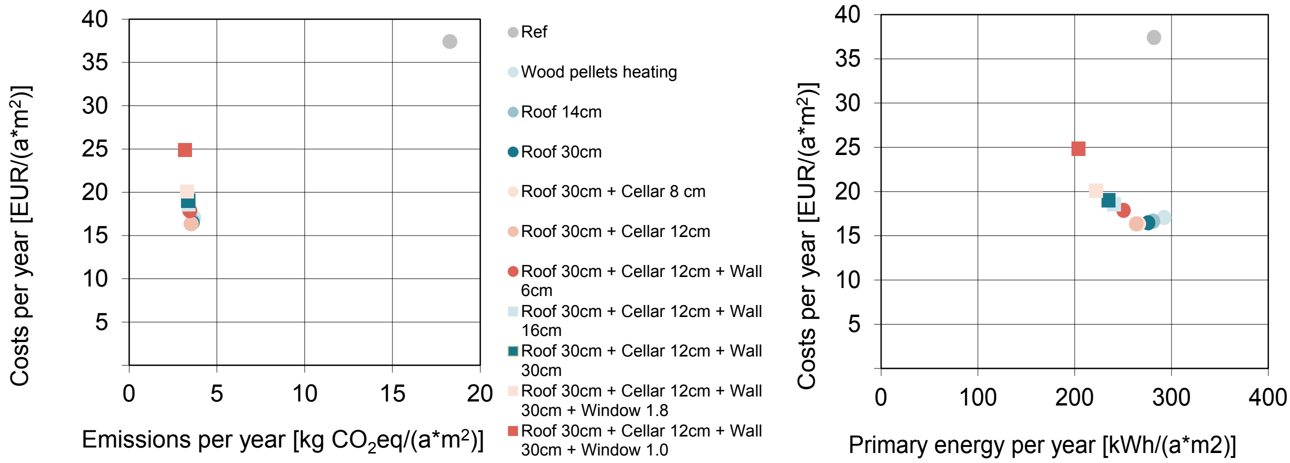


Figure 43 Comparison of cost effectiveness of energy efficiency renovation measures for single-family building in Sweden for <u>different heating systems</u>: district heating (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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:

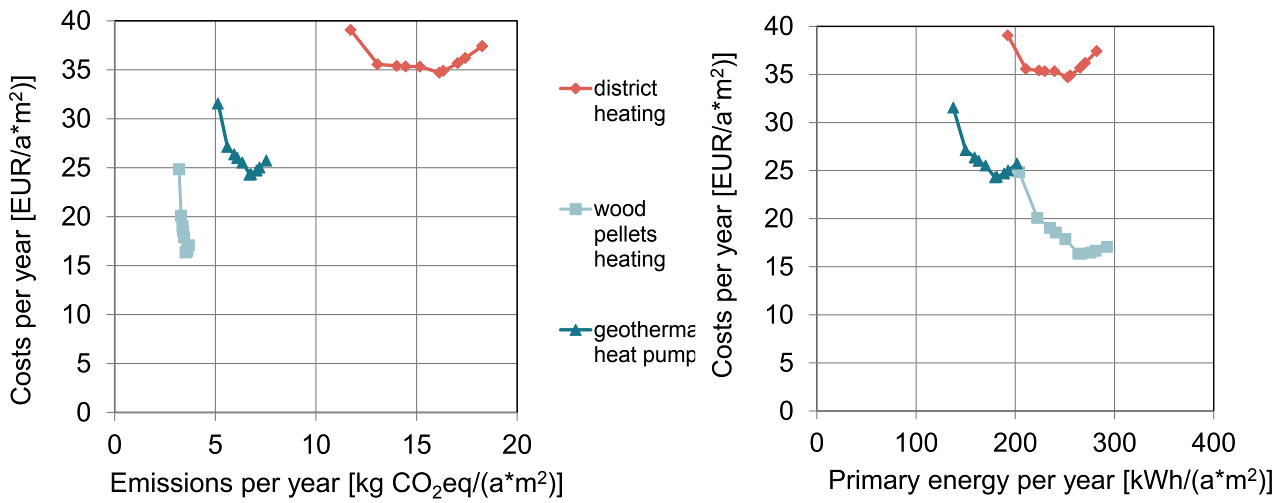


Figure 44 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Sweden, for single-family building. The reference case is the point on the district heating curve with the highest 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 are approximately cost-neutral. The high efficiency window with a U-value of 1.0 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.

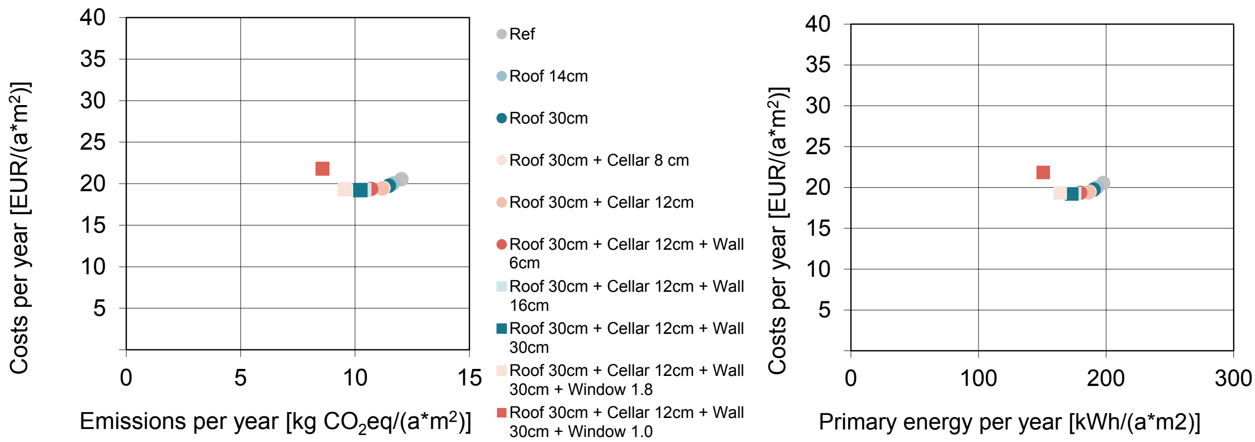
Table 36 Data for different packages of renovation measures M1 to M9 and of the reference case for a multi-family house in Sweden.

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^{2}K	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
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 demand: 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

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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:



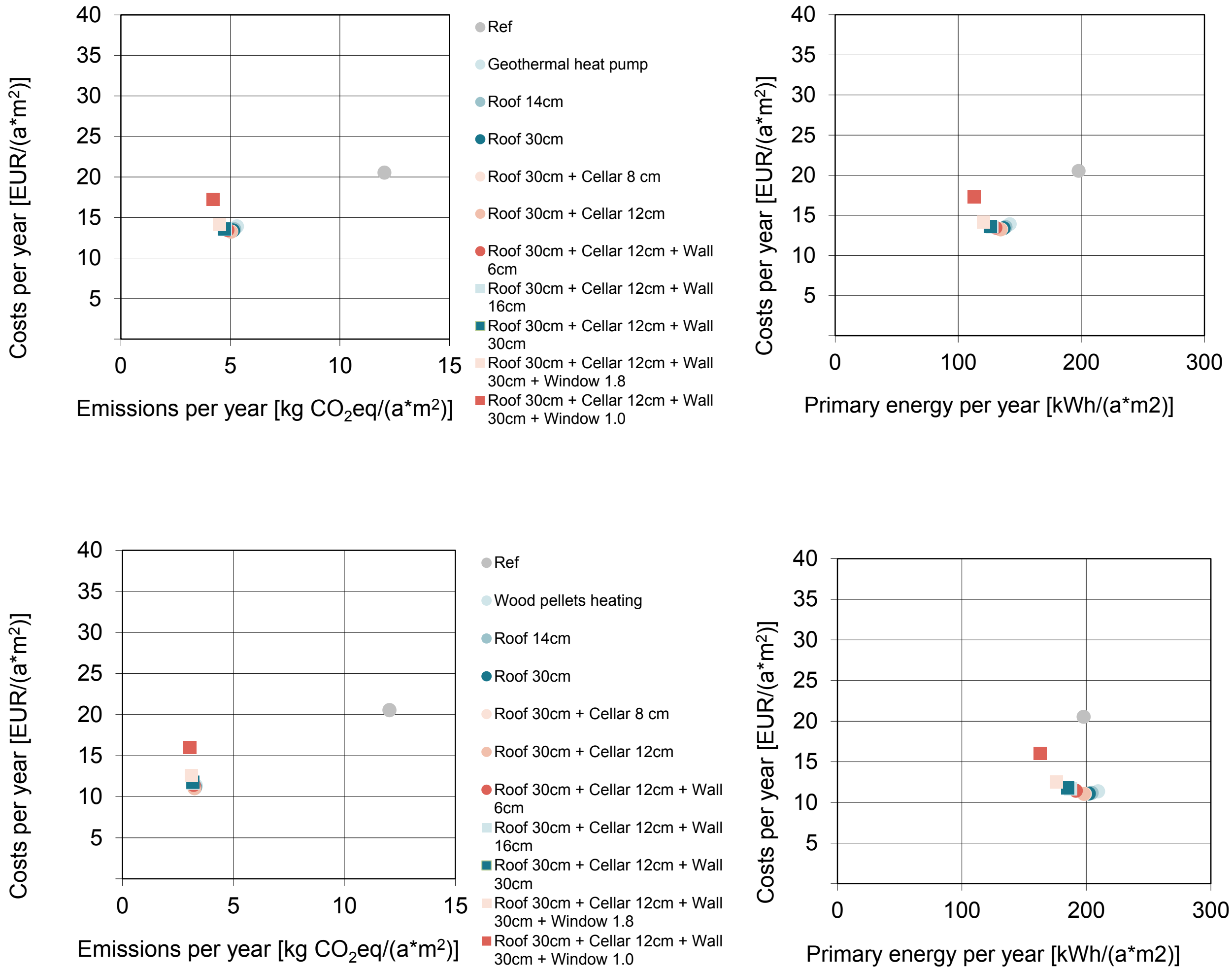


Figure 45 Comparison of cost effectiveness of energy efficiency renovation measures for for multi-family building in Sweden different heating systems: district heating system (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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.

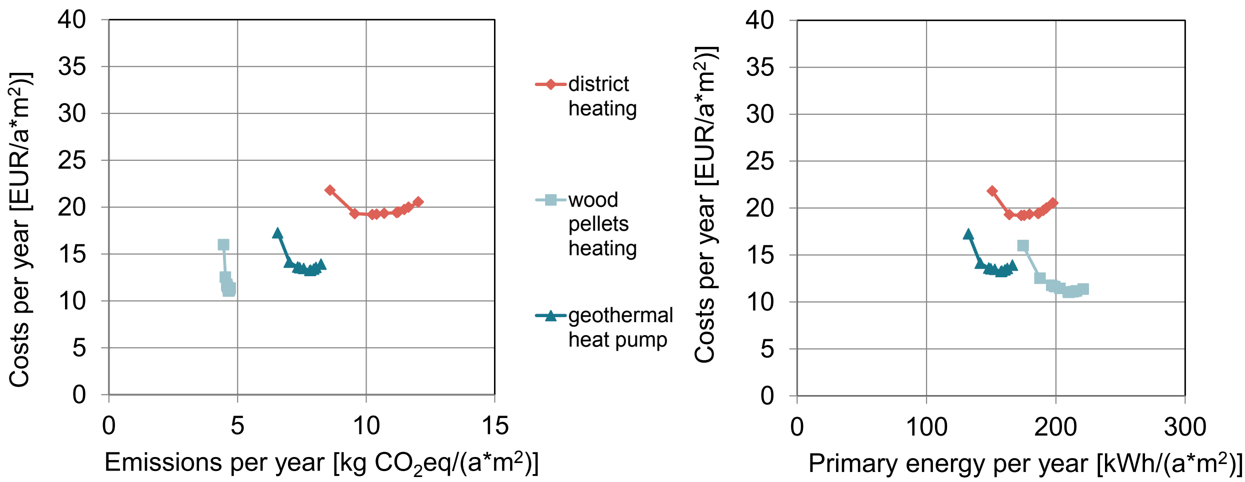


Figure 46 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Sweden, for a multi-family building, The reference case is the point on the district heating curve with the highest 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 energies 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 energies, 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 37 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual 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	✓	
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. 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 38 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual 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	✓	
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 demand.

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

Table 39 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	✓

3.5.8. 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 40 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.

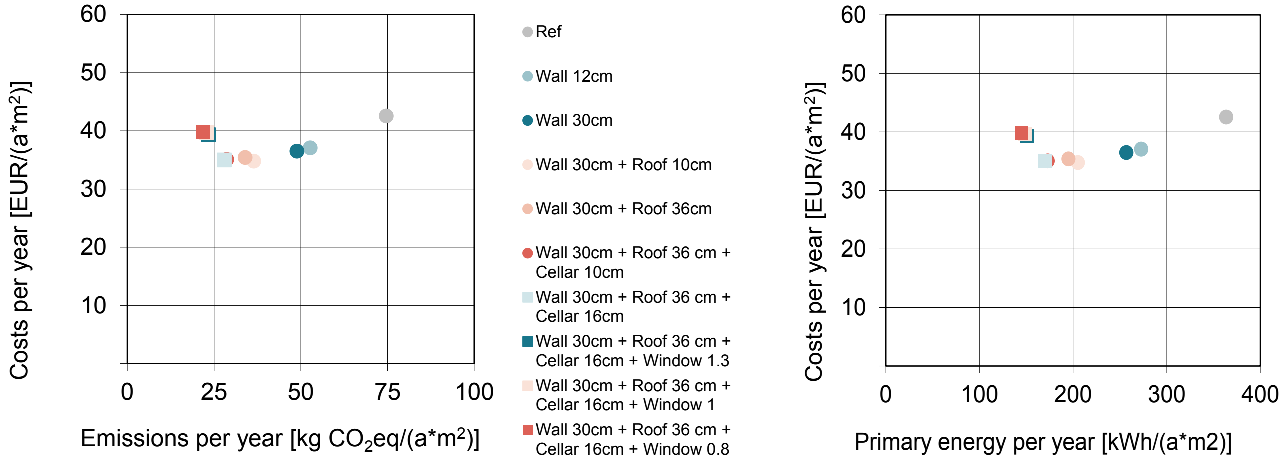
Table 41 Data for different packages of renovation measures M1 to M9 and the reference case for a single-family house in Switzerland. Sources: Lifetimes of building elements: AHB 2009, SIA 2004, Bund Technischer Experten (BTE) 2008, Bundesministeriums für Verkehr, Bau- und Wohnungswesen (BVBW) 2001, SIA 2010. The energy demand 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.

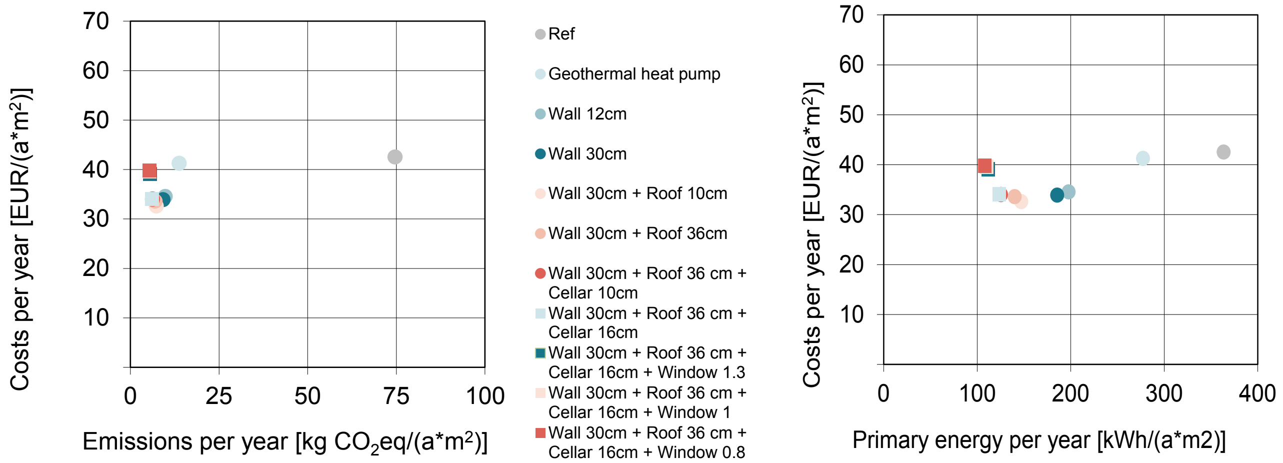
Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wall - Costs	EUR/m^2 wall	62	142	167	167	167	167	167	167	167	167
Wall - thickness of insulation material	cm	-	12	30	30	30	30	30	30	30	30
Wall - λ of insulation material	W/mK	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wall - lifetime of renovation measure	a	40	40	40	40	40	40	40	40	40	40
Window - Costs	EUR/m^2 window	33	33	33	33	33	33	33	763	832	875

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
Window - U-Value	W/m²K	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/m² 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/m² 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 demand for heating	kWh/m²	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:





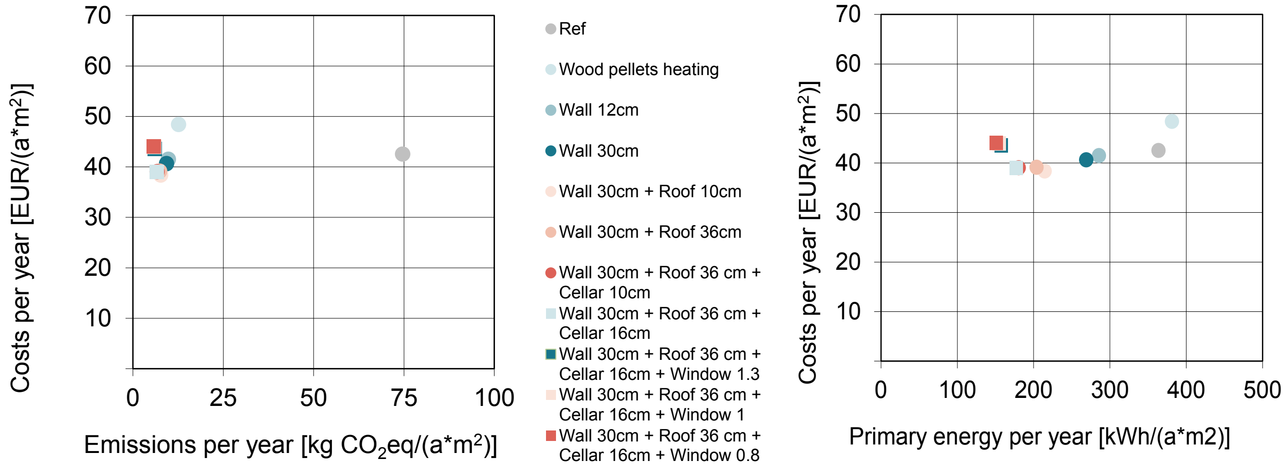


Figure 47 Single-family building Switzerland: Comparison of cost effectiveness of energy efficiency renovation measures for different heating systems: oil heating (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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:

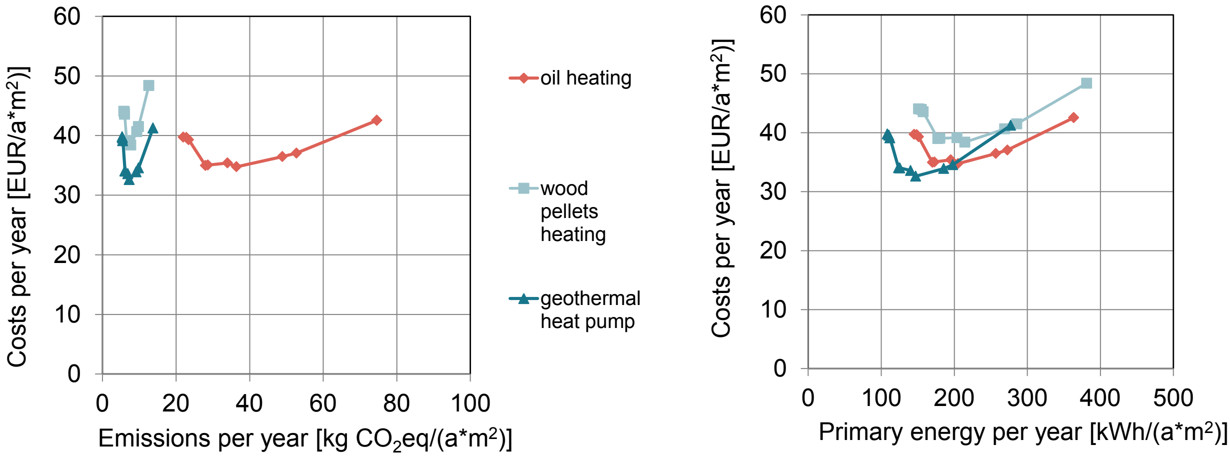


Figure 48 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for single-family building. The reference case is the point on the oil heating curve with the highest 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.

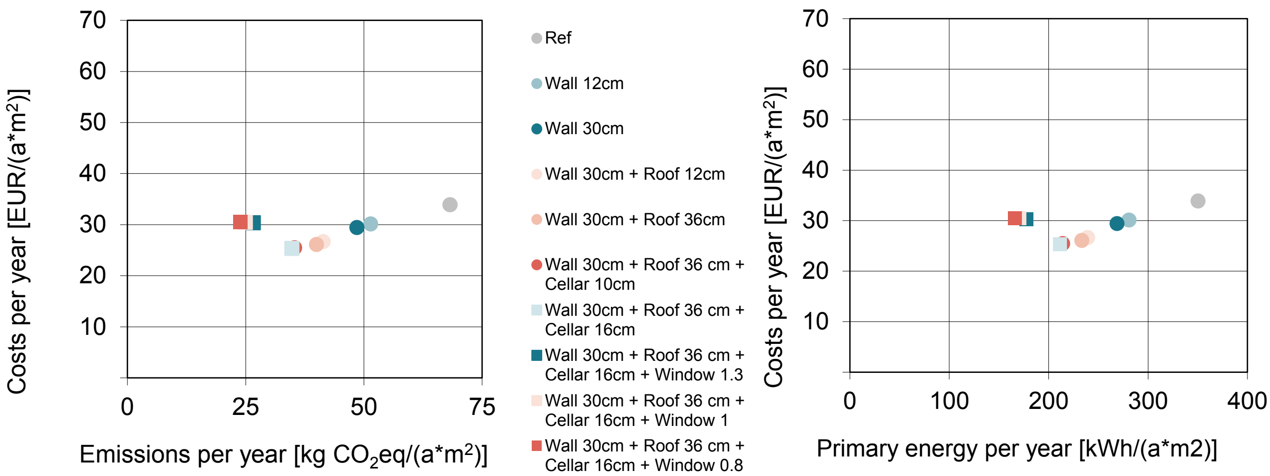
Table 42 Data for different packages of renovation measures M1 to M9 and the reference case for a multi-family house in Switzerland. Sources: Lifetimes of building elements: AHB 2009, SIA 2004, Bund Technischer Experten (BTE) 2008, Bundesministeriums für Verkehr, Bau- und Wohnungswesen (BVBW) 2001, SIA 2010. The energy demand 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 of renovation measure	a	-	-	-	-	-	40	40	40	40	40
Energy demand for heating	kWh/m^2	158	107	99	77	73	58	57	32	27	23

Parameter	Unit	Reference / new heating system without further measures	M1	M2	M3	M4	M5	M6	M7	M8	M9
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:



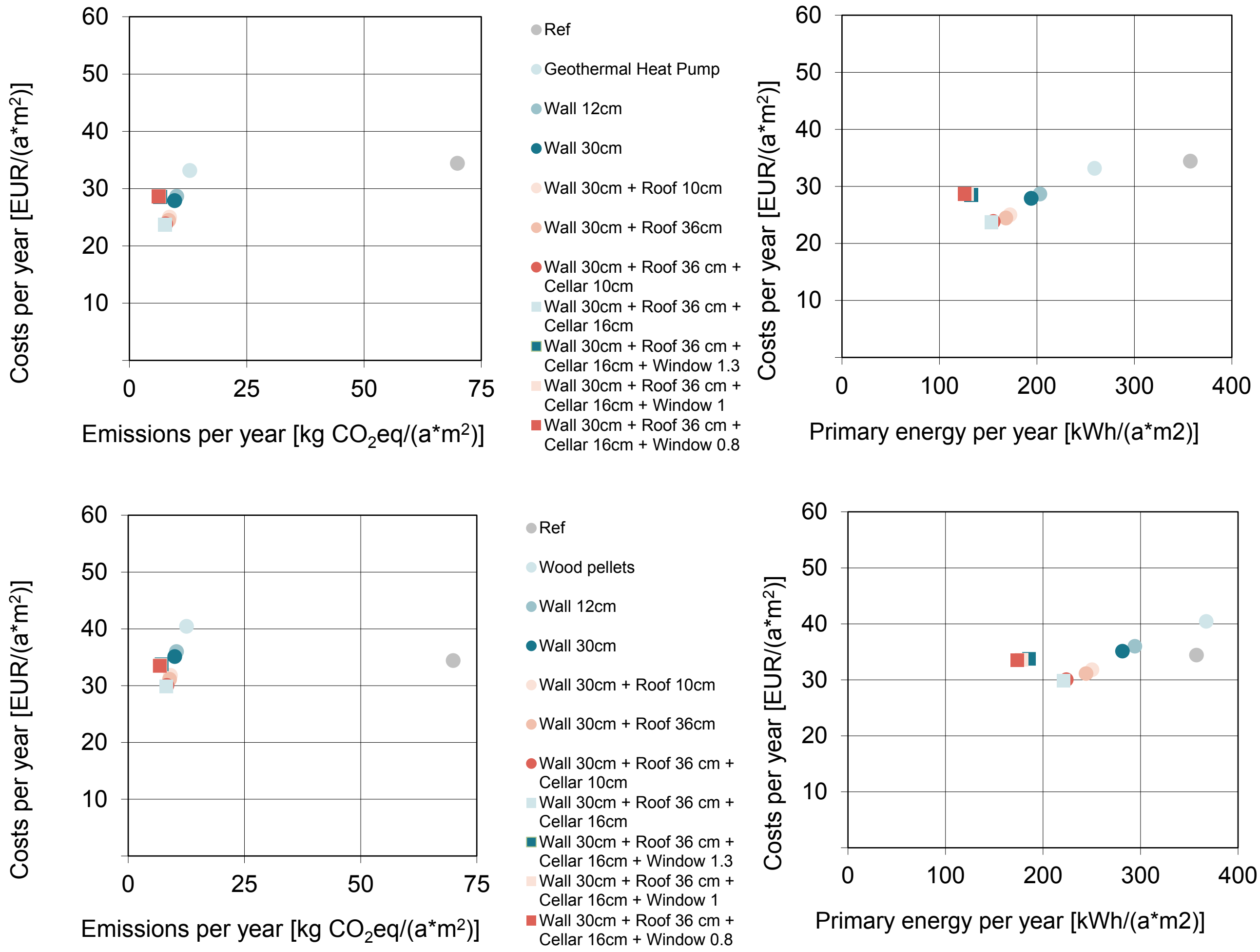


Figure 49 Multi-family building Switzerland: Comparison of cost effectiveness of energy efficiency renovation measures for different heating systems: oil heating (top), geothermal heat pump (middle) and wood pellets (bottom), as well as related impacts on carbon emissions and primary energy use. In all graphs, the reference shown as a grey dot refers to a situation with a replacement of the 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:

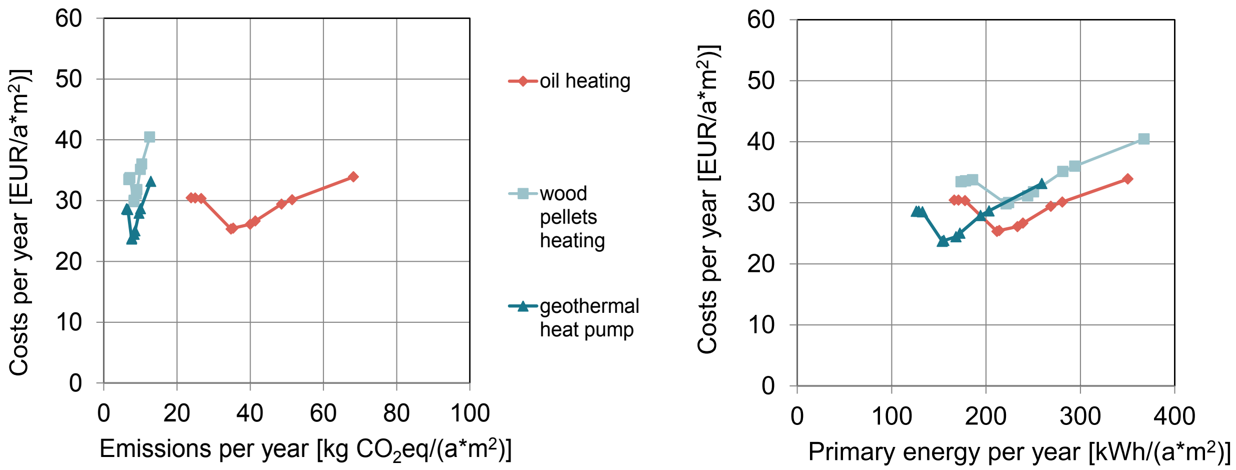


Figure 50 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for multi-family building The reference case is the point on the oil heating curve with the highest 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 43 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 number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓
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 with the multi-family building in confirm the main hypotheses which are investigated, as summarized in the following table:

Table 44 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	✓
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 the hypothesis that in multi-family buildings, the synergies between RES measures and energy efficiency measures are larger. 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 single-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 45 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	✓

3.6. Ventilation

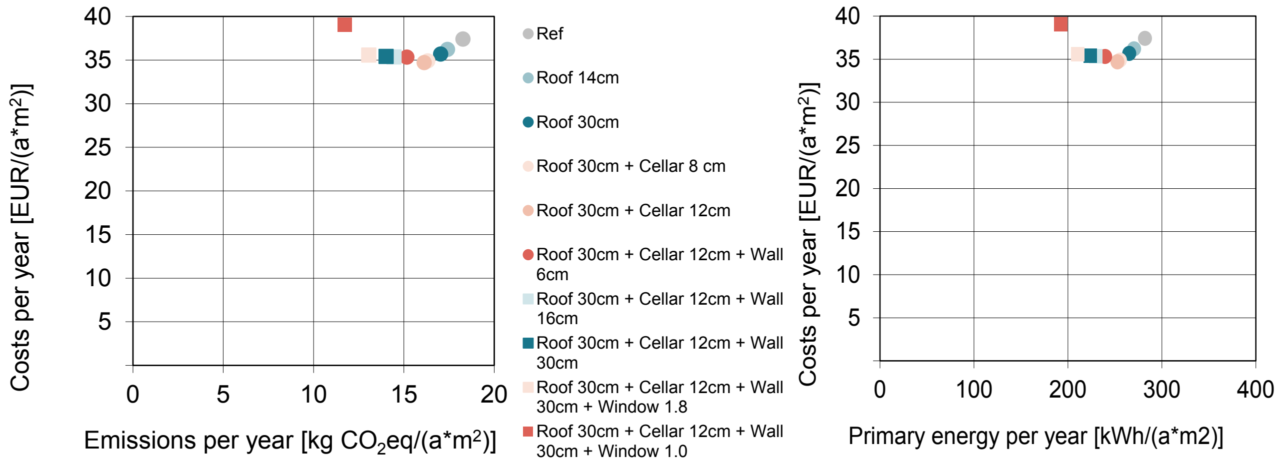
3.6.1. *Parameters and results for Sweden*

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 46 Parameters for ventilation system in Sweden in single-family building (SFB) and multi-family building (MFB).

Parameter	Unit	SFB	MFB
Investment costs 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.



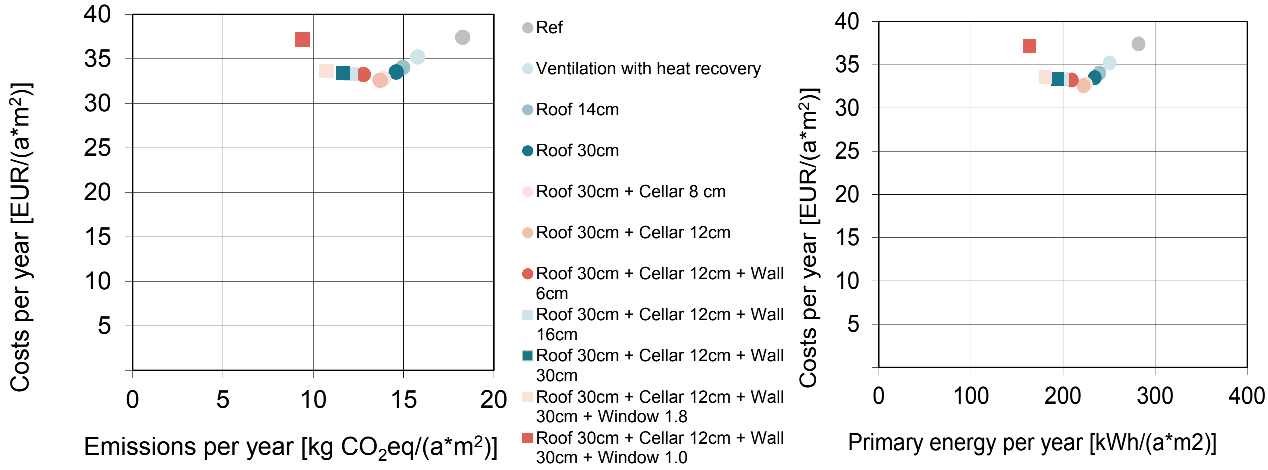
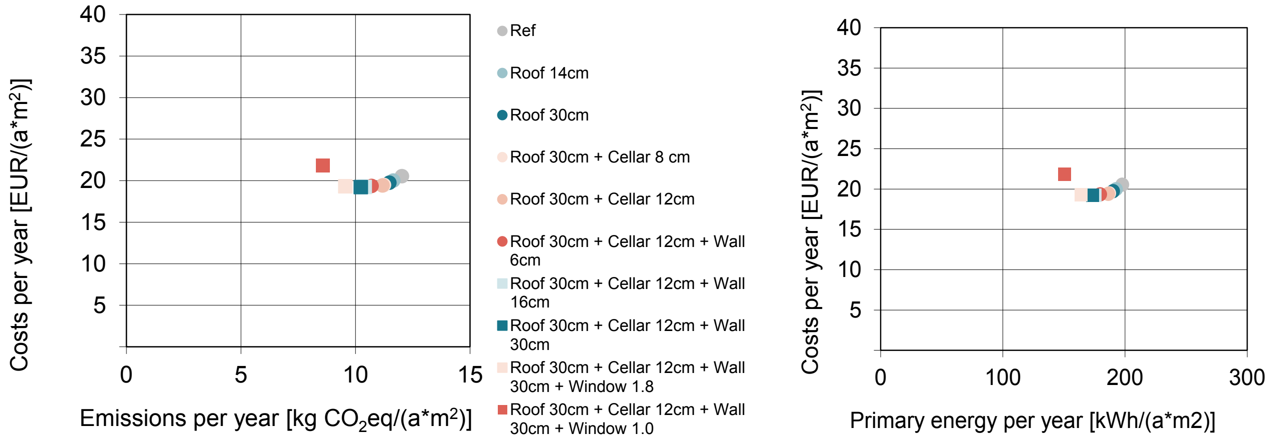


Figure 51 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost effectiveness and environmental impacts of different renovation packages in single-family building in Sweden. The graphs above show renovation measures without improving the energy performance 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.



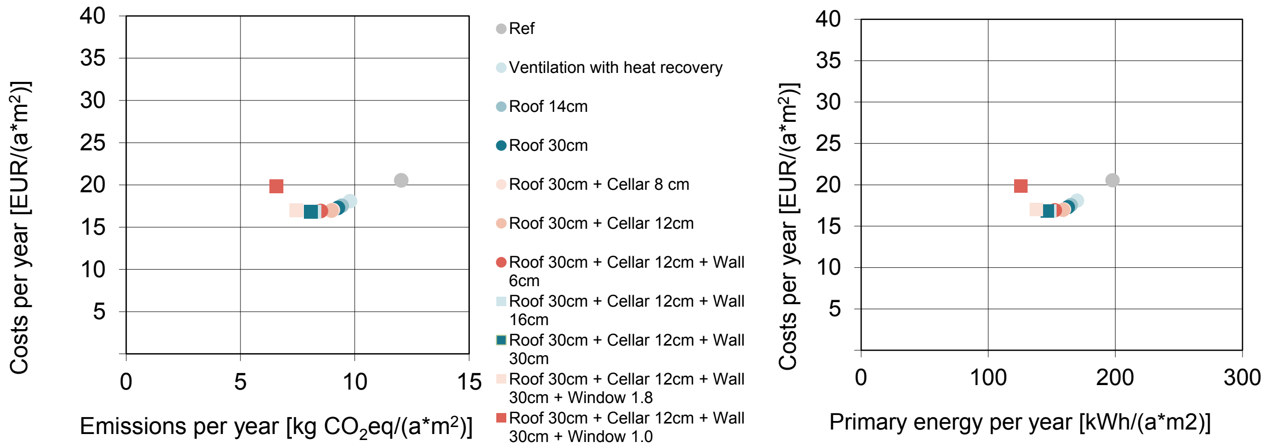


Figure 52 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost effectiveness and environmental impacts of different renovation packages in multi-family building in Sweden. The graphs above show renovation measures without improving the energy performance 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.

3.6.2. Parameters and results for 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 47 Parameters for ventilation system in Switzerland in single-family building (SFB) and 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

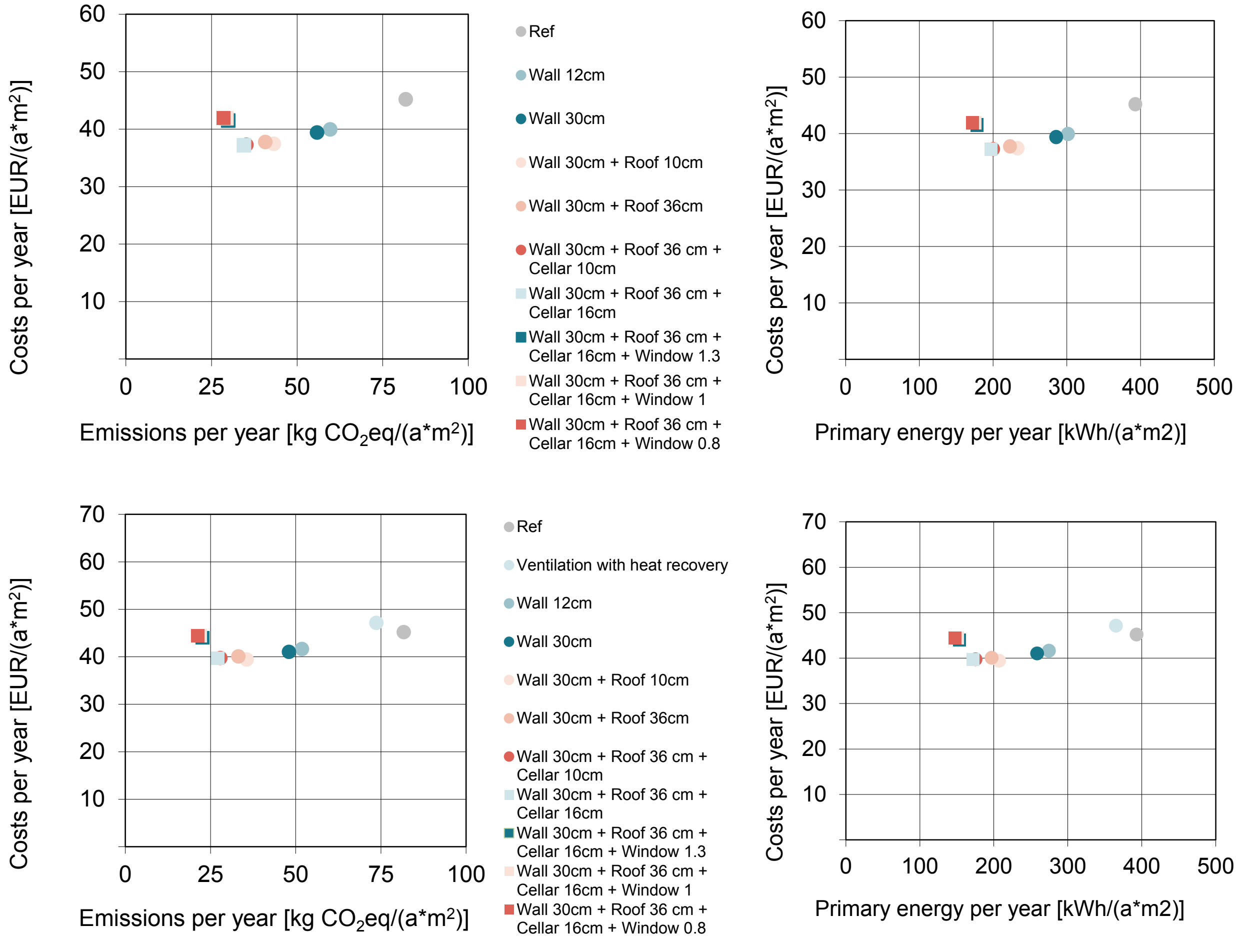
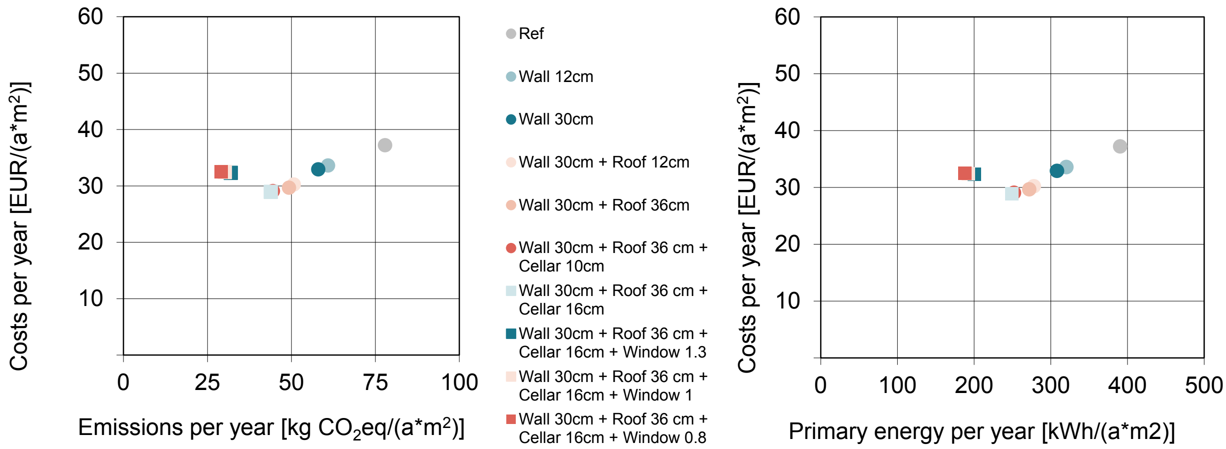


Figure 53 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost effectiveness and environmental impacts of different renovation packages in single-family building in Switzerland, assuming an oil heating system. The graphs above show renovation measures 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.



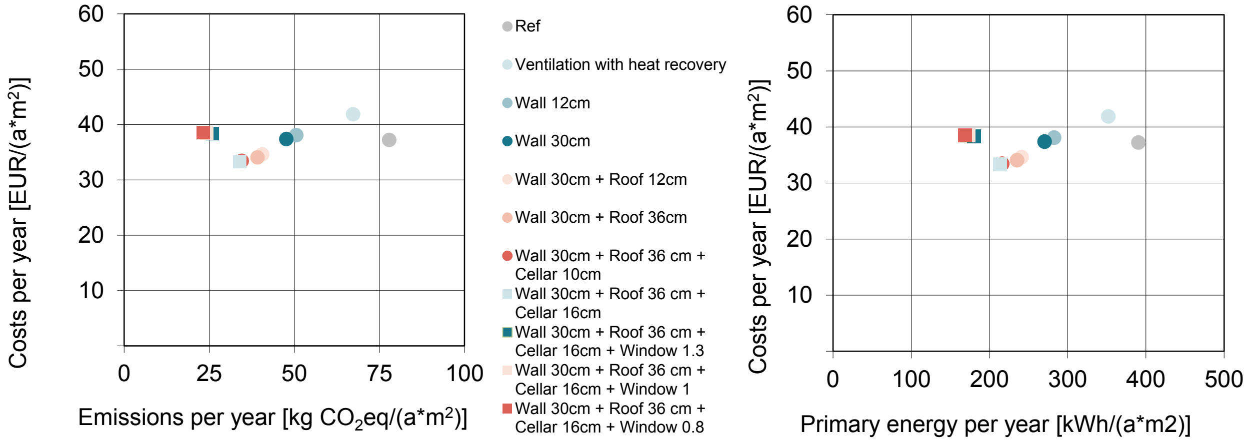


Figure 54 Effect of upgrading an existing ventilation system to a ventilation system with heat recovery on cost effectiveness and environmental impacts of different renovation packages in <u>multi-family building</u> in Switzerland. The graphs above show renovation measures without existing ventilation 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.

3.6.3. Discussion

The installation of a ventilation system with heat recovery is an effective measure to reduce both emissions and energy demand. 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 48 Results for the investigated hypothesis for the multi-family and single family reference buildings in Sweden and in Switzerland.

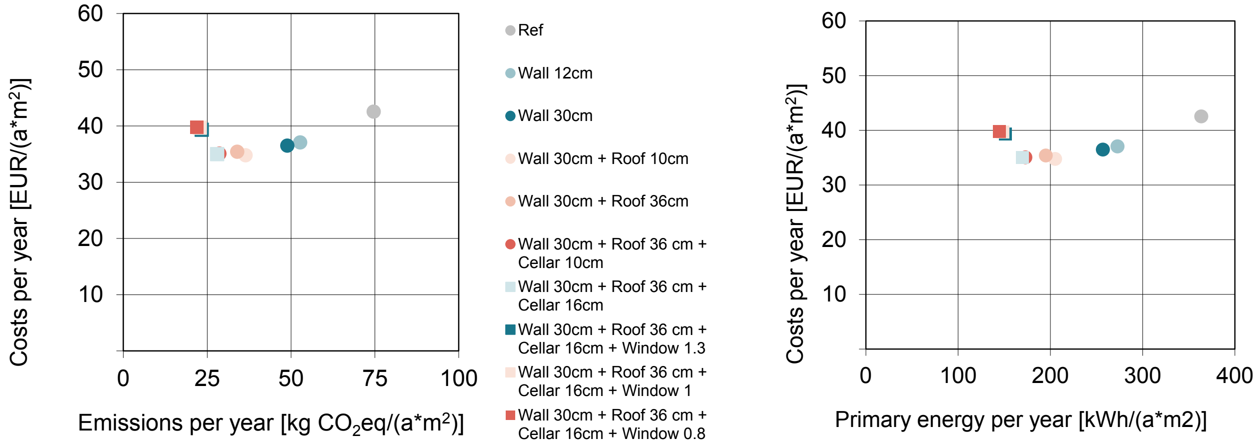
Hypothesis	Results from SFB in Sweden	Results from MFB in Sweden	Results from SFB in Switzerland	Results from MFB in Switzerland
The installation of a ventilation system with heat recovery has effects on the energy performance comparable with measures on other building elements	✓	✓	✓	✓

In Sweden, the impact is bigger in relative terms than in Switzerland, which can be explained by the larger average temperature difference between indoor and outdoor. 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. Whereas the difference in the price level between Switzerland and Sweden may explain a part of this difference, it is also an indication that the numbers indicated here for the costs need to be looked with caution. 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 probably achieved only in special circumstances. 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.

3.7. Energy in materials

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 materials. The results of the calculations are shown in the following graphs:

Energy in materials not included



Energy in materials included

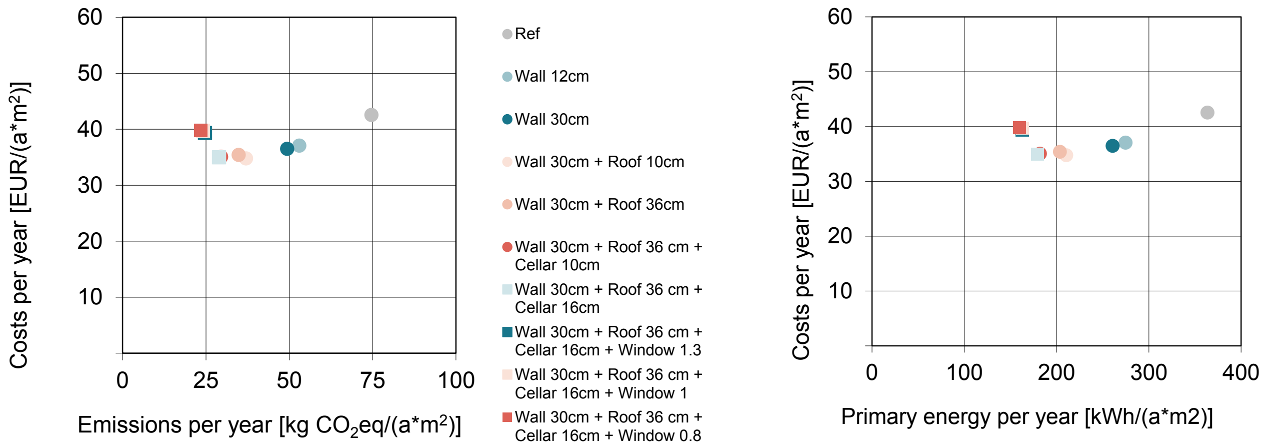
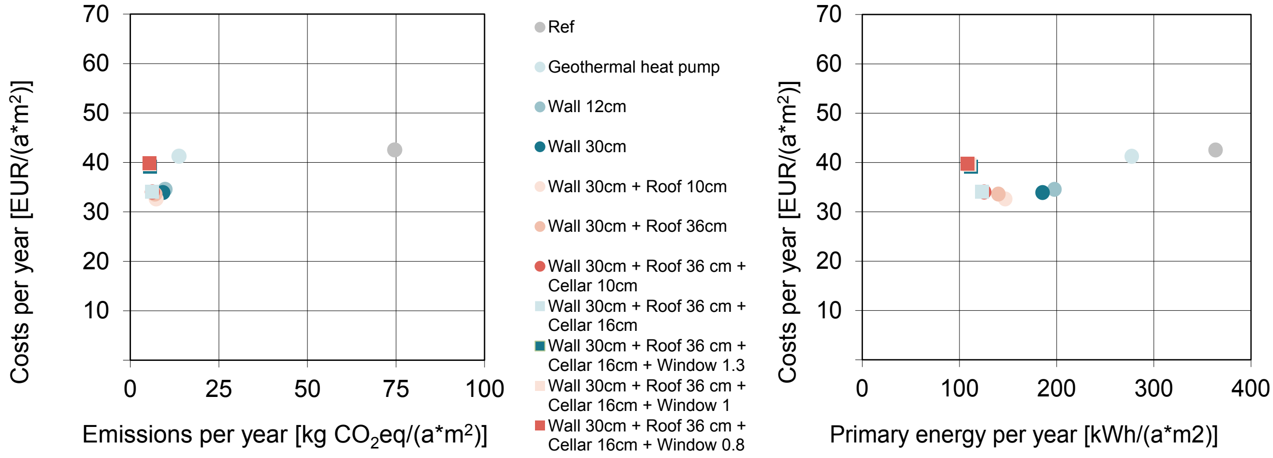


Figure 55 Comparison of calculations for single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including the renewal of an **oil heating system**.

Energy in materials not included



Energy in materials included

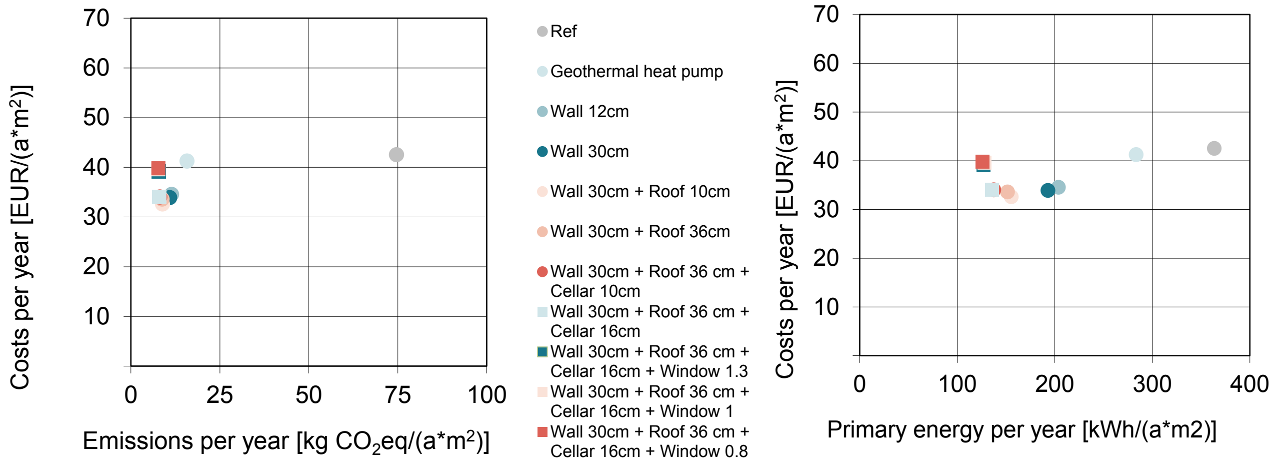
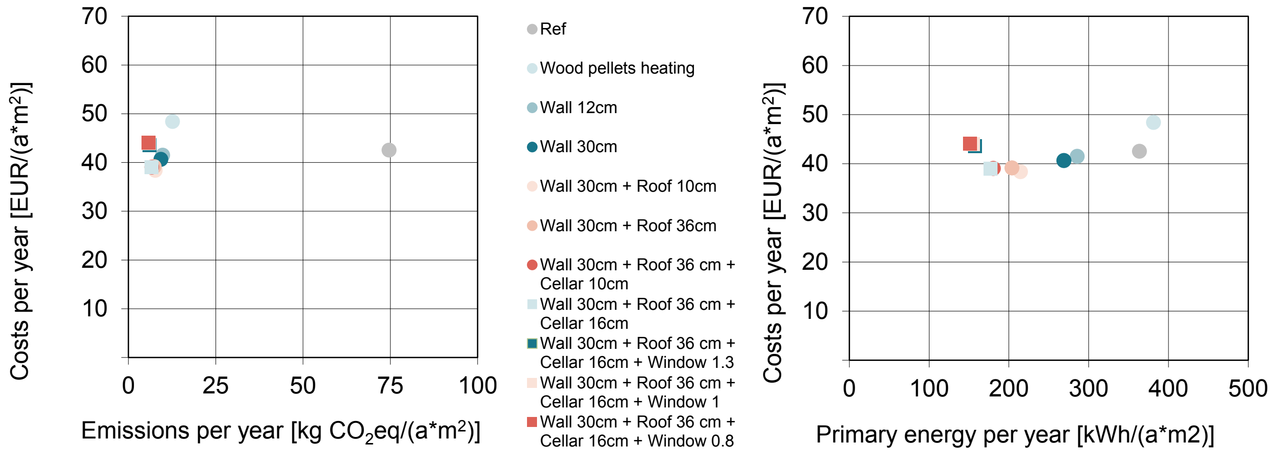


Figure 56 Comparison of calculations for single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including a switch to a **geothermal heat pump**.

Energy in materials not included



Energy in materials included

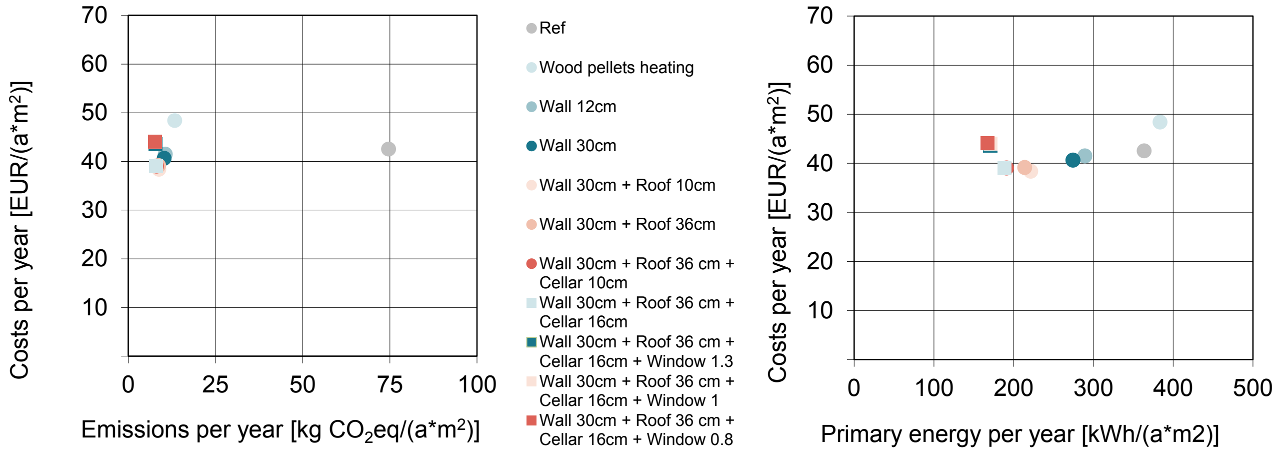


Figure 57 Comparison of calculations for single-family building in Switzerland without including embodied energy (above) and with including embodied energy (below), for different renovation packages, including a switch to a **wood pellet heating system**.

The effects of including embodied energy use in the calculations is in general more visible if looking at the primary energy use than looking at carbon emissions. The most far-reaching measures are a bit less favourable in terms of reduction of primary energy use when taking into account the additional energy use for the insulation material. This is particularly visible for the windows: When taking into account embodied energy in this reference building, the more energy efficient windows do not have an environmental advantage compared to less energy efficient windows.

Embodied energy use of the geothermal HP 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. 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.

3.8. 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.

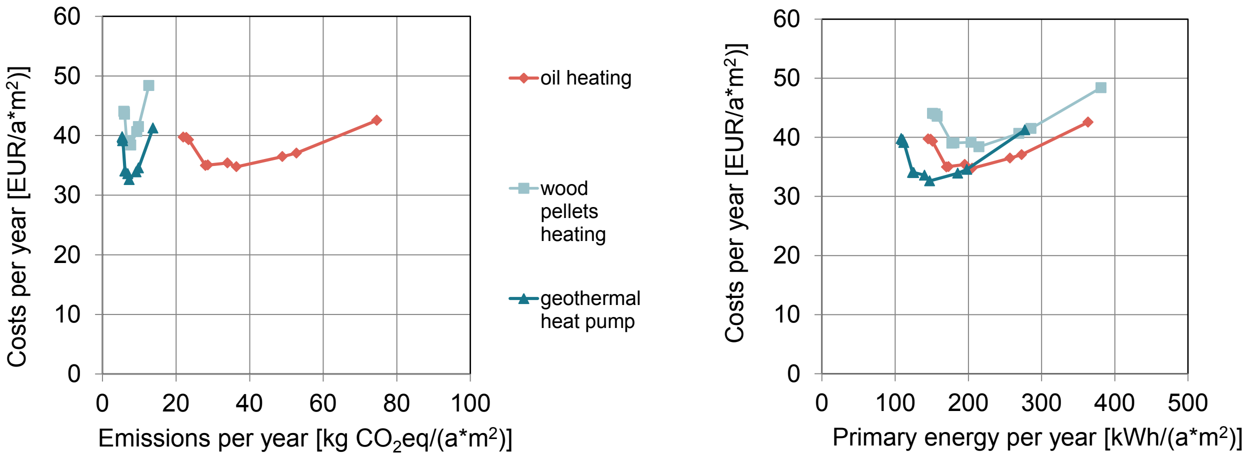


Figure 58 Aggregated comparison of different renovation packages for single-family reference building in Switzerland

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

The following graph is based on a change of building dimensions from SFB to MFB, while leaving the other parameters the same.

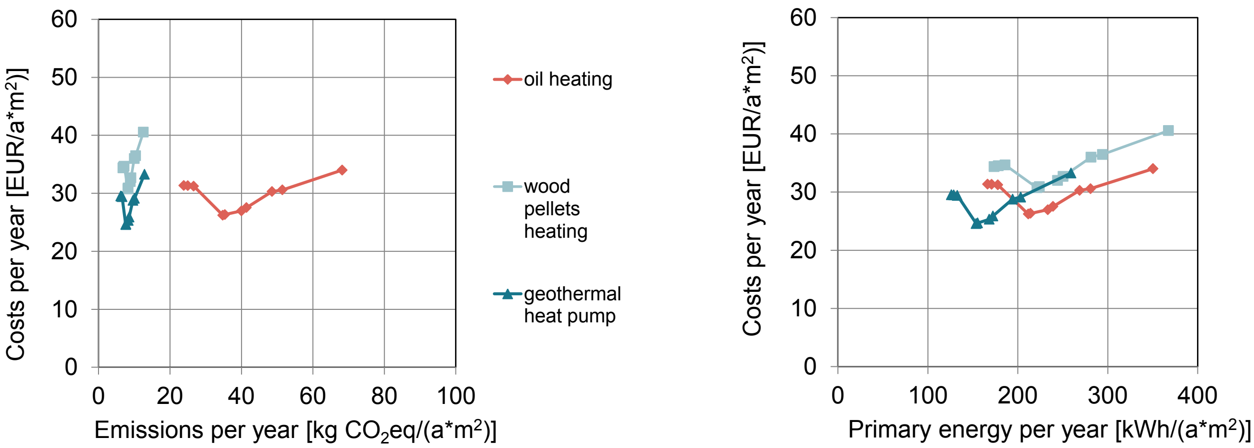


Figure 59 Aggregated comparison of different renovation packages for a multifamily reference building in Switzerland with changes in the building dimensions

Specific costs 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.

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 m^2 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 49 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	0.8
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 Multi-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 effect, by including changes to the specific costs of measures for the MFB:

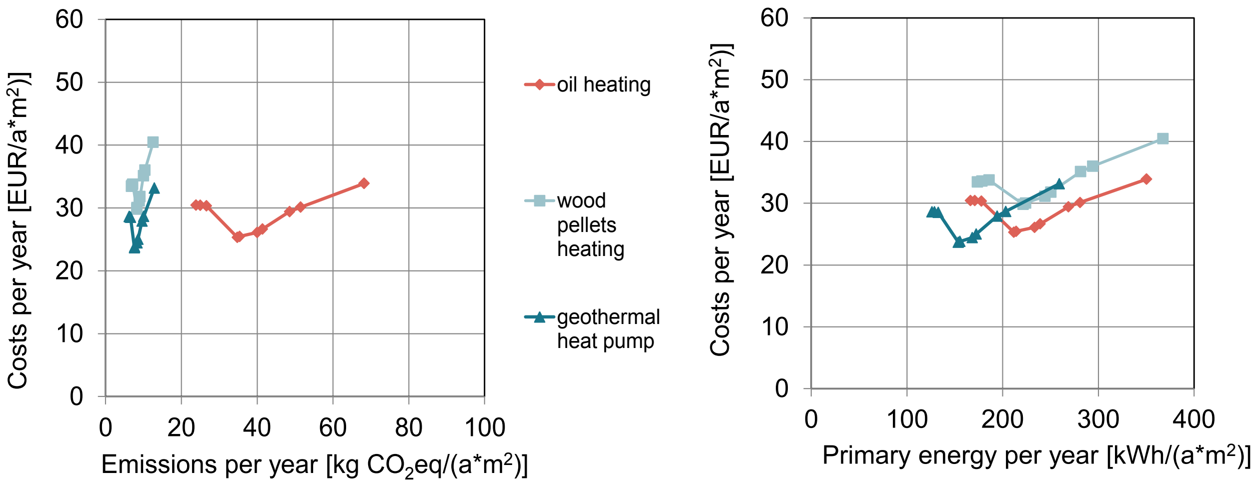


Figure 60 Energy performance and cost effectiveness for multi-family building in Switzerland taking into account lower specific costs for renovation measures in multi-family buildings than in single-family buildings

Compared to the change in building dimensions, the change in specific costs has little effect on the position of the curves.

Effect of change of investment costs for heating system based on energy efficiency measures

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 heating system. The energy use is adapted to actual heating demand, yet the investment costs in these calculations for the new heating systems are not lowered 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 to the heating demand: The lower the energy demand 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 with the previous graphs:

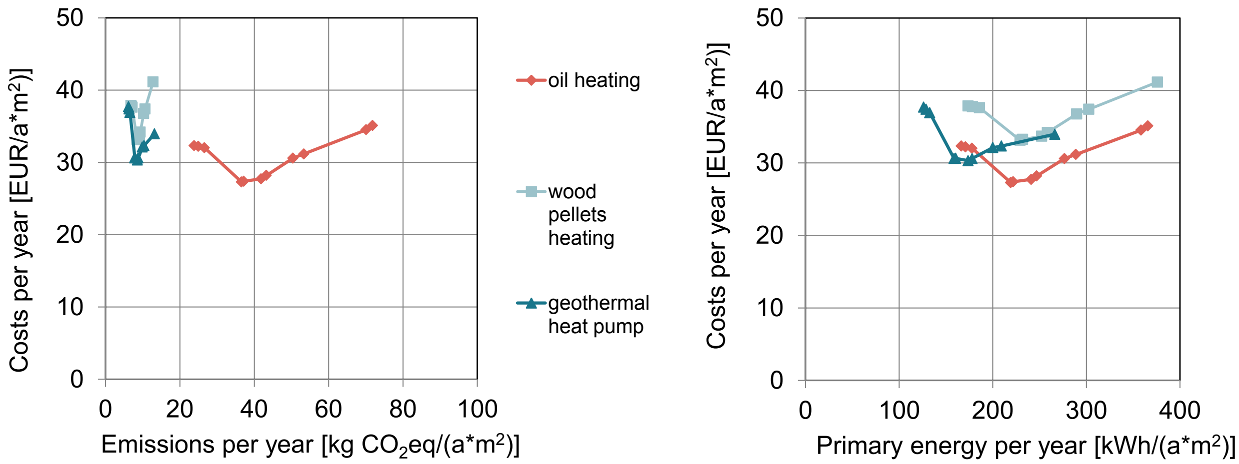


Figure 61 Energy performance and cost effectiveness for multi-family building in Switzerland, without any reduction of peak capacity of heating system for more far reaching energy efficiency measures

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

1. Far-advanced energy efficiency measures including the installation of new windows are significantly less cost-effective for heating systems with renewable energies
2. Whereas a change from the oil heating to a geothermal heat pump is still cost-effective, the most cost-optimal of the investigated renovation packages includes an oil-heating.
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 when more far reaching 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. This cost optimum reduces carbon emissions and primary energy use significantly more than the cost optimum 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.

In the two following graphs, 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.

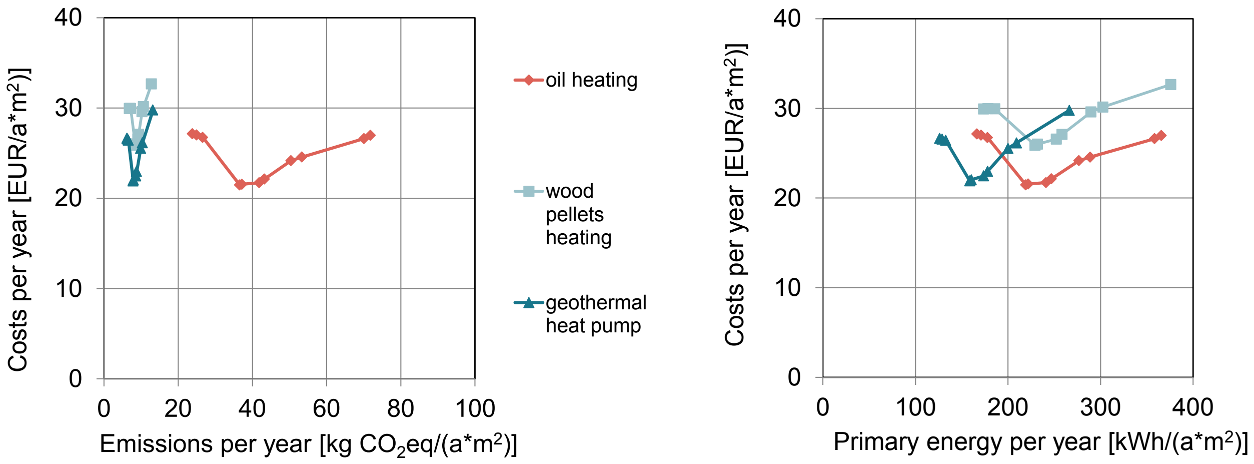


Figure 62 Energy performance and cost effectiveness for multi-family building in Switzerland in low energy price scenario

The effect of assuming lower energy prices is that a change to a geothermal heat pump system is less cost-effective than installing a new oil based system when combined with no or few measures on the building envelope, whereas when more energy efficiency measures are carried out, 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.

In the two following graphs, 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, whereas in normal calculations the related values are 0.1 EUR/kWh and 0.2 EUR/kWh, respectively.

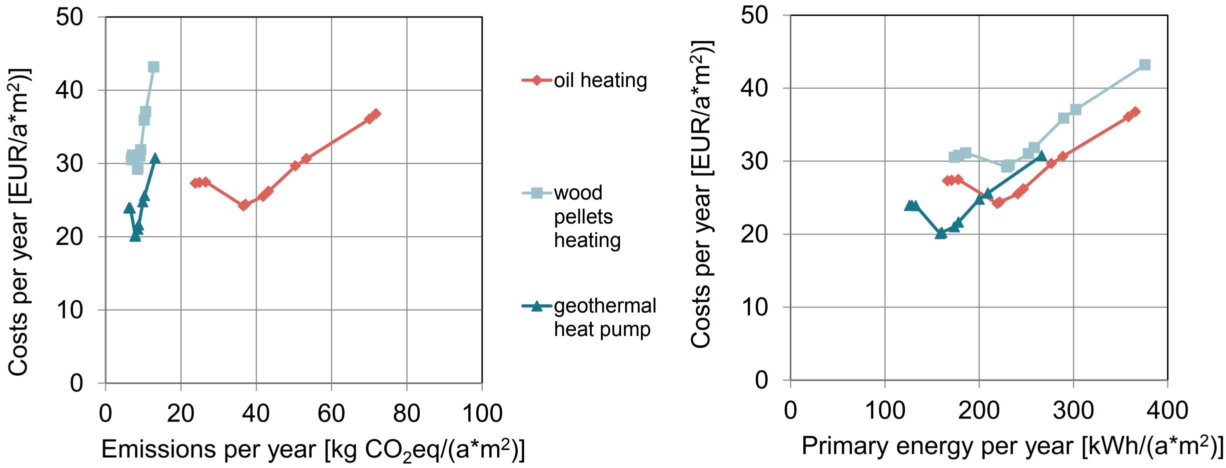


Figure 63 Energy performance and cost effectiveness for multi-family building in Switzerland in high energy price scenario

In this case, a change to a geothermal heat pump is more cost-effective now, for no or all renovation packages on the building envelope. The cost-optimal renovation package on the building envelope is the same as in the low-price scenario.

3.9. Summary table and summary graphs

3.9.1. Summary table

To summarize the results of the generic calculations with reference buildings, a summary table is presented and the main graphs for the different countries and buildings investigated are shown next to each other.

Comments on the results are made in the following chapters.

The following summary table summarizes the impacts of different renovation packages in the reference buildings investigated:

Table 50 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	91	23	432	151
		Wood pellets	15	6	453	157
		Geothermal heat pump	16	5.5	330	112
	MFB	Oil	68	23	352	165
		Wood pellets	13	6.2	261	125
		Geothermal heat pump	13	6.2	369	172
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

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
		Geothermal heat pump	11	8.0	219	162
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	92	43	427	194
		Air source heat pump	94	42	414	185
		Air source heat pump + PV	52	0	229	0
Portugal	MFB	Gas heating	61	36	278	163
		Air source heat pump	58	36	254	160
		Air source heat pump + PV	47	26	207	112
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

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	13	5.8	381	151
		Geothermal heat pump	14	5.4	277	108
	MFB	Oil heating	68	24	350	166
		Wood pellets	13	6.8	367	174
		Geothermal heat pump	13	6.2	259	126

3.9.2. Summary graphs

The following graphs summarize the main findings for the generic calculations with the reference buildings.

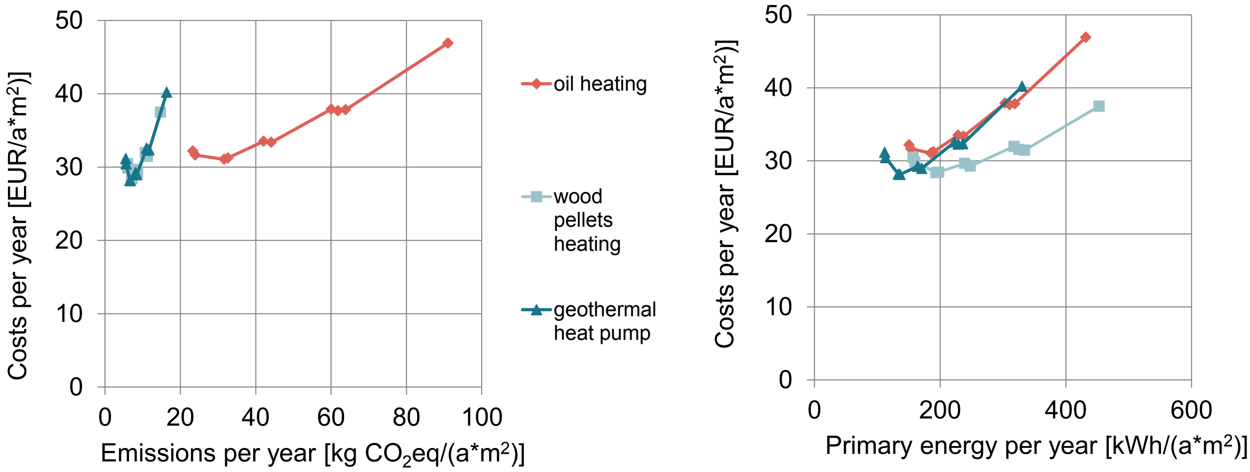


Figure 64 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Austria**, for a **single-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

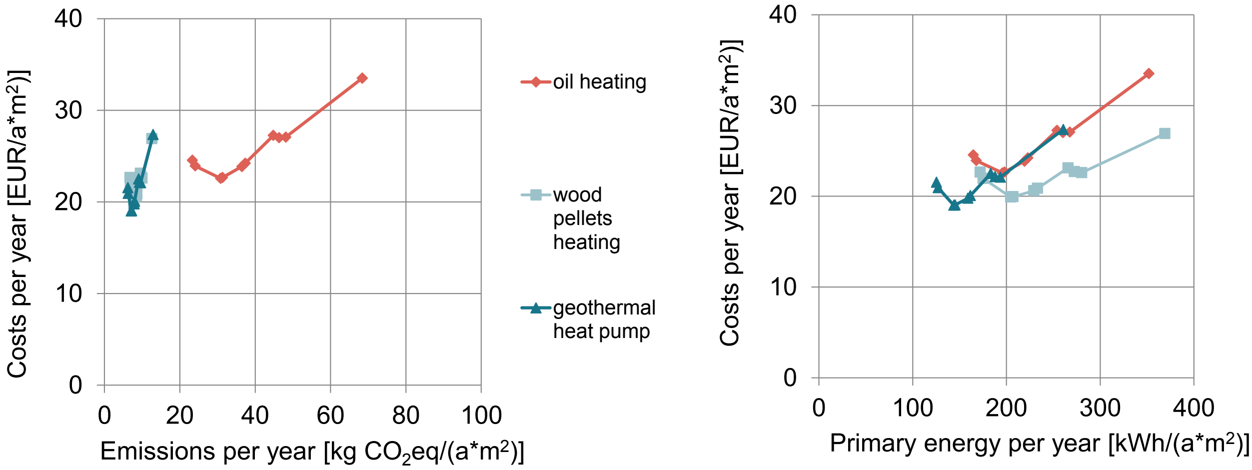


Figure 65 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Austria**, for a **multi-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

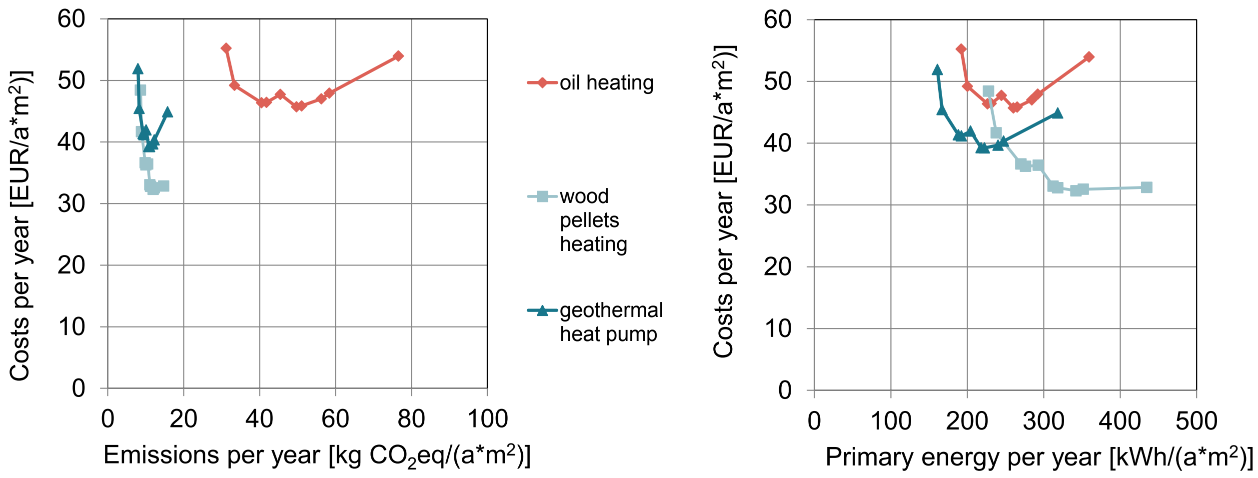


Figure 66 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Denmark**, for a **single-family building**, The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

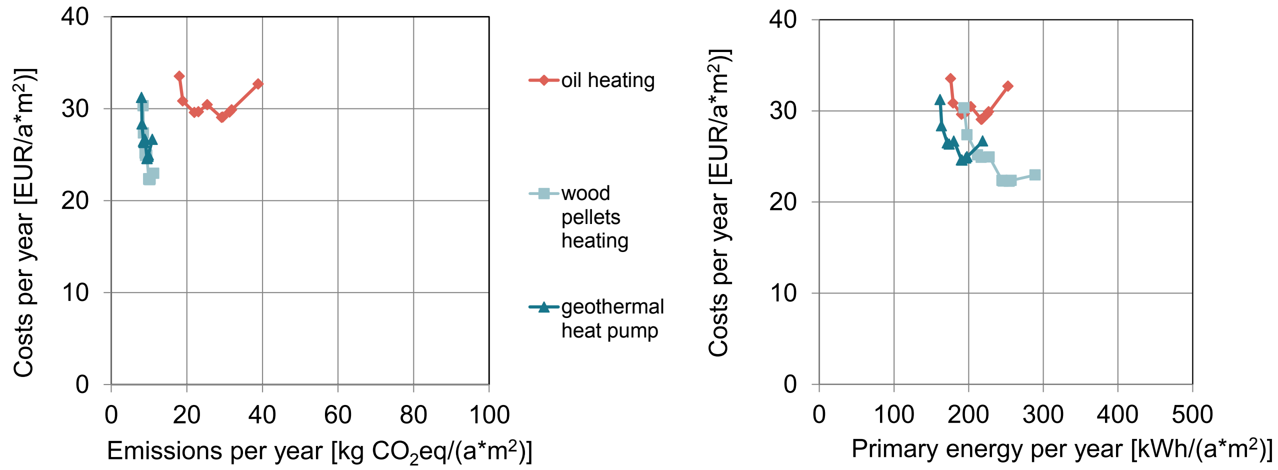


Figure 67 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Denmark**, for **multi-family building**. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

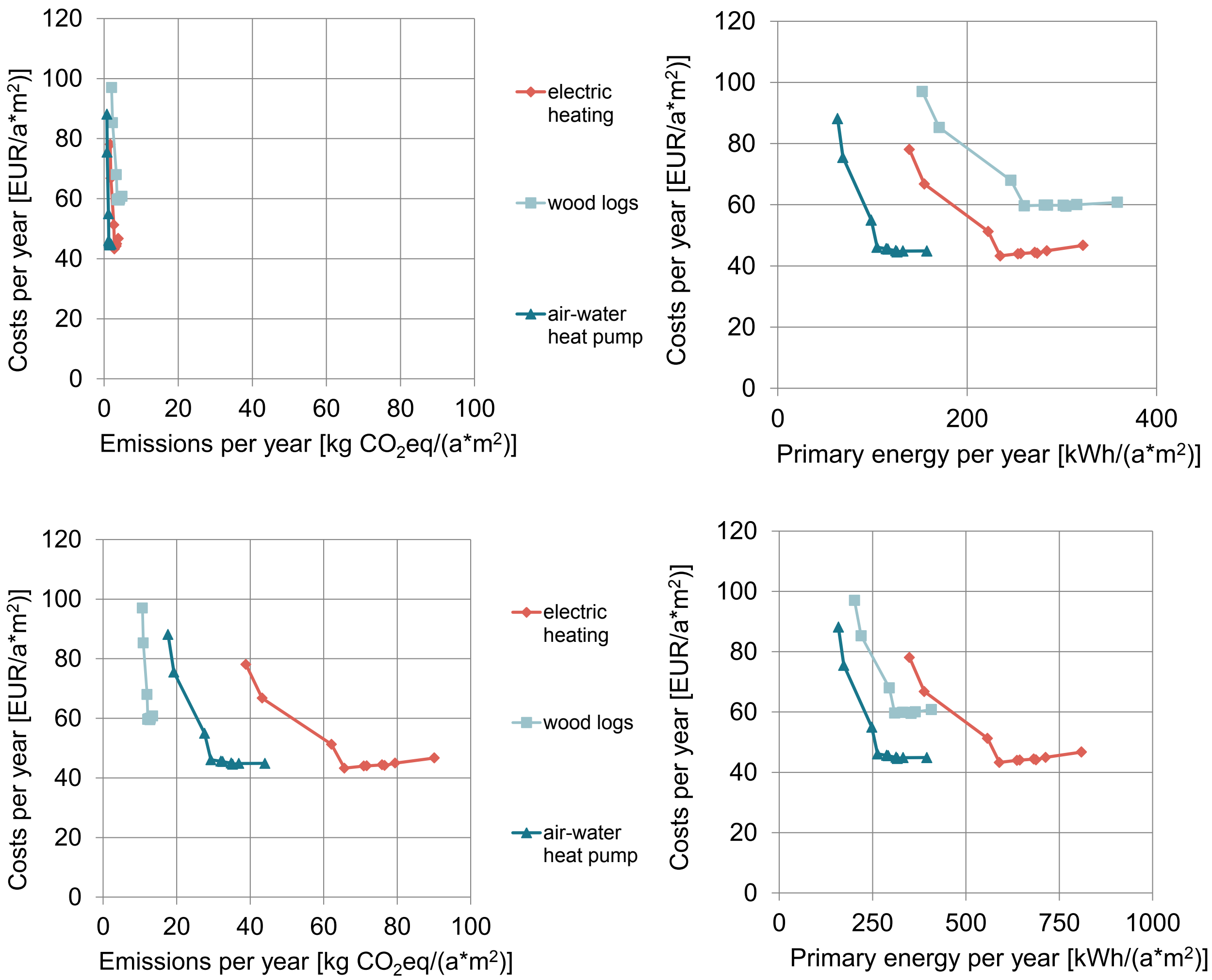


Figure 68 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Norway**. The upper graphs are calculated with the **production electricity mix of Norway as well as imports 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**.

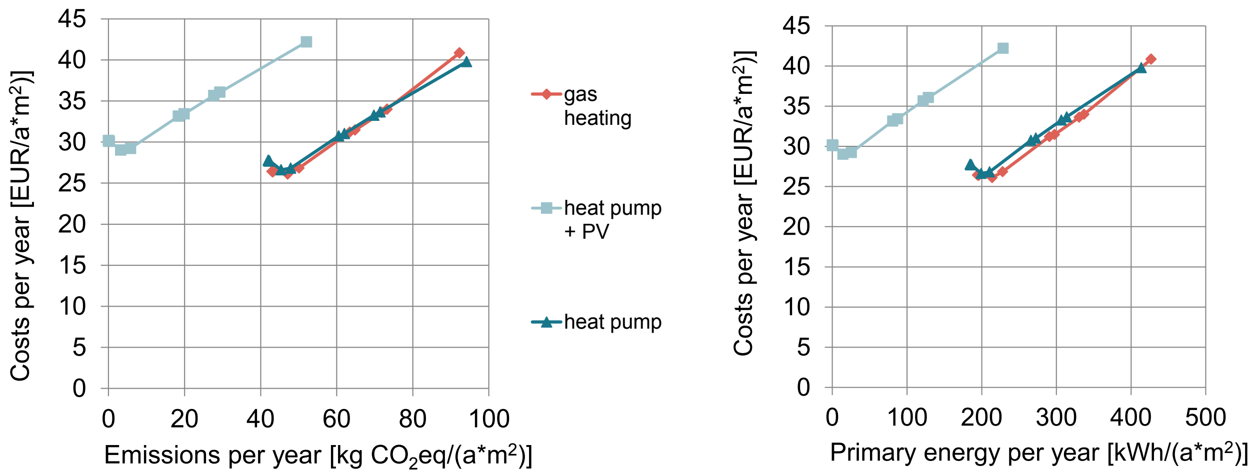


Figure 69 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Portugal**, for **single-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

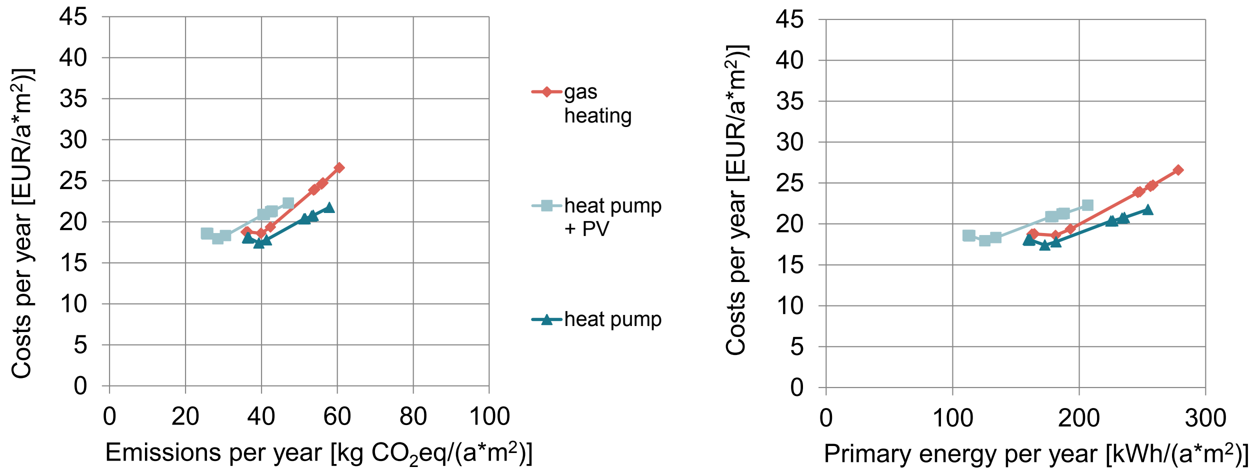


Figure 70 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Portugal**, for **multi-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

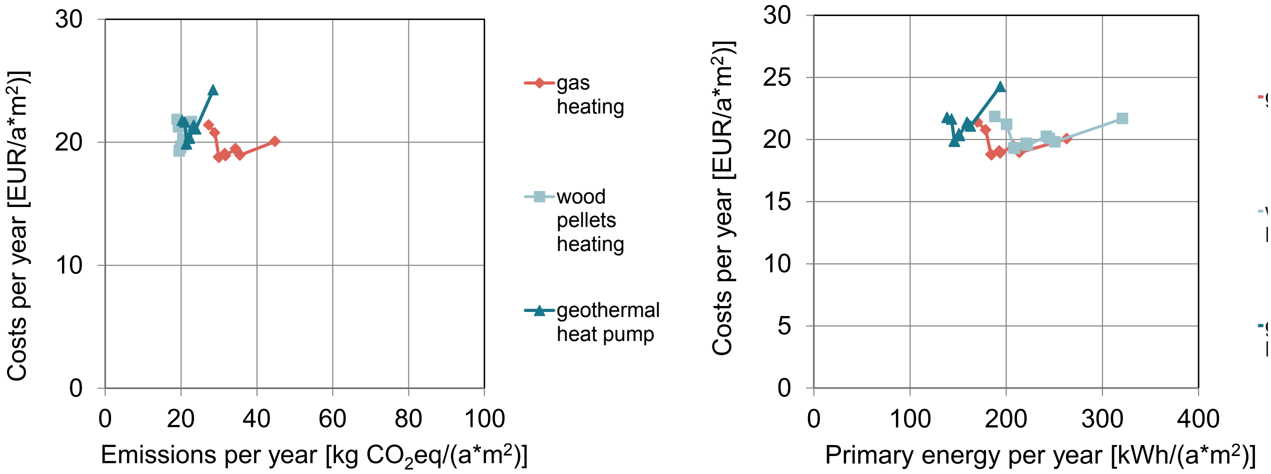


Figure 71 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Spain**, for **multi-family building**. The reference case is the point on the natural gas heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

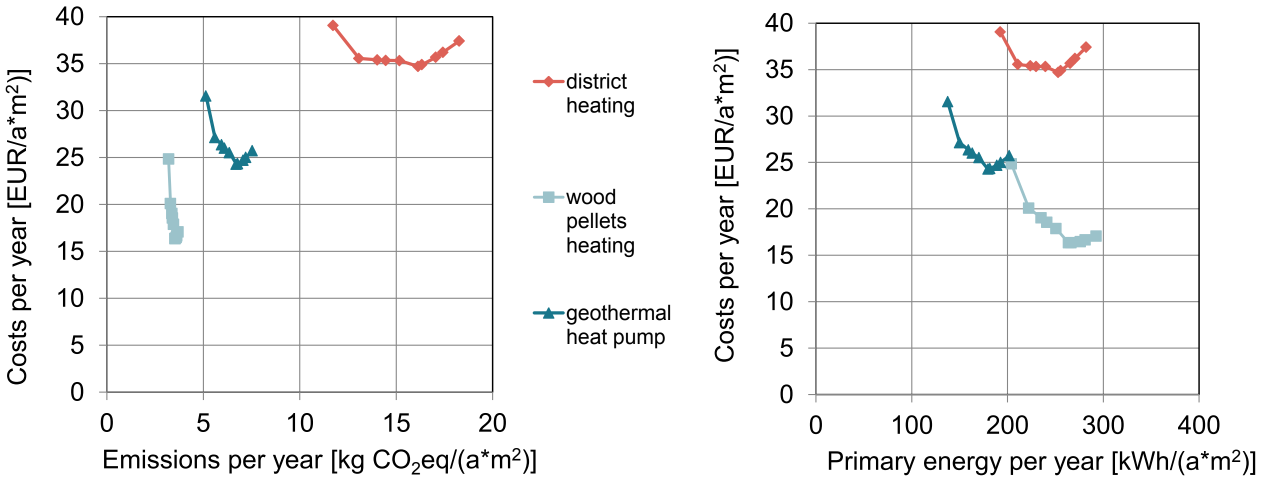


Figure 72 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Sweden**, for **single-family building**. The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

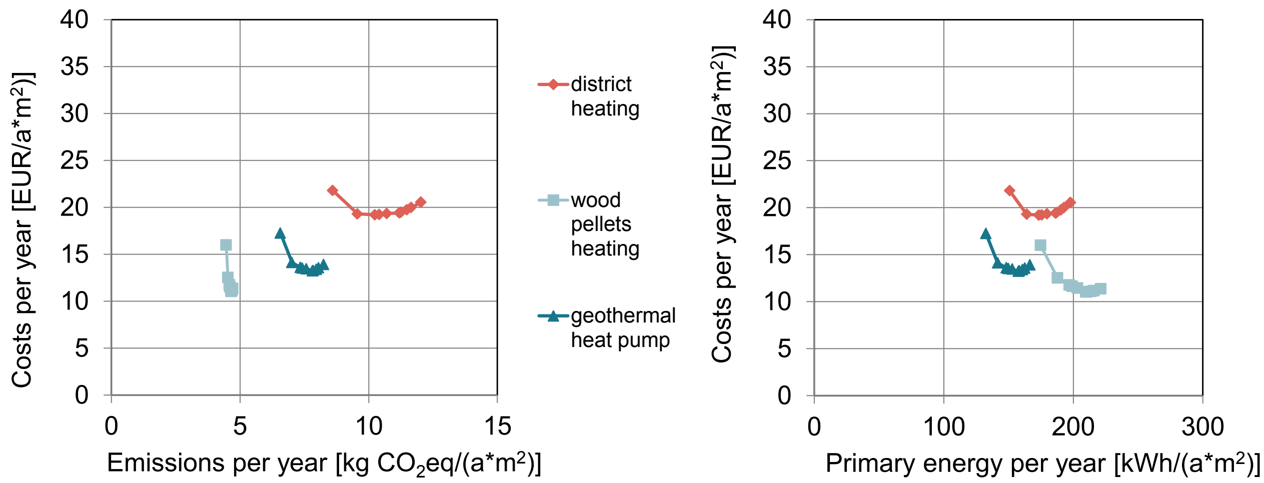


Figure 73 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Sweden**, for a **multi-family building**, The reference case is the point on the district heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

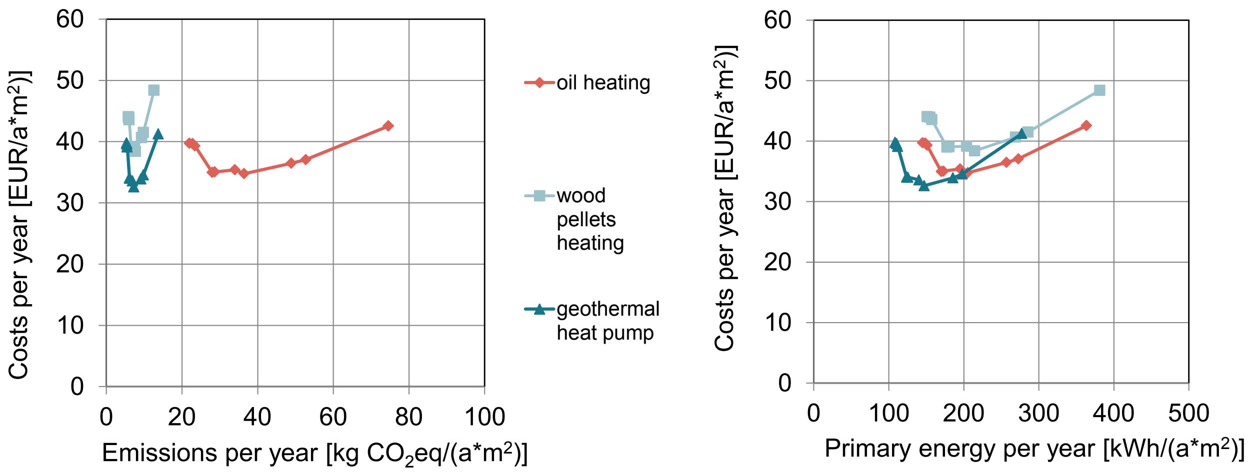


Figure 74 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in Switzerland, for single-family building. The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

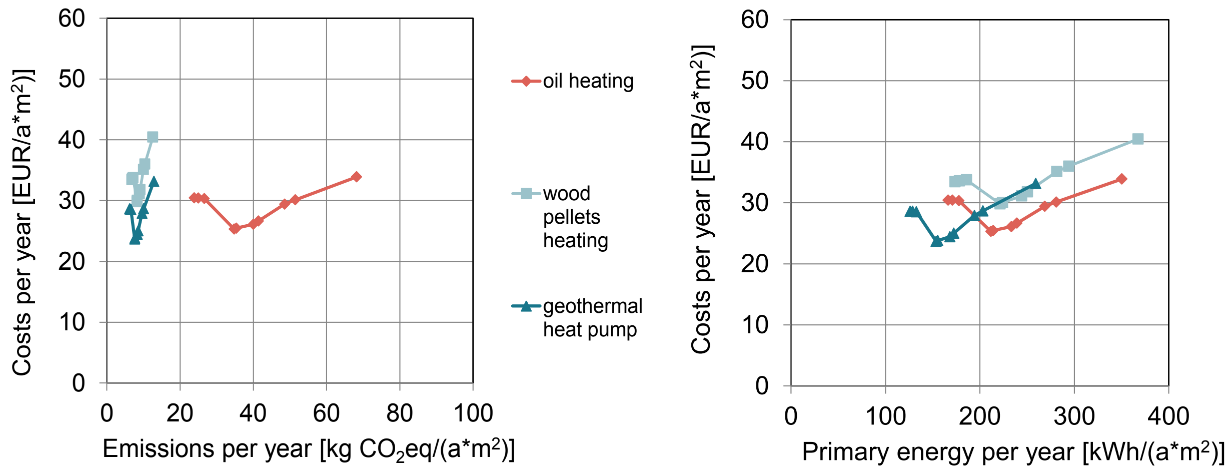


Figure 75 Aggregated comparison of cost effectiveness of energy efficiency renovation measures for different heating systems and related impacts on carbon emissions and primary energy use in **Switzerland**, for **multi-family building.** The reference case is the point on the oil heating curve with the highest emissions/primary energy use, as no measures are carried out to improve the energy performance in that case.

3.10. Discussion

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

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

Table 51 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. In the case of the countries AT, DK, ES, SE, CH, geothermal heat pumps and wood pellets heatings have been investigated as RES systems; in the case of NO an air-water heat pump and wood logs; and in the case of PT only a combination of air-water heat pump and PV was investigated as RES system.

SFB refers to single-family building, **MFB** to multi-family building.
Countries are abbreviated with their two-letter code.

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	SFB NO Mix1	SFB NO Mix2	SFB PT	MFB PT	MFB ES	SFB SE	SFB SE	SFB CH	MFB CH
The number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	✓	✓
A switch to RES reduces emissions more significantly than energy efficiency measures	✓	✓	✓	✓	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 these results obtained from the calculations with the reference buildings, the following can be concluded with respect to the hypotheses investigated. 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, for example, and not for all reference buildings all other types of renewable energy systems were looked at.

Hypothesis 1 «The number of building elements renovated is more important for the energy performance of the building than the efficiency level of individual elements»

The hypothesis is confirmed to a large extent in different country contexts, both in single-family buildings and in multi-family buildings. The finding reflects 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 relative 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 have a high insulation standard at once than to increase it later, especially if the marginal cost-/benefit-ratio of later increasing the insulation level is taken into account.

The exceptions among the examples assessed are the buildings in Sweden. In the examined reference building from Sweden, 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. Nevertheless, it also needs to be kept in mind that the generic reference buildings from Sweden also have the lowest U-values from the reference buildings investigated.

Hypothesis 2 «A switch to RES reduces emissions more significantly than energy efficiency measures »

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. Especially 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. At least if the emission target is given equal or higher relevance than the primary energy target, these findings may imply a shift in energy related renovation strategy for existing buildings. The currently prevailing two step approach recommended (see EU and EPBD) for striving for nearly zero energy buildings has to be challenged for the case of building renovation (but not for 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 taken as a basis for the primary energy conversion factor for electricity consumption without taking into account trading of guarantees of origin. But this conversion factor doesn't reflect the Norwegian reality, since it doesn't take into account the trading of guarantees of origin. Only if this is not taken into account, is there not much to reduce by switching to RES when the starting situation is an electrically heated building, as is the case for the Norwegian reference building.

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 reference 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). 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 structure of the optimum looking at the set of renovation packages available 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 the different reference buildings indicate that if measures reducing energy demand 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 demand and renewable energy measures. A factor that leads to synergies is that 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 demand 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»

This hypothesis is confirmed without exception for all reference 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 reference buildings investigated (except for the case of the building in Norway which led for the same reasons to the 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 are supposed to 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 striving towards nearly zero energy buildings, it is crucial to consequently 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.

3.10.2. *Comparison between multi-family buildings and single-family buildings*

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

Table 52 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	✓	✓	✓

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 demand of the building, are more significant for larger systems. However, at the same time the specific energy demand 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.

3.10.3. *Effects of ventilation system*

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

Table 53 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 demand.

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.

3.10.4. Effects of energy in materials

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

The effects of including embodied energy use in the calculations is in general more visible when looking at the primary energy use than when looking at carbon emissions. The most far-reaching measures are a bit less favourable in terms of reduction of primary energy use when taking into account the additional energy use because of the insulation material. This is particularly visible for the windows: When taking into account embodied energy in this reference building, the more energy efficient windows do not have an environmental advantage compared to less energy efficient windows.

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.

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

4.1. Methodology for the assessment and optimization of costs, energy use and carbon emissions for building renovation

The methodology outlined has to provide the necessary basics for the assessment of existing buildings undergoing energy related renovation processes. The assessment comprises as main impact categories the cost, primary energy use and carbon emissions impacts of energy related building renovation for the entire life cycle. The results of the assessment shall allow to appraise the energy performance of the building as well as the level of reduction of energy use, carbon emissions mitigation and related costs of building renovation strategies or measures for the sake of:

- Evaluating and optimizing different renovation measures, taking into account costs, energy use and carbon emissions impacts for a specific building or renovation project
- Appraise the outcome of energy or carbon emissions related policy programs targeted at mobilizing mitigation potentials from the renovation of the stock of existing buildings
- Standard setting for energy performance or carbon emissions of existing buildings after renovation
- Guidelines for building owners and investors seeking cost effective building renovation measures with the highest reductions of energy use and carbon emissions at lowest possible costs.

4.1.1. Scope and boundaries of the assessment

The **scope** comprises costs, primary energy use and carbon emissions of building renovation measures.

Components of energy use to be taken into account:

Basis for the assessment of energy related renovation measures and resulting energy performance of the building is the energy use for space heating, space cooling, domestic hot water heating, and operational energy (electricity for fans, pumps, building automation) in the building.

Energy use of common building appliances like lifts, escalators, washing machines, dryers, etc. is suggested to be at least monitored, since their share on overall energy use of a building increases with decreasing energy demand of renovated buildings. Full integration in the assessment has to be decided depending on the context, since appliances like washing machines, dryers, refrigerators, etc. are installed sometimes by the building owners and sometimes by the occupants.

Embodied primary energy use of building components used for building renovation is suggested to be integrated in the assessment if necessary LCIA-data is available. The share of embodied energy use with respect to total use of primary energy is increasing with decreasing operational energy use due to energy related building renovation. But the relevance of embodied energy use is lower than in the case of new buildings.

Plug in appliances (home appliances) are not necessarily integrated in the assessment, although their relevance is given and even increasing with decreasing energy demand of the building. Electricity use of plug in appliances depends highly on the users and not on the building (which holds also for energy use for DHW heating).

The **system boundary for energy** use corresponds to the consumption of net delivered energy after renovation plus embodied energy use for building renovation. Net delivered energy comprises final energy deliveries plus on site generation of renewable energy minus exported energy to the grid.

Primary energy (PE) use has to be determined from final energy use of energy carriers by a PE-conversion factor. The primary energy factor takes into account energy used for the upstream processes necessary between the energy source and the delivery of final energy to the building. It is crucial to determine the PE-conversion factor as precisely as possible for each country. «Political» factors or factors used for specific labels should not be applied. Special attention has to be paid to the PE-conversion factor of electricity. It should represent the mix of electricity consumed in a particular country and not the production mix.

Carbon emissions are determined by country specific carbon emissions conversion factors comprising upstream emissions for the delivery of final energy carriers to the building

Cost assessment of energy related renovation measures: The costs are determined dynamically (i.e. future costs are discounted) on a life cycle cost basis. They comprise initial investment costs and replacement costs of energy related renovation measures during the period considered as well as energy costs, operational costs and maintenance costs. Assuming a private cost perspective, taxes and fees are included and subsidies are excluded (for the sake of transparency). Within a societal perspective taxes and subsidies are not taken into account, except taxes internalizing external costs.
For assessing cost and economic efficiency of energy and carbon related renovation measures, it is crucial to define a **reference situation** to properly determine the effects of an energy related renovation on energy use, carbon emissions reductions and costs. The assessment is based on

a **full cost approach,** comprising full costs of renovation and cost of subsequent operation (energy costs and energy related maintenance costs). Since the focus is on the evaluation of energy related renovation measures a reference case is defined which comprises renovation measures to the extent necessary to restore the functionality of the building, without improving the energy performance of the building. This reference case is called an **«anyway renovation»** and comprises only renovation measures which have to be carried out «anyway» because the end of the technical life of building elements has been achieved or the functionality or service quality of a building element is not sufficient any more.

Cost assessment might provide acceptable guidelines for policy making. The costs of a renovation can be divided in three parts:

1. Costs that should be covered by the maintenance budget – "anyway renovation"
2. Costs which raise the energy standard, building quality and thermal comfort, which can result in an increased rent (or building value)
3. Cost which lower the energy and maintenance costs, which ideally pay for themselves (and rise the building value)

Besides the cost perspective, for investors and building owners it is basically the value of a building, which is of interest at the very end. For the owners and investors the value of the building is reflected best by the willingness to pay of users, occupants, owners for using the building, comprising an implicit monetary valuation of the building quality for the particular use (like useful area, thermal comfort, indoor air quality, natural lighting comfort, comfort for the users (elevators, technical building systems, etc.). Unfortunately the value of high energy performance of buildings are often perceived adequately only if the performance is exceptional.

Acknowledging the primacy of the value of the building, it is indispensable to supplement the cost, energy and carbon emissions assessment of building renovation measures with coexisting quality aspects of these energy related renovation measures, called co-benefits of energy performance improvements.
(The issue of co-benefits is still work in progress and will be part of the final report from Subtask A.)

4.2. Conclusions from evaluation of cost effective renovation measures

4.2.1. General conclusions

The challenge: Significantly higher energy performance and less emissions of the building stock

Midterm and long term targets announced by climate and energy policy are ambitious. The EU has set medium and long term targets to reduce energy demand and carbon emissions as well as to increase renewable energy generation and use. A target of reducing greenhouse gas emissions by 40% below 1990 levels until 2030 was communicated; furthermore, the EU has declared to strive for greenhouse gas emission reductions in the range of 80% - 95% below 1990 levels by 2050 (European Commission 2014).

Since most of energy use and carbon emissions in the building sector will be caused by the stock of existing buildings, 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 increased and good solutions are often not straightforward.

The opportunity: Make use of a major renovation needed "anyway" to carry out major energy retrofits

Many of the existing residential buildings are currently in major need of renovation, which is one of the reasons why investments in rebuilds have increased in recent years. Often the buildings' apartments need to be renovated urgently (renewal of technical building functions, technical installations). This represents an excellent opportunity to make these homes more energy-efficient. Many energy efficiency measures are profitable when an "anyway renovation" is needed. If an energy related renovation is not carried out together with a major "anyway renovation" it might take another 20-40 years until the next major renovation opportunity will be upcoming.

Distinct standards, targets and policies for building renovation with high relevance on cost aspects

Given the high relevance of the building stock for energy savings and carbon emissions mitigation, it is important to tailor standards, targets and policies to the requirements of the existing building stock. Costs matter: Considering the higher complexity of energy and carbon emissions mitigation in building renovation, cost effective solutions yielding far reaching energy and/or carbon emissions reductions are a key factor of successful energy and climate policy in the sector of existing buildings.

Costs and seeking for least cost solutions or for a least cost path to renovated buildings becoming nearly zero energy and emissions buildings play a major role for giving renovation strategies a chance to enabling the transformation of the building stock towards the nearly zero emissions and (non-renewable) energy level. Special situation and barriers in the case of existing buildings require new approaches

Since hindering conditions limit often the range of feasible renovation measures, especially on the building envelope, deployment of renewable energy and on-site energy generation from renewable sources can be especially attractive in the case of building renovation.

The challenge is high: Cost optimal renovation packages will not be sufficient for a sustainable development of the building stock

The EU established in the Energy Performance of Buildings Directive as minimal standard for the building envelope an energy performance level corresponding to the performance resulting if the cost optimal energy related renovation measures are carried out. Since cost optimal solutions won't result in nearly zero energy buildings yet, it is indispensable to go a step further and tap the full potential of **cost effective** energy related renovation measures, which extends the range for energy savings as well as for use of renewable energy and on-site-renewable energy generation in the case of building renovation. Thereby, all renovation packages having lower costs than the reference case are considered to be cost effective and should be considered even if costs are beyond the minimal costs of the cost optimal package of renovation measures.

Putting an additional focus on emission targets supplementing energy targets in the building sector

The EPBD of the EU is the standard for energy use in the European building sector. It regulates how (minimal) energy targets for new and existing buildings have to be determined by the Member States. Targets for the energy performance of buildings have to correspond at least with the energy performance level achieved by cost optimal energy efficiency measures on the building. Additionally, EPBD requires to further reduce non-renewable energy demand and emissions by the use of renewable energy sources to achieve nearly zero (non-renewable) energy and emissions buildings (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.

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. From there, it is often more cost effective, to use renewable energy sources (if economically available) than to strive for reducing energy demand of buildings by further increasing the energy performance of the building envelope.

At the same time, in many cases the use of renewable energy sources is not only cost effective, it also leads to significant reductions in emissions and non-renewable energy use, even if the effects on total primary energy use may be small.

Parametric calculations performed with different packages of energy related renovation measures in seven 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. Marginal cost/benefit ratios of renewable energy use are often better than further increasing energy performance of the building envelope, if the level of emissions and non-renewable energy use has to be lowered significantly towards nearly zero energy use and emissions.

In this situation it is appropriate to increase the relevance of carbon emissions reduction goals by establishing carbon emissions targets for buildings. Apart from targets on the energy performance of the building envelope, targets on emissions deserve to get a more prominent function as well. In order to reach the overall reduction goal of reducing greenhouse gas emissions in the EU by 80% - 95% by the year 2050 compared to 1990, the opportunities arising with building renovation do not only need to be used to reduce energy use at least as far as cost effective, but also to switch to renewable energies whenever possible to reduce emissions.

These targets should supplement targets for the energy performance of the building envelope, corresponding to the target setting required e.g. by the EPBD (at least performance level of cost optimal efficiency measures). Energy targets remain highly important, even if additional carbon emission targets are adopted. The reduction of energy use in buildings is a well understood and accepted concept. Carbon emission targets alone do not create incentives to reduce the use of electricity provided by nuclear energy. Furthermore, energy targets also ensure sufficient quality of the building envelope and installations, thermal comfort and good indoor air quality as well as avoid problems with building physics.

The setting of an emissions related target supplementing existing energy targets would allow for achieving nearly zero emissions and (non-renewable) energy goals in the future. At the same time it allows overall cost optimization and maximal freedom of choice by selecting appropriate energy related measures within building renovation (this is also the case for new building construction). Energy efficiency requirements of the building envelope are particularly suited up to the cost optimal levels of the building envelope; beyond that point, it may be 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 context conditions (like energy prices, interest rates, etc.) 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 (thereby assuming that their use is restricted to a sustainable level).

4.2.2. Conclusions from parametric assessment of renovation solutions for generic buildings

General conclusions

Mix of cost optimal renovation measures mostly does not depend on the type of heating system

The results obtained from the generic calculations indicate that in most of the cases, a switch to wood pellets or ground source heat pump has no or hardly any impact on the mix of energy related renovation measures at the cost optimum even if the level of the cost optimum as well as the impact on primary energy use and carbon emissions at the cost optimum are depending on the heating system considered. This means that in many cases, there are no trade-offs between renewable energy measures and energy efficiency measures; often no differentiation of cost optimality of energy efficiency measures needs to be made with respect to different heating systems.

However, the results also show that there are cases where the mix of measures in the cost optimum can be slightly changed by a switch to wood pellets or ground source heat pump. In order to not penalize RES systems such as a heat pump or wood pellets compared to conventional heating systems, it is therefore important to take into account in standard setting such possible changes in the mix of energy efficiency measures at cost optimum. This could for example include a provision allowing building owners to get permission to fulfil energy efficiency building codes only to a smaller degree, if at the same a change is made from a conventional heating system to a RES based heating system.

Renewable energy (in this study mainly wood pellets heating and ground source heat pumps were investigated): 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. Heat pumps and wood heating systems play an important role, as they allow to replace conventional heating systems completely. In countries where the greenhouse gas emission factor of the electricity mix is high, on-site renewable electricity production can be used in combination with a heat pump to reduce emissions and primary energy use. Carbon emissions can thereby be reduced effectively also in these cases.

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 (except in ES and heat pumps in PT). Sensitivity calculations indicate that lower energy prices favour conventional energy use and efficiency measures but deployment of wood pellets heating or ground source heat pumps are still the measures with the highest single impact on emissions mitigation from the measures investigated.

Heat pumps often reduce primary energy use significantly, 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, similary to its impact on reducing carbon emissions. If overall primary energy use is considered, however, the situation is less straightforward than in the case of carbon emissions. 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). The change to a ground source heat pump 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. From an economical point of view, deployment of ground source heat pumps or wood pellets is often cheaper than the conventional system, except for ES and except for wood pellets heating in the case of NO and CH.

Improvement of energy performance of building envelope within building renovation is indispensable

To ensure sufficient thermal quality of the building envelope and to prevent bad comfort and damages resulting from problems with building physics, renovation of existing buildings should comprise the improvement of the energy performance of low performing building envelopes even though the use of renewable energy might have already a large impact on carbon emissions and non-renewable energy use. In addition, less energy demand as a result of a better building envelope is a prerequisite for making use of cost savings by reduction of the capacity needed for the newly installed (renewable) heating system.

Conclusions for standard setting und policy making

Having in mind the preceding observations and conclusions for building renovation the following indications for standard setting and policy making are made:

Higher relevance of emission targets supplementing energy targets

Transformation of the stock of existing buildings towards ambitious energy and emission targets has to be effected by the least possible costs to give this transformation a chance within the renovation of buildings. Acknowledging the large possible contribution of renewable energy based heating systems to emission goals and taking into account the eminent role of costs incurred by energy related renovation measures, it is recommendable to put more focus on ambitious emission targets as mentioned above. Under such circumstances, it is advisable to set the requirements on the energy efficiency of the building envelope not too strict in order not to provoke far reaching efficiency measures with an unfavourable ratio of costs related to emissions and energy savings. Nevertheless energy efficiency measures remain important for several reasons: To ensure an improvement of the energy performance independent of the heating system, to ensure reductions in energy use also where the electricity mix driving heat pumps is to a large extent CO_2-free, to increase thermal comfort, to contribute to good indoor air quality, to prevent air pollution and to avoid building physics problems as well as to allow benefits from lower costs for capacity adjusted heating systems. Moreover, the following specific reasons for targets related to reducing primary energy use can be indicated:

- At least a part of the renewable energy sources are limited: E.g. biomass is a limited resource. Biomass can also be used for other purposes than for heating buildings. Apart from being used as a resource in production processes, it can be transformed into liquid fuels for transportation. If biomass is used for heating, it may be advantageous to burn it in CHP plants rather than in small-scale domestic heating. On the one hand, biomass can thereby also be used to generate electricity in winter months, when sunshine and electricity output from PV plants is smaller; on the other hand, local air pollution by particular 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). The sustainability of biomass, exploited in a sustainable way, is furthermore an important aspect.

- If a large number of heat pumps using geothermal or hydrothermal resources are located close to each other, they may negatively affect each other, by lowering the temperature of the heat source and thereby reducing the efficiency of the heat pumps. If the energy demand of the buildings is reduced, such negative factors are reduced as well. Furthermore, in some areas the installation of a large number of heat pumps may require grid reinforcements. If the energy demand of buildings is reduced, so are the peak capacities required for the heat pumps and related grid reinforcements.
- In areas where district heating is used, the lower space heating demand of new buildings offers the possibility to run the district heating system at lower temperatures. However, normally there are both new and old buildings in district heating systems and lowering the supply temperature of the heat carrier is only possible if the energy demand of existing buildings is reduced considerably.

Therefore, the two step approach of the EPBD still holds, even if in the case of building renovation it can be appropriate if the two steps are primarily conceived as a model to determine the energy targets for the quality of the building envelope within the limits of cost effectiveness in step one, whereas for the step 2 it may be advisable to set the focus rather on midterm to long term emission targets or on non-renewable energy targets. In the realm of carrying out cost effective building renovations these two steps do not necessarily imply that step one is carried out first, followed secondly by step two. If these two steps are not carried out at the same time, their sequence will be rather determined by the upcoming renovation needs of the particular building, taking into account existing restrictions as well as taking into account the fact that synergies may be foregone if the heating system is replaced first without improving energy performance of the building envelope.

Standards and incentives in the case of replacement of heating system

The results found in this study indicate that from a perspective of reducing carbon emissions at least costs, it can be recommended to consider a shift to renewable energies. A change to heating with renewable energy can reduce emissions substantially and cost effectively and this often to a further extent than single energy efficiency measures while keeping the previously used 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.

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 demand of the building is reduced, peak capacity of the heating system can be reduced as well, which is a key driver for making many renovation measures of the building envelope cost effective when a new heating system using renewable energies is installed as the main source for heating. 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.

However, financial resources (liquidity) can 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. To avoid simple replacements of existing conventional heating systems by the same type for the sake of reducing initial investment costs, exceptions from required improvements of the building envelope could be offered if emissions are reduced significantly by a switch to a renewable energy based heating system. It could be made mandatory in such cases to elaborate a future strategy to improve the energy performance of the envelope for the point of time in which a renovation of the envelope will be necessary (being aware that the synergies and cost savings due to a capacity reduced heating system are foregone by splitting the two steps in time).

Focusing on more than one building element, with high energy efficiency ambition levels where possible

From parametric calculations the following conclusions can be derived: Due to distinctly decreasing marginal benefits and increasing marginal costs, it is more beneficial to improve the energy performance of several elements of the building envelope than to costly maximise energy performance of selected elements (e.g. the increase of wall insulation from 12 cm to 30 cm has less impact on energy savings and carbon emissions than supplementing the walls insulated with 12 cm by a roof insulation of 10 cm).

This aspect is particularly important, if financial resources are scarce, which is often the case. In such cases it might be more advantageous to involve several building elements in an energy related renovation, but with lower energy efficiency ambition levels.

At the same time, it is also recommendable to choose ambitious energy efficiency levels to the extent possible or economical, in order not to miss opportunities in building renovation, if 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, 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.

Encouraging the use of synergies between renewable energy measures and energy efficiency measures

In sensitivity calculations it was shown for a specific reference building that a switch from a conventional oil heating system to a geothermal heat pump is not cost effective, if the replacement of the heating system and energy efficiency measures on the building envelope are carried out independently, not making use of the synergies possible. However, a switch to a geothermal heat pump combined with energy efficiency measures is more cost effective than any combination with an oil heating system, reducing at the same time emissions and primary energy use significantly. Required size of the heat pump and related investment costs can be reduced significantly, if energy efficiency measures are carried out reducing the energy need; furthermore, the efficiency of the heat pump is higher, if the energy use is reduced, since the temperature of the heat distribution system can be kept lower. This case illustrates the importance of using synergies between renewable energy measures and energy efficiency measures.

In order to benefit from cost related synergies of improving energy performance of the building envelope combined with a shift to a heating system using renewable energy as well as to exploit the full potential of renewable energy deployment and energy efficiency measures to reduce carbon emissions and primary energy use, it is favourable to combine a switch to a renewable energy system with energy efficiency measures on the building envelope. This requires an overall renovation at once, combining step one and step two according to the EPBD logic, or carrying out related efficiency measures on the building before the replacement of the heating system.

Constraints and non-synchronism in building renovation

As mentioned above already, 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.

4.2.3. The sensitivities: Relevance of energy prices, climate and interest rates

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.

As shown by sensitivity calculations, energy prices play an important role related to the cost effectiveness of renovation measures and 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.

Four important parameters which were so far not investigated in detail are the energy performance of the building before renovation, climate, lifetimes and the interest rate.

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.

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.

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. A higher interest rate raises the capital costs for these investments more strongly than for renovations which do not improve the energy performance of the building and which require accordingly a lower investment.

4.2.4. Impact of including embodied energy use of renovation measures

First results obtained from calculations taking into account the embodied energy use of renovation measures indicate that it has an impact on the environmental performance of high-efficiency insulation measures. In particular the environmental benefit of high-efficiency windows is reduced or even neutralized by increased use of energy for the production of such windows. 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. For installing a geothermal heat pump, additional embodied energy use occurs for drilling the borehole. However, the related impact is relatively small, and does not change significantly the advantages of changing from a fossil fuel based system to such a renewable energy based system.

4.2.5. Outlook

The results presented can be further tested and refined 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 solar thermal energy, 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, are recommended to be carried out in more detail in different country contexts. It is recommended to take related results into consideration in standard setting by policy makers. For systematic assessments, and also for case-specific evaluations, tools like the INSPIRE tool used for this report can play a supporting role and can be further refined, adapted and developed.

5. Appendices

Selected aspects of life cycle impact assessment LCIA for energy related building renovation

Components and materials included in the LCIA of energy related renovation measures

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

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

Components to be included in the LCIA

Annex 56 focuses on cost and environmental benefits of energy related renovation measures. Therefore, the LCIA must at least include the environmental impacts of the following components:

- Components added for the renovation of the thermal envelope of the building (see below) and for building integrated technical systems (see subsequent paragraphs).
- Components that need to be replaced to provide the same building function before and after renovation (see subsequent paragraphs)

These categories are defined more in detail in the following paragraphs.

Components for the thermal envelope

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

A wall as element of the thermal envelope can be decomposed in layers, as schematised in Figure 76.

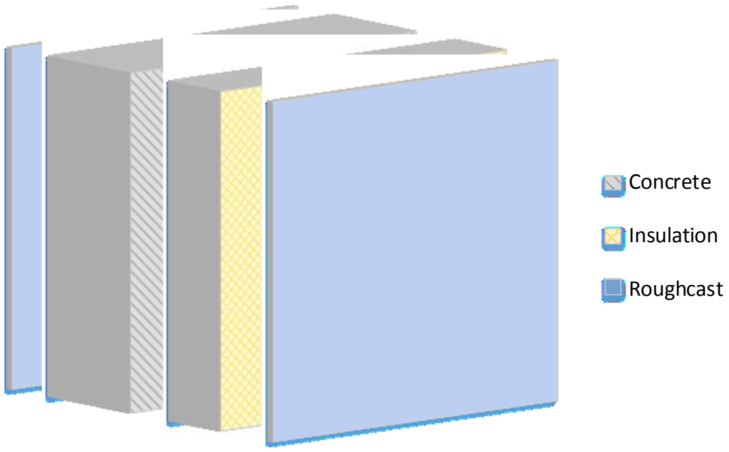


Figure 76 Example of a construction element composed of different materials (layers)

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

The service life of the component should also be reported and allows to calculate the number of replacements during the life of a building (see subsequent paragraph). The position and role of a material in the construction element, will affect its service life of the component. This aspect is detailed in one of the following paragraphs.

In the framework of Annex 56, the name, weight, impact data and service life of components used to perform the LCIA have be reported and documented.

Components for building integrated technical systems (BITS)

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

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

During the renovation, added components which have no particular influence on energy use, production, distribution and on carbon emissions should not be taken into account (for instance: sinks, bathtub, replacement of piping, etc.). In the case of energy related renovation measures and its materials during the reference study period, having reached the end of their service life, it is assumed that they are replaced by the same components (corresponding to the cost calculations).

It might be difficult to find LCI-data for BITS. One possible source of information, is the Swiss-KBOB database ("KBOB database," 2012), which provides a complete set of information for energy related BITS. The information is easy to apply for the calculation. Table 54 describes the information required to model the technical equipment of a building with the KBOB database.

Table 54 Information required for assessing the environmental impacts of building integrated technical systems (BITS)

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

In the framework of Annex 56, the sources of information used to assess the impacts of the BITS' materials should be reported and documented.

It is important to define the service life of BITS components to be able to calculate the number of replacements that will occur during the life time of the building.

Components added to provide the same function.

To directly compare renovation scenarios, the buildings should fulfil the same performance requirements. In reality this might not exactly be the case. During renovation, some building elements are removed, replaced or added but are indirectly related to energy related renovation measures. One typical example is the case of a balcony, which is an extension of the internal storey slab before the renovation. In order to prevent this thermal bridge, the original balcony is removed. The thermal envelope is improved and a new balcony is added alongside the renovated façade. Subsequently, there are some more examples:

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

Two different situations can occur:

- If new elements and components, indirectly related to energy related renovation measures, are added to provide the same building function (before and after renovation): In this case the impacts of these elements and components have to be included in the LCIA. For instance the components of the new balcony that replaces the old balcony to reduce the thermal bridge, the components added to reinforce the building bearing structure in order to support additional on-site energy-production, etc.;
- If a component, indirectly related to energy related renovation measures, is removed during the renovation and is not replaced, it cannot be included in the LCIA (for instance a balcony removed to prevent the thermal bridge). In this case, it must be documented and reported in the co-benefits (negative or positive).

If new components are added during building renovation, but are not energy related (directly or indirectly), they must not be taken into account.

Service life and replacement period

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

Service life of building elements

In a construction element, not all layers (products) have to be replaced at the same time and some are never replaced (e.g. bearing structure of the building probably never replaced during the life cycle of the building). As shown in Figure 77, a construction element can be divided in different parts or layers.

To assess the environmental impacts of the product or material replacement, the layer's service life and its location in the construction element are crucial. Subsequently, there are some examples that must be analysed in detail to perform a correct LCIA:

- If a layer with a short service life is located in between the structure (which is never replaced) and another layer with a longer service life, the replacement of the layer with the shorter service life, will also determine the replacement of other layer with the longer service life (but not of the structure).

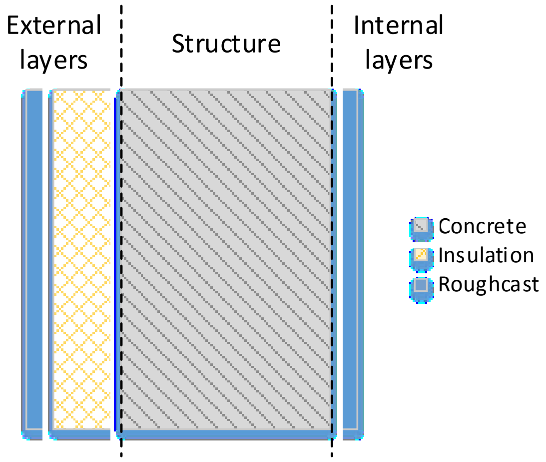


Figure 77 Example of a construction element with a bearing layer (structure) and non-bearing materials

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

In order to define the service life of components, it is therefore important to take into account the following parameters:

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

Different sources of information can be used to define the service life of building elements, such as manufacturers, scientific papers, and officials documents such as ISO 15686 and followings ("ISO 15686 Buildings and constructed assets -- Service life planning," 2012).

Service life of construction components suggested in Annex 56

It is not realistic to use constant service life for a particular type of material or product. While their reference service life is basically the same, their service life in the in-use situation might be different: For instance, insulation, such as mineral wool, will have a shorter service life in a roof, than in an internal partition. For a specific product, its service life will depend on its physical properties (water resistant, moisture sensitivity, etc.) and its context of use (in contact with outside, the soil, etc.).

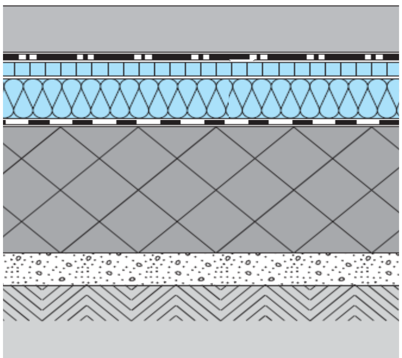
Table 55 lists the service life of BITS and Table 56 the service life of constructions components suggested to be used in Annex 56

Table 55 Service life of building integrated technical systems suggested in Annex 56

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

Figure 78 shows an example of service life for the different layers of a floor in contact with the ground (top) and a ventilated surface (bottom).

Floor above the ground



- Internal surface (tiles, carpet, ...): not included
- Floating screed: 30 years
- Air sealing : 30 years
- Insulation: 30 years
- Water sealing : 30 years
- Concrete (structure): RBSL
- Light concrete : remaining BSL

Figure 78 Examples for the service life of components in a construction element

Table 56 Service life of construction products for the thermal envelope suggested in Annex 56 (*RSP = Reference study period which assumes that the product won't be replaced)

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

Reference assessment period of the renovated building

LCIA is carried out on the basis of a chosen reference study period, for which all impacts of components and energy consumed are determined. This period has therefore an important and direct influence on the results.

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

- The period between the current renovation and the next major upcoming one. A typical value is 30 (to 40) years, which corresponds to the period between the building construction and the first important renovation, which could be motivated by energetic purpose or more likely motivated by wear and tear.
- The period between the current renovation and the end of the life of the building.

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

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

The reference study period should be equal or longer than the service life of the (energy related) building components analysed in order to avoid any misinterpretation of the results. Therefore, it is suggested to assume a reference study period of **50-60 years** in Annex 56.

If another reference study period is assumed, it should be reported and documented.

Number of replacements during the assessment period

Due to a limited service life, construction products will usually be replaced one or several times before the end of the building's life. These additional replacements also have to be assessed.

The following statements need to be taken into account for the calculation of the number of replacements

- The number of replacements for construction elements and components of a building integrated technical system (BITS) depends on their estimated service life (ESL) and the study or assessment period for the building (SP).
- No replacement is required if the service life of a building element meets or exceeds the required service time of the building (foundations, bearing wall, etc.).
- In practice, only a full number of replacements (no partial replacements) can be taken into the calculation and assessment of the impacts of building elements replaced; in the case of a partial number of replacements resulting from the estimated service life of the components and the reference study period of the building, the number of replacements is rounded upward.

The number of replacements of a building component (material or BITS component) is given by:

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

Where:

N_R Number of replacements of the element

Round Function that rounds up to the nearest integer value

SP Study period of the building

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

Example: Assuming a component with a service life *SL* = 15 years and the study period *SP* = 60, the number of replacements is

$$N_R = Round\left(\frac{60}{15} - 1\right) = 3$$

During the life cycle of the building, the components will be manufactured a first time for the building construction and then replaced three times, after 15, 30 and 45 years.

The replacement of components, occurring during building operation, is assessed separately in a specific stage. The contribution of the replacement stage should not be merged with the one from the “production“ stage.

Indicators for the LCIA of renovated buildings

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

- The indicators have achieved widespread consensus and acceptance among the scientific communities. This would reject indicators such as human toxicity, biodiversity, Eco-indicator, EPS or UBP.
- The building sector must have a significant contribution to the world contribution for this indictor. It is not relevant to keep an indicator for which the building sector as a minor or insignificant contribution.
- The data for components and energy vectors used in the building sector should be available for the indicator.

According to the previous considerations, the number of indicators used in Annex 56 has been limited to the three following indicators:

- **CED: Cumulative Energy Demand**. It represents total primary energy used, renewable or not. It includes the non-renewable part NRE (fossils, nuclear, primary forests) as well as the renewable part (hydro, solar, wind, biomass). CED is expressed in [MJ].
- **NRE: Non-Renewable Energy use**. It represents the non-renewable part of the CED, i.e the non-renewable primary energy used. It indicates the depletion of non-renewable energy sources (at a human scale), such as fossil fuels, nuclear resources and primary forests. NRE is also expressed in [MJ].
- **GWP: Global Warming Potential.** The GWP is related to the emissions of greenhouse gases. It is not measured in an absolute unity, because each gas has a different impact on the greenhouse effect (for the same quantity). Their potential is compared to CO_2 used as reference. GWP is expressed in [kg- CO_{2e}].

In Annex 56, impact databases, calculation methods and results should deal with these three indicators.

Cooling in residential buildings

Quasi steady state calculation method

As shown in Figure 23, total cooling demand according to the quasi steady state calculation method per month is the result of the total heat gain reduced by the total heat transfer, which is attenuated by the utilization factor $\eta_{C,ls}$. In case of continuous cooling ($Q_{C,nd,cont}$), the net energy demand for cooling ($Q_{C,nd}$) is defined as

$$Q_{C,nd} = Q_{C,nd,cont} = Q_{C,gn} - \eta_{C,ls} \cdot Q_{C,ht} \qquad (1),$$

where $Q_{C,gn}$ denotes the total heat gains, $Q_{C,ht}$ denotes the total heat transfer for cooling and $\eta_{C,ls}$ denotes the utilization factor for cooling. According to the standard ISO 13790, using the utilization factor, instead of the actual calculated thermal response of the building[10], allows simplifying the complex detailed dynamic simulation. The utilization factor for cooling $\eta_{C,ls}$ is determined by the ratio of the heat gain ($Q_{C,gn}$) to the heat transfer ($Q_{C,ht}$) depending on the thermal capacity of the building components (C_m). For further details, please refer to chapter 12 of the standard EN ISO 13790.

The total heat transfer ($Q_{C,ht}$) is defined as the sum of the heat flow rates due to heat transfer at the building envelope and by ventilation. In case of higher exterior temperatures compared to interior temperature, the total heat transfer becomes negative and as a result the energy demand for cooling increases. The total heat gain is calculated by

$$Q_{C,ht} = Q_{tr} + Q_{ve} \qquad (2),$$

where Q_{tr} denotes the heat transfer by transmission at the building envelope and Q_{ve} denoted the heat transfer by ventilation.

The total heat gain $Q_{C,gn}$ is defined as the sum of all internal heat gains plus heat gains from solar radiation as shown by

$$Q_{C,gn} = Q_{int} + Q_{sol} \qquad (3),$$

where Q_{int} denotes the internal heat gains and Q_{sol} denotes the heat gains from solar radiation.

Besides the continuous cooling, intermittent operation modes of cooling can apply, if different operation modes with reduced set points exist, for example during the night or during weekends or holidays. The cooling demand for intermittent operation modes $Q_{C,nd,interm}$ is calculated by

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[10] The building mass performs as a thermal energy storage that is partly charged by the $Q_{C,ht}$. Consequently, the balance of the heat flows is not only affected by the direct external and internal heat flows, but also by the discharged indirect heat flows from the building mass. This depends on the building mass and the surface materials.

$$Q_{C,nd} = Q_{C,nd,interm} = \alpha_{C,red} \cdot Q_{C,nd,cont} \quad (4),$$

where $\alpha_{C,red}$ denotes a reduction factor. Basically, the correction factor $\alpha_{C,red}$ corresponds to the percentage of the full load hours of continuous cooling.

In case of a longer user absence during vacations etc., the net cooling demand is further reduced by the percentage of periods without cooling by

$$Q_{C,nd} = \left(1 - f_{C,nocc}\right) \cdot Q_{C,nd,occ} + f_{C,nocc} \cdot Q_{C,nd,nocc} \quad (5),$$

where $f_{C,nocc}$, denotes the period of the absence of occupants, $Q_{C,nd,occ}$ denotes the regular cooling demand in times of user presence and $Q_{C,nd,nocc}$ denotes the cooling demand during the period of the absence of occupants.

Heat flow rate due to transmission

The heat transfer by transmission Q_{tr} to adjacent spaces or to the exterior environment depends on the temperature difference between the exterior temperature θ_e and the set point temperature for cooling $\theta_{int,set,C}$ of the interior space by

$$Q_{tr} = H_{tr,adj} \cdot \left(\theta_{int,set,C} - \theta_e\right) \cdot t \quad (6),$$

where t denotes the time period of the specific temperature difference, θ_e denotes the exterior temperature and and $\theta_{int,set,C}$ denotes the set point temperature for cooling.

The total heat transfer coefficient $H_{tr,adj}$ represents all heat transfer coefficients to adjacent spaces (which can be interior spaces and the environment) that is calculated by

$$H_{tr,adj} = H_D + H_g + H_U + H_A \quad (7),$$

where H_D denotes the direct heat transfer coefficient to the external environment, H_g denotes the heat transfer coefficient to the ground, H_U denotes the heat transfer coefficient to unconditioned adjacent spaces and H_A denotes the heat transfer to adjacent buildings.

Each of the heat transmission coefficients shown in equation (7), is based on the same calculation method, expressed with H_x as

$$H_X = b_{tr,x} \cdot \left(\sum_i A_i \cdot U_i + \sum_k l_k \cdot \psi_k + \sum_j \chi_j\right) \quad (8),$$

where A_i denotes the area of the considered building component, U_i denotes the according thermal transmittance of that area, l_k denotes the length of linear thermal bridges, ψ_k denotes the according linear thermal transmittance of the thermal bridges and χ_j denotes the local point thermal transmittance. The correction factor $b_{tr,x}$ adjusts the coefficient if the considered adjacent space is not equal to the external environment, which is the case for unconditioned interior space. Some inhomogeneous building components consist of more than one material, which has to be considered in the area and the heat transfer coefficient, i.e. windows with a percentage of window framing.

Heat flow rate due to ventilation

Similar to Q_{tr}, the heat transfer due to ventilation Q_{ve} is defined by the temperature difference between the exterior temperature θ_e and the set point temperature for cooling $\theta_{int,set,C}$ of the interior space, as shown by

$$Q_{ve} = H_{ve,adj} \cdot \left(\theta_{int,set,C} - \theta_e\right) \cdot t \quad (9),$$

where t denotes the time period of the specific temperature difference, θ_e denotes the exterior temperature and $\theta_{int,set,C}$ denotes the set point temperature for cooling and $H_{ve,adj}$ denotes the heat transfer coefficient due to ventilation. $H_{ve,adj}$ is defined by

$$H_{ve,adj} = \rho_a \cdot c_a \cdot \left(\sum_k q_{ve,k,mn} \cdot b_{ve,k}\right) \quad (10),$$

where ρ_a denotes the specific density of air, c_a denotes the thermal capacity of the air, $q_{ve,k,mn}$ denotes the mean volume flow of the air and $b_{ve,x}$ denotes an correction factor to adjust the coefficient if the considered adjacent space is not equal to the external environment. The correction factor allows considering the effects of heat recovering by

$$b_{ve,k} = \left(1 - f_{ve,frac,k} \cdot \eta_{hru}\right) \quad (11),$$

where $f_{ve,frac,k}$ denotes the fraction of air that is circulated by the recovery unit and η_{hru} denotes the efficiency of the recovery unit. The latter depends on the installed Heat Recovery Ventilators (HRV) or the Energy Recovery Ventilators (ERV).

Heat flow rate due to internal gains

The interior heat gains can be categorized as

- Heat gains due to the metabolism of the users with the heat flow rate $\phi_{int,OC}$. National standards determine the heat flow rate based on occupancy level etc. (typically 50% radiative and 50% convective heat flow rates).
- Heat gains from electrical appliances with the heat flow rate $\phi_{int,A}$. National standards determine the heat flow rate based on building type etc. (typically 50% radiative and 50% convective heat flow rates).

- Heat gains from heating or cooling systems with the heat flow rate $\phi_{int,HVAC}$. This is the sum of the recoverable heat flow rates according to EN 15316-2-1 to 15316-2-3 for heating systems, EN 15241 for ventilation systems and EN 15243 for cooling systems.
- Heat gains from electrical lighting with the heat flow rate $\phi_{int,L}$. This is the sum of all internal heat flow rates from lighting systems according to EN 15193-1.
- Heat gains from hot water systems with the heat flow rate $\phi_{int,WA}$. This is the sum of all internal heat flow rates from hot water systems according to EN 15316-3-1-1.
- Heat gains due to production processes with the heat flow rate $\phi_{int,Proc}$. National standards determine the heat flow rate based on building type etc. (typically 50% radiative and 50% convective heat flow rates).

The temperature of a space is affected by heat gains that occur within the considered space, but also by heat gains that occur in adjacent spaces.

$$Q_{int} = \left(\sum_k \phi_{int,mn,k}\right) \cdot t + \left(\sum_l \phi_{int,mn,u,l} \cdot \left(1 - b_{tr,l}\right)\right) \cdot t \qquad (12)$$

where $\phi_{int,mn,k}$ denotes mean heat flow rates, $\phi_{int,mn,u,l}$ denotes the sum of all mean heat flow rates in the adjacent unconditioned spaces, t denotes the considered time period. The correction factor $b_{tr,l}$ is required if the time period of the internal and the adjacent spaces are not the same.

Heat flow rate due to solar irradiation

Similar to the calculation method of the internal heat gains, the heat gains due to solar irradiation are calculated by

$$Q_{sol} = \left(\sum_k \phi_{sol,mn,k}\right) \cdot t + \left(\sum_l \phi_{sol,mn,u,l} \cdot \left(1 - b_{tr,l}\right)\right) \cdot t \qquad (13),$$

where $\phi_{sol,mn,l}$ denotes the heat flows due to solar radiation in the considered space, $\phi_{sol,mn,u,l}$ denotes heat flows from adjacent spaces to the considered space due to solar radiation (i.e from solar radiation in winter gardens), t denotes the considered time period. The correction factor $b_{tr,l}$ is required if the time period of the internal and the adjacent spaces are not the same.

The heat flow rate through building components $Q_{sol,k}$ is calculated by

$$Q_{sol,k} = F_{sh,ob,k} \cdot A_{sol,k} \cdot I_{sol,k} - F_{r,k} \cdot \phi_{r,k} \qquad (14),$$

where $A_{sol,k}$ denotes that the effective collecting area of surface area hit by solar irradiance, $I_{sol,k}$ denotes the mean energy of the solar irradiation over the time step of the calculation (see equation (14),, $F_{sh,ob,k}$ denotes the shading reduction factor due to exterior obstacles, which reduce the solar irradiance. To simplify the calculation of the radiation, it is assumed that also a heat flow rate $\phi_{r,k}$ exists due to radiation of the building component back to the sky. This heat flow rate depends on the orientation of the component, which is expressed by the form factor $F_{r,k}$.

The shading reduction factor $F_{sh,ob,k}$ is the product of several factors as shown by

$$F_{sh,ob,k} = F_{hor} \cdot F_{OV} \cdot F_{fin} \qquad (15),$$

Where F_{hor} denotes the influence of surrounding obstacles, like trees, buildings, hills etc., is represented by the factor, F_{OV} denotes the shading created by overhangs of building components (roof etc.) and F_{fin} denotes the effect of vertical sun protection at both sides of windows to the South if applicable. National/regional tables can be used to determine this factor, which depends on the angle of the terrain and the location of the building.

The effective solar collecting area $A_{sol,k}$ of opaque building components is calculated by

$$A_{sol,k} = A_{c,p} \cdot R_{se} \cdot U_c \cdot \alpha_{S,c} \qquad (16),$$

where $A_{c,p}$ denotes the projected area, $\alpha_{S,c}$ denotes the absorption coefficient which is defined by national standards, R_{se} denotes the exterior thermal heat resistance of the surface (according to ISO 6946) and U_c denotes the thermal transmittance of the component (according to ISO 6946).

The effective solar collecting area $A_{sol,k}$ of transparent building components (windows etc.) is calculated by

$$A_{sol,k} = A_{w,p} \cdot (1 - F_F) \cdot g_{gl} \cdot F_{sh,gl} \qquad (17),$$

where $A_{w,p}$ denotes the projected area, $F_{sh,gl}$ denotes the shading coefficient due to adjustable sun protection, g_{gl} denotes the effective solar energy transmittance of the glazing and F_F denotes the ratio of the projected frame area to the overall projected area of the glazed element.

Calculation methods to determine the energy demand for cooling

The primary energy demand and the GWP due to cooling of residential buildings depend on the efficiency of the installed system and the source of the purchased power to operate the appliances.

Cooling with ventilation: power demand of fan

The chapters above describe the quasi steady state method to determine the cooling demand. The according air volume flow can be determined according to the explanations above. The required pressure difference to provide the air volume flow depends on the chosen system. The electricity demand of the ventilation system depends on fan characteristics, which is defined by the air volume flow and the pressure difference.

Cooling with free cooling: power demand of pump

The mass flow rate can be determined similar to the approach described above. The power demand is determined by

$$P_i = \rho \cdot g \cdot H \cdot \left(\sum_k q_k \cdot b_k\right) / \eta \qquad (18),$$

where H denotes the energy Head added to the flow (m), ρ denotes the fluid density, g denotes the standard acceleration of gravity (9.80665 m/s2), q denotes the flow rate (m3/s) and η denotes the efficiency of the pump.

Cooling with air conditioning, chiller etc.: power demand of chiller SEER

The power demand of a chiller itself depends on the Carnot efficiency of the chiller ς_{Carnot} and the ideal coefficient of performance COPideal. This is defined by

$$COP_{real} = COP_{ideal} \cdot \varsigma_{Carnot} = \varsigma_{Carnot} \cdot \frac{T_H}{T_H - T_C} \qquad (19),$$

where TH denotes the temperature of the hot sink and TC denotes the cold source . The power demand for cooling is defined by

$$P_{el} = \frac{Q_H}{EER_{real}} = Q_H / \left(\varsigma_{Carnot} \cdot \frac{T_C}{T_H - T_C}\right) + P_{el,aux} \qquad (20),$$

where Q_H denotes the heat provided to the sink (cooling demand plus the electricity demand), EERreal denotes the real energy efficiency ratio of the process and $P_{el,aux}$ all additional electricity demands from auxiliary units.

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