ANNEX 75

EBC

Energy in Building and Communities Programme

International Energy Agency

Cost-effective building renovation strategies at the district level combining energy efficiency & renewables – investigation based on parametric calculations with generic districts

Energy in Buildings and Communities Technology Collaboration Programme

May 2023

Technology Collaboration Programme

by iea

ANNEX 75

EBC

Energy in Building and Communities Programme

International Energy Agency

Cost-effective building renovation strategies at the district level combining energy efficiency & renewables – investigation based on parametric calculations with generic districts

Energy in Buildings and Communities Technology Collaboration Programme

May 2023

Authors

Toivo Säwén, StruSoft AB, Sweden (sawen@chalmers.se)

Johnny Kronvall, StruSoft AB, Sweden (johnny.kronvall@strusoft.com)

Contributing Authors

David Venus, AEE – Institute for Sustainable Technologies, Austria (office@aee.at)

Jørgen Rose, Aalborg University, Denmark (jro@build.aau.dk)

Kirsten Engelund Thomsen, SBi, Aalborg University, Denmark (ket@build.aau.dk)

Ole Balslev Olesen, Kuben Management, Denmark (olba@kubenman.dk)

Tiziano Dalla Mora, University IUAV of Venice, Italy (tdallamora@iuav.it)

Piercarlo Romagnoni, University IUAV of Venice, Italy (pierca@iuav.it)

Lorenzo Teso, University IUAV of Venice, Italy (lorenzo.teso@natec.unibz.it)

Teresa Blázquez, Politecnico di Milano (ABC), Italy (mariateresa.blazquez@polimi.it)

Simone Ferrari, Politecnico di Milano (ABC), Italy (simone.ferrari@polimi.it)

Federica Zagarella, Politecnico di Milano (ABC), Italy (federica.zagarella@polimi.it)

Manuela Almeida, University of Minho, Portugal (malmeida@civil.uminho.pt)

Anita Tan De Domenico, University of Minho, Portugal (anitadomenico@civil.uminho.pt)

Juan Maria Hidalgo-Betanzos, Universidad del País Vasco UPV/EHU, Spain (juanmaria.hidalgo@ehu.eus)

Raúl Briones Llorente, Universidad de Burgos, Spain (rbriones@ubu.es)

Henrik Davidsson, Lund University, Sweden (henrik.davidsson@ebd.lth.se)

Erik Johansson, Lund University, Sweden (erik.johansson@hdm.lth.se)

Roman Bollinger, INDP, Switzerland (roman.bolliger@indp.ch)

Silvia Domingo-Irigoyen, INDP, Switzerland (silvia.domingo@indp.ch)

Published by the University of Minho, Largo do Paço, 4710-057 Braga, Portugal

ISBN: 978-989-33-4464-4

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Additional copies of this report may be obtained from: EBC Executive Committee Support Services Unit (ESSU), C/o AECOM Ltd, The Colmore Building, Colmore Circus Queensway, Birmingham B4 6AT, United Kingdom
www.iea-ebc.org
essu@iea-ebc.org

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stake-holders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to opera-tions and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

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 (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme 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 and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)

Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and 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 Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems 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 (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes
(*) – completed working groups

Executive Summary

Introduction

Buildings are a major source of carbon emissions and cost-effectively reducing their energy use and associated emissions is particularly challenging for the existing building stock, mainly because of many architectural and technical hurdles. The transformation of existing buildings into low-emission and low-energy buildings is particularly challenging in cities, where many buildings continue to rely too much on heat supply from fossil fuels. However, at the same time, there are specific opportunities to develop and take advantage of district-level solutions at the urban scale. In this context, the project aims to clarify the cost-effectiveness of various approaches combining both energy efficiency measures and renewable energy measures at the district level.

Objectives and contents of the generic districts calculation report

The work documented in the present report aims to study cost-effective strategies to combine energy efficiency measures and renewable energy use in building renovation at the district level and to investigate factors influencing the choice of a cost-effective strategy. This is done through generic district assessments, where hypothetical, "generic" districts are generated to model typical conditions in various European countries.

For the generic districts, relevant variables were defined to carry out parametric assessments, applying and testing the methodology developed in IEA EBC Annex 75. The generic districts were generated and selected based on the typical conditions in each country, and the hypothetical nature of the assessment allowed for studying different starting conditions and renovation measures. It is, in particular, investigated to what extent there are synergies and to what extent there are trade-offs for combining energy efficiency measures and renewable energy measures. Cost-effective renovation strategies are determined for the investigated districts considering both energy efficiency and renewable energy measures.

Investigated generic districts

Within the IEA EBC Annex 75 project, seven generic district assessments from seven different European countries were carried out. Countries participating in the generic district assessments were Austria, Denmark, Italy, Portugal, Spain, Sweden, and Switzerland.

Results and conclusions

Five out of seven studies confirmed one of the eight stated hypotheses, namely that the cost-optimal level of energy efficiency measures does not significantly differ when considering centralised or decentralised renewable energy systems.

It was further found that the cost-effective level of energy efficiency measures differed vastly based on the starting level of thermal insulation and climate conditions. The environmental impact also differs between cases. It was found that energy efficiency measures reduced carbon emissions and primary energy use in most cases, while a small or negative impact on emissions was identified in some cases due to the embodied energy associated with the materials used. Results on the choice of centralised or decentralised systems and the benefits of using solar energy were also conflicting. From a cost perspective, district heating systems were more cost-effective when an existing district heating system was considered. When investment costs on a new district heating network were taken into account, in some cases district heating solutions were also the most cost-effective, but in others, decentralised solutions were more cost-effective.

There was a great variety of cost-effective solutions, including switching to centralised heat pumps, switching from district heating to decentralised renewables, applying no measures at all or keeping a fossil gas system. This demonstrated that the starting situation in terms of energy efficiency and existing energy systems, as well as local factors such as the climate and the public acceptance of measures, need to be investigated on a country-by-country and project-by-project basis.

In the assessments carried out, renewable energy-based solutions were, in most cases, cost-effective compared to a reference case assuming a continuation of the use of fossil fuels.

When comparing cost savings associated with the most cost-effective energy efficiency measures on the building envelopes for various heating systems, it was found in the cases considering a fossil fuel-based reference case that such cost savings are often larger for renewable energy systems based on heat pumps than in the reference case.

When comparing optimal combinations of energy efficiency measures with centralised and decentralised renewable energy options, the difference in the overall cost-effectiveness between centralised and decentralised renewable energy-based solutions was small in most studies.

The results of this report need to be considered based on many assumptions regarding construction and equipment life cycle cost, future energy prices, and energy-related emissions.

Table of contents

Abbreviations

Abbreviations	Countries
AT	Austria
CH	Switzerland
DK	Denmark
ES	Spain
IT	Italy
PT	Portugal
SE	Sweden

Abbreviations	Meaning
ACH	Hourly air change rate
ASHP	Air source heat pump
AtoW	Air to water
BB	Biomass boiler
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
EEM	Energy efficiency measure
EER	Energy efficiency ratio
ESS	Energy supply system
GDA	Generic District assessment
GHFA	Gross heated floor area
GSHP	Ground source heat pump
HDD	Heating degree days
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IEA EBC	International Energy Agency – Energy in Buildings Council
KPI	Key performance indicator
LCC	Life cycle cost assessment
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
PV	PV panels
SCOP	Seasonal coefficient of power

SEET	Seasonal energy efficiency ratio
SH	Solar heat collectors
SpH	Space heating
SpC	Space cooling
WtoW	Water to water

Definitions[1]

Various IEA EBC Annex 75 reports use a common language for communication between local authorities, professionals, researchers, inhabitants and, in general, all stakeholders and international partners.

Each term is defined in the context and scope of IEA EBC Annex 75, namely building renovations at the district level, and combines definitions from the European legal framework, common definitions of English dictionaries, related projects, research papers, and other professional publications. The concepts are sorted alphabetically.

Anyway renovation: Renovation measures necessary to restore a building's functionality without improving its energy performance. The anyway measures may be hypothetical if the renovations without improving energy efficiency are legally not allowed or are not practically reasonable.

Building renovation: An improvement of the building envelope or the energy system of a building, at least to restore its functionality, and usually to improve its energy performance. Within IEA EBC Annex 75, building renovation is understood to refer to energy efficiency measures in buildings, particularly on building envelopes, as well as renewable energy measures in buildings, in particular for heating or cooling purposes, whether through a decentralised energy system of a building or a connection to a centralised district heating/cooling system.

Carbon emissions: Shorthand expression used by IEA EBC to represent all greenhouse gas emissions to the atmosphere (this means carbon dioxide, methane, certain refrigerants, and so on) from the combustion of fossil fuels and non-combustion sources such as refrigerant leakage. It should be quantified in terms of 'CO_2 equivalent emissions'.

Cost-optimal level: The energy performance level which leads to the lowest cost during the estimated economic life cycle of a building (European Commission, 2010).

Decentralised heating or cooling: A decentralised system where heating or cooling is generated for each building or small group of buildings without extensive distribution networks.

District: A group of buildings in an area of a town or city that has limited borders chosen for purposes of, for example, building renovation projects, energy system planning, or others. This area can be defined by building owners, local government, urban planners, or project developers, e.g. along realities of social interactions, the proximity of buildings or infrastructural preconditions in certain territorial units within a municipality. IEA EBC Annex 75 focuses on residential buildings, both single and multi-family houses, but districts with other buildings with similar characteristics, such as schools or simple office buildings without complex HVAC systems, can also be included in the district.

[1] A comprehensive list of all IEA EBC Annex 75 definitions can be found here: (Hidalgo-Betanzos et al., 2023) - https://annex75.iea-ebc.org/publications

District heating or District cooling: A centralised system with the distribution of thermal energy in the form of steam, hot water, or chilled liquids, from a central production source through a network to multiple buildings or sites, for use in space heating or cooling, domestic hot water, or other services.

Embodied Energy: The total energy inputs consumed throughout a product's life cycle. Initial embodied energy represents the energy used to extract raw materials, transportation to the factory, processing and manufacturing, transportation to the site, and construction. Once the material is installed, recurring embodied energy represents the energy used to maintain, replace, and recycle materials and components of a building throughout its life. One fundamental purpose for measuring this quantity is to compare the amount of energy produced or saved by the product in question to the amount of energy consumed in making it.

Energy carrier: A substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes. An energy carrier is a transmitter of energy that includes electricity and heat, as well as solid, liquid, and gaseous fuels. The energy carriers occupy intermediate steps in the energy-supply chain between primary sources and end-user applications (IPCC, 2007).

Energy performance of a building: The calculated or measured amount of energy needed to meet the energy need associated with the typical or standard use of the building services.

Individual heating or cooling: A system where heating or cooling is generated for each individual housing unit (house or apartment).

Life Cycle Impact Assessment (**LCIA**): A phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" (ISO 14044:2006). Impact assessment should address ecological and human health effects; it should also address resource depletion.

Non-renewable energy: Energy taken from a source depleted by extraction (e.g., fossil fuels).

Primary energy: Energy that has not been subjected to any conversion or transformation process. Primary energy includes both non-renewable and renewable energy. For a building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers using conversion factors. Upstream processes and related losses are considered.

Renewable energy: Energy from sources that are not depleted by extraction, such as wind power, solar power, hydroelectric power, ocean energy, geothermal energy, heat from the ambient air, surface water or the ground, or biomass and biofuels. These alternatives to fossil fuels contribute to reducing greenhouse gas emissions, diversifying the energy supply and reducing dependence on unreliable and volatile fossil fuel markets, particularly oil and gas.

Introduction

About IEA EBC Annex 75 - Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables

Buildings are a major source of carbon emissions. Cost-effectively reducing their energy use and associated emissions is particularly challenging for the existing building stock, mainly because of many architectural and technical hurdles. The transformation of existing buildings into low-emission and low-energy buildings is particularly challenging in cities, where many buildings continue to rely too much on heat supply by fossil fuels. On the other hand, there are specific opportunities to develop and take advantage of district-level solutions at the urban scale. In this context, the project IEA EBC Annex 75 - Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables - aims to clarify the cost-effectiveness of various approaches combining energy efficiency and renewable energy measures at the district level. At this level, finding the balance between renewable energy measures and energy efficiency measures for the existing building stock is a complex task, and many research questions still need to be answered, including:

- What are the cost-effective combinations between renewable energy measures and energy efficiency measures to achieve far-reaching reductions in carbon emissions and primary energy use in urban districts?
- What are the cost-effective strategies to combine energy efficiency measures applied to building envelopes with district-level heating or cooling based on available environmental heat, solar energy, waste heat or natural heat sinks?
- When coupled with energy efficiency measures applied to building envelopes, how do different strategies that promote a switch to decentralised renewable energy sources compare in terms of cost-effectiveness and impact?
- Under which circumstances is it more appropriate to use the available renewable energy potentials at a district level in an urban context? Under which circumstances are decentralised renewable energy solutions more advantageous, combined with energy efficiency measures applied to building envelopes?

IEA EBC Annex 75 project (Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables) aims to address these research questions.

Objectives of IEA EBC Annex 75

The project aims to investigate cost-effective strategies for reducing carbon emissions and energy use in buildings at the district level in urban contexts, combining energy efficiency and renewable energy measures. The objective is to guide policymakers, companies working in the field of energy transition, as well as building owners to cost-effectively transform energy use in the existing building stock in cities to low-emission and low-energy solutions.

Given the limitations due to available financial resources and the large number of investments needed to transform the cities' energy use in buildings, identifying cost-effective strategies is important for accelerating the necessary transition towards low-emission and low-energy districts.

The planned project focuses on the following objectives:

- Give an overview of various technology options, taking into account existing and emerging efficient technologies with the potential to be successfully applied within that context and how challenges specifically occurring in an urban context can be overcome
- Develop a methodology which can be applied to urban districts to identify such cost-effective strategies, supporting decision-makers in the evaluation of the efficiency, impacts, cost-effectiveness and acceptance of various strategies for renovating urban districts

- Illustrate the development of such strategies in selected case studies and gather related best-practice examples
- Give recommendations to policymakers and energy-related companies on how they can influence the uptake of cost-effective combinations of energy efficiency and renewable energy measures in building renovation at the district level and guide building owners/investors on related cost-effective renovation strategies
- Provide accurate and understandable information, guidelines, tools, and recommendations to support decision-makers from the public and private sectors in making better decisions and choosing the best options that apply to their specific needs

Objectives of the Generic Districts Calculations

The work documented in the present report aims to show in selected generic districts the development of cost-effective strategies combining energy efficiency measures and renewable energy use in building renovation at the district level and to investigate the factors influencing the choice of a cost-effective strategy. It is also intended to obtain information regarding the necessary framework conditions or policy instruments for facilitating the uptake of cost-effective strategies for far-reaching renovations of districts.

The methodology developed within IEA EBC Annex 75 (Bolliger et al, 2023) is tested by being applied to assess different generic districts. Generic districts are defined based on typical building typologies and district sizes in the participating countries to allow for the study of more variations than in a traditional case study. The selected generic districts were existing or fictional urban districts where renovation was needed and whose assessment results could provide guidance in choosing an appropriate renovation strategy for similar districts in the same country. In particular, it is investigated to what extent synergies and trade-offs exist for combining energy efficiency and renewable energy measures. It is envisaged to determine cost-effective renovation strategies for the investigated districts considering both energy efficiency and renewable energy measures.

1. Evaluation framework

1.1 Evaluation methodology

The evaluation methodology developed in the IEA EBC Annex 75 project is detailed in the IEA EBC Annex 75 Methodology report (Bolliger et al., 2023). The following is a quick overview. In general, it was permitted for each participating country to tweak the methodology based on relevant conditions, but a few general steps were well-defined:

- Definition of a generic district
- Definition of the relevant starting situation
- Definition of relevant renovation measures
  - Building envelope renovation measures
  - Energy systems
- Modelling of relevant Key Performance Indicators for the various combinations of building renovation measures and energy systems
- Responses to the stated research questions are provided
- Confirmations/rejections of the stated hypotheses are provided.

The following section further details the evaluation steps specific to the Generic Districts assessments.

Generic districts

The "Generic District" concept was defined as part of the project to allow performing calculations without the inherent boundary conditions in real-life case studies. As the context in terms of typical building typologies, climate, existing energy systems, etc. varies greatly between countries, each participating country could freely define what constitutes a Generic District in its country. Some common guidelines were agreed upon and adhered to in each assessment:

- The Generic District should be defined according to the local context of the country
- The Generic District should contain a variety of building typologies representing the most typical typologies of the country from different periods
- The Generic District should contain mainly housing
- A suitable number of buildings, between 10-50, should be considered
- The climate of the Generic District may be parametrically varied to study the effects of different climate zones within a country
- Generic Districts may be based on a real district, tweaked to allow for more parameters studied, or entirely fictional

Starting situations

The project aims to clarify the cost-effectiveness of various approaches combining energy efficiency and renewable energy measures concerning a starting situation in a specific city district. The scope of the project is based on the following three starting situations:

- Urban districts previously decentrally heated by natural gas, oil or electricity, or cooled through decentralised cooling devices
- Urban districts previously connected to district heating systems with a high share of fossil fuel
- Urban districts previously connected to district heating systems with a substantial share of renewable energy carriers.

Research Questions

Distinguishing the identified starting situations, the following questions are investigated:

- What are the cost-effective combinations between renewable energy measures and energy efficiency measures to achieve far-reaching reductions in carbon emissions and primary energy use in urban districts that meet pre-set targets?
    - In particular: What are the cost-effective strategies to combine district-level heating or cooling based on available environmental heat, solar energy, waste heat or natural heat sinks, with energy efficiency measures on the buildings' envelopes?
- How do related strategies compare in terms of cost-effectiveness and impact with strategies that combine a decentralised switching of energy carriers to renewable energy with energy efficiency measures on the building envelopes?
    - In particular: Under which circumstances does it make sense to use the available renewable energy potentials in cities at a district level, and under which circumstances are decentralised renewable energy solutions, combined with energy efficiency measures on the buildings' envelopes, more advantageous?

The investigations focus on renovation scenarios that are entirely based on renewable energy combined with varying energy efficiency measures on building envelopes.

It is intended that this allows also to investigate the following questions:

- Which approaches, considering the various possibilities for energy efficiency and renewable energy measures, allow districts to be supplied entirely with renewable energy at the lowest cost?
- Which factors determine the cost-efficient balance between efficiency measures on the building envelopes and measures using renewable energy if far-reaching reductions in carbon emissions and primary energy use in urban districts are the target?
- To what extent is the cost-effectiveness of renovation measures in building envelopes different when comparing a local district heating system based on renewable energy with a decentralised (in each building) heating system using renewable energy?

Hypotheses

The validity of several hypotheses is examined based on the investigation of the research questions. The hypotheses can be understood as assumptions. Through the assessment, it is then determined whether the hypotheses can be validated.

The hypotheses focus, in particular, on comparing the cost-optimal level of energy efficiency measures on building envelopes in different scenarios. The following hypotheses were investigated:

Hypothesis 1: Comparing centralised and decentralised renewable energy systems

«The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»

Hypothesis 2: Comparing a fossil fuel-based district heating system with a centralised switch to renewable energy

«The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»

Hypothesis 3: Comparing a fossil fuel-based district heating system with a decentralised switch to renewable energy

«The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»

Hypothesis 4: Comparing decentralised fossil fuel systems with a centralised switch to renewable energy

«The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»

Hypothesis 5: Comparing decentralised fossil fuel systems with a low-temperature renewable energy-based district heating system

«The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based heating system associated with decentralised heat pumps.»

Hypothesis 6: Comparing a new renewable energy-based district heating system with a switch of an existing district heating system to renewable energy

«The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»

Hypothesis 7: Districts with initial low level of thermal insulation

«In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»

Hypothesis 8: Districts with initial high level of thermal insulation

«In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»

In these hypotheses, the expression «level of energy-efficiency measures on the envelopes» refers to the level of energy need of the respective buildings considering energy-efficiency measures undertaken.

The expressions «low level of thermal insulation» and «high level of thermal insulation» are supposed to be understood from the perspective of each country, taking into account, for example, that Southern European countries have overall lower levels of thermal insulation than Northern European countries.

Key performance indicators

A set of Key Performance Indicators (KPIs) is evaluated for each scenario to define the sustainability and cost-effectiveness of the renovation projects. These KPIs help assess to what extent the project goals are achieved, providing means for measuring and managing the progress towards those goals for further learning and improvement (Kylili et al. 2016).

The following KPIs are considered the most essential and selected for use in IEA EBC Annex 75:

- Carbon emissions, expressed as CO_2-equivalents per m² of conditioned gross floor area and per year.
- Primary energy use, expressed as kWh per m² of conditioned gross floor area and per year.
- Annualised total costs, expressed as € per m² of conditioned gross floor area and per year.

Limitations of the Generic Districts Calculation

As different starting conditions, tools, assumptions, boundary conditions, financial and emission factors were used in each assessment, and as the methodology and focus in each assessment were selected based on the relevant conditions in each participating country, it is acknowledged that a direct quantitative comparison between the results of each assessment is not very useful.

Instead, the aforementioned hypotheses were developed to investigate the same relevant topics but account for the variation between countries regarding starting conditions and relevant solutions to the optimisation problem. In discussing the results, the hypotheses serve as a main anchor for comparison to identify whether the same trends could be observed between countries or whether the different conditions provided different optimal solutions.

1.2 Assumptions and boundary conditions

Energy performance calculation tools

Table 1 describes the tools and databases used to calculate buildings' energy performance.

Table 1. Tools used for the energy performance calculations.

Country	Name of tool	Calculation time step	Link to tool
Austria	PHPP	Monthly (heating and cooling), annually (electricity)	https://passive-house.com/04_phpp/04_phpp.htm
Denmark	ASCOT	Monthly	https://www.iea-ebc.org/projects/pro-ject?AnnexID=56
Italy	Design Builder/ EnergyPlus	Hourly	https://www.designbuilderitalia.it
Portugal	OpenStudio/ EnergyPlus	Hourly	https://openstudio.net/ https://energyplus.net/
Spain	SG SAVE (E+)	Hourly	http://www.efinovatic.es/energyPlus/ https://energyplus.net/
Sweden	EnergyPlus		https://energyplus.net/
Switzerland	INSPIRE	Monthly	https://www.energieschweiz.ch/tools/in-spire/

Embodied energy and emissions calculation tools

Table 2 describes the tools and databases used to calculate the embodied energy of building components and energy systems.

Table 2. Tools and databases used for Life Cycle Assessment.

Country	Name of database	Name of tool	Link to database and tool
All		A75CT	https://annex75.bim.energy
Austria	KBOB		
Denmark	ÖKOBAUDAT	ASCOT	https://www.iea-ebc.org/projects/project?AnnexID=56
Italy	Not done		
Portugal	Not done		
Spain	Not done		
Sweden		A75CT	https://annex75.bim.energy
Switzerland	KBOB	INSPIRE	https://www.kbob.admin.ch/dam/kbob/it/dokumente/Publika-tionen/Nachhaltiges%20Bauen/Archiv_2015-2019/2009_1-2016%20Oekobilanzdaten%20im%20Baubereich.pdf https://www.energieschweiz.ch/tools/inspire/

Energy prices

Table 3 contains the assumed current energy price, while Table 4 contains the project energy prices in 2030.

Table 3. Energy prices in EUR per kWh final energy for the year of the assessment.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	€/kWh final energy	NA	0.326	0.232	0.219	0.213	0.148 0.061	0.21
Wood pellets	€/kWh final energy	NA	0.074	0.063	0.068	0.050	0.040	0.08
Oil	€/kWh final energy	NA	0.204	NA	0.170	0.140		0.10
Natural Gas	€/kWh final energy	NA	0.120	0.089	0.081	0.058	0.115 0.052	0.10
Electricity for district heating system	€/kWh final energy	NA	NA	0.232	0.170	NA	NA	0.17
Wood for district heating system	€/kWh final energy	NA	NA	0.063	0.027	NA	NA	0.07
District heating	€/kWh final energy	NA	0.096	NA	0.068	NA	0.087 0.082	NA

Table 4. Expected energy prices in EUR per kWh final energy for the year 2030.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	€/kWh final energy	0.200	0.407	NA	NA	0.270	0.029 0.038	0.340
Wood pellets	€/kWh final energy	0.050	0.092	NA	NA		NA	0.100
Oil	€/kWh final energy	0.090	0.255	NA	NA	0.175	NA	0.130
Natural Gas	€/kWh final energy	0.090	0.149	NA	NA	0.084	NA	0.130
Electricity for district heating system	€/kWh final energy	NA	NA	NA	NA	NA	NA	0.280
Wood for district heat-ing system	€/kWh final energy	NA	NA	NA	NA	NA	NA	0.090
District heating	€/kWh final energy	0.100	0.119	NA	NA	NA	NA	NA

1 Sources for Austria: Kranzl et al. (2017)

2 Sources for Denmark: Danish Housing and Planning Authority (2016)

3 Sources for Spain: Eurostat (2020) and Avebiom (2022)

4 Sources for Italy: AIEL (2021), Eurostat (2021)

5 Sources for Portugal: Market value 2019, PNEC 2030 (2020)

6 Sources for Sweden: SCB (2020a, 2020b, 2022), Energiföretagen (2021), Pelletsförbundet (n.d.), Energimyndigheten (2019)

7 Sources for Switzerland: Federal Statistical Office (2021)

Emission factors

Table 5 shows current carbon emission factors for various energy carriers, while

Table 6 shows projected emission factors in 2030.

Table 5. Current conversion factors for various energy carriers.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	kg CO_{2eq} / kWh final energy	0.524	0.135	0.360	0.430	0.144	0.047	0.100
Wood pellets	kg CO_{2eq} / kWh final energy	0.027	0.042	0.018	0.03	0.045	0.044	0.027
Oil	kg CO_{2eq} / kWh final energy	0.301	0.331	0.310	0.260	0.267	0.290	0.300
Natural Gas	kg CO_{2eq} / kWh final energy	0.228	0.251	0.250	0.200	0.202	0.230	0.230
District heating	kg CO_{2eq} / kWh final energy	0.022	0.088	-	0.360	-	0.009	NA

Table 6. Projected conversion factors in 2030 for various energy carriers.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	kg CO_{2eq} / kWh final energy	0.524	0.041	0.36	NA	0.144	0.047	0.048
Wood pellets	kg CO_{2eq} / kWh final energy	0.027	0.042	0.018	0.030	0.045	0.044	0.027
Oil	kg CO_{2eq} / kWh final energy	0.301	0.331	0.310	0.260	0.267	0.290	0.300
Natural Gas	kg CO_{2eq} / kWh final energy	0.228	0.251	0.250	0.200	0.202	0.230	0.230
District heating	kg CO_{2eq} / kWh final energy	0.022	0.069	-	0.360	-	0.009	NA

[1] Sources for Austria: KBOB(2022), Kranzl et al. (2017)

2 Sources for Denmark: Danish Housing and Planning Authority (2016)

3 Sources for Spain: Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento (2016)

4 Sources for Italy: Lombardy Regional Decree n. 18546/2019

5 Sources for Portugal: DRE (2021), EcoInvent (2010)

6 Sources for Sweden: Björnsson et al. (2021), Gode et al. (2011)

7 Sources for Switzerland: KBOB (2021)

Primary energy factors

Table 7 shows current primary energy factors for various energy carriers, while **Table 8** shows projected primary energy factors in 2030.

Table 7. Current primary energy factors for various energy carriers.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	kWh per kWh of final energy	3.18	2.153	2.40	2.42	2.50	1.60	3.01
Wood pellets	kWh per kWh of final energy	1.20	0.044	1.11	1.00	1.00	1.00	1.20
Oil	kWh per kWh of final energy	1.24	1.280	1.18	1.07	1.00	1.00	1.24
Natural gas	kWh per kWh of final energy	1.07	1.160	1.20	1.05	1.00	1.00	1.06
District heating	kWh per kWh of final energy	1.53	1,156	-	1.50	NA		

Table 8. Projected primary energy factors in 2030 for various energy carriers.

Energy carrier	Unit	AT[1]	DK[2]	ES[3]	IT[4]	PT[5]	SE[6]	CH[7]
Electricity	kWh per kWh of final energy	3.18	1.695	2.40	NA	2.50	2.10	1.35
Wood pellets	kWh per kWh of final energy	1.20	0.044	1.11	1.00	1.00	1.11	1.20
Oil	kWh per kWh of final energy	1.24	1.280	1.18	1.07	1.00	1.11	1.24
Natural gas	kWh per kWh of final energy	1.07	1.160	1.20	1.05	1.00	1.09	1.06
District heating	kWh per kWh of final energy	1.53	1.083	-	1.50	NA		NA

1 Sources for Austria: based on KBOB (2022) and Kranzl et al. (2017)

2 Sources for Denmark: Danish Housing and Planning Authority (2016)

3 Sources for Spain: Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento (2016)

4 Sources for Italy: Governo Italiano (2015)

5 Sources for Portugal: DRT (2021), EcoInvent (2010)

6 Sources for Sweden: Boverket (2011), Gode et al., (2011)

7 Sources for Switzerland: KBOB (2021)

2. Generic District assessments

Generic District assessments were performed by seven participating countries, as shown in Figure 1. For each assessment, the selected district was a real or a hypothetical district that could be considered representative of the country. The generic districts were used to explore combinations of measures that could not be studied within the case studies analysed in the project, whose conclusions are available in the IEA EBC Annex 75 report 'Investigation of cost-effective building renovation strategies at the district level combining energy efficiency & renewables – a case studies-based assessment' (Venus et al., 2023).

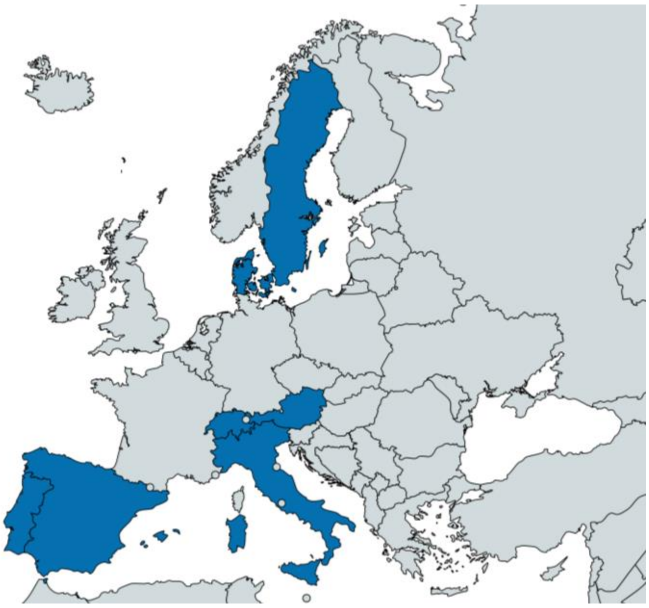

Figure 1. Countries participating in the Generic District assessments are highlighted in blue (from: "GeoNames", by GeoNames, nd.).

Table 9 shows an overview of the performed generic district assessments, showing that from 12 to 1296 different scenarios were performed for districts with between 2 and 200 buildings and 1-5 typologies. For this study, a scenario refers to one combination of energy efficiency measures and energy systems, following the methodology defined in IEA EBC Annex 75 (Bolliger et al., 2023).

Table 9. Overview of Generic District assessments.

General info	AT	DK	ES	IT	PT	SE	CH
Number of buildings	27	200	22	10	32	2	20
Number of typologies	5	3	2	1	2	2	2
Climate zone (Köppen classification)	Dfb	Cfb	Cfb	Cfa/Csa	Csb	Cfb	Cfb
Total number of scenarios (including the ref. case)	12	21	56	33	25	1296	56

Table 10 shows the energy system options investigated in each assessment. Different energy systems were investigated in each of the assessments, depending on the relevant starting situations and potential replacement of the existing systems.

Table 10. Energy system options considered in the Generic District assessments.

Energy system	AT	DK	ES	IT	PT	SE	CH
Central natural gas heating	X						
Central CHP				X			
Central air source heat pump	X		X		X		
Central ground source heat pump	X		X	X			X
Central lake water source heat pump							X
Ground-water district heating							X
Cold lake water district heating							X
Central biomass plant			X	X	X		
District heating	X	X				X	
Solar thermal system	X	X		X	X		
Photovoltaic system	X	X		X	X	X	
Decentralised air source heat pump		X	X	X			X
Decentralised gas boiler				X	X		X
Decentralised ground source heat pump							X
Electric heating			X		X		
Decentralised biomass boiler			X				

Table 11 shows the renovation measure options investigated in each assessment. Different measures were investigated in each of the assessments, depending on the starting situations, climate, and availability.

Table 11. Renovation measures considered in the Generic District assessments.

Energy system	AT	DK	ES	IT	PT	SE	CH
Improved walls	X	X	X	X	X	X	X
Improved roofs	X	X	X	X	X	X	X
Improved floors			X				X
Improved windows	X	X	X	X	X	X	X
Improved ventilation system		X	X				

2.1 Austria

Description of the generic district

The generic district in Austria is defined based on a real district with buildings defined as “typical" for Austria. In previous investigations, multi-family buildings constructed between 1960 and 1980 were identified as having major potential for energy and carbon emission reductions. There are two reasons for that: these buildings' very low energy performance and the large number of buildings constructed in this period. They have now reached an age where thermal renovation is an absolute necessity. In the generic district calculations, the assumption was that none of the buildings in the considered district had already been renovated, but, in reality, this might not be true.

Table 12. General Information about the Austrian district.

Parameter	Explanation/definition
Location	Kapfenberg
Latitude	E: 15.31
Longitude	N: 47.45
Climate zone (Köppen classification)	Dfb (Humid continental climate – warm summer subtype)
Number of buildings in total	27

Figure 2. Aerial view of the Austrian generic district in Kapfenberg. From Digital Atlas GIS Styria, © GIS-Steiermark, 2022, http://www.gis.steiermark.at/

Table 13. Building typologies of the Austrian generic district.

Parameter	Unit	building typology 1	building typology 2	building typology 3	building typology 4	building typology 5
			Building Information			
Number of buildings per typology		3	3	13	7	1
Construction period		1960 - 1980	1960 – 1980	1960 – 1980	1960 – 1980	1960 – 1980
			Geometry			
Gross heated floor area (GHFA)	m^2	2654,4	2654,4	2654,4	1327,2	1327,2
Heated volume	m^3	8427,72	8427,72	8427,72	4213,86	4213,86
Façade area incl. window area	m^2	1871,98	1871,98	1871,98	1069,34	1069,34
Roof area if flat roof	m^2	-	-	-	-	-
Roof area if pitched roof	m^2	663,6	663,6	663,6	331,8	331,8
In case of pitched roof: Is room below roof heated or not?	Yes/No	no	no	no	no	no
Area of windows to North	m^2	-	-	-	-	-
Area of windows to East	m^2	120,56	120,56	120,56	60,28	60,28
Area of windows to South	m^2	-	-	-	-	-
Area of windows to West	m^2	107,44	107,44	107,44	53,72	53,72
Area of basement ceiling	m^2	663,6	663,6	663,6	331,8	331,8
Area of basement wall	m^2	-	-	-	-	-
Area of basement floor	m^2	-	-	-	-	-
Number of floors above ground	-	4	4	4	4	4
			Usage			
Type of use		Residential	Residential	Residential	Residential	Residential
Area per occupant	m² / person	35	35	35	35	35

Parameter	Unit	building typology 1	building typology 2	building typology 3	building typology 4	building typology 5
Typical indoor temperature (for calculations)	°C	20	20	20	20	20
Average electricity consumption per year and m² (excluding heating, cooling, ventilation)	kWh/(m².a)	14	14	14	14	14
HVAC systems						
Type of existing heating system (boiler, heat pump, etc.)		Boiler	Boiler	Boiler	Boiler	Boiler
Existing energy carrier (Gas, Electricity, etc.)		Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
Is ventilation system without heat recovery installed?	Yes/No	no	no	no	no	no
Is ventilation system with heat recovery installed?	Yes/No	no	no	no	no	no
Efficiency of heat recovery	%	-	-	-	-	-
Ventilation rate	ach	0,4	0,4	0,4	0,4	0,4
Is cooling system installed?	Yes/No	no	no	no	no	no
Hot water consumption	l/person/day	30	30	30	30	30

Calculation parameters and scenarios

Table 14. General parameters for the Austrian generic district.

Date the calculations were made	**2019-2020**
Weather file used	Kapfenberg
External shading (by surrounding buildings) considered	No

The weather file of Kapfenberg was used to calculate the energy performance. The weather file represents a standard climate and is included in the energy performance calculation tool.

External shading by surrounding buildings was not considered.

Eleven renovation scenarios were investigated, including insulation of the exterior walls, roofs, new windows, solar thermal installation, photovoltaics, electric batteries, and the installation of new mechanical ventilation with heat recovery. Besides these scenarios that lead to a reduction of the energy demand and an improvement of the thermal behaviour, a reference scenario was calculated, which does not lead to any energy improvements.

The renovation measures include two energy standards: renovation to the minimum required energy standard and renovation to the Passive House standard (regarding insulation thickness and U-values of the building components).

In summary, the renovation scenarios include the following measures:

- Scenario 1: roof_national
- Scenario 2: roof_PH
- Scenario 3: Scenario 2 + facade_national
- Scenario 4: Scenario 2 + facade_PH
- Scenario 5: Scenario 4 + windows_PH
- Scenario 6: Scenario 5 + Solar thermal small
- Scenario 7: Scenario 5 + Solar thermal large
- Scenario 8: Scenario 7 + PV small
- Scenario 9: Scenario 7 + PV large
- Scenario 10: Scenario 9 + electric battery
- Scenario 11: Scenario 10 + MVHR

"national" refers to national standards and regulations

"_PH" refers to Passive House standards

"MVHR" represents mechanical ventilation with heat recovery

Table 15. Measures on the building envelope applied to the Austrian generic district.

Parameter	Unit	Ref	1	2	3	4	5
			Walls				
U-values	W/m²K	0,867	0,867	0,867	0,272	0,115	0,115
Investment costs	€/m²$_{\text{building element}}$	29,98	29,98	29,98	70,81	89,15	89,15
Maintenance costs	€/m²$_{\text{building element}}$.year	0,45	0,45	0,45	1,06	1,3	1,3
Service life of insulation measures	years	-	-	-	40	40	40
Roofs							
U-values	W/m²K	0,732	0,131	0,093	0,093	0,093	0,093
Investment costs	€/m²$_{\text{building element}}$	No measures	65,38	73,80	73,80	73,80	73,80
Maintenance costs	€/m²$_{\text{building element}}$.year	No measures	0,98	1,1	1,1	1,1	1,1
Service life of insulation measures	years	-	40	40	40	40	40

Parameter	Unit	Ref	1	2	3	4	5
			Floors				
U-values floors	W/m²K	0,39	0,39	0,39	0,39	0,39	0,39
Investment costs	€/m²$_{\text{building element}}$	No measures	No Measures	No Measures	No Measures	No Measures	No Measures
Maintenance costs	€/m²$_{\text{building element}}$.year	No measures	No measures	No measures	No Measures	No Measures	No Measures
Service life of insulation measures	years	No measures	No measures	No measures	No Measures	No Measures	No Measures
			Windows				
U-values windows	W/m²K	2,33	2,33	2,33	2,33	2,33	2,33
Investment costs	€/m²$_{\text{building element}}$	30,00	30	30	30	30	30
Maintenance costs	€/m²$_{\text{building element}}$.year	0,45	0,45	0,45	0,45	0,45	0,45
Service life of insulation measures	years	-	-	-	-	-	-
Ventilation							
Investment costs	€/m²floor area	0	0	0	0	0	0
Maintenance costs	€/m²floor area.year	0	0	0	0	0	0
Service life of insulation measures	years	-	-	-	-	-	-

Measures on the building envelope applied to the Austrian generic district (continued).

Parameter	Unit	6	7	8	9	10	11
			Walls				
U-values	W/m²K	0,115	0,115	0,115	0,115	0,115	0,115
Investment costs	€/m²$_{\text{building element}}$	89,15	89,15	89,15	89,15	89,15	89,15
Maintenance costs	€/m²$_{\text{building element}}$.year	1,3	1,3	1,3	1,3	1,3	1,3
Service life of insulation measures	years	40	40	40	40	40	40

			Roofs				
U-values	W/m²K	0,093	0,093	0,093	0,093	0,093	0,093
Investment costs	€/m²$_{building\ element}$	73,80	73,80	73,80	73,80	73,80	73,80
Maintenance costs	€/m²$_{building\ element}$.year	1,1	1,1	1,1	1,1	1,1	1,1
Service life of insulation measures	years	40	40	40	40	40	40
			Floors				
U-values floors	W/m²K	0,39	0,39	0,39	0,39	0,39	0,39
Investment costs	€/m²$_{building\ element}$	No Measures	No Measures	No Measures	No Measures	No Measures	No Measures
Maintenance costs	€/m²$_{building\ element}$.year	No Measures	No Measures	No Measures	No Measures	No Measures	No Measures
Service life of insulation measures	years	No Measures	No Measures	No Measures	No Measures	No Measures	No Measures
Windows							
U-values windows	W/m²K	0,90	0,90	0,90	0,90	0,90	0,90
Investment costs	€/m²$_{building\ element}$	390	390	390	390	390	390
Maintenance costs	€/m²$_{building\ element}$.year	5,87	5,87	5,87	5,87	5,87	5,87
Service life of insulation measures	years	40	40	40	40	40	40
Ventilation							
Investment costs	€/m²floor area	0	0	0	0	0	30
Maintenance costs	€/m²floor area.year	0	0	0	0	0	0,62
Service life of insulation measures	years	-	-	-	-	-	25

Table 16 shows the assumptions which were made for characterising the HVAC systems. For the nine scenarios, different energy supply systems were investigated:

- At the building level:
    - Natural gas heating
    - Air source heat pump
    - Ground source heat pump

- At the district level:
    - District heating based on renewable energy

The mentioned energy supply systems are also supported by solar thermal installations and PV.

Table 16. Measures on the HVAC systems, including renewable energy generation on-site.

Parameter	Unit	Ref	1	2	3	4	5
			Natural gas heating				
Capacity	kW	3264	2990	2972	2318	2146	1831
Investment costs	€/kW	12,06	12,57	12,61	14,20	14,73	15,90
Maintenance costs	€/year	787	752	750	658	632	582
Service life	Years	20	20	20	20	20	20
			Air source heat pump				
Capacity	kW	3264	2990	2972	2318	2146	1831
Investment costs	€/kW	78,29	81,09	81,28	89,80	92,63	98,72
Maintenance costs	€/year	5111	4849	4831	4163	3976	3615
Service life	Years	20	20	20	20	20	20
			Ground source heat pump				
Capacity	kW	3264	2990	2972	2318	2146	1831
Investment costs	€/kW	238,16	242,65	242,95	256,16	260,41	269,37
Maintenance costs	€/year	15547	14510	14441	11876	11177	9864
Service life	Years	20	20	20	20	20	20
			District heating				
Capacity	kW	3264	2990	2972	2318	2146	1831
Investment costs	€/kW	32,90	33,83	33,89	36,69	37,61	39,56
Maintenance costs	€/year	2148	2023	2014	1701	1614	1449
Service life	Years	20	20	20	20	20	20
			Solar thermal system				
Size	m^2	0	0	0	0	0	0
Investment costs	€/$m^2_{\text{solar thermal}}$	-	-	-	-	-	-
Maintenance costs	€/year	-	-	-	-	-	-
Service life	Years	-	-	-	-	-	-

Parameter	Unit	Ref	1	2	3	4	5
			PV system				
Size	kWp	0	0	0	0	0	0
Investment costs	€/kWp	-	-	-	-	-	-
Maintenance costs	€/year	-	-	-	-	-	-
Service life	years	-	-	-	-	-	-

Measures on the HVAC system including renewable energy generation on-site (continued).

Parameter	Unit	6	7	8	9	10	11
			Natural gas heating				
Capacity	kW	1831	1831	1831	1831	1831	1077
Investment costs	€/kW	15,90	15,90	15,90	15,90	15,90	20,48
Maintenance costs	€/year	582	582	582	582	582	441
Service life	Years	20	20	20	20	20	20
			Air source heat pump				
Capacity	kW	1831	1831	1831	1831	1831	1077
Investment costs	€/kW	98,72	98,72	98,72	98,72	98,72	122,12
Maintenance costs	€/year	3615	3615	3615	3615	3615	2630
Service life	Years	20	20	20	20	20	20
Capacity	kW	1831	1831	1831	1831	1831	1077
			Ground source heat pump				
Investment costs	€/kW	269,37	269,37	269,37	269,37	269,37	301,58
Maintenance costs	€/year	9864	9864	9864	9864	9864	6496
Service life	Years	20	20	20	20	20	20
Capacity	kW	1831	1831	1831	1831	1831	1077
			District heating				
Investment costs	€/kW	39,56	39,56	39,56	39,56	39,56	46,84
Maintenance costs	€/year	1449	1449	1449	1449	1449	1009
Service life	Years	20	20	20	20	20	20

Parameter	Unit	6	7	8	9	10	11
				Solar thermal system			
Size	m²	2571	5141	5141	5141	5141	5141
Investment costs	€/m²$_{solar\ thermal}$	619,31	619,31	619,31	619,31	619,31	619,31
Maintenance costs	€/year	7961	15919	15919	15919	15919	15919
Service life	Years	20	20	20	20	20	20
				PV system			
Size	kWp	0	0	459	919	919	919
Investment costs	€/kWp	-	-	1100	1100	1100	1100
Maintenance costs	€/year	-	-	5049	10109	10109	10109
Service life	years	-	-	30	30	30	30

Generic district calculation results

The following graphs (Figure 3 to Figure 6) give an overview of specific yearly primary energy use and yearly carbon emissions, respectively, vs. costs of various renovation packages on the building envelopes for various heating systems investigated.

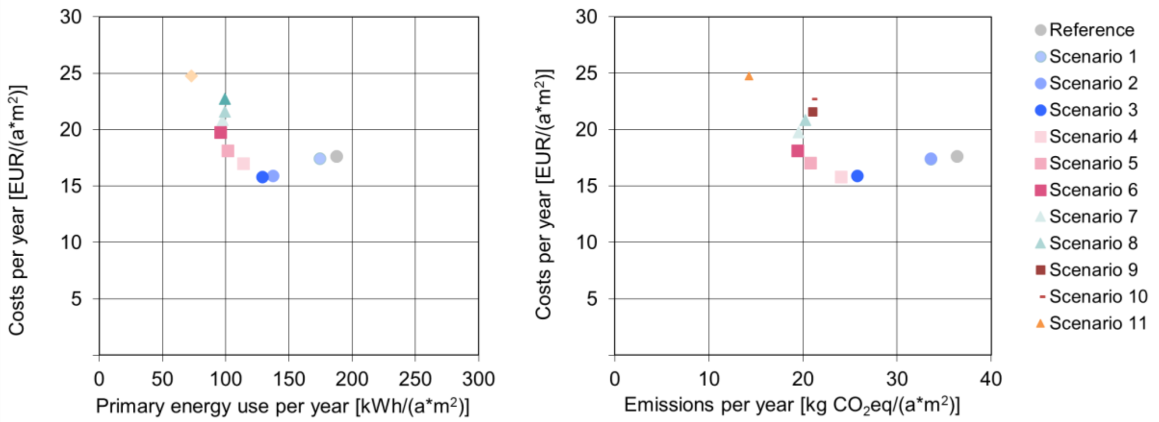

Figure 3. Results for Heating system 1 – Reference [natural gas].

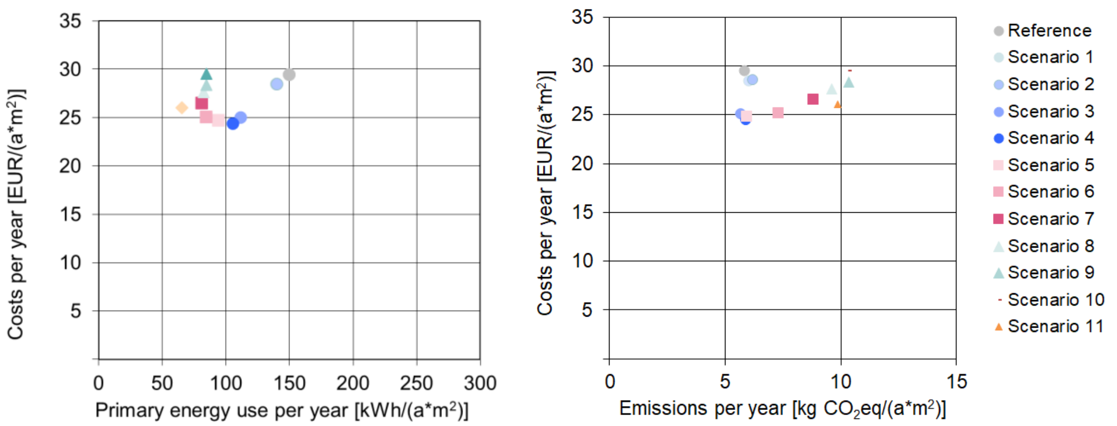

Figure 4. Results for Heating system 2 - [heat pump air source].

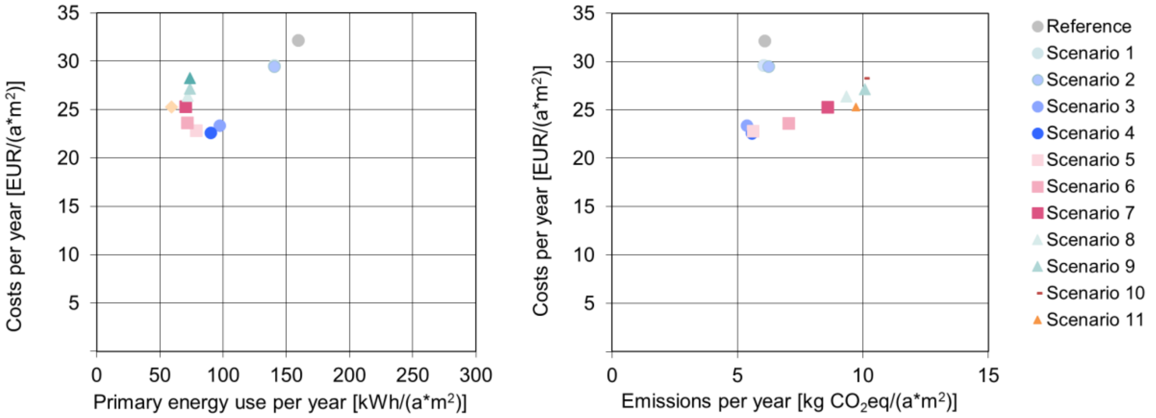

Figure 5. Results for Heating system 3 - [heat pump ground source].

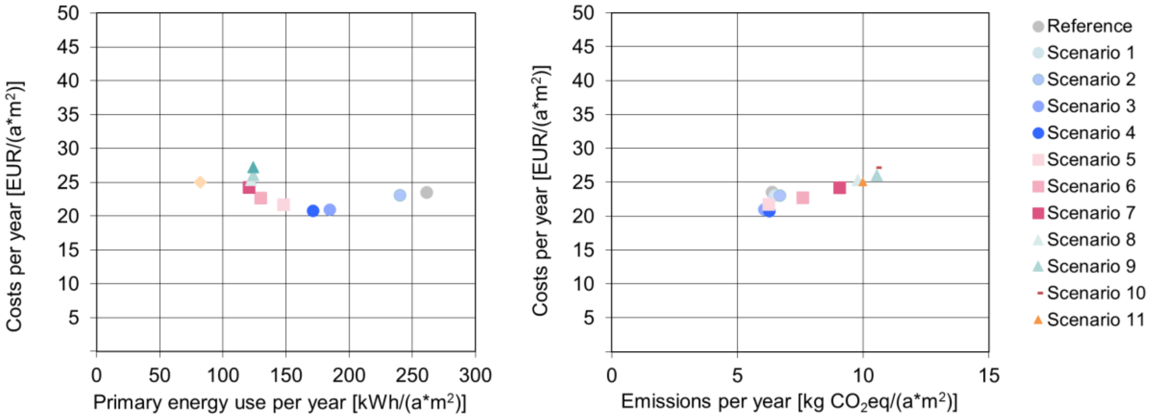

Figure 6. Results for Heating system 4 - [district heating].

The following graph (Figure 7) contains an overview combining the various renovation packages on the building envelopes and the various heating systems investigated. It summarises the relationship between specific yearly primary energy use and yearly carbon emissions, respectively, vs. costs of various renovation packages on the building envelopes for various heating systems investigated. Each point in the curves corresponds to one renovation package associated with the respective energy supply system.

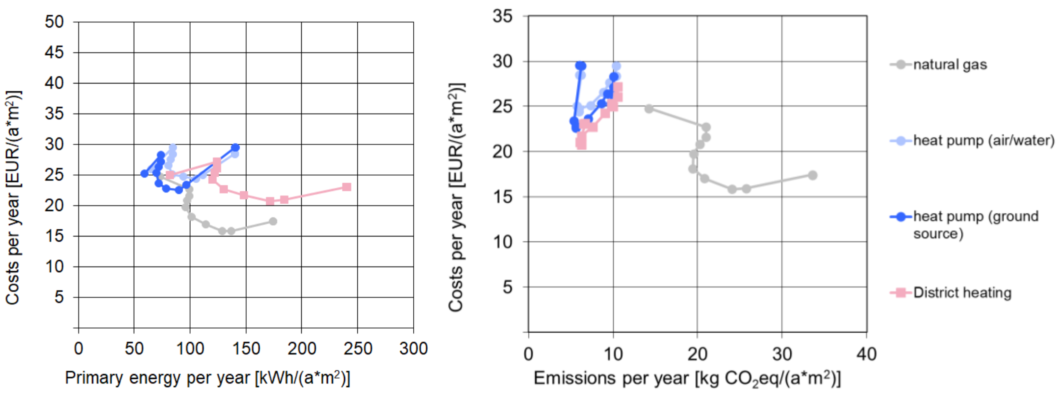

Figure 7. Overview of the combinations of renovation packages and heating systems.

The following graphs (Figure 8 to Figure 11) specifically show the most cost-effective renovation packages for the various heating systems investigated. They show the cost-effectiveness of various renovation packages on the building envelopes for various types of heating systems investigated. The most cost-effective renovation package is marked with a yellow circle.

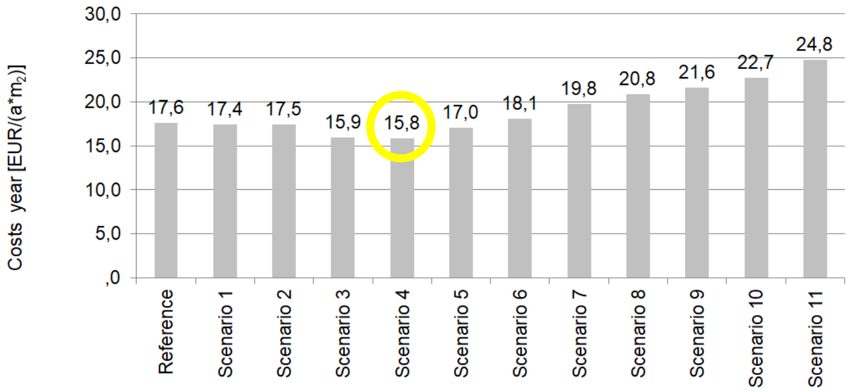

Figure 8. Cost-effective renovation packages for Heating system 1 – Reference [natural gas].

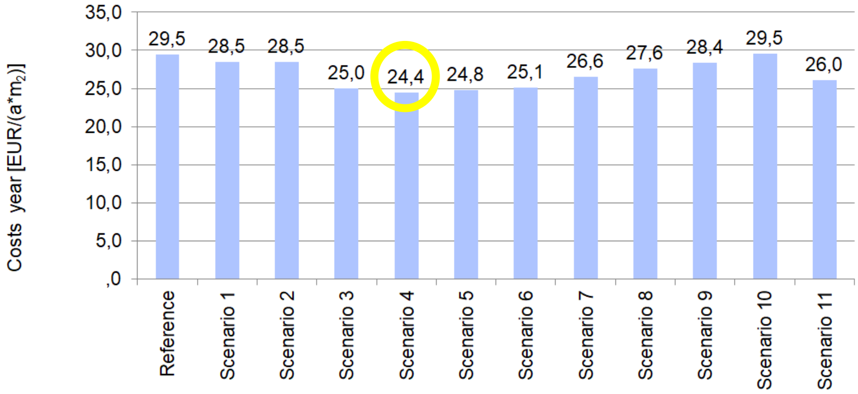

Figure 9. Cost-effective renovation packages for Heating system 2 - [heat pump air source].

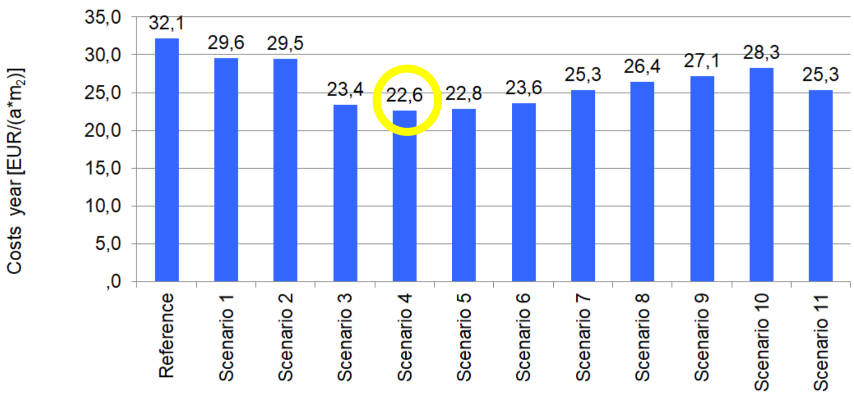

Figure 10. Cost-effective renovation packages for Heating system 3 - [heat pump ground source].

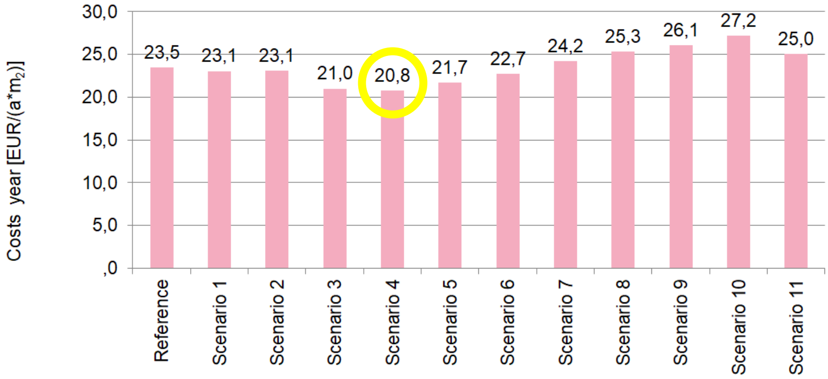

Figure 11. Cost-effective renovation packages for Heating system 4 - [district heating].

The following graph (**Figure 12**) summarizes the cost savings of the most cost-effective renovation package on the building envelopes for various types of heating systems investigated, compared to a scenario in which only the heating system is replaced.

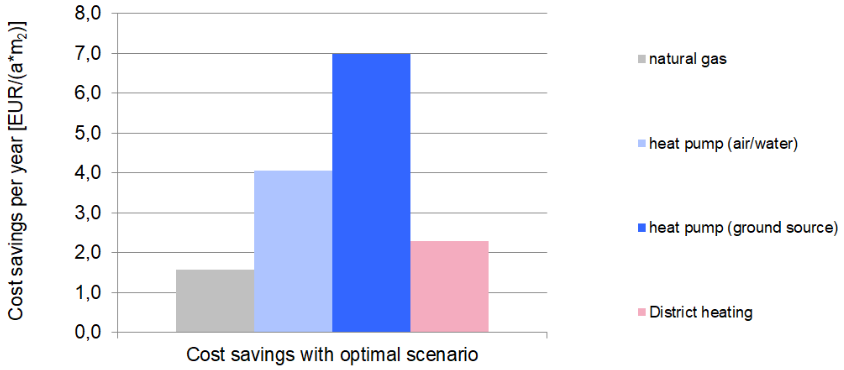

Figure 12. Cost savings for the most cost-effective renovation package for each heating system.

Discussion

The cost-effectiveness of the measures on the building envelope strongly depends on the heating system. Combined with the air source heat pump and the ground source heat pump, all investigated measures on the building envelope, together with the installation of a solar thermal system, a PV system, an electric battery and a mechanical ventilation system with heat recovery, are cost-efficient.

Combining the same measures with district heating or natural gas leads to the cost-effectiveness of the following renovation measures: renovation of roofs, façades and windows to Passive House standards. Renewable energy generation on-site is not cost-efficient. Likewise, the mechanical ventilation system with heat recovery is also not.

Another interesting finding is that the combination of building envelope measures, on-site renewable energy generation and the addition of a mechanical ventilation system with heat recovery does not automatically lead to carbon emission reductions. Combined with air source heat pumps, geothermal source heat pumps and district heating partially lead to increased carbon emissions. The reason for this is the embodied emissions associated with these measures.

A look at the primary energy demand shows a completely different picture. All investigated measures lead to a primary energy reduction when compared to the anyway renovation, independent of the heating system.

The comparison of the investigated heating systems shows that the lowest carbon emissions are achieved by the heat pump systems (air source and ground source) and the district heating system. The results are quite similar. Higher emissions are caused by natural gas heating. Similarly is the picture when looking at the primary energy demand. Here, the district heating systems show interesting results. When combined with the anyway measures, the primary energy demand is highest, but combining the measures on the building envelope and the renewable energy generation on-site can reduce the primary energy demand very effectively. The cost comparison of the different heating systems shows the lowest life cycle costs for natural gas heating, followed by the district heating system, the ground source heat pump and the air source heat pump. The highest cost-saving potential is shown by the ground source heat pump.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 17. Responses to the hypotheses according to the Austrian generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✓
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	−
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	✗
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	✓
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	−
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	✓
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	✓
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»	−

✓ Confirmed   − Not investigated   ✗ Not confirmed

2.2 Denmark

Description of the generic district

Table 18. General Information about the Danish district.

Parameter	Explanation/definition
Location	Kildeparken, Aalborg DK
Latitude	57º04
Longitude	-9º91
Climate zone (Köppen classification)	Cfb (Oceanic)
Number of buildings in total	1019 (number of dwellings)

Figure 13. Aerial view/schematic of the Danish generic district in Aalborg. From http://www.kildeparken2020.dk (with permission).

The Danish generic calculations are performed for a district based on a case study, where the building typologies have been simplified. The district is reasonably representative of typical Danish suburban neighbourhoods around the larger cities (Copenhagen, Århus, Odense and Aalborg).

Kildeparken is part of the Aalborg East district, consisting primarily of 1,019 dwellings from the 1970s located in a park landscape. The district is a mixed development with single-family houses, terraced houses and apartment blocks.

In 2010, a state assessment of the development was carried out, and a summary is reproduced here.

Taking into account the age and construction method used, the buildings are in need of renovation.

In general, the buildings are in a poor state and, in some places, they lack insulation of façades, gables and terrain decks. The low level of thermal insulation is confirmed by high energy consumption.

The development has a general problem with mould growth of varying natures. This is due to the poor thermal insulation in façades and gables and many thermal bridges in the building envelope. The façade has about 70 mm of insulation in the hollow wall. There are many thermal bridges in wall corners and joints to the floor and roof.

To improve the buildings, the insulation of façades and gables must be increased, which requires their renovation. At the same time, the improved insulation of the buildings will reduce heat consumption and carbon emissions, as well as increase the comfort and indoor climate of the homes.

Figure 14. Photo of the single-family houses with flat roofs, poor thermal insulation in façades and gables, as well as many thermal bridges in the building envelope. Photo: Ole Balslev-Olesen.

Figure 15. Photo of the apartment block. Photo: Ole Balslev-Olesen.

The heating supply of the district comes from a central district heating network and the electricity from the electricity supply system in the area. The supply system is illustrated in **Figure 16**.

Total final consumption (TFC) is the energy needs in the district calculated with the energy calculation programme and includes space heating, domestic hot water, electricity for operation and household and losses from the internal district heating network.

A district heating heat loss of 20% of district heating production and 7% of electricity production (total primary energy supply, TPES) is included in the calculations.

The analysis includes heat production from district heating with average data for district heating in Denmark and from renewable energy such as solar heating, biofuel and heat pumps.

Electricity consumption is covered by the general grid with average data of electricity in Denmark and from renewable energy such as photovoltaic panels and wind turbines.

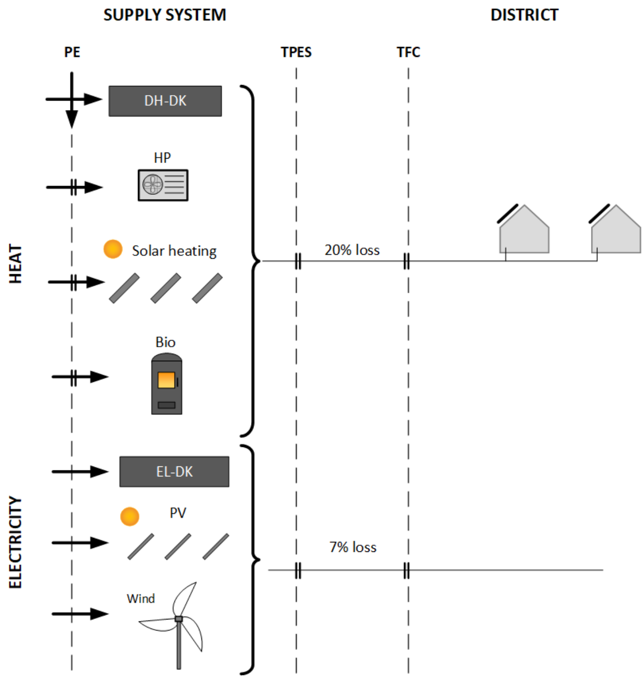

Figure 16. Principle of the central heating and electricity supply system in the area. PE: Primary energy is the total energy need for the supply system; TPES: Total primary energy supply; FTC: Total final consumption of the district. Diagram by Jesper Kragh.

Building typologies

In the district, there are three different types of dwellings with a distribution of one-family houses, apartment blocks and row houses, as can be seen from **Table 19**.

Table 19. Building typologies of the Danish generic district.

Parameter	Unit	Building typology 1	Building typology 2	Building typology 3
		Building information		
Type		Single-family	Apartment Blocks	Terraced houses
Number of units		155	432	432
Number of buildings per typology	No	155	18	27
Construction period		1968-72	1968-72	1968-72

Parameter	Unit	Building typology 1	Building typology 2	Building typology 3
		Geometry		
Gross heated floor area (GHFA) per unit	m^2	120	90	100
Heated volume per units	m^3	360	270	300
Façade area incl. window area	m^2	164.3	57.3	67.5
Roof area if flat roof per units	m^2	120	30	50
Roof area if pitched roof	m^2			
In case of pitched roof: Is room below roof heated or not?	Yes/No	No	No	No
Area of windows to North per units	m^2	13.2	9.9	11.0
Area of windows to East per units	m^2	0	0	0
Area of windows to South per units	m^2	13.2	9.9	11.0
Area of windows to West per units	m^2	0	0	0
Area of basement ceiling	m^2	0	0	0
Area of basement wall	m^2	0	0	0
Area of basement floor	m^2	0	0	0
Number of floors above ground	-	1	3	2
		Usage		
Type of use				
Area per occupant	m^2 / person			
Typical indoor temperature (for calculations)	°C	20	20	20
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/(m^2.a)	30	30	30
		HVAC systems		
Type of existing heating system (boiler, heat pump, etc.)		District Heating		
Existing energy carrier (Gas, Electricity, etc.)		District heating		
Is ventilation system without heat recovery installed?	Yes/No	Yes, natural ventilation		
Is ventilation system with heat recovery installed?	Yes/No	No	No	No
Efficiency of heat recovery	%	-	-	-

Parameter	Unit	Building typology 1	Building typology 2	Building typology 3
Ventilation rate	l/s per m^2	0.30	0.30	0.30
Is cooling system installed?	Yes/No	No	No	No
Hot water consumption	l/m^2/day	250	250	250

Calculation parameters and scenarios

Table 20. General parameters for the Danish generic district.

Date the calculations were made	**December 2021**
Weather file used	TRY, Danish Test Reference Year, DK
External shading (by surrounding buildings) considered	No

Scenarios

To identify cost-effective solutions for reducing the district's carbon emissions and needs for primary energy, various energy-saving measures have been studied.

The measures are summarized below. The reference is based on the registered condition of the buildings from 2010, which corresponds to the insulation levels at the time of construction.

Traditional energy-saving measures are included in the study together with decentralised renewable energy plants in the form of solar heating for domestic hot water and photovoltaic panels on the roof. In addition to individual measures, combinations of several measures are also included in the study.

The scenarios denoted M0 to M11 in Table 21 are supplied with district heating corresponding to the actual supply in the district. The scenarios denoted A0 to A5 are supplied with decentralised renewable energy plants and are not connected to a district heating network. The reference case M0 corresponds to insulation levels from the 1961 Building Regulations (BR61).

Table 21. Scenarios defined for the Danish generic district.

Scenario	Measure	Description
M0	Reference BR61	Reference with district heating systems
M1	3-layer LE	New low energy windows 3-layer.
M2	200 mm roof	Extra insulation of the roof
M2a	100 mm roof	Extra insulation of the roof
M2b	150 mm roof	Extra insulation of the roof
M2c	250 mm roof	Extra insulation of the roof
M3	150 mm wall	Extra insulation of external wall
M4	HP	Air-to-water heat pump (840 kW)

Scenario	Measure	Description
M5	Solar	Solar heating for domestic hot water. Collector area single-family: 7,5 m^2, terraced house: 7,5 m^2, apartment block: 2 m^2.
M6	PV	Solar cells. PV area single-family: 20 m^2, terraced house: 2 m^2, apartment block: 2 m^2.
M7	MVHR	Mechanical ventilation with heat recovery
M8	M1+M6	Combining several actions at the same time
M9	M1+M2+M6+M3	Combining several actions at the same time
M10	M1+M2+M6	Combining several actions at the same time
M11	M1+M2+M6+M7+M3	Combining several actions at the same time
A0	Reference with RE	Decentralised heating based on renewable energy (HP).
A1	M1	A0 + replacing windows with 3-layer low-energy windows
A2	M1+M6	A0 + combination of several measures.
A3	M1+M6+M2	A0 + combination of several measures.
A4	M1+M2+M3+M6	A0 + combination of several measures.
A5	M1+M2+M6+M7+M3	A0 + combination of several measures.

The calculation parameters of the various measures are shown below, in **Table 22**.

Table 22. Calculation parameters adopted for the Danish generic district.

		Unti	Reference BR61	M1 3-layer LE	M2 200 mm roof	M2a 100 mm roof	M2b 150 mm roof	M2c 250 mm roof	M3 150mm wall	M4 HP	M5 Solar	M6 PV	M7 MVHR
Wall	U-value	W/m²K	0.7						0.19				
	Extra thickness, mm	mm	0						150				
	Material	W/mK	0.040						0.040				
	Maintenance	% of Io	0%						0%				
	Lifetime	years	40						80				
Windows	U-value	W/m²K	2.9	0.7									
	g-value		0.75	0.53									
	Maintenance	% of Io	2%	1%									
	Lifetime		20	60									
Roof	U-value	W/m²K	0.40		0.13	0.20	0.16	0.11					
	Extra thickness, mm	mm	-		200	100	150	250					
	Material	W/mK	0.040		0.040	0.040	0.040	0.040					
	Maintenance	% of Io	0%		0%	0%	0%	0%					
	Lifetime	years	80		80	80	80	80					
HP	COP		-							3.5			
	Flow temp	°C	70							70			
	Return temp	°C	50							50			
	Maintenance	% of Io	0%							5%			
	Lifetime	years	-							20			
PV	PV Type		-									Mono	
	Peakpower	W	-									150	
	Efficiency	%	-									85%	
	PV-area	m² pr. dwel.	-									7,5/20	
	Maintenance	% of Io	0%									1%	
	Lifetime	years	-									25	
SH	SH Area	m² pr. dwel.	-								2		
	Maintenance	% of Io	0%								2%		
	Lifetime	years	-								20		
Ventilation	Airchange	l/s pr. m²	0.34										0.34
	Efficient		-										90%
	Air thightness	50 Pa	4.0										1.5
	SEL	kJ/m³	-										1.2
	Maintenance	% of Io	0%										5%
	Lifetime	years	-										20
	Investment costs	**Euro/m²**	**0**	**132**	**19**	**9**	**14**	**23**	**106**	**87**	**15**	**32**	**73**

Supply

The district is supplied with heat and electricity from central supply systems corresponding to the average for Danish systems, which is expected to be achieved in 2025.

The importance of the increased use of renewable energy in the central supply systems has been studied with data as shown below. ESC is the energy-saving cost. 1 Euro = 7.5 DKK.

Table 23. Supply systems characteristics of the Danish generic district.

Supply systems solar heating					
	Solar fraction	10.0%			
	Solar performance	600	kWh/m²		
	Investment costs	1600	DKK/m²	4,420,457	DKK
	Maintenance	2.0%		88,409	DKK/year
	Lifetime	20	years ESC=	0.55	DKK/kWh
	Solar heat contribution	1,657,671	kWh/year		
Supply system Heatpump (Air)					
	HP fraction	40.0%			
	Size - heat	0.84	MW		MWH/year
	COP	3.58	El HP =	1,852,147	kWh/year (el)
	Operation time	4800	hours		
	Investment costs	6.20	mio/MW	10,195,995	DKK
	Maintenance	15	DKK/MWh	99,460	DKK/year
	Lifetime	20	years ESC=		
	HP contribution	6,630,686	kWh/year (heat)		
Supply system PV electricity					
	PV fraction	10.0%			
	Performance	0.200	kWh/m²/år	362	kWp
	Investement	6200	kr/kWp	2,241,485	DKK
	Maintenance	1.0%		22,415	DKK/year
	Lifetime	25	years ESC=	0.33	DKK/kWh
	Contribution	361,530	kWh/year		
Supply system Wind turbine electricity					
	Wind fraction	40.0%			
	Size	2.00	MW	4,697,920	kWh/year
	Investment costs	14.89	mio DKK	4,584,627	DKK
	Maintenance	5.0%		229,231	DKK/year
	Lifetime	15	years ESC=	0.32	DKK/kWh
	Contribution	1,446,119	kWh/year		

Generic district calculation results

The energy needs for space heating, domestic hot water and electricity for operation and household appliances are calculated for the three building typologies of the district. The analysis includes a calculation of energy needs and investment for various energy measures.

As an example, the calculation of the reference scenario (M0) and window replacement (M1) is shown in Table 24. The annual heat requirements of the reference, including internal district heating heat loss, are calculated as 165 kWh/m², which corresponds well to the measured heat consumption in the district of 170 kWh//m². The internal district heating network is in very poor condition, and therefore, an annual heat loss equivalent to 28 kWh/m² has been assumed. The annual net energy consumption of the buildings is, therefore, 137 kWh/m², which is significantly greater than the energy requirements for new constructions in the current Danish Building Regulations (BR18), i.e., 30 kWh/m² per year.

Table 24. Calculation example of reference (M0) and window replacement (M1). NPV is the Net Present Value.

			Ref M0	M1
Total final Consumption, TFC				
	Heat	kWh/(a m^2)	165	126
	Electricity	kWh/(a m^2)	36	35
Operation costs				
	Heat	Euro/(a m^2)	14.3	11.0
	Electricity	Euro/(a m^2)	10.6	10.4
	Total	Euro/(a m^2)	24.9	21.4
Primary energy, PE				
	Heat	kWh/(a m^2)	190.6	146.2
	Electricity	kWh/(a m^2)	77.4	75.9
	Total	kWh/(a m^2)	268.0	222.2
Emission, GWP				
	Heat	[kg CO_2-Equiv.]	14.5	11.1
	Electricity	[kg CO_2-Equiv.]	4.9	4.8
	Total	[kg CO_2-Equiv.]	19.3	15.9
LCC				
	Investment, Io	Euro/(a m^2)	0	132
	Operating Costs, O	NPV, Euro/m^2	879	754
	Maintenance, M	NPV, Euro/m^2	97	59
	Replacement costs, R	NPV, Euro/m^2	58	0
	NPV (Io+O+M+R)	Euro/(a m^2)	20.7	18.9

Calculation 1: DH(RE) // IH(RE)

DH = District Heating system; IH = Decentralised Heating system, RE = Renewable Energy

Calculation 1 provides an answer to Hypothesis 1.

This calculation analyses the increased use of renewable energy sources both in a district energy system and in a decentralised heating system. The results of the calculations are given in Figure 17.

DH(RE): District heating energy system with an increased share of renewable energy sources in the heating and electricity system. Renewable energy in the district heating system is increased by adding a solar heating system and a heat pump system. Renewable energy in the district electricity system is increased by adding a photovoltaic system and wind turbines. The size of the renewable system is defined as a fraction of the total final consumption of the reference (TFC_{ref}).

Solar heating:	10% of TFC_{ref} thermal heat
HP:	40% of TFC_{ref} thermal heat
PV:	10% of TFC_{ref} electricity
Wind Power:	40% of TFC_{ref} electricity

IH(RE): The existing district heating supply is transformed into a decentralised heating system with heat pumps and solar heating for the domestic hot water. The investment of the transformation is included in the reference (A0) costs. The district heating system is disconnected from the district and the electricity supply corresponds to the average for Denmark.

IH(RE)+: As IH(RE), but with an increased share of renewable energy in the district electricity supply.

PV:	10% of TFCref electricity
Wind Power:	40% of TFCref electricity

DH(RE)+: As DH(RE), but with an increased share of renewable energy.

Solar heating:	10% of TFC_{ref} thermal heat
HP:	90% of TFC_{ref} thermal heat
PV:	10% of TFC_{ref} electricity
Wind Power:	90% of TFC_{ref} electricity

Figure 17 shows the increased use of renewable energy in a district energy system and a decentralised heating system.

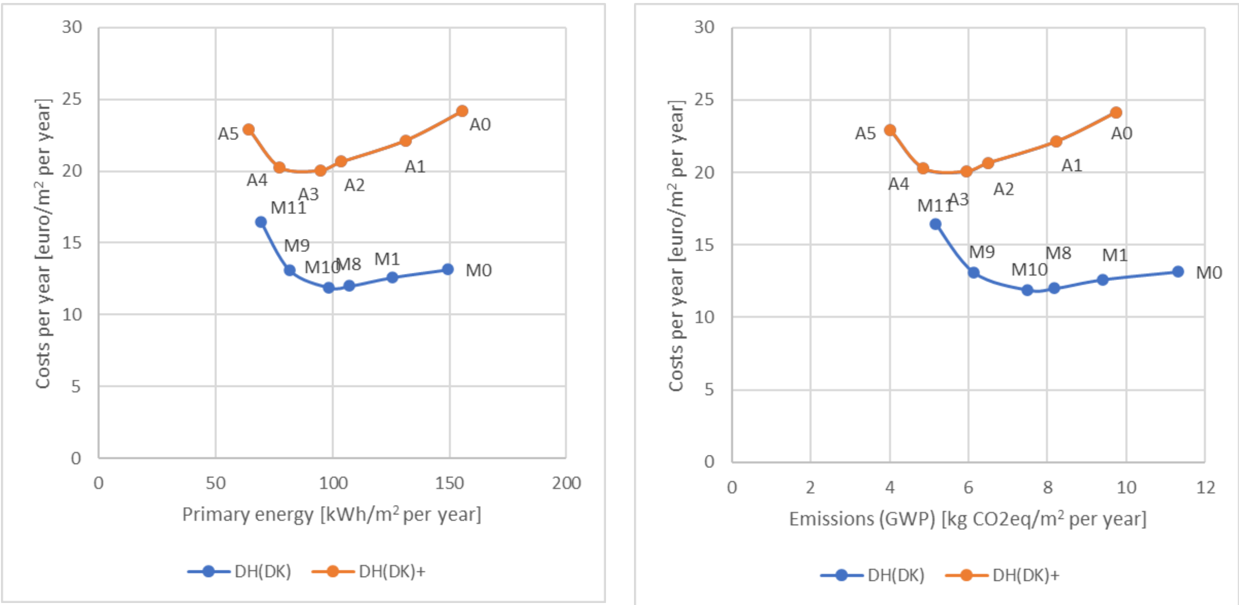

Figure 17. Results for increased use of renewable energy in the heating system.

The graph can be interpreted as follows: switching to renewable energy in a central supply is much more cost-effective compared to a switch to a decentralised renewable heat supply (M0<A0). Energy saving measures are cost-effective in central as well as in decentralised systems but are more relevant in a decentralised system.

Figure 18 and Figure 19 show the results for an increased share of renewable energy in the district electricity supply.

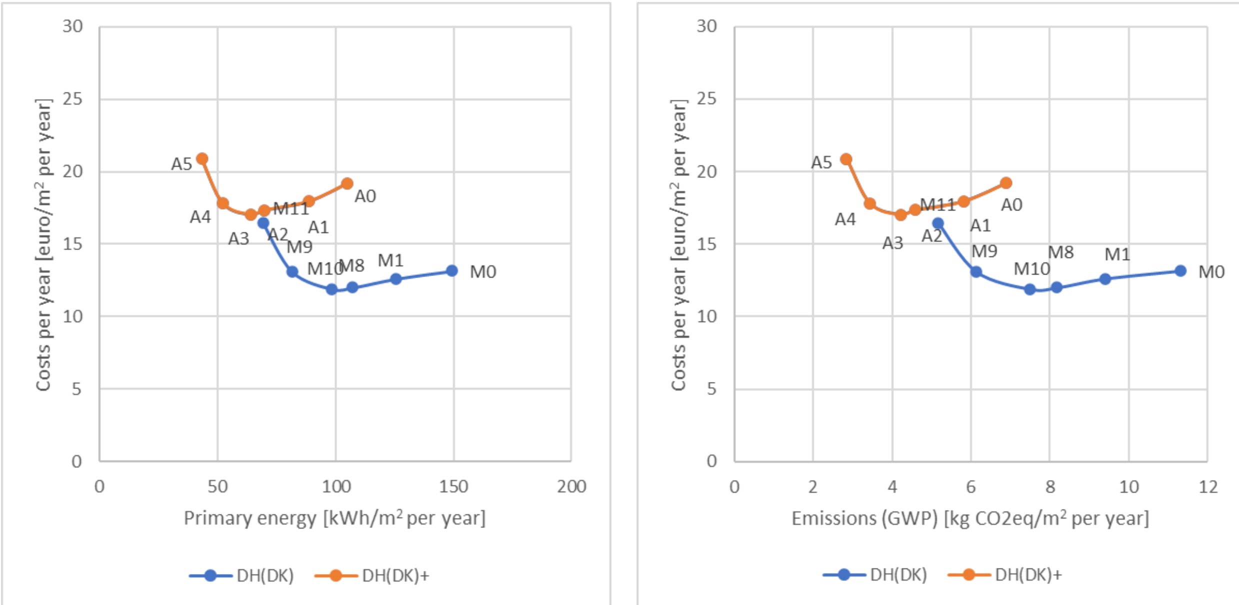

Figure 18. Results for increased use of renewable energy in the electricity supply.

Interpretation: Increasing the share of renewable energy in the electricity supply improves both the economy and the environmental impact of a decentralised supply based on renewable energy. The decentralised solution achieves lower primary energy consumption and emissions. However, the cost is significantly higher.

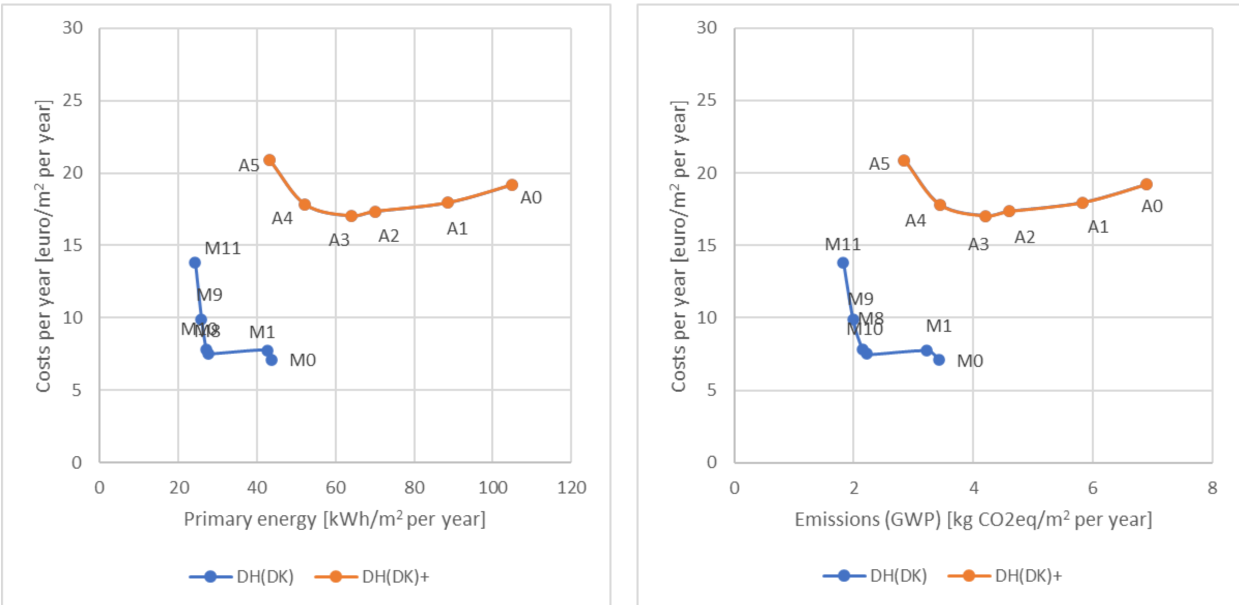

Figure 19. Results for a 100% switch to renewable energy in electricity supply.

Interpretation: increasing the share of renewables in the central supply to 100% renewable energy DH(RE)+ achieves significant reductions in primary energy use and emissions. However, it is clear that in this situation the cost-effectivity of energy-saving measures is significantly lower.

Calculation 2: DH(DK) // DH(RE)

Calculation 2 provides an answer to Hypothesis 2.

This calculation analyses the increased use of renewable energy in a district heating and electricity system. The results of the calculations are given in Figure 20.

DH(DK): District systems with average data for district heating and electricity systems in Denmark.

DH(RE): See calculation 1.

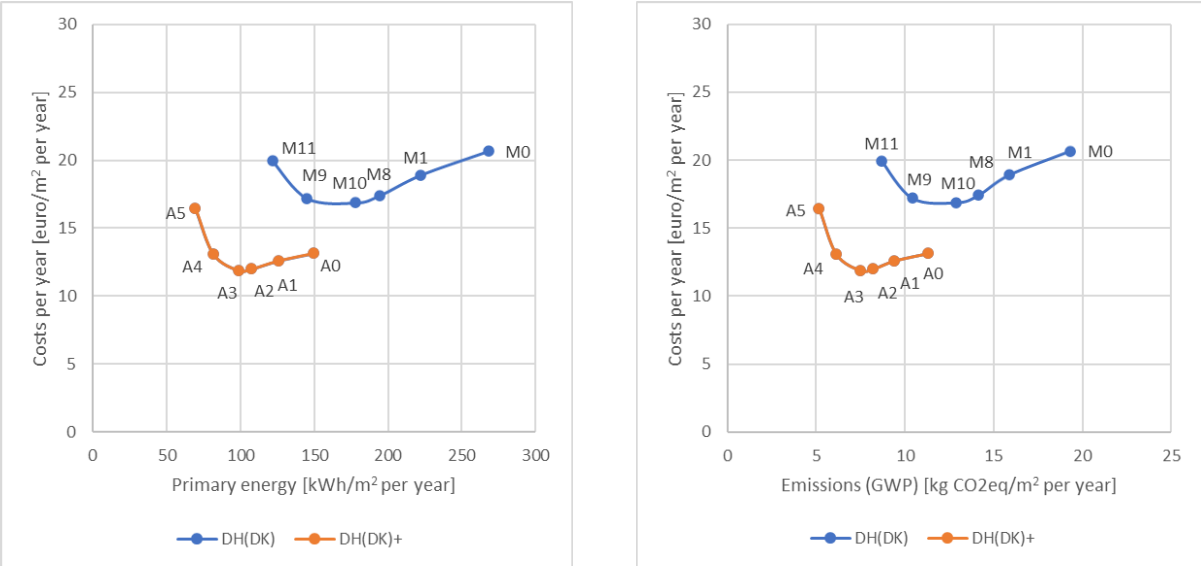

Figure 20. Results of increased use of renewable energy in a district heating and electricity system.

Interpretation: both environmental and economic advantages are achieved by increasing the use of renewable energy in the district heating and electricity system.

Calculation 3: DH(FF) // IH(RE)

Calculation 3 provides an answer to Hypothesis 3.

The calculation analyses the increased use of renewable energy in a decentralised heating system and a district heating system based on natural gas. The results of the calculations are given in Figure 21.

DH(FF): District heating systems based on natural gas (fossil fuels) and a district electricity system based on average electricity supply data in Denmark.

IH(RE): See calculation 1.

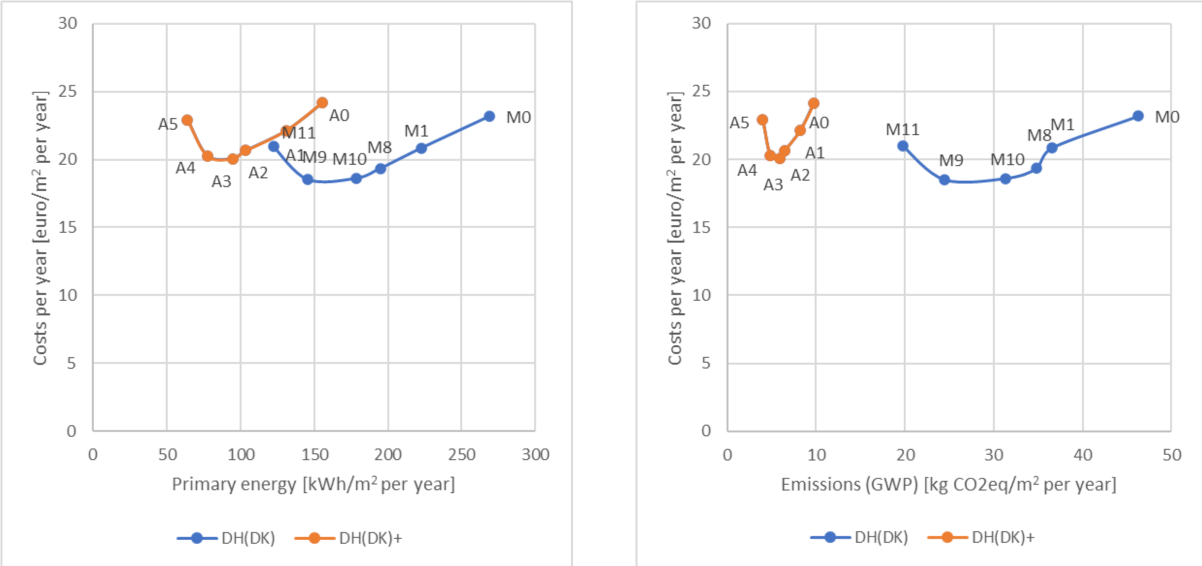

Figure 21. Results of the increased use of renewable energy in a decentralised heating system and a district heating system based on natural gas.

Interpretation: there are major environmental advantages in converting a district heating system based on fossil fuels into a decentralised supply based on renewable energy. The conversion is largely cost-neutral.

Calculation 4: Uncertainties.

Calculation 4 provides answers to the greatest uncertainties in the assumptions, i.e., demonstrating the reliability of the results. The results are shown in Figure 22 and Figure 23.

Two different analyses are carried out. Firstly, the importance of a 25% increase in the price of energy-saving measures is analysed. This analysis will indicate how much the changes in prices influence the results. Secondly, an analysis using the expected future energy data regarding emissions is carried out. The energy data is given in Section 2.2.3. Denmark must meet ambitious climate goals in the coming years, and this is done with lower use of fossil fuels and an increased share of renewable energy in the Danish energy supply. The analysis provides answers to the use of the expected energy factors in 2035.

DH(DK): See calculation 1.

DH(DK)+: All building investments (energy-saving measures) have increased by 25%.

DH(DK)2035: Energy data change from the year 2025 to 2035.

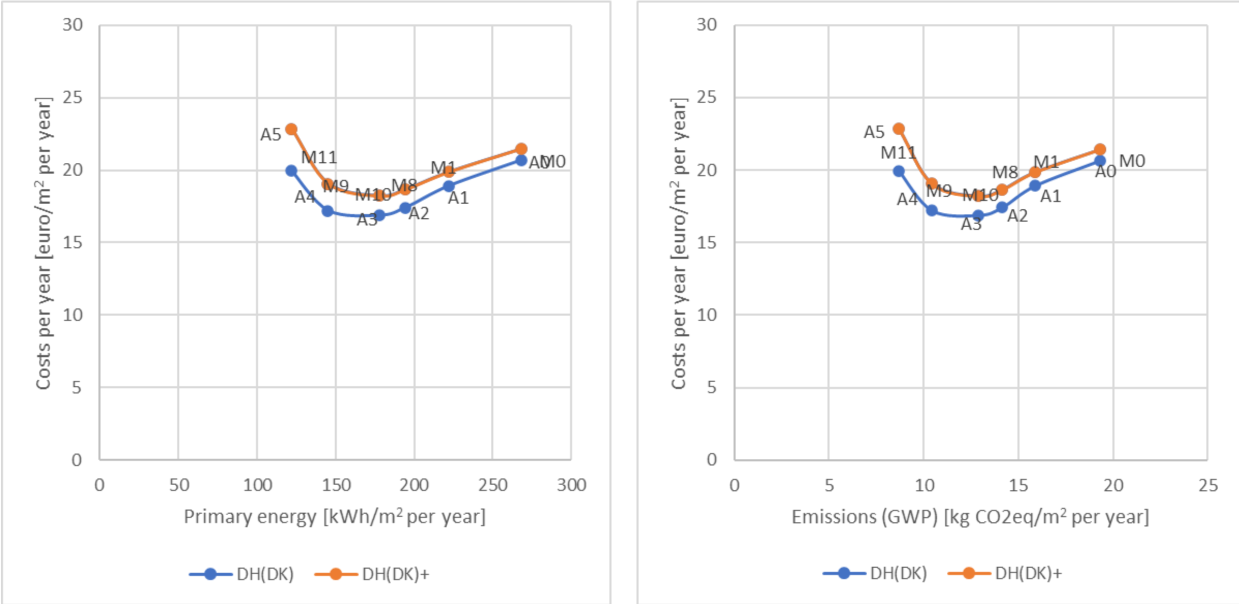

Figure 22. Uncertainty related to investment costs increasing 25%.

Interpretation: a general increase of 25% in the cost of energy-saving measures changes the overall cost only slightly. The conclusions remain unchanged.

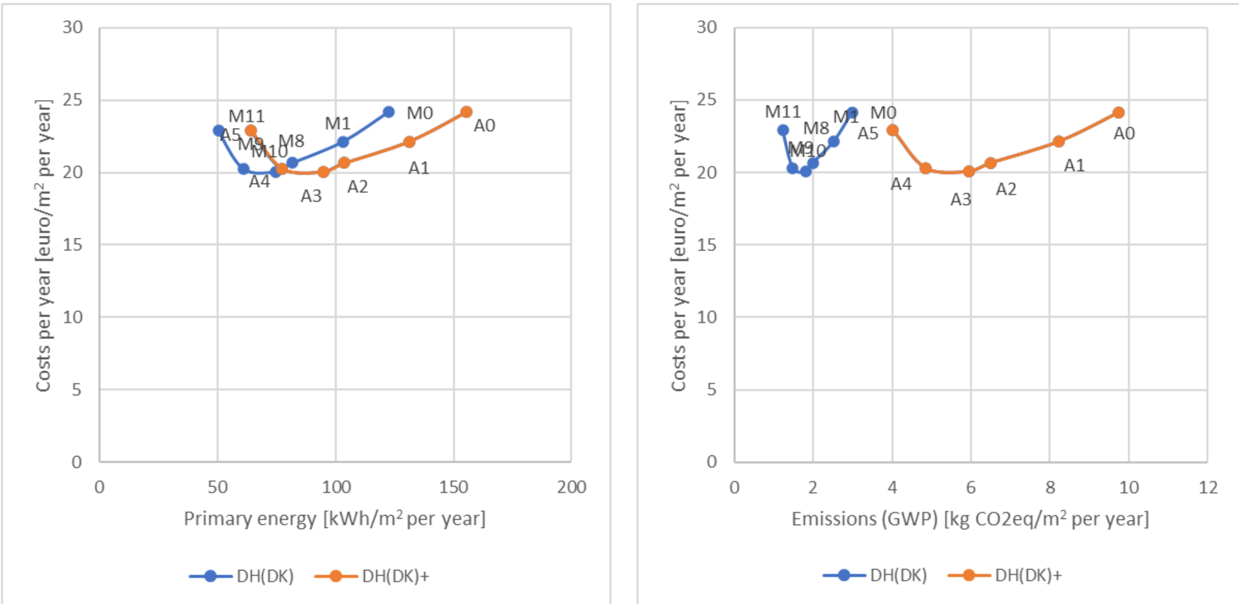

Figure 23. Uncertainty of changing energy data from the year 2025 to 2035.

Interpretation: using energy data from 2035 reduces primary energy consumption by 20-25% and emissions are significantly reduced. It is noted that it remains cost-effective to introduce energy-saving measures even if the Danish energy supply in the coming years is converted more-and-more towards renewable energy. It should also be noted that reductions in primary energy consumption are still desirable since this will increase the robustness and resiliency of the energy supply system.

Calculation 5: Cost-effectiveness of combinations of measures

Calculation 5 provides answers to which measures are the most cost-effective.

The most cost-effective solutions of the scenarios (M10 and A3) are given in **Figure 24**.

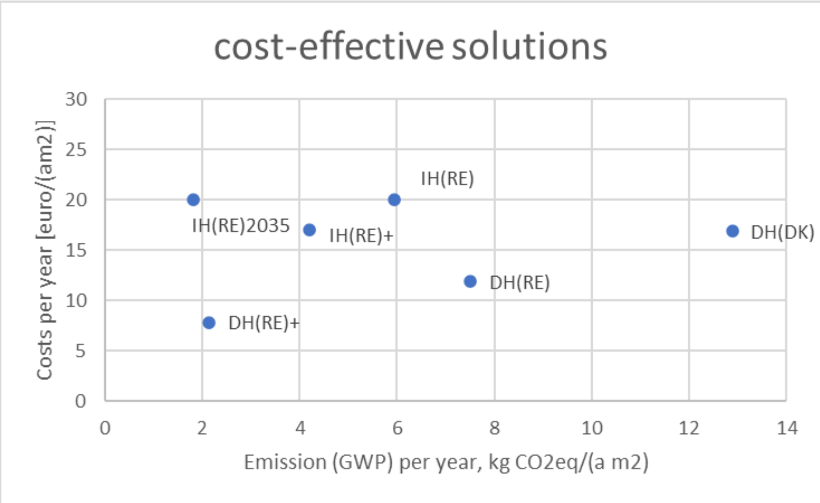

Figure 24. The most cost-effective solutions in the scenarios (M10) and (A3).

Interpretation: a shift to renewable energy and the use of energy-saving measures in the Danish housing sector bring significant environmental improvements in both central and decentralised solutions. In both scenarios, the shift in the central supply can be implemented with significant economic savings. For this particular generic district, it is clear that the existing district heating infrastructure plays a significant role concerning costs.

Calculation 6: Additional calculations

The purpose of the following calculation is to clarify the importance of the insulation standard in the reference building or the energy needs of the buildings for heating before renovation. The result is shown in **Figure 25**.

DH(DK)77: The insulation standard corresponds to the requirements of the Danish Building Regulations of 1977 (shift from 1961 to 1977).

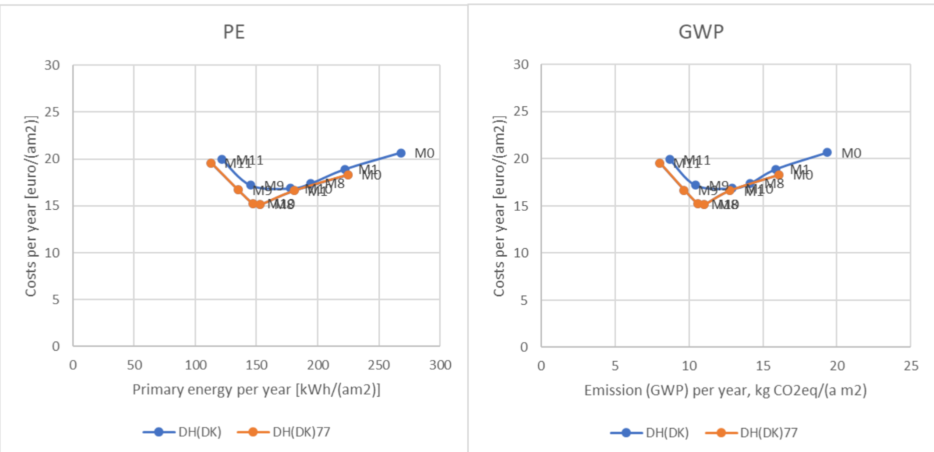

Figure 25. The insulation standard corresponds to the requirements of the Danish Building Regulations of 1977 (shift from 1961 to 1977).

Interpretation: clearly, it is still cost-effective to introduce energy-saving measures in a district that does not meet modern energy-efficiency requirements. It should be noted that if the starting point (the reference buildings) is shifted further towards today's standards, the system losses (heat loss in the district heating network and electricity network) will make investments less and less cost-effective.

Discussion

What stands out when interpreting the results?

Significant reductions in carbon emissions and primary energy use can be achieved by improving the energy performance of buildings regardless of the type of supply.

An increased share of renewable energy in district systems reduces carbon emissions and primary energy use while at the same time expecting a better operating economy.

Significant reductions in carbon emissions and primary energy use are achieved by increasing the share of renewable energy in centralised as well as decentralised energy supply systems. At the same time, the reduction of carbon emissions and primary energy use of central supply systems can be achieved with significant economic savings, as opposed to decentralised supply systems, where the economy is less attractive.

What are the most cost-effective solutions?

All the calculations show that the most cost-effective solution is basic energy measures regardless of the supply type. In the current district, the replacement of windows, decentralised photovoltaic systems and roof insulation provide the most cost-effective solution. Which combination of measures is the optimal depends on the specific building and the degree to which the individual building elements meet modern insulation requirements. However, decentralised photovoltaic panels are independent of the building conditions and will therefore always be cost-effective (assuming that PV-produced electricity can only be used for common consumption).

Figure 17 shows that a large CO_2 reduction is achieved with basic energy measures and a shift from district heating to decentralised heating based on renewable energy (IH(RE)). The reduction increases with renewable energy in the district electricity system (IH(RE)+) and can be implemented without extra cost.

Figure 17 also shows that general energy measures, together with an increased share of renewable energy in a district system (DH(RE)), provide a large CO_2 reduction, and this is also more cost-effective than changing to a decentralised system.

The calculations show that significant CO_2 reductions can be achieved with increased use of renewable energy, both in district systems and in decentralised heating systems.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

The calculations are based on experience-based costs, collected from different projects. Construction costs are always subject to uncertainties and may also be affected by unforeseen societal changes. **Figure 22** shows the importance of a 25% cost increase. It is clear that the curve shifts somewhat, however, the overall conclusion remains the same.

The calculations are based on energy data for the year 2025. As more renewable energy plants are established and coal and natural gas are removed from electricity production in Denmark, these data will change significantly. This is particularly important where district heating is converted into decentralised solutions based on renewable energy and significant reductions in GWP can be expected.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 25. Responses to the hypotheses according to the Danish generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✔
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	✔
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	✔
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	−
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	−
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	−
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	✔
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»	−

✔ Confirmed   − Not investigated   ✖ Not confirmed

2.3 Italy

Description of the generic district

The case-study buildings considered in the present research stem from the definition of generic districts. Consequently, a generic district refers to an archetypal representation of existing buildings, leaving aside the inherent boundary conditions of any case.

In accordance with the guidelines agreed by the member countries involved in the IEA EBC Annex 75 project, the Italian generic district was defined as a representation of the local existing built stock. A set of ten four-storey residential blocks, schematically represented in Figure 26, was chosen as a result of a previous analysis of the prevailing typologies of a group of buildings in Italy, built between 1960-1980 and probably managed by a single entity.

To analyse the performance of the generic districts in a broader climatic context, the set of buildings was placed in three different climatic zones in Italy: Milan (MI), in zone E with 2404 Heating Degree Days (HDDs); Rome (RO), in zone D with 1415 HDDs; and Palermo (PA), in zone B with 751 HDDs. The effects of different environmental conditions were tested for different weather data corresponding to the three mentioned cities.

An energy model of a building block, generated for the reference case and the upgraded scenarios, has been defined and simulated with the DesignBuilder software (EnergyPlus calculation engine), which provides hourly energy profiles for space heating (SpH), space cooling (SpC), and electricity demand. To consider the random orientation in urban contexts, the building model has been rotated along the main exposures and the average results were considered.

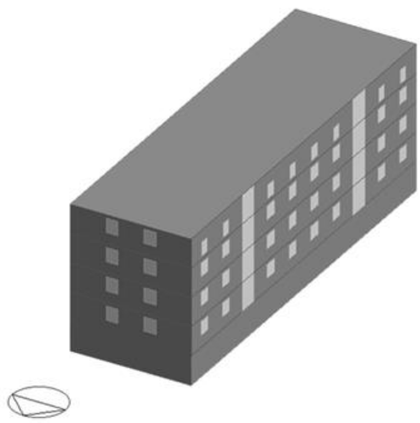

Figure 26. 3D model of the building block (simulation model defined and simulated in DesignBuilder software).

Table 26. General Information about the district in Milan.

Parameter	Explanation/definition
Location	Milan (MI)
Latitude	45º N
Longitude	9º E
Climate zone	E (Italian classification) – 2404 HDDs
Number of buildings in total	10

Table 27. General Information about the district in Rome.

Parameter	Explanation/definition
Location	Rome (RO)
Latitude	41º N
Longitude	12º E
Climate zone	D (Italian classification) – 1415 HDDs
Number of buildings in total	10

Table 28. General Information about the district in Palermo.

Parameter	Explanation/definition
Location	Palermo (PA)
Latitude	38º N
Longitude	13º E
Climate zone	B (Italian classification) – 751 HDDs
Number of buildings in total	10

Table 29. Building typologies of the Italian generic districts.

Parameter	Unit	Building typology 1
	Building information	
Number of buildings per typology		10
Construction period		1960-1980
	Geometry	
Gross heated floor area (GHFA)	m^2	1616
Heated volume	m^3	4850
Façade area incl. window area	m^2	1258
Roof area if flat roof	m^2	496
Roof area if pitched roof	m^2	0
In case of pitched roof: Is room below roof heated or not?	Yes/No	
Area of windows to North	m^2	57
Area of windows to East	m^2	16
Area of windows to South	m^2	57

Parameter	Unit	Building typology 1
Area of windows to West	m^2	16
Area of basement ceiling	m^2	496
Area of basement wall	m^2	0
Area of basement floor	m^2	0
Number of floors above ground	-	4
	Usage	
Type of use		Residential
Area per occupant	m^2 / person	30
Typical indoor temperature (for calculations)	°C	20-26
Average electricity consumption per year and m² (excluding heating, cooling)	kWh/(m².a)	11
	HVAC systems	
Type of existing heating system (boiler, heat pump, etc.)		Decentralised boiler
Type of existing DHW system (boiler, heat pump, etc.)		Decentralised gas based (MI/RO) Combined with decentralised SpH boiler (PA)
Existing energy carrier (Gas, Electricity, etc.)		Gas and electricity
Is ventilation system without heat recovery installed?	Yes/No	No ventilation system
Is ventilation system with heat recovery installed?	Yes/No	No ventilation system
Efficiency of heat recovery	%	
Ventilation rate	ach	0.2
Is cooling system installed?	Yes/No	Yes
Hot water consumption	l/person/day	30

Calculation parameters and scenarios

Table 30. General parameters for the Italian generic districts.

Date the calculations were made	**2021-2022**
Weather file used	Milan, Rome, and Palermo TRY
External shading (by surrounding buildings) considered	No

To calculate the costs of the renovation measures, reference was made to the price lists for public buildings works, available at the time of processing, which are usually used in public tenders (involving large-size works). In more detail, the following price lists were adopted: for Milan, the price list of Lombardy Region in 2020; for Rome, the price list of Lazio Region in 2020; and for Palermo, the pricelist of Sicily Region in 2019. No extra-discounts have been considered, including design and administrative building process costs. In case of missing data in one or two price lists of different locations, the costs were taken from other price lists. In case of measures not included in all the price lists, average costs available from scientific literature/ technical documentation were considered.

In particular, the envelope renovation measures include hiring scaffolding for the period required, transporting and disposing of waste and, in general, finishing surfaces (e.g., wall painting); in the case of insulation, adaptations to the new thickness of the sill, balcony joints, etc. were considered. The thermal systems renovation measures costs include the decommissioning of existing supply units and the installation of new ones together with the appropriate devices for adapting them to the existing distribution and regulation system and other technical requirements (e.g., heat exchangers in DH substations, airside connection for the decentralised AtoW DHW production, etc.). For the Palermo case, substituting the decentralised heating boilers with reversible split systems also includes decommissioning the existing radiators.

The **anyway renovation of the building envelopes** consists of three types of intervention:

- Replacement of the existing deteriorated external plaster of the walls, covering up to 30% of the overall surface
- Overlapping of roof waterproof covering with an upper-slated finished new one
- General repair of existing windows (replacement of damaged hardware, sanding of window wood, filling, and final painting)

On the other hand, **Energy Efficiency Measures (EEMs) on building envelopes** go further in the implementation of the existing constructions, intending to improve the buildings' energy performance up to the targets set by the national regulation. They consider three refurbishing actions as follows:

- Replacement of the existing low-performing double-glazed windows with double or triple-glazed windows
- Addition of thermal insulation on opaque vertical envelope elements
- Addition of thermal insulation in building roofs

Hence, for all the case studies, the three EEMs on building envelope are sorted into three retrofit scenarios, described below:

- M1: Includes the replacement of the existing windows by low-e triple-glazed units with argon-filled cavities in Milan, low-e double-glazed units with argon-filled cavities in Rome, and low-e double-glazed units with air-filled cavities in Palermo
- M2: It builds on M1 and adds a polystyrene (EPS) external thermal insulation composite system (ETICS) on the existing façades (in all three case studies)
- M3: It is a combination of the three strategies of intervention on the thermal envelope, adding external walkable EPS insulating panels on the roof of the buildings, overlapped by a waterproof covering with a new upper-slated finish, together with M1 and M2

Table 31. Measures on the building envelope.

Parameter	Unit	Anyway Milan	EEMs-Env. Milan	Anyway Rome	EEMs-Env. Rome	Anyway Palermo	EEMs-Env. Palermo
				Walls			
U-values	W/m²K	0.98	0.22	0.98	0.26	0.98	0.36
Investment costs	$EUR/m^2_{building\ element\ (façade)}$	71	130	83	151	75	101
Maintenance costs	$EUR/m^2_{building\ element}.year$						
Service life of measures	years	30	30	30	30	30	30
				Roofs			
U-values	W/m²K	0.92	0.20	0.92	0.22	0.92	0.27
Investment costs	$EUR/m^2_{building\ element}$	23	47	27	68	25	48
Maintenance costs	$EUR/m^2_{building\ element}.year$						
Service life of measures	years	30	30	30	30	30	30
				Windows			
U-values	W/m²K	3.02	1.3	3.02	1.6	3.02	2.6
Investment costs	$EUR/m^2_{building\ element}$	155	639	144	739	157	650
Maintenance costs	$EUR/m^2_{building\ element}.year$						
Service life of measures	years	30	30	30	30	30	30

All the measures regarding the thermal systems have been selected among those not implying the resettlement of the tenants.

Regarding the anyway measures on thermal systems for the districts placed in Milan and Rome, the following measures were considered for space heating (SpH) and domestic hot water (DHW):

- Substitution of the decentralised gas-based boiler
- Substitution of the decentralised gas-based water heaters

Regarding anyway measures on thermal systems for the district placed in Palermo, the following measures were considered:

- Substitution of the decentralised gas-based boiler, combined for SpH and DHW

For all the cases, the substitution of the decentralised condensing units and the gas refill of the direct expansion cooling systems was also considered. This anyway measure, assuming a service life of 15 years and regular yearly maintenance, is also accounted for in all the upgraded thermal systems scenarios (except for the Palermo case, which implies a new reversible direct expansion (DX) system for space heating (SpH)). The activation of the splits and their related energy consumption was configured to cover 50% of the cooling needs referring to the entire air volume and to be used only in alternatively occupied spaces.

Considering the reference case envelope performances, the upgrading of building systems based on renewables was defined, considering the installation of decentralised air-to-water heat pumps (AtoW HPs) for DHW in each flat, coupled with the scenarios as below.

For Milan and Rome cases:

- SA0 (noEnv + AtoW_HP + DHW_HP): decentralised gas boilers are replaced by decentralised high-temperature Air-to-Water heat pumps (to maintain the proper level of water temperature supply to radiators in the absence of envelope insulation)
- SA0-2 (SA0+PV): scenario SA0 is improved with free-standing photovoltaic panels (PV) installed on the building's roof

For Palermo's case:

- SA0 (noEnv + DHW_HP + DX Splits): decentralised gas boilers are replaced by decentralised reversible multi-split systems activated to cover the heating need of the entire air volume
- SA0-2 (SA0+PV): scenario PA-SA0 is improved with free-standing photovoltaic panels (PV) installed on the building's roof

The PV installation covers 50% of the available building roof surface in all cases.

Considering the improved building envelopes, starting from M3 scenario, the upgrading of the building equipment based on renewables was defined as follows.

For the space heating of the case districts placed in Milan and Rome, along with an improved decentralised scenario, the connection of the buildings to a new district heating (DH) network with different options for the energy supply was considered, obtaining the following scenarios:

- S0: it foresees the installation of decentralised air-to-water heat pumps
- S1: the DH is fuelled by a biomass plant with exchangers as substations
- S2: the DH is fuelled by a ground source heat pump (GSHP) with exchangers as substations
- S3: the DH is fuelled by a gas-based combined heat and power (CHP) with exchangers as substations.
- S4: the DH is fuelled by a solar system adopting seasonal thermal storage (SH) with water-to-water heat pumps (WtoW HPs) as substations
- S5: scenario S0 is improved with free-standing PV panels installed on the building's roof
- S6: scenario S1 is improved with free-standing PV panels installed on the building's roof
- S7: scenario S2 is improved with free-standing PV panels installed on the building's roof
- S8: scenario S4 is improved with free-standing PV panels installed on the building's roof

For the case district placed in Palermo, two scenarios were considered:

- S0: it foresees the installation of new reversible multi-split systems (thermal-sized), with three internal units per flat
- S5: in addition to scenario S0, the installation of PV panels on the building's roof was considered

In this case, the multi-split system refers to multi-split air conditioners with a single outdoor unit connected to two or more indoor units. In all scenarios, the installation of decentralised AtoW HPs for DHW for each flat was considered for all the district cases. The choice was made due to the starting situation before the intervention, where an individual DHW system is provided per flat, so the substitution with a new centralised distribution system would imply the resettlement of the tenants and high costs for system adaptation.

The PV installation covers 50% of the available building roof surface in all cases.

Table 32. Measures on the HVAC system including renewable energy generation on-site.

Parameter	Unit						
		Space heating (SpH) with Reference case envelope					
		Milan (MI-SA0)	**Rome (RO-SA0)**	**Palermo (PA-SA0)**			
Capacity	kW	920	657	330			
Investment costs	EUR/kW	408	457	4480			
Maintenance costs	EUR/year	7500	6000	4910			
Service life	Years	15	15	15			
		Domestic hot water					
		Anyway Milan	**Anyway Rome**	**Anyway Palermo**	**EEM for all cases**		
Investment costs	EUR/kW	1970	1970	See SpH	4930		
Maintenance costs	EUR/year	3840	3840	See SpH	9600		
Service life	Years	15	15	15	15		
		Space cooling					
		Anyway Milan	**Milan**	**Anyway Rome**	**Rome**	**Anyway Palermo**	**Palermo**
Capacity	kW	115	60	175	130	180	110
Investment costs	EUR/kW	720	2660	490	1300	350	4480
Maintenance costs	EUR/year	6520	6520	6830	6830	4914	4910
Service life	Years	15	15	15	15	15	15
		Space heating - Milan					
		Anyway	S0	S1	S2	S3	S4
Capacity	kW	920	350	350	350	350	350
Investment costs	EUR/kW	112	710	1100	1600	2450	7135
Maintenance costs	EUR/year	1950	5000	7700	11200	17200	33400
Service life	Years	15	15	15	15	15	15

Parameter	Unit						
		Space heating - Rome					
		Anyway	S0	S1	S2	S3	S4
Capacity	kW	657	260	260	260	260	260
Investment costs	EUR/kW	222	775	1180	1680	2520	1900
Maintenance costs	EUR/year	1456	4000	6140	8720	13090	9900
Service life	Years	15	15	15	15	15	15
		Space heating - Palermo					
		Anyway SpH (and DHW)	S0				
Capacity	kW	330 (97)	66				
Investment costs	EUR/kW	1455 (4928)	24190				
Maintenance costs	EUR/year	9600	19700				
Service life	Years	15	15				
		PV system - All cases					
		Milan	Rome	Palermo			
Size	kWp	26	26	26			
Investment costs	EUR/kWp	2240	2130	2020			
Maintenance costs	EUR/year	11850	11260	10670			
Service life	Years	30	30	30			

Table 33 reports a scheme of analysed scenarios.

Table 33. Analysed scenarios for the Italian generic districts.

	Milan - Rome	Palermo
	Reference case	
SpH	Decentralised gas-based boiler	Decentralised combined gas-based boilers
DHW	Decentralised gas-based boilers	
	Anyway renovation	
SpH	New decentralised gas-based boiler	New decentralised combined gas-based boilers
DHW	New decentralised gas-based boilers	
	New systems maintaining reference envelope	
SpH	New decentralised High Temp AtoW heat pumps	New decentralised reversible multi-splits
DHW	New decentralised AtoW heat pumps	New decentralised AtoW heat pumps
Electricity	PV integration option (SA0-2)	PV integration option (SA0-2)
	Scenarios of new systems coupled with M3 envelopes	
SpH	New decentralised AtoW heat pumps (S0 and S5)	New decentralised reversible multi-splits (S0 and S5)
	Connection to a DH network fuelled by a bio-mass plant (S1 and S6)	
	Connection to a DH network fuelled by a GSHP (S2 and S7)	
	Connection to a DH network fuelled by a CHP (S3)	
	Connection to a DH network fuelled by solar thermal storage and WtoW HPs (S4 and S8)	
DHW	New decentralised AtoW heat pumps (from S0 to S8)	New decentralised AtoW heat pumps (S0 and S5)
Electricity	PV (from S5 to S8)	PV (S0 and S5)

Generic district calculation results

The following graphs (Figure 27 to Figure 29) give an overview of specific yearly carbon emissions and yearly primary energy use vs. costs for the various renovation packages on the building envelopes for the different types of heating systems investigated.

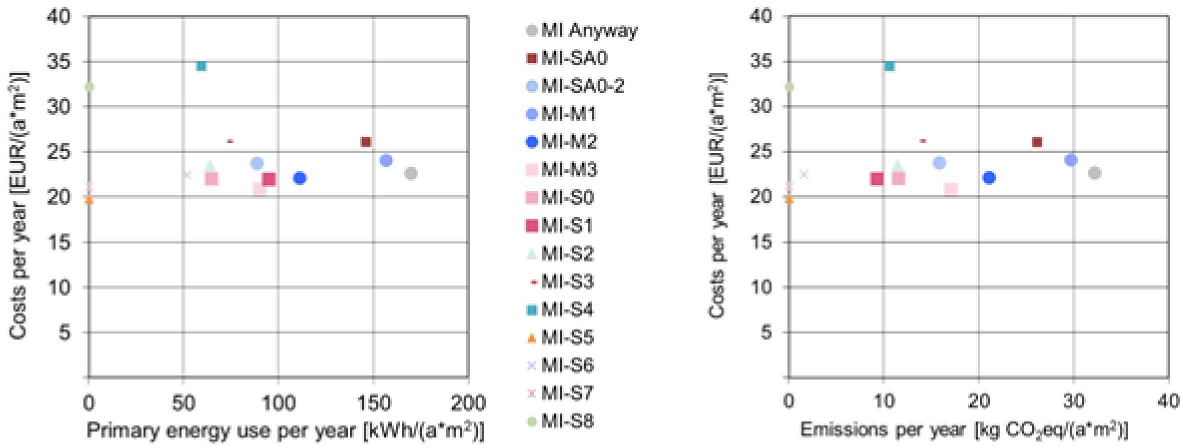

Figure 27. Results of calculations for the generic district in Milan.

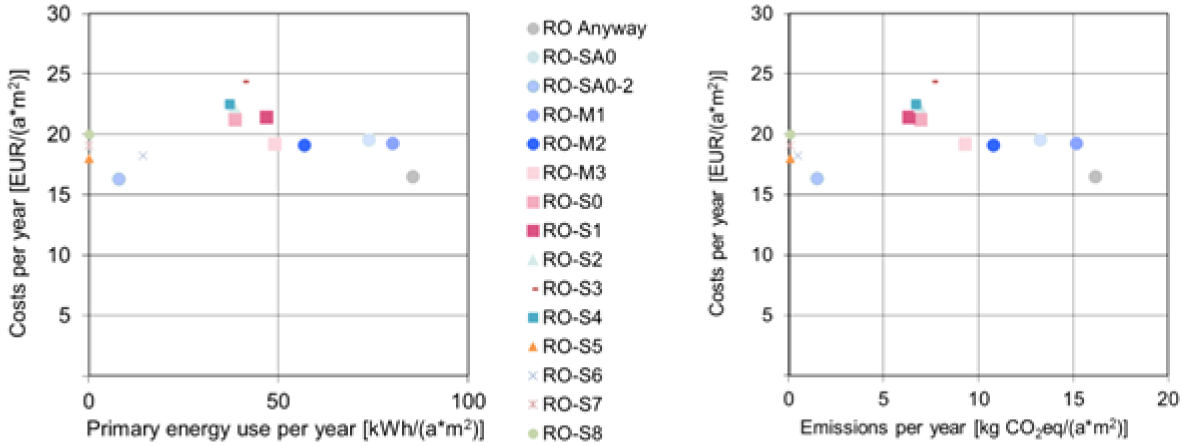

Figure 28. Results of calculations for the generic district in Rome.

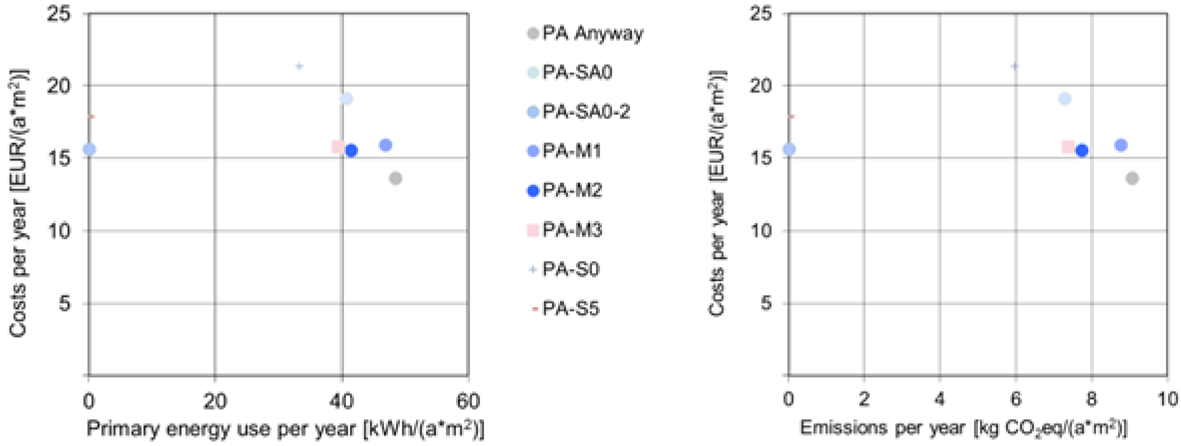

Figure 29. Results of calculations for the generic district in Palermo.

Based on the charts above, the cost-optimal scenario in Milan generic district is MI-S5 (EEMs on the envelope, decentralised AtoW heating systems, decentralised AtoW DHW production, and PV), with the most cost-effective reduction on annual carbon emissions and primary energy. Excluding the scenarios with PV installation, the cost-optimal scenario is MI-M3 (EEMs on the envelope with anyway renovation of building systems).

The cost-optimal scenario in Rome generic district is RO-SA0-2 (reference envelope with High-Temperature AtoW heating systems,decentralised AtoW DHW production, and PV). All the other scenarios are not cost-effective compared to the Anyway Renovation scenario.

Lastly, none of the scenarios considered in Palermo generic district are cost-effective compared to the Anyway Renovation scenario.

Figure 30 provides a summary of relationships between specific yearly carbon emissions or yearly primary energy use vs. costs for various renovation packages on the building envelopes for various types of heating systems investigated in the three locations.

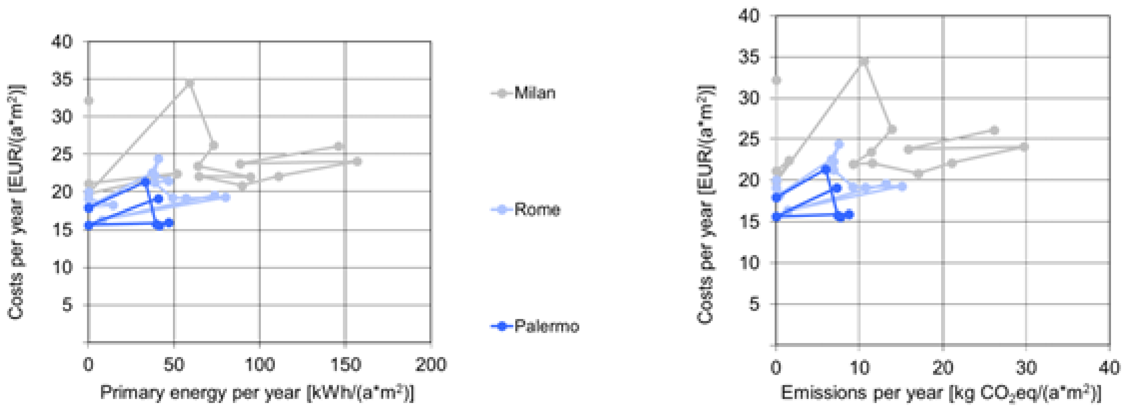

Figure 30. Overview of combinations of renovation packages and heating systems in the three locations.

The specific costs, carbon emissions, and primary energy decrease in most cases as we move to different climatic zones towards the southern areas.

The following graphs (Figure 31 to Figure 33) show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

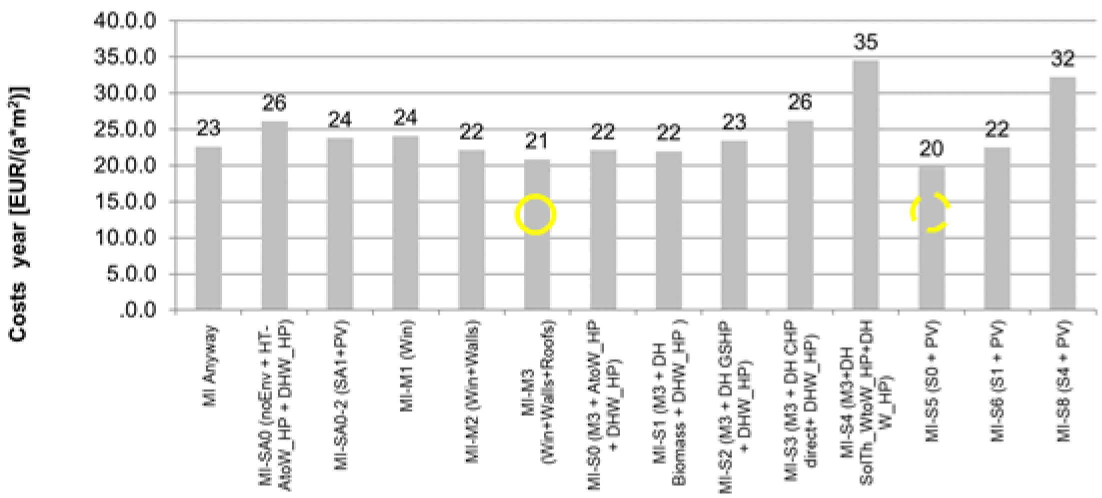

Figure 31. Comparison of energy systems for the generic district in Milan.

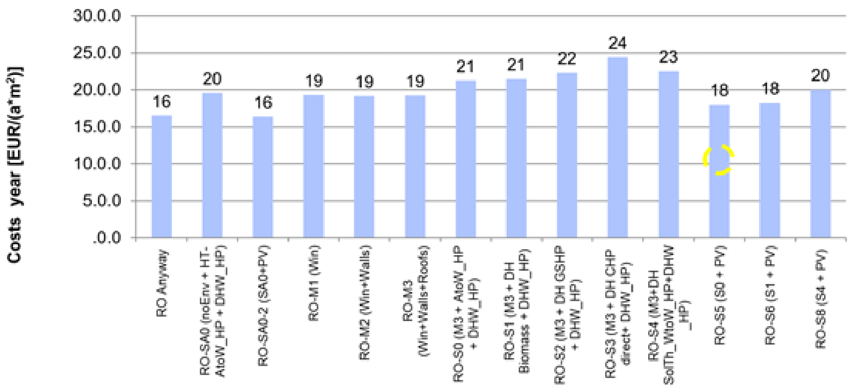

Figure 32. Comparison of energy systems for the generic district in Rome.

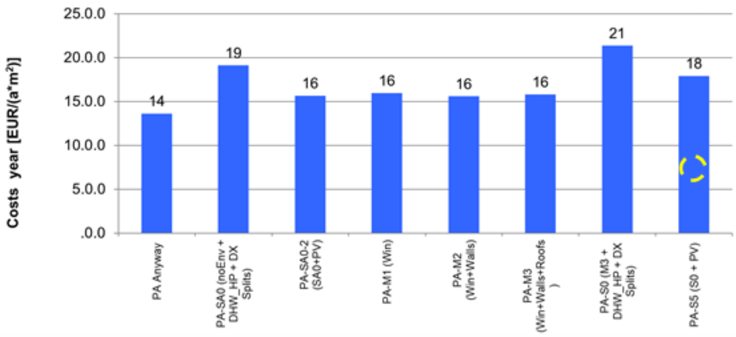

Figure 33. Comparison of energy systems for the generic district in Palermo.

Regarding the global cost, the anyway renovation scenario shows as the cheapest strategy, followed by the S5, for all generic districts.

Figure 34 summarizes the cost savings of the most cost-effective renovation package on the building envelopes for various types of heating systems considered, compared with a scenario where only the heating system is replaced. The comparison distinguishes scenarios with PV (dashed columns) or without PV (filled columns), with a scenario where only the heating system is replaced.

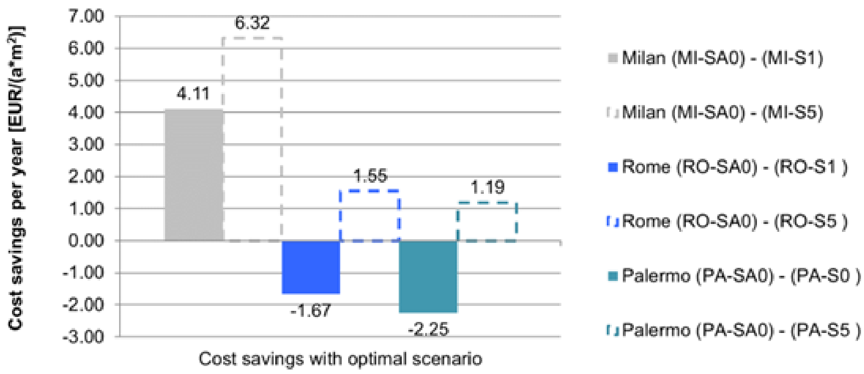

Figure 34. Cost savings of the most cost-effective renovation package.

Based on the chart above, the greatest cost savings in Milan are observed for a generic district with PV. For both the generic districts in Rome and Palermo, only a scenario with PV shows convenient cost savings.

Discussion

What stands out when interpreting the results?

Switching to a centralised district heating system implies higher costs due to the deployment of the network distribution.

What are the most cost-effective solutions?

The most cost-effective solution in Milan generic district is MI-S5 (EEMs on the envelope, decentralised AtoW heating systems with decentralised AtoW, DHW production and PV); in Rome, the generic district is RO-SA0-2 (reference envelope with High-Temperature AtoW heating systems, decentralised AtoW DHW production and PV), while none of the scenarios considered in Palermo generic district is cost-effective compared to the Anyway Renovation case.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

The present research is developed through virtual energy models representing generic districts; the uncertainties remain, given the fact that no on-site measures were taken into account.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 34. Responses to the hypotheses according to the Italian generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✓
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	−
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	−
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	−
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy based district heating system associated with decentralised heat pumps.»	−
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	−

Hypotheses	
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	Confirmed
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel based heating system, every optimal solution includes at least a switch to a renewable energy based heating system.»	Confirmed

Confirmed Not investigated Not confirmed

Justification:

Hypothesis 1: Assuming EEMs on building envelopes, district heating systems based on Biomass make similar sense as decentralised heating systems based on renewable energy for both Milan and Rome cases.

Hypothesis 2: The hypothesis cannot be investigated because our scenarios do not include an existing DH.

Hypothesis 3: The hypothesis cannot be investigated because our scenarios do not include DH without EEM on building envelopes.

Hypothesis 4: The hypothesis cannot be investigated because our scenarios do not include an existing DH.

Hypothesis 5: The hypothesis cannot be investigated because our scenarios do not include decentralised fossil fuel heating systems without EEM on building envelopes.

Hypothesis 6: The hypothesis cannot be investigated because our scenarios do not include an existing DH.

Hypothesis 8: Yes, for both Milan and Rome cases, but only considering the PV integration and excluding the DH based on the solar thermal system coupled with low-temperature WtoW HP.

2.4 Portugal

Description of the generic district

Table 35. General Information about the Portuguese district.

Parameter	Explanation/definition
Location	Braga, Portugal
Latitude	41.5518
Longitude	-8.4229
Climate zone (Köppen classification)	Csb (Warm-summer Mediterranean climate)
Number of buildings in total	32 buildings comprising 256 apartments

The Portuguese Generic District is based on a real social housing district with the adoption of generic construction and occupancy characteristics.

Andorinhas neighbourhood, shown in Figure 35, can be considered a typical social housing development as it is a multi-family development located in an urban context, and built in the 1980s, when reinforced concrete structures were introduced and most social housing was built in Portugal. The social housing developments of this period are characterised by low construction quality and poor energy performance, often leading to building pathologies and inadequate and even unhealthy indoor thermal comfort conditions, especially during winter. At that time, affordability and lower costs were prioritized over quality, and energy performance was not a mandatory requirement, as the first thermal regulations would only come into force in Portugal in 1991.

Other characteristics that make Andorinhas a representative of social housing in Portugal are its geometry, dwelling typologies, and construction methods.

Figure 35. Aerial view of Andorinhas neighbourhood. From "Google Earth," by Google, n.d. Copyright by Google.

Built in 1983, Andorinhas neighbourhood is located in Braga, Northern Portugal, where the average annual temperature is 14.2 ºC, with the hottest month being July (average of 20.3 ºC) and January being the coldest (average of 8.4 ºC). It is owned and managed by BragaHabit (Braga Municipal Housing Company) and comprises 32 buildings, whose example is shown in **Figure 36**, grouped in diverse compositions, with a total heated area of 22 617m^2. There are 2 building typologies: 50% of the buildings are 2 and 3-bedroom apartments (T2 and T3 typologies) and 50% are 3 and 4-bedroom apartments (T3 and T4 typologies). All buildings have 4 floors and a single entrance leading to the staircase (no lifts), totalling 256 apartments.

For this assessment, the fact that buildings are oriented North-South (15 buildings) and East-West (17 buildings) brings an opportunity to investigate the energy performance of different solar orientations. Multi-family buildings, meaning a higher density of inhabitants and, therefore, higher energy needs for space conditioning and DHW, should also show how district solutions can be more attractive.

For this generic district study, construction characteristics representing typical solutions found in social housing developments built from 1970 through 1980 were adopted. Construction methods and their respective U-values were based on real characteristics and determined with the aid of ITE50 (a U-value reference guide for common construction solutions found in Portugal in different periods, developed by LNEC, Civil Engineering National Laboratory (dos Santos & Matias, 2006)), as follows. Walls comprise two layers of hollow bricks (0.11 m + 0.11 m) with an air gap of 0,15 m and no insulation (U-value of 1.5 W/m^{2}K). The sloping roof is made of a metal decking system (U-Value of 2.3 W/m^{2}K), and the windows are single-glazed with a U-value of 3.40 W/m^{2}K, g = 0.68 and visible light transmittance of 0.66. A high infiltration rate of 1.7 ach was adopted as the building envelope was considered leaky.

Since centralised heating systems are still very incipient in Portugal, decentralised electric heaters were considered the typical equipment to provide space heating. A gas boiler is considered in each apartment as the DHW supplier.

Figure 36. Building typology of Andorinhas neighbourhood. By the University of Minho research group.

Table 36. Building typologies of the Portuguese generic district.

Parameter	Unit	Building typology 1 N-S orientation	Building typology 2 E-W orientation
		Building information	
Number of buildings per typology		15	17
Construction period		1983	1983
		Geometry	
Gross heated floor area (GHFA)	m^2	9 868.80	12 748.80
Heated volume	m^3	24 672.00	31 872.00
Façade area incl. window area	m^2	8 094.72	9 999.36
Roof area if flat roof	m^2	-	-
Roof area if pitched roof	m^2	2 904.00	3 794.56
In case of pitched roof: Is room below roof heated or not?	Yes/No	No	No
Area of windows to North	m^2	676.80	-
Area of windows to East	m^2	-	889.60
Area of windows to South	m^2	334.00	-
Area of windows to West	m^2	-	378.00
Area of basement ceiling[2]	m^2	2 467.20	3 187.20
Area of basement wall	m^2	-	-
Area of basement floor	m^2	-	-
Number of floors above ground	-	4	4
		Usage	
Type of use		Residential	Residential
Area per occupant	m^2 / person	25.00	25.00
Typical indoor temperature (for calculations)	°C	18 (heating season) 25 (cooling season)	18 (heating season) 25 (cooling season)

[2] Groundfloor area (there is no basement in this building development).

Parameter	Unit	Building typology 1 N-S orientation	Building typology 2 E-W orientation
Average electricity consumption per year and m² (excluding heating, cooling, ventilation)[3]	kWh/(m².a)	247	280
		HVAC systems	
Type of existing heating system (boiler, heat pump, etc.)		Decentralised electric heaters and DHW gas boilers	Decentralised electric heaters and DHW gas boilers
Existing energy carrier **(Gas, Electricity, etc.)**		Electricity and Natural Gas	Electricity and Natural Gas
Is ventilation system without heat recovery installed?	Yes/No	Yes, natural ventilation	Yes, natural ventilation
Is ventilation system with heat recovery installed?	Yes/No	No	No
Efficiency of heat recovery	%	-	-
Ventilation rate[4]	ach	1.7	1.7
Is cooling system installed?	Yes/No	No	No
Hot water consumption	l/person/day	40	40

Calculation parameters and scenarios

Table 37. General parameters for the Portuguese generic district.

Date the calculations were made	**2020**
Weather file used	PRT_Porto.085450_IWEC.epw
External shading (by surrounding buildings) considered	Yes

The energy performance of the buildings was determined with the aid of Open Studio associated with Energy Plus, which dynamically calculates the energy needs of the buildings.

[3] Estimated value calculated in the building simulation.

[4] Estimated value calculated in the building simulation.

Occupancy was determined according to the Portuguese regulation regarding the calculation of DHW energy needs, which defines that three occupants should be considered for a T2, four occupants for a T3 and five occupants for a T4.

Two significant buildings with different solar orientations were modelled in detail and evaluated to then extrapolate their results to the district scale. An initial assessment of the reference case scenario (anyway measures) and of the 15 proposed renovation measures was conducted, and the best-performing ones were combined into five renovation packages for a new assessment.

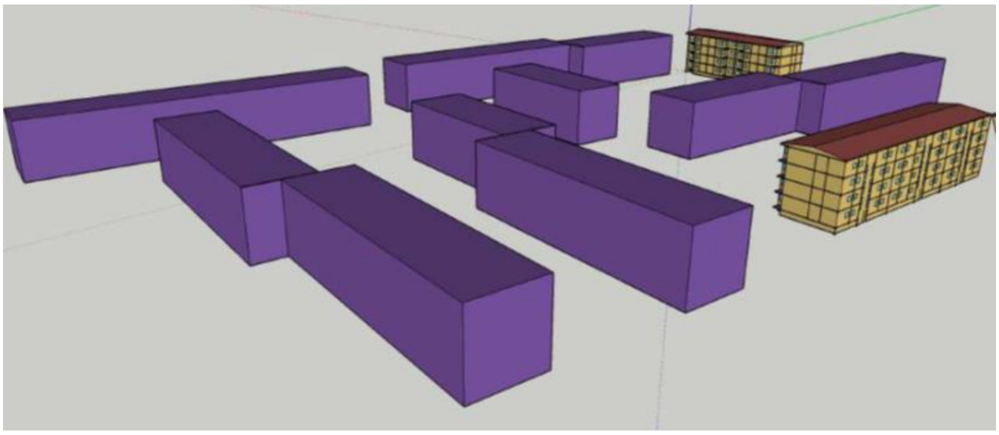

Figure 37. The district model shows the significant buildings that were modelled in detail and assessed. By the authors.

The choice of the building envelope renovation measures used in the Andorinhas neighbourhood aimed to assess the impact of common renovation strategies applied in Portugal (such as the application of ETICS), as well as the impact of others that are not so common but are efficient (such as the ventilated facade). The envelope renovation measures can be grouped into three categories:

- Improvement of the building envelope by façade insulation (insulated ventilated façades or ETICS, in different compositions).
- Improvement of the building envelope by roof insulation or substitution of the existing roof for an insulated green roof.
- Replacement of windows with double-glazed ones, varying the glazing type.

The selected renovation packages for this generic district are shown below (Table 38) and were considered to be implemented in all buildings.

Table 38. Renovation packages (scenarios M1 to M5) for the improvement of the building envelope.

	Façade	Roof	Windows
M1	ETICS EPS 100mm	EPS 80mm	PVC frame with double glazing (6mm-13mm air), clear glass (U=2.31 W/m^{2}K; g = 0.62)
M2	Ventilated Façade MW 100mm	EPS 80mm	PVC frame with double glazing (6mm-13mm air), clear glass (U=2.31 W/m^{2}K; g = 0.62)
M3	ETICS EPS 100mm	Green roof EPS 80mm	PVC frame with double glazing (6mm-13mm air), clear glass (U=2.31W/m^{2}K; g=0,62)
M4	Ventilated Façade MW 100mm	Green roof EPS 80mm	PVC frame with double glazing (6mm-13mm air), clear glass (U=2.31W/m^{2}K; g = 0.62)
M5	Ventilated Façade MW 100mm	Green roof EPS 80mm	PVC frame with double glazing (6mm-13mm air), grey tinted glass (U=2.67W/m^{2}K; g = 0.48)

ETICS | External Thermal Insulation Composite System; EPS | Expanded Polystyrene; MW | Mineral Wool; PVC | Polyvinyl Chloride

Insulation improvements and costs for implementation and maintenance of each proposed renovation package can be compared in the following table, where:

- Investment, maintenance, and replacement costs were calculated with the aid of CYPE Cost Generator, a market-based information tool widely used in Portugal (Gerador de Preços Para Construção Civil. Portugal. CYPE Ingenieros, S.A., n.d.).
- Investment costs per building element considered not only the insulation measure itself but also the measures related to the preparation of the building for the renovation measures (e.g., mechanical cleaning of the façade, dismantling and transport to the landfill of the building elements to be replaced, and scaffolding costs).
- An economy of scale discount of 14% was always applied to the investment costs except for the Reference (Anyway Measures case), since in the latter the application of maintenance measures is limited to where it is needed.
- The 30-year period of cost-optimal analysis was adopted in compliance with Commission Delegated Regulation (EU) nº 244/2012 of 16 January 2012.

Table 39. Measures on the building envelope.

Parameter	Unit	Reference | Anyway Measures	Scenario 1 | M1	Scenario 2 | M2	Scenario 3 | M3	Scenario 4 | M4	Scenario 5 | M5
			Walls				
U-values	W/m^2K	1.1	0.38	0.35	0.38	0.35	0.35
Investment costs	$€/m^2_{building\ element}$	57.81	100.18	144.21	100.18	144.21	144.21
Maintenance costs	$€/m^2_{building\ element.year}$	1.75	0.52	1.00	0.52	1.00	1.00
Service life of insulation measures	years	-	30	30	30	30	30
			Roofs				
U-values	W/m^2K	2.3	0.45	0.45	0.40	0.40	0.40
Investment costs	$€/m^2_{building\ element}$	45.57	109.30	109.30	127.24	127.24	127.24
Maintenance costs	$€/m^2_{building\ element.year}$	0.30	2.96	2.96	3.39	3.39	3.39
Service life of insulation measures	years	-	30	30	30	30	30
			Windows				
U-values	W/m^2K	3.6	2.31	2.31	2.31	2.31	2.67
Investment costs	$€/m^2_{building\ element}$	595.18	499.28	499.28	499.28	499.28	540.94
Maintenance costs	$€/m^2_{building\ element.year}$	3.49	1.74	1.74	1.74	1.74	1.74
Service life of insulation measures	years	-	30	30	30	30	30

As a next step, five energy supply systems (ESS) were selected and dimensioned to meet the neighbourhood energy needs for both space conditioning (heating and cooling) and domestic hot water needs (DHW). ESS1 is representative of the typical solutions adopted in Portuguese housing (individual space conditioning and DHW equipment, supplied by decentralised energy sources, as there are no district systems in the country). All the other systems are centralised options, still not adopted in Portugal, and chosen to evaluate their feasibility in the Portuguese context.

ESSs were dimensioned and associated aiming to reach a nearly zero-energy neighbourhood. This way, a biomass boiler (considered by Portuguese legislation as equipment based on renewable energy) supported by a solar thermal system is proposed in ESS2 and ESS3. In ESS2, the solar thermal solution meets 50% of DHW needs, whilst in ESS3 a larger solar thermal system is sized to meet 100% of DHW needs. As a biomass boiler cannot provide cooling, the cooling energy needs were calculated under the Portuguese regulations, which require considering a predefined system (in this case, a multi-split air conditioning with EER = 3.01). The last two energy systems are based on heat pump systems. In ESS4, the association of a heat pump system designed to attend to both space conditioning and DHW energy needs with a photovoltaic system capable of providing 100% of the neighbourhood energy needs is proposed. Finally, in ESS5, a heat pump system is supported by a solar thermal system dimensioned to provide 100% of DHW needs, associated with a photovoltaic system that supplies 100% of the space conditioning energy needs.

A summary of the characteristics of the energy supply systems is shown below, in Table 40.

Table 40. Energy supply systems characteristics.

		Heating	Cooling	DHW	RES
ESS1	Decentralised Conventional	Electric Heater η=1	Multi-split EER=3	Natural Gas Heater η=0,71	-
ESS2	Centralised Biomass Boiler + SH (50% DHW)	High-efficiency condensing biomass Boiler η=1.07	Multi-split EER=3	Biomass Boiler η=1.07	ST (50% DHW)
ESS3	Centralised Biomass Boiler + SH (100% DHW)	High-efficiency condensing biomass Boiler η=1.07	Multi-split EER=3	Biomass Boiler η=1.07	ST (100% DHW)
ESS4	Centralised Heat Pump + PV (100%)	Heat Pump COP/SCOP=3.47/3.31	Heat Pump EER/SEER=3.28/5.52	Heat Pump COP=3.65	PV (100% primary energy needs)
ESS5	Centralised Heat Pump + SH + PV	Heat Pump COP/SCOP=3.47/3.31	Heat Pump EER/SEER=3.28/5.52	Heat Pump COP=3.65	ST (100% DHW) + PV (100% heating and cooling)

SH | Solar Heat Collector; PV | Photovoltaic System ; η | equipment efficiency; COP | Coefficient of Performance; SCOP | Seasonal Coefficient of Performance; EER | Energy Efficiency Ratio; SEER | Seasonal Energy Efficiency Ratio

Table 41. Measures on the HVAC system including renewable energy generation on-site.

Parameter	Unit	Scenario M1	Scenario M2	Scenario M3	Scenario M4	Scenario M5
ESS1 | Decentralised Conventional						
Capacity	kW	2 944.00				
Investment costs	€/kW	151.00				
Maintenance costs	€/year	3 295.00				
Service life	Years	15 (heater and multi-split); 20 (natural gas water heater)				
ESS2 | Centralised Biomass Boiler (BB) + Solar Thermal (50% DHW) (SH)						
Capacity	kW	489.69				
Investment costs	€/kW	1 650.11				
Maintenance costs	€/year	3 807.46				
Service life	Years	15 (BB); 20 (SH)				
ESS3 | Centralised Biomass Boiler + Solar Thermal (100% DHW)						
Capacity	kW	519.38				
Investment costs	€/kW	1 854.91				
Maintenance costs	€/year	4 221.90				
Service life	Years	15 (BB); 20 (SH)				
ESS4 | Centralised Heat Pump (HP) + Photovoltaic (100%) (PV)						
Capacity	kW	939.05				
Investment costs	€/kW	1 257.70				
Maintenance costs	€/year	1 214.75				
Service life	Years	15 (HP); 20 (HP DHW); 35 (PV)				
ESS5 | Centralised Heat Pump + Solar Thermal + Photovoltaic						
Capacity	kW	674.63				
Investment costs	€/kW	1 801.19				
Maintenance costs	€/year	2 075.15				
Service life	Years	15 (HP); 20 (HP DHW); 20 (SH); 35 (PV)				

References:
In compliance with Portuguese legislation (Despachos 3156/2016 and 6476-H, 2021), the calculation of the renewable energy systems was done with the aid of the following tools:

SCE-ER, software provided by the General Direction of Energy and Geology of Portugal, DGEG (*SCE.ER*, n.d.).
PVGIS, a web-based application offered by the European Commission Joint Research Centre (*Photovoltaic Geographical Information System (PVGIS) | EU Science Hub*, n.d.).

Generic district calculation results

The following graphs (Figure 38 to Figure 42) give an overview of the results obtained:

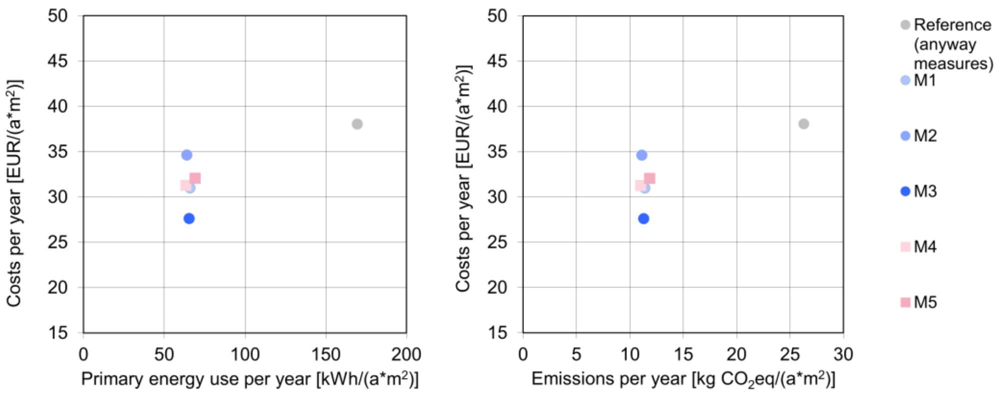

Figure 38.Results for Heating system 1 – Decentralised Conventional [ESS1].

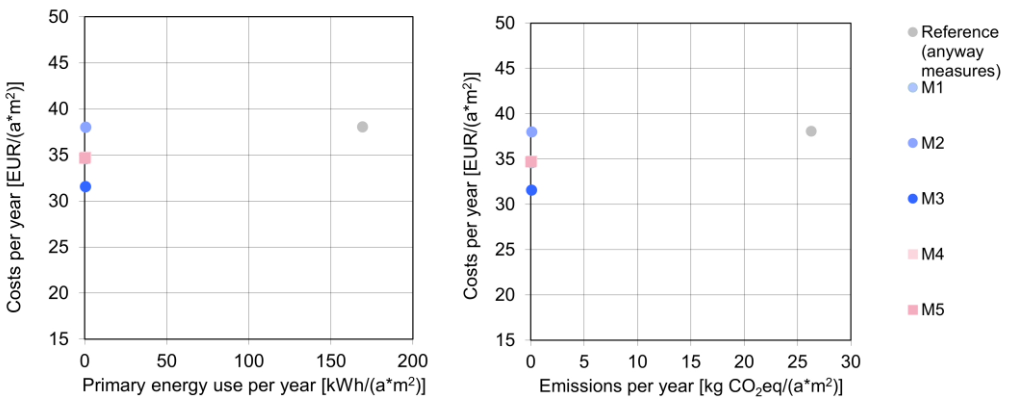

Figure 39. Results for Heating system 2 – Centralised Biomass Boiler + Solar Thermal (50%) [ESS2].

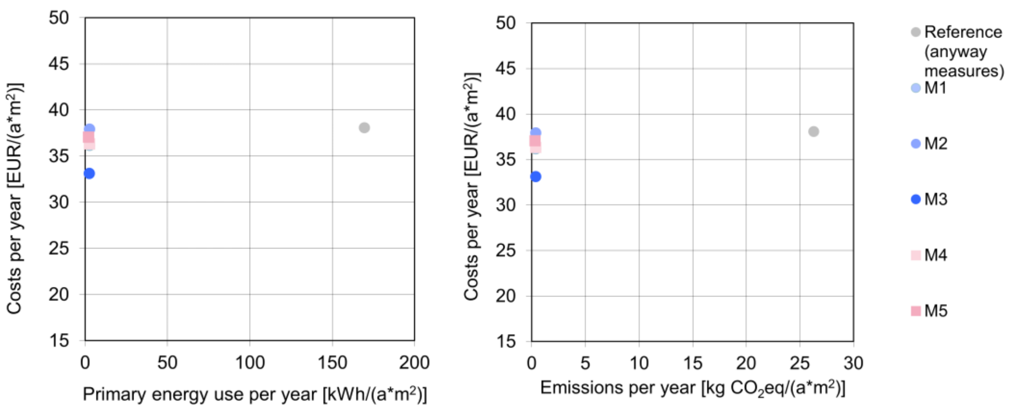

Figure 40. Results for Heating system 3 – Centralised Biomass Boiler + Solar Thermal (100%) [ESS3].

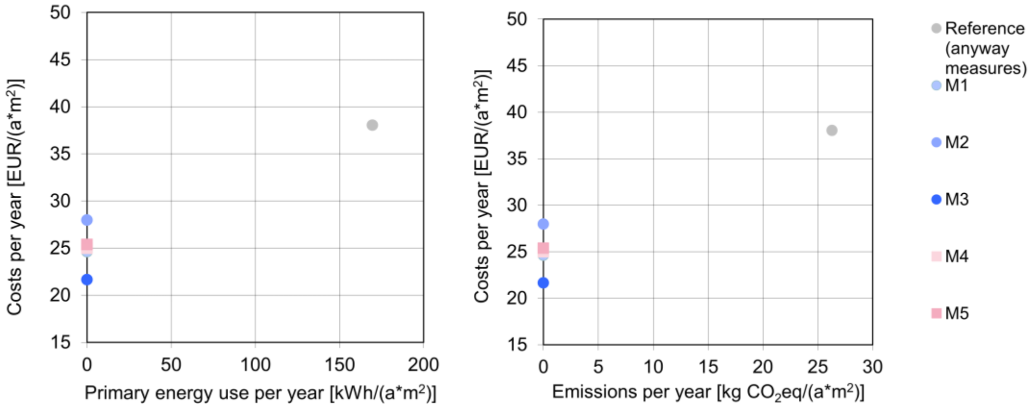

Figure 41. Results for Heating system 4 – Centralised Heat Pump + PV (100% energy needs) [ESS4].

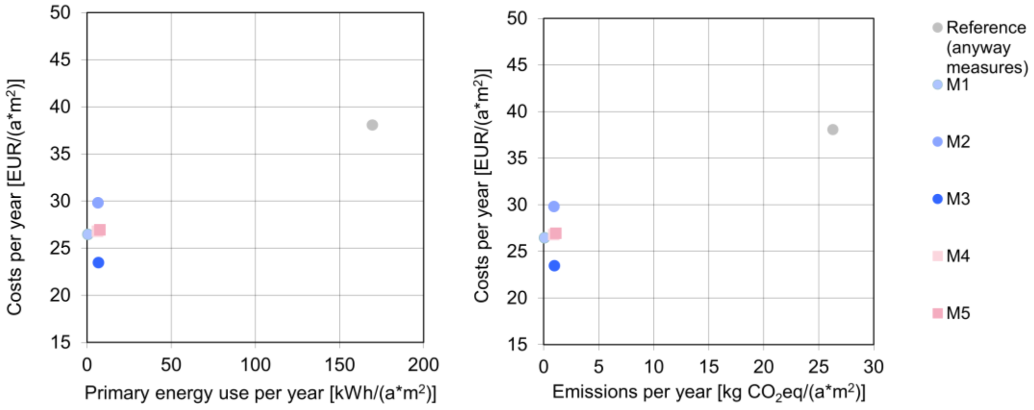

Figure 42. Results for Heating system 5 – Centralised Heat Pump + SH (DHW) + PV [ESS5].

Figure 43 contains an overview where the various renovation packages on the building envelopes are combined with the types of heating systems investigated:

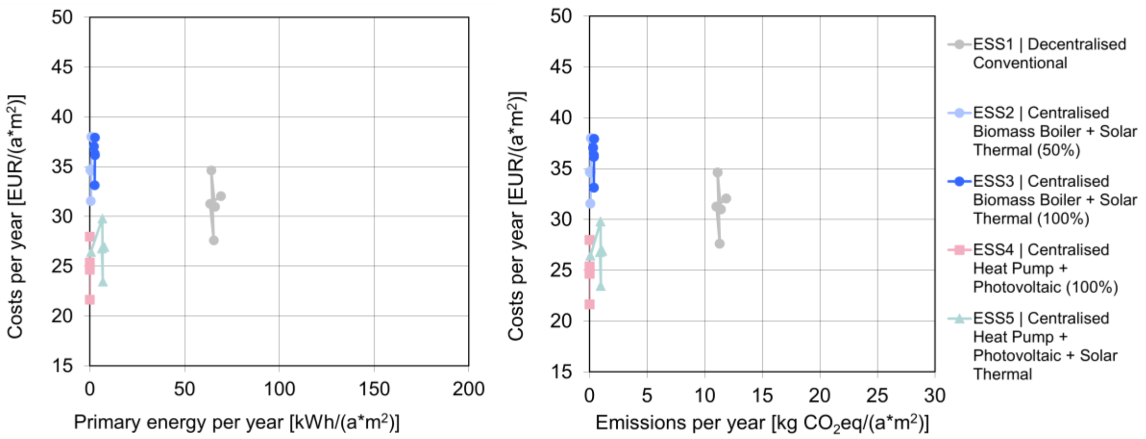

Figure 43. Overview of combinations of renovation packages and heating systems.

The following graphs (**Figure 44** to **Figure 48**) show more specifically which are the most cost-effective renovation packages for the various heating systems investigated. The yellow circle highlights the most cost-effective renovation package.

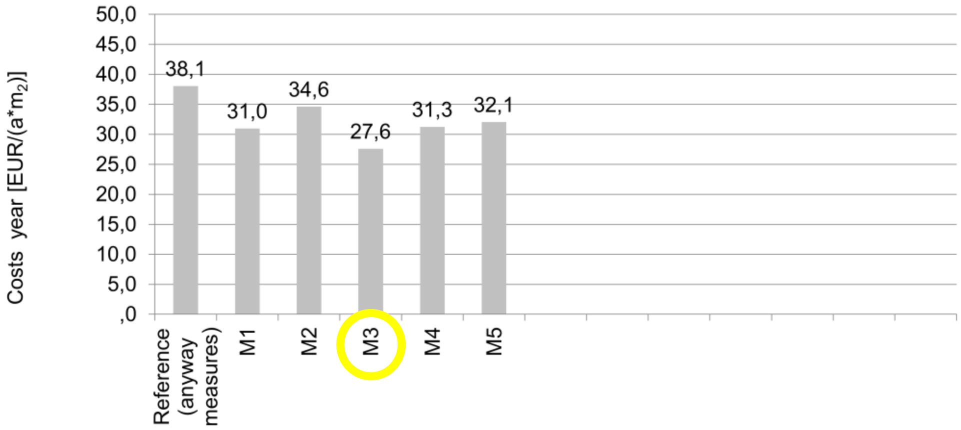

Figure 44. Cost-effectiveness of renovation packages for Heating system 1 – Conventional Decentralised Reference [ESS1].

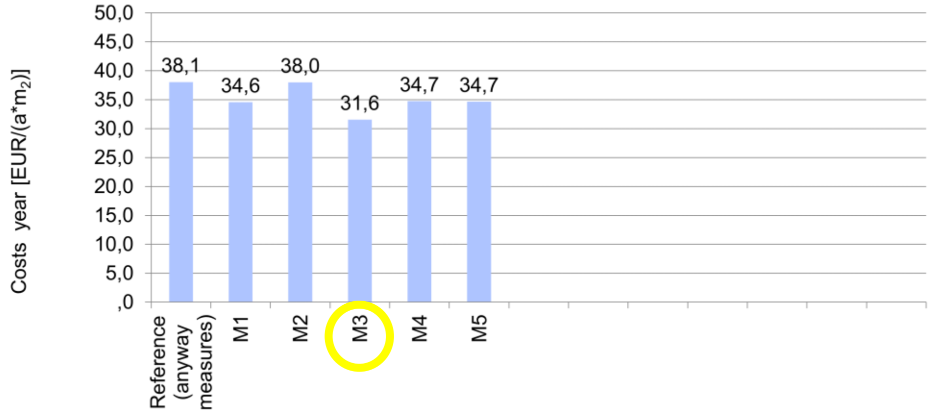

Figure 45. Cost-effectiveness of renovation packages for Heating system 2 – Centralised Biomass Boiler + Solar Thermal (50%) [ESS2].

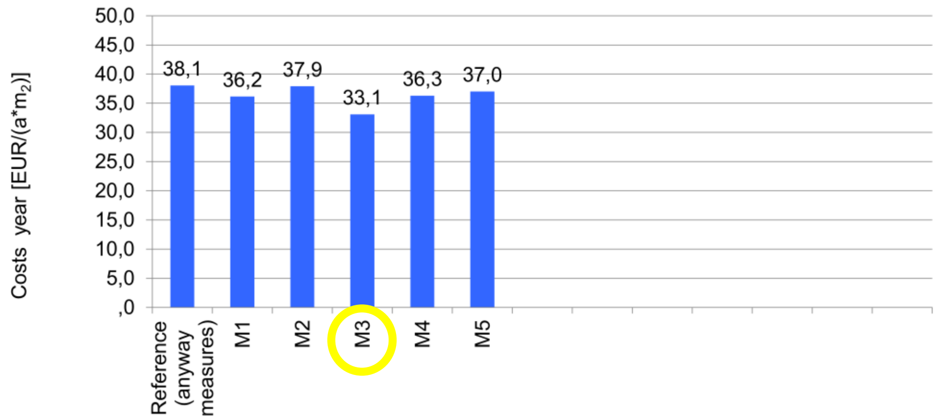

Figure 46. Cost-effectiveness of renovation packages for Heating system 3 – Centralised Biomass Boiler + Solar Thermal (100%) [ESS3].

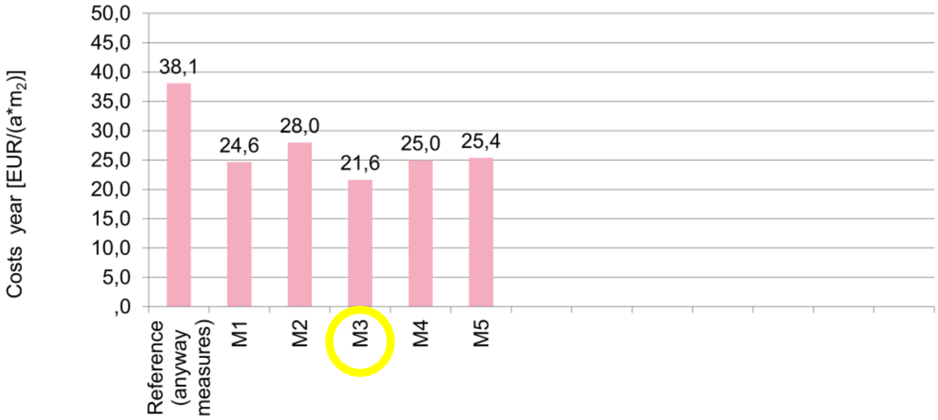

Figure 47. Cost-effectiveness of renovation packages for Heating system 4 – Centralised Heat Pump + PV (100% energy needs) [ESS4].

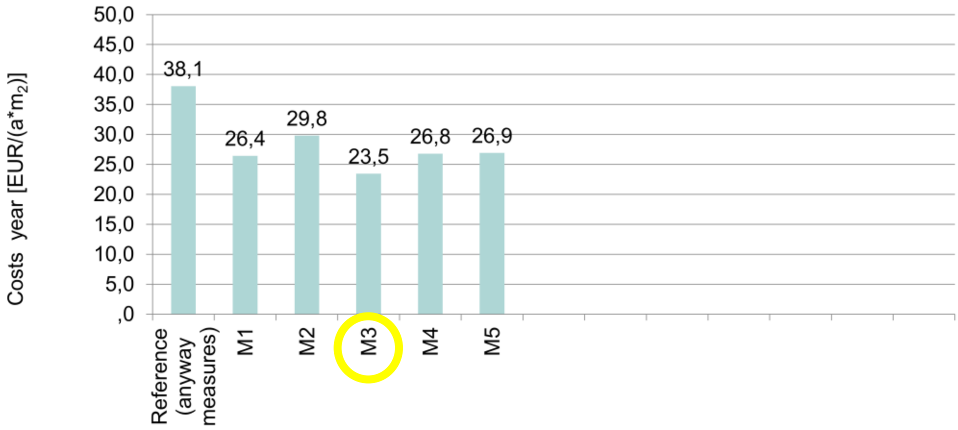

Figure 48. Cost-effectiveness of renovation packages for Heating system 5 – Centralised Heat Pump + SH (DHW) + PV [ESS5].

Figure 49 summarizes the cost savings of the most cost-effective renovation package (M3) on the building envelopes investigated for various types of heating systems considered, in comparison with the Reference Case scenario (anyway measures). The graph shows a comparison of the cost-effectiveness of the most-effective renovation package on the building envelopes investigated (M3) for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

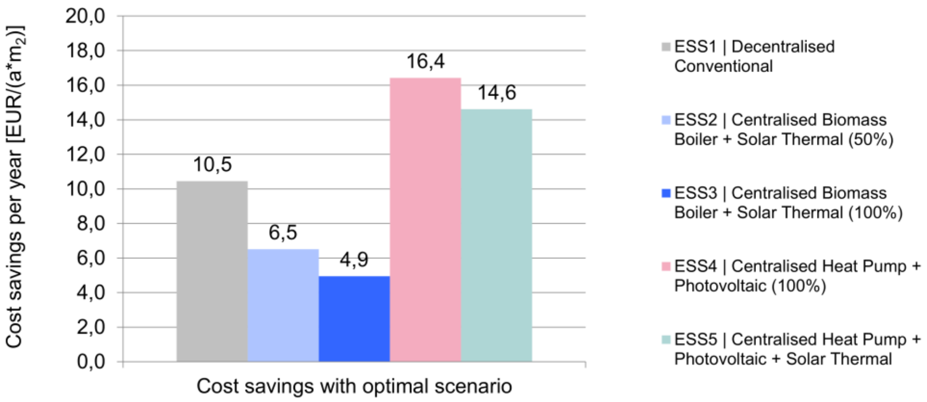

Figure 49. Cost savings for the most renovation package for each heating system.

Based on these graphs, the following outcomes can be recognized regarding the renovation packages:

- All renovation packages are cost-effective when compared with the reference case, anyway measures, which refers to the necessary district renovation but without energy efficiency improvement.
- For all the energy supply systems investigated, renovation package M3, which comprises wall insulation by adding ETICS EPS 100 mm, roof replacement with EPS 80 mm insulated green roof, and the substitution of single-glazed windows with double-glazed PVC frame windows (6-13 mm air, clear glass with U = 2.31 W/m2K and g = 0.62), is the most cost-effective.
- Consistently, M3 is followed by M1, M4, M5 and M2 renovation packages, in that order, regardless of the associated energy systems.
- All the renovation packages with ETICS EPS 100 mm were more cost-effective than those with ventilated façade MW 100 mm.
- When comparing the performance of the roof solutions, the packages with insulated green roof showed to be more cost-effective than the ones with only roof insulation (where both roof renovation measures have the same insulation specification – EPS 80mm). M3 and M1 are both characterised by walls with ETICS 100 mm and windows with clear glass double-glazing. M3, with an insulated green roof, is more cost-effective than M1, with only roof insulation. When comparing M4 and M2, both with insulated ventilated façade and windows with clear glass double-glazing, again the package with insulated green roof (M4) showed to be more cost-effective than the one with only roof insulation (M2). This is an interesting and promising conclusion that needs further research to accurately evaluate the performance of green roofs at the neighbourhood level.
- Regarding the cost-optimal performance of the glazing type, clear glass, with a higher solar heat gain coefficient (SHGC or g-value) showed, in this study, to perform slightly better than grey-tinted glass, as can be seen especially by the comparison of M4 and M5, whose characteristics only differ by the type of glazing. M4, with clear glass, is more cost-effective than M5, with grey-tinted glass. As in Portugal, cooling needs are generally much smaller than heating needs, buildings with higher g-value would lead to a better global performance, benefiting from higher heat gains during the heating season. In addition, clear glass has a lower U-value than grey-tinted glass, meaning that clear glass would have a better thermal performance.

In terms of the energy source systems (ESSs) associated with the renovation packages, these conclusions were reached:

- All the ESSs associating high-performance systems with renewable energy sources reached almost zero carbon emissions and non-renewable primary energy needs, characterising nearly zero-energy neighbourhoods. This implies that it is technically possible to decarbonise the housing sector by 2050.
- ESS4 (heat pump system for space conditioning and DHW associated with a photovoltaic system dimensioned to provide 100% of the energy needs) has the best performance in the two KPI analysed (carbon emissions and non-renewable primary energy needs), being also the most cost-effective.
- Still regarding the KPIs, ESS4 is followed by ESS2 and ESS3 (both a combination of biomass boiler with solar thermal), ESS5 (heat pump associated with solar thermal and photovoltaic system) and ESS1 (decentralised conventional systems), in that order. This confirms that building envelope energy improvement associated with high-performance systems and supplied by renewable energy sources has a much better environmental performance than conventional decentralised systems (ESS1).
- In terms of cost-effectiveness, it is worth noting that, for this study, ESSs combining heat pumps with photovoltaic systems (ESS4 and ESS5) are more cost-effective than those associating biomass boilers with solar thermal systems (ESS2 and ESS3). These performed worse than the conventional decentralised system (ESS1).

For this generic district, although the choice of energy systems is relevant in terms of carbon emissions and primary energy consumptions, it does not change the order of cost-effectiveness ranking of the building envelope renovation packages.

Further research should now be conducted with the investigation of the generic district's energy performance in other climates in Portugal.

Discussion

What stands out when interpreting the results?

Considering the social housing context in Portugal, with buildings poorly or not insulated at all, building renovation with envelope insulation leads to better indoor comfort levels and, as expected, much lower primary energy needs and carbon emissions. In this generic district study, the cost-effectiveness of the five proposed renovation measures (M1 to M5) was demonstrated in association with all the energy supply systems proposed (including the decentralised conventional system ESS1) when compared with the reference case (anyway measures).

Therefore, the results obtained in this generic district suggest that energy sources centralised in the neighbourhood can be cost-effective in Portugal, although this is not a practice in the country. Furthermore, building envelope improvement associated with high-performance systems supplied by renewable energy sources reached nearly zero carbon emissions and primary energy needs, indicating that the available existing technology can lead to nearly zero-energy buildings and the decarbonisation of the housing sector.

What are the most cost-effective solutions?

In the analysis carried out for this generic district, the ten most cost-effective solutions were combined with heat pumps associated with a photovoltaic system as energy source systems (ESS4 and ESS5, the latter also with solar panels to provide DHW). In terms of envelope renovation, the most cost-effective package is M3 (ETICS EPS 100 mm on the facade, green roof insulated with EPS 80 mm, and double-glazed PVC frame windows with clear glass), always followed by M1, M4, M5 and M2, in that order.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

Probably the greatest uncertainties are related to the dimensioning and the cost estimation of the centralised energy systems (equipment and urban infrastructure) due to the lack of references in Portugal.

The discount related to the economy of scale has also been estimated based on other studies, but there may be space for variation. In addition, it is well known the difficulty to predict user behaviour and how the assumptions made in the building simulation may impact the calculated results.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 42. Responses to the hypotheses according to the Portuguese generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	⊖
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	⊖
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	⊖

Hypotheses
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»

Confirmed   Not investigated   Not confirmed

Justification:

Hypothesis 4:

In this generic district, the switch to a centralised district heating system based on renewable energy led to an improvement in the cost-optimal level of energy efficiency measures in the envelopes, when compared with the reference case. However, the level of improvement varied according to the energy system.

The ten renovation packages combined with ESS4 and ESS5 (both associating heat pumps and a photovoltaic system, the latter also adding solar thermal) were the most cost-effective, with the highest reductions being of 43% for ESS4 M3 and 38% for ESS5 M3.

ESS2 and ESS3, which combine a biomass boiler with solar thermal energy, were less cost-effective than ESS1, which is defined by decentralised conventional systems. Nevertheless, ESS2 M2, the renovation package with the highest annuity, still has slightly lower costs than the reference case.

Hypothesis 7:

As the original building envelope does not perform well in terms of energy efficiency and indoor thermal comfort, due to the lack of any type of insulation, all the renovation packages provide insulation measures for the walls and the roof. Furthermore, the single-glazed windows are replaced with double-glazed ones.

2.5 Spain

Description of the generic district

For this generic district study, a group of buildings from one of Spain's most abundant periods of construction was selected, the 1960s. It is an example of the fast expansion of Spanish cities due to industrialization after the 50s. This period is particularly interesting because of their high energy needs and lack of thermal insulation, which was only enforced in 1979. They are also buildings with accessibility issues and more than 50 years of use, which makes them a good target for renovations in the short term.

The Spanish generic district was defined as representing the local existing built stock. A set of twenty-two residential building blocks of Adurtza, in Vitoria-Gasteiz (shown in Figure 50) was selected. They have three to five floors that share similar construction and can be identified as two main architectural typologies. The first buildings are the basic apartment unit for the recently arrived workers and families, while the second typology includes a somewhat larger indoor area and balconies to improve the apartment features. Local institutions studied this area to determine the conditions of these buildings and the risks of energy poverty and social vulnerability in general. So there was a good understanding of the living conditions and the need for renovations.

When analysing the energy performance of this generic district, the simulations were made for only one weather condition, allowing to focus on the development of other parameters, such as the different levels of efficiency measures or the decentralisation of the energy supply system. To choose which climate and location, the SPA-HOUSEC project (idea, 2011), the most complete study on residential energy use, was consulted, indicating the continental housing as the largest energy consumer (and therefore with the greatest renovation potential). For the choice of the climatic zone to be evaluated, a more detailed classification found in the Spanish Building Technical Code was studied. Among all the cities included in the continental classification, between warmer and colder zones, an intermediate climate zone was chosen. In this way, the weather used was D1 (embracing seven region capitals), as it has an average winter severity, with about 2 500 HDD. The other Spanish climates, in the North Atlantic and Mediterranean, will be studied in future works.

Table 43. General Information about the Spanish district.

Parameter	Explanation/definition
Location	Vitoria-Gasteiz
Latitude	42.835
Longitude	- 2.661
Climate zone (Köppen classification)	Cfb
Number of buildings in total	22

In the case of Adurtza neighbourhood, in the last decades, most buildings maintained their original envelope and were equipped with elevators placed outside as a new addition to the building. Only one building envelope has been renovated. The energy supply systems consist of 90% natural gas decentralised boilers and 10% electric heaters and boilers. In general, only minor renovations have been made to windows. These conditions are consistent with the study on Spanish residential consumption.

Figure 50. Aerial view of Adurtza neighbourhood and identified building typologies. From "Google Maps", n.d. Copyright by Google. Edited by authors.

In the generic district calculation, the assumptions include that none of the buildings has been renovated yet, but the windows were replaced a few years ago by aluminium frame windows with thermal break and double glazing. Energy supply systems are 90% based on gas boilers and 10% on electric heaters.

Table 44. Building typologies of the Spanish generic district.

Parameter	Unit	Building typology 1	Building typology 2
		Building information	
Number of buildings per typology		14	8
Construction period		1956 - 1962	1964 - 1968
		Geometry	
Gross heated floor area (GHFA)	m^2	618	652.3
Heated volume	m^3	1,643.7	1,669.9
Façade area incl. window area	m^2	714.8	544.3
Roof area if flat roof	m^2	-	-
Roof area if pitched roof	m^2	135.4	147.5
In case of pitched roof: Is room below roof heated or not?	Yes/No	No	No
Area of windows to North	m^2	35.7	36.4
Area of windows to East	m^2	16.0	16.3
Area of windows to South	m^2	26.8	27.4
Area of windows to West	m^2	21.9	22.4
Area of basement ceiling	m^2	131.1	144.9
Area of basement wall	m^2	-	-
Area of basement floor	m^2	-	-
Number of floors above ground	-	5 (12 buildings), 3 (2 buildings)	5
		Usage	
Type of use		Residential	Residential
Area per occupant	m^2 / person	17.2	15.5
Typical indoor temperature (for calculations)	°C	17 - 20	17 - 20
Average domestic electricitycon-sumption	kWh/(m^2.a)	38.5	38.5
		HVAC systems	
Type of existing heating system (boiler, heat pump, etc.)		90% Gas 10% electric boilers	90% Gas 10% electric boilers

Parameter	Unit	Building typology 1	Building typology 2
Existing energy carrier (Gas, Electricity, etc.)		90% Gas 10% Electricity	90% Gas 10% Electricity
Is ventilation system without heat recovery installed?	Yes/No	No	No
Is ventilation system with heat recovery installed?	Yes/No	No	No
Efficiency of heat recovery	%	-	-
Ventilation rate	ach	0.63	0.63
Is cooling system installed?	Yes/No	No. Night-time natural ventilation 4.0 ACH June-September	No. Night-time natural ventilation 4.0 ACH June-September
Hot water consumption	l/person/day	28	28

Calculation parameters and scenarios

Table 45. General parameters for the Spanish generic district.

Date the calculations were made	**2021/06 - 2022/04**
Weather file used	D1_peninsula - ESP CTE_DB_HE WMO
External shading (by surrounding buildings) considered	Yes, the built environment is included

The energy efficiency measures include interventions in roofs, façades, windows, ground floor slab, infiltration levels, and mechanical ventilation with heat recovery in the deepest renovations. For each façade, roof, window, and ground floor slab, four options (or levels) are considered. Being "0" the reference case, the first (1) refers to the minimal requirements set out by the current Spanish regulation, the Spanish Building Technical Code. The second (2) refers to the same document, but in this case, to the recommendations made in Annex E of this document. The third option (3) is an intermediate between the second and the fourth, the latter (4) being the one used for Passive House Institute certification. As far as infiltrations are concerned, two additional levels are considered: one comprehending the previous renovation levels 1 to 3, acting on the façades for reducing infiltration rate (0.1 ACH as equivalent non-controlled ventilation), and another for level 4 (Passive House level), acting on façades and internal partitions for reducing the infiltration rate to 0.03 ACH. Finally, renovation levels 3 and 4 are duplicated to equip them with mechanical ventilation with heat recovery to assess the suitability of the deepest renovation scenarios. These renovation measures are applied as kits of homogeneous intervention due to the regulation requirements (CTE DB-HE, 2019) that aim for a global performance instead of partial or step-by-step renovations.

Considering these measure levels and their application as kits, a set of 7 combinations was considered for simulation. Energy needs for the different scenarios were obtained by dynamic simulation of the whole district using the software SG-SAVE and Energy Plus engine (see Figure 51 below). Some simplifications were assumed in the building (the effects of these simplifications in the final results were previously evaluated and validated for both typologies' detailed single-building models).

Figure 51. General view of the SG-SAVE simulation model of Adurtza neighbourhood. From Open Studio software, created by authors, R. Briones-Llorente and J.M. Hidalgo-Betanzos.

Table 46. Measures on the building envelope.

Parameter	Unit	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
				Walls				
U-values	W/m²K	1.37	0.41	0.27	0.26		0.25	
Investment costs	€/m$^2_{building\ element}$		11.83	16.65	21.49		26.31	
Maintenance costs	€/m$^2_{building\ element}$.year		0.024	0.03	0.044		0.053	
Service life of insulation measures	years		30	30	30		30	
				Roofs				
U-values	W/m²K	1.35	0.35	0.22	0.20		0.18	
Investment costs	€/m$^2_{building\ element}$		18.42	25.84	28.44		31.02	
Maintenance costs	€/m$^2_{building\ element}$.year		0.04	0.05	0.058		0.063	
Service life of insulation measures	years		30	30	30		30	

Parameter	Unit	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Floors								
U-values	W/m²K	1.34	0.65	0.58	0.39		0.30	
Investment costs	€/$m^2_{building\ element}$		12.73	15.27	17.82		22.91	
Maintenance costs	€/$m^2_{building\ element}$.year		0.13	0.16	0.184		0.237	
Service life of insulation measures	years		30	30	30		30	
Windows								
U-values	W/m²K	3.48	1.83	1.57	1.30		1.05	
Investment costs	€/$m^2_{building\ element}$		591.3	591.6	596.3		622.6	
Maintenance costs	€/$m^2_{building\ element}$.year		6.3	6.3	6.4		6.9	
Service life of insulation measures	years		20	20	20		20	
Ventilation system								
Efficiency Heat Recovery	%					85%		85%
Investment costs	€/$_{dwelling}$					4603		463
Maintenance costs	€/$_{dwelling}$.year					20.00		20.00
Service life of insulation measures	years					20		20

As far as the HVAC systems are concerned, according to the SPAHOUSEC study, the Spanish continental residential share of DHW and heating systems and is 88% for those based on gas and 12% for those based in electricity, which is almost identical to the current situation of Adurtza neighbourhood (90% and 10%). These shares were rounded to 90% and 10% in the reference scenario.

The analysis performed evaluates the implementation of active measures at three levels: individual systems (at the apartment scale), decentralised systems (at the building level), and centralised (district heating) systems. An air-to-water heat pump is studied at the dwelling level and for the DHW demand. For both DHW and heating demand, a natural gas boiler and an air-to-water heat pump are proposed. Further, the study evaluated decentralised systems that supply energy at a building level, such as a natural gas boiler, an air-to-water heat pump, and a biomass boiler. Finally, the district heating solutions include centralised air-to-water heat pumps, geothermal heat pumps and biomass boilers. In total, eight heating solutions, including the reference case, are studied.

Regarding the simulation of the different energy systems scenarios, the simulation tool SG-SAVE presented some unexpected limitations and the consumption calculations were done using seasonal coefficients of performance. These SCOPs were obtained by defining another model with similar energy hourly demands, running in Design Builder, and defining in detail (Detailed HVAC) the energy systems in each case. This way, the Final and Primary Energy consumption values were calculated using the SCOP of each system type using a spreadsheet with the hourly simulated energy demands of each renovation scenario.

The general approach to determining system sizing was based on load capacity. The base load was the heating load during constant operation, close to its expected rated or nominal power, while the DHW supply (constant per person) was calculated using a system with similar features operating in a shorter time-response (8 hours to generate all-day DHW need). These installations operate in conjunction. Some system sizes were finally chosen according to standard market offers, and in other cases, they were set using a price ratio per capacity in kW.

For the integration into district heating networks, the sizing of the generation and storage was done following design recommendations or features for this weather, used by real DH in close locations, that were gathered during the IEA EBC Annex 75 project.

Table 47. Measures on the HVAC system including renewable energy generation on-site.

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario X
Heating system 1: Mix 90% Gas + 10% Electric boilers (individual) - REFERENCE						
Capacity	kW	Gas 25.2 Electric size based on-demand				
Investment costs	€/kW	Gas 59.5 Electric - no cost (included in anyway measures)				
Maintenance costs	€/year	Gas 37.48 Electric - no maintenance cost (included in anyway measures)				
Service life	Years	Gas 20 Electric - no limit (included in anyway measures)				
Heating system 2: Air Source Heat Pump for DHW and heating (individual)						
Capacity	kW	4.5 kW (per apartment)				
Investment costs	€/kW	681.11				
Maintenance costs	€/year	76.62 (per apartment)				
Service life	Years	20				
Heating system 3: Compact Air Source Heat Pump for DHW, electric heating (individual)						
Capacity	kW	1.8 kW (HP) per apartment				
Investment costs	€/kW	824.4				
Maintenance costs	€/year	37.10 (per apartment)				
Service life	Years	20				

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario X
Heating system 4: Air Source Heat Pump for DHW and heating (decentralised-building)						
Capacity	kW	205 (per building)				
Investment costs	€/kW	194.4				
Maintenance costs	€/year	996.4 (per building)				
Service life	Years	20				
Heating system 5: Biomass boiler for DHW and heating (decentralised-building)						
Capacity	kW	220 (per building)				
Investment costs	€/kW	349.6				
Maintenance costs	€/year	1,923.03 (per building)				
Service life	Years	20				
Heating system 6: Biomass boiler for DHW and heating (central-district)						
Capacity	kW	1,854 - 457				
Investment costs	€/kW	159.8 – 244.6 (+35,891.56 € water storage +375,500 € distribution)				
Maintenance costs	€/year	2,5% of the investment cost				
Service life	Years	20				
Heating system 7: Ground Source Heat Pump for DHW and heating (central-district)						
Capacity	kW	1,854 - 457				
Investment costs	€/kW	699.59 – 815.70 (+35,891.56 € water storage +375,500 € distribution)				
Maintenance costs	€/year	2,5% of the investment cost				
Service life	Years	20				
Heating system 8: Air Source Heat Pump for DHW and heating (central-district)						
Capacity	kW	2,584 - 640				
Investment costs	€/kW	123.22 – 150.65 (+44,827.63 € water storage +375,,500 € distribution)				
Maintenance costs	€/year	2,5% of the investment cost				
Service life	Years	20				

Generic district calculation results

The following graphs (Figure 52 to Figure 59) give an overview of the combinations between renovation interventions on the envelope and heating systems substitutions. The graphs show an overview of specific yearly carbon emissions and yearly primary energy use vs. costs for various renovation packages on the building envelopes for the different heating systems investigated.

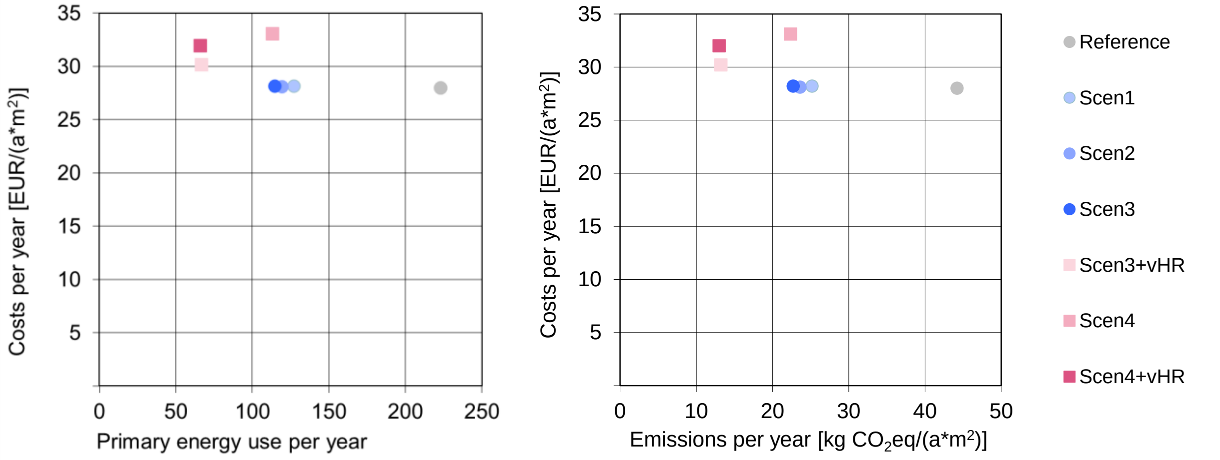

Figure 52. Results for Heating system 1 : Mix 90% Gas + 10% Electric boilers (individual) – REFERENCE.

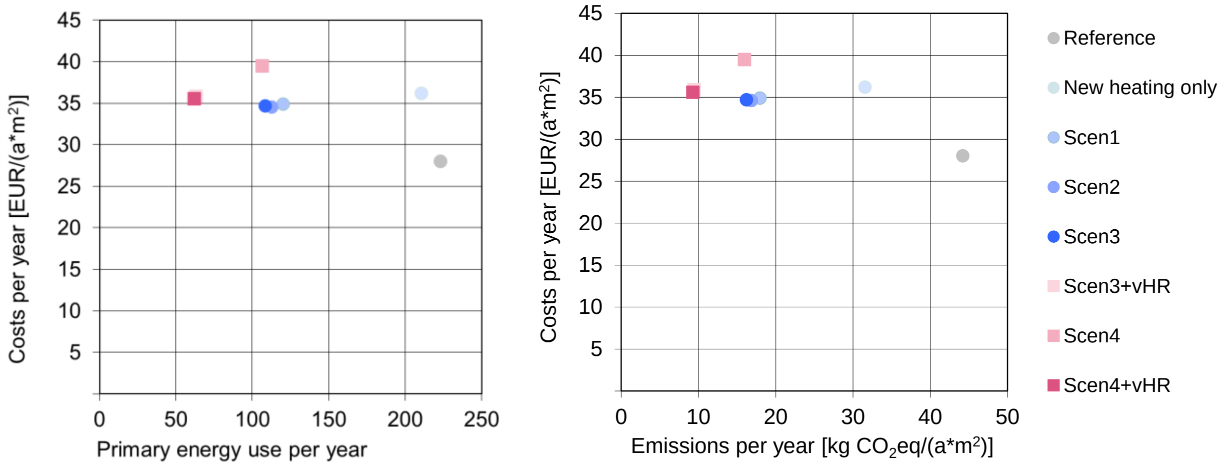

Figure 53. Results for Heating system 2 : Air Source Heat Pump for DHW and heating (individual).

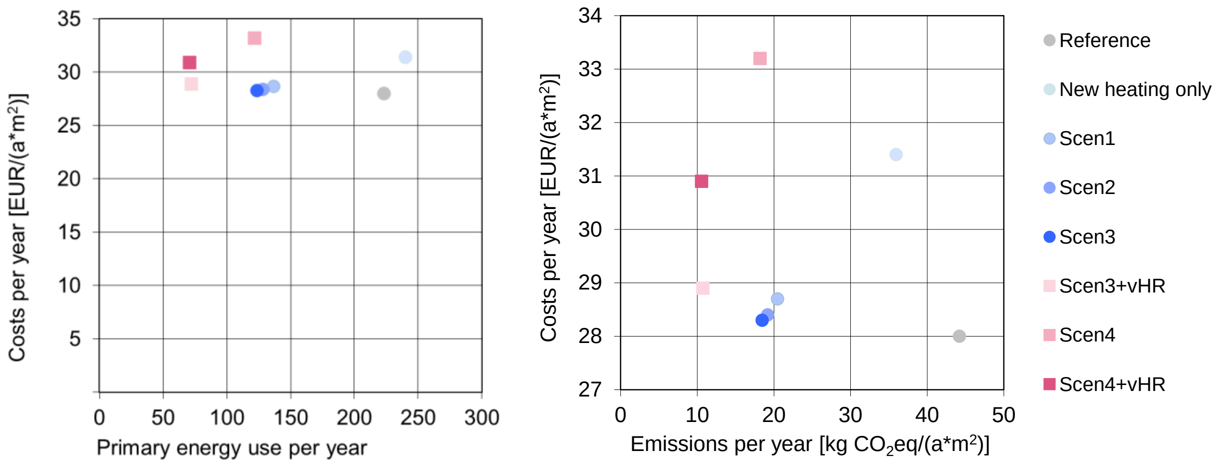

Figure 54. Results for Heating system 3: Compact Air Source Heat Pump for DHW, electric heating (individual).

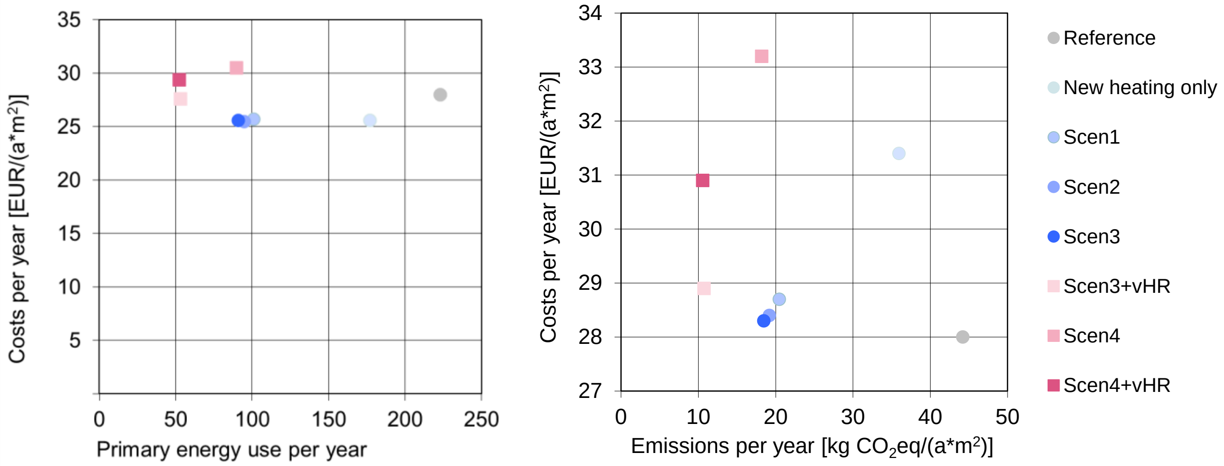

Figure 55. Results for Heating system 4: Air Source Heat Pump for DHW and heating (decentralised-building).

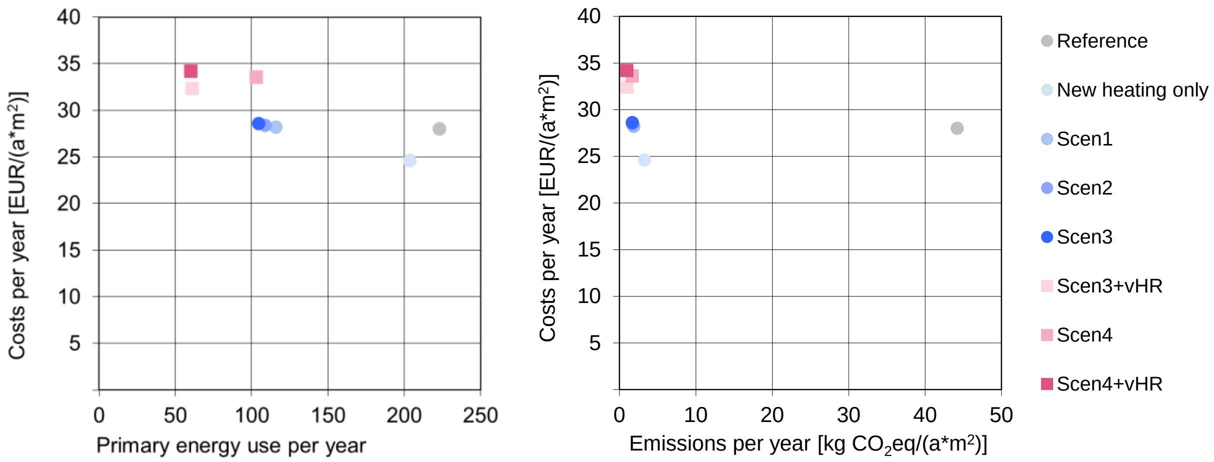

Figure 56. Results for Heating system 5: Biomass boiler for DHW and heating (decentralised-building).

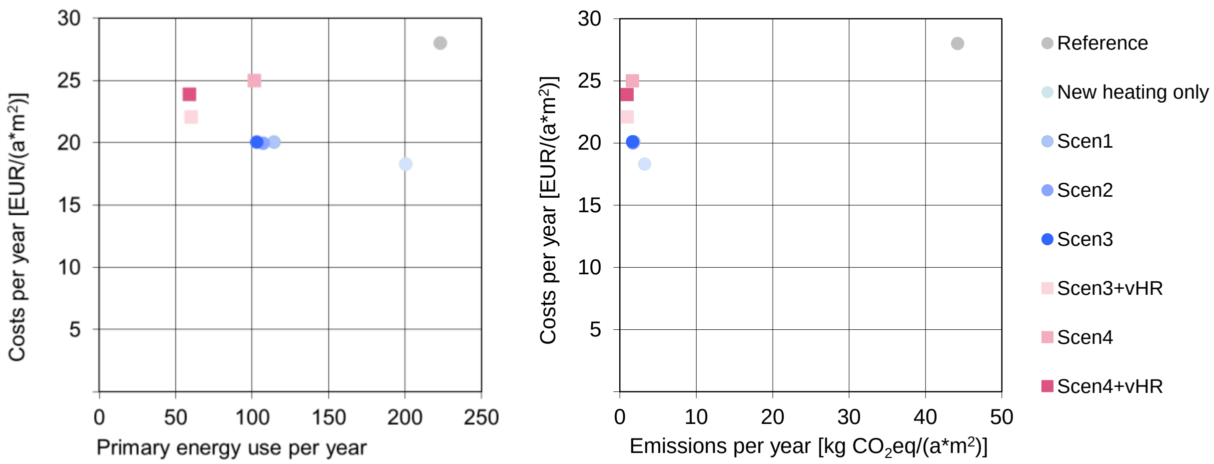

Figure 57. Results for Heating system 6: Biomass boiler for DHW and heating (central-district).

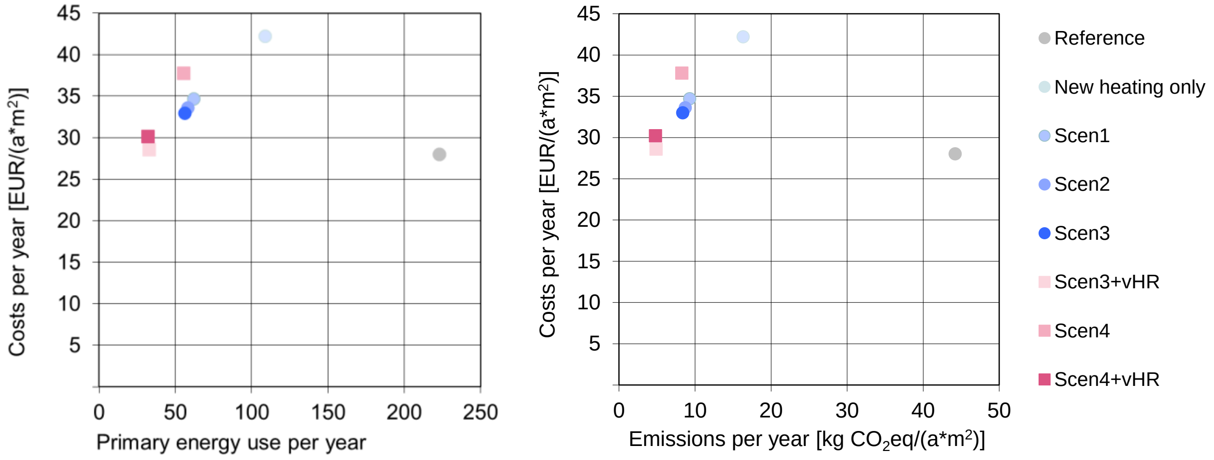

Figure 58. Results for Heating system 7: Ground Source Heat Pump for DHW and heating (central-district).

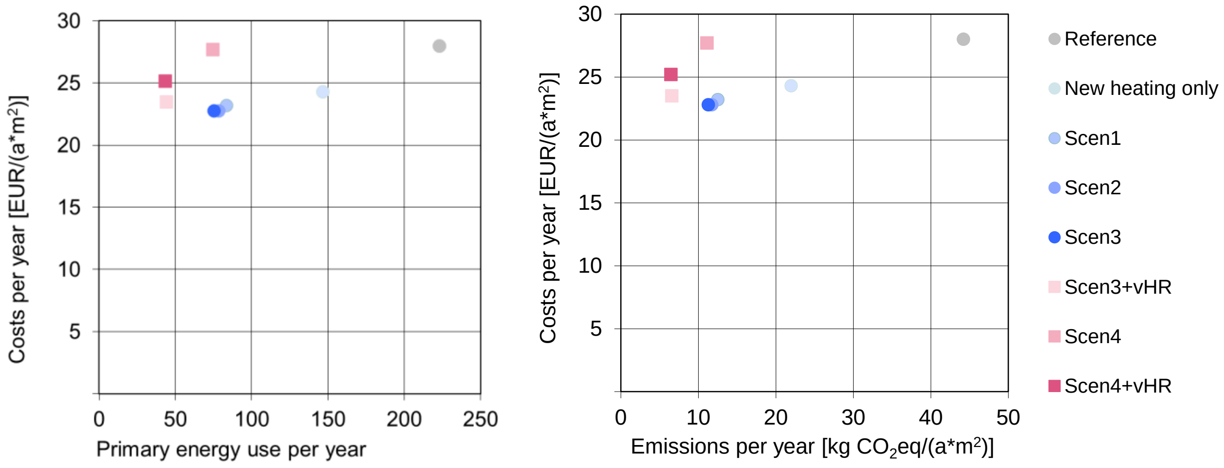

Figure 59. Results for Heating system 8: Air Source Heat Pump for DHW and heating (central-district).

Figure 60 contains an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated. The graphs summarise relationships between specific yearly carbon emissions or yearly primary energy use vs. costs of various renovation packages on the building envelopes for various heating systems investigated. Each point in the curves corresponds to one renovation package associated with the respective energy supply system.

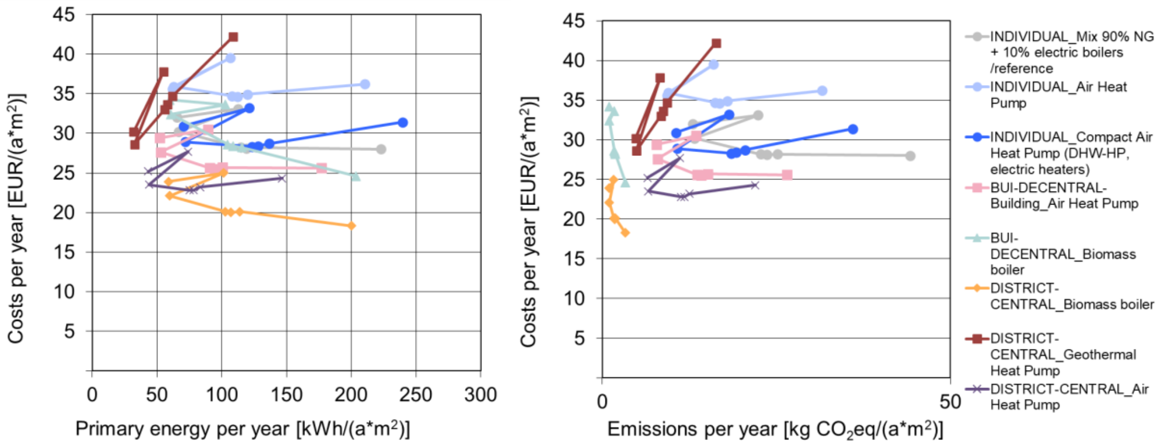

Figure 60. Overview of the combinations of renovation packages and heating systems.

The following graphs (Figure 61 to Figure 68) specifically show the most cost-effective renovation packages for the various heating systems investigated. The most cost-effective renovation package is marked with a yellow circle.

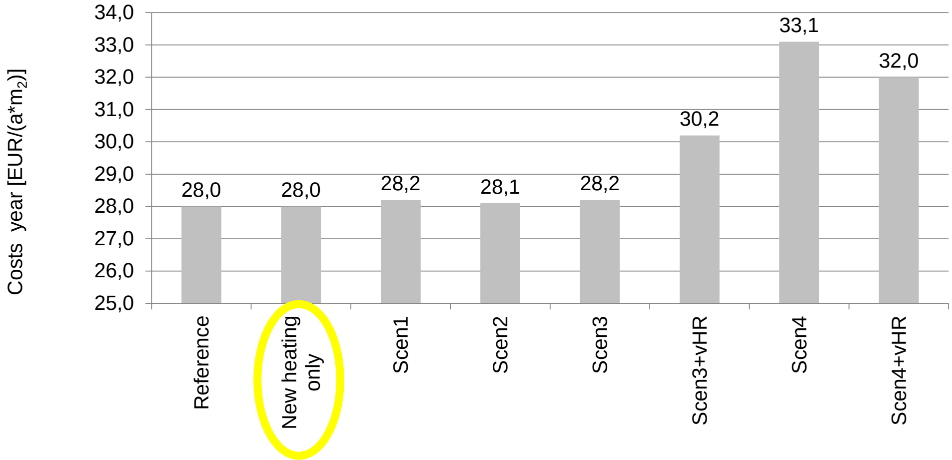

Figure 61. Cost-effective renovation package for Heating system 1: Mix 90% Gas + 10% Electric boilers (individual) – REFERENCE.

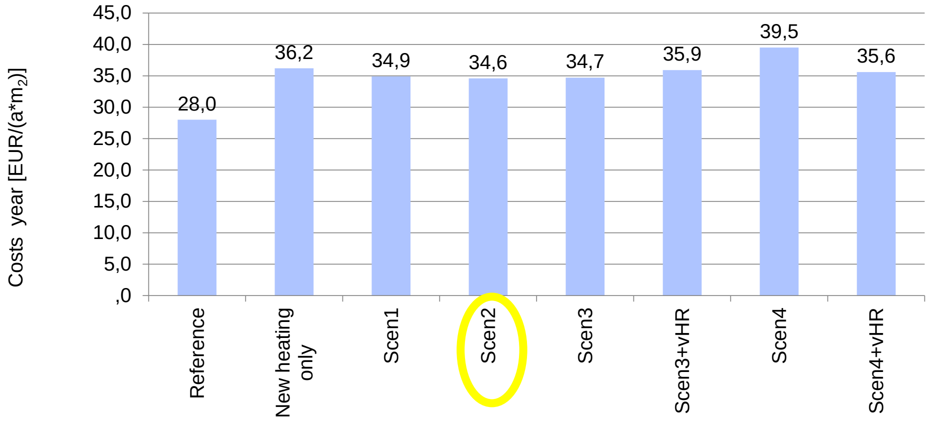

Figure 62. Cost-effective renovation package for Heating system 2: Air Source Heat Pump for DHW and heating (individual).

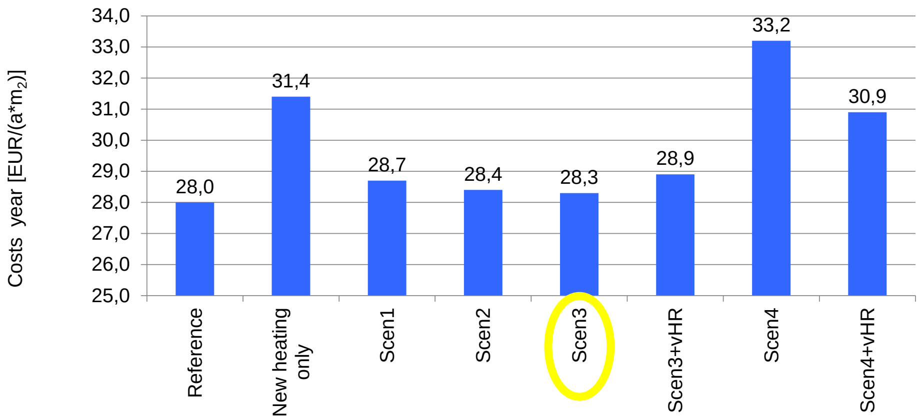

Figure 63. Cost-effective renovation package for Heating system 3: Compact Air Source Heat Pump for DHW, electric heating (individual).

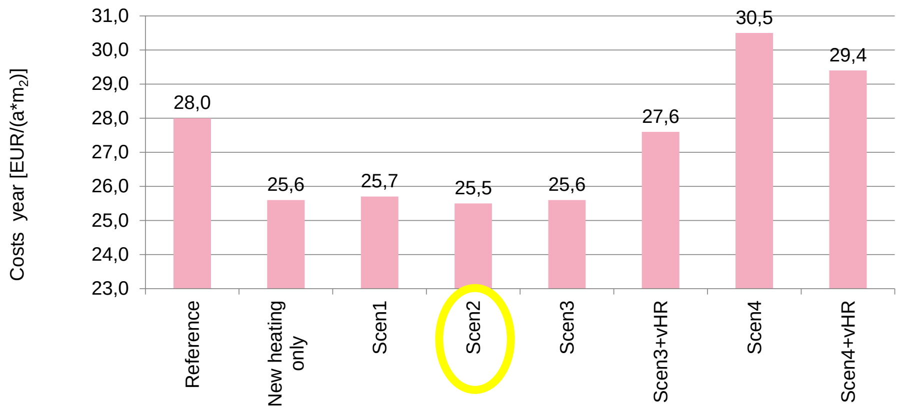

Figure 64. Cost-effective package for Heating system 4: ASHP for DHW and heating (decentralised-building).

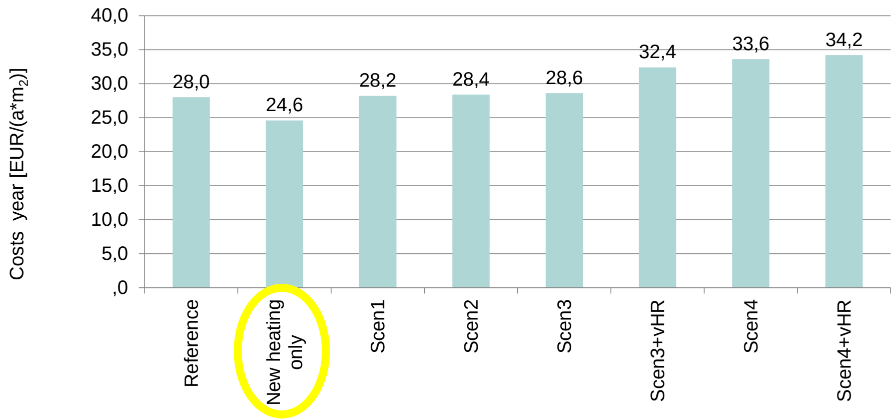

Figure 65. Cost-effective package for Heating system 5: Biomass boiler for DHW and heating (decentralised-building).

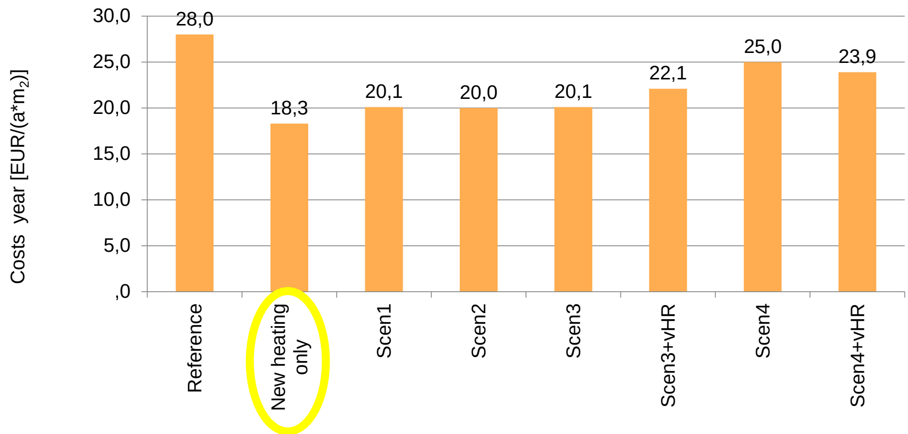

Figure 66. Cost-effective package for Heating system 6: Biomass boiler for DHW and heating (central-district).

Figure 67. Cost-effective package for Heating system 7: GSHP for DHW and heating (central-district).

Figure 68. Cost-effective package for Heating system 8: ASHP for DHW and heating (central-district).

Figure 69 summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems, compared to a scenario in which only the heating system is replaced.

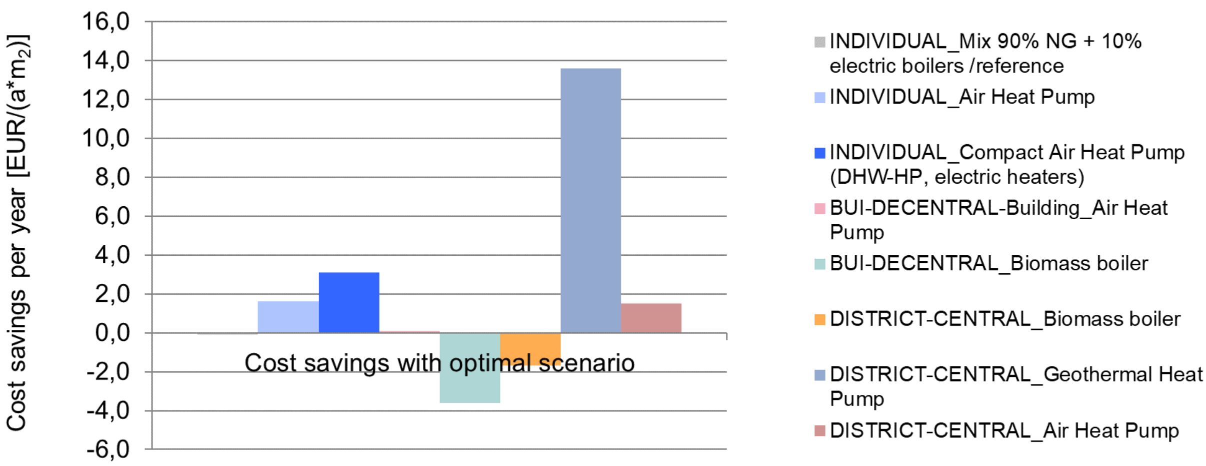

Figure 69. Cost savings for the most cost-effective renovation package for each heating system.

Based on these graphs, the following can be recognized:

About the potential to reduce the primary energy use of this district with an affordable solution:

- None of the individual solutions can provide clear cost-optimal solutions. The obtained annual costs remain very similar to the reference or above the 28.0 €/m².a.
- The decentralised-building Air Source HP shows 9% of annual cost reduction, from the reference 28.0 to 25.5 €/m², with a significant cut down of 40% in the primary energy. The biomass decentralised solution is, in general, over the reference value.
- Among the central-district solutions, both biomass boiler and the air source HP show margins to affordably reduce energy use. They obtained energy savings of 73% and 80% with cost reductions of 21% and 16%, respectively, when compared to the reference case.

About the annual cost assessment:

- Regarding the degree of the renovations, most of the investigated systems reflect cost-optimal results between scenarios 2 and 3 (5 out of 9 studied systems). This is consistent with the Spanish regulation that was defined in 2019, based on the updated cost-optimality. However, in 3 out of the investigated 8 energy systems, the cost-optimal result remains without any renovation, only with active measures and replacing the current gas and electric boilers.
- The study of different scales of systems (individual, decentralised-building and central-district) show that some District solutions can be cost-effective in this district and climate conditions.
- The individual-apartment solutions do not reduce the annual costs in comparison with the reference case, with values of 34.6 €/m².a for Air Source HP and 28.3 €/m².a for compact Air Source HP and electric heaters.
- The decentralised-building solutions can be cost-effective. The Air Source HP shows annual costs of 25.5 €/m².a, somewhat lower than the reference 28.0 €/m²,a. On the other hand, the biomass boiler at the building scale indicates higher values than the reference and can only be cost-effective without the passive renovation.
- The district solutions based on biomass boiler and Air Source HP provide annual costs (EUAC) of around 20 and 23 €/m².a, respectively. On the other hand, the central-district Ground Source HP requires very high investment costs. Even for the deepest passive renovations, it obtains annual costs over the reference with a minimum of 28.6 €/m².a.

In addition, the following results were found in this generic district calculation:

- The passive renovation solutions were not very interesting from the cost-optimal approach. The defined homogeneous solutions might have been very ambitious, and further intermediate solutions should be assessed in future works.
- The investigated solutions with heat recovery showed high costs, which do not get recovered in most cases. It provided benefits only in the district with an air-source heat pump.
- However, among the studied scenarios, some solutions achieved a significant 70% reduction in primary energy, with affordable cost-optimal solutions, particularly with district-scale systems.
- The obtained results could probably be improved with additional renewables such as PV or solar thermal to reduce the costs and make more decarbonisation options affordable. In the present study, these measures were not calculated due to their implementation uncertainties, such as the novelty and uncertainty of the Spanish regulation framework regarding PV and the technical and management limitations to installing solar thermal panels in a residential district renovation in Spain. These measures could be assessed individually when looking at a specific district, as an extra measure.

Discussion

What stands out when interpreting the results?

From a cost-effectiveness perspective, the results show some controversial aspects. Analysing the impact of the energy-efficiency measures (improvements of envelope and ventilation with heat recovery), we can conclude that, in general, their cost is not paid back by the savings potential, and only in the case of a DH based on ground source heat pumps we could see a significant benefit. Looking into more detail, the average annual cost improvements are very small. Actually, the average percentage of savings is only 1% for scenario 1, 2% for scenarios 2 and 3, and, for scenarios 4, 5 and 6, the costs increase 3%, 16% and 9%, respectively. This points to the first main outcome: the optimal renovation levels are between scenarios 2 and 3. This is influenced by the climate conditions, that are not severe and explain the low ratios of renovations in similar buildings.

On the other hand, regarding the different explored energy supply systems, we can conclude that scale matters. The study includes individual systems for apartments, decentralised for each building or centralised as DH. First, the studied three individual systems are not cost-effective. Second, among the decentralised systems, biomass boiler shows a similar 30 years cost (depending on the envelope and renovation degree) while the ASHP is slightly cheaper. And third, the district-scale solutions can be cheaper, as the biomass and the ASHP show reductions of up to 29% with biomass DH and 19% with ASHP DH. But in the case of GSHP, the high costs of investments are not recovered by the savings and, even in the best case, there is an increase of the annual costs by 2%, compared to the original reference case.

The analysis of the distribution of the annual costs per investment, energy and maintenance also shows some interesting findings. In low-ambition renovations, the weight of energy costs can become up to 84% of the total costs, while in deep renovations they get reduced to 19%. On the contrary, the weight of the investment costs ranges from 11% to 71% in the same scenarios. The weight of maintenance costs is more constant in all cases, from 5% to 11%. So, investment cost and energy needs are almost inversely proportional.

What are the most cost-effective solutions?

Regarding the best chances for this district, the use of biomass district heating is clearly the winner for all the building renovation degrees. The average savings are around 24% for 30 years. However, the use of ASHP DH is also attractive, with average savings of 14% for 30 years.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

The methodology of IEA EBC Annex 75 and this generic district study include different assumptions in the boundary conditions, modelling, calculations, etc. It is probably impossible to determine which aspects introduce the greatest uncertainties, but we can read the results to identify which aspects have significant influence and, at the same time, can be uncertain in reality.

First, energy prices are one of the driving reasons for conducting renovations, so their variation has a direct influence on the results. On the other hand, high energy prices also influence the materials, products and all the living costs in general. So, the social scene could be very complex.

Second, the cost of products and systems have been calculated from the available databases, but the market prices have been increasing since the pandemic (2020-2022) and shifting greatly due to the recent war in Ukraine and all the events in the global economy that provoked resource limitations worldwide.

Third, regarding the construction and system renovation measures definition, the materials are expected to be accurate, but the definition of the energy supply systems is rather basic - calculated by the generation power sizing - and some of the equipment and auxiliary costs may be insufficient. So the final investment costs are uncertain.

Finally, the user behaviour in residential buildings and their energy use is rarely as planned by the regulations or norms, so there is considerable uncertainty here. For example, the new generation of EPC is proposing new calculation methodologies based on real monitored data and energy bills, but local studies of Social Housing found that low-income families have less than half of the predicted heating use (Hernández-Cruz, 2021).

The generic district results are generally solid as they indicate clear trends consistent with market solutions, costs and homeowners' decisions.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 48. Responses to the hypotheses according to the Spanish generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✔
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	⊖
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	✖
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	✖
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	✔
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy. This is due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	⊖
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	✖
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»	⊖

✔ Confirmed ⊖ Not investigated ✖ Not confirmed

2.6 Sweden

Description of the generic district

The definition of the generic district used a statistical database on the existing residential stock (Boverket, National board of housing). Within this database, there are five groups of years of construction for the buildings. The chosen period (1961-1975) was the largest group in this division. The type of building was chosen as the most common construction typology during those years. The chosen neighbourhood was constructed in 1968.

Table 49. General Information about the Swedish generic district.

Parameter	Explanation/definition
Location	Lund
Latitude	55°42′30″
Longitude	13°11′57″
Climate zone (Köppen classification)	Cfb
Number of buildings in total	22

Table 50. Building typologies of the Swedish generic district.

Parameter	Unit	Typology 1	Typology 2
	Building information		
Number of buildings per typology	1	South-North	East-West
Construction period	1968		
	Geometry		
Gross heated floor area (GHFA)	m^2	3 681	1 476
Heated volume	m^3	9 939	3 985
Façade area incl. window area	m^2	1 937	859
Roof area if flat roof	m^2	955	492
Roof area if pitched roof	m^2		
In case of pitched roof: Is room below roof heated or not?	Yes/No		
Area of windows to North	m^2	406	304
Area of windows to East	m^2	599	449
Area of windows to South	m^2	541	405

Area of windows to West	m^2	522	391
Area of basement ceiling	m^2	-	-
Area of basement wall	m^2	-	-
Area of basement floor	m^2	-	-
Number of floors above ground	-	4	3
		Usage	
Type of use		Apartments	Apartments
Area per occupant	m^2/person	33	33
Typical indoor temperature (for calculations)	°C	22	22
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/(m^2,a)	45	45
		HVAC systems	
Type of existing heating system (boiler, heat pump, etc.)		District heating	District heating
Existing energy carrier (Gas, Electricity, etc.)		-	-
Is ventilation system without heat recovery installed?	Yes/No	Yes	Yes
Is ventilation system with heat recovery installed?	Yes/No	No	NO
Efficiency of heat recovery	%		
Ventilation rate	ach	0.37 l/s/m^2	0.37 l/s/m^2
Is cooling system installed?	Yes/No	No	No
Hot water consumption	l/person/day	25 kWh/m^2/year	25 kWh/m^2/year

Calculation parameters and scenarios

The Swedish team performed many more simulations than what is indicated in the table below. The simulations were based on 6 different façade insulation thicknesses, 3 façade types, 2 roof insulation thicknesses, 3 different materials for the roof, 3 different window cases and 4 different sizes of PV installations. Combining all these solutions adds up to 1 296 different cases.Table 52, therefore, does not explain 5 scenarios but rather forms the basis for the different combinations of simulation cases that were carried out.

Table 51. General parameters for the Swedish generic district.

Weather file used	https://energyplus-weather.s3.amazonaws.com/europe_wmo_region_6/DNK/DNK_Copenhagen.061800_IWEC/DNK_Copenhagen.061800_IWEC
External shading (by surrounding buildings) considered	Yes

Table 52. Measures on the building envelope.

Parameter	Unit	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
			Walls				
U-values	W/m²K	0,449	0,27	0,20	0,16	0,13	0,11
Investment costs	€/$m^2_{building\ element}$	1,73 €/m²/year	EPS 47,25 €/m²/year Rockwool 52 €/m²/year Woodfibre 54 €/m²/year	EPS 51,5 €/m²/year Rockwool 58 €/m²/year Woodfibre 62 €/m²/year	EPS 54,3 €/m²/year Rockwool 61,3 €/m²/year Woodfibre 66 €/m²/year	EPS 59,1 €/m²/year Rockwool 63,6 €/m²/year Woodfibre 69 €/m²/year	EPS 62,6 €/m²/year Rockwool 65,3 €/m²/year Woodfibre 71 €/m²/year
Maintenance costs	€/$m^2_{building\ element}$.year	Included	Included	Included	Included	Included	Included
Service life of insulation measures	years	30	30	30	30	30	30
			Roofs				
U-values	W/m²K	0,25	0,05	0,052	0,052		
Investment costs	€/$m^2_{building\ element}$	7,6 €/m²/year	30 cm Glass wool 29,8 €/m²/year	30 cm wood fibre 34,5 €/m²/year	30 cm cellulose 30,8 €/m²/year		
Maintenance costs	€/$m^2_{building\ element}$.year	Included	Included	Included	Included	Included	Included
Service life of insulation measures	years	30	30	30	30	30	30

Parameter	Unit	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
			Windows				
U-values	W/m²K	3	1,7	0,8			
Investment costs	€/m² heated floor area	0,02 €/m²/year	0,25 €/m²/year	3,26 €/m²/year			
Maintenance costs	€/m² heated floor area/year	Included	Included	Included			
Service life of insulation measures	years	30	30	30			

Only one option for heating system was investigated: a district heating system, which was assumed to have unlimited capacity (modelled as an "ideal heater"), zero investment cost as it already exists, zero maintenance cost compared to alternatives, and an indefinite service life.

Table 53. Measures on the HVAC system including renewable energy generation on-site.

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3
		District heating		
Capacity	kW	Infinite	Infinite	Infinite
Investment costs	€/kW	0	0	0
Maintenance costs	€/year	0	0	0
Service life	Years	Infinite	Infinite	Infinite
		PV system		
Size	kWp	36	91	145
Investment costs	€/kWp	1160	1160	1160
Maintenance costs	€/year	-	-	-
Service life	Years	30	30	30

Generic district calculation results

Figure 70 gives an overview of the combinations between renovation interventions on the envelope and heating systems substitutions. The graph gives an overview of yearly carbon emissions and yearly primary energy use vs. costs for various renovation packages on the building envelopes for the investigated different heating systems.

Two heating systems were investigated:

1. Keeping the old district heating system. This case is labelled DH in the graph.

2. Installing a ground source heat pump. This case is labelled GSHP in the graph.

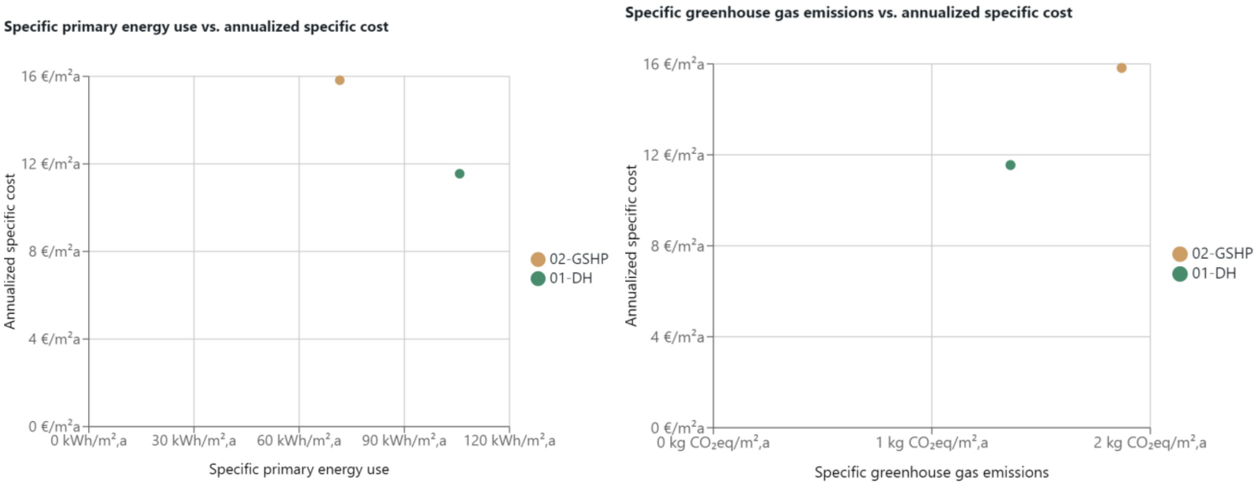

Figure 70. Results for the two considered heating systems.

The graph on the left shows that GSHP costs are higher while primary energy use is lower than district heating. The graph on the right shows that the specific carbon emissions are higher for GSHP than for district heating.

The following graphs (Figure 71 to Figure 73) represent the 1296 combinations of different renovation strategies. The graphs show the cost-effectiveness of various renovation packages on the building envelopes for the different heating systems investigated. The most cost-effective renovation package is marked with a yellow circle.

- Wall insulation materials: EPS, Mineral wool, Wood Fibre.
- Wall insulation thickness: 0 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm.
- Roof insulation material: Cellulose fibre, Mineral wool, Wood Fibre.
- Roof insulation thickness: 10 cm, 30 cm.
- Window options: Existing, adding one pane of glass, new triple-glazed window.
- PV coverage of the roof, 0 %, 20 %, 50 %, 80 %.

Figure 71 shows the annual cost per m² heated floor area as a function of GWP, in kg CO_2 equivalents per m² heated floor area per year. In black are the cases with a new triple-glazed window, in blue are the cases with one pane of glass added, and in orange are the cases with the existing glazing. In red is the base case, where no renovation was carried out. All renovation cases have a higher GWP compared to the base case. However, monetary savings can be realized in some cases. In Figure 71, it is shown that adding one pane of glass to the window has the best financial implication out of the different window renovation cases.

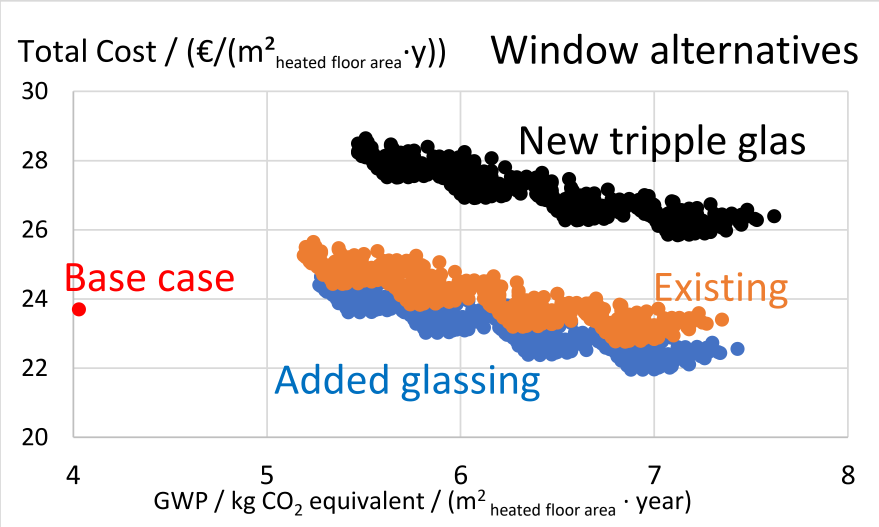

Figure 71. Results for different window strategies.

Figure 72 shows the cost per m² heated floor area per year as a function of GWP in kg CO_2 equivalents per m² heated floor area per year. In blue are cases with 0 % (of the roof area) covered with PV. In orange, 20% of the roof is covered with PV, while the black and green dots show results with 50 % and 80 % of roof coverage, respectively. In red is the base case where no renovation was carried out. Adding more PV modules is beneficial from a financial perspective but not from a GWP perspective.

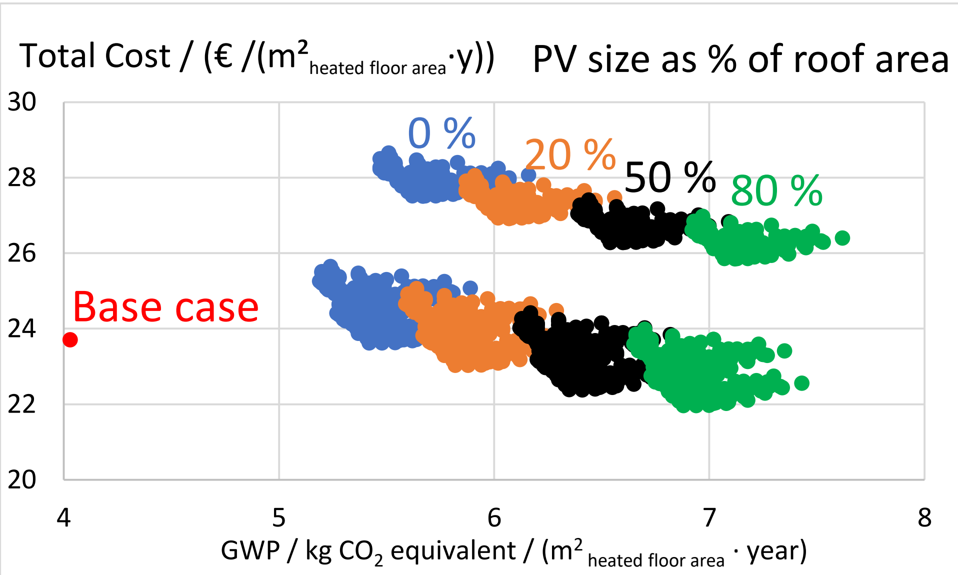

Figure 72. Results for different renewable strategies according to the combination with PV panels. The upper cluster represents triple-glazed windows and the lower cluster represents the existing windows and the existing windows with one additional pane (see **Figure 71**).

Figure 73 shows the cost per m² floor area per year as a function of GWP in kg CO_2 equivalents per m² heated floor area per year. In blue are all the cases except the ones with 10 cm mineral wool added to the roof and no insulation in the walls. These are, instead, shown with yellow dots. In red is the base case where no renovation was carried out. Not adding any insulation or adding only a small amount of insulation is financially better than adding a larger amount of insulation.

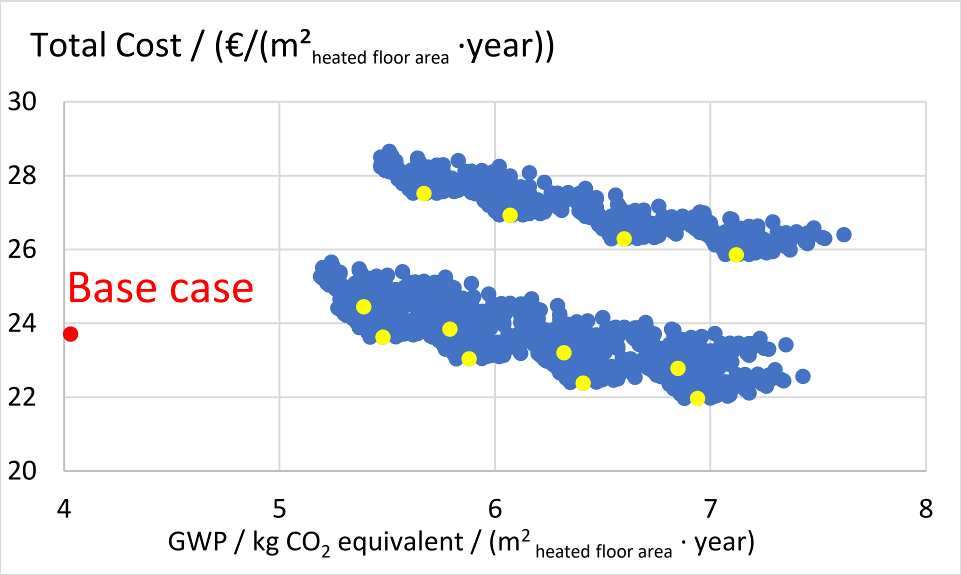

Figure 73. Results for all renovation strategies according to insulation added to the walls and to the roof.

Discussion

What stands out when interpreting the results?

Almost all renovation strategies tested for the generic district in Sweden had only a small or even negative economic profitability. The environmental consequences are also negative for all cases because of the low environmental impact of district heating and the low carbon emissions of Swedish electricity. Also adding to this conclusion is the fact that most buildings in Sweden already have some level of insulation. This makes savings from additional insulation much smaller and thus less economically beneficial.

Installing a new heat pump to replace the district heating is negative from an economic perspective, as well as from an ecological perspective. This can be seen in Figure 70.

What are the most cost-effective solutions?

Adding one extra glazing to the existing window is profitable.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

The largest uncertainty lies in the values used for carbon emissions per produced/used kWh of electricity and district heating. Sweden has very low emissions from both. Still, there are large variations between municipalities within the country. Performing the simulations mentioned above in different municipalities would lead to very different conclusions.

Future energy cost and cost variations between different regions are likely to shift the calculations considerably.

Responses to the hypotheses

The generic calculations in Sweden were not performed in such a way that the hypotheses could be answered. Sweden generally has fossil fuel-free district heating systems, depending on the municipality. Thus there are no strong incentives to change them.

Furthermore, changing the district heating in Sweden would have to consider many different aspects. For instance, if we are not going to burn garbage, what will we do with it? If we are going to lower the temperature in the district heating grid to use more waste heat from industry, how do we ensure that we can meet the maximum power demand for the buildings?

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 54. Responses to the hypotheses according to the Swedish generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	−
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	−
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	−
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	−
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	−
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy, due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	−
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	−
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system.»	−

Confirmed   Not investigated   Not confirmed

2.7 Switzerland

Description of the generic district

The generic district in Switzerland is defined based on a real district, which is reasonably representative of typical Swiss suburban neighbourhoods of cities. It consists of a group of multi-family apartment buildings. The number of buildings in the district was changed, and the number of building types was reduced to two, with ten buildings each, for the purpose of carrying out the generic assessment. The construction period from 1950 to 1970 was assumed for the buildings in question, with relatively poor energy performance of the buildings' envelopes. Availability of access to the ground for ground-source heat pumps and groundwater for groundwater heat pumps was assumed, as well as access to a lake for lake water-based district heating and the possibility of using air-source heat pumps.

Table 55. General Information about the Swiss generic district.

Parameter	Explanation/definition
Location	Luzern
Latitude	E: 8.331808n
Longitude	N: 47.035004
Climate zone (Köppen classification)	Dfb (Humid continental climate)
Number of buildings in total	20

Table 56. Building typologies of the Swiss generic district.

Parameter	Unit	Building typology 1	Building typology 2
	Building information		
Number of buildings per typology		10	10
Construction period		1950-1970	1950-1970
	Geometry		
Gross heated floor area (GHFA)	m^2	2122	1963
Heated volume	m^3		
Façade area incl. window area	m^2	1175	949
Roof area if flat roof	m^2	534	514
Roof area if pitched roof	m^2	-	
In case of pitched roof: Is room below roof heated or not?	Yes/No	-	
Area of windows to North	m^2	11	87
Area of windows to East	m^2	87	13

Parameter	Unit	Building typology 1	Building typology 2
Area of windows to South	m^2	15	114
Area of windows to West	m^2	114	11
Area of basement ceiling	m^2	341	341
Area of basement wall	m^2	-	-
Area of basement floor	m^2	-	-
Number of floors above ground	-	4	4
		Usage	
Type of use		Apartment building	Apartment building
Area per occupant	m^2 / person	40	40
Typical indoor temperature (for calculations)	°C	20 °C	20 °C
Average electricity consumption per year and m² (excluding heating, cooling, ventilation)	kWh/(m².a)	17	17
		HVAC systems	
Type of existing heating system (boiler, heat pump, etc.)		Boiler	Boiler
Existing energy carrier (Gas, Electricity, etc.)		Oil	Gas
Is ventilation system without heat recovery installed?	Yes/No	No	No
Is ventilation system with heat recovery installed?	Yes/No	No	No
Efficiency of heat recovery	%		
Ventilation rate	$m^3/(h*m^2)$	0.7	0.7
Is cooling system installed?	Yes/No	No	No
Hot water consumption	l/person/day	40	40

Calculation parameters and scenarios

Table 57. General parameters for the Swiss generic district.

Date the calculations were made	**2021-2022**
Weather file used	Regional climate data
External shading (by surrounding buildings) considered	No

Description of building envelope measures

The following scenarios for building envelope measures were taken into account. Different thicknesses of insulation layers are assumed for the two building types, as the original U-values of the thermal envelopes differ. Differences between the two building types are indicated with a slash:

- Reference case: renovation of walls, roof and windows to restore the building's functionality, yet without improving efficiency
- Scenario M1: Insulation of exterior wall with 8/ 10 cm of rock wool
- Scenario M2: Insulation of exterior wall with 18/ 21 cm of rock wool
- Scenario M3: Scenario M2 + insulation of cellar ceiling with 12/ 7 cm of PUR
- Scenario M4: Scenario M2 + insulation of cellar ceiling with 17/ 18 cm of PUR
- Scenario M5: Scenario M4 + insulation of roof with 2/ 13 cm of EPS
- Scenario M6: Scenario M4 + insulation of roof with 12/ 24 cm of EPS
- Scenario M7: Scenario M6 + new windows with U-value of 1.3 W/(m²K)
- Scenario M8: Scenario M6 + new windows with U-value of 0.78 W/(m²K)

The following table (Table 58) gives information on data associated with the various building envelope measures used in the calculations. In the column for the reference case, the original U-values are indicated for the two building types. In the columns for the scenarios, the resulting U-values take into account energy efficiency measures.

Table 58. Measures on the building envelope.

Parameter	Unit	Reference	M1	M2	M3	M4	M5	M6	M7	M8
					Walls					
U-values	W/m²K	0.48 0.69	0.25 0.25	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15
Investment costs	€/m²$_{building\ element}$	70 70	153 153	158 160	158 160	158 160	158 160	158 160	158 160	158 160
Maintenance costs	€/m²$_{building\ element}$.year	-	-	-	-	-	-	-	-	-
Service life of insulation measures	years	20	30	30	30	30	30	30	30	30
					Roofs					
U-values	W/m²K	0.28 2.10	0.28 2.10	0.28 2.10	0.28 2.10	0.28 2.10	0.25 0.25	0.15 0.15	0.15 0.15	0.15 0.15
Investment costs	€/m²$_{building\ element}$	66 66	66 66	66 66	66 66	66 66	196 203	199 224	199 224	199 224
Maintenance costs	€/m²$_{building\ element}$.year	-	-	-	-	-	-	-	--	

Parameter	Unit	Reference	M1	M2	M3	M4	M5	M6	M7	M8
Service life of insulation measures	years	30	40	40	40	40	40	40	40	40
					Windows					
U-values	W/m²K	2.08 2.82	2.08 2.82	2.08 2.82	2.08 2.82	2.08 2.82	2.08 2.82	2.08 2.82	1.31 1.31	0.78 0.78
Investment costs	€/m²$_{building\ element}$	40	40	40	40	40	40	40	916	1038
Maintenance costs	€/m²$_{building\ element}$.year	-	-	-	-	-	-	-	-	-
Service life of insulation measures	years	15	25	25	25	25	25	25	25	25
					Cellar ceiling					
U-values	W/m²K	0.75 0.90	0.75 0.90	0.75 0.90	0.20 0.30	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15	0.15 0.15
Investment costs	€/m²$_{building\ element}$	-	-	-	161 157	171 173	171 173	171 173	171 173	171 173
Service life of insulation measures	years	30	40	40	40	40	40	40	40	40

Description of HVAC systems

The following types of HVAC systems were considered:

- Heating system 1: decentralised oil or gas heating systems as a reference case
- Heating system 2: decentralised air-source heat pumps
- Heating system 3: decentralised ground-source heat pumps
- Heating system 4: Lake water district heating with centralised heat pump
- Heating system 5: Cold lake water district heating with decentralised heat pumps
- Heating system 6: Geothermal district heating with centralised heat pump
- Heating system 7: Groundwater district heating with centralised heat pump

Two different lake water-based district heating systems are considered. Heating system 4 refers to a lake water district heating system with a centralised heat pump, and heating system 5 to a cold lake water district heating system where cold water is transported through the grid and heat is produced through decentralised heat pumps. Two additional district heating systems with a centralised heat pump considered, one extracting energy from the ground through borehole heat exchangers and the other extracting energy from groundwater. For the generic assessment, it is assumed that related energy sources are available.

The following table (Table 59) gives information on data associated with the various HVAC systems used in the calculations. The detailed data for calculations of heating systems 4-7 was obtained under a confidentiality agreement and cannot be shared here.

Table 59. Characteristics of the HVAC systems.

Parameter	Unit	Reference	M1	M2	M3	M4	M5	M6	M7	M8
Heating system 1: fossil fuel reference, decentralised oil or gas heating										
Capacity	kW	1’542	1’349	1’290	1’202	1’186	916	886	730	656
Investment costs	EUR/kW	1’019	1’090	1’118	1’163	1’171	1’346	1’374	1’556	1’675
Maintenance costs	EUR/year	27’300	27’100	26’900	26’’700	26’700	26’500	26’400	25’900	25’600
Service life	Years	20	20	20	20	20	20	20	20	20
Heating system 2: decentralised air-source heat pumps										
Capacity	kW	1’542	1’349	1’290	1’202	1’186	916	886	730	656
Investment costs	EUR/kW	2’678	2’724	2’744	2’776	2’781	2’868	2’885	3’030	3’147
Maintenance costs	EUR/year	16’300	16’100	16’00	15’900	15’900	15’600	15’600	15’400	15’400
Service life	Years	20	20	20	20	20	20	20	20	20
Heating system 3: decentralised ground-source heat pumps										
Capacity	kW	1’542	1’349	1’290	1’202	1’186	916	886	730	656
Investment costs	EUR/kW	3’561	3’640	3’674	3’728	3’736	3’885	3’914	4’102	4’224
Maintenance costs	EUR/year	13’400	13’200	13’200	13’100	13’100	12’800	12’800	12’600	12600
Service life	Years	24	24	24	24	24	24	24	24	24

The conversion efficiency of the heat pumps for heating was estimated to vary between 2.5 and 3.1 for decentralised air source heat pumps depending on the level of the energy performance of the buildings; between 3.0 and 3.8 for decentralised ground source heat pumps; between 2.2 and 2.6 for a centralised water source heat pump based on lake water or groundwater or a centralised ground source heat pump, taking into account the relatively high temperatures to be reached in a centralised system; and between 3.2. and 4.1 for decentralised water source heat pumps in connection with a cold district heating system.

Generic district calculation results

The following graphs (Figure 74 to Figure 80) give an overview of the combinations between renovation interventions on the envelope and heating systems substitutions. The graphs provide an overview of specific yearly carbon emissions and yearly primary energy use vs. costs for various renovation packages on the building envelopes for the different heating systems investigated.

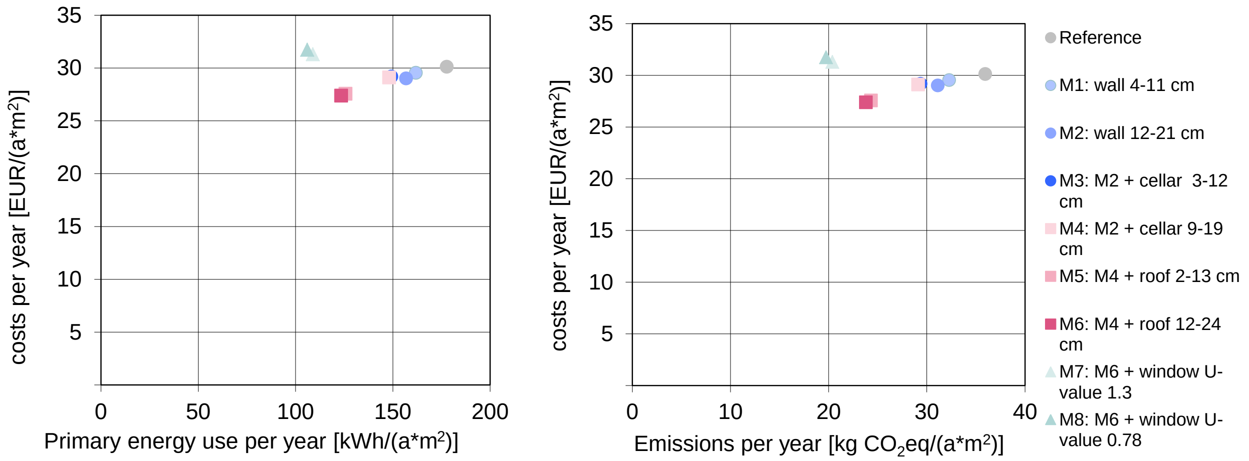

Figure 74. Results for Heating system 1: decentralised oil/gas heating systems as reference.

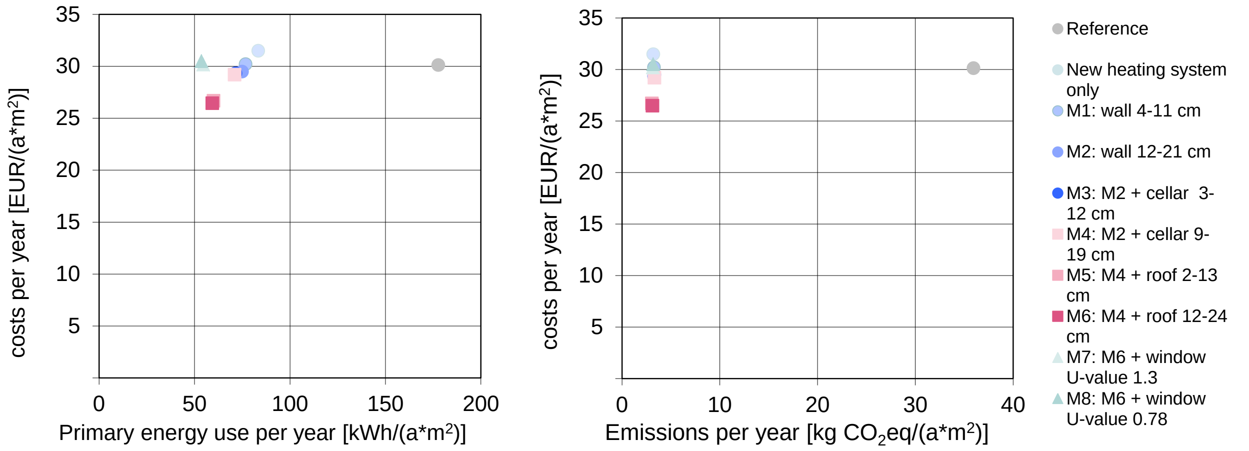

Figure 75. Results for Heating system 2: decentralised air-source heat pumps.

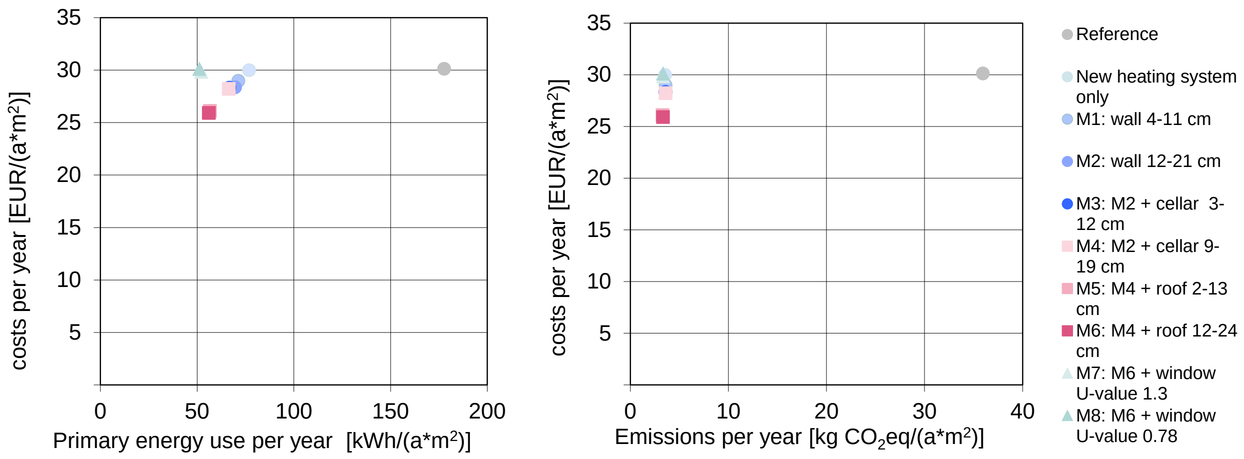

Figure 76. Results for Heating system 3: decentralised ground-source heat pumps.

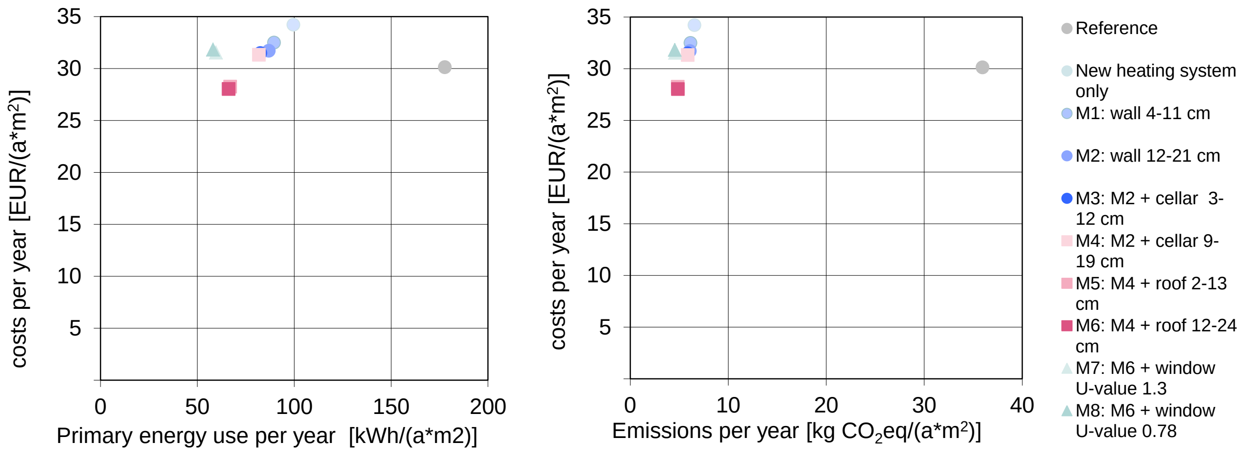

Figure 77. Results for Heating system 4: lake water district heating with central heat pump.

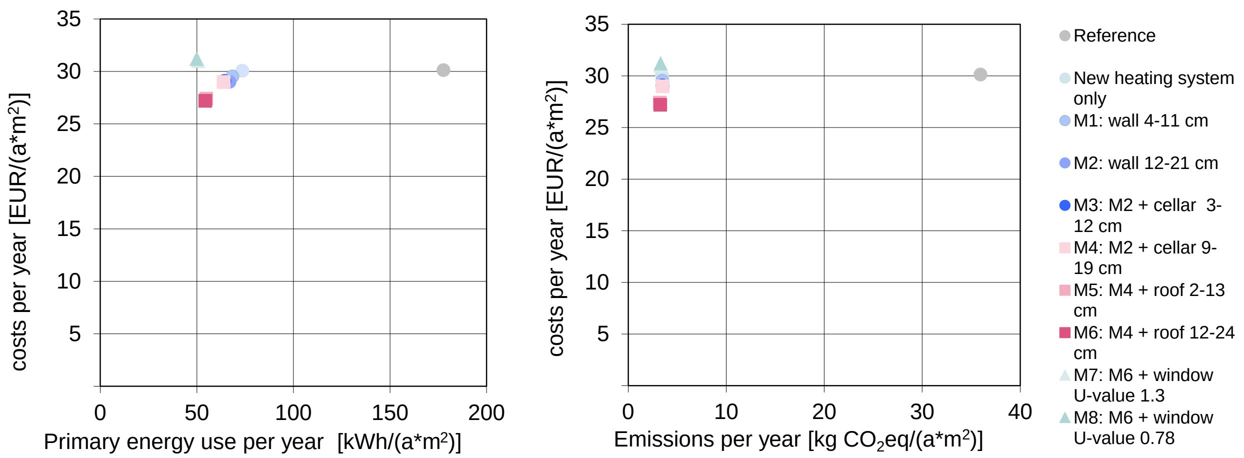

Figure 78. Results for Heating system 5: cold lake water district heating with decentralised heat pumps.

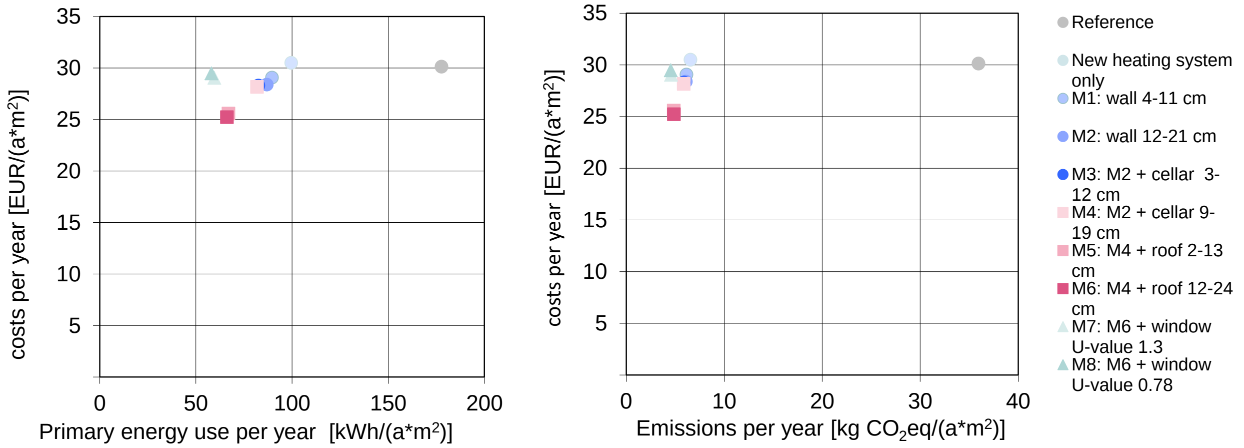

Figure 79. Results for Heating system 6: geothermal district heating with centralised heat pump.

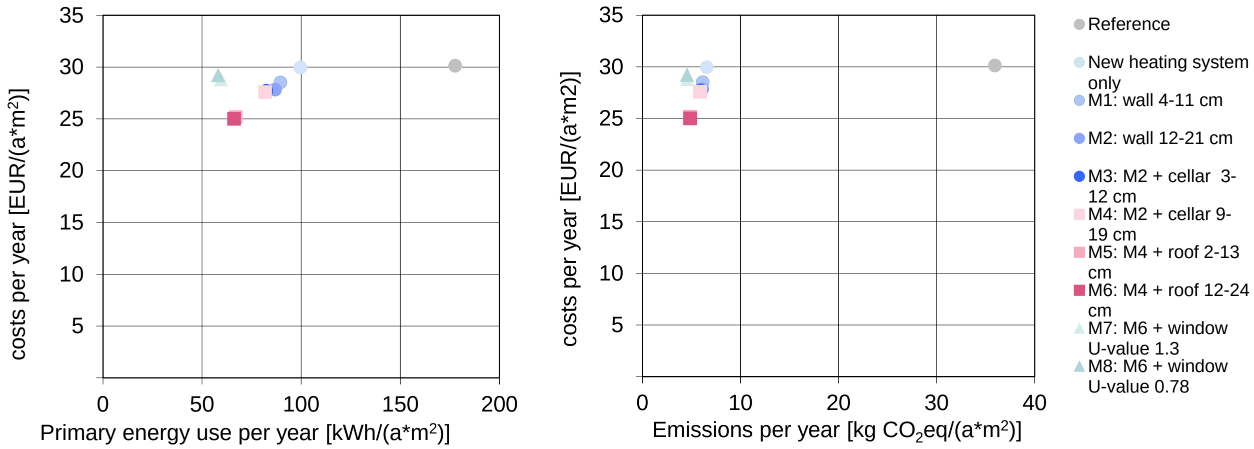

Figure 80. Results for Heating system 7: groundwater district heating with centralised heat pump.

Figure 81 contains an overview of the various renovation packages on the building envelopes and the various heating systems investigated. It summarises the relationships between specific yearly carbon emissions or yearly primary energy use vs. costs for various renovation packages on the building envelopes for the different heating systems investigated. Each point in the curves corresponds to one renovation package associated with the respective energy supply system.

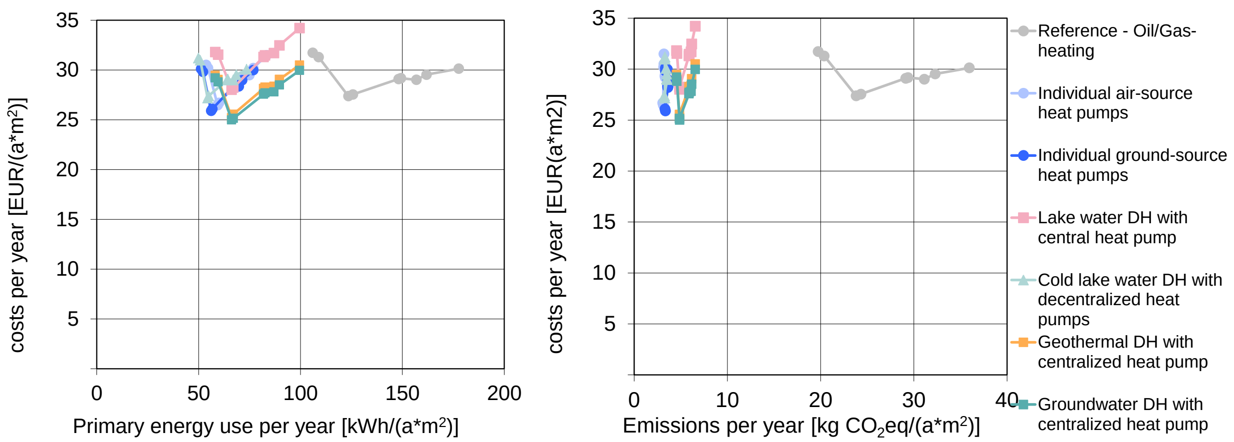

Figure 81. Overview of combinations of renovation packages and heating systems.

The following graphs (Figure 82 to Figure 88) specifically show the most cost-effective renovation packages for the various heating systems investigated. The most cost-effective renovation package is M6, marked with a yellow circle.

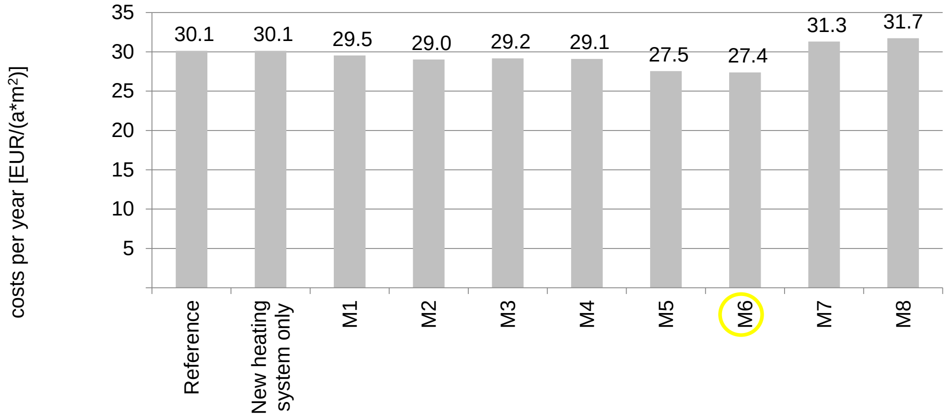

Figure 82. Cost-effective renovation package for Heating system 1: decentralised oil/gas heating systems as reference.

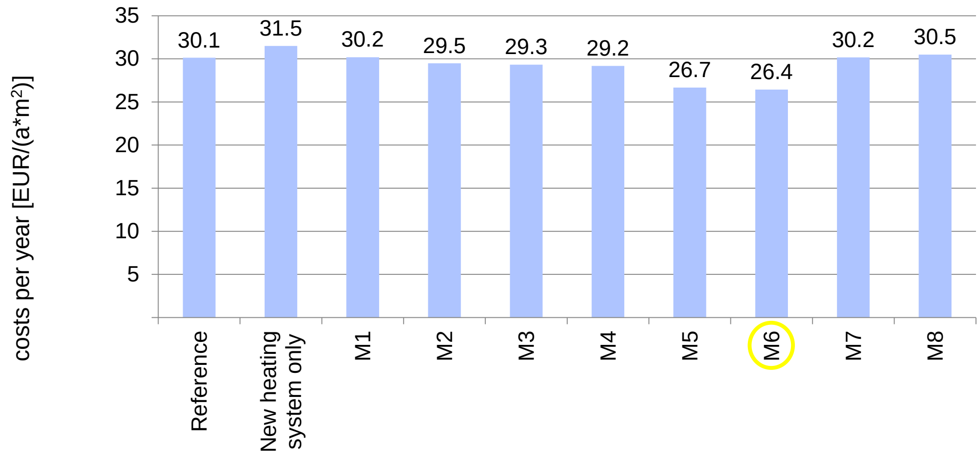

Figure 83. Cost-effective renovation package for Heating system 2: decentralised air-source heat pumps.

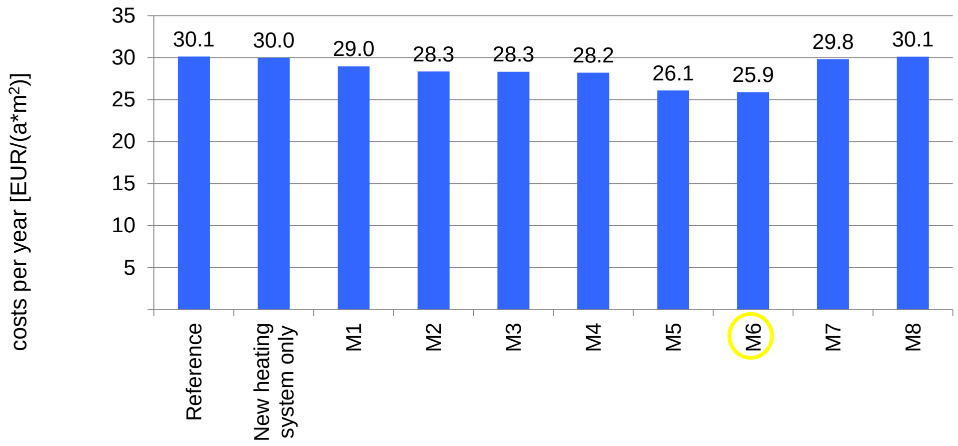

Figure 84. Cost-effective renovation package for Heating system 3: decentralised ground-source heat pumps.

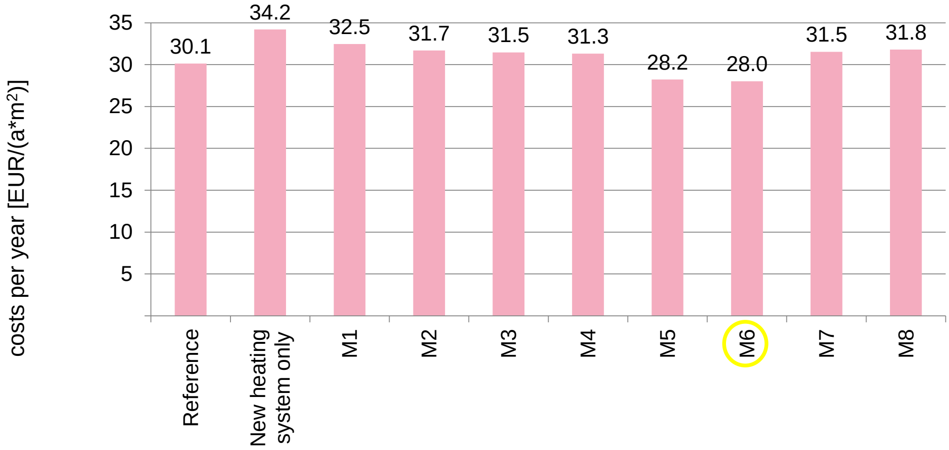

Figure 85. Cost-effective renovation package for Heating system 4: lake water district heating with central HP.

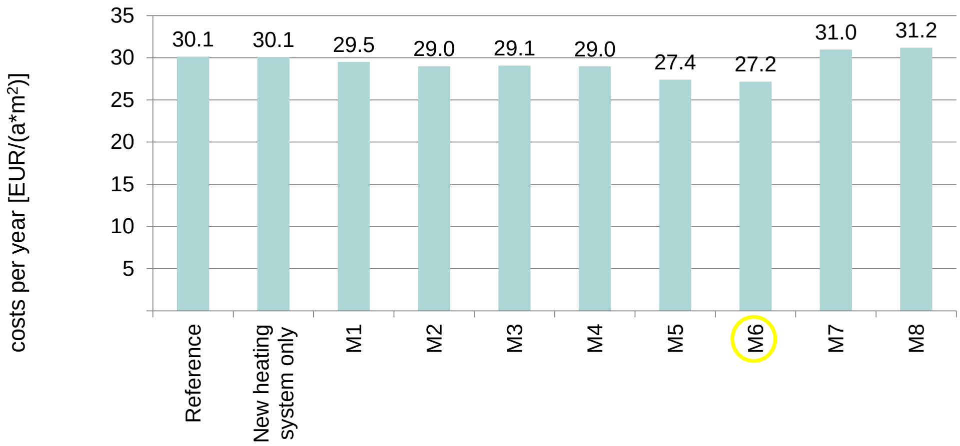

Figure 86. Cost-effective renovation package for Heating system 5: cold lake water district heating with decentralised heat pumps.

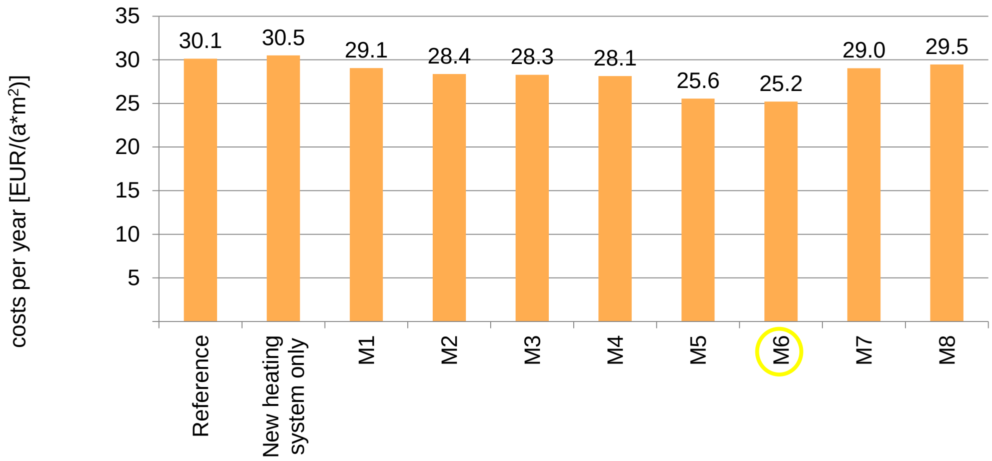

Figure 87. Cost-effective renovation package for Heating system 6: geothermal district heating with centralised heat pump.

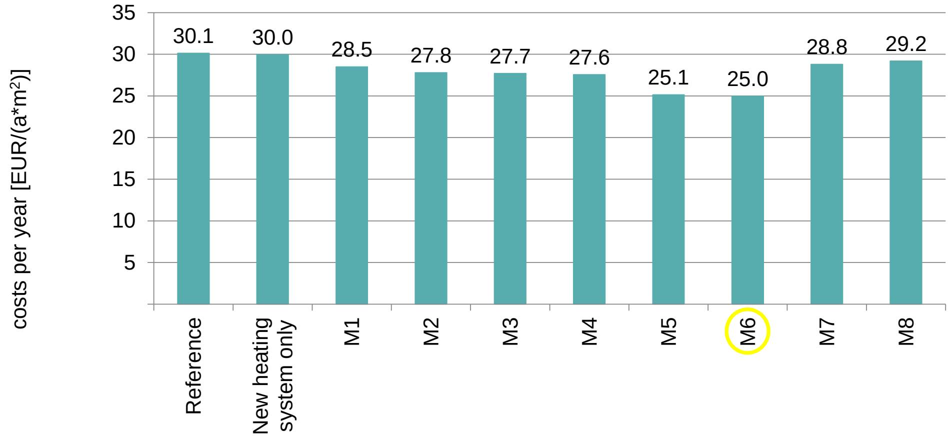

Figure 88. Cost-effective renovation package for Heating system 7: groundwater district heating with centralised heat pump.

Figure 89 summarizes the cost savings of the most cost-effective renovation package on the building envelopes (M6) investigated for various types of heating systems, compared to a scenario in which only the heating system is replaced.

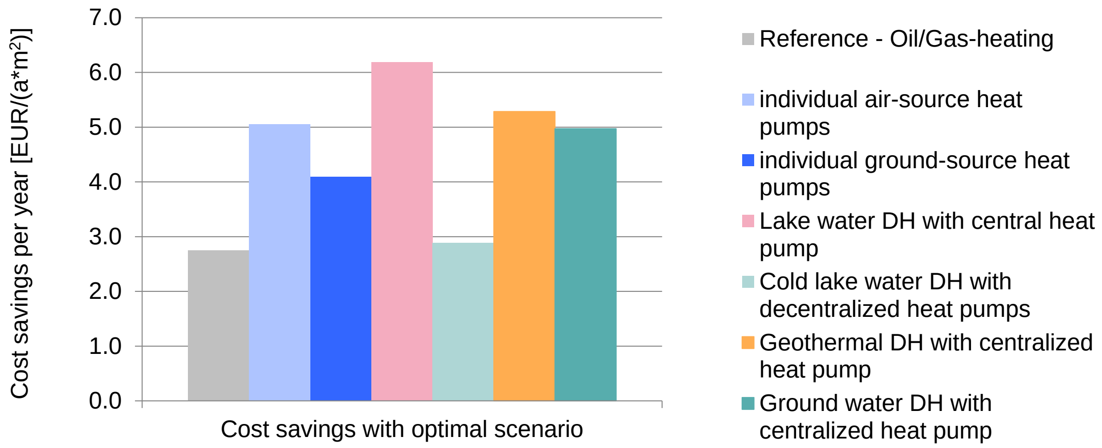

Figure 89. Cost savings of the most cost-effective renovation package for each heating system.

The following graphs (**Figure 90**) show a comparison of the cost-effectiveness of various heating systems considered, with and without considering energy efficiency measures on the building envelopes.

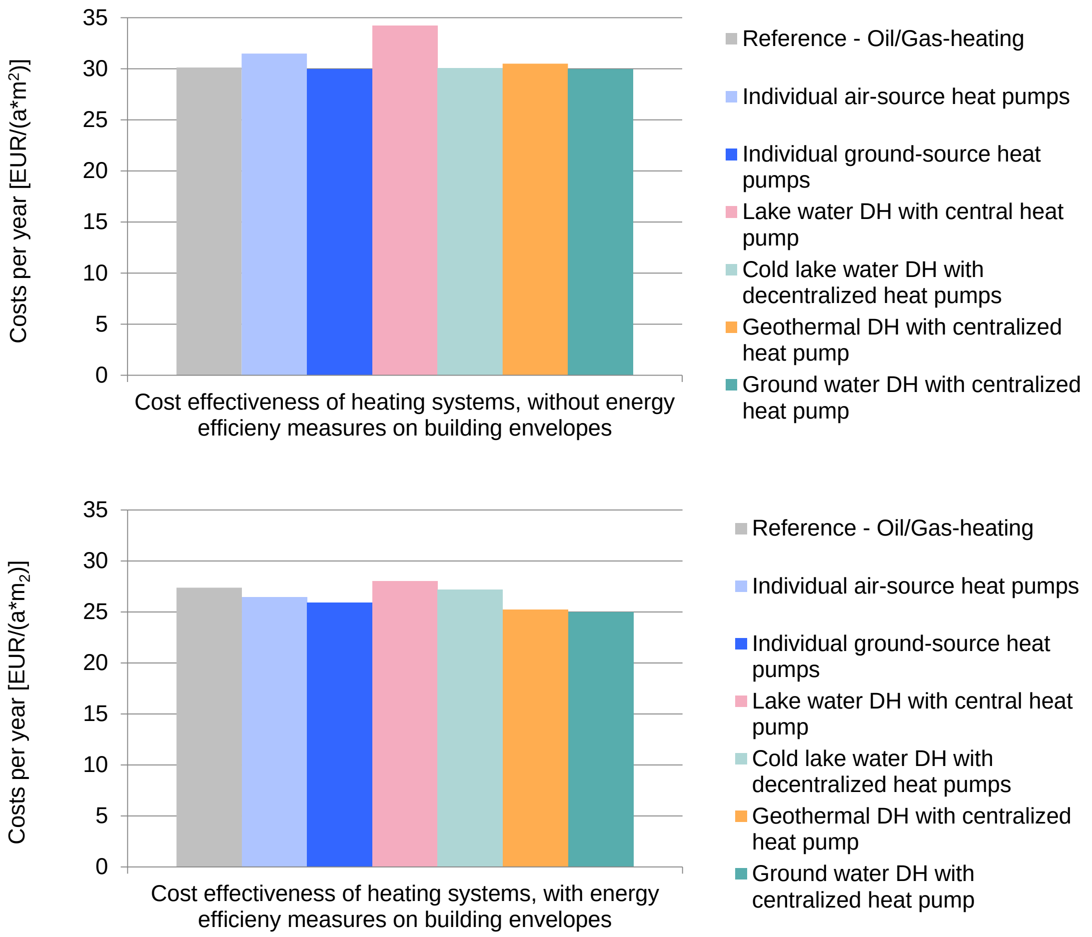

Figure 90. Effectiveness of the heating systems when comparing scenarios without (top) and with (bottom) EEMs.

Based on these graphs, the following outcomes can be recognized:

- Energy efficiency measures on the building envelopes are cost-effective for all heating system scenarios.
- Package M6 of energy efficiency measures on the building envelopes is the most cost-effective of all the packages investigated for all heating systems considered.
- For all renewable energy-based heating systems considered, measures on the building envelope are at least as cost-effective as for the fossil fuel-based reference.
- The installation of new windows was not found to be cost-effective in combination with any type of heating system.
- Cost savings that can be achieved through energy efficiency measures are larger for heating systems based on renewable energy than for heating systems based on using fossil fuels.
- The largest cost savings through efficiency measures on the building envelopes can be achieved in the case of a lake water district heating system with a centralised heat pump.
- Without energy efficiency measures, two of the investigated renewable energy-based heating systems offer cost advantages in comparison with heating systems based on fossil fuels; these are decentralised ground source heat pumps and a groundwater-based district heating system with a centralised heat pump. With energy efficiency measures, there are scenarios with all types of investigated renewable energy-based heating systems that are more cost-effective than scenarios with fossil fuel-based heating systems. An exception is the lake water district heating system with a centralised heat pump, whose costs remain higher than the fossil fuel-based reference scenario even with energy efficiency measures; however, still in that case, at least the gap in cost-effectiveness compared to a fossil fuel-based system is significantly reduced when energy efficiency measures are taken into account.

In addition, the following results were found in this generic district calculation:

- Of the various types of heating systems investigated, groundwater-based district heating with a centralised heat pump offers the most cost-effective solution, combined with efficiency measures on the building envelopes.
- The second most cost-effective solution was the geothermal energy-based district heating system with a centralised heat pump and efficiency measures on the building envelopes.
- The solution that leads to the lowest carbon emissions is the cold lake water district heating system with decentralised heat pumps and energy efficiency measures on the building envelopes.

Discussion

What stands out when interpreting the results?

Fossil fuel-based heating systems are no longer an option as the significant amount of carbon emissions they cause is incompatible with the achievement of climate protection targets. In addition, the results of the calculations show that switching to renewable energy-based heating systems is cost-effective for most types of heating systems investigated. This cost-effectiveness becomes even more pronounced when combinations with energy efficiency measures are taken into account.

Carbon emissions are similarly low for all scenarios with renewable energy-based heating systems and significantly lower than the scenarios with heating systems based on fossil fuels. Primary energy use is also lower for scenarios with renewable energy-based heating systems than fossil fuel-based heating systems, but the difference is smaller. For heating systems based on a centralised heat pump, whether with lake water, ground or groundwater as a heat source, carbon emissions and primary energy use are higher than for decentralised air source heat pumps or decentralised geothermal heat pumps or cold lake water district heating system with decentralised heat pumps. The reason is that the overall efficiency of the former energy systems is a bit smaller than that of the latter. This is due to the following facts: in the case of a district heating system with a centralised heat pump, that heat pump has to reach a higher temperature level than if each building is heated decentrally, because on the one hand, a district heating system has to deliver the highest temperature that any of the connected buildings require, and on the other hand, because energy losses in the grid make it necessary that at the central location of heat generation, the temperature is higher than required in each of the buildings. In addition, energy losses occurring when distributing energy in the grid reduce the overall system's efficiency.

Results show that for all renewable energy-based heating systems considered, measures on the building envelope are at least as cost-effective as for the fossil fuel-based reference. This is an important finding as this indicates that energy efficiency measures are at least as attractive for investors in combination with renewable energy-based heating systems as this was in the previous case with fossil fuel-based heating systems. This result may be surprising at first sight because renewable energy-based heating systems have, in principle, lower energy costs than fossil fuel-based systems and benefit less from energy consumption savings. However, there are two effects which contribute to making energy efficiency measures on building envelopes cost-effective in combination with renewable energy-based heating systems: renewable energy-based heating systems typically have higher investment costs than those based on fossil fuels; the lower the energy need, the lower is also the required capacity of the installed heating system, and renewable energy-based heating systems benefit from this effect more strongly than fossil fuel-based systems. In addition, heat pumps work more efficiently if the temperature difference between the source and the heat distribution system is low; energy efficiency measures on the building envelopes allow to reduce the temperature in the heat distribution system, increasing the heat pump's efficiency. This contributes to the cost-effectiveness of energy efficiency measures on the building envelopes in combination with renewable energy-based heating systems if such heating systems are heat pumps.

It was even found that efficiency measures on the building envelopes benefit renewable energy systems more than fossil fuel-based systems. Apparently, this can be explained by the fact that savings on investment costs and increased efficiencies of heat pumps are stronger factors than savings on energy consumption.

It might initially look plausible that energy efficiency measures are more cost-effective combined with decentralised heating systems based on renewable energy than combined with district heating systems based on renewable energy. The reason is that it might be assumed that there are significant economies of scale in the case of district heating systems, which would mean that the costs of respective systems increase only to a small extent as the required capacity increases because such district heating systems have a large share of costs which are mostly fixed and less variable with the installed capacity. However, it is found that the same package of efficiency measures on the building envelopes is most cost-effective for all types of heating systems investigated.

This can be explained by the fact that also in the case of district heating systems, efficiency measures on building envelopes allow for reduced investment costs, and because the efficiency of centralised heat pumps can be strongly increased if efficiency measures on building envelopes allow decreasing temperatures in the district heating system.

Nevertheless, it was found that decentralised renewable energy systems have less economies of scale than district heating systems. One explanation is that, even though there are economies of scale for smaller systems like heat pumps, there are other factors, such as the need to meet noise restrictions or challenges associated with drilling boreholes, which become more than proportionally larger if the size of heating systems increases. This may therefore cancel out any benefits that might be gained from economies of scale obtained for heat pumps alone. This reinforces the attractiveness of energy efficiency measures on building envelopes at the level of decentralised buildings compared to district-based solutions.

It also has to be considered that in the case of district heating, increasing the energy efficiency of the building envelopes is particularly attractive for the buildings with the worst energy performance. This contributes to lowering the temperature in the district heating systems for the reasons indicated above.

Synergies of energy efficiency measures on building envelopes combined with a renewable energy-based heating system are the lowest in the case of a cold lake water district heating system. This can be explained by the fact that the heat pumps already have a relatively high efficiency in this case, as their operating temperature can be optimally set for each building and because there are virtually no heat transport losses in the grid.

The cost-effectiveness of energy efficiency measures on building envelopes is slightly higher for air heat pumps than for ground-source heat pumps. One reason could be that ground source heat pumps already have relatively high efficiency and therefore benefit less, in relative terms, from efficiency measures on building envelopes.

What are the most cost-effective solutions?

Concerning the efficiency measures on building envelopes, the same package of efficiency measures was found to be most cost-effective in combination with all types of heating systems investigated. The package of efficiency measures includes improving the efficiency of the walls, roof andcellar ceiling. The installation of new windows was found not cost-effective in combination with any type of heating system; a related renovation measure, therefore, requires a different type of motivation than to save costs.

Based on the calculations and related assumptions for the investigated heating systems, it is found that a groundwater district heating system and a geothermal district heating system, each with a centralised heat pump, are the most cost-effective solutions, in combination with energy efficiency measures. However, it has to be kept in mind that groundwater is only available in specific locations, and in the costs for a centralised geothermal heat pump, the costs required for regenerating the heat in the ground were not yet included.

Of the other systems investigated, decentralised air-source heat pumps or decentralised ground-source heat pumps are the next most cost-effective solutions, combined with energy measures, with a slight advantage of the decentralised ground-source heat pump compared to the air-source heat pumps. The difference between air-source heat pumps and ground-source heat pumps can be explained by the higher efficiency of ground-source heat pumps, which makes these systems more cost-effective under the assumptions made, despite their higher investment costs due to drilling boreholes.

Lake water-based district heating systems are a bit less cost-effective under the assumptions made. Cold lake water district heating with decentralised heat pumps is slightly more cost-effective than with a centralised heat pump. This may be explained by the fact that the efficiency of a cold lake water district heating system is higher than in the case of a centralised heat pump. In the former case, there is no need to reach a relatively high temperature which is enough to serve all buildings in the district. This benefits the efficiency of the heat pumps involved. Furthermore, in this case there are fewer heat losses associated with the grid because lake water is distributed at cold temperatures, which saves energy and is also a factor that makes the heat pumps run more efficiently in a decentralised situation compared to a centralised heat pump. However, there are higher investment costs in the case of a cold lake water district heating system, and there are no economies of scale for the heat pumps, as they are installed for each building.

There are several factors which contribute to the cost-effectiveness of centralised district heating systems:

- There are economies of scale concerning the heat pump: a large heat pump costs less than the sum of several small heat pumps with the same total capacity.
- District heating systems offer the opportunity to use energy resources that single buildings could not access. Groundwater is, for example, a particularly attractive heat source, as its temperature is higher in winter than the air and because with water the heat exchange can be easily achieved; often, groundwater is only permitted to be accessed for energy purposes if it is used for a group of buildings, not only for an individual building, to reduce risks for contamination of the groundwater. Other attractive energy resources are waste heat, water from rivers or lakes, or stored solar heat.
- In the case of a district heating system accessing a heat source such as a lake, this also has the advantage of avoiding the need for drilling boreholes or preventing noise emissions of air source heat pumps.

However, there are several factors which favour decentralised solutions:

- Pipes associated with district heating systems are a cost factor that can be avoided in the case of decentralised systems.
- Extracting heat from a lake or other surface water requires specific installations, which can be avoided in the case of decentralised solutions.
- In the case of decentralised installations, each heating system can be specifically designed to deliver the minimum temperature level for the building, thereby ensuring that heat pumps have the lowest temperature hubs possible and, accordingly, work most efficiently. This contrasts with a district heating system, which has to provide heat at a temperature level suitable also for the building with the highest temperature needs.
- There are often fewer losses than in centralised solutions.

In the present case, economies of scale of the centralised heat pump are key for making a centralised groundwater heat pump and centralised geothermal heat pumps cost-effective, but the cost advantages of decentralised solutions prevail when air-source heat pumps or geothermal heat pumps are compared, for example, with lake-water district heating.

Where are the greatest uncertainties in the assumptions? How reliable are the results?

The largest uncertainty concerns energy prices. The future level of energy prices has an important impact on the cost-effectiveness of various heating systems as well as energy efficiency measures on the building envelopes.

For the calculations in this assessment, an increase in oil and gas energy prices of 30% until 2030, compared to 2021, was assumed. This might underestimate price increases if considering, for example, that the war in Ukraine has a long-term impact on energy prices. In case energy prices of fossil fuels increase further, this would favour further renewable energy-based heating systems and energy efficiency measures on the building envelopes.

Concerning the electricity supply, it was assumed that it would be based on renewable energy sources to comply with the Paris Agreement. This is justifiable because heat pumps imply an increase in electricity consumption, which likely has to be covered by renewable energy sources. It was also assumed that a third of the electricity consumed would have to be provided through seasonal storage from summer to winter. In case it is possible, in the future, to obtain enough electricity during the winter months from other neighbouring countries instead, for example, through wind energy or solar energy from countries further South, electricity prices would likely be smaller than assumed here. If this was the case, strategies based on renewable energy systems would have even additional advantages compared to fossil fuel systems previously used.

However, it also has to be kept in mind that other external costs in connection with electricity consumption were not yet considered in the energy prices. This concerns, for example, the interest in having a landscape with as few energy installations as possible or in allowing rivers to flow naturally. If such external costs were considered, strategies with the lowest possible energy consumption would increase attractiveness.

There is a potential advantage of a lake-water district heating system, which was not yet taken into account. The assessment was so far only carried out for the specific district investigated; the option that the buildings concerned are connected to a larger lake water-based district heating system was not yet considered. Connection to such a larger system would likely lead to larger synergies and economies of scale than for the system investigated here.

Furthermore, there are additional advantages for the cost-effectiveness of district heating systems in general, which were not yet taken into account:

- In the calculations carried out, the same electricity price was applied for decentralised heat pumps and district heating systems with centralised heat pumps for the sake of transparency in comparing cost-effectiveness. However, from the perspective of investors or building owners, it has to be considered that a centralised heat pump is a large electricity consumer which can obtain tariffs with lower electricity prices than decentralised systems.
- If an electricity supply company can operate a district heating system, it is interested in selling heat, not just electricity, to customers. This increases the turnover of the company and possibly also its profit. The energy company may therefore have an interest and the possibility to define even lower electricity costs, if necessary, to be cost-effective compared with other types of heating systems.

If these additional factors are considered, it can be expected that the costs associated with a district heating system, particularly a lake-water-based district heating system, are lower than estimated here. These effects may be relatively large, whereas the comparison indicates that under current assumptions, the cost-effectiveness of various heating systems is relatively similar. These additional factors are, therefore, likely to have an important impact on the cost-effectiveness of district solutions, particularly the lake-water-based district heating systems, in comparison with decentralised solutions.

Responses to the hypotheses

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated generic district:

Table 60. Responses to the hypotheses according to the Swiss generic district assessment.

Hypotheses	
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✓
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	⊖
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	⊖
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	✓
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	✓
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy, due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	⊖
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	✓
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system»	⊖

✓ Confirmed ⊖ Not investigated ✗ Not confirmed

3. Discussion of overall results

Cost-effectiveness of energy efficiency measures combined with various heating systems

From the assessment of the generic districts under analysis concerning energy efficiency measures applied to the buildings' envelopes, it was observed that there are cases in which these measures are cost-effective in all scenarios, others in which these measures are never cost-effective and other cases where these measures are sometimes cost-effective.

In the Portuguese case, all proposed renovation measures on building envelopes were cost-effective combined with all energy systems due to the absence of building insulation in the starting situation. In the Swiss case, energy efficiency measures on the walls, the roof and the cellar ceiling were cost-effective combined with all energy systems, whereas the installation of new windows was not found to be cost-effective. In the Danish case, all energy efficiency measures were cost-effective, with the renovation of windows and improvement of roof insulation proving to be the most cost-effective. In the Austrian case, the cost-effectiveness of building envelope measures depends on the heating system. All proposed measures were cost-effective for air and ground source heat pumps, while for a district heating or natural gas solution, the use of solar thermal, photovoltaics and a heat recovery ventilation system were not. In the Spanish case, the cost-effectiveness of energy efficiency measures was typically not achieved, except for a ground source heat pump-based district heating system. This could be explained by the limited effect of envelope renovations in the mild climate of Spain and the high investment costs needed to install ground source heat pumps (that can, however, be lowered by applying energy efficiency measures on the envelopes). However, for air source heat pumps, whether at the apartment level, at the building level or in the district heating system, at least some efficiency measures on the building envelopes were cost-effective. In the Swedish case, most renovation strategies showed small or negative economic profitability. Two factors could be mentioned as causing this variation in results, both related to the starting conditions. One factor is the low environmental impact of district heating and the low carbon emissions associated with Swedish electricity. Another factor is the fact that most buildings in Sweden already have some level of insulation. This makes savings from additional insulation much smaller and thus less economically beneficial. In the Italian case study, the installation of new windows and energy efficiency measures on the walls and roof were cost-effective in the reference case for Milan, yet not for the other investigated locations.

A noteworthy finding is that in the assessments from Austria, Portugal, Denmark, and Switzerland, the same package of renovation measures on the building envelope was the most cost-effective for all heating systems investigated.

Environmental impact of energy efficiency improvements

Variations were observed regarding the environmental impact of energy efficiency improvements.

In most assessments, energy efficiency improvements always lead to carbon emissions and primary energy use reductions.

In Sweden, on the contrary, all efficiency measures had a negative environmental impact due to the high insulation level at the starting point and the low emissions of the existing energy system.

Environmental impact of renewable energy measures

Variations were also observed regarding the environmental impact of renewable energy measures. Most generic districts found that carbon emissions and primary energy use were reduced by implementing renewables. This was true both for centralised and decentralised solutions. In some cases, impacts on primary energy use and emissions differed significantly. In the Swiss case, for example, switching to renewable-based energy systems caused a large reduction in carbon emissions and a smaller reduction in primary energy use. Such differences even extended to negative impacts of some measures. In the Austrian case, solar energy measures sometimes led to increased carbon emissions due to the embodied impact, while the primary energy use was reduced in all cases.

Environmental impact of choosing between centralised and decentralised systems

There were also different conclusions on the environmental impact concerning the choice between centralised and decentralised systems.

In the Swedish case, for example, replacing the existing district heating system with new heat pumps has a negative environmental impact. In the Swiss case, the environmental impact of centralised systems based on heat pumps is higher than for decentralised heat pump solutions due to reduced efficiency.

Life cycle costs (LCC)

The LCC assessments suggested that district heating solutions were more cost-effective when an existing district heating system was considered than decentralised options.

However, when investment costs of a new district heating network were considered, in some assessments, district heating solutions were also found to be the most cost-effective, while in others, decentralised solutions were more cost-effective.

In the Austrian case, natural gas had the lowest LCC, followed by district heating and heat pump solutions. In Italy, decentralised gas boilers had the lowest LCC in the Palermo case, whereas free-standing PV panels were cost-effective in the Rome and Milano cases. Renewable energy-based solutions were otherwise found to be cost-effective compared to a reference case assuming a continuation of the use of fossil fuels. The Spanish generic district assessment compared individual, decentralised and centralised solutions, finding that individual solutions were not cost-effective, while for decentralised systems, an air source heat pump was slightly more cost-effective than a biomass boiler, and for a district scale system, the greatest cost reductions could be achieved with a biomass boiler. In the Swiss case, it was found that decentralised solutions have fewer economies of scale regarding investment costs than district heating solutions due to challenges such as noise restrictions (for air source heat pumps) and boreholes (for ground source heat pumps). In the Italian case, switching to a district heating system caused higher costs due to investments in the network. In Portugal, the calculations suggest that centralised solutions have the potential to be cost-effective despite not being a common practice and, thus, should be further investigated.

In the Austrian, Italian, Portuguese, Spanish and Swiss case studies, comparing the cost savings associated with the most cost-effective energy efficiency measures on building envelopes for various heating systems, it is found that these cost savings are often greater for renewable energy systems based on heat pumps than for a fossil fuel-based reference case.

Most cost-effective solutions

In the Danish case, the most cost-effective solutions were district heating solutions. Switching from a district heating system to decentralised heating based on renewables only achieved a marginal improvement in terms of emissions.

In the Italian cases, different solutions were cost-effective in different climates. In Milan, energy efficiency measures applied to building envelopes combined with decentralised air source heat pumps and PV were the most cost-effective. In Rome, the “anyway” renovation of the envelope combined with a high-temperature air source heat pump decentralised heating system and PV was the most cost-effective. None of the studied measures were cost-effective in the Palermo case. In the Portuguese study, envelope improvements combined with centralised heat pumps were the most cost-effective solution. In Sweden, the only cost-effective improvement was adding one extra glazing to the existing windows. In the Spanish case, a biomass-based district heating system was the most cost-effective solution for all the renovation packages analysed. In the Swiss case, a combination of envelope improvements, not including windows replacement, was the most cost-effective solution, combined with centralised groundwater or geothermal heat pump systems.

In general, it can be summarized that the cost-effective solution differs greatly depending on the context, the thermal insulation level, the state of the existing heating system, the climate, and other factors.

When comparing optimal combinations of energy efficiency measures with centralised and decentralised renewable energy options, the difference in the overall cost-effectiveness between centralised and de-centralised renewable energy-based solutions was small in the Austrian, Italian, Spanish and Swiss cases, whereas in the Danish case, the difference was more significant.

Uncertainties

The Danish case mentioned construction costs as a great source of error. Also, the rate of switching energy plants from fossil fuels to renewables has a large influence. The Italian case highlights the lack of monitoring data and measurements to back up the results, noting that only virtual energy models were employed. In Portugal, a centralised energy system's design and cost estimation was mentioned as uncertain, as no Portuguese references exist. Also, the effect of economies of scale and variations due to user behaviour have not been accounted for in all considered energy systems. In Sweden, the greatest source of uncertainty was the emissions associated with electricity and district heating due to variations within the country and uncertain future energy prices. The Swiss case also mentioned energy prices as a large source of uncertainty for cost-effectiveness. It is also highlighted that this study mainly focuses on economic aspects. Other factors, such as nature preservation, were not yet considered.

Responses to hypotheses

As discussed in detail in Section 2.1.4, eight hypotheses were formulated based on the methodology developed as part of IEA EBC Annex 75 project (Bolliger et al., 2023). This section covers the general trends that could be seen from the responses. An overview of the responses is provided in **Table 61**.

Hypothesis 1*: Comparing centralised and decentralised renewable energy systems*

This hypothesis was confirmed in five out of seven generic district assessments. This indicates that the optimisation of energy efficiency measures can occur without considering the future energy system choice.

Hypothesis 2*: Comparing a fossil fuel-based district heating system with a centralised switch to renewable energy*

Due to the relevance of the starting situation, only Denmark could study this hypothesis, confirming it.

Hypothesis 3*: Comparing a fossil fuel-based district heating system with a decentralised switch to renewable energy*

This hypothesis has conflicting responses from the Austrian, Spanish and Danish generic district assessments. In the Danish case, cost-effective measures were always the same, while differences could be seen in the Austrian and Spanish cases.

Hypothesis 4*: Comparing decentralised fossil fuel systems with a centralised switch to renewable energy*

Two generic district assessments (from Austria and Switzerland) confirm this hypothesis, while the ones from Portugal and Spain do not. Different starting situations and climates could explain the difference.

Hypothesis 5*: Comparing decentralised fossil fuel systems with a low-temperature renewable energy-based district heating system*

Two cases, the Spanish and Swiss ones, were able to study this hypothesis andconfirmed it.

Hypothesis 6*: Comparing a new renewable energy-based district heating system with a switch of an existing district heating system to renewable energy*

Due to the relevance of the starting situation, only Austria could study this hypothesis, confirming it.

Hypothesis 7*: Districts with initially low levels of thermal insulation*

Five out of seven generic district assessments confirmed this hypothesis, while Spain could not confirm it. The mild climate of the Spanish case can likely explain this difference.

Hypothesis 8*: Districts with initially high levels of thermal insulation*

Due to the relevance of the starting situation, only Italy could study this hypothesis, confirming it.

Table 61. Summary of the responses to the hypotheses.

Hypotheses	AT	DK	IT	PT	ES	SE	CH
1. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when these measures are associated either with a district heating system based on renewable energy or with decentralised heating systems based on renewable energy.»	✓	✓	✓	–	✓	–	✓
2. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is switched to a centralised heating system based on renewable energy.»	–	✓	–	–	–	–	–
3. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an existing district heating system based (fully or to a large extent) on fossil fuels is replaced by decentralised heating systems based on renewable energy.»	✗	✓	–	–	✗	–	–
4. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a centralised heating system based on renewable energies.»	✓	–	–	✗	✗	–	✓
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when existing decentralised heating systems based on fossil fuels are replaced by a low-temperature renewable energy-based district heating system associated with decentralised heat pumps.»	–	–	–	–	✓	–	✓
6. «The cost-optimal level of the energy efficiency measures on building envelopes involves a lower level of insulation when an existing district heating system is switched centrally to renewables than when switched to a newly installed centralised heating system based on renewable energy, due to a lower potential for synergies between renewable energy measures and energy efficiency measures in the former case.»	✓	–	–	–	–	–	–

Hypotheses	AT	DK	IT	PT	ES	SE	CH
7. «In case the starting situation is a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, the implementation of energy efficiency measures on the building envelopes.»	✓	✓	✓	✓	✗	–	✓
8. «In case the starting situation is a district with a high level of thermal insulation in the building envelopes and a fossil fuel-based heating system, every optimal solution includes at least a switch to a renewable energy-based heating system»	–	–	✓	–	–	–	–

✓ Confirmed – Not investigated ✗ Not confirmed

4. Conclusions

In this parametric study, generic districts were defined based on the relevant starting situations in seven different countries to study combinations of energy efficiency measures with renewable energy systems options. The cost-effectiveness and environmental impact of the various scenarios were investigated. Of the hypotheses stated, only one could be conclusively confirmed: it was shown in five out of seven studies that the cost-effective level of energy efficiency measures did not significantly differ when comparing centralised and decentralised renewable energy-based approaches, which indicates that the optimisation of energy efficiency measures can be implemented regardless of future choices for renewable energy systems.

No general conclusion could be drawn about the cost-effective level of energy efficiency measures. In some cases, no measures were cost-effective, while in some, all investigated measures were cost-effective. The situation needs to be considered based on the starting level of the thermal insulation and climate conditions. The environmental impact was also different between cases. In most cases, carbon emissions and primary energy use were reduced by efficiency measures, while only a small or negative impact on emissions was discovered in some cases due to the influence of embodied energy associated with the materials used.

Regarding solar energy use, there were also conflicting results. One case found that using solar energy reduced emissions and primary energy use. In contrast, another case, with an electricity mix mostly based on hydro-energy, suggested that the embodied impact of solar energy measures negatively impacted the emissions.

There was some disagreement on the environmental benefits of centralised and decentralised systems. In some cases, implementing or keeping a district heating system was environmentally the most suitable choice, both in terms of emissions and primary energy use. In another case, decentralised solutions were shown to have less environmental impact due to higher efficiency.

The LCC assessments suggested that, when an existing district heating system was taken into account, district heating solutions were more cost-effective than decentralised options. When the investment costs of a new district heating network were considered, in some assessments district heating solutions were also found to be the most cost-effective. In others, decentralised solutions were more cost-effective.

There was a great variety of results when considering the most cost-effective energy system. In two cases, a switch to district heating based on centralised heat pumps was found to be the most cost-effective; one case suggested decentralised renewables; and one study found that keeping a fossil gas system was the most cost-effective. One highlighted differences due to different climates. This demonstrated that the starting situation regarding energy efficiency, existing energy systems, and local factors, such as the climate and public acceptance of measures, need to be investigated on a country-by-country and project-by-project basis.

Most assessments carried out found that renewable energy-based solutions were cost-effective compared to a reference case assuming a continuation of the use of fossil fuels. The assessments, including a fossil-fuel-based reference case, found that cost savings associated with the most cost-effective energy efficiency measures on the building envelopes were often larger for renewable energy systems based on heat pumps than in the fossil-fuel-based reference case.

When comparing optimal combinations of energy efficiency measures with centralised and decentralised renewable energy options, the difference in the overall cost-effectiveness between centralised and decentralised renewable energy-based solutions was small in most of the assessments.

The results of this report need to be considered based on many assumptions regarding construction and equipment life cycle costs, future energy prices, and energy-related emissions. In addition, the definition of cost-effectiveness in this study only considers economic parameters, disregarding factors such as nature preservation.

Acknowledgements

The authors of the Portuguese generic district assessment would like to thank the University of Burgos for their contribution to the BITS calculations. The authors of the Swiss generic district assessment would like to thank the canton of Luzern, the canton of Zürich, ewl, ewz, and Basler&Hofmann for their contributions to the calculations.

References

AIEL (2020). Mercati & prezzi, *Agriforenergy* 12(1). Retrieved from https://www.aielenergia.it/public/pubblicazioni/162_M_P_1-2020.pdf. Accessed 5 July 2021.

Avebiom (2022). Indice AVEBIOM Precio Medio Pellets de Madera al consumidor final. Retrieved from https://www.avebiom.org/proyectos/indice-precios-biomasa-al-consumidor. Accessed 1 May 2022.

Björnsson, L., Pettersson, M., Börjesson, P., Ottosson, P., & Gustavsson, C. (2021). Integrating bio-oil production from wood fuels to an existing heat and power plant-evaluation of energy and greenhouse gas performance in a Swedish case study. *Sustainable Energy Technologies and Assessments*, *48*, 101648.

Bolliger R., Terés-Zubiaga, J., Almeida, M., Barbosa, R., Davidsson, H., Engelund Thomsen, K., Domingo Irigoyen, S., Ferrari, S., Johansson, E., Konstantinou, T., Limacher, R., Matuska, T., Mlecnik, E., Mørck, O. C, Ott, W., Romagnoni, P., Rose, J., Säwén, T., Talnum, H. T., Venus, D., and Z. Winkels (2023). Methodology for investigating cost-effective building renovation at district level combining energy efficiency & renewables. Report prepared within IEA EBC Annex 75 on Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables. ISBN: 978-989-35039-6-6. https://annex75.iea-ebc.org/publications

Boverket (2011). Boverkets byggregler (2011:6) – föreskrifter och allmänna råd, BBR.

Código Técnico de la Edificación, Documento básico de Ahorro de Energía (CTE DB-HE) (2019). Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314/2006, de 17 de marzo. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-18528. Acessed 1 November 2022.

Danish Housing and Planning Authority (2016). Nye emissionsfaktorer for el og fjernvarme.

Dos Santos, C. A., & Matias, L. (2006). Coeficientes de Transmissão Térmica de Elementos da Envolvente dos Edifícios (LNEC (ed.); 2006th ed.). Laboratório Nacional de Engenharia Civil, LNEC.

DRE (2021). Despacho 6476-H/2021. Retrieved from https://dre.pt/dre/detalhe/despacho/6476-h-2021-166300890

EcoInvent (2010). EcoInvent v2.2.

Energiföretagen (2021). Fjärvärmepriser. Retrieved from https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmepriser/

Energimyndigheten (2019). Scenarier över Sveriges energysystem 2018. Retrieved from https://energimyndigheten.a-w2m.se/Home.mvc?resourceId=133529

Eurostat (2021). Eurostat Energy Database, Report and Database of statistics on electricity and natural gas prices. Retrieved from https://ec.europa.eu/eurostat/web/energy/methodology/prices. Accessed July 2021.

Eurostat (2020). Eurostat Energy Database, Energy statistics - natural gas and electricity prices (from 2007 onwards), NRG_PC_202 and NRG_PC_204. Retrieved from https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_202/default/table?lang=en. Accessed May 2022.

Federal Statistical Office (2021).

Gode, J., Martinsson, F., Hagberg., L., Öman, A., Höglund, J., and Palm , D. (2011).Uppskattade emissionsfaktorer för bränslen, el, värme och transporter. *In: Miljöfaktaboken 2011.*

Governo Italiano (2015). Decreto Ministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifice.

Hernández-Cruz, P. (2021) Guaranteeing a minimum temperature of 18 degrees C in low income dwellings. Making Decarbonisation Fair, online. https://www.engager-energy.net/wp-content/uploads/2021/05/Making-Decarbonisation-Fair-ProceedingsRR.pdf. Accessed November 2022.

Kranzl L., Müller A., Maia I., Büchele R. (2017). *Wärmewende 2030: Analyse der Erfordernisse und Konsequenzen - Teilbericht zur Wirtschaftlichkeitsanalyse von Heizsystemen*, Vienna

KBOB (2021) Life Cycle Assessment Data in Construction, 2009/1:2016, https://www.kbob.admin.ch/dam/kbob/it/dokumente/Publikationen/Nachhaltiges%20Bauen/Archiv_2015-2019/2009_1-2016%20Oekobilanzdaten%20im%20Baubereich.pdf.download.pdf/2009_1-2016%20Oekobilanzdaten%20im%20Baubereich.pdf

KBOB (2022). Ökobilanzdaten. Retrieved from: https://www.kbob.admin.ch/dam/kbob/de/dokumente/Themen%20und%20Trends/Oekobilanzen/%C3%96kobilanzdaten%20im%20Baubereich_Donn%C3%A9es%20des%20%C3%A9cobilans%20dans%20la%20construction%202009-1-2022.zip.download.zip/%C3%96kobilanzdaten%20im%20Baubereich_Donn%C3%A9es%20des%20%C3%A9cobilans%20dans%20la%20construction%202009-1-2022.zip

Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento (2016). Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España. Retrieved from: https://energia.gob.es/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Reconocidos/Otros%20documentos/Factores_emision_CO2.pdf. Accessed May 2022.

Pelletsförbundet (n.d.). Statistik. Retrieved from http://pelletsforbundet.se/statistik/

PNEC (2020). National Plan for Energy and Climate 2030.

SCB (2020a). Priser på el för hushållskunder 2007–2020. Retrieved from https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/elpriser-och-elavtal/pong/tabell-och-diagram/aldre-statistik/priser-pa-el-for-hushallskunder-20072020/

SCB (2020b). Priser på el för industrikunder 2007-2020. Retrieved from https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/elpriser-och-elavtal/pong/tabell-och-diagram/aldre-statistik/priser-pa-el-for-industrikunder-20072020/

SCB (2022). Gaspriser och gasavtal. Retrieved from https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/gaspriser-och-gasavtal/

Venus, D., Romagnoni, P., Dalla Mora, T., Teso, L., Almeida, M., Tan De Domenico, A., Celador, A. C., Terés Zubiaga, J., Hidalgo-Betanzos, J. M., Davidsson, H., Johansson, E., Bolliger, R., Domingo-Irigoyen, S., Christen, C., Walnum, H. T., & van den Brom, P. (2023). Investigation of cost-effective building renovation strategies at the district level combining energy efficiency & renewables – a case studies-based assessment. Report prepared within IEA EBC Annex 75 on Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables. ISBN: 978-989-33-4463-7. https://annex75.iea-ebc.org/publications

www.iea-ebc.org