ANNEX 75

EBC

Energy in Building and Communities Programme

International Energy Agency

Investigation of cost-effective building renovation strategies at the district level combining energy efficiency & renewables – a case studies-based assessment

Energy in Buildings and Communities Technology Collaboration Programme

April 2023

Technology Collaboration Programme by iea

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 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 stakeholders 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 operations 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 CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 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 (*)
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Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
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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 are particularly challenging for the existing building stock, mainly because of many architectural, socio-economical, 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 case study report

This report aims to show in selected case studies the application of cost-effective strategies to combine energy efficiency measures and renewable energy use in building renovation at the district level, investigate factors influencing the choice of a cost-effective strategy, and gather related best-practice examples.

For selected case studies, the necessary data was gathered to carry out parametric assessments, applying and testing the methodology developed in IEA EBC Annex 75. It was intended to select, as case studies, existing urban districts in need of renovation where the results of the analysis of these case studies could guide the choice of an adequate renovation strategy for the respective district. It is investigated to what extent there are synergies and to what extent there are trade-offs for combining energy efficiency measures 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.

Limitations

The Annex focuses mainly on residential buildings, both single and multifamily houses. Districts with other buildings with similar characteristics, such as schools or simple office buildings without complex HVAC systems, could be included by considering parameters specific to the related building type.

The energy performance calculations and analyses focus mainly on heating, domestic hot water, and electricity. Cooling was not considered in the calculations as it was not relevant in the available case studies.

It is also important to state that the cost calculations presented here are mainly based on the prices from 2019 (energy, construction, and maintenance costs). Due to geo-political circumstances in Europe, today's prices are much higher, which means that if the calculations were done today, they might lead to different results and conclusions.

Investigated case studies

Within the IEA EBC Annex 75 project, nine case studies from eight different European countries were investigated. The necessary data was gathered to carry out parametric assessments, applying and testing the methodology developed in IEA EBC Annex 75.

Countries participating in the case study investigations are Austria, Italy, Norway, Portugal, Spain, Sweden, Switzerland, and the Netherlands.

Results and conclusions

- The renovation of the thermal envelope is generally recommended, although the cost-effectiveness of the renovation process can vary. Sometimes it is only one measure, e.g., window replacement, and sometimes the renovation of the complete envelope. Sometimes, however, it can be in between. Which measures are cost-effective depends on several factors. Influencing factors are, for example, the initial situation (building already insulated or not), the climatic conditions (how much heating is required), and the prices (ratio of investment to energy costs).

- Concerning the energy supply systems studied, no clear recommendation can be derived about the heat generation system. Both decentralised, on the building level, heat pumps (air-water as well as geothermal) and district heating lead to good results and savings. This means that district projects are often likely to require a justification other than economic attractiveness. In the case studies where a supply on the apartment level was investigated, these were mostly not recommendable.

- Results may differ if district heating systems are particularly large and benefit from strong economies of scale. In such a case, district heating systems to use renewable energy may have clearer economic advantages. However, in a large district heating system, it may be more challenging to benefit from energy efficiency measures on building envelopes for reducing the temperature in the grid, as it becomes more challenging that the energy performance of all buildings in the district is increased.

- A common finding supported by results of most, although not all case studies, is that the cost-optimal level of energy efficiency measures on building envelopes does not differ significantly when comparing, on the one hand, a combination of such measures with a district heating system based on renewable energy and, on the other hand, a combination of such measures with decentralised heating systems based on renewable energy. This is an important finding as this indicates that energy efficiency measures are similarly attractive for the use of renewable energy at the district level as at the level of individual buildings.

- Energy efficiency measures on building envelopes may yield particularly strong synergies with renewable energy measures if these are carried out for all buildings in a district, allowing, accordingly, to reduce the temperature of the grid. This has benefits for increasing the efficiency of a centralised heat pump and reducing thermal losses in the grid. Furthermore, in the case of using the ground as a heat source at the district level in connection with heat pumps, energy efficiency measures on building envelopes reduce the need to regenerate heat in the ground. This is another reason for synergies between energy efficiency measures and renewable energy measures.

- A finding supported by most case studies is that in a district with a low level of thermal insulation in the building envelopes, every optimal solution includes, to some extent, implementing energy efficiency measures on the buildings' envelopes.

- In the case studies examined, photovoltaics were largely investigated as a renewable energy source on site. It has been shown that installing a PV system makes sense from an energy point of view (and thus also carbon emissions), but the economic viability is not always immediately given.

- Renovation measures on the building envelope, measures to replace the energy supply systems, and measures to use renewable energy sources can lead to carbon emissions and primary energy savings but are not always cost-effective or cost-optimal. This is where the conflicting priorities become apparent — savings to protect the environment vs. cost-effectiveness.

- Since the cost-effectiveness is determined by comparing the investigated scenarios with the reference case, the definition of the reference case plays a special role. The reference cases differ from country to country, but even within a country, districts can have different initial situations and, thus, different reference variants.

- Many assumptions must be made for the calculation of different scenarios. This concerns assumptions about costs, such as investment costs for the renovation of the building envelope, energy supply and renewable energy sources, maintenance and repair costs, and energy costs. But assumptions must also be made about user behaviour: what room temperature is used for calculations, what hot water consumption is assumed, and is active cooling also used? All these assumptions can influence the calculation results and, if individual parameters are changed, can also lead to different results or recommendations. Therefore, it is important not only to investigate different technical renovation measures but also the influence of such parameters. Also, the choice of the calculation software can influence the results. This must be considered as well.

- In addition to cost, carbon emissions, and primary energy savings, measures on the building envelope and the energy supply system also have other effects that were not part of the case studies but must nevertheless be considered (the so-called “co-benefits”). For example, the thermal renovation of the exterior wall and the replacement of windows positively affect thermal comfort indoors. Likewise, using a PV system, for example, can reduce energy dependency.

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Abbreviations

Abbreviations	Countries
AT	Austria
BE	Belgium
CH	Switzerland
DE	Germany
ES	Spain
NED	The Netherlands
PT	Portugal
SE	Sweden

Acronyms	Meaning
EPBD	European Performance of Buildings Directive
ESCO	Energy service company
EPS	Expanded polystyrene
FIT	Feed-in tariff
LC(I)A	Life Cycle (Impact) Assessment
nZEB	Nearly zero energy building
PV	PV panels

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).

Deep renovation: A renovation which transforms a building or building unit into a nearly zero-energy building (until 2030) or a zero-emission building (after 2030), according to the latest European Commission proposal (European Commission, 2021). The previous EU legal framework didn't define deep renovations in detail, but they were typical of more than 60% energy savings. (European Commission, DG Energy, 2014) (BPIE – Deep renovation, 2021).

Delivered energy: Energy, expressed per energy carrier, supplied to the technical building systems through the system boundary to satisfy the users, taking into account heating, cooling, ventilation, domestic hot water, lighting, appliances, etc.

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 Certificate: An official energy-efficiency evaluation of a building or part of a building aiming at informing building owners, occupiers, and property actors on the energy performance of their buildings so that they can compare and assess different buildings and make informed decisions. Energy Performance Certificates are often accompanied by advice and practical information on how to improve the energy efficiency of buildings and their performance class (BPIE – Glossary of Terms, 2021).

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.

Energy source: Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy tariffs: The way energy providers charge building users or renters for their effective energy use, such as electricity, gas, heating, cooling, hot water, and so on. Tariffs can be fixed or variable. A fixed-rate tariff sets a cost of energy for a certain amount of time, typically one year or more, while variable tariffs can go up or down according to the market or establish categories defined by other parameters.

Feed-in tariff (FIT): To promote renewable energy generation, some support schemes define fixed electricity prices paid to renewable energy producers for each unit of energy produced and injected into the electricity grid. The payment of the FIT is guaranteed for a certain period that is often related to the economic life of the respective renewable energy project (usually between 15-25 years). Another possibility is to calculate a fixed maximum number of full-load hours of renewable energy electricity production for which the FIT will be paid. FIT is usually paid by the electricity grid, system, or market operators, often in the context of Power Purchasing Agreements (PPA) (Energypedia UG Nonprofit, nd).

Funding: The money provided, especially by an organisation or government, for purposes related to building renovations, such as energy-efficient measures or renewable energy implementations (European Commission, DG Energy, 2015).

Housing association: An association that owns, lets and manages rented housing, usually under special conditions, for people that cannot reach the market or rented housing due to vulnerability or other socio-economic situations.

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.

Nearly zero-energy building (nZEB): A building with a very high energy performance, where the nearly zero or very low amount of energy required should be covered to a significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Commission, 2010).

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

Non-renewable primary energy factor: Non-renewable primary energy for a given energy carrier, including the delivered energy and the calculated energy overheads of delivery to the points of use, divided by the delivered energy (European Commission, 2021).

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.

Renewable primary energy factor: The renewable primary energy from an on-site, nearby, or distant energy source that is delivered via a given energy carrier, including the delivered energy and the calculated energy overheads of delivery to the points of use, divided by the delivered energy (European Commission, 2021).

Renovation: Construction activities related to interventions onto existing buildings or connected infrastructure. These interventions range from simple repairs and maintenance to adaptive conversion, transformation, and reuse. In the framework of IEA EBC Annex 75, renovation can refer to both renewal/retrofit of building envelopes and energy system changes.

Social housing: A type of housing particularly oriented to vulnerable people who cannot afford the market cost of rent due to vulnerability or other socio-economic situations. It can also refer to the institutions that manage these homes and associations that own, let, and manage social housing. Social housing associations, institutions or councils can become key partners in scaling up building renovations due to their market presence as landlords of a considerable number of dwellings. Social housing might be offered by not-for-profit or market actors.

Stakeholders: The persons, homeowners, companies, public institutions and in general every agent with an interest or concern in an ongoing or future project. The stakeholders in renovation projects can be a wide and diverse list of agents, including decision-making actors and also other involved participants that can influence the success or failure of the renovation process.

Stakeholder dialogue: The process whereby a lead actor, usually a local administration, facilitates communication and interaction with stakeholders, particularly also building owners, in a certain community area/neighbourhood/district to get them going in the direction that is politically favoured i.e., climate neutrality, energy efficiency, enhanced use of renewables. This dialogue can be implemented through various formats of information and communication and can be based either on regulations (if applicable) or on persuasion and commitment.

Subsidy: A financial incentive given by authorities to partly or fully offset the costs related to building renovation or renewable energy implementation over a lengthy period.

Technical building system: Technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site renewable energy electricity generation and storage, or a combination thereof, including those systems using energy from renewable sources, of a building or building unit (European Commission, 2021).

Total primary energy factor: The weighted sum of renewable and non-renewable primary energy factors for a given energy carrier (European Commission, 2021).

Zero-emission building: A building with a remarkably high energy performance, where the very low amount of energy still required is fully covered by energy from renewable sources at the building or district or community level where technically feasible (notably those generated on-site, from a renewable energy community or renewable energy or waste heat from a district heating and cooling system) (European Commission, 2021).

1. Introduction

1.1 About IEA EBC Annex 75

Buildings are a major source of carbon emissions and cost-effectively reducing their energy use and associated emissions are 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. 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 district-level heating or cooling based on available environmental heat, solar energy, waste heat, or natural heat sinks, with energy efficiency measures applied to building 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 sources with energy efficiency measures applied to building envelopes?
- Under which circumstances is it more appropriate to use available renewable energy potentials in cities at a district level, and under which circumstances are decentralised renewable energy solutions more advantageous, combined with energy efficiency measures applied to building envelopes?

1.2 Objectives of IEA EBC Annex 75

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

The project focuses on the following objectives:

- Give an overview of various technology options, considering 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 that 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.

1.3 Objectives of the Case Studies Report

This report aims to show, in selected case studies, the development of cost-effective strategies (as defined in Bolliger et al., 2023) to combine energy efficiency measures and renewable energy use in building renovation at the district level. It is also purpose to investigate factors influencing the choice of a cost-effective strategy and to gather related best-practice examples. It is also intended to obtain information regarding necessary framework conditions or policy instruments for facilitating the uptake of cost-effective strategies for far-reaching renovations of districts. Furthermore, the role of co-benefits is also investigated.

In a first step, success stories involving district-based solutions for renewable energy use and energy efficiency measures were gathered and characterised. This includes the transformation of previously existing district heating systems and the creation of district heating systems based on renewable energy in districts previously heated with decentralised installations. Furthermore, this includes success stories for a massive renovation of thermal envelopes in a specific district. It is documented to what extent the combination with energy efficiency measures on the building envelopes has been considered in the selected cases investigated and to what extent grid-based solutions were advantageous concerning heating or cooling solutions in the district.

In the second step, the necessary data was gathered for selected case studies to carry out parametric assessments, applying and testing the methodology developed in IEA EBC Annex 75. It was intended to select case studies in existing urban districts with renovation needs where the results of the case studies can guide in choosing an appropriate renovation strategy for the respective district. It is investigated to what extent there are synergies and to what extent there are trade-offs for combining energy efficiency measures and renewable energy measures. It is envisaged to determine cost-effective renovation strategies for the investigated districts considering both energy efficiency measures and renewable energy measures.

1.4 Limitations

The Annex focuses mainly on residential buildings, both single and multifamily houses. Districts with other buildings with similar characteristics, such as schools or simple office buildings without complex HVAC systems, could be included by considering parameters specific to the related building type.

The energy performance calculations and analyses focus mainly on heating, domestic hot water, and electricity. Cooling was not considered in the calculations as it was not relevant in the available case studies.

It is also important to state that the cost calculations were mainly based on the prices from 2019 (energy, construction and maintenance costs). Due to geo-political circumstances in Europe, today’s prices are much higher, which means that if the calculations were done today, they might lead to different results and conclusions.

2. Evaluation framework

2.1 Objectives of the analysis

2.1.1 Starting situations

The project aims to assist in clarifying the cost-effectiveness of various approaches combining energy efficiency measures and renewable energy measures for a starting situation in a specific city district. The scope of the project is based on the following three starting situations, as discussed in (Bolliger et al., 2023):

- Urban districts previously heated decentrally by natural gas, oil, or electricity or cooled decentrally through cooling devices at the building level.
- 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.

2.1.2 Research Questions

Distinguishing these starting situations, the following questions are investigated:

- What are cost-effective combinations between renewable energy and energy efficiency measures to achieve far-reaching reductions in carbon emissions and primary energy use in urban districts meeting the pre-set targets?
    - In particular: What are 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 buildings' envelopes?
    - In particular: Under which circumstances does it make sense to use available renewable energy potentials in cities at a district level, and under which circumstances are decentralised renewable energy solutions, in combination with energy efficiency measures on the buildings' envelopes, more advantageous?

The investigations focused on renovation scenarios that are fully based on the use of renewable energy, combined with varying levels of energy efficiency measures on building envelopes.

Also, the following questions have been investigated:

- Which approaches, considering various possibilities for energy efficiency and renewable energy measures, allow achieving districts supplied entirely with renewable energy at the least cost?
- Which factors determine the cost-efficient balance between efficiency measures on the building envelopes and measures to use renewable energy if far-reaching reductions in carbon emissions and primary energy use in urban districts are the targets?
- To what extent does the cost-effectiveness of renovation measures on the building envelopes in the case of a local district heating system based on renewable energy differ from the cost-effectiveness of such measures in the case of decentralised use of renewable energy sources for heating in each building?

2.1.3 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 on comparing the cost-optimal level of energy efficiency measures on building envelopes in different scenarios. The following hypotheses are investigated:

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

When comparing centralised and decentralised renewable energy systems, the hypothesis is as follows:

«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 switch to a centralised renewable energy system.*

When comparing a fossil fuel-based district heating system with a centralised switch to renewable energy, the hypothesis is as follows:

«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 switch to decentralised renewable energy systems.*

When comparing a fossil fuel-based district heating system with a decentralised switch to renewable energy, the hypothesis is as follows:

«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 switch to a centralised renewable energy system.*

When comparing decentralised fossil fuel systems with a centralised switch to renewable energy, the hypothesis is as follows:

«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 energy.»

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

When comparing decentralised fossil fuel systems with a low-temperature renewable energy-based district heating system, the hypothesis is as follows:

«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.»

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

When comparing a new renewable energy-based district heating system with a switch of an existing district heating system to renewable energy, the hypothesis is as follows:

«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.*
Regarding districts with an initial low level of thermal insulation, the hypothesis is as follows:
«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.*
Regarding districts with an initial high level of thermal insulation, the hypothesis is as follows:
«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 needed by 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, considering for example that Southern European countries have overall lower levels of thermal insulation than Northern European countries.

2.1.4 Key performance indicators

A set of Key Performance Indicators (KPIs) was evaluated for each scenario to define the sustainability and cost-effectiveness of 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 most essential and accordingly selected for use within IEA EBC Annex 75:

- Carbon emissions are expressed as CO_2-equivalents per square meter of conditioned gross floor area and year.
- Primary energy use is expressed as kWh per square meter of conditioned gross floor area and year.
- Annualised total costs (LCC) are expressed as EUR per square meter of conditioned gross floor area and year.

2.2 Assumptions and Boundary conditions

This chapter gives an overview of the tools and databases used to perform the calculations. Furthermore, this chapter includes the energy prices and conversion factors used in the calculations.

2.2.1 Tools and databases

Table 1: Tools used for energy performance calculation.

Country	Name of tool	Calculation time step	Link to tool
Austria	PHPP	monthly	https://pas-sivehouse.com/04_phpp/04_phpp.htm
Italy	CEA	hourly	https://cityenergyanalyst.com/ Fonseca, J.A. Energy Efficiency Strategies in Urban Communities: Modeling, Analysis, and Assessment. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 2016. Fonseca, J.A.; Thomas, D.; Willmann, A.; Elesawy, A.; Schlueter, A. The City Energy Analyst Toolbox V0.1. In Proceedings of the Sustainable Built Environment (SBE) Regional Conference, Zurich, Switzerland, 15–17 June 2006.
Norway	SIMIEN	hourly	https://www.programbyggerne.no/SIMIEN/
Norway	Butler	Optimal investment	K. B. Lindberg, G. Doorman, D. Fischer, M. Korpås, A. Ånestad, and I. Sartori, “Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming,” *Energy Build.*, vol. 127, pp. 194–205, Sep. 2016
Portugal	Open Studio and Energy Plus	hourly	https://openstudio.net/ https://energyplus.net/
Spain	Design Builder (Energy Plus)	hourly	https://designbuilder.co.uk/
Sweden	Sefaira	hourly	https://www.sketchup.com/products/sefaira
Sweden	System Advisor Model	Simulation for PV	https://sam.nrel.gov/
Switzerland	INSPIRE	monthly	https://www.energychweiz.ch/tools/inspire/
The Netherlands	TRNSYS	hourly	https://www.trnsys.com/

Table 2: Additional tools used supporting the energy performance calculation.

Country	Name of tool	Calculation goal	Link to tool
Norway	Butler	Optimal investment	K. B. Lindberg, G. Doorman, D. Fischer, M. Korpås, A. Ånestad, and I. Sartori, "Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming," *Energy Build.*, vol. 127, pp. 194–205, Sep. 2016
Sweden	System Advisor Model	Simulation for PV	https://sam.nrel.gov/

Table 3: Databases used for Life Cycle Assessments.

Country	Name of database	Name of tool	Link to database and tool
Austria, Norway, Switzerland	KBOB	-	https://www.kbob.admin.ch/dam/kbob/it/dokumente/Publikationen/Nachhaltiges Bauen/Archiv_2015-2019/2009_1-2016 Oekobilanzdaten im Baubereich.pdf.download.pdf/2009_1-2016 Oekobilanzdaten im Baubereich.pdf
Italy	Dm 26/6/2015 AIEL		https://www.mise.gov.it/index.php/it/normativa/decreti-interministeriali/2032966-decreto-interministeriale-26-giugno-2015-applicazione-delle-metodologie-di-calcolo-delle-prestazioni-energetiche-e-definizione-delle-prescrizioni-e-dei-requisiti-minimi-degli-edifici https://www.aielenergia.it/public/pubblicazioni/198_M_P_2-2021.pdf
Norway	Norsk Prisbok	-	https://www.norskprisbok.no/Home.aspx
Portugal	ecoinvent	SimaPro	https://ecoinvent.org/ https://simapro.com
Sweden	EPD	Handcalc	Environmental Product Declarations (EPD), https://www.environdec.com

2.2.2 Energy prices

Table 4: Energy prices in EUR per kWh final energy for the assessment.

Energy carrier	AT	CH	ES	IT	NED	NO	PT	SE
Electricity	0.20	0.21	0.2323	0.219	0.048	0.095	0.213	0.148
Wood pellets	0.05	0.08	0.0635	0.067	NA	0.04	0.05	0.04
Oil	0.09	0.10	NA	0.170	0.035	NA	0.14	NA
Natural Gas	0.09	0.10	0.089	0.081	0.019	NA	0.058	0.115
Electricity for the district heating system	NA	0.17	0.2323	0.150	NA	0.052*	NA	NA
Wood for district heating system	NA	0.07	0.0635	0.060	NA	0.027	NA	NA
District heating	0.10	NA	NA	0.068	0.029	0.085	NA	0.087

2.2.3 Conversion factors

Table 5: Current carbon emission factors in kg CO_2 per kWh final energy.

Energy carrier	AT	CH	ES	IT	NED	NO	PT	SE
Electricity	0.524	0.10	0.36	0.483	0.34	0.018	0.144	0.047
Wood pellets	0.027	0.027	0.018	0.030	0.372	0.014	0.045	0.044
Oil	0.301	0.30	0.31	0.267	0.26	0.32	0.267	0.29
Natural Gas	0.228	0.23	0.25	0.250	0.183	0.26	0.202	0.23
District heating	0.022	NA	NA	0.360	0.17	0.011	NA	0.011

Table 6: Current primary energy conversion factors in kWh primary energy per kWh final energy.

Energy carrier	AT	CH	ES	IT	NED	NO	PT	SE
Electricity	3.18	3.01	2.40	2.42	1.45	1.54	2.50	1.60
Wood pellets	1.20	1.20	1.11	1.11	1.00	1.11	1.00	1.00
Oil	1.24	1.24	1.18	1.07	1.00	1.11	1.00	1.00
Natural gas	1.07	1.06	1.20	1.05	1.00	1.09	1.00	1.00
District heating	1.53	NA	NA	NA	NA	0.35	NA	NA

3. Case Studies

3.1 Overview

Within the IEA EBC Annex 75 project, nine case studies from eight different European countries were investigated. The necessary data was gathered to carry out parametric assessments, applying and testing the methodology developed in IEA EBC Annex 75. It was intended to select case studies in existing urban districts with renovation needs where the results of the case studies can guide in choosing an appropriate renovation strategy for the respective district.

It was investigated to what extent there are synergies and to what extent there are trade-offs for combining energy efficiency measures and renewable energy measures. It is envisaged to determine cost-effective renovation strategies for the investigated districts considering both energy efficiency measures and renewable energy measures.

Figure 1 shows a country map of Europe. In this map, the eight countries, which participated in the parametric assessments of the Case Studies, are highlighted in orange. These countries are Austria, Italy, Norway, Portugal, Spain, Sweden, Switzerland, and the Netherlands.

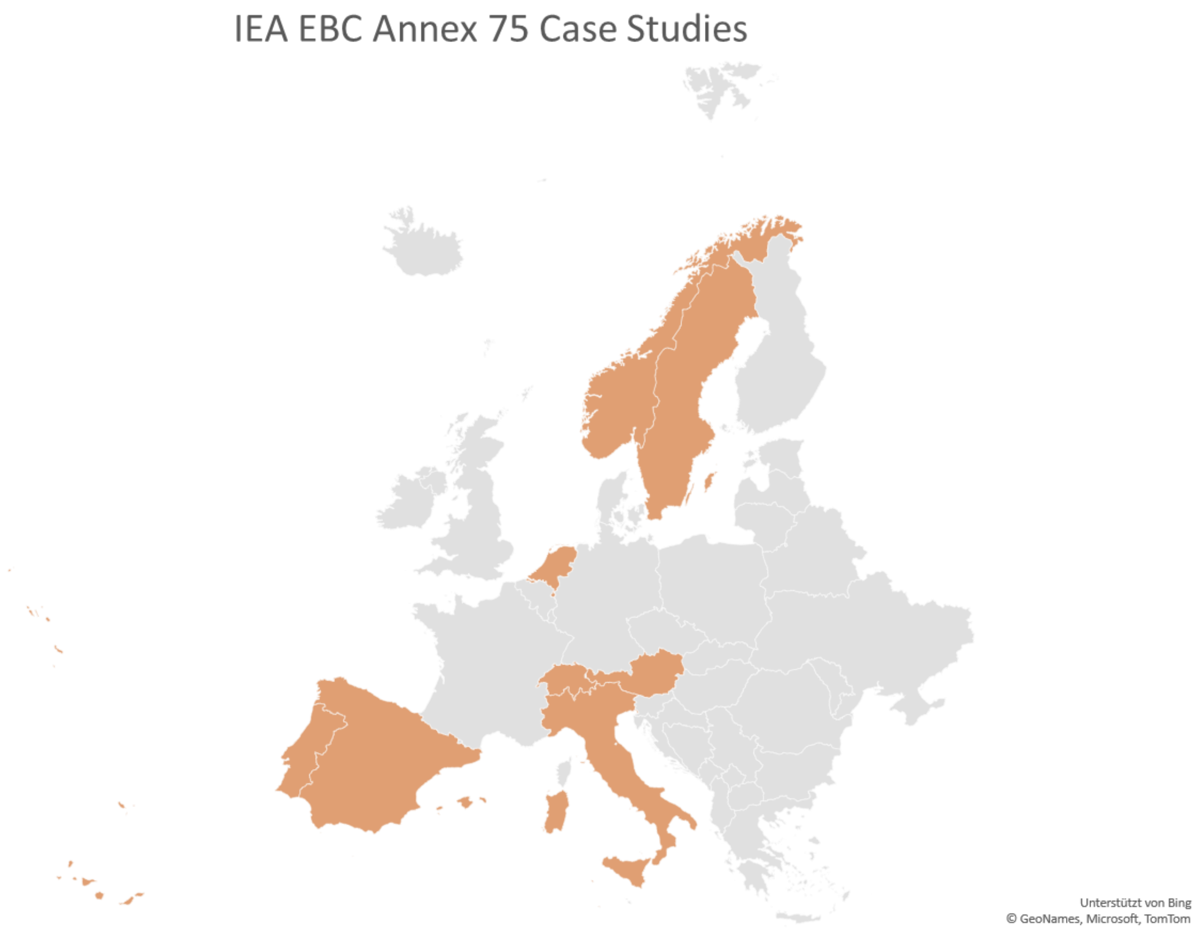

Figure 1: Countries participating in the Case Study investigations are highlighted in orange (from: “GeoNames”, by GeoNames, nd.).

The assessment of the Case Studies followed a defined process:
- Definition of the building typologies.
- Definition of measures on the building envelope.
- Definition of energy supply measures, including renewable energy generation on-site.
- Combination of the individual measures into meaningful scenarios.
- Calculation of the scenarios and evaluation concerning the defined key performance indicators.

The building typologies were defined according to the real situation on site. Parameters describing the buildings and typologies were collected and, if necessary, complemented.

Measures on the building envelope include insulation of walls, roofs, floors, and new windows. Additionally, mechanical ventilation with heat recovery was considered as a renovation option.
The investigated energy supply systems can be classified in:
- Decentralised energy supply per apartment.
- Decentralised energy supply per building.
- Centralised energy supply for the entire district.

Renewable energy generation on-site includes mainly photovoltaic installations but also solar thermal systems for heating and domestic hot water production.

As mentioned in Chapter 2.1.4, the investigated key performance indicators are the life cycle costs (LCC), the carbon emissions, and the total primary energy demand. More information on the key performance indicators can be found in the Methodology report of IEA EBC Annex 75 (Bolliger et al., 2023).

In the following chapters, the nine Case Studies are presented.

3.2 Austria

3.2.1 Description of the district

The case study is in Gleisdorf, Styria, in the south-eastern part of Austria. Gleisdorf is close to the capital city of Styria, Graz. The case study consists of 23 buildings constructed between 1915 and 2011. Table 7 gives some general information on the district and its location. Figure 2 shows the aerial view of the case study.

Based on the characteristics of the buildings, they were classified into three building typologies (see Table 8).

Table 7: General information about the district.

Parameter	Explanation/definition
Location	Gleisdorf
Latitude	E: 15.707246
Longitude	N: 47.101077
Climate zone	Dfb (Humid continental climate)
Number of buildings in total	23

Figure 2: Aerial view of the Case Study in Austria (source: edited by the authors, based on "Google Maps" by Google n.d.).

Table 8: Building typologies of the Austrian Case Study.

Parameter	Unit	building typology 1	building typology 2	building typology 3
Building information				
Number of buildings per typology		8	10	5
Construction period		1975-2011	1915-1977	1915
Geometry				
Gross heated floor area (GHFA)	m^2	8064	5180	4033
Heated volume	m^3	92348	53770	47334
Façade area incl. window area	m^2	9051	5581	4164
Roof area if flat roof	m^2	2610	-	-
Roof area if a pitched roof	m^2	-	2030	1578
Is the room below the roof heated or not?	Yes/No	-	No	Yes
Area of windows to North	m^2	1692	1042	901
Area of windows to East	m^2	1756	1144	717
Area of windows to South	m^2	1722	994	884
Area of windows to West	m^2	1901	1180	792
Area of basement ceiling	m^2	2610	1663	1293
The average number of floors above ground	-	3.375	2.9	3
Usage				
Type of use		Residential	Residential	Residential
Average area per occupant	m^2 / person	59	54	94
Typical indoor temperature (for calculations)	°C	20	20	20
HVAC systems				
Type of existing heating sys-tem		Diverse	Diverse	Diverse
Existing energy carrier		Oil, gas, electricity	Gas, electricity	gas
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No
Ventilation rate	ach	0.4	0.4	0.4
Is a cooling system installed?	Yes/No	No	No	No
Hot water consumption	l/person/day	25	25	25

3.2.2 Calculation parameters and scenarios

Table 9: General parameters for the calculations of the Austrian Case Study.

Parameter	Explanation/definition
Date the calculations were made	2019-2020
Weather file used	Graz
External shading (by surrounding buildings) considered	No

In total, nine renovation scenarios were investigated, including insulation of the exterior walls, the 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 doesn´t 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).

Summarized the renovation scenarios include the following measures:

- Scenario 1: roof_national
- Scenario 2: roof_PH
- Scenario 3: roof_PH + facade_national
- Scenario 4: roof_PH + facade_PH
- Scenario 5: roof_PH + facade_PH + windows_PH
- Scenario 6: roof_PH + facade_PH + windows_PH + SolarThermal
- Scenario 7: roof_PH + facade_PH + windows_PH + SolarThermal + PV
- Scenario 8: roof_PH + facade_PH + windows_PH + SolarThermal + PV + electric battery
- Scenario 9: roof_PH + facade_PH + windows_PH + SolarThermal + PV + electric battery + MVHR

"national" refers to national standards and regulations
"_PH" refers to passive house standards
"MVHR" represents mechanical ventilation with heat recovery

Table 10 and Table 11 give an overview of the investigated scenarios and the assumptions for the measures on the building envelope and the energy supply system.

Table 10: Measures on the building envelope for the reference scenario ("Ref") as well as for scenarios 1 to 9.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8	9
Walls											
U-values	W/m²K	0.87	0.87	0.87	0.27	0.12	0.12	0.12	0.12	0.12	0.12
Investment costs	EUR/m²$_{\text{building element}}$	29.98	29.98	29.98	70.81	89.15	89.15	89.15	89.15	89.15	89.15
Maintenance costs	EUR/m²$_{\text{building element}}$.year	0.45	0.45	0.45	1.06	1.3	1.3	1.3	1.3	1.3	1.3
Service life	years	-	-	-	40	40	40	40	40	40	40
Roofs											
U-values	W/m²K	0.73	0.13	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Investment costs	EUR/m²$_{\text{building element}}$	No measures	65.38	73.80	73.80	73.80	73.80	73.80	73.80	73.80	73.80
Maintenance costs	EUR/m²$_{\text{building element}}$.year	No measures	0.98	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Service life	years	-	40	40	40	40	40	40	40	40	40
Windows											
U-values	W/m²K	2.33	2.33	2.33	2.33	2.33	0.90	0.90	0.90	0.90	0.90
Investment costs	EUR/m²$_{\text{building element}}$	30	30	30	30	30	390	390	390	390	390
Maintenance costs	EUR/m²$_{\text{building element}}$.year	0.45	0.45	0.45	0.45	0.45	5.87	5.87	5.87	5.87	5.87
Service life	years	40	40	40	40	40	40	40	40	40	40

The following table shows the assumptions which were made for describing the HVAC systems. For the nine scenarios, different energy supply systems were investigated:

- At the building level:
  - Natural gas heating
  - Air source heat pump
  - Pellets heating
- At the district level:
  - District heating based on renewable energy

All investigated energy supply systems are also supported by solar thermal installations and PV.

Table 11: Measures of the HVAC system including renewable energy generation on-site.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8	9
Central natural gas heating											
Capacity	kW	1271	1181	1175	873	805	644	644	644	644	553
Investment costs	EUR/kW	18.93	19.60	19.65	22.64	23.54	26.18	26.18	26.18	26.18	28.18
Maintenance costs	EUR/year	481	463	462	395	379	337	337	337	337	312
Service life	Years	20	20	20	20	20	20	20	20	20	20
Central air source heat pump											
Capacity	kW	1271	1181	1175	873	805	644	644	644	644	553
Investment costs	EUR/kW	114.29	117.68	117.94	132.84	137.22	150.05	150.05	150.05	150.05	159.58
Maintenance costs	EUR/year	2904	2780	2771	2319	2210	1934	1934	1934	1934	1764
Service life	Years	20	20	20	20	20	20	20	20	20	20
Pellets heating											
Capacity	kW	1271	1181	1175	873	805	644	644	644	644	553
Investment costs	EUR/kW	170	170	170	170	170	170	170	170	170	170
Maintenance costs	EUR/year	4319	4017	3994	2968	2738	2191	2191	2191	2191	1879
Service life	Years	20	20	20	20	20	20	20	20	20	20
District heating											
Capacity	kW	1271	1181	1175	873	805	644	644	644	644	553
Investment costs	EUR/kW	44.45	45.49	45.58	50.10	51.41	55.20	55.20	55.20	55.20	57.97
Maintenance costs	EUR/year	1129	1074	1070	875	828	711	711	711	711	640
Service life	Years	20	20	20	20	20	20	20	20	20	20
Solar thermal system											
Size	m²	0	0	0	0	0	0	501	501	501	501
Investment costs	EUR/m²$_{solar\ thermal}$	-	-	-	-	-	-	619.31	619.31	619.31	619.31
Maintenance costs	EUR/year	-	-	-	-	-	-	1550	1550	1550	1550
Service life	Years	-	-	-	-	-	-	20	20	20	20
PV system											
Size	kWp	0	0	0	0	0	0	0	325	325	325

Parameter	Unit	Ref	1	2	3	4	5	6	7	8	9
Investment costs	EUR/kWp	-	-	-	-	-	-	-	1100	1100	1100
Maintenance costs	EUR/year	-	-	-	-	-	-	-	3575	3575	3575
Service life	years	-	-	-	-	-	-	-	30	30	30
Mechanical ventilation with heat recovery											
Investment costs	EUR/$m^2_{floor\ area}$	0	0	0	0	0	0	0	0	0	30
Maintenance costs	EUR/$m^2_{floor\ area}$.year	0	0	0	0	0	0	0	0	0	0.62
Service life	years	-	-	-	-	-	-	-	-	-	25

3.2.3 Case study results

The following graphs give an overview of the results obtained:

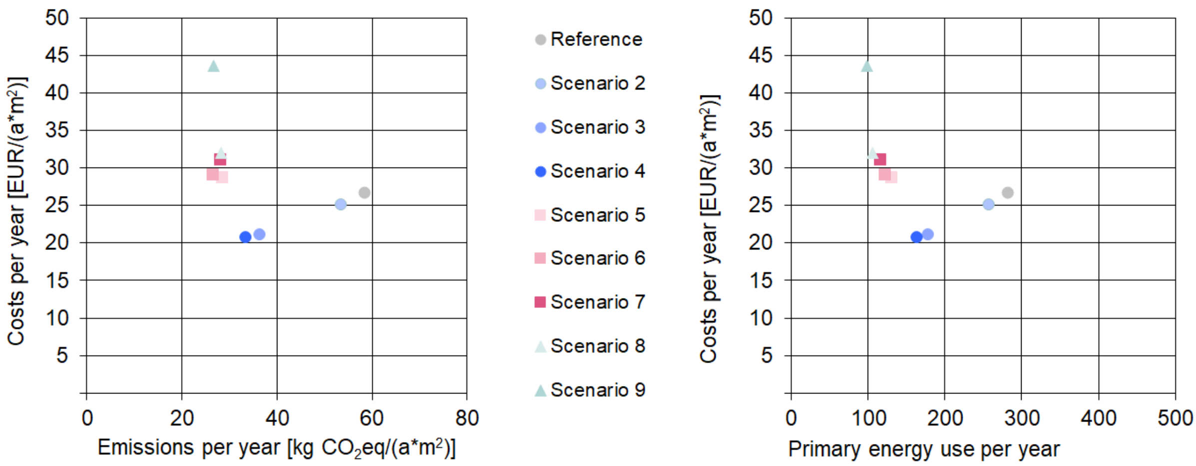

Figure 3: Reference heating system (natural gas).

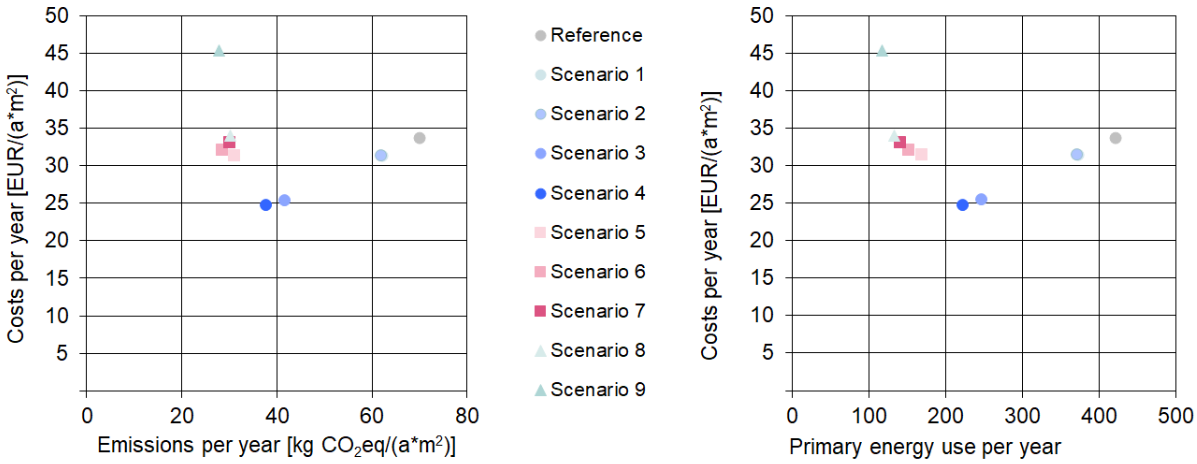

Figure 4: Heating system 2 - heat pump.

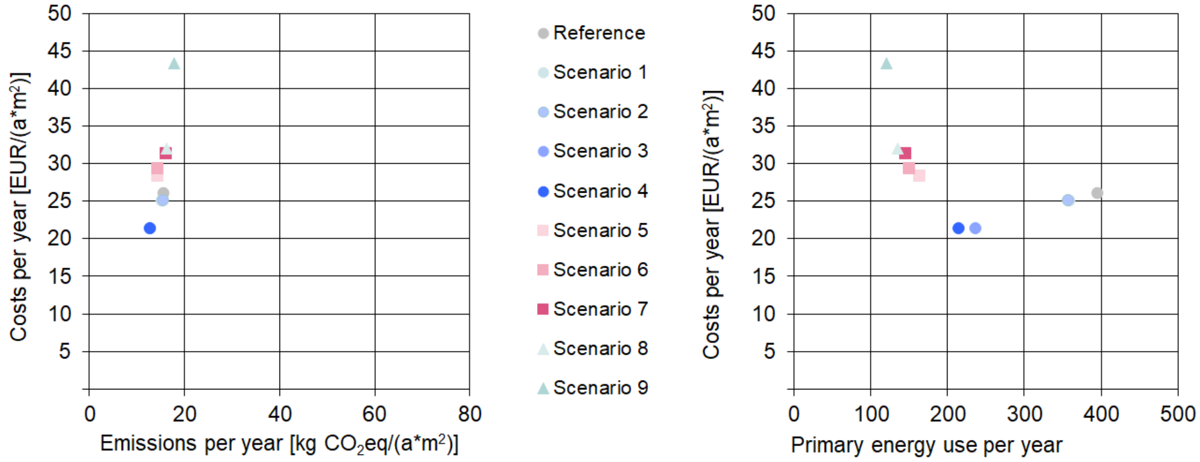

Figure 5: Heating system 3 – pellets.

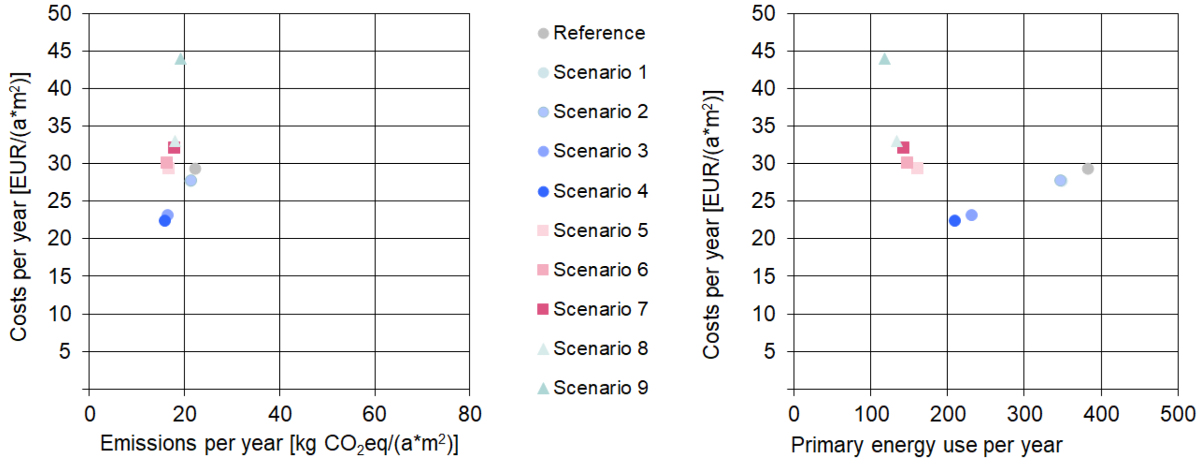

Figure 6: Heating system 4 - district heating.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

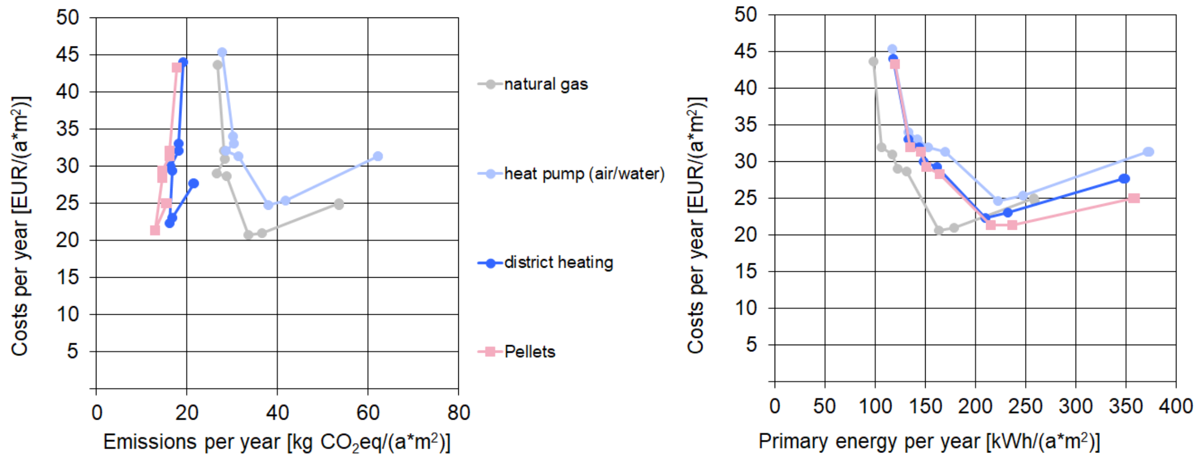

Figure 7: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

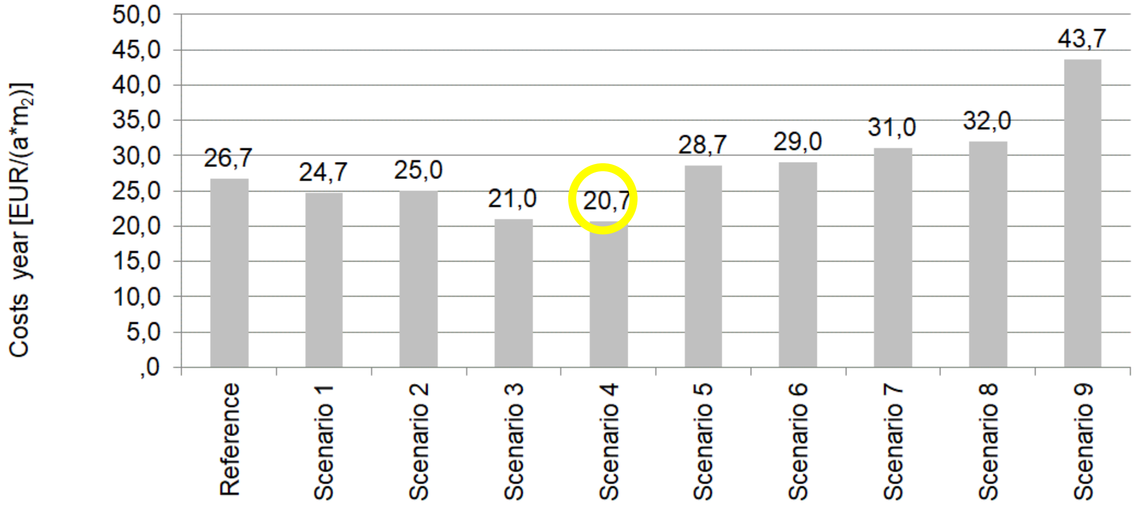

Figure 8: Reference heating system (natural gas).

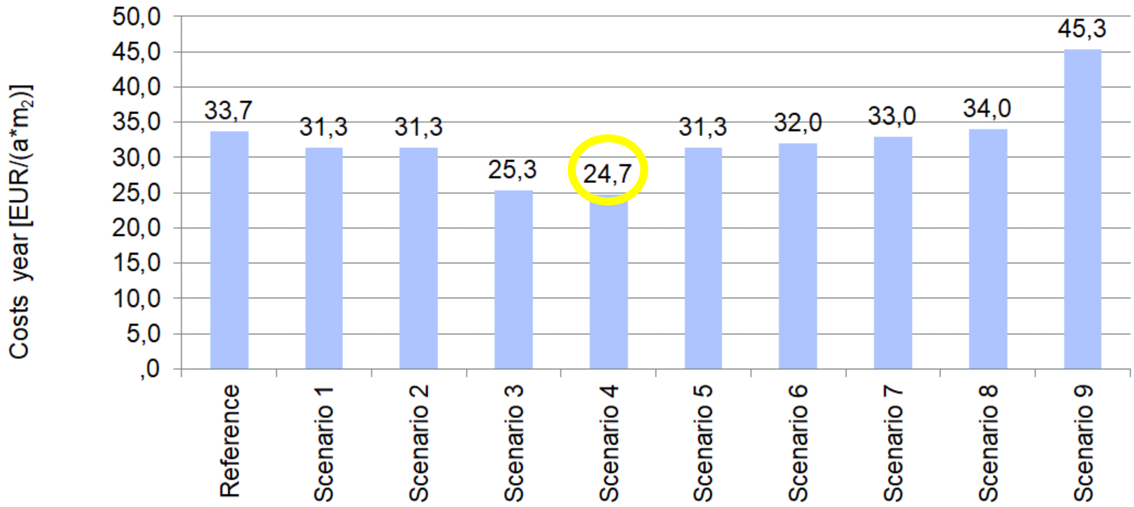

Figure 9: Heating system 2 - heat pump.

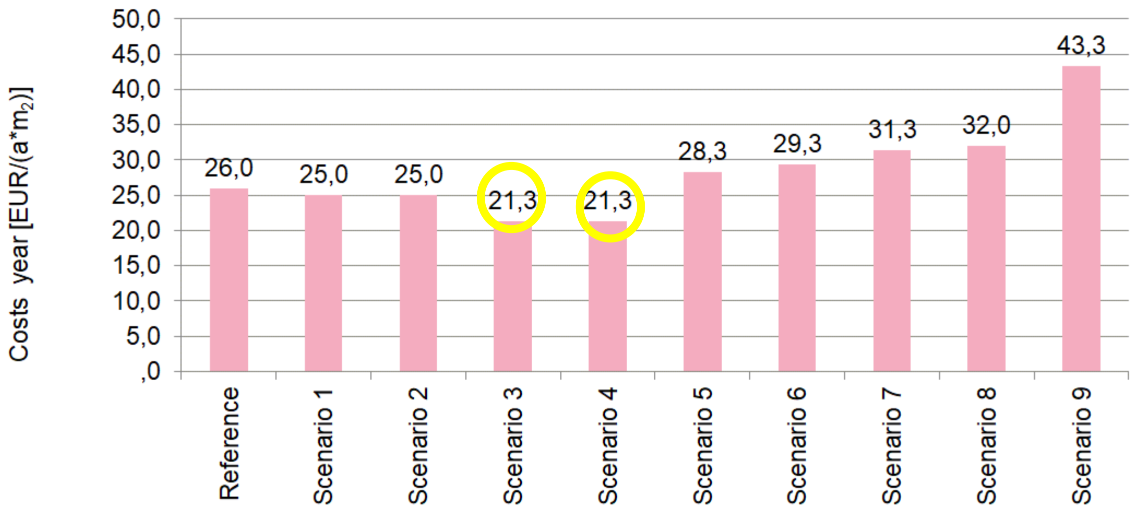

Figure 10: Heating system 3 – pellets.

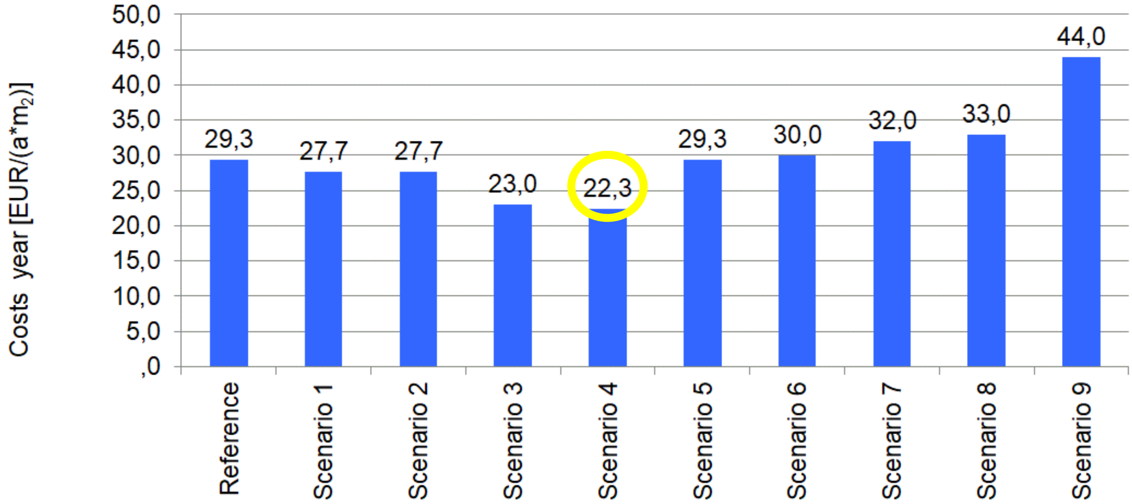

Figure 11: Heating system 4 - district heating.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

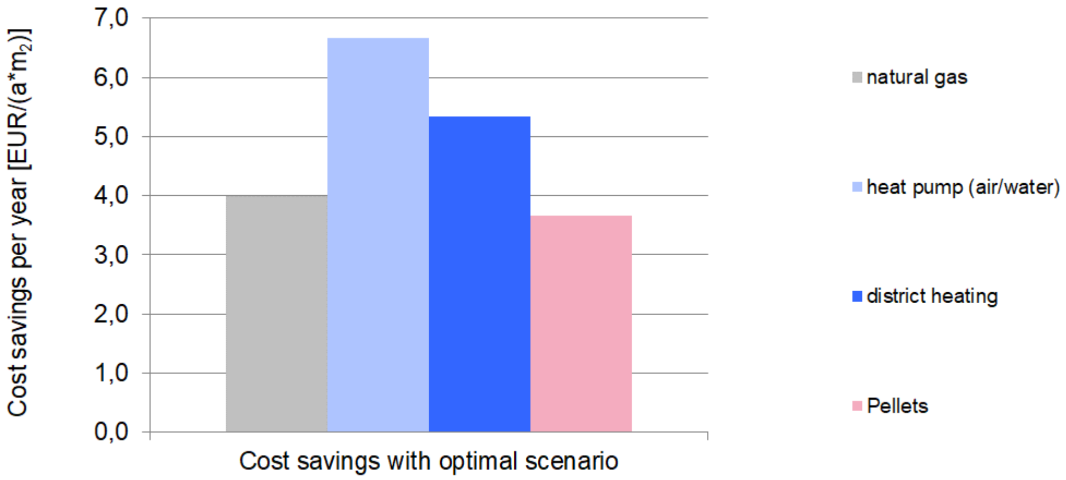

Figure 12: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized:

Changing only the energy source for heating and domestic hot water doesn´t automatically lead to any reductions. The opposite is the case for the heat pump system: carbon emissions, primary energy demand, and life cycle costs increase when only the energy supply system is changed and no other measures are considered.

Furthermore, comparing the investigated energy supply systems, the air-water heat pump achieves the worst result. Even if renovation measures on the building envelopes are considered, the primary energy demand, the carbon emissions, and the life cycle costs are the highest compared to natural gas heating, district heating, and pellet heating.

If the goal is to reduce carbon emissions, switching to district heating or pellet heating is advisable. The switch of the energy supply system reduces the carbon emissions more effectively than the measures on the building envelope.

Looking at the cost-effectiveness of the investigated renovation measures, the results show that the insulation of the roof and the façade are always cost-effective when compared to the reference case. The other investigated measures are only cost-effective when combined with the heat pump system.

3.2.4 Discussion

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Yes
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.»	Not investigated
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.»	Not investigated
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 energy.»	Yes
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.»	Not investigated
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.»	Not investigated
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.»	Yes
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.»	Not investigated

3.3 Italy

3.3.1 Description of the district

From the beginning of the twentieth century, the Italian political class sought to end the precarious conditions in which the low-income population lived. In 1903, Italian congressman Luigi Luzzatti founded the Istituto Case Popolari (Public Housing Institute; ICP). This institution aimed to provide workers with low-cost housing that respected the latest sanitary and hygienic regulations. In 1914, a chapter of ICP was opened in Venice with the same goal: improving the living condition of the low-income population. The institution's name changed various times until the mid 90s when the ICP became Aziende territoriali per l'edilizia residenziale (Local Agency for Residential Buildings) or ATER.

Table 12: General information about the district.

Parameter	Explanation/definition
Location	Venice
Latitude	45.4313341
Longitude	12.3127562
Climate zone	Cfb (Marine West Coast Climate)
Number of buildings in total	54

The district studied, named "Santa Marta IACP housing", was part of this social housing construction wave. It is in the western part of Dorsoduro, one of the six districts that compose the old town of Venice, situated at the city's southwest end. The district's shape is irregular, but the dimensions are approximately 400 m x 160 m, for a total surface area of 3.78 hectares (ha) (equal to 0.04 km^2). The project for this neighbourhood dated back to 1920, when the municipality started the construction of the first set of 14 buildings for a total of 148 housing units. It was targeted at low-income workers from the nearby industries and maritime workshops. These buildings were completed in 1928. In 1930, a second intervention in the area led to the construction of 365 new units divided into more than 21 new buildings.

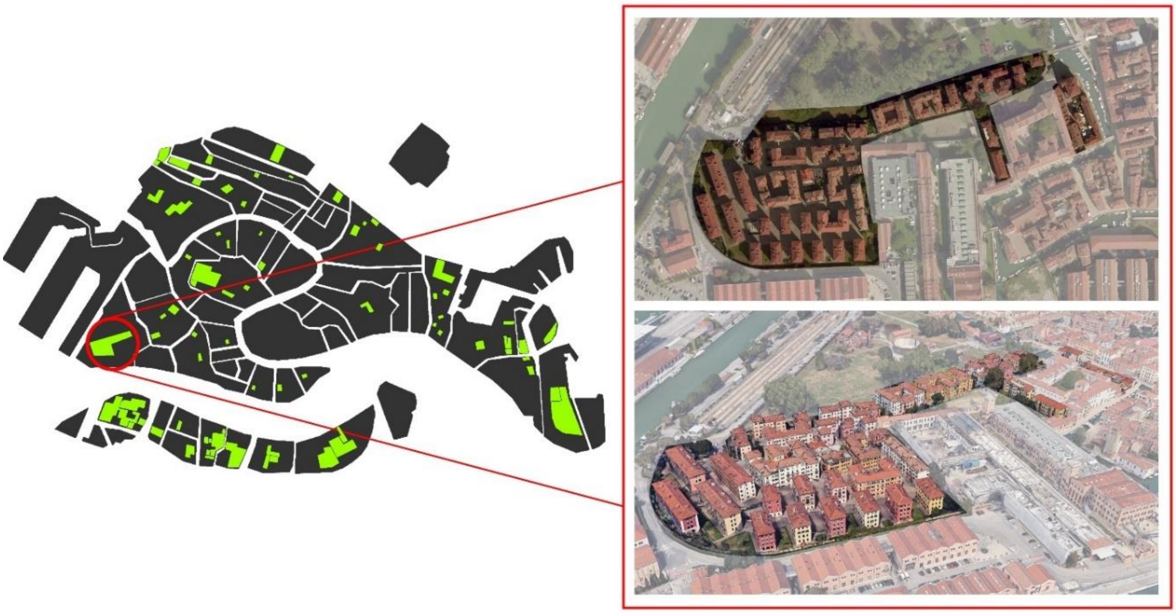

Figure 13: Aerial view of the Case Study in Italy (source: edited by the authors, based on "Google Maps" by Google n.d.).

The case study is composed mostly of multi-family buildings; only four can be classified as mixed-use with retail spaces or restaurants on the ground floor. The construction can be divided into two groups by age and varies slightly with the geometry of the buildings. The first group of buildings, built between 1920 and 1928, have a regular rectangular shape with dimensions ranging from 18 to 50 m for the long side of the buildings. The short side of the buildings is always 12.5 m long. All have four floors and several apartments, between two and six per floor, depending on the building's dimensions.

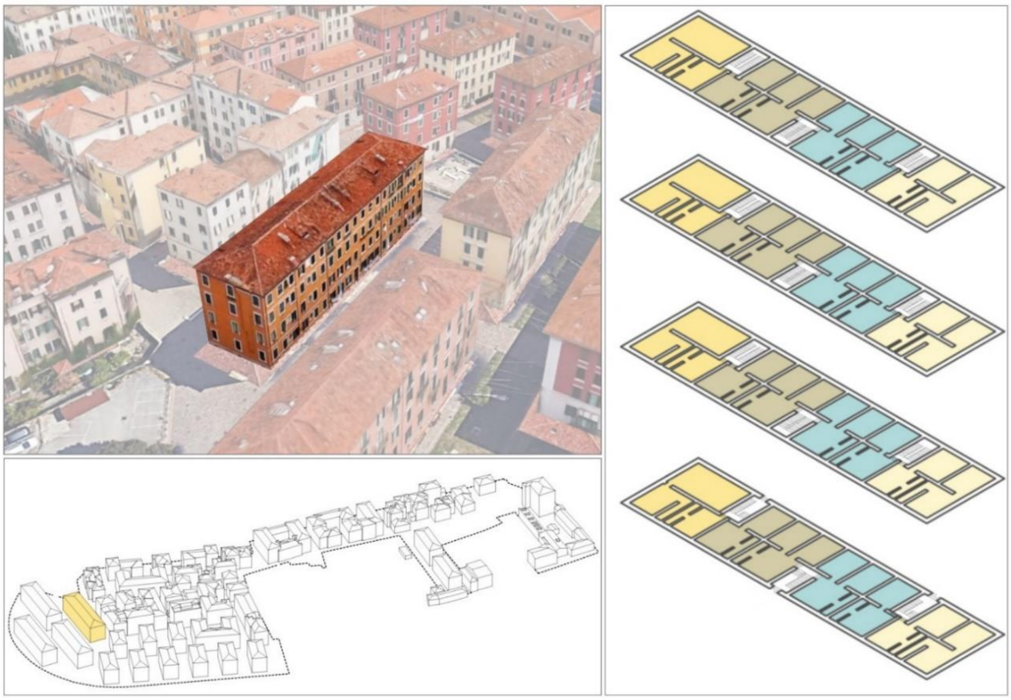

Figure 14: Geometry type 1 of the Italian Case Study (source: edited by the authors, based on "Google Maps" by Google n.d.).

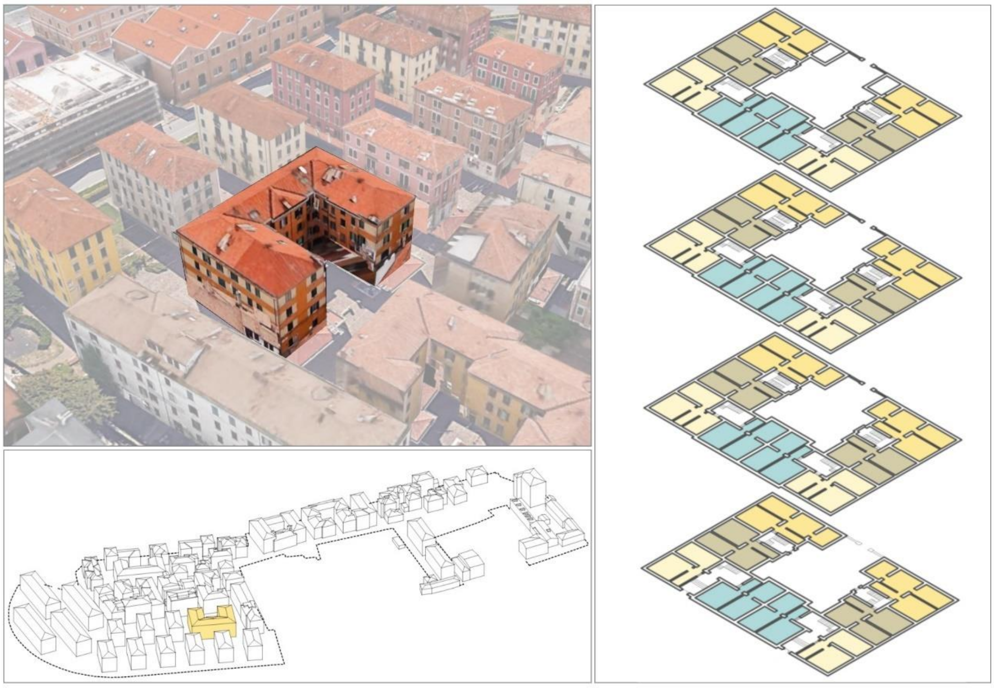

Figure 15: Geometry type 2 of the Italian Case Study (source: edited by the authors, based on "Google Maps" by Google n.d.).

The second group, completed in 1936, shows more complex and varied geometries: the buildings are for the most part built around a central void or in a “C” shape. The dimensions of these buildings are very different from each other, ranging from footprints of only 170 m^2 to complexes of more than 1500 m^2. Variation also can be found in the number of floors and apartments, from simple two-floor houses with one apartment per floor to considerable five-story buildings with up to fourteen apartments per floor.

The techniques used for the building envelope were the same in the two phases. The exterior walls are made of solid brick masonry, without any kind of insulation, and plaster on both the internal and external sides. The ground floor consists of a non-insulated concrete slab laid down on a rock foundation with tiles on the internal surface. An inclined wooden roof with no insulation and clay tiles covers the building. Some differences can be found in the transparent envelope: double-glazed wooden frame windows have replaced some single-glazed systems with a wooden frame, depending on the owners’ willingness to retrofit the apartment. A gas boiler installed in every building provides heating to the apartments, whereas cooling systems were not planned and are usually not present. In some cases, a simple one-apartment air conditioner has been installed over the years. Domestic hot water (DHW) is provided by an electric or gas-fired water heater installed in every apartment. The overall efficiency used to define boiler characteristics considers generation, distribution, emission, and regulation efficiencies, pipes commonly not insulated due to the age of construction, and heat mainly supplied by cast iron radiators.

Table 13: Building typology of the Italian Case Study.

Parameter	Unit	Building typology
	Building information	
Number of buildings per typology		54
Construction period		1920-1936
	Geometry	
Gross heated floor area (GHFA)	m^2	58606
Heated volume	m^3	138250
Façade area incl. window area	m^2	50753
Roof area if pitched roof	m^2	15241
Is the room below the roof heated or not?	Yes/No	No
Area of windows to North	m^2	1569
Area of windows to East	m^2	2239
Area of windows to South	m^2	1572
Area of windows to West	m^2	2233
Number of floors above ground	-	1-5
	Usage	
Type of use		Residential
Area per occupant	m^2 / person	30.45
Typical indoor temperature (for calculations)	°C	20

Parameter	Unit	Building typology
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/(m².a)	28
	HVAC systems	
Type of existing heating system		Boiler
Existing energy carrier		Natural gas
Is a ventilation system without heat recovery installed?	Yes/No	No
Is a ventilation system with heat recovery installed?	Yes/No	No
Ventilation rate	ach	/
Is a cooling system installed?	Yes/No	No
Hot water consumption	l/person/day	40

3.3.2 Calculation parameters and scenarios

Table 14: General parameters for the calculations of the Italian Case Study.

Parameter	Explanation / definition
Date the calculations were made	2020
Weather file used	ITA_VENEZIA-TESSERA_IGDG.epw (E+ standard)
External shading (by surrounding buildings) considered	Yes

For the thermal renovation of the selected case study, six different scenarios of renovation measures on the building envelope are evaluated.

- Reference (M1): no envelope interventions
- Scenario 1 (M2): windows replacement
- Scenario 2 (M3): insulation of roof with EPS
- Scenario 3 (M4): insulation of façade with EPS
- Scenario 4 (M5): windows replacement + insulation of façade
- Scenario 5 (M6): windows replacement + insulation of façade + insulation of roof.

Each renovation scenario, except for Scenarios 1 and 2, was studied using 4 different types of insulating material: rock wool panels, wood fibre panels, aerogel panels, and Expanded Polystyrene (EPS) panels. To make the results of this study easier to understand, interpret, and disseminate, only results related to EPS are reported. The reason is that in the energy performance calculations, the thermal transmittance of the walls was the same for all investigated materials. So, the insulation material did not influence the buildings' energy performance. Therefore, only the results of the EPS insulation are shown because EPS is the cheapest material among the ones investigated.

An important aspect needs to be highlighted. The Superintendency of Cultural Heritage imposes restrictions on the work that can be done on the external envelope of buildings in the historical centre of Venice. To bypass restrictions and avoid problems, the insulating material is applied from the inside of the flats. This action has major repercussions on the initial investment price since no need for scaffoldings reduces the price to be paid for the intervention. As a negative aspect of the insulation inside, the reduction of useful floor area must be mentioned but this fact was not included in the investigations in this report.

More specific data regarding each intervention can be found in the following table.

Table 15: Measures on the building envelope.

Parameter	Unit	Ref	1	2	3	4	5
				Walls			
U-values	W/m²K	1.71			0.25	0.25	0.25
Investment costs	EUR/$m^2_{building\ element}$				66.38	66.38	66.38
Maintenance costs	EUR/$m^2_{building\ element}$.year	1.27			1.70	1.70	1.70
Service life	years				30	30	30
				Roofs			
U-values	W/m²K	2.70		0.20			0.20
Investment costs	EUR/$m^2_{building\ element}$			114.77			114.77
Maintenance costs	EUR/$m^2_{building\ element}$.year	2.09		2.84			2.84
Service life	years			30			30
				Windows			
U-values	W/m²K	5.80	1.00			1.00	1.00
Investment costs	EUR/$m^2_{building\ element}$		333.80			333.80	333.80
Maintenance costs	EUR/$m^2_{building\ element}$.year	1.60	3.78			3.78	3.78
Service life	years		30			30	30

In the current scenario, each flat is equipped with a condensing boiler fuelled by natural gas, with a water-based distribution system. For the study, four different supply systems are considered: a decentralised solution replacing the boilers installed in each flat with a decentralised system (in which a natural gas-fired boiler is installed in every building (scenario 7)). Additionally, three different central heat supply systems are considered, each of them with a centralised heat distribution system. The first system considered is a gas-fired combined heat and power (CHP) generator. The second system is a geothermal heat pump, and lastly, biomass powered CHP generator is considered.

For the decentralised system, each building is equipped with an up-to-date natural gas-fired boiler.

Additionally, every case with a centralised system is studied with and without the contribution of a renewable source. In particular, the CHP generator is coupled with a solar thermal system, and a PV system aids the heat pump and biomass CHP generator. Regarding this latest technology, a particular solution is applied to circumvent possible restrictions applied by the Superintendency for Cultural Heritage: instead of using classic photovoltaic panels, photovoltaic roof tiles are used in the simulations.

All the different heat supply systems are coupled with all the energy efficiency measure scenarios, totalling 42 cases, including the scenario in which no envelope interventions are foreseen, only the substitution of the generators with the centralised and decentralised solutions is studied.

Below is a recap of the seven different renovation scenarios for the buildings' energy systems:

- Scenario 1 (I1): centralised gas CHP
- Scenario 2 (I2): centralised gas CHP with solar thermal storage
- Scenario 3 (I3): centralised heat pump
- Scenario 4 (I4): centralised heat pump with photovoltaic panels
- Scenario 5 (I5): centralised biomass CHP
- Scenario 6 (I6): centralised biomass CHP with photovoltaic panels
- Scenario 7 (I7): decentralised traditional gas condensing boilers.

Calculations were performed in June 2021 and updated in January 2022.

Table 16: Measures of the HVAC system including renewable energy generation on-site.

Parameter	Unit	Ref	1	2	3	4	5
Central heating system 1 (Natural gas CHP)							
Capacity	kW	2241	1810	1717	1797	1375	1012
Investment costs	EUR/kW	830	830	830	830	830	830
Mainte-nance costs	EUR/year	102282	82631	78383	82056	62786	46218
Service life	Years	15	15	15	15	15	15
Central heating system 2 (Geothermal heat pump)							
Capacity	kW	3521	3058	2912	3038	2374	1802
Investment costs	EUR/kW	1100	1100	1100	1100	1100	1100
Mainte-nance costs	EUR/year	96824	84108	80081	83556	65286	49560
Service life	Years	20	20	20	20	20	20
Central heating system 3 (Biomass CHP)							
Capacity	kWe	604	524	499	521	407	309
Investment costs	EUR/kW	500	500	500	500	500	500
Mainte-nance costs	EUR/year	5359	53552	51492	53320	41908	32771
Service life	Years	15	15	15	15	15	15
Decentralised heating system 1 (Natural gas boilers)							
Capacity	kWt	8.350	7.620	7.325	7.600	5.730	4.325
Investment costs	EUR/kW	100	100	100	100	100	100

Parameter	Unit	Ref	1	2	3	4	5
Mainte-nance costs	EUR/year	1821	1676	1620	1671	1317	1046
Service life	Years	15	15	15	15	15	15
Solar thermal system							
Size	m²		2741				
Investment costs	EUR/m²solar thermal		428				
Mainte-nance costs	EUR/year		15657				
Service life	Years		20				
PV system							
Size	kWp				1197		1197
Investment costs	EUR/kWp				7561		7561
Mainte-nance costs	EUR/year				90533		90533
Service life	Years				20		20

3.3.3 Case study results

The following picture gives an overview of the combinations between renovation interventions on the envelope and heating systems substitutions.

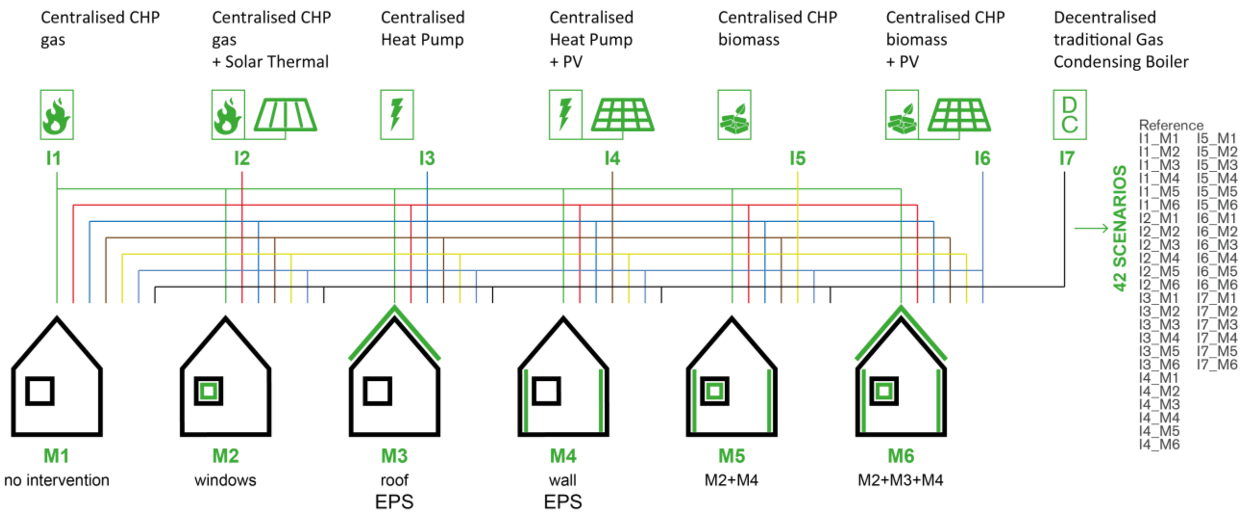

Figure 16: Overview of renovation measures and scenarios.

The following graphs give an overview of the results obtained:

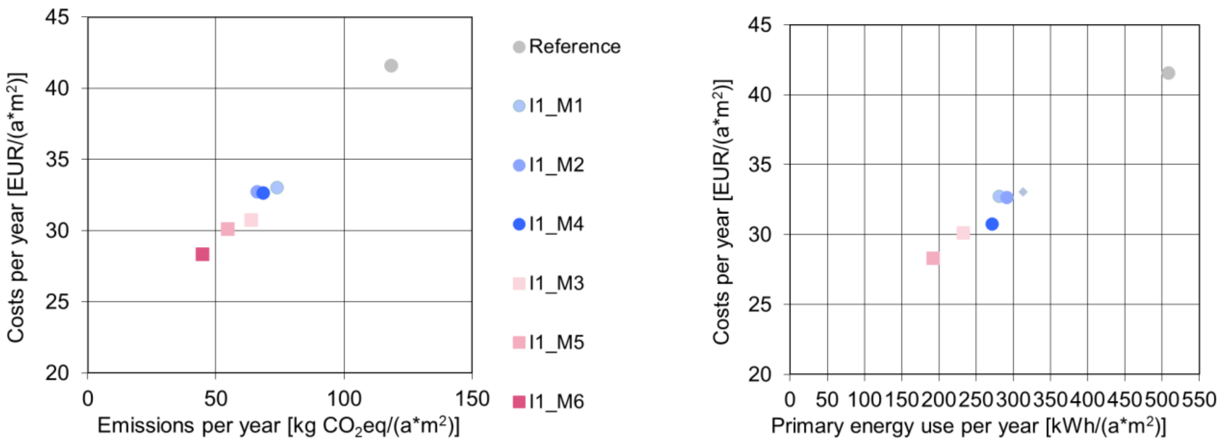

Figure 17: Heating system 1 – Centralised Natural gas CHP.

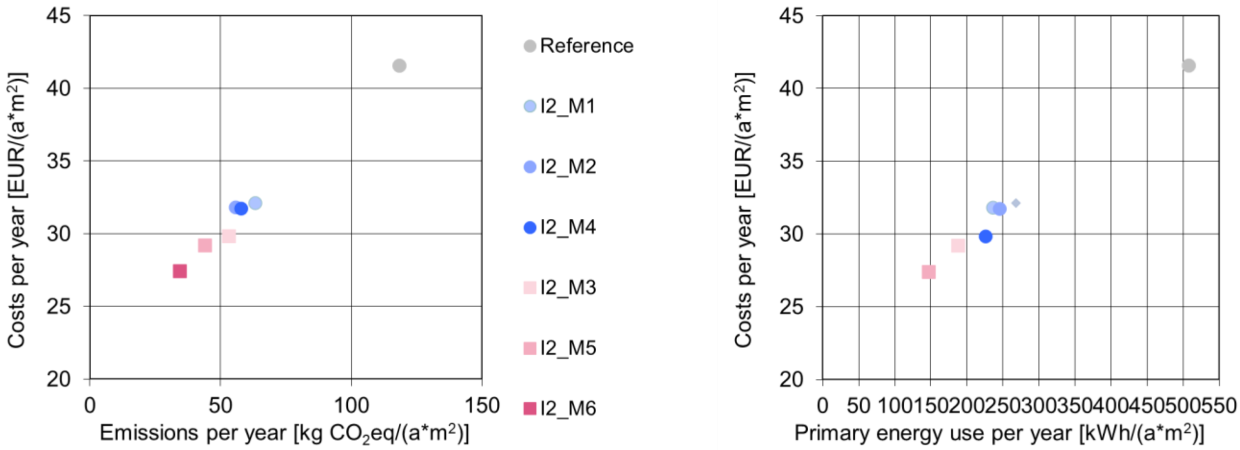

Figure 18: Heating system 2 - Centralised Natural gas CHP + solar thermal.

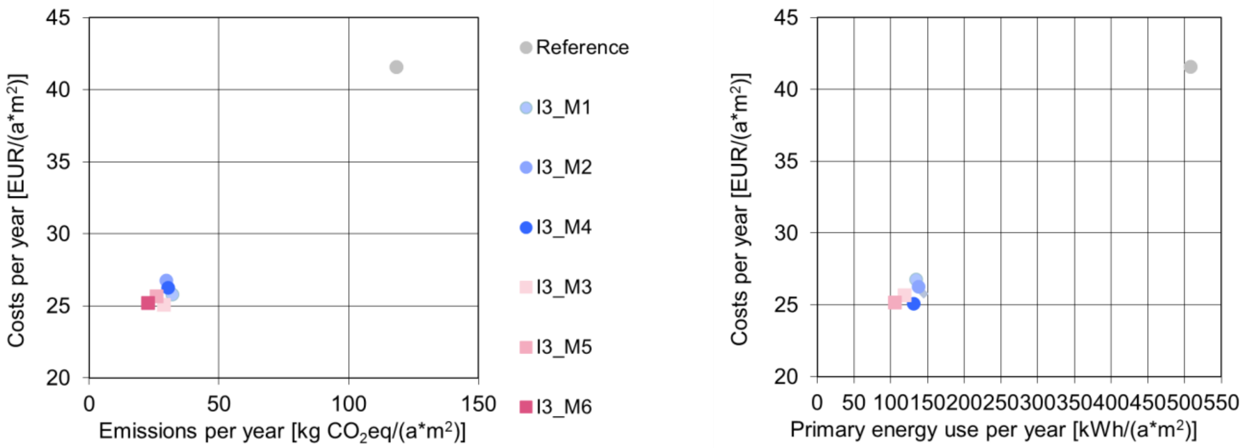

Figure 19: Heating system 3 – Centralised Geothermal heat pump.

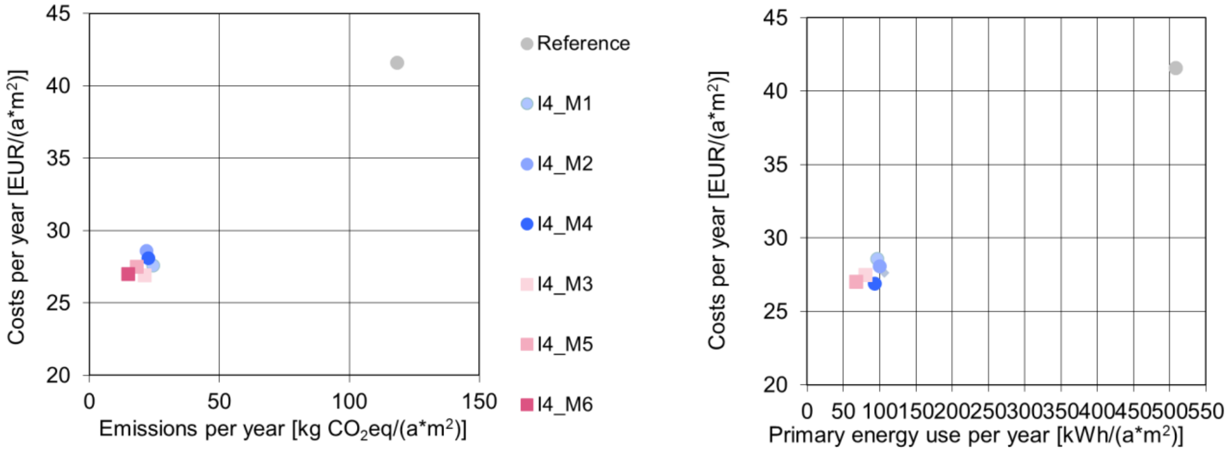

Figure 20: Heating system 4 – Centralised Geothermal heat pump + PV.

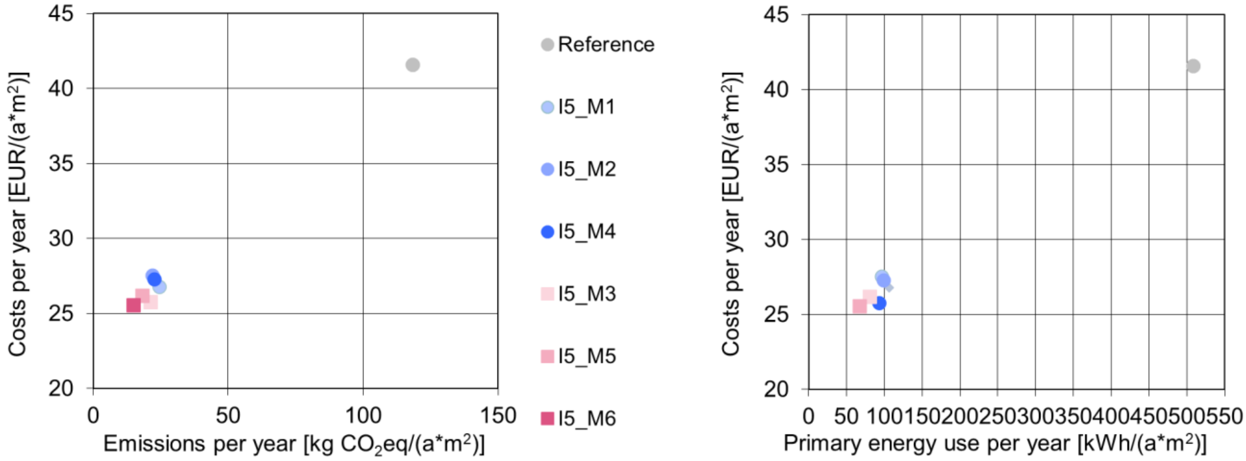

Figure 21: Heating system 5 - Centralised Biomass CHP.

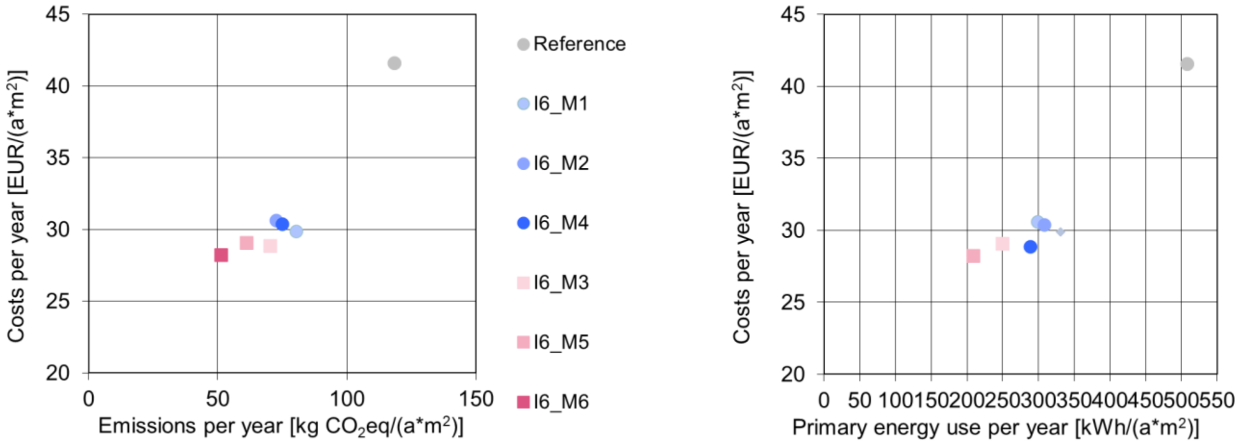

Figure 22: Heating system 6 - Centralised Biomass CHP + PV.

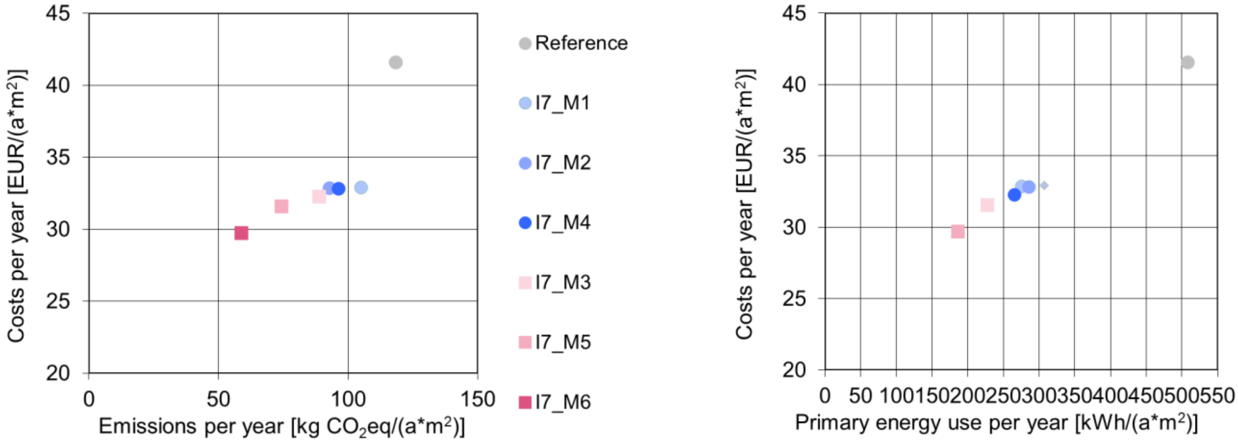

Figure 23: Heating system 7 – Decentralised Natural gas boilers.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

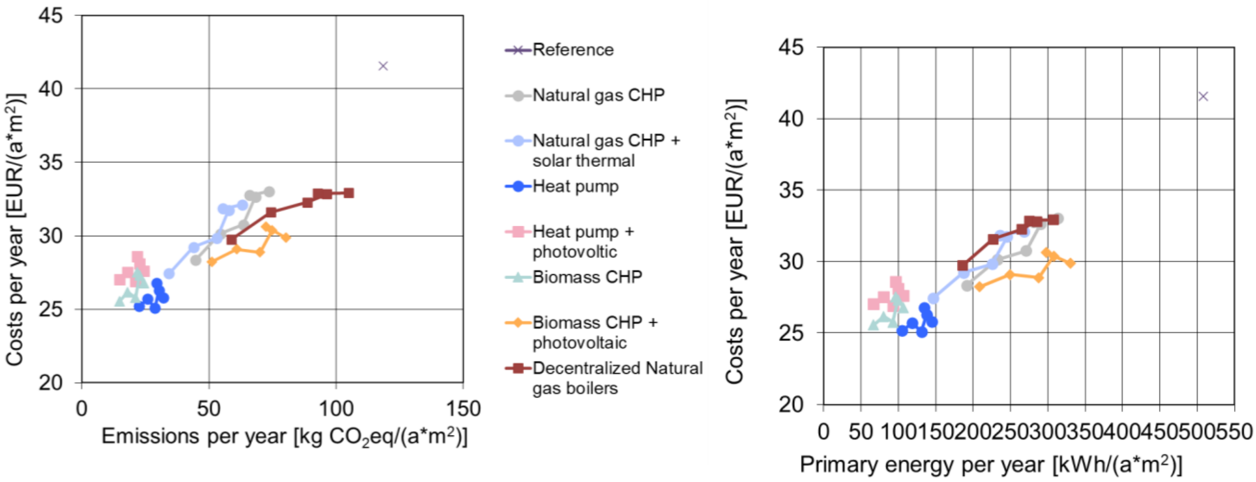

Figure 24: Overview of the combination of renovation packages on the building envelope with various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

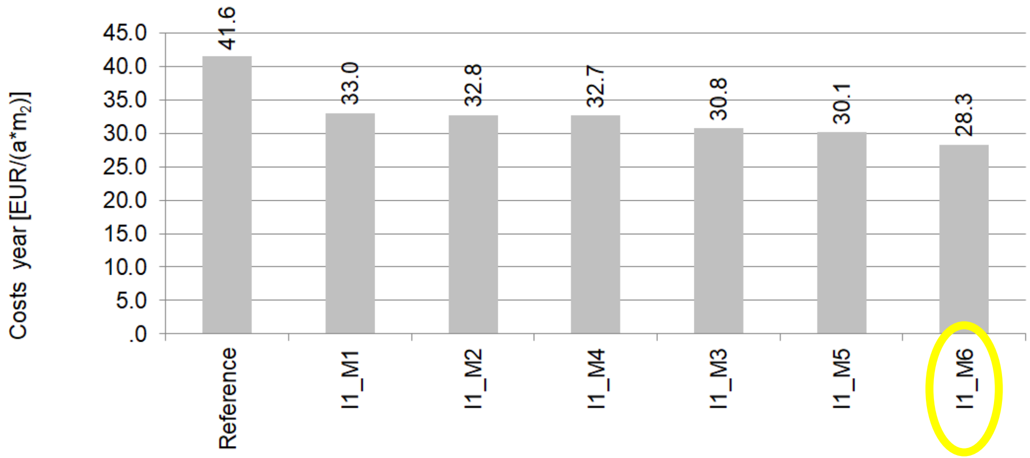

Figure 25: Heating system 1 – Centralised Natural gas CHP.

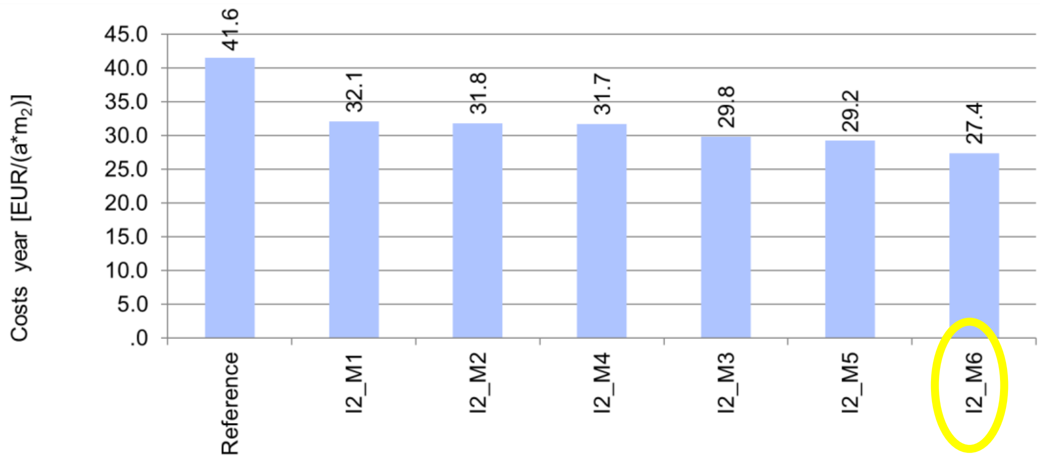

Figure 26: Heating system 2 – Centralised Natural gas CHP + solar thermal.

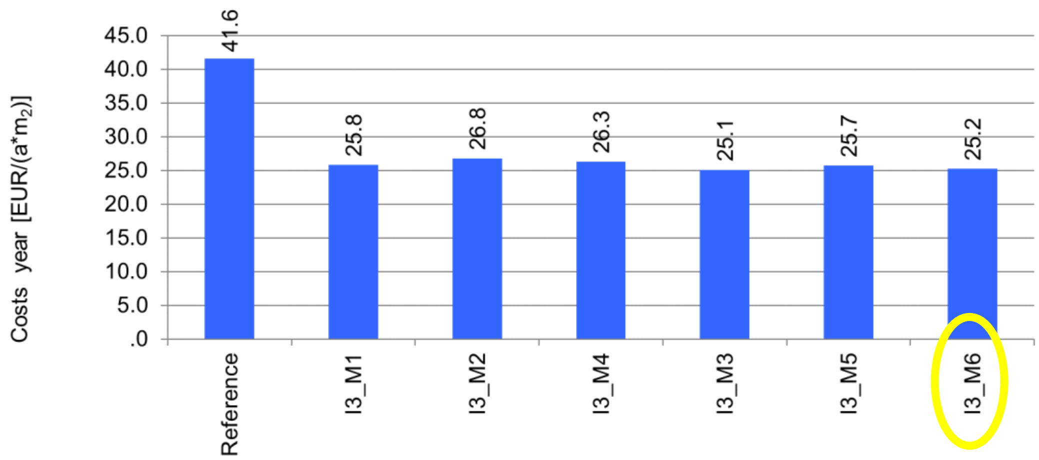

Figure 27: Heating system 3 – Centralised Geothermal heat pump.

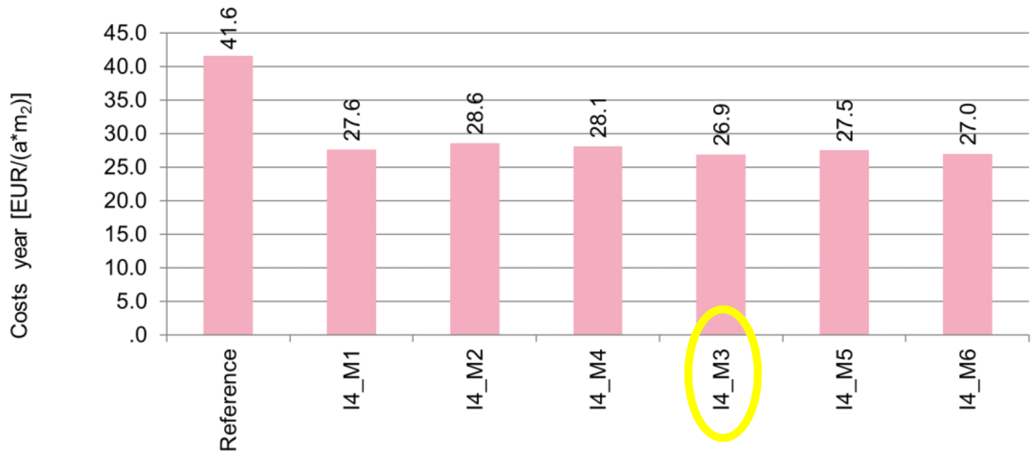

Figure 28: Heating system 4 - Centralised Geothermal heat pump + PV.

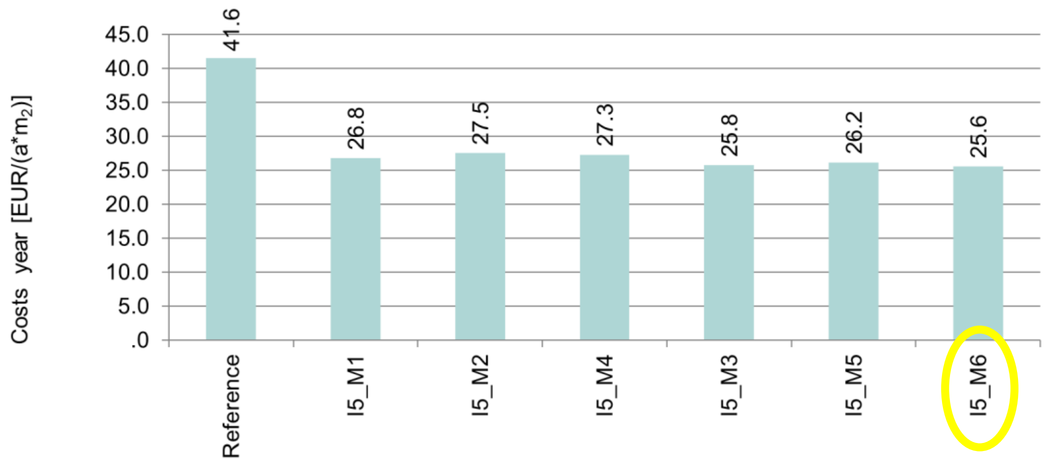

Figure 29: Heating system 5 – Centralised Biomass CHP.

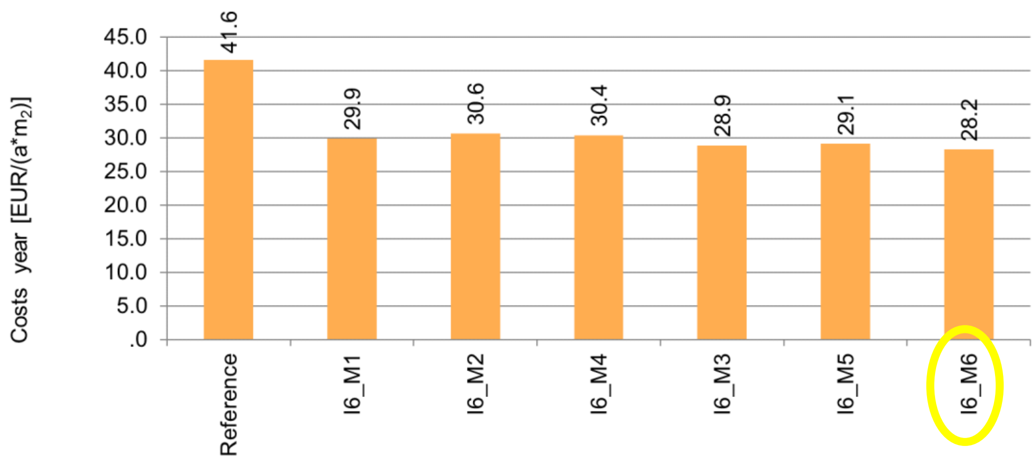

Figure 30: Heating system 6 – Centralised Biomass CHP + PV.

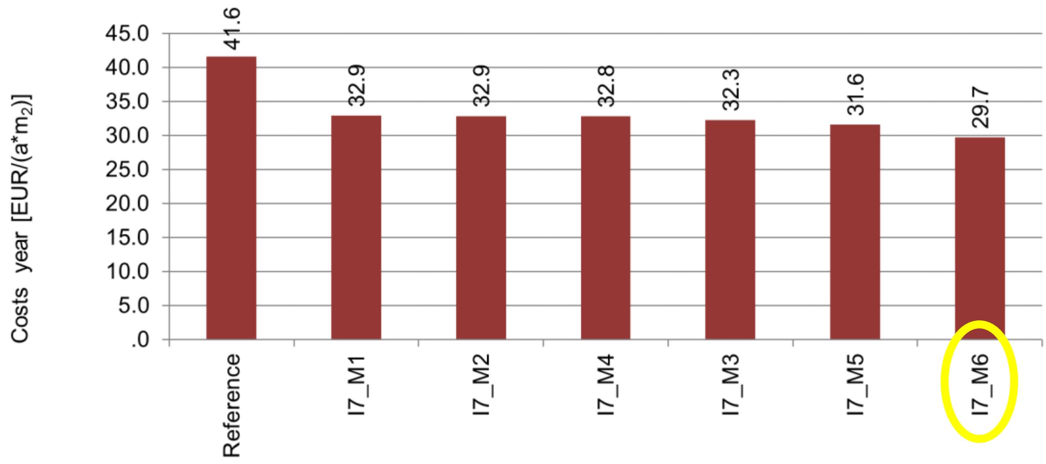

Figure 31: Heating system 7 – Decentralised Natural gas boilers.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

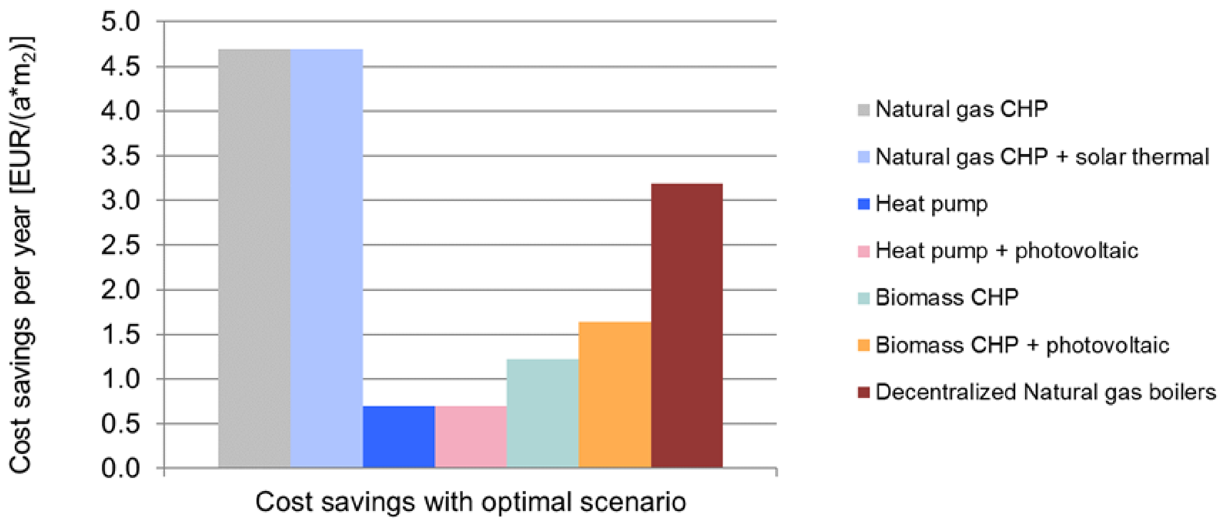

Figure 32: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following outcomes can be recognized: in all the scenarios, the best cost-effective measure concernes the renovation of the whole envelope (windows, façade, and roof) because the savings can be achieved by decreasing the energy demand and improving the heating supply system.

For this case study, the most cost-effective scenarios consider the enhancement of the heating system by the substitution of an existent single boiler for each flat by a centralised system at the district level with a geothermal heat pump. However, among these scenarios, the best cost-effective measure is coupling the renovation of the building's external walls, not the whole envelope. But it must be mentioned that the difference is small to those variants where the entire external walls are renovated. The envelope interventions consider the application of insulation material on the inner side of external walls because of the heritage restrictions for Venice, so this intervention applies minor investment costs for external scaffoldings concerning standard external insulation.

Moreover, the impact of external insulation shows a weighty impact among the proposed measures because of the geometry and shape factor of district building: in this case, the building typology is characterised by a tall building, so by a wall surface greater than even the sum of roof and windows surfaces. In this sense, the thermal loss impact is also reduced by intervention on external walls more than other measures.

Regarding the proposed interventions, the cost-optimal scenario for the neighbourhood is the one identified by the acronym I3_M3.

In general, in terms of primary energy use, the most energy-saving measures consider the installation of RES, particularly PV plants, even if the chosen technology (PV roof tile) is not cheaper enough. Applying a solar thermal plant is useful only in the case of DHW reduction, but it needs a complex installation and a bureaucratic evaluation in Venice, so it's not considered a feasible, affordable, and appropriate measure to adopt in similar cases.

In terms of global costs, considering the whole service life, the study reveals how in most measures the energy costs represent the greatest impact. This is due to two factors: the increase in the cost of energy expected for the next few years (also following the Covid-19 crisis), Italy's historical gap in the supply of energy sources dependent on supply abroad and the consequent price for electricity and natural gas for the end-user.

However, it is also evident that a higher investment cost in intervention measures leads to lower energy consumption and lower carbon emissions. The most convenient measures are precisely those in which the intervention includes whole envelope insulation and transfer to a centralised plant, regardless of the energy vector used.

3.3.4 Discussion

What stands out when interpreting the results?

In the case of building renovation, the transition from a traditional decentralised plant to an innovative centralised one is even an energy-saving intervention. The switching to renewable energy measures is energy efficient but not cost-effective. The insulation of the external façade is cost-effective and energy-efficient due to the shape factor of the district buildings, whose prevailing typology is a multi-story building.

What are the most cost-effective solutions?

The most cost-effective solution considers external wall insulation combined with switching to a centralised heat pump system. The same system combined with intervention on the whole envelope (windows, wall insulation, and roof insulation) solutions is slightly less cost-efficient. The same measures combined with a PV system are less convenient but more energy-saving.

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

The greatest uncertainty is related to equipment costs and centralised systems. The reason is that these systems are not present in the common or national price lists as for the rest of the prices reported for the case study, but they are costs deriving from specific estimates; moreover, the parametric costs per generator size do not represent a reliable value.

The results are reliable, but it is important to underline the specificity of the case of Venice, namely:

- The external envelope of buildings is constrained and only the internal side can be insulated.
- Also, the PV is limited to some uses and the roof tile with cells is accepted but has much higher costs and lower efficiencies than the polycrystalline panel.
- The centralised generator with biomass vector is not a technological solution applicable to the Venetian case of the difficulty of installation and maintenance costs.

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Not investigated
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.»	Not investigated
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.»	Not investigated
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 energy.»	No
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.»	Not investigated
6. «The cost-optimal level of the energy efficiency measures in 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.»	Not investigated
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.»	Yes
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.»	Not investigated

3.4 Norway

3.4.1 Description of the district

The selected case study is a housing cooperative located in central Norway. The neighbourhood was developed in the 1970s and consists of about 1000 apartments. The façades and roofs were renovated in the mid-1990s. As part of this renovation, an extra layer of 10 and 5 cm insulation was added to the façades and roofs, respectively. No façade refurbishment is therefore included in the reference scenario. The windows are of similar age and are expected to be replaced within the near future. Therefore, the reference scenario includes a new set of windows with the same thermal properties as the existing ones.

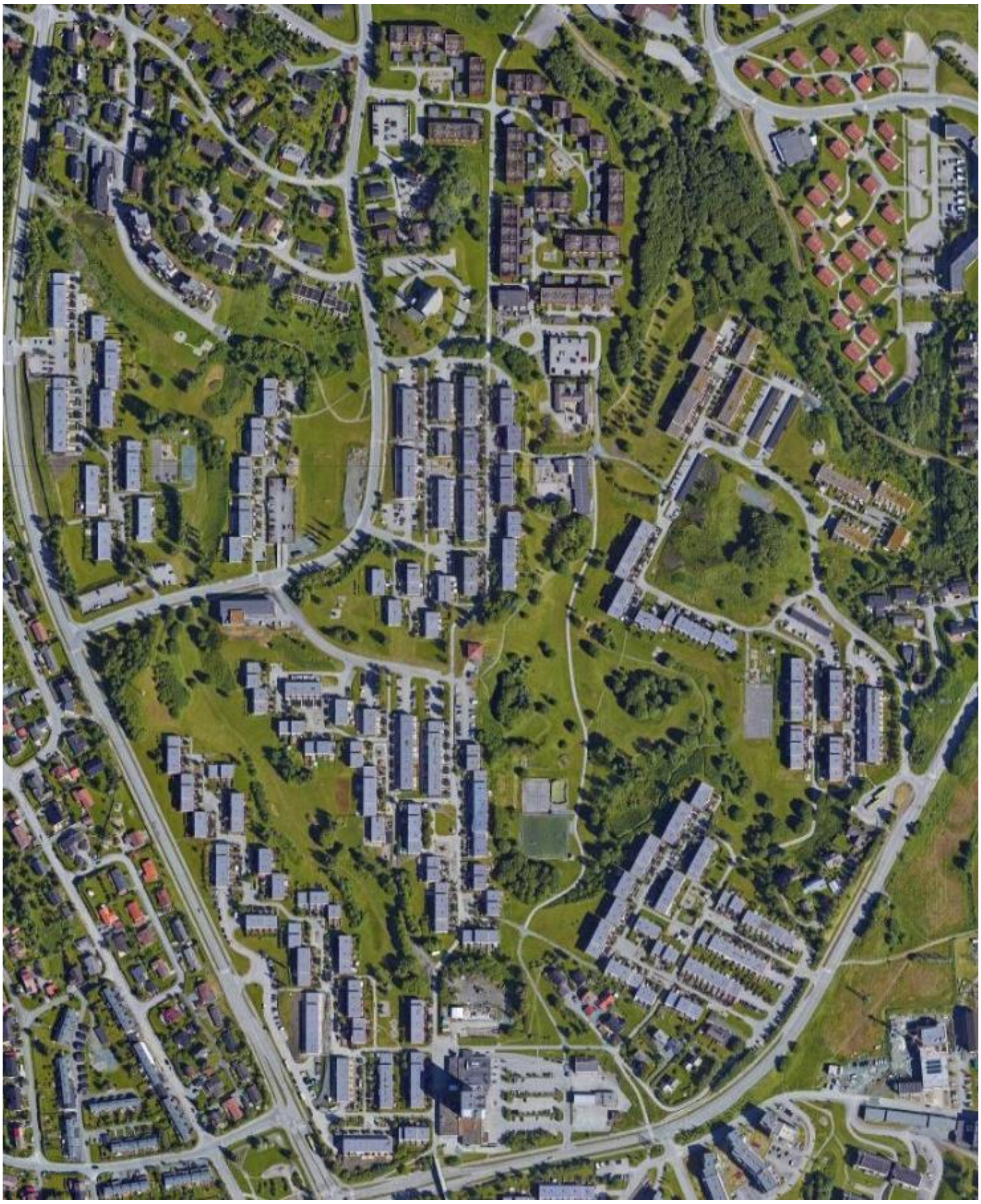

Figure 33: Aerial view of the Case Study in Norway (from "Google Maps" by Google n.d. Copyright by Google).

Table 17: General information about the district.

Parameter	Explanation/definition
Location	Trondheim
Latitude	63.4
Longitude	10.4
Climate zone	Dfc (Subarctic climate)
Number of buildings in total	34

The heat is supplied through a district heating system. The district heating is distributed from a primary substation (P-sub) to 20 secondary substations (S-sub) through three main distribution lines. At the S-subs, the heat is split into separate circuits for space heating (SH) and domestic hot water (DHW).

The heat supply system, from the P-sub to the radiators requires renovation, and the estimated costs of this are included in the relevant scenarios.

For this case study, it was decided to study one of the three branches from the P-sub. This branch supplies 30490 m^2 gross heated floor area (GHFA), about 30% of the total GHFA of the neighbourhood. It consists of 6 S-subs, 35 buildings, and a total of 351 apartments.

Table 18: Building typologies of the Norwegian Case Study.

Parameter	Unit	Building typology 1	Building typology 2	Building typology 3	Building typology 4
Building information					
Number of buildings per typology		14	9	7	5
Construction period		1970s	1970s	1970s	1970s
Geometry					
Gross heated floor area (GHFA)	m^2	440-960	1000-1580	320-840	1000-1620
Heated volume	m^3	1100-2400	2400-3950	800-2100	2500-4050
Façade area incl. window area	m^2	1860-4060	4050-6470	1380-3460	4100-6630
Roof area if flat roof	m^2	220-380	380-640	160-320	500-660
Area of windows to North	m^2	0	0	7-68	110-180
Area of windows to East	m^2	14-105	68-170	0	0
Area of windows to South	m^2	0	0	8-52	65-104
Area of windows to West	m^2	21-123	100-175	0	0
Number of floors above ground	-	2-3	2-3	2-3	2-3
Usage					
Type of use		Residential	Residential	Residential	Residential
Area per occupant[1]	m^2 / person	40	40	40	40

Parameter	Unit	Building typology 1	Building typology 2	Building typology 3	Building typology 4
Typical indoor temperature (for calculations)	°C	21	21	21	21
Average electricity consumption per year and m[2] (excluding heating, cooling, ventilation)	kWh/(m².a)	50	50	50	50
		HVAC systems			
Type of existing heating system		District heating	District heating	District heating	District heating
Existing energy carrier		District heating	District heating	District heating	District heating
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No	No
Is the cooling system installed?	Yes/No	No	No	No	No
Hot water consumption[2]	l/person/day	56	56	56	56

[1] Average for the whole district

[2] Calculated from energy demand. Assumed 60°C outlet temperature.

3.4.2 Calculation parameters and scenarios

Table 19: General parameters for the calculations of the Norwegian Case Study.

Parameter	Explanation/definition
Date the calculations were made	2020
Weather file used	NOR_TD_Trondheim-Voll.012570_TMYx.2003-2017
External shading (by surrounding buildings) considered	No

A total of five different energy efficiency measures on the building envelope are evaluated, as shown in the next table.

Table 20: Name and description of renovation measures on the building envelope.

Name	Description
F1	Add additional 10 cm insulation of façades. Reduces U-value from 0.27 to 0.18 W/m^2K
R1	Add additional 5 cm insulation of roof. Reduces U-value from 0.18 to 0.05 W/m^2K
W0	Replace existing windows with new windows with the same thermal properties (1.6 W/m^2K)
W1	Install new windows with a U-value of 1.2 W/m^2K instead of the existing 1.6 W/m^2K
W2	Install new windows with a U-value of 0.8 W/m^2K instead of the existing 1.6 W/m^2K
V1	Install heat recovery ventilation with a thermal efficiency of 85%

The energy efficiency measures are composed of five different renovation scenarios, in addition to the reference scenario. These are denoted Scenario 1-5 in the table below.

Table 21: Investigated scenarios including measures on the building envelope.

Scenario	Energy efficiency measures
Reference	W0
Scenario 1	W1
Scenario 2	W2
Scenario 3	F1+R1+W1
Scenario 4	F1+R1+W2
Scenario 5	F1+R1+W2+V1

Table 22: Measures on the building envelope.

Parameter	Unit	Ref	1	2	3	4	5
			Walls				
U-values	W/m^2K	0.27	0.27	0.27	0.18	0.18	0.18
Investment costs	$EUR/m^2_{building\ element}$	-	-	-	180	180	180
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	-	-	0	0	0
Service life	years	-	-	-	60	60	60
			Roofs				
U-values	W/m^2K	0.18	0.18	0.18	0.05	0.05	0.05
Investment costs	$EUR/m^2_{building\ element}$	0	-	-	130	130	130
Maintenance costs	$EUR/m^2_{building\ element}.year$	0	-	-	0	0	0
Service life	years	-	-	-	60	60	60
			Windows				
U-values	W/m^2K	1.6	1.2	0.8	0.8	0.8	0.8

Investment costs	EUR/$m^2_{\text{building element}}$	1070	1090	1130	1130	1130	1130
Maintenance costs	EUR/$m^2_{\text{building element}}$.year	0	0	0	0	0	0
Service life	years	30	30	30	30	30	30
		Ventilation system					
Investment costs	EUR/$m^2_{\text{building element}}$	-	-	-	-	-	80
Maintenance costs	EUR/$m^2_{\text{building element}}$.year	-	-	-	-	-	0
Service life	years	-	-	-	-	-	30

Five different heat supply systems are considered. They are split into three main heat distribution concepts: central distribution (cen), decentral waterborne distribution (wb), and point source (ps).

The central distribution concept (cen) is based on the utilization of the district heating network already in place, with a central heat production/distribution from the existing P-sub. Two heat production systems are considered for this option: renovation of the existing DH substation or installation of a ground source heat pump system (GSHP). The cases with centralised distribution systems ("cen") have an additional maintenance cost of 72000 €/year, which covers the renovation of the central heat distribution system.

The decentral waterborne distribution (wb) concept is based on the installation of new heat production units at the location of the existing S-subs, discarding the P-sub and the distribution system between the P-sub and the S-subs. GSHP and air source heat pump (ASHP) systems are considered for this option. For both "cen" and "wb" options, the system includes hot water tanks (HWT) for energy storage. There are no HWTs present in the current system. The "cen" and "wb" scenarios also need to invest in a renovation of the existing hydronic heating (HY) systems inside the buildings. All heat pump systems are designed with the heat pump as a base load unit and an electric boiler (EB) as backup and peak load. To ensure full backup from the EB, the capacity is forced to be equal to the peak demand.

The point source (ps) concept is based on the individual heat supply to each apartment. This requires the installation of individual hot water boilers for DHW production (EB DHW) and electric resistance heaters (ERH).

All the different heat supply systems are coupled with all the energy efficiency measure scenarios, yielding a total of 25 cases.

In addition, all cases are modelled with and without a solar PV system. An evaluation of the performance of a PV system for this neighbourhood was performed by Sorensen et al.(2019). The hourly production profile from this study is used as input to the system optimization tool. As investment in solar PV is not cost-effective under the predefined conditions, the model is forced to invest in a fixed-size PV system. Based on the result, a total system size of 600 kWp (4080 m²) is used.

The table below gives some data on the evaluated heating systems. The capacity and cost data are a result of investment optimization. In the model, the investment and maintenance costs are given as both fixed and capacity-dependent cost parameters, and the resulting costs are shown below. Data are given for the cases without PV. There is some small difference in the installed capacity of heat pumps for cases with and without PV.

Table 23: Measures of the HVAC system including renewable energy generation on-site.

Parameter	Unit	1	2	3	4	5
Central district heating (cen_DH)						
Capacity	kW	1444	1373	1392	1321	975
Investment costs	EUR/kW	2934	3061	3025	3161	4105
Maintenance costs	EUR/year	79271	78914	79011	78656	76925
Service life	Years	30	30	30	30	30
Central GSHP (cen_GSHP)						
Capacity	kW	1444	1373	1392	1321	975
Investment costs	EUR/kW	2953	3064	3027	3146	4047
Maintenance costs	EUR/year	87078	85912	86076	84934	80720
Service life	Years	20	20	20	20	20
Decentral GSHP (wb_GSHP)						
Capacity	kW	1382	1314	1314	1264	933
Investment costs	EUR/kW	3243	3358	3368	3446	4294
Maintenance costs	EUR/year	19422	18031	18300	16921	9920
Service life	Years	20	20	20	20	20
Central ASHP (wb_ASHP)						
Capacity	kW	1382	1314	1314	1264	933
Investment costs	EUR/kW	2990	3114	3121	3213	4165
Maintenance costs	EUR/year	12428	11623	11797	11037	7513
Service life	Years	20	20	20	20	20
Individual (ps)						
Capacity	kW	1382	1314	1332	1264	933
Investment costs	EUR/kW	1652	1738	1714	1806	2447
Maintenance costs	EUR/year	24574	24574	24574	24574	24574
Service life	Years	20	20	20	20	20
PV system						
Size	kWp	600	600	600	600	600
Investment costs	EUR/kWp	25	25	25	25	25

3.4.3 Case study results

The following graphs give an overview of the results obtained:

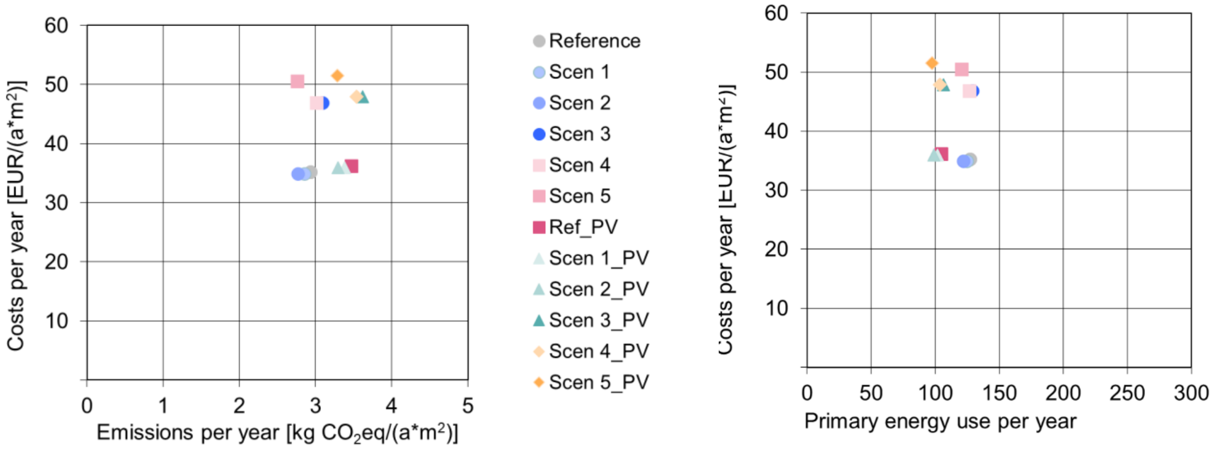

Figure 34: Reference heating system (centralised district heating).

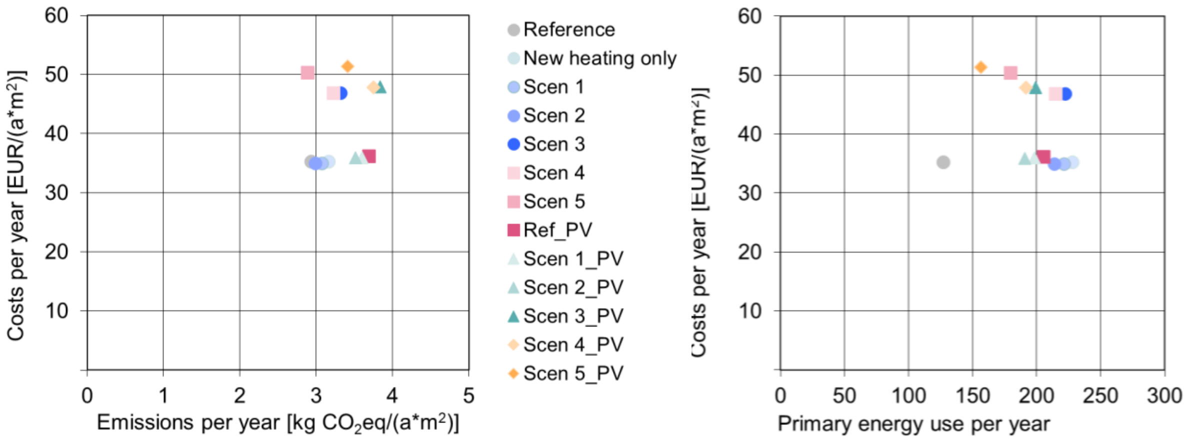

Figure 35: Heating system 2 – Centralised Ground Source Heat Pump.

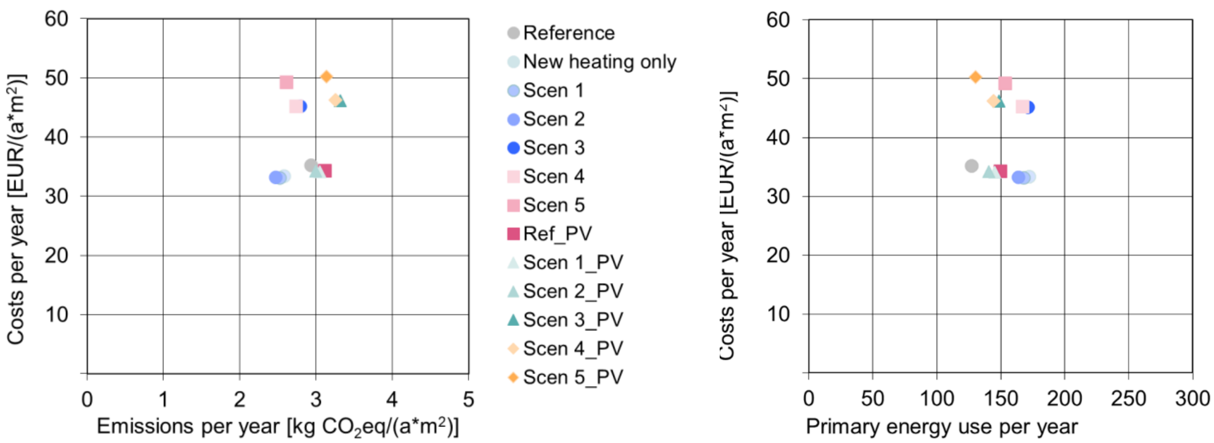

Figure 36: Heating system 3 – Decentralised Ground Source Heat Pump.

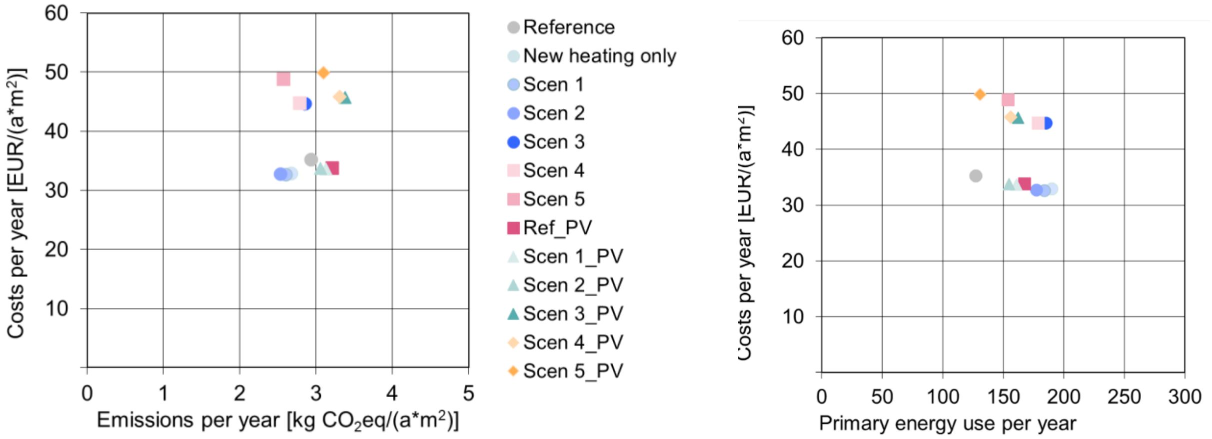

Figure 37: Heating system 4 – Decentralised Air Source Heat Pump.

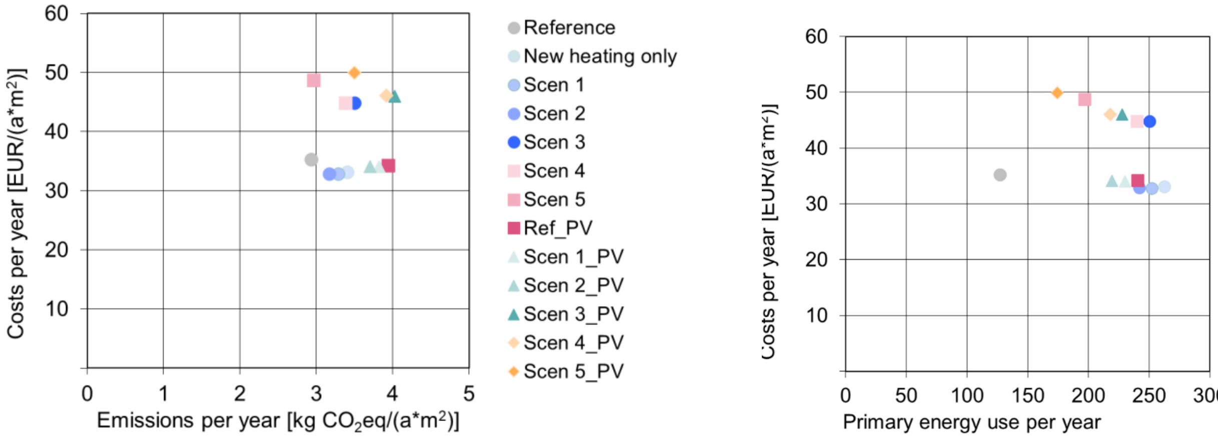

Figure 38: Heating system 5 – Point Source.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

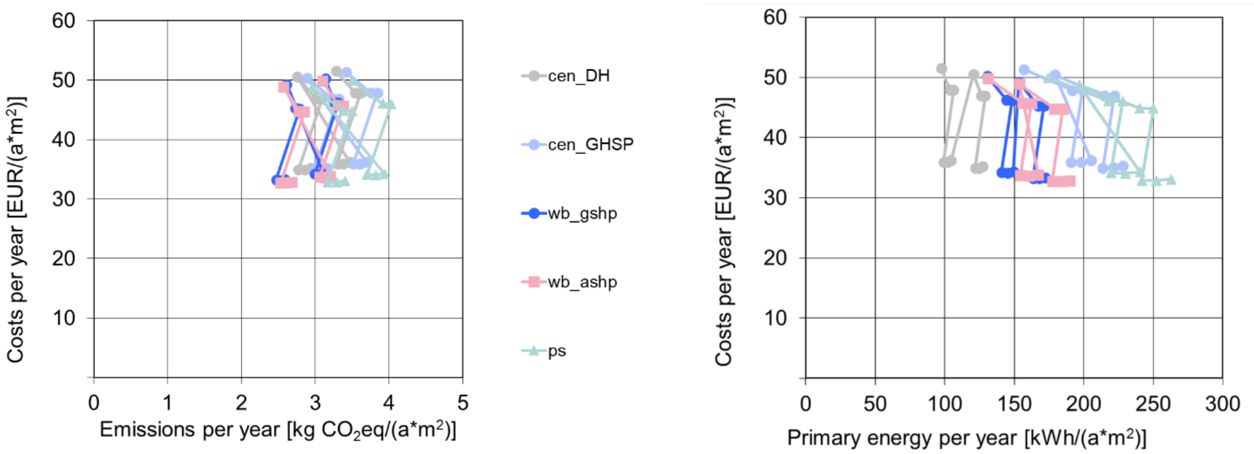

Figure 39: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

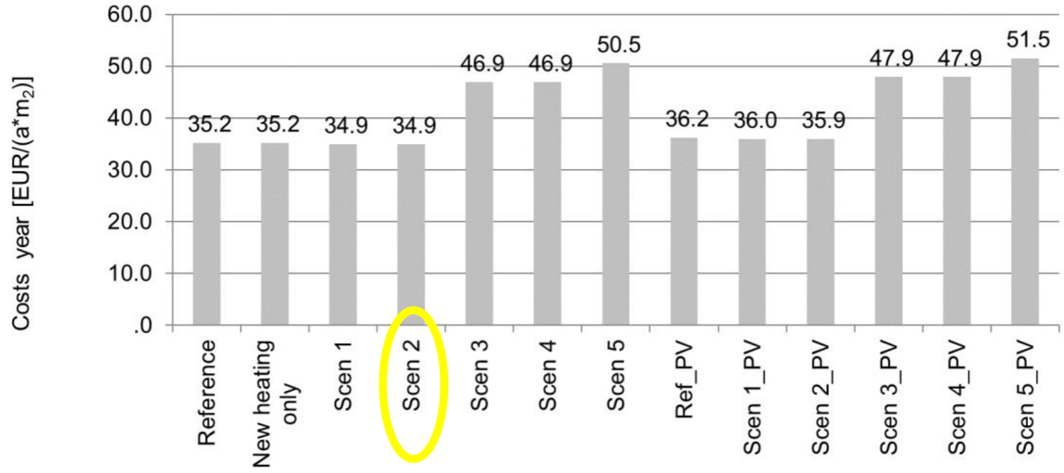

Figure 40: Reference heating system (centralised district heating).

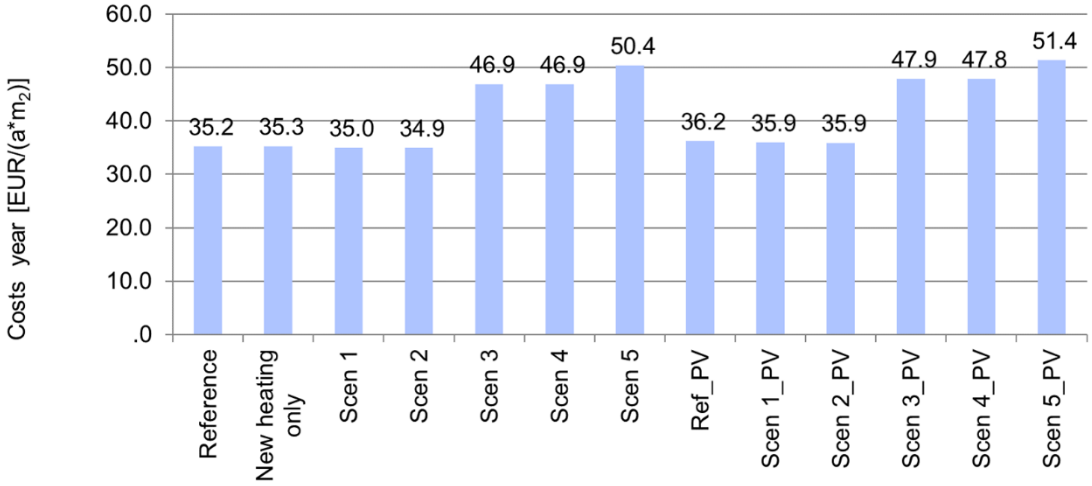

Figure 41: Heating system 2 – Centralised Ground Source Heat Pump.

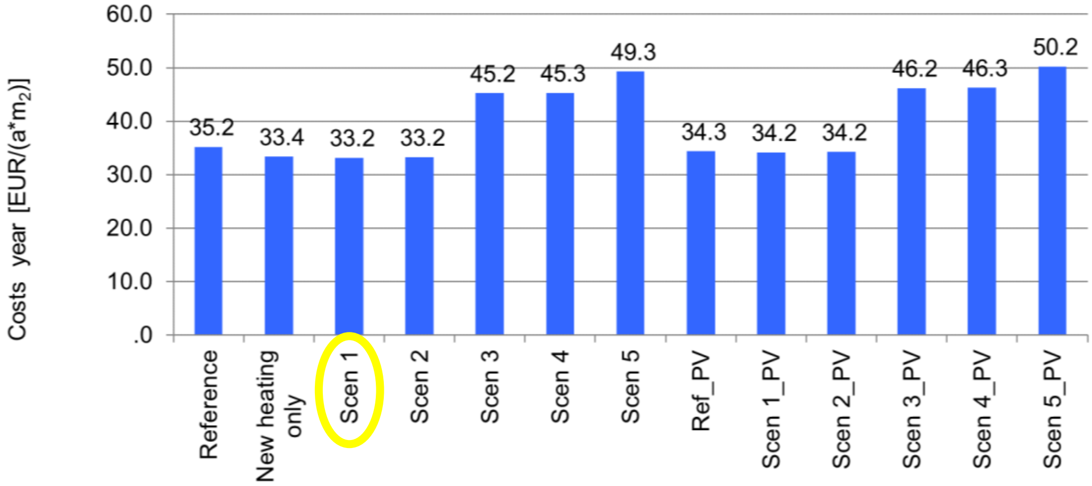

Figure 42: Heating system 3 – Decentralised Ground Source Heat Pump.

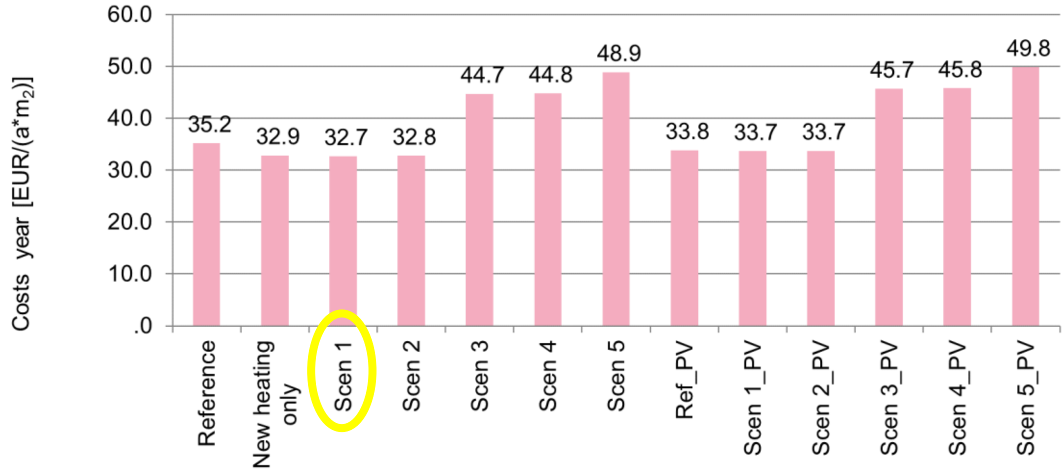

Figure 43: Heating system 4 – Decentralised Air Source Heat Pump.

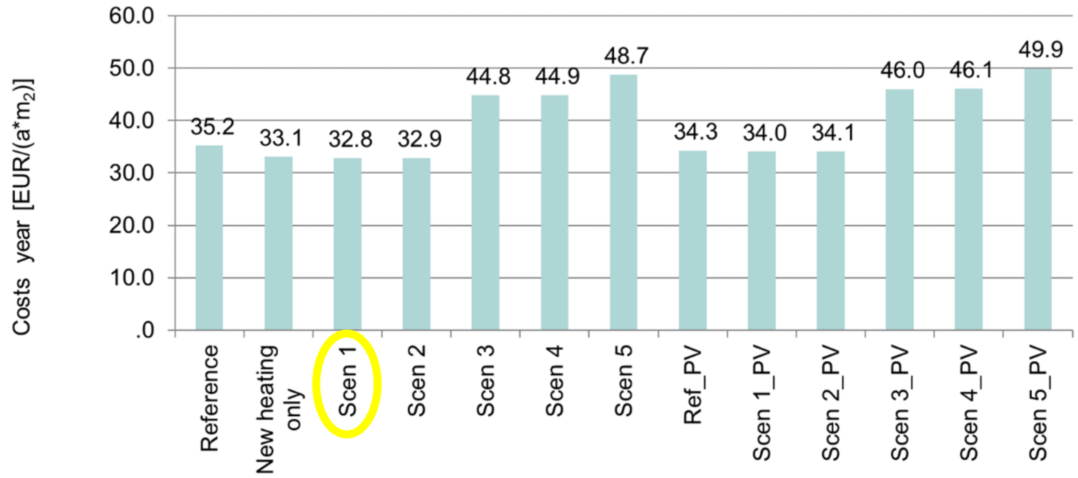

Figure 44: Heating system 5 – Point Source.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

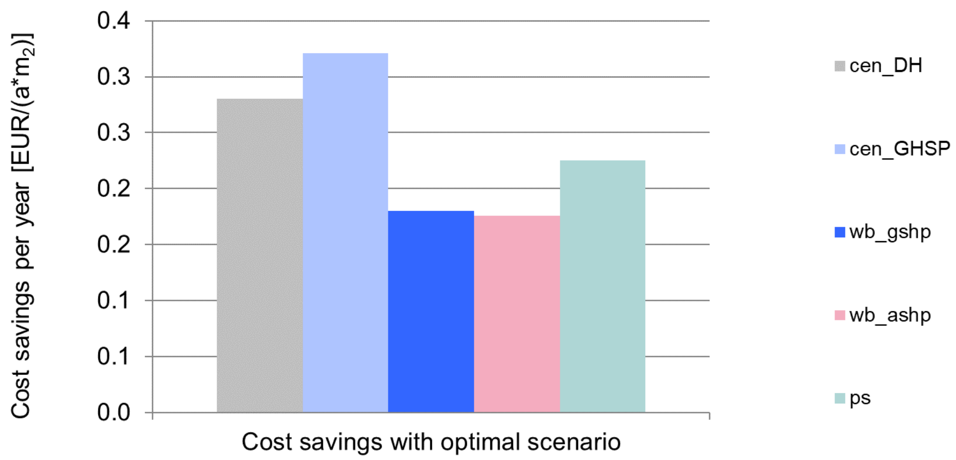

Figure 45: Cost saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized:

There are only minor effects of the choice of energy supply system on the cost-effectiveness of the energy efficiency measures. The case with the best windows is the most cost-effective for the centralised solution, while for the decentralised and point source solutions, the medium solution is the most cost-effective. Still, the difference is very small and within the uncertainty of the calculations. The rest of the energy efficiency measures have too high investment costs to be cost-effective. The decentralised heat pump solutions are the most cost-efficient for heating systems. These solutions also have the lowest carbon emissions from an LCC perspective. The district heating solutions have the lowest primary energy consumption. From an LCC perspective, the installation of PV does not make sense in these calculations, as the LCC emissions per kWh produced energy is higher than the emission factor for the electric grid.

In addition, the following results were found in this case study:

As demanded by the Norwegian standard for LCC calculations (NS3720), the calculations have also been performed with a carbon emissions factor for electricity aiming to represent an average for the European market (EU28) in the next 60 years (123 g/kWh). With this factor, the solutions with district heating have the lowest emissions. Also, the cases with PV have lower emissions than those without.

3.4.4 Discussion

What stands out when interpreting the results?

The main outcome is that the only energy efficiency measures that are cost-efficient are those that are related to an anyway renovation, meaning that there are related costs also in the reference case. An effect of the low emission factor for the energy supply systems is that the cases with added insulation have a higher yearly emission factor, due to the embodied emissions. Both these results highlight the need for coordination between renovation measures and energy efficiency measures during the lifetime of the buildings. Also, the fact that the insulation level of the existing buildings is already decent, affects the cost-efficiency of the energy efficiency measures.

What are the most cost-effective solutions?

The most cost-effective solution is installing new windows and switching to a decentralised heat pump system. The ASHP solution is slightly more cost-efficient than the GSHP solution.

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

There are large uncertainties related to the assumptions, especially the cost of the energy efficiency measures. These are based on generic data and are not linked to the actual neighbourhood. Also, the cost connected to the renovation of the existing piping system is very uncertain.

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Yes
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.»	Not investigated
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.»	Not investigated
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 energy.»	Not investigated
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.»	Not investigated
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.»	Not investigated
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.»	Not investigated
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.»	Not investigated

3.5 Portugal

3.5.1 Description of the district

In Portugal, most social housing neighbourhoods were built after 1986 and significantly promoted after 1993, with the implementation of PER (Special Resettlement Program). This is also when cooperative housing and municipal housing emerged. However, in most of these neighbourhoods, affordability and reduced costs were prioritized over quality and energy efficiency criteria, often leading to inadequate and even unhealthy indoor thermal comfort conditions and several building pathologies.

Table 24: General information about the district.

Parameter	Explanation/definition
Location	Braga, Portugal
Latitude	41.5518
Longitude	-8.4229
Climate zone	Csb (Warm-summer Mediterranean climate)
Number of buildings in total	7 buildings comprising 50 residential units

Built in the 1990s, the Picoto neighbourhood is representative of the social housing context in Portugal in terms of low-quality construction, poor energy performance, and inadequate thermal comfort conditions. Picoto neighbourhood is 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 is composed of seven buildings comprising 50 residential units. The mix of 25 2-bedroom (T2) and 25 3-bedroom (T3) units is arranged as follows: buildings A1 to A5 comprise three T2 (52 m^2 and three T3 (63 m^2) residential units each, while buildings B1 and B2 comprise five T2 (56 m^2) and five T3 (66 m^2) residential units each. These buildings have two predominant orientations – North/South and East/West – and a total heated area of 1.767 m^2.

As for the constructive characteristics, building envelopes comprise two types of façades in each building. The main façades are made of façade type 1 (F1), composed of two layers of hollow bricks (9 cm + 9 cm) without insulation (U-value of 1.1 W/m^2K). The smaller façades are constituted by façade type 2 (F2), which is composed of concrete blocks with a U-value of 1.9 W/m^2K. The sloping roof is constituted by asbestos cement undulating panels (U-Value of 3.8 W/m^2K), and single-glazed aluminium windows with a U-value of 5.70 W/m^2K were used. Individual electric heaters provide space heating and a gas boiler in each residential unit supplies DHW. These are the most common solutions found in this social context in Portugal, a country characterised by the absence of district heating. Further information can be found in (Terés-Zubiaga et al., 2020).

Figure 46: Aerial view of the Case Study in Portugal (from "Google Earth" by Google n.d. Copyright by Google).

Table 25: Building typologies of the Portuguese Case Study.

Parameter	Unit	Building typology 1 (A1 to A5)	Building typology 2 (B1 and B2)
Building information			
Number of buildings per typology		5	2
Construction period		1990's	1990's
Geometry			
Gross heated floor area (GHFA)	m^2	1059.10	707.96
Heated volume	m^3	5426.18	3851.26
Façade area incl. window area	m^2	3903.37	2377.18
Roof area if flat roof	m^2	-	-
Roof area if a pitched roof	m^2	996.25	667.66
Is the room below the roof heated or not?	Yes/No	No	No
Area of windows to North	m^2	29.16	-
Area of windows to East	m^2	6.00	20.00
Area of windows to South	m^2	29.16	-
Area of windows to West	m^2	8.58	28.62
Area of basement ceiling[2]	m^2	851.55	655.06
Number of floors above ground	-	2	2

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

Parameter	Unit	Building typology 1 (A1 to A5)	Building typology 2 (B1 and B2)
Usage			
Type of use		Residential	Residential
Area per occupant	m² / person	30	30
Typical indoor temperature (for calculations)	°C	18 (heating season) | 25 (cooling season)	18 (heating season) | 25 (cooling season)
Average electricity consumption per year and m² (excluding heating, cooling, ventilation)[3]	kWh/(m².a)	144.49	57.82
HVAC systems			
Type of existing heating system (boiler, heat pump, etc.)		Individual electric heaters and DHW gas boilers	Individual electric heaters and DHW gas boilers
Existing energy carrier (Gas, Electricity, etc.)		Electricity and Gas	Electricity and Gas
Is a ventilation system without heat recovery installed?	Yes/No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No
Ventilation rate[4]	ach	1.5 (infiltration) | 2.5 (summer natural night ventilation)	1.5 (infiltration) | 2.5 (summer natural night ventilation)
Is a cooling system installed?	Yes/No	No	No
Hot water consumption	l/person/day	40	40

3.5.2 Calculation parameters and scenarios

Table 26: General parameters for the calculations of the Portuguese Case Study

Parameters	Explanation/description
Date the calculations were made	2019
Weather file used	PRT_Porto.085450_IWEC.epw
External shading (by surrounding buildings) considered	Yes

Four types of building envelope measures were chosen for the Picoto neighbourhood:

- Improvement of the building envelope by façade insulation.
- Improvement of the building envelope by roof insulation.
- Replacement of windows with double-glazing (plain glass in M1-M4 and low emissivity glazing in M5).
- Reduction of thermal bridges.

[3] Estimated value calculated in the building simulation.
[4] Estimated values, adopted in the building simulation.

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. An initial assessment of the reference case scenario (anyway measures) and the 15 proposed renovation measures was conducted, and the best-performing ones were combined into 5 renovation packages that represent common practices in Portugal and this social housing context. Even so, more efficient renovation measures can be further explored, especially if considering contexts other than social housing.

The selected renovation packages for this case study are shown below and were implemented in all buildings.

Table 27: Renovation packages (scenarios M) for the improvement of the building envelope.

	Façade	Roof	Windows
M1	ETICS MW 80mm (F1* and F2**)	Sandwich panel PUR 30mm	PVC frame with double low emissivity glazing (U=1.40 W/m^{2}K) with solar protection (g=0.20)
M2	ETICS EPS 80mm (F1* and F2**)	Sandwich panel MW 30mm	Aluminium frame with double glazing (U=3.30 W/m^{2}K and g=0.76)
M3	ETICS EPS 80mm (F1* and F2**)	Sandwich panel PUR 30mm	Aluminium frame with double glazing (U=3.30 W/m^{2}K and g=0.76)
M4	ETICS EPS 80mm (F1*); ETICS EPS 120mm (F2**)	Sandwich panel MW 100mm	Aluminium frame with double glazing (U=3.30 W/m^{2}K and g=0.76)
M5	ETICS MW 160mm (F1*); ETICS MW 200mm (F2**)	Sandwich panel MW 100mm	PVC frame with double low emissivity glazing (U=1.40 W/m^{2}K) and solar protection (g=0.20)

ETICS | External Thermal Insulation Composite System; EPS | Expanded Polystyrene; MW | Mineral Wool; PUR | Polyurethane Foam; PVC | Polyvinyl Chloride; F1* | Façade type 1; F2** | Façade type 2

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

- Investment and maintenance costs were calculated with the aid of the 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 F2, 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 Case (Anyway Measures) since in the latter the application of maintenance measures is limited to where it is needed.
- The 30 years of cost-optimal analysis was adopted in compliance with Commission Delegated Regulation (EU) nº 244/2012 of 16 January 2012.

Table 28: Measures on the building envelope.

Parameter	Unit	Ref	1	2	3	4	5
			Walls				
U-values	W/m²K	Façade type F1* | 1.1	0.34	0.35	0.35	0.35	0.19
		Façade type F2* | 1.9	0.39	0.41	0.41	0.29	0.17
Investment costs	EUR/$m^2_{building\ element}$	55.93	103.55	90.34	90.34	91.39	140.75
Maintenance costs	EUR/$m^2_{building\ element}$.year	1.90	0.26	0.26	0.26	0.26	0.26
Service life	years	-	30	30	30	30	30
			Roofs				
U-values	W/m²K	3.80	0.90	1.30	0.90	0.39	0.39
Investment costs	EUR/$m^2_{building\ element}$	57.77	50.76	64.14	50.76	81.71	81.71
Maintenance costs	EUR/$m^2_{building\ element}$.year	0.30	0.02	0.26	0.02	0.26	0.26
Service life	years	-	30	30	30	30	30
			Windows				
U-values	W/m²K	5.7	1.4	3.3	3.3	3.3	1.4
Investment costs	EUR/$m^2_{building\ element}$	460.98	674.70	567.36	567.36	567.36	674.70
Maintenance costs	EUR/$m^2_{building\ element}$.year	3.90	3.65	4.86	4.86	4.86	3.65
Service life	years	-	30	30	30	30	30

After choosing the renovation packages, five energy supply systems (ESS) were selected and dimensioned to meet the neighbourhood energy needs for space conditioning (heating and cooling) and DHW.

ESS1 is representative of the typical solutions adopted in Portuguese housing (individual space conditioning and DHW equipment supplied by decentralised energy sources, as the presence of district systems in the country, is still very incipient).

All the other systems are centralised options, chosen to evaluate their viability in the Portuguese context. ESS3, the biomass boiler solution, does not consider cooling energy needs (suitable solution under Portuguese thermal regulation because, especially due to the high ventilation rates in this building typology, the risk of overheating is minimized for Braga climate and can be disregarded for the energy performance calculation). Heat pump systems were selected for the other three energy supply systems, either alone, as in ESS2, or complemented by other systems: in ESS4, a solar thermal system provides DHW and, in ESS5, a photovoltaic system was designed to supply the total energy needs, aiming at reaching a zero-energy neighbourhood.

Solar thermal panels have become a recurrent solution with the advent of new thermal regulations and subsidies in Portugal, especially due to the local availability of solar radiation and affordable prices. For ESS4, it would be necessary with approximately 150 m^2 of solar panels. For ESS5, 670 m^2 of crystalline silicon photovoltaic panels supported by battery storage would be needed. It is noteworthy, however, that this study focused on the cost-benefit of the system, disregarding space limitations.

Table 29: Overview of the investigated energy supply scenarios.

		Heating	Cooling	DHW	RES
ESS1	Decentral-ised Con-ventional	Electric Heater h=1	Multi-split EER=3	Natural Gas Heater H=0.71	-
ESS2	Centralised Heat Pump	Heat Pump COP/SCOP=4.06/3.77	Heat Pump COP/SCOP=3.97/8.41	Heat Pump COP=4.10	-
ESS3	Centralised Biomass Boiler	Biomass Boiler h=1.07	Not applicable	Biomass Boiler h=1.07	-
ESS4	Centralised Heat Pump + ST	Heat Pump COP/SCOP=4.06/3.77	Heat Pump COP/SCOP=3.97/8.41	Heat Pump COP=4.10	ST (DHW)
ESS5	Centralised Heat Pump + PV	Heat Pump COP/SCOP=4.06/3.77	Heat Pump COP/SCOP=3.97/8.41	Heat Pump COP=4.10	PV (supply the total primary energy needs)

ST | Solar Thermal; PV | Photovoltaic System

Table 30: Measures on the HVAC system including renewable energy generation on-site.

Parameter	Unit	Value
Conventional Decentralised (ESS1)		
Capacity	kW	537.50
Investment costs	EUR/kW	131.95
Maintenance costs	EUR/year	643.02
Service life	Years	15 (heater and multi-split); 20 (natural gas water heater)
Centralised Heat Pump (ESS2)		
Capacity	kW	184
Investment costs	EUR/kW	1072.29
Maintenance costs	EUR/year	238.60
Service life	Years	15 (heat pump). 20 (heat pump DHW)
Centralised Biomass Boiler (ESS3)		
Capacity	kW	180
Investment costs	EUR/kW	960.95
Maintenance costs	EUR/year	645.38
Service life	Years	15 (biomass boiler)

Parameter	Unit	Value
Centralised Heat Pump + Solar Thermal (ESS4)		
Capacity	kW	173.40
Investment costs	EUR/kW	1395.56
Maintenance costs	EUR/year	252.00
Service life	Years	15 (heat pump); 20 (heat pump DHW); 20 (solar thermal)
Centralised Heat Pump + Photovoltaic System (ESS5)		
Capacity	kW	278.50
Investment costs	EUR/kW	1150.83
Maintenance costs	EUR/year	262.48
Service life	Years	15 (heat pump); 20 (heat pump DHW); 35 (photovoltaic)

3.5.3 Case study results

The following graphs give an overview of the results obtained:

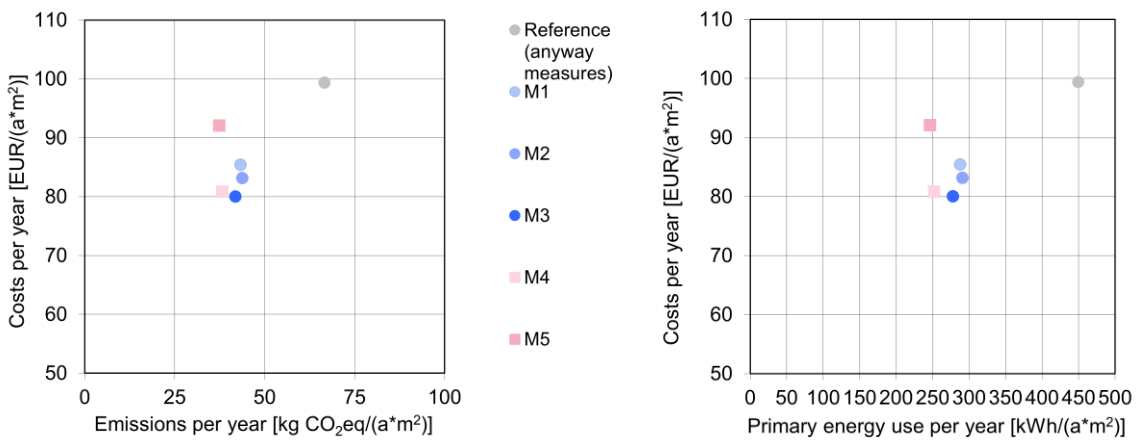

Figure 47: Reference heating system - Conventional Decentralised [ESS1].

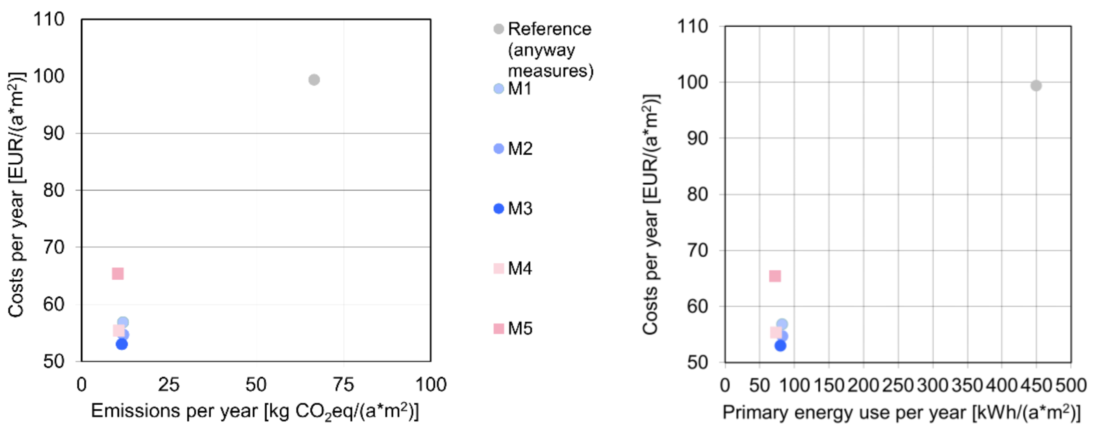

Figure 48: Heating system 2 – Centralised Heat Pump [ESS2].

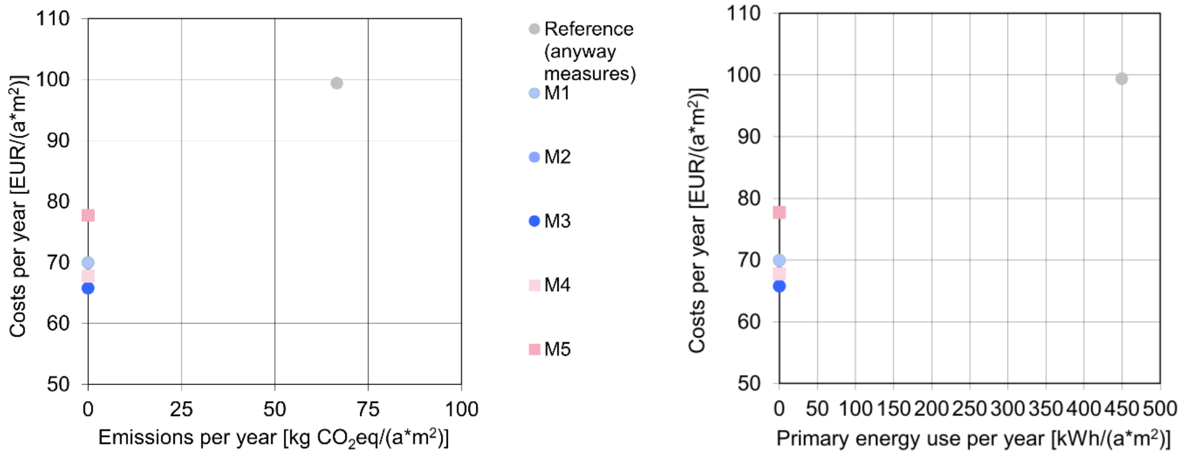

Figure 49: Heating system 3 – Centralised Biomass Boiler [ESS3].

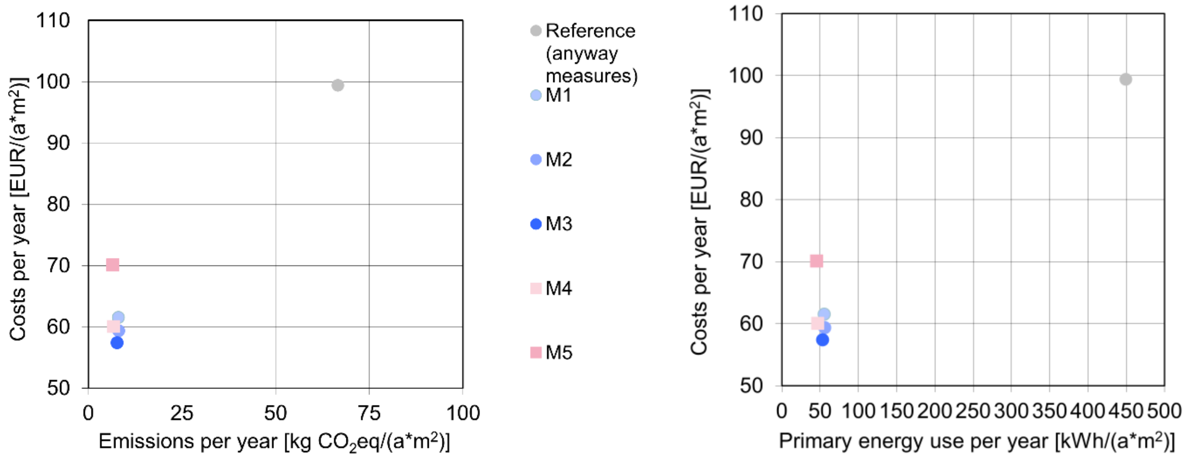

Figure 50: Heating system 4 – Centralised Heat Pump + Solar Thermal [ESS4].

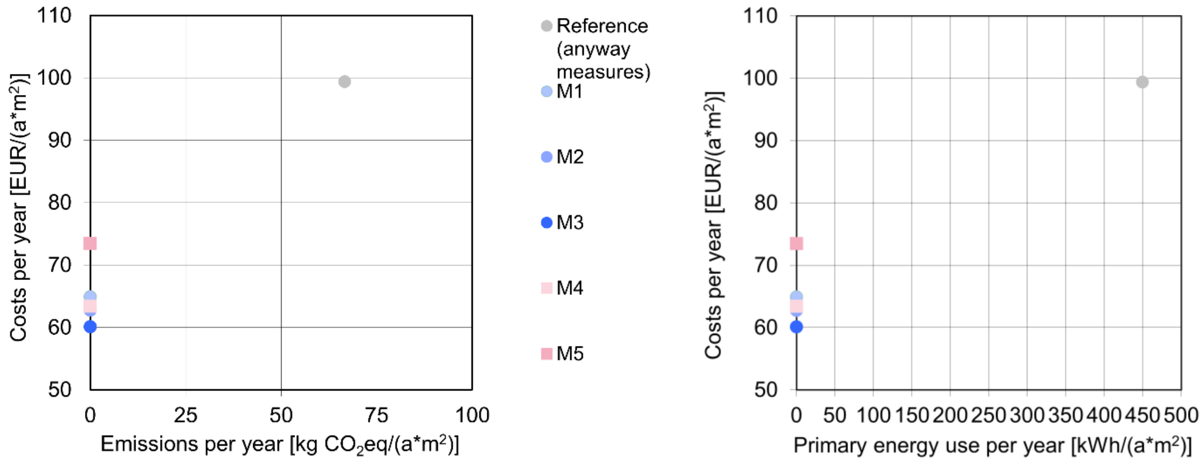

Figure 51: Heating system 5 – Centralised Heat Pump + Photovoltaic System [ESS5].

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

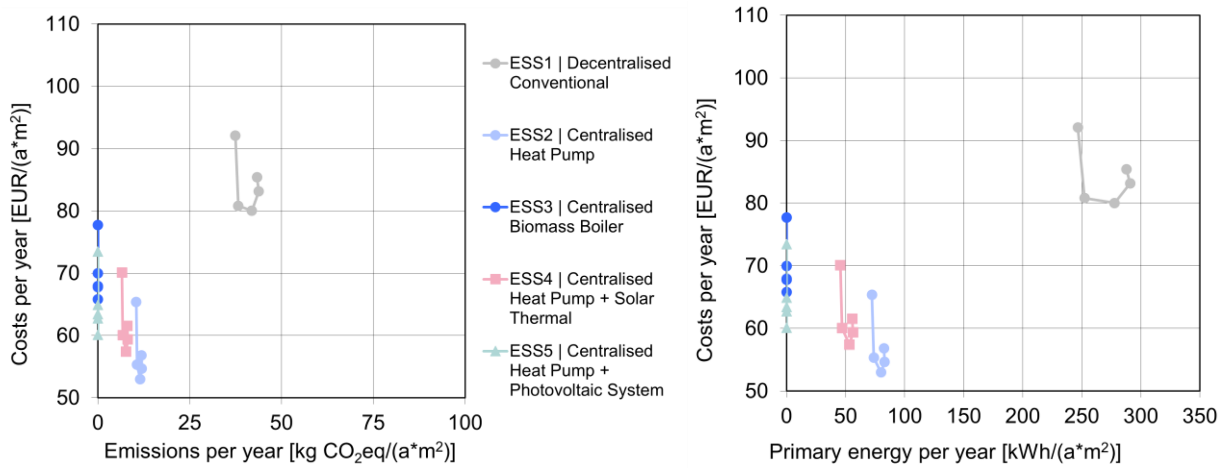

Figure 52: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

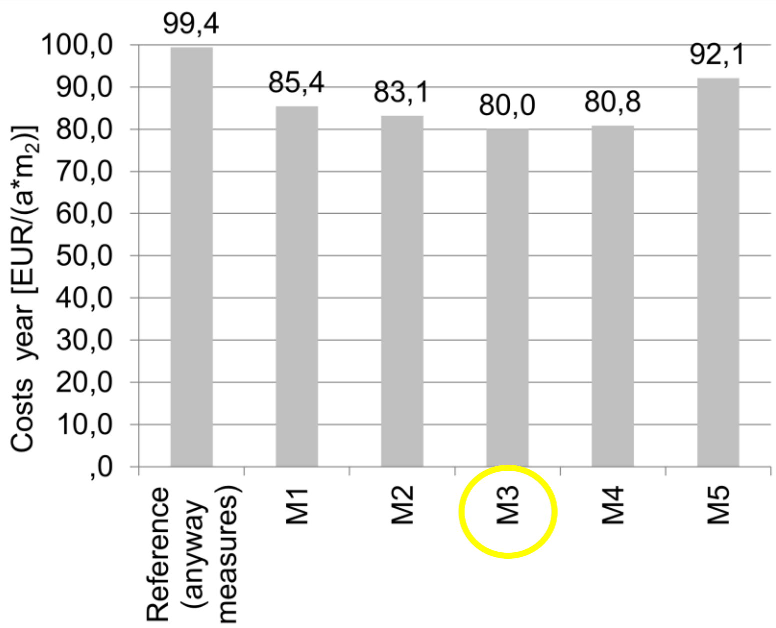

Figure 53: Reference heating system – Conventional Decentralised [ESS1].

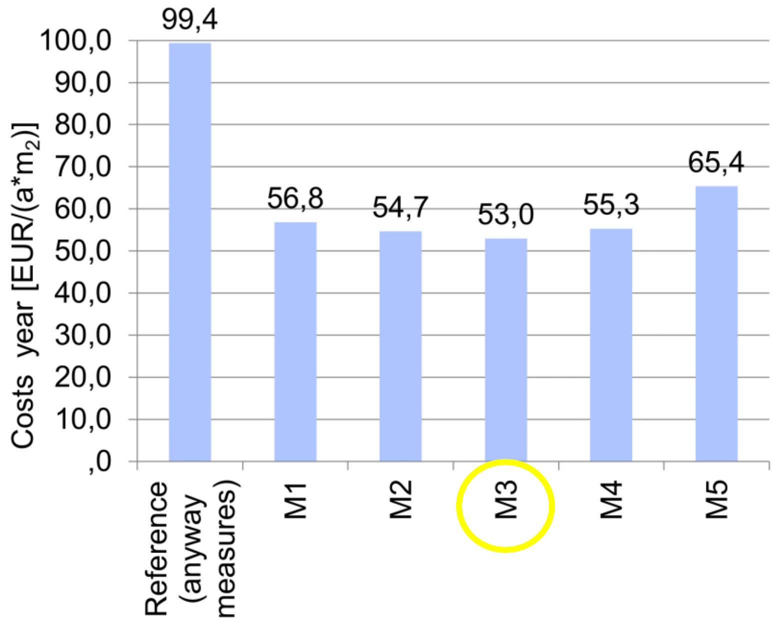

Figure 54: Heating system 2 - Centralised Heat Pump [ESS2].

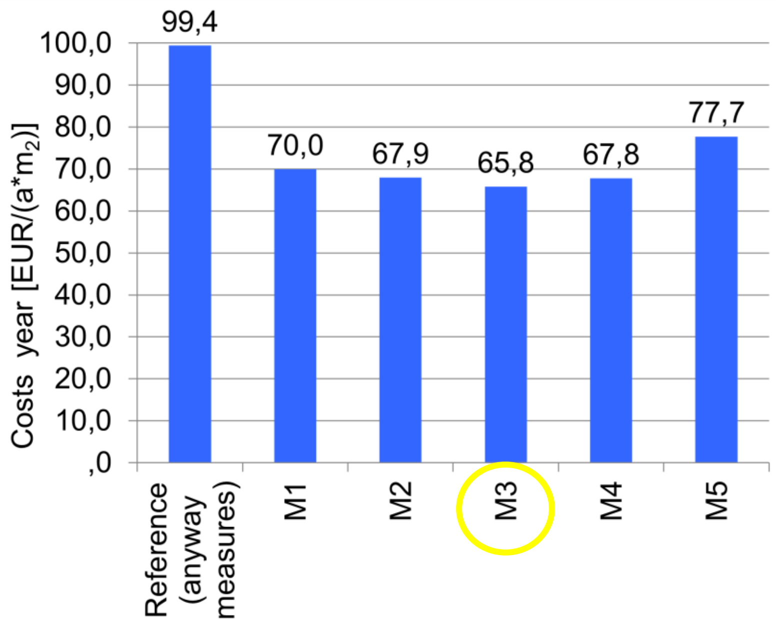

Figure 55: Heating system 3 - Centralised Biomass Boiler [ESS3].

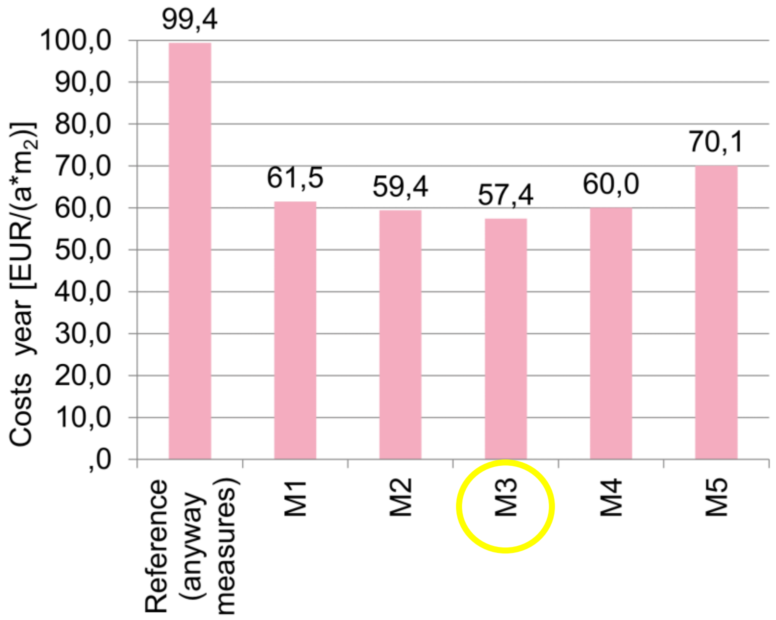

Figure 56: Heating system 4 - Centralised Heat Pump + Solar Thermal [ESS4].

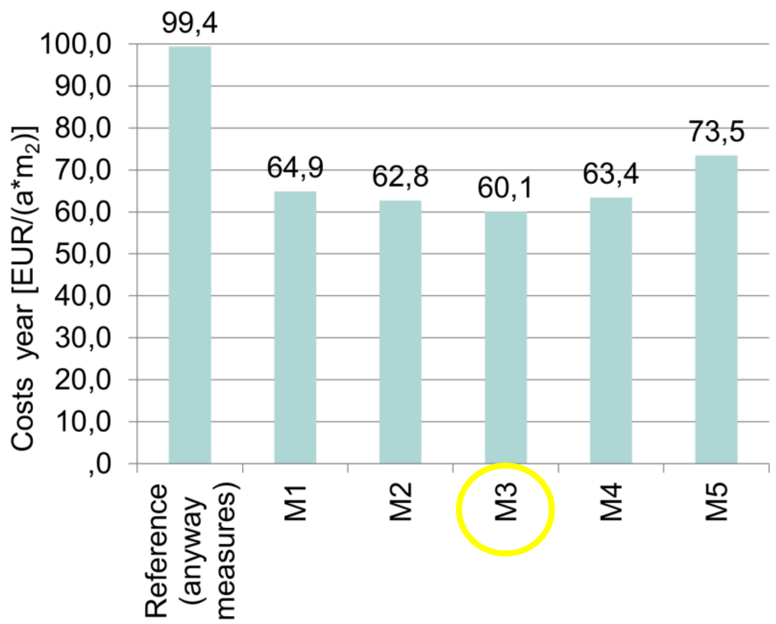

Figure 57: Heating system 5- Centralised Heat Pump + Photovoltaic System [ESS5].

The following graph 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).

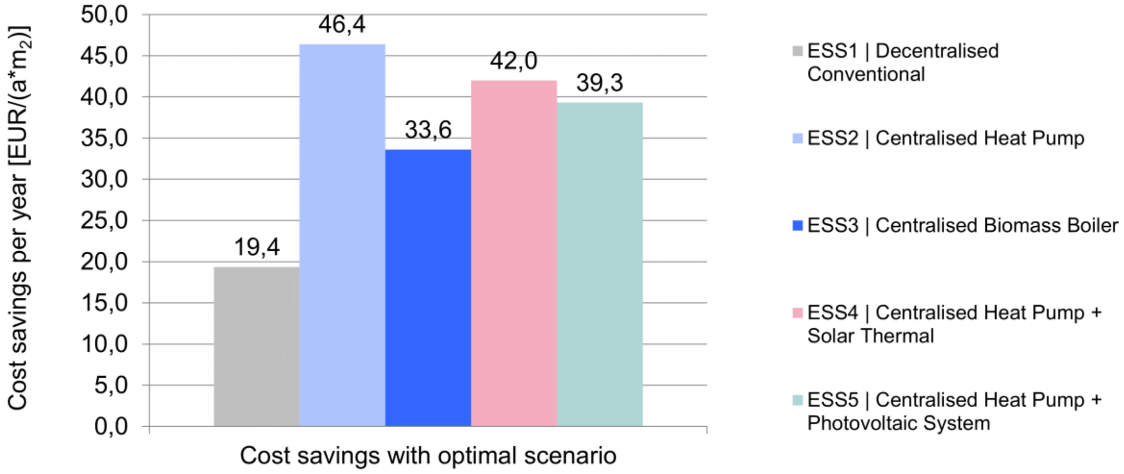

Figure 58: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized in terms of the building renovation packages.

Al the renovation packages are cost-effective when compared with the reference case, remembering that the latter is not insulated, and thus does not offer good energy performance. Remarks can be done for:

- M5 | Comprises a combination of ETICS MW 160 mm and ETICS MW200 mm for walls, sandwich panel MW 100mm for the roof, and double-low emissivity PVC frame windows with solar protection. This renovation package represents a substantial improvement in the wall thermal insulation performance. Whilst the other renovation packages (M1 to M4) lead to wall U-values around 0,3 to 0,4 W/m^{2}K, M5 reaches U-values lower than 0,20 W/m^{2}K. M5 presents the highest costs in association with each of the energy source systems considered, as would be expected, whilst its emissions and primary energy use values (although the smallest ones) do not differ so significantly from the other renovation packages if compared with the reference case. In other words, M5 is still a cost-effective solution when compared with the reference case, providing the highest reduction in emissions and primary energy use but this also implied significantly higher costs.
- M3 | For the energy supply systems investigated, M3 is the most cost-effective renovation package, followed by M2. They both comprise ETICS EPS 80 mm and double-glazed aluminium frame windows, differing only on the insulation material of the roof sandwich panel (for M2, mineral wool 30 mm and, for M3, polyurethane foam 30 mm).

In terms of energy source systems, all 5 systems selected for this study proved to be cost-effective, with savings ranging from 7% (M5, ESS1) to 47% (M3, ESS2) when compared with the reference case. It is also clear the cost gap between the centralised and the decentralised conventional system (ESS1): whilst the most cost-effective renovation package (M3) associated with ESS1 reduces the annual costs by EUR 19.4/m^2.a, the least cost-effective renovation package associated with a centralised system (M5 associated with ESS3) reduces the annual costs in EUR 21.7/m^2.a.

The centralised systems also consistently show emissions and primary energy use significantly lower than the ones from ESS1 and the reference case (anyway measures). Furthermore, this good performance is associated with reduced global costs, proving that district energy supply can be cost-effective in Portugal.

The centralised heat pump system, ESS2, shows the highest cost reductions in comparison with the reference case. Its optimal scenario, in association with M3, reaches 47% of global cost reductions.

Centralised biomass boiler (ESS3) and heat pump associated with the photovoltaic system (ESS5), although not the most cost-effective, offer better environmental performance, leading to zero emissions and zero primary energy consumption for all the renovation packages analysed.

In addition, the impact assessment of adding embodied energy to the cost-optimal analysis was also conducted for this case study. The following results were reached, based on the Life Cycle Analysis of the proposed renovation packages (M1 to M5) associated with the energy systems (ESS1 to ESS5):

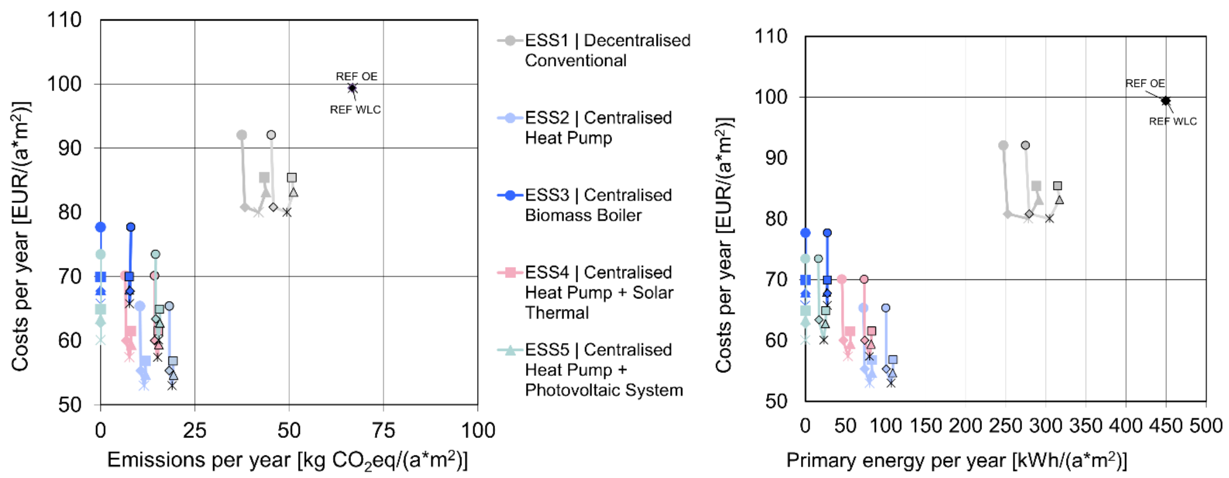

Figure 59: Combination of renovation packages on the building envelopes with the various types of heating systems.

When looking at the renovation packages before and after adding their embodied energy to the analysis, there is a shift towards higher carbon emissions and primary energy consumption, as expected. However, it is notable that there is no change in the results in terms of the hierarchy from the smallest to the largest environmental impact of each renovation package.

On the other hand, the results show that the choice of the ESS makes a difference in the environmental impacts, and this is especially noticeable for the Photovoltaic system (ESS5). In the left figure of Figure 59, ESS3 (biomass boiler) and ESS5 (heat pump associated with photovoltaic system) have zero-emission when only the operational energy is considered. When embodied energy is added to the analysis, ESS3 still offers the lowest emissions of the systems under study. ESS5, instead, moves to the second position concerning the highest emissions, very close to ESS4 (heat pump associated with solar thermal system) and below ESS2 (heat pump) only. When analysing the right figure of Figure 59, however, ESS5 is the system with the lowest primary energy needs, followed by ESS3, ESS4, and ESS2, respectively.

Nevertheless, even when embodied energy is considered, all the renovation packages associated with renewable energy systems offer substantially better environmental performance than those associated with decentralised conventional fossil fuel systems at the district level.

Moreover, conclusions from this case study also confirm and validate the two hypotheses raised in Annex 56 “Cost-Effective Energy & CO_2 Emissions Optimization in Building Renovation”[5], where the cost-optimal assessment of renovation packages was conducted at the building scale:

“The operational savings are higher than the additional embodied energy and embodied carbon emissions in any cost-effective renovation measures.

Integrating embodied energy and carbon emissions does not change the cost-effective renovation packages.” (Sébastien Lasvaux et al., 2017, p.XIV).

[5] https://www.iea-ebc.org/projects/project?AnnexID=56

3.5.4 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 lower emissions. For this case study, its cost-effectiveness was demonstrated in association with all the energy supply systems proposed, including the conventional decentralised system (ESS1). Therefore, the results of this case study suggest that centralised neighbourhood energy sources can be cost-effective in Portugal, although this is not a practice in the country.

What are the most cost-effective solutions?

In the analysis carried out in this neighbourhood, the four most cost-effective solutions are associated with heat pumps as energy source systems (ESS2). Regarding envelope renovation, the most cost-effective package is M3 (ETICS EPS 80mm on the facade, sandwich panel PUR 30mm on the roof, and double-glazed aluminium frame windows), followed by M2, M4, and M1, in this order. It must be said that in this case study, a limited number of renovation measures was chosen based on common solutions usually adopted in the social housing context. Further analysis, using more energy-efficient and diverse solutions must be done, especially if considering different contexts.

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, the difficulty to predict user behaviour and how the assumptions made in the building simulation may impact the calculated results is well known.

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Not investigated
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.»	Not investigated
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.»	Not investigated
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 energy.»	No
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.»	Not investigated

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.»	Not investigated
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.»	Yes
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.»	Not investigated

3.6 Spain

3.6.1 Description of the district

Table 31: General information about the district.

Parameter	Explanation/definition
Location	Bilbao (Otxarkoaga District)
Latitude	43.257
Longitude	-2.92
Climate zone	Cfb (Marine West Coast Climate)
Number of buildings in total	110

The case study is in the North-West of Spain, in the Basque Country. The Otxarkoaga neighbourhood is in the eastern part of the city of Bilbao (see **Figure 60**). The terrain is a steeply sloping hillside. It can be described as a climate with relatively moderate summer and winter temperatures as a reflection of the adjacent ocean. In the summer, the average maximum temperature is between 25 ºC and 26 ºC, while the average minimum in winter is between 6 ºC and 7 ºC.

Figure 60: Aerial view of the Case Study in Spain (source: based on “Google Earth” by Google n.d.).

The morphological study of buildings points out four different main construction shapes (they were described in more detail in Iturriaga et. al (2021)). As shown in **Figure 61**, the buildings are “comb” or E-shaped (E) and 15 are H-shaped (H). Buildings with different shapes (N) are non-residential buildings, and since the scope of work was directed to residential buildings with remarkably the same parameters, these non-residential buildings were excluded from evaluation. Most of the buildings in the neighbourhood have a North-West/South-East (NW/SE) and North-East/South-West (NE/SW) layout. Still, buildings with other orientations such as East-West (E/W) or North/South (N/S) exist. Most buildings were built in 1961 and have many similar constructive characteristics. This building type was already described in detail in Terés-Zubiaga et. al (2015).

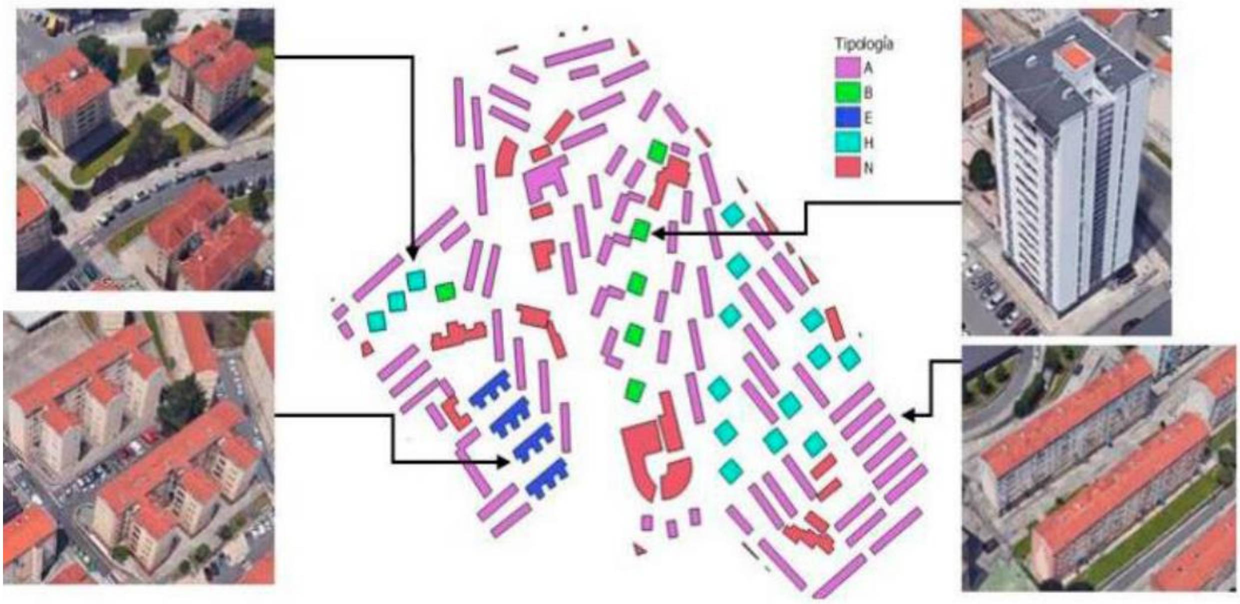

Figure 61: Overview of the different building typologies in the Spanish Case Study (source: authors, images from "Google Earth" by Google n.d.).

Table 32: Building typologies of the Spanish Case Study.

Parameter	Unit	Building typology 1 (B)	Building typology 2 (E)	Building typology 3 (H)	Building typology 4 (A1)	Building typology 5 (A2)	Building typology 6 (A3)
Building information							
Number of buildings per typology		7	4	15	4	9	71
Construction period		1959-1961	1959-1961	1959-1961	1959-1961	1959-1961	1959-1961
Geometry							
Gross heated floor area (GHFA)	m^2	3655	3340	1494	690-750	1200-2400	2280-3600
Heated volume	m^3	9868	9025	4032	1865-2030	3200-6500	6170-10000
Façade area incl. window area	m^2	3400	3449	1570	600-700	960-2100	1960-3650
Roof area if flat roof	m^2	261	-	-	-	-	-
Roof area if a pitched roof	m^2	-	3555	1590	735-800	1280-2560	2425-3830

Parameter	Unit	Building typology 1 (B)	Building typology 2 (E)	Building typology 3 (H)	Building typology 4 (A1)	Building typology 5 (A2)	Building typology 6 (A3)
Is the room below the roof heated or not?	Yes / No	-	No	No	No	No	No
Number of floors above ground	-	14	6	6	3	5	6
Usage							
Type of use		Residential	Residential	Residential	Residential	Residential	Residential
Typical indoor temperature (for calculations)	°C	17-20	17-20	17-20	17-20	17-20	17-20
Average electricity consumption per year and m^2 (excluding heating. cooling. ventilation)	kWh/(m².a)	38.5	38.5	38.5	38.5	38.5	38.5
HVAC systems							
Type of existing heating system		Electric heaters	Electric heaters	Electric heaters	Electric heaters	Electric heaters	Electric heaters
Existing energy carrier		Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No	No	No	No
Is a cooling system installed?	Yes/No	No	No	No	No	No	No
Hot water consumption	l/person/day	22-28	22-28	22-28	22-28	22-28	22-28

3.6.2 Calculation parameters and scenarios

Table 33: General parameters for the calculation of the Spanish Case Study.

Parameters	Explanation/definition
Date the calculations were made	2019-2020
Weather file used	ESP_Bilbao.08250_SWEC.epw
External shading (by surrounding buildings) considered	Yes

Different solutions options are specified for façade, roof, windows separation from non-habitable spaces, and infiltration levels. For each façade, roof, window, and internal partition with non-habitable spaces, 4 options are considered. Being "0" the reference case, the first (1) refers to the minimal requirements set out by the Spanish Technical Code of Buildings, the current Spanish regulation. 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. Regarding infiltrations, two additional levels are considered: 3 levels acting on the façades to reduce the infiltration rate (0.1 ACH), and level 4 (PH level) acting on façades and internal partitions to reduce the infiltration rate to 0.03 ACH. Considering these scenarios, a set of 41 combinations has been considered for simulation, and between them, the most representative ones have been selected to combine them with different energy systems at the individual, building, and district levels. Each combination is named with a number code with 4 digits, where the first represents the renovation level in façades, the second in roofs, the third in windows, and the fourth in internal partitions. Thus, scenario 1.2.0.3. would indicate that this scenario considered the first renovation level (CTE) for façades, 2nd renovation level for roofs, no action on windows, and the third renovation level for internal partitions. Energy demands for the different scenarios were obtained by dynamic simulation of the whole district using Design Builder (see Figure 62). Some simplifications were assumed in the building (the effects of these simplifications in the results were previously evaluated and validated).

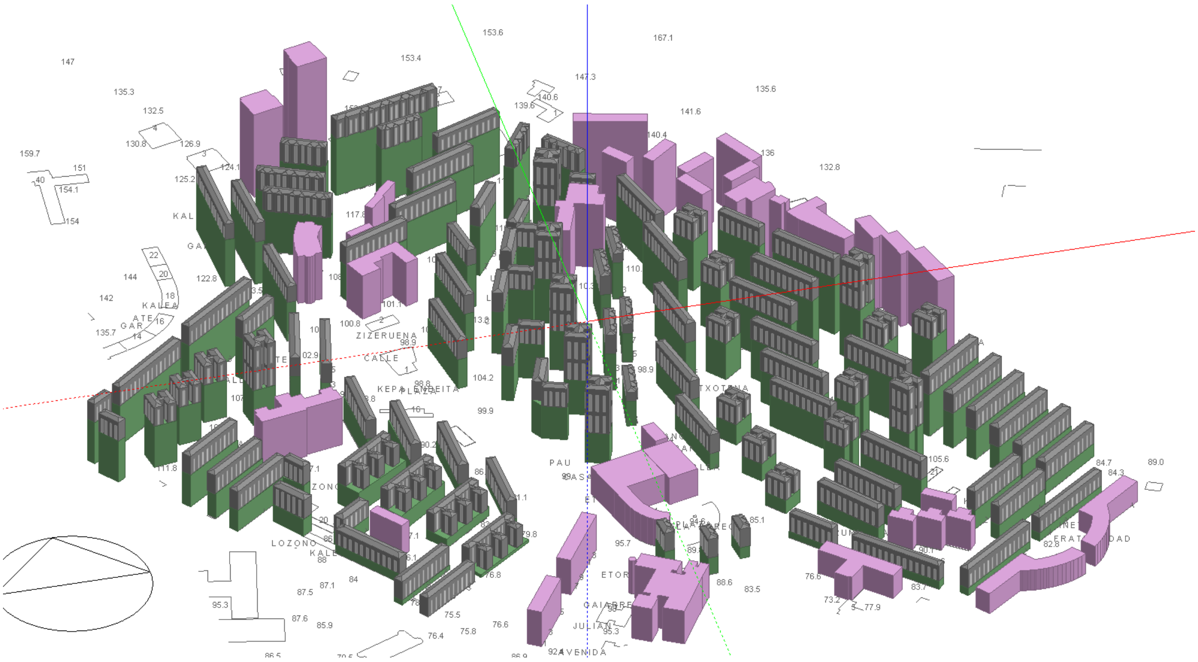

Figure 62: General view of the model of the district (source: authors, district model made in Design Builder).

Table 34: Measures of the building envelope.

Parameter	Unit	Ref	1	2	3	4
		Walls				
U-values	W/m²K	0.75	0.49	0.29	0.23	0.19
Investment costs	EUR/$m^2_{building\ element}$		11.83	15.65	21.49	26.31
Maintenance costs	EUR/$m^2_{building\ element}$.year		0.02	0.03	0.044	0.053
Service life	years		20	20	20	20
		Roofs				
U-values	W/m²K	2.84	0.35	0.23	0.21	0.19
Investment costs	EUR/$m^2_{building\ element}$		18.4	25.9	28.44	31.02
Maintenance costs	EUR/$m^2_{building\ element}$.year		0.04	0.05	0.058	0.063
Service life	years		20	20	20	20
		Internal partitions (heated – non-heated areas)				
U-values	W/m²K	1.45	0.60	0.47	0.38	0.27
Investment costs	EUR/$m^2_{building\ element}$		12.7	15.3	18.00	23.29
Maintenance costs	EUR/$m^2_{building\ element}$.year		0.13	0.16	0.184	0.237
Service life	years		20	20	20	20
		Windows				
U-values	W/m²K		2.1	1.8	1.57	1.05
Investment costs	EUR/$m^2_{building\ element}$		591.2	591.6	596.2	622.6
Maintenance costs	EUR/$m^2_{building\ element}$.year		6.2	6.3	6.4	6.9
Service life	years		20	20	20	20

Based on these criteria, the different combinations evaluated in this study are presented in the following table:

Table 35: Investigated combinations and scenarios.

Combination	Scenario name
0.0.0.0.	Reference
1.1.0.0.	Scenario 1
1.1.0.1.	Scenario 2
1.1.1.1.	Scenario 3
2.2.0.2.	Scenario 4
2.2.2.2.	Scenario 5
3.3.0.0.	Scenario 6
3.3.0.3.	Scenario 7
3.3.3.3.	Scenario 8
4.4.0.0.	Scenario 9
4.4.0.4.	Scenario 10
4.4.4.4.	Scenario 11
4.4.4.4. + INF 0,03	Scenario 12

Regarding HVAC systems, In Otxarkoaga, most of the dwellings are heated with electric heaters, although natural gas boilers have been installed in some of them. Cooling systems are not usual at all in general in residential buildings in this region. In this study, individual electric heaters for supplying the heating demand and electric boilers for the DHW demand will be assumed as the base case.

The analysis performed evaluates the implementation of active measures at three levels: individualized systems (at the apartment scale), decentralised systems (at the building level), and district heating systems. At the dwelling level and for the DHW demand an air-to-water heat pump is studied. For both DHW and heating demand, an electric boiler and an air-to-water heat pump are proposed.

On the other hand, a natural gas boiler, an aerothermal heat pump, and a biomass boiler are considered as decentralised systems at the building level.

Regarding the simulation of the different energy systems scenarios, scenarios with a district system were run in Design Builder (DB) by defining in detail (Detailed HVAC) the energy system in each case. Final and Primary Energy consumption values for those "district heating system scenarios" are then obtained directly from the dynamic simulations.

Mainly, the general approach has been formed according to load capacity: the base load-interval – has been taken for constant operation of the installation close to its expected rated power production during the year, primarily for DHW supply; the backup load-interval - is aimed to cover a high demand mainly related to the heating period, based on hourly consumption (30% of the total design heating capacity). These installations operate in conjunction. Finally, the peak load interval is covered by installation with the same characteristics and parameters applied throughout all scenarios to maintain a required peak load.

Similarly, for the integration into district heating networks, this maximum supply temperature or required power load in many cases is too high so the operation of large heat pumps seems not appropriate. It is a typically described approach that if the flow temperature of the heat pump is not sufficient, there is an option of post-heating with auxiliary systems. For such auxiliary systems, electrical boiler installations are widely applied. Thus, the sizing approach for heat pump scenarios is based on HP installation, and a thermal storage system in the form of a water storage tank to provide an additional heat buffer for the system. The Base load-interval (from 0 to 4,000 kW) is for constant operation within the year covered by the heat pump. The Backup and Peak load-interval (4,000 kW to a maximum limit of a particular passive measure application) – includes the operation of a Backup boiler together with an installed HP.

Regarding the scenarios at the building and apartment level, a model of a representative building of the district is used in the case of decentralised systems at the building level, and a model of a representative dwelling (previously validated) was selected in the case of individualized energy systems. The different evaluated systems are simulated in detail (in a dynamic simulation, using Design Builder, and defining the systems with "detailed HVAC" mode. Detailed values of the systems (pressure drops of pumps, pipe diameters, consumption of the pumps in the distribution system…) are also considered. Simulations at the building and apartment level are run for every energy system, considering the different passive scenarios obtaining in this way the seasonal performance of the systems for each passive scenario. The final energy consumption for each scenario considering the whole district is then calculated based on these calculated seasonal performances and the energy demand obtained for the whole district (using the model described in the previous section 3.6.2). This way, it is not necessary to define an energy system for every apartment or building in DB, and the simulation time is significantly reduced without affecting the accuracy of the results.

Table 36: Measures of the HVAC system including renewable energy generation on-site.

Parameter	Unit	Scenario
Heating system 1: Electric heaters and electric boiler (individual) – REFERENCE CASE		
Capacity	kW	Size based on the demand
Investment costs	EUR/kW	-
Maintenance costs	EUR/year	-
Service life	Years	-
Heating system 2: Air HP for DHW and heating (individual)		
Capacity	kW	4.5 kW (per apartment)
Investment costs	EUR/kW	681.11
Maintenance costs	EUR/year	76.62 (per apartment)
Service life	Years	20
Heating system 3: Air HP for DHW, electric boiler for heating (individual)		
Capacity	kW	1.8 kW (HP) per apartment
Investment costs	EUR/kW	824.4
Maintenance costs	EUR/year	37.10 (per apartment)
Service life	Years	20
Heating system 4: Air HP for DHW and heating (decentralised at the building level)		
Capacity	kW	205 (per building)
Investment costs	EUR/kW	194.4

Parameter	Unit	Scenario
Maintenance costs	EUR/year	996.4 (per building)
Service life	Years	20
Heating system 5: Biomass boilers for DHW and heating (decentralised at the building level)		
Capacity	kW	220 (per building)
Investment costs	EUR/kW	349.6
Maintenance costs	EUR/year	1923.03 (per building)
Service life	Years	20
Heating system 6: Biomass-based district heating		
Capacity	kW	11615-15600
Investment costs	EUR/kW	145.7-159.4 (+4.5 M€ for distribution)
Maintenance costs	EUR/year	2.5% of the investment cost
Service life	Years	20
Heating system 7: Geothermal-based district heating		
Capacity	kW	12000 + (3110-8293)
Investment costs	EUR/kW	734-983 (+4.5 M€ for distribution)
Maintenance costs	EUR/year	2.5% of the investment cost
Service life	Years	25
Heating system 8: Air Heat Pump based district heating		
Capacity	kW	4000 + (11109-16293)
Investment costs	EUR/kW	37.1-47.1 (+4.5 M€ for distribution)
Maintenance costs	EUR/year	2.5% of the investment cost
Service life	Years	20

3.6.3 Case study results

The following graphs give an overview of the results obtained:

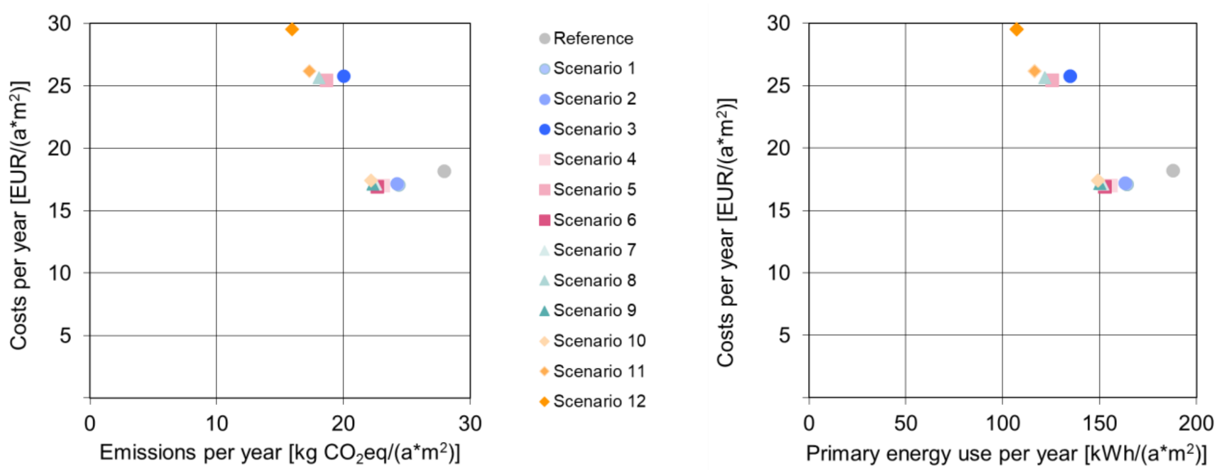

Figure 63: Reference heating system (electric heaters and electric boiler (individual)).

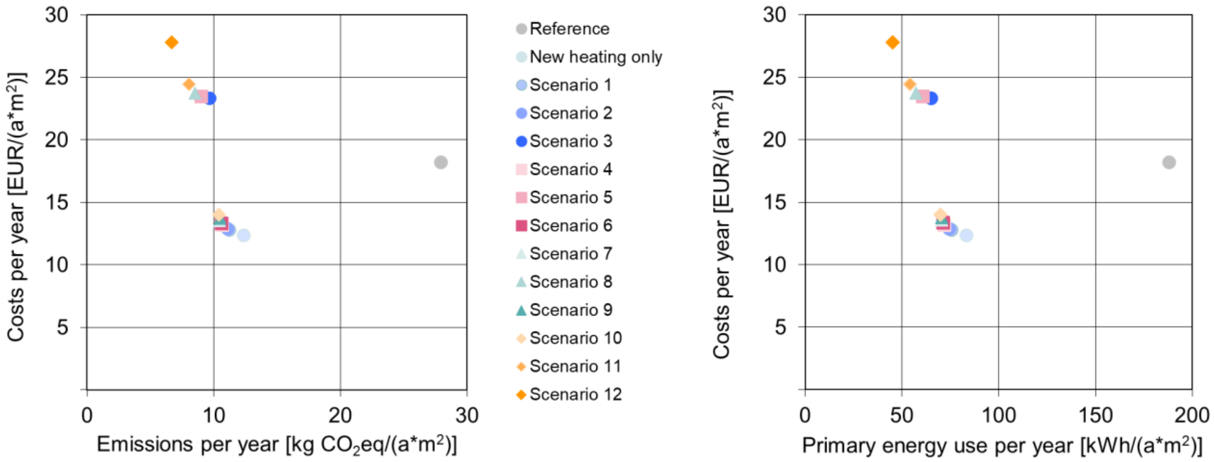

Figure 64: Heating system 2 - Air HP for DHW and heating (individual).

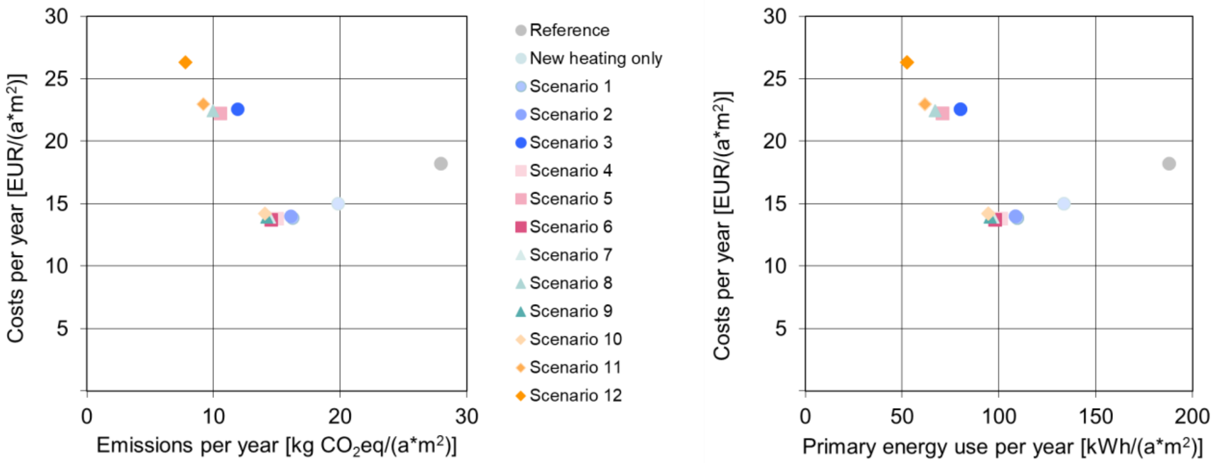

Figure 65: Heating system 3 - Air HP for heating, electric boiler for DHW (individual).

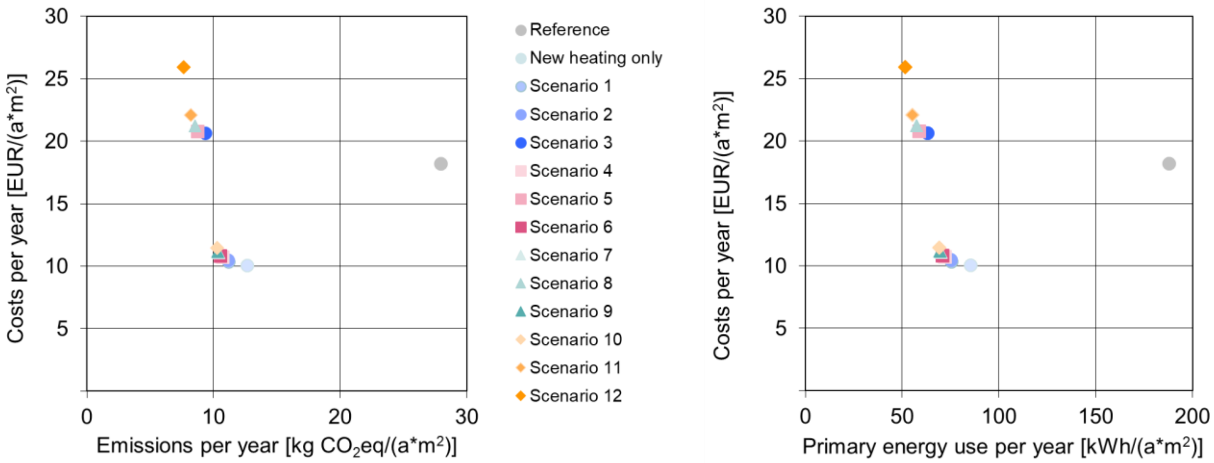

Figure 66: Heating system 4 - Air HP for DHW and heating (decentralised at the building level).

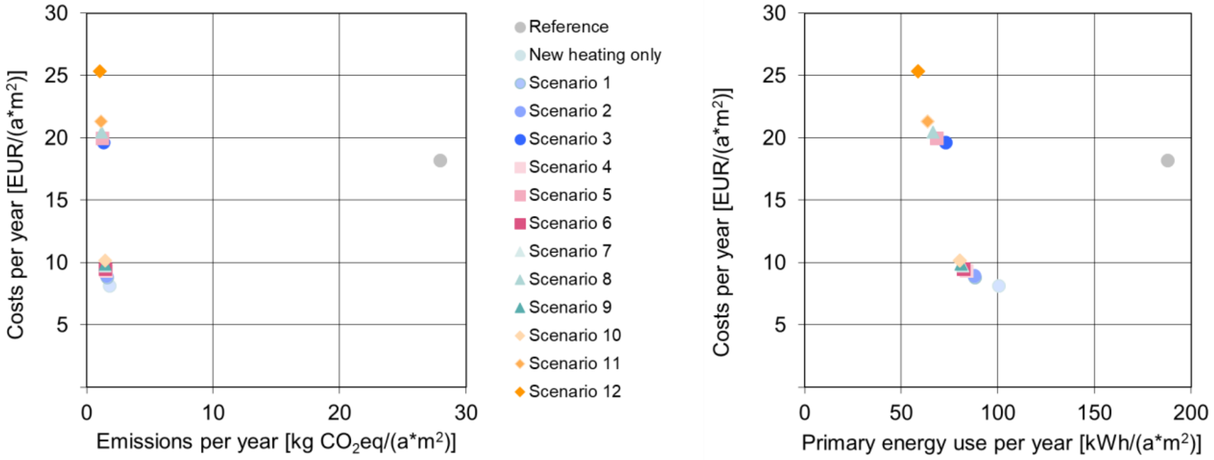

Figure 67: Heating system 5- Biomass boilers for DHW and heating (decentralised at the building level).

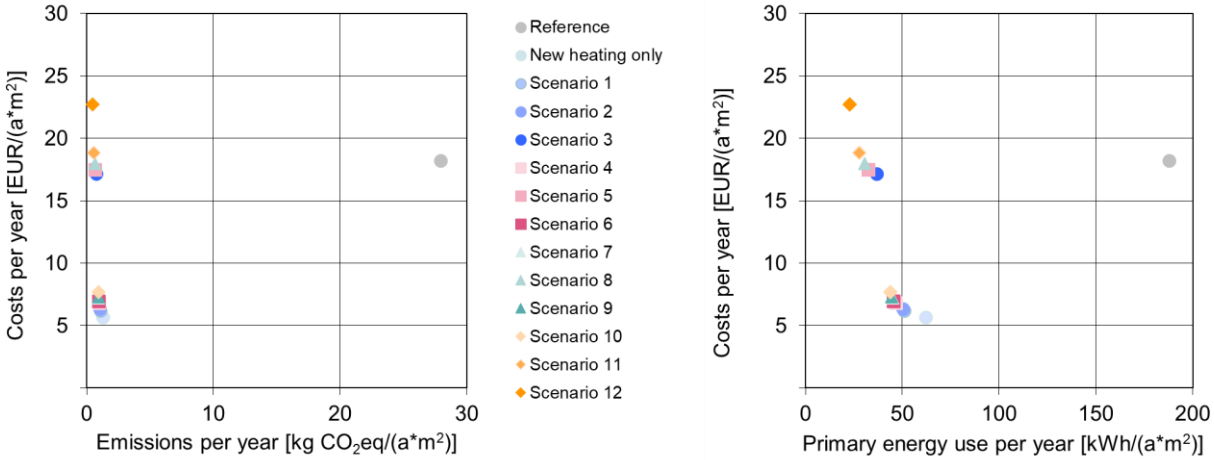

Figure 68: Heating system 6 - Biomass-based district heating.

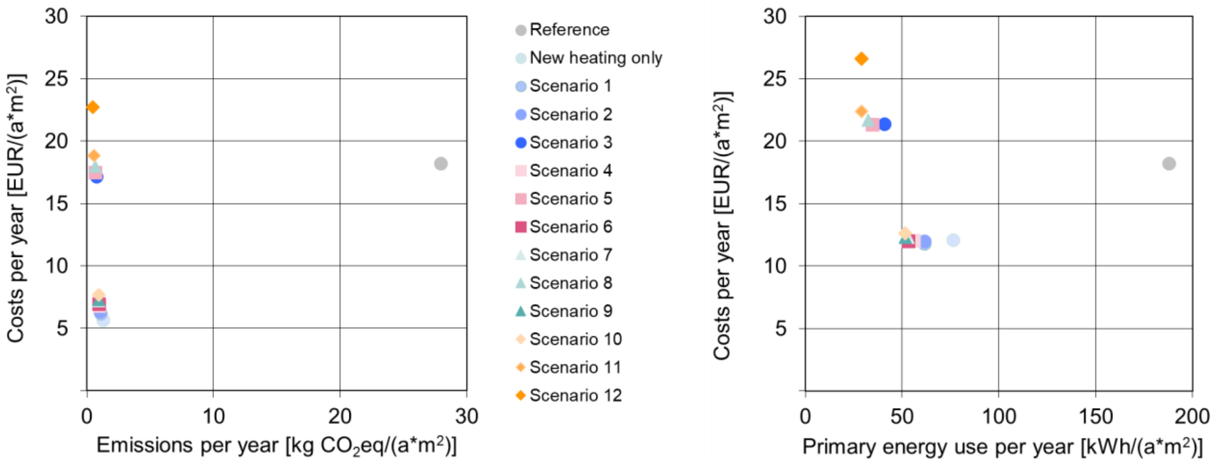

Figure 69: Heating system 7- Geothermal based district heating.

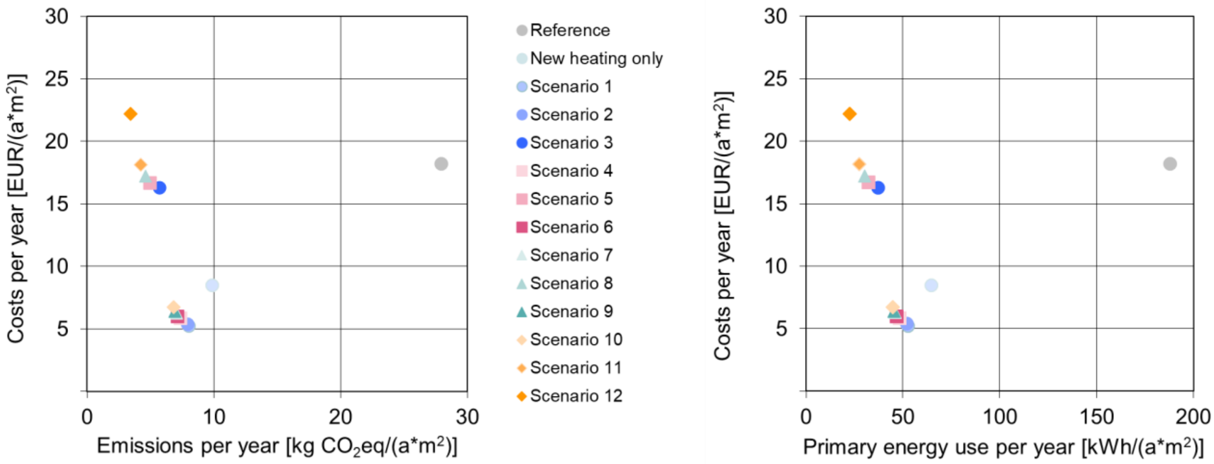

Figure 70: Heating system 8- Air Heat Pump based district heating.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

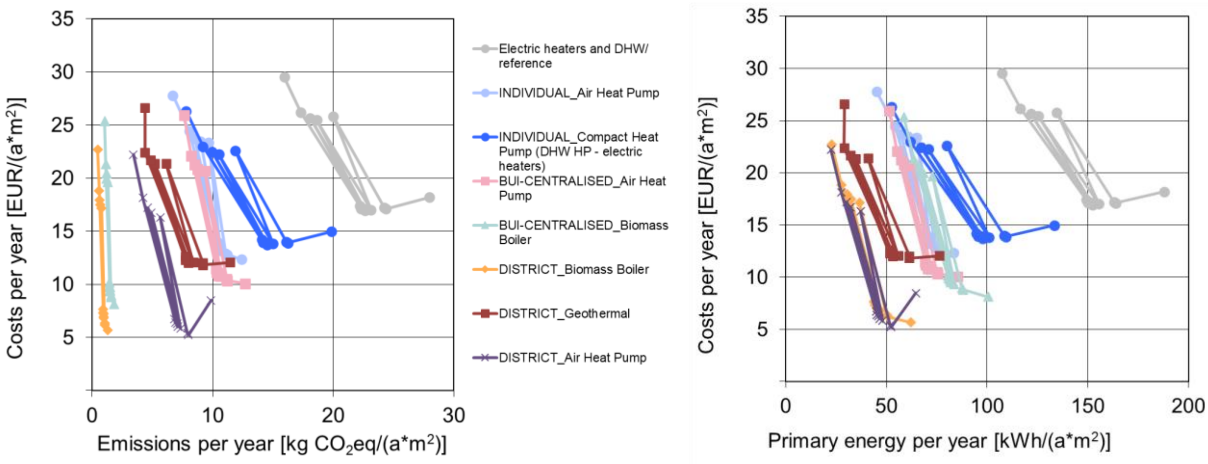

Figure 71: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

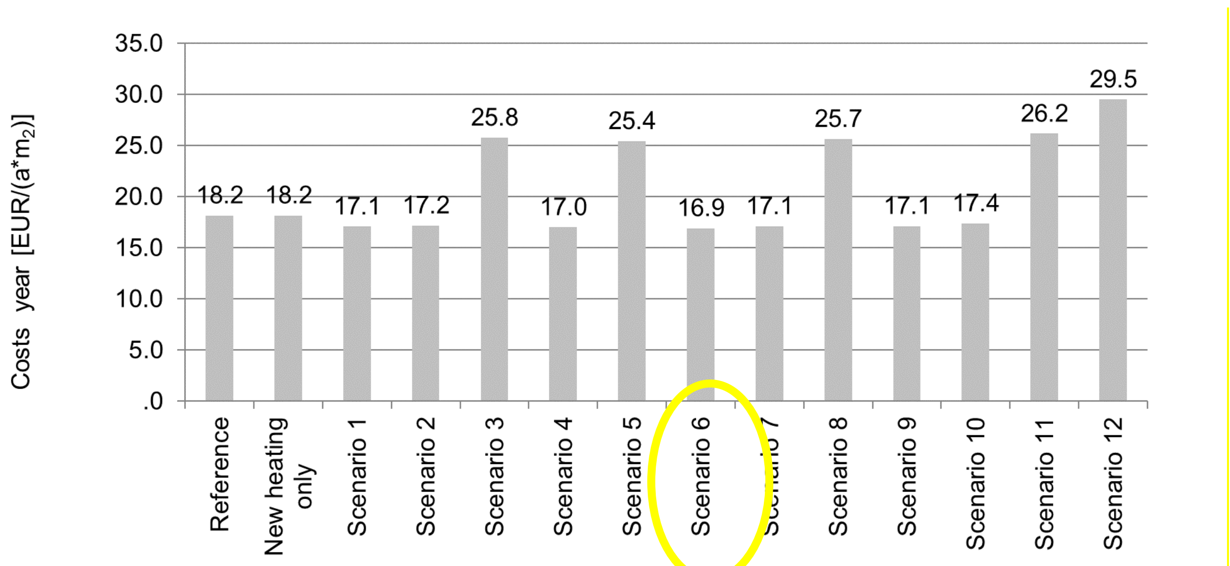

Figure 72: Reference heating system - Electric heaters and electric boiler (individual).

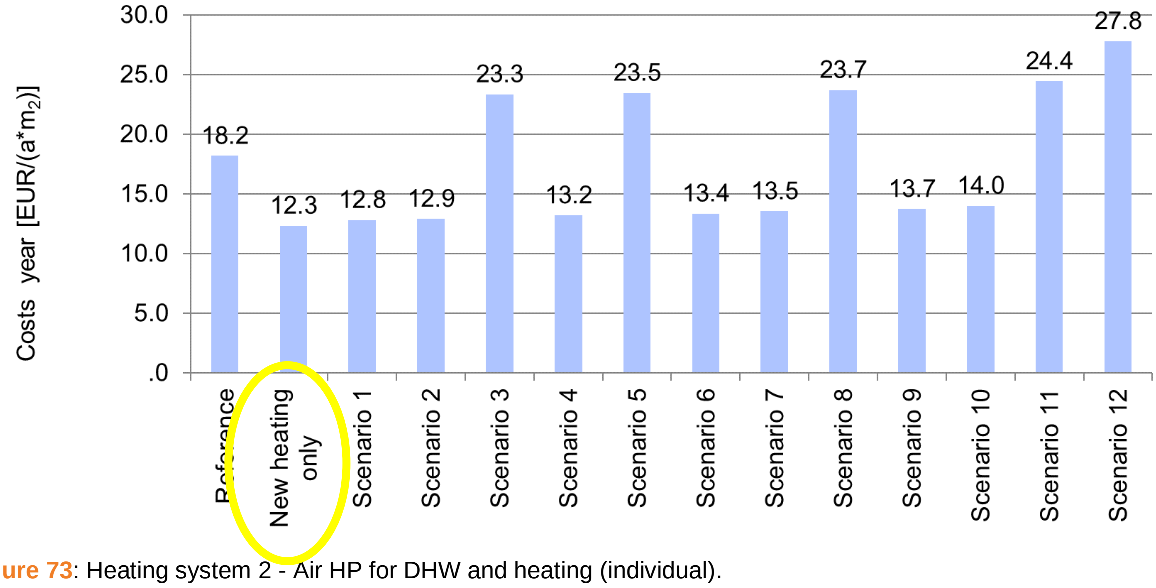

Figure 73: Heating system 2 - Air HP for DHW and heating (individual).

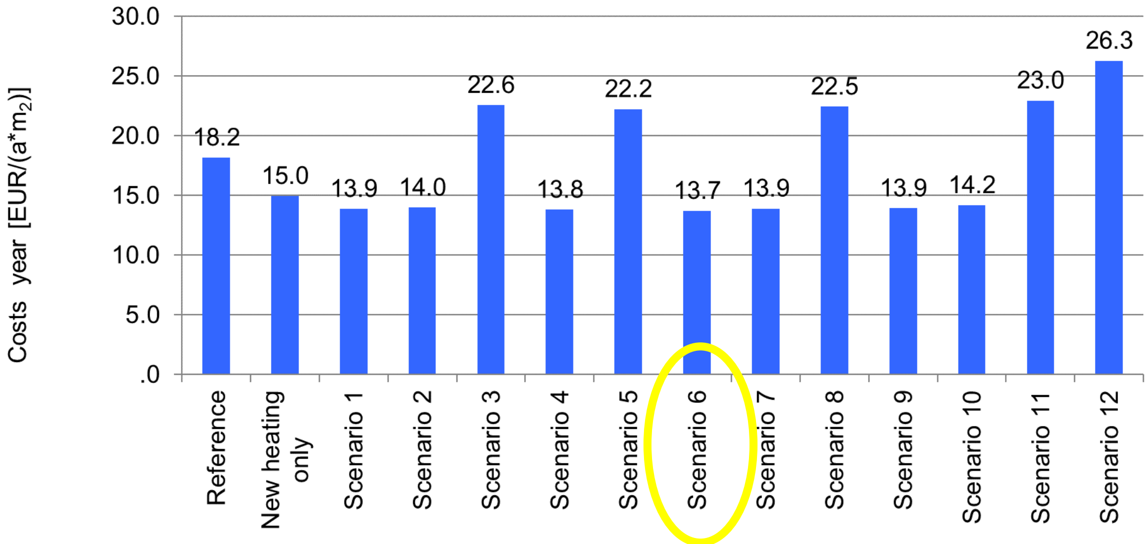

Figure 74: Heating system 3 - Air HP for heating, electric boiler for DHW (individual).

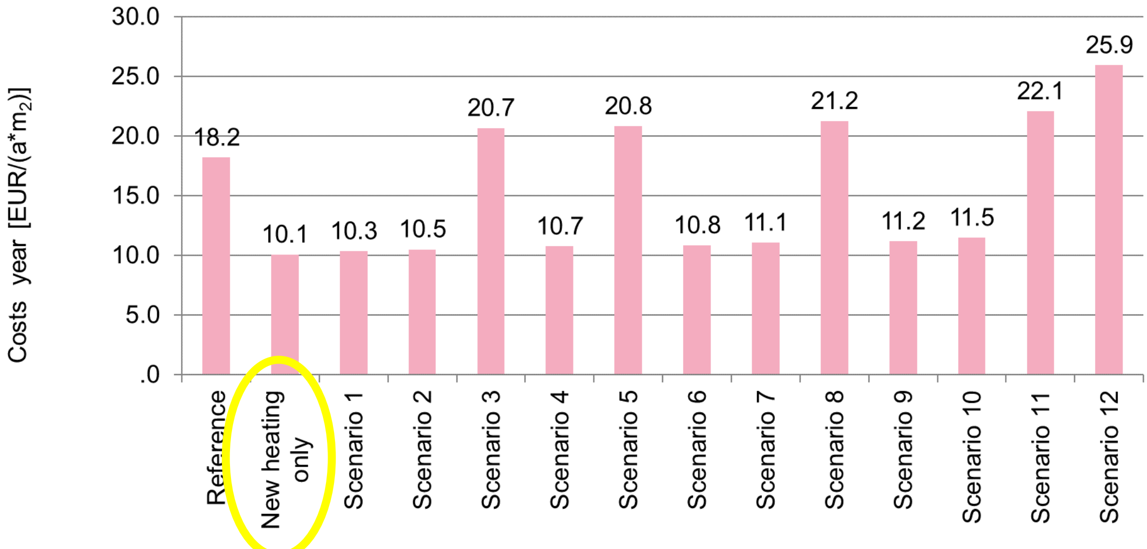

Figure 75: Heating system 4 - Air HP for DHW and heating (decentralised at the building level).

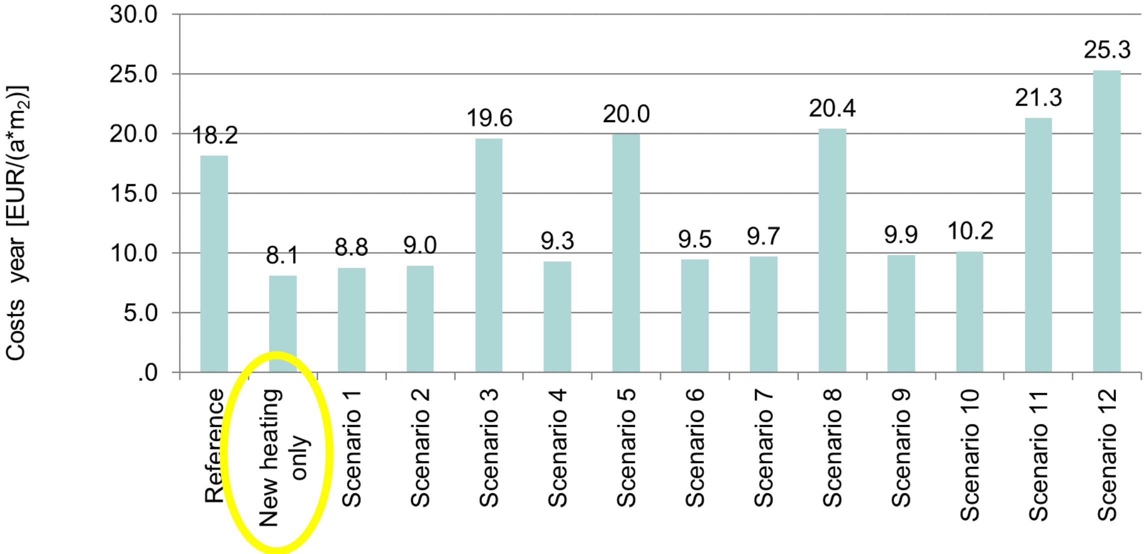

Figure 76: Heating system 5 - Biomass boilers for DHW and heating (decentralised at the building level).

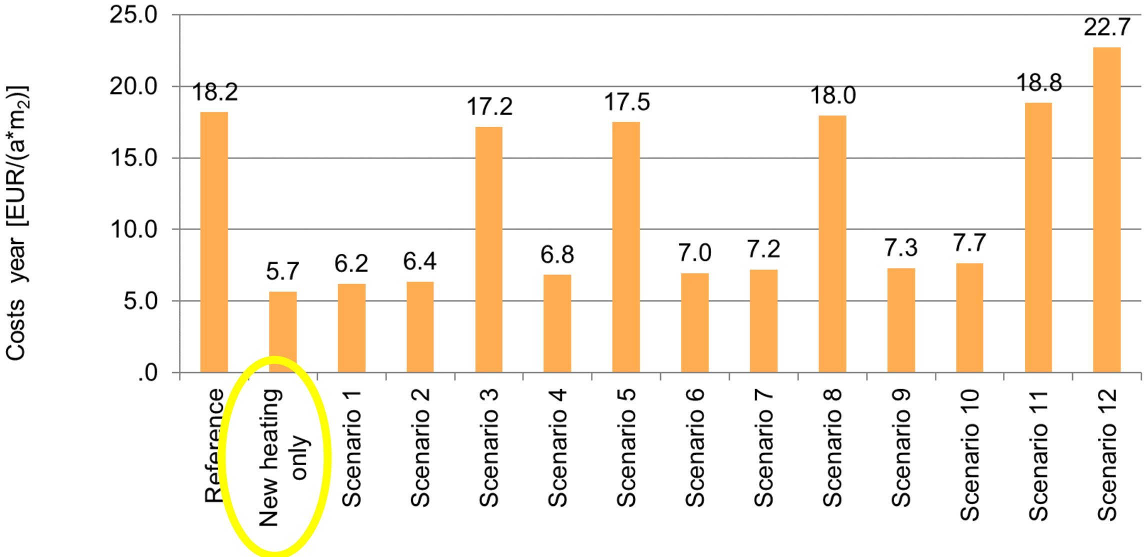

Figure 77: Heating system 6 - Biomass-based district heating.

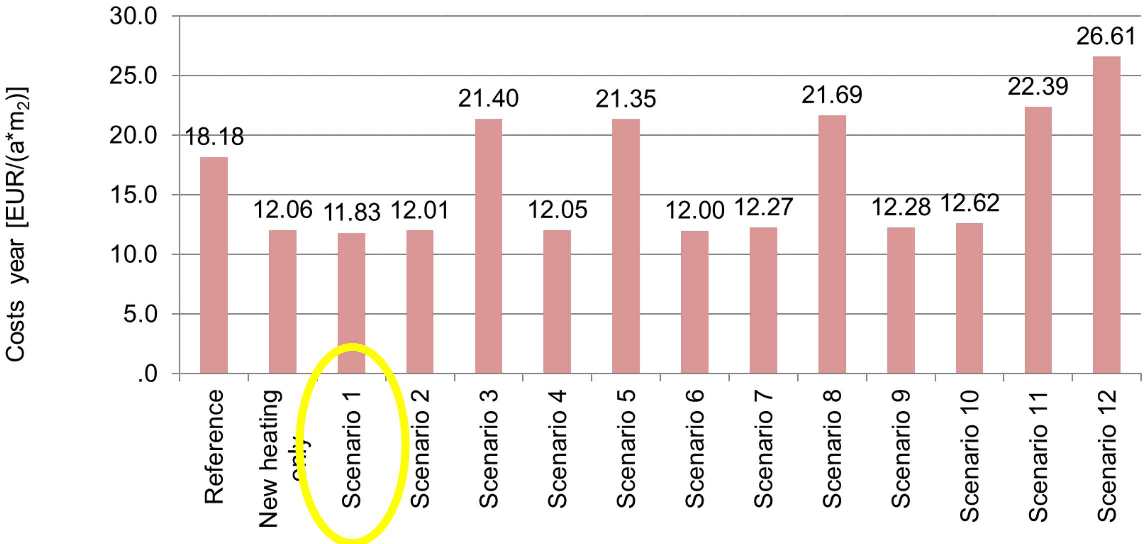

Figure 78: Heating system 7 - Geothermal based district heating.

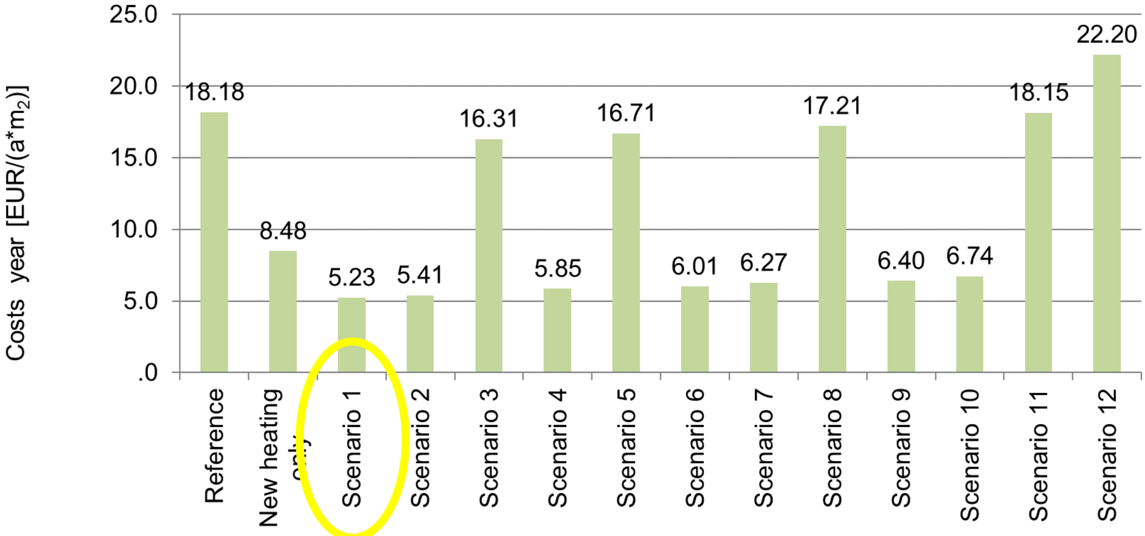

Figure 79: Heating system 8 - Air Heat Pump based district heating.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

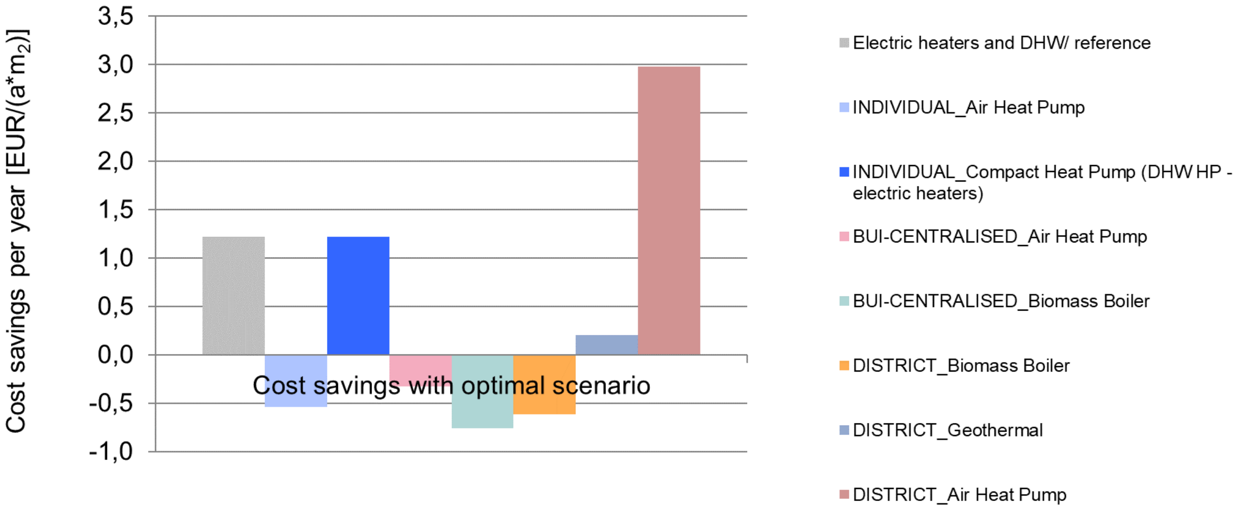

Figure 80: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized:

Windows replacement costs significantly affect the cost-efficiency analysis. In all the graphs, results can be gathered into two different groups: those energy efficiency measures which include windows replacement and those which do not include them. Windows replacement involves in general a sensible reduction in PE consumption (e.g., heating system 3, where windows replacement reduces the PE from around 100 kWh/m^2.year to 50 kWh/m^2.year in some cases, but, at the same time, it almost doubles the yearly costs, from around 15€/m^2.year to 25-30 €/m^2.year).

In addition, in this case study, it can be highlighted the weight that investment costs have on the overall economic analysis, compared to the energy-related costs during the lifetime of the building. In general terms, except for some scenarios where the cost-optimal solution is considering the 3rd level of renovation in the façade and roof (those scenarios more intensive on electricity: reference scenario and scenario 3), in general, the rest of the scenarios reach the optimal cost with no deep-renovations, even, 4 out 8 scenarios present the optimal cost with no energy efficiency measures, only replacing the energy systems. It should be highlighted, however, that in some of those cases, the differences in the annualized costs when different energy efficiency measures are compared are very low (e.g., lower than 1 €/m^2.year in scenario 7, if windows replacements are not considered).

Thus, in the following graph where the comparison of cost savings with optimal scenarios for the different types of heating systems evaluated are presented unlike when n=20 years and e=0% are considered, when n=50 years and e=8% are assumed, every technology presents its optimal value considering, to some extent, an energy efficiency action.

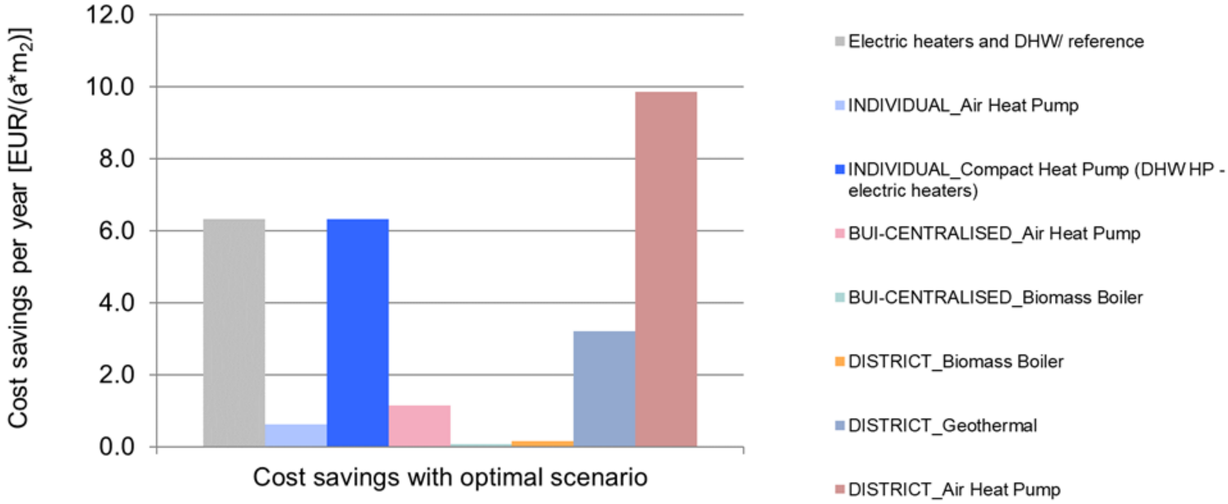

Figure 81: Cost-saving potential of the optimal scenario per energy supply variant.

3.6.4 Discussion

What stands out when interpreting the results?

One of the main issues that can be identified when analysing results is the increase of the cost when window replacement is considered. It should be taken into consideration, however, that windows replacement, unlike other energy efficiency measures, involves additional effects (reduction of noise, increase of indoor comfort, maintenance, reduction of moisture-related problems...) which are not considered in this study but that can play an important role as a motivation for carrying out them.

What are the most cost-effective solutions?

At first sight, regardless of the energy system considered, in most cases, the cost-optimal solution presents a low grade of energy efficiency measures (even, in some cases, as already mentioned, the cost-optimal solution is the new heating system without implementing any energy efficiency measures). This can be explained, to some extent, since the winter severity in the case study evaluated is not too high, and then, the weight of the investment cost is not compensated by the energy savings achieved by the energy efficiency measures during the lifespan considered.

Nevertheless, this should be also put into context, and other restrictions should be considered, such as those presented by the regulatory framework. In the case of Spain, the Spanish Technical Building Code limits the non-renewable and overall primary energy consumption depending on if it is a new building or a renovation of an existing building. In renovating an existing building, the limit is set considering the climate zone where the building is located. For this case study, the limit would be 90 kWh/m^2.year. Considering these limits, some of the solutions would not be possible (mainly several of the solutions considered in the “Heating System D”). If the limit of 64 kWh/m^2.year is considered (not mandatory in this case, but it can be used as a reference for going beyond the minimum requirements and fixing more ambitious objectives), it can be observed that for the majority of the individual and building-level solutions this is only reached if deep energy efficiency measures are considered (level 3 and 4), and in any case, including also the windows replacement.

Where are the greatest uncertainties in the assumptions? How reliable are the results?
The main uncertainties in the assumptions are related to the energy costs considered (and the evolution of them in the close future), as well as the hypotheses and simplifications considered in the costs of auxiliary elements, especially in the case of district heating solutions. Regarding the first one (uncertainties related to energy costs), these uncertainties could affect the identification of the optimal solution for each energy system, since the differences in the annualized costs related to the different energy efficiency measures are quite small (especially in those scenarios in which windows replacement is not considered) and small variations in the energy costs could make that the optimal cost moves from one solution to another. In any case, it should be highlighted that those small differences make that with low increases in the cost sensible savings on primary energy consumption could be achieved, mainly in several heating systems, e.g., when considering the heating system 4 (decentralised heat pump) an increase of 1.5 €/m^2. year involves a reduction in primary energy consumption of 16.14 kWh/ m^2.year, almost 20% (from the reference scenario to scenario 9).

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Yes
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.»	Not investigated
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.»	Not investigated
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 energy.»	No
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.»	No
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.»	Not investigated

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.»	No
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.»	Not investigated

3.7 Sweden

3.7.1 Description of the district

Table 37: General Information about the district.

Parameter	Explanation/definition
Location	Lund
Latitude	13°11′42″E
Longitude	55°42′14″N
Climate zone	Cfb (Marine West Coast Climate)
Number of buildings in total	2 × 3 buildings in a cluster. Calculations focused on 3 of them.

Figure 82: View of the Case Study in Sweden (source: “Google Earth” by Google n.d.).

- Place: Lund
- District: South (Klostergården)
- Address: High-rise building: Gråvädersvägen 4 G-N and Sunnanväg 2 H-P. Low-rise building: Gråvädersvägen 2 A-F and Sunnanväg 2 A-G
- Type of building: multi-family
- Year of construction: 1965
- Architect: Leif Hörberg Wigot Konsult AB

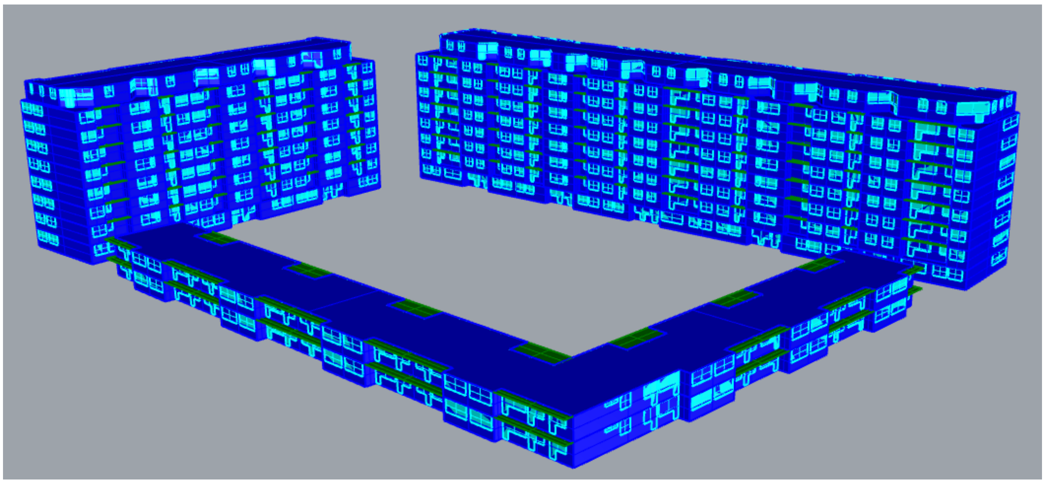

Figure 83: Simulation model of the Swedish Case Study (source: project group).

Table 38: Building typology of the Swedish Case Study.

Parameter	Unit	Building typology
Building information		
Number of buildings per typology		3
Construction period		1965
Geometry		
Gross heated floor area (GHFA)	m^2	21069
Heated volume	m^3	52673
Façade area incl. window area	m^2	11769
Roof area if flat roof	m^2	3150
Area of windows to North	m^2	541
Area of windows to East	m^2	014
Area of windows to South	m^2	722
Area of windows to West	m^2	1276
Area of basement ceiling	m^2	3462
Area of basement wall	m^2	2060
Area of the basement floor	m^2	3462
Number of floors above ground	-	20
Usage		
Type of use		Residential
Area per occupant	m^2 / person	37.86
Typical indoor temperature (for calculations)	°C	21
Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation)	kWh/(m^2.a)	30

Parameter	Unit	Building typology
HVAC systems		
Type of existing heating system		District Heating
Existing energy carrier		District Heating
Is a ventilation system without heat recovery installed?	Yes/No	Yes
Is a ventilation system with heat recovery installed?	Yes/No	No
Ventilation rate	ach	0.504*
Is a cooling system installed?	Yes/No	No
Hot water consumption	kWh/person/day	2.08

* The exact ventilation flow is not known. The ventilation system is not in good condition as many tenants complain about the air quality.

3.7.2 Calculation parameters and scenarios

Table 39: General parameters for the calculation of the Swedish Case Study.

Parameter	Explanation/definition
Date the calculations were made	2020
Weather file used	Lund weather file
External shading (by surrounding buildings) considered	No

Table 40: Measures on the building envelope.

Parameter	Unit	Ref	Scenario
Walls			
U-values	W/m²K	0.34	0.25
Investment costs	$EUR/m^2_{building\ element}$		49.36
Maintenance costs	$EUR/m^2_{building\ element}$/year		
Service life	years		50
Windows			
U-values	W/m²K	3	0.8
Investment costs	$EUR/m^2_{building\ element}$		508.84
Maintenance costs	$EUR/m^2_{building\ element}$.year		
Service life	years		45

The existing ventilation is an exhaust air system with minimum heat recovery. Today there exists an old poorly working exhaust-air heat pump. In the performed calculations a decentralised ventilation unit was added if possible due to building regulations concerning minimum airflow from the kitchen and the toilet. The installed ventilation units consist of an indoor and an outdoor unit connected with a short duct and are situated in each room. The ventilation Smart 1 unit has a built-in regenerative heat exchanger. The unit has two ceramic heat exchangers where one is being charged with heat from outgoing air while the other is discharged at the same time with cold incoming air. After approximately 60 seconds, the flow direction is changed and the now empty heat exchanger gets charged while the charged heat exchanger is discharged by the incoming air. It is not possible to use the unit in dark toilets (no window, thus not at an outer exterior wall). Also, the unit was not assumed to replace the exhaust ventilation from the kitchen. Such solutions are principally possible but not used today. Therefore, the ventilation unit was assumed to be used in rooms with at least one exterior wall and if there was a greater need for fresh air than what is already supplied for the kitchen and toilet exhaust ventilation (one additional unit for the kitchen).

The heat recovery for the unit itself is dependent on the airflow. In the performed calculations an average heat recovery rate of 85 % was used for the unit itself. Combined with the exhaust ventilation from the kitchen and toilet an average of 32 % heat recovery was used for the entire building.

The ground source heat pump solution came from the company "Energy Machines". The COP for the three different sizes differ slightly but are all in the range between 3.3 to 3.4.

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

Parameter	Unit	Scenario
Ventilation units (decentralised)		
Capacity	l/s	3049
Investment costs	EUR	236733
Maintenance costs	EUR/year	4174
Fan replacement in the year 20	EUR	18950
Service life	Years	
GSHP "Energy Machines 4"		
Capacity	kW	387.7
Investment costs	EUR/kW	2800
Maintenance costs	EUR/year	500
Service life	Years	50
GSHP "Energy Machines 5"		
Capacity	kW	469.7
Investment costs	EUR/kW	2700
Maintenance costs	EUR/year	500
Service life	Years	50
GSHP "Energy Machines 6"		
Capacity	kW	611.7
Investment costs	EUR/kW	2600

Parameter	Unit	Scenario
Maintenance costs	EUR/year	500
Service life	Years	50
	PV system small	
Size	kWp	100.6
Investment costs	EUR/kWp	1300
Inverter replacement every 9 years	EUR	22769
Service life	Years	35
	PV system large	
Size	kWp	201.2
Investment costs	EUR/kWp	1300
Inverter replacement every 9 years	EUR	45538
Service life		35

3.7.3 Case study results

The following graphs give an overview of the results obtained.

Table 42: Overview of scenarios and included measures.

Scenario	Windows	Ventilation	PV
Scenario 1	Old	Exhaust	No
Scenario 2	Old	Exhaust	Small
Scenario 3	Old	Exhaust	Large
Scenario 4	Old	Smart1+Exhaust	No
Scenario 5	Old	Smart1+Exhaust	Small
Scenario 6	Old	Smart1+Exhaust	Large
Scenario 7	New	Exhaust	No
Scenario 8	New	Exhaust	Small
Scenario 9	New	Exhaust	Large
Scenario 10	New	Smart1+Exhaust	No
Scenario 11	New	Smart1+Exhaust	Small
Scenario 12	New	Smart1+Exhaust	Large

Explanatory table for the different cases involved in the study.

For more information, see https://lup.lub.lu.se/student-papers/search/publication/9057310

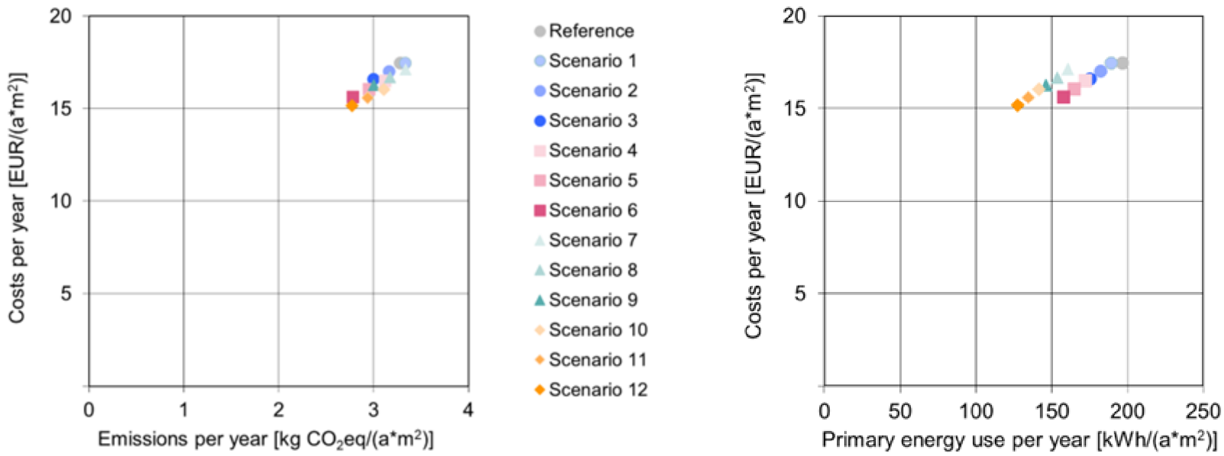

Figure 84: Reference heating system (district heating).

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

New heating only means keeping the old building and changing the heating supply to a GHSP system.

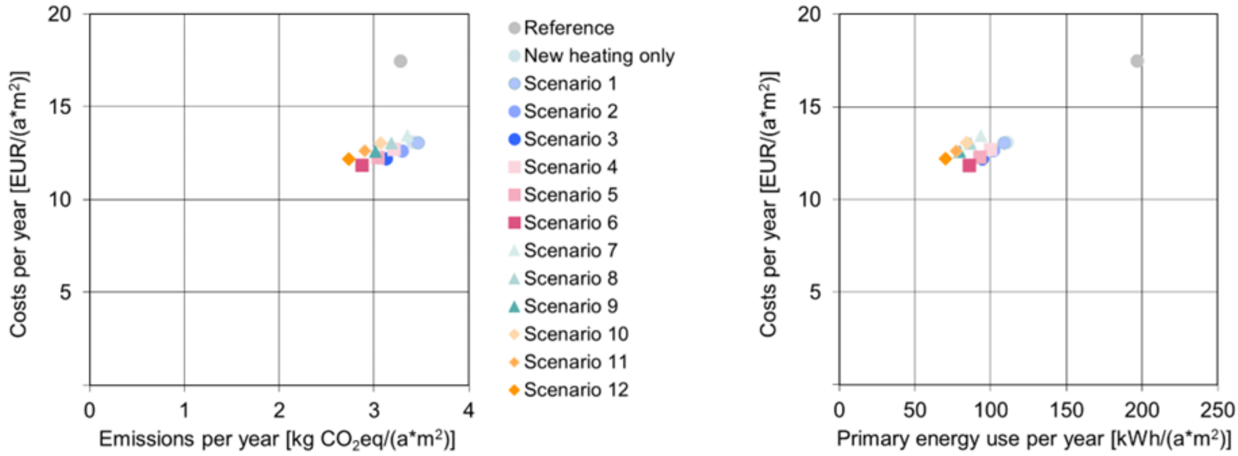

Figure 85: Heating system 2 – Ground Source Heat Pump.

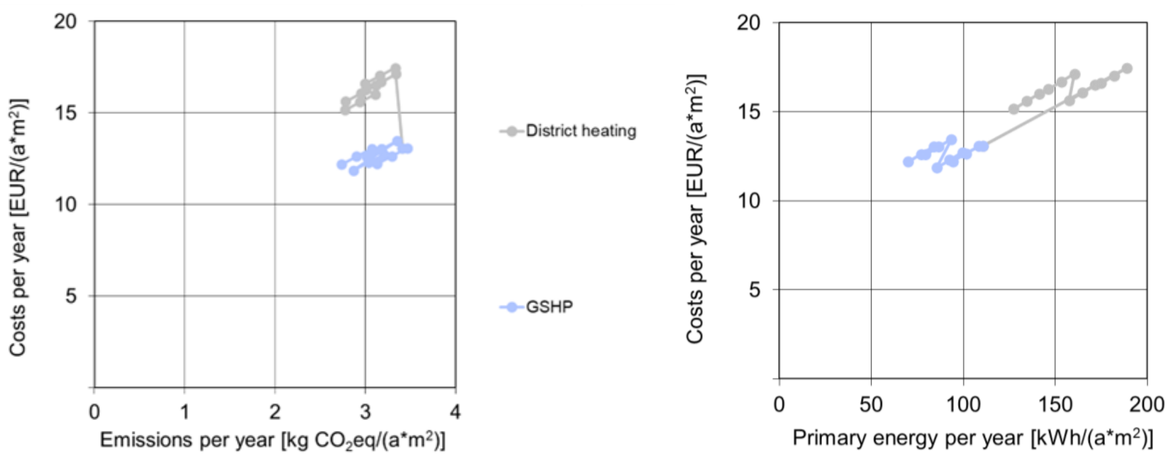

Figure 86: Comparison of district heating and GSHP for the different renovation scenarios.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

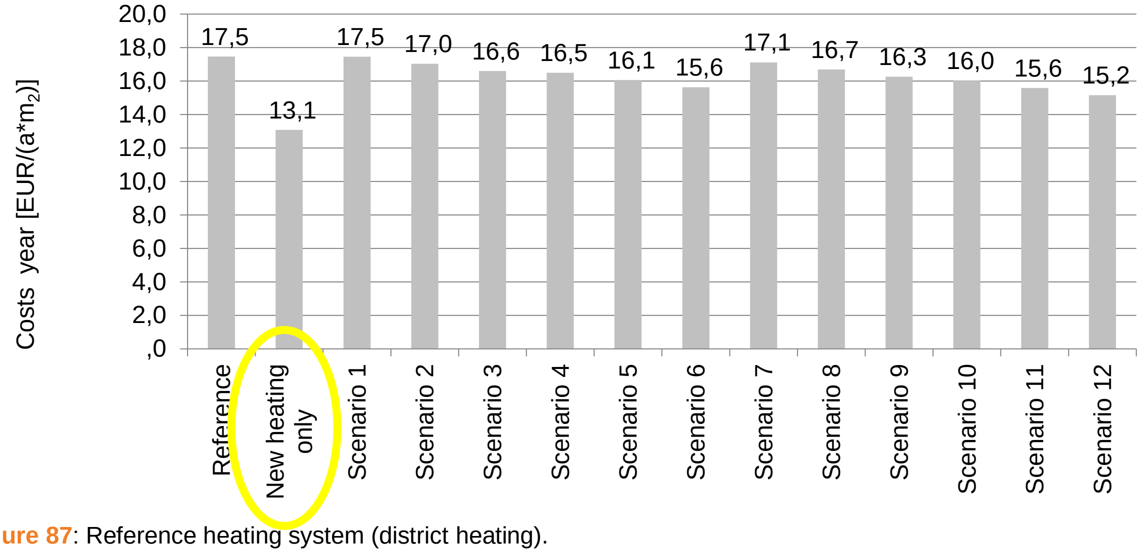

Figure 87: Reference heating system (district heating).

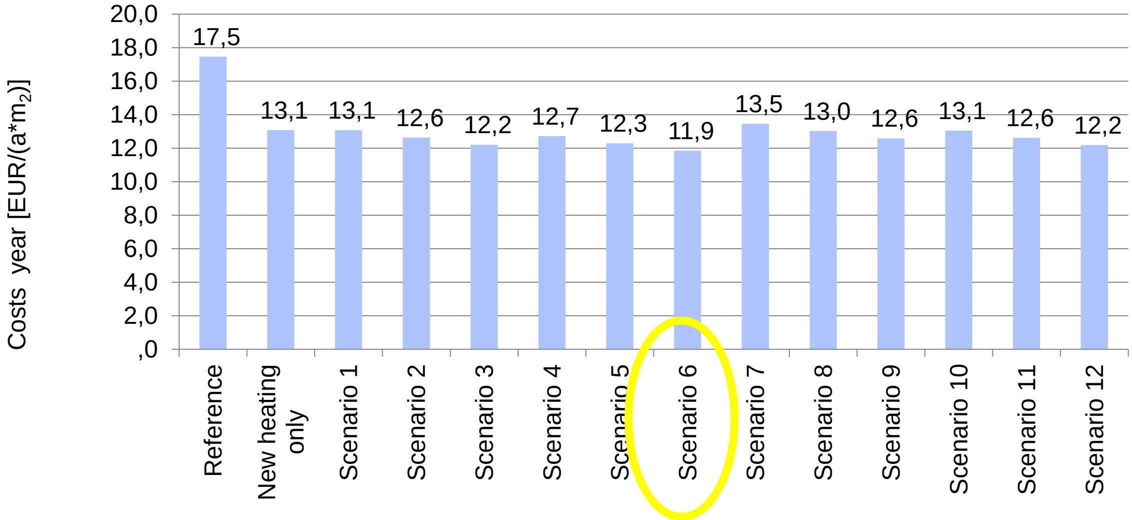

Figure 88: Heating system 2 – GSHP.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for two types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

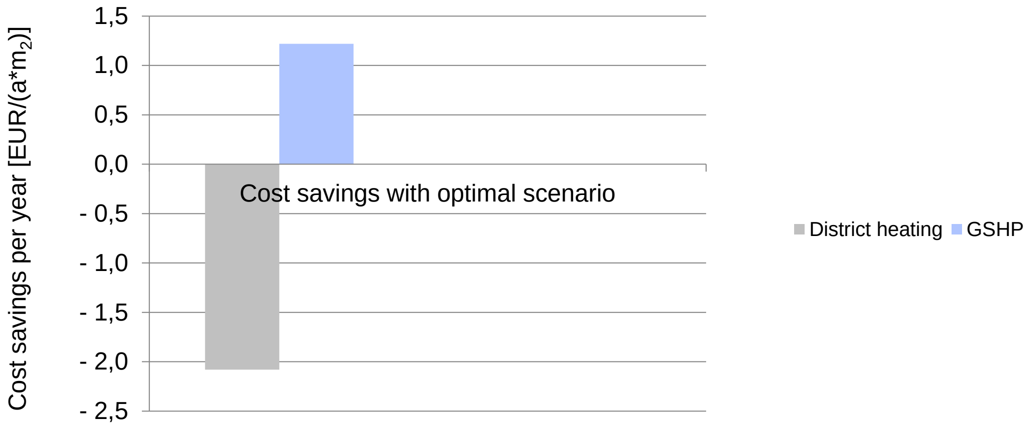

Figure 89: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized:

Cost savings is mainly carried out by disconnecting the district heating system and installing a heat pump system. However, as discussed below this can have negative effects on society at large.

The rather low numbers for carbon emissions for all the investigated cases are due to the low environmental impact of district heating in Sweden (see **Table 5**).

3.7.4 Discussion

Many, if not all, of the costs related to renovation projects like the one planned at Klostergården in Lund are highly dependent on technical solutions. Such solutions are often not available while performing preliminary energy simulations and cost estimations. Questions such as what beams are needed to support the added insulation, how can these beams be fastened in the existing construction, how can the balcony be insulated without losing a large fraction of the space on the balcony, and how can new holes be made in the existing walls to allow for new ventilation devices, how hard is it to drill in the neighbourhood in case ground source heat pumps will be installed, etc. will all affect the total costs and thus also what solutions will be chosen for the project.

The problem is larger for neighbourhoods with many types of buildings. In this case, the technical solutions will differ considerably from each other. This will also be a clear risk for introducing larger mistakes in the calculations and, consequently, the chosen solution for the renovation project. On the other hand, if there are many buildings of the same type, the renovation work can be more effective. This problem strongly limits the usefulness of the results as it adds large uncertainties.

The different renovation strategies that are likely to be carried out in a renovation project all have different service life. Some renovations are likely to last for 50 years, some shorter and some might even last longer. No matter what, a time frame for the energy calculations and the carbon emission calculations must be chosen.

A larger complication arises if we consider that Sweden plans to be carbon-neutral by 2045. That means that energy used after 2045 will not negatively affect the climate. We can also assume that the dirtiest and high carbon-emitting energy counting from now and onwards is the energy that we use right now. The energy mix is getting cleaner in the future.

Thus, the energy that we spend now producing insulation, heat pumps, ventilation units, PV panels, etc. can be the dirtiest electricity used during these products' service life. These products do not save energy that is equally dirty as the energy that was used to produce these products. Rather they are used to save future cleaner energy with no or fewer carbon emissions per produced kWh.

However, if we do not insulate and improve our buildings, using this dirty energy in the production phase, we run the risk of never reaching the high-set goals of climate-neutral energy production in the future.

Uncertainty in calculation results due to the limited available data for LCA calculations.

Many products do not have a full EPD file (Environmental Product Declarations). Complicated products such as ventilation units, heat pumps, etc are not easily estimated for LCA consideration. Some products have data for the raw material in the product but not for maintenance, end-of-life, etc. This increases the uncertainty of the calculations.

This problem strongly limits the usefulness of the results as it adds large uncertainties.

Esthetical considerations should be included in the evaluation. Many buildings are historically and/or culturally important for the community. This will put strong limitations on what renovation measures can be taken for a specific building.

Daylight is not included as a factor in this study. If windows are improved from a thermal perspective, there is likely that the new modern window results in less daylight than the original window. Furthermore, adding insulation to the wall might reduce daylight availability. This should be included in the evaluation.

Energy-renovated/retrofitted building has the potential to lower the annual heating need for the inhabitants and society. However, one of the main points of doing this type of renovation is to increase the thermal comfort in the building. This increase in comfort should be included in the evaluation of the building.

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.»	Yes
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.»	No
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.»	No
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 energy.»	No
5. «The cost-optimal level of the energy efficiency measures on building envelopes does not differ significantly when an 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.»	No

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.»	No
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.»	Yes
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.»	No

3.8 Switzerland - Luzern

3.8.1 Description of the district

The case study is in Luzern, in the central part of Switzerland. The case study consists of 18 buildings constructed between 1958 and 1968. **Table 43** gives some general information on the district and its location, **Figure 90** shows the aerial view of the case study.

Table 43: General information about the district.

Parameter	Explanation/definition
Location	Luzern
Latitude	E: 8.331808
Longitude	N: 47.035004
Climate zone	Dfb (Humid continental climate)
Number of buildings in total	18

Figure 90: Aerial view of the Case Study in Luzern in Switzerland (source: based on “Google Earth” by Google n.d.).

Based on the characteristics of the buildings, they were classified into 14 building typologies (see **Table 44** and **Table 45**).

Table 44: Building typologies of the Swiss Case Study in Luzern, for building types 1-7

Parameter	Unit	type 1	type 2	type 3	type 4	type 5	type 6	type 7
Building information								
Number of buildings per typology		2	1	1	1	1	2	1
Construction period		1958	1958	1958	1958	1958	1958	1958
Geometry								
Gross heated floor area (GHFA)	m^2	2122	2122	1963	1963	2122	2995	3255
Heated volume	m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Façade area incl. window area	m^2	1175	1175	1175	1175	1175	1700	1700
Roof area if flat roof	m^2	534	534	534	534	534	547	547
Area of win-dows to North	m^2	11	8	8	8	10	114	9
Area of win-dows to East	m^2	87	87	87	87	87	9	179
Area of win-dows to South	m^2	15	14	14	14	15	179	10
Area of win-dows to West	m^2	114	114	114	114	114	10	114
Area of base-ment ceiling	m^2	341	341	341	341	341	338	338
Area of floor to ground	m^2	116	116	116	116	116	118	118
Area of floor to exterior	m^2	71	71	71	71	71	54	54
The average number of floors above ground	-	4	4	4	4	4	6	6
Usage								
Type of use		Residen-tial	Residen-tial	Residen-tial	Residen-tial	Residen-tial	Residen-tial	Residen-tial
Average area per occupant	m^2 / person	40	40	40	40	40	40	40
Typical indoor temperature (for calculations)	°C	20	20	20	20	20	20	20

				HVAC systems				
Type of existing heating system		Boiler	Boiler	Boiler	Boiler	Boiler	Boiler	Boiler
Existing energy carrier		Oil	Gas	Gas	Gas	Gas	Gas	Gas
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No	No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No	No	No	No	No
Ventilation rate	ach	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Is a cooling system installed?	Yes/No	No	No	No	No	No	No	No
Hot water consumption	l/person/day	40	40	40	40	40	40	40

Table 45: Building typologies of the Swiss Case Study in Luzern, for building types 8-14

Parameter	Unit	type 8	type 9	type 10	type 11	type 12	type 13	type 14
				Building information				
Number of buildings per typology		1	1	1	1	1	3	1
Construction period		1958	1958	1958	1958	1958	1958	1968
				Geometry				
Gross heated floor area (GHFA)	m^2	3255	3255	1963	2122	2122	1890	2125
Heated volume	m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Façade area incl. window area	m^2	1700	1700	949	949	953	888	729
Roof area if flat roof	m^2	547	547	514	514	514	515	560
Area of windows to North	m^2	114	9	87	87	87	159	230
Area of windows to East	m^2	9	114	13	13	15	21	2
Area of windows to South	m^2	179	10	114	114	109	123	131

Area of windows to West	m^2	10	179	11	11	11	21	2
Area of basement ceiling	m^2	338	338	341	341	341	487	460
Area of floor to ground	m^2	118	118	116	116	116	28	76
Area of floor to exterior	m^2	54	54	70	70	70	-	24
The average number of floors above ground	-	6	6	4	4	4	4	4
Usage								
Type of use		Residential	Residential	Residential	Residential	Residential	Residential	Residential
Average area per occupant	m^2 / person	40	40	40	40	40	40	40
Typical indoor temperature (for calculations)	°C	20	20	20	20	20	20	20
HVAC systems								
Type of existing heating system		Boiler	Boiler	Boiler	Boiler	Boiler	Boiler	Boiler
Existing energy carrier		Gas	Oil	Gas	Oil	Gas	Gas	Gas
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No	No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No	No	No	No	No
Ventilation rate	ach	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Is a cooling system installed?	Yes/No	No	No	No	No	No	No	No
Hot water consumption	l/person/day	40	40	40	40	40	40	40

3.8.2 Calculation parameters and scenarios

Table 46: General parameters for the calculations of the Swiss Case Study.

Parameter	Explanation/definition
Date the calculations were made	2021-2022
Weather file used	Central Plateau
External shading (by surrounding buildings) considered	No

For the calculation of the energy performance, the weather file for the Central Plateau in Switzerland was used. The weather file is a standard climate that is included in the energy performance calculation tool. The external shading by surrounding buildings is not considered.

Eight renovation scenarios were investigated for the building envelope, including insulation of the exterior walls, the roofs, new windows, and the cellar ceiling. Besides these scenarios that lead to a reduction of the energy need and an improvement of the thermal behaviour, a reference scenario was considered which restores the building's functionality, without any energy improvements.

The renovation measures include two energy standards: renovation to the Minergie standard and renovation to the Minergie-P standard, regarding insulation thickness and U-values of the building components. The insulation thickness required for each building type differs and depends on the energetic properties of the building before renovation.

The following scenarios for building envelope measures were considered – the range in insulation thicknesses for the building types considered is indicated with a hyphen:

- Reference case: renovation of wall or roof and windows to restore the building's functionality, yet without improving efficiency
- Scenario 1: Insulation of exterior wall with 4-11 cm of rock wool
- Scenario 2: Insulation of exterior wall with 12-21 cm of rock wool
- Scenario 3: Scenario 2 + insulation of cellar ceiling with 3-12 cm of PUR
- Scenario 4: Scenario 2 + insulation of cellar ceiling with 9-19 cm of PUR
- Scenario 5: Scenario 4 + insulation of roof with 2-13 cm of EPS
- Scenario 6: Scenario 4 + insulation of roof with 12-24 cm of EPS
- Scenario 7: Scenario 6 + new windows with U-value of 1.3 W/(m²K)
- Scenario 8: Scenario 6 + new windows with U-value of 0.78 W/(m²K)

Table 47 and Table 48 give an overview of the investigated scenarios and the assumptions for the measures on the building envelope and the energy supply system.

Table 47: Measures on the building envelope for the reference scenario ("Ref") as well as for scenarios 1 to 8; the range between the various building types is indicated with a hyphen.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8
Walls										
U-values	W/m²K	0.16 - 0.73	0.16 - 0.25	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16
Investment costs	EUR/m²building element	70	153	153 - 160	153 - 160	153 - 160	153 - 160	153 - 160	153 - 160	153 - 160
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	20	30	30	30	30	30	30	30	30
Cellar ceiling										
U-values	W/m²K	0.27 - 1.50	0.27 - 1.50	0.27 - 1.50	0.20 - 0.30	0.15	0.15	0.15	0.15	0.15
Investment costs	EUR/m²building element	-	-	-	157 - 161	157 - 176	157 - 176	157 - 176	157 - 176	157 - 176
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	-	-	-	40	40	40	40	40	40
Roofs										
U-values	W/m²K	0.16 - 2.10	0.16 - 2.10	0.16 - 2.10	0.16 - 2.10	0.16 - 2.10	0.16 - 0.25	0.15 - 0.16	0.15 - 0.16	0.15 - 0.16
Investment costs	EUR/m²building element	66	66	66	66	66	195 - 203	199 - 224	199 - 224	199 - 224
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	30	30	30	30	30	35	35	35	35
Windows										
U-values	W/m²K	2.00 - 2.80	2.00 - 2.80	2.00 - 2.80	2.00 - 2.80	2.00 - 2.80	2.00 - 2.80	2.00 - 2.80	1.31	0.78
Investment costs	EUR/m²building element	40	40	40	40	40	40	40	916	1038
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	15	15	15	15	15	15	15	25	25

The following table shows the HVAC systems that were considered. For the eight scenarios of packages of renovation measures on the building envelopes, combinations with the following energy supply systems were investigated:

- At the building level:
  - decentralised oil or gas heating systems as the reference case
  - decentralised air-source heat pumps
  - decentralised ground-source heat pumps
- At the district level:
  - Lake water district heating with centralised heat pump
  - Cold lake water district heating with decentralised heat pumps, i.e., water is transported as a heat source to each building for use in decentralised heat pumps
  - District heating with centralised ground source heat pump

Table 48: Measures of the HVAC system; the detailed data for calculations of heating systems 4-7 was obtained under a confidentiality agreement and cannot be shared here.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8
Decentralised oil or gas heating systems as the reference case										
Capacity	kW	1 307	1 184	1 142	1 070	1 052	920	898	769	692
Investment costs	EUR/kW	1 066	1 131	1 155	1 197	1 208	1 298	1 317	1 445	1 545
Mainte-nance costs	EUR/year	22 590	22 440	22 360	22 370	22 240	22 140	22 100	21 850	21 700
Service life	Years	20	20	20	20	20	20	20	20	20
Decentralised air-source heat pumps										
Capacity	kW	1 307	1 184	1 142	1 070	1 052	920	898	769	692
Investment costs	EUR/kW	2 756	2 788	2 802	2 832	2 840	2 893	2 906	3 002	3 092
Mainte-nance costs	EUR/year	15 180	14 860	14 730	14 490	14 430	14 040	13 960	13 720	13 700
Service life	Years	20	20	20	20	20	20	20	20	20
Decentralised ground-source heat pumps										
Capacity	kW	1 307	1 184	1 142	1 070	1 052	920	898	769	692
Investment costs	EUR/kW	3 580	3 639	3 662	3 706	3 717	3 818	3 838	3 976	4 083
Mainte-nance costs	EUR/year	12 590	12 510	12 480	12 410	12 400	12 280	12 250	12 130	12 050
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 3.7 for decentralised air source heat pumps depending on the level of 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 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.

3.8.3 Case study results

The following graphs give an overview of the results obtained:

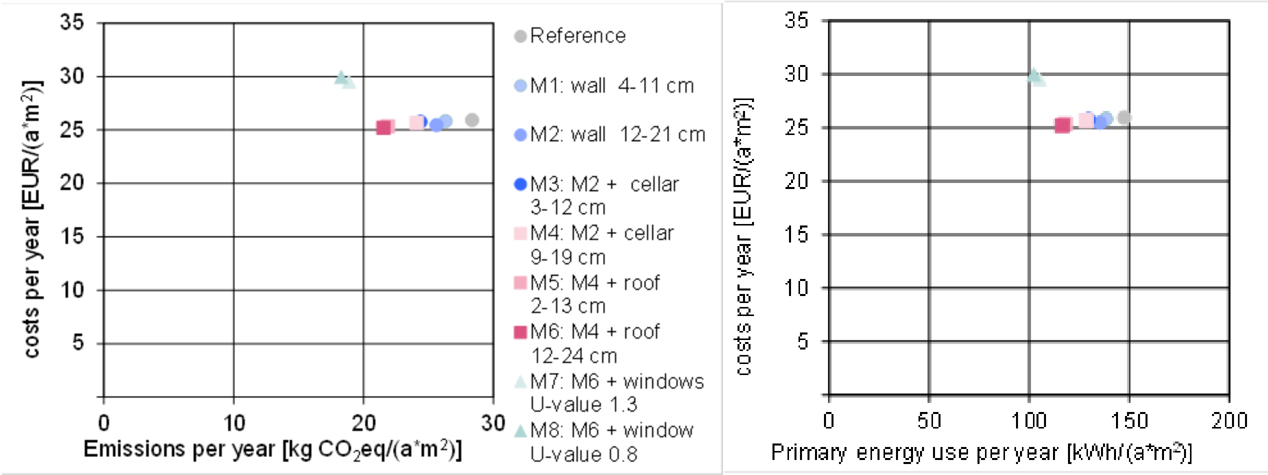

Figure 91: Reference heating system (decentralisedl oil/gas heating).

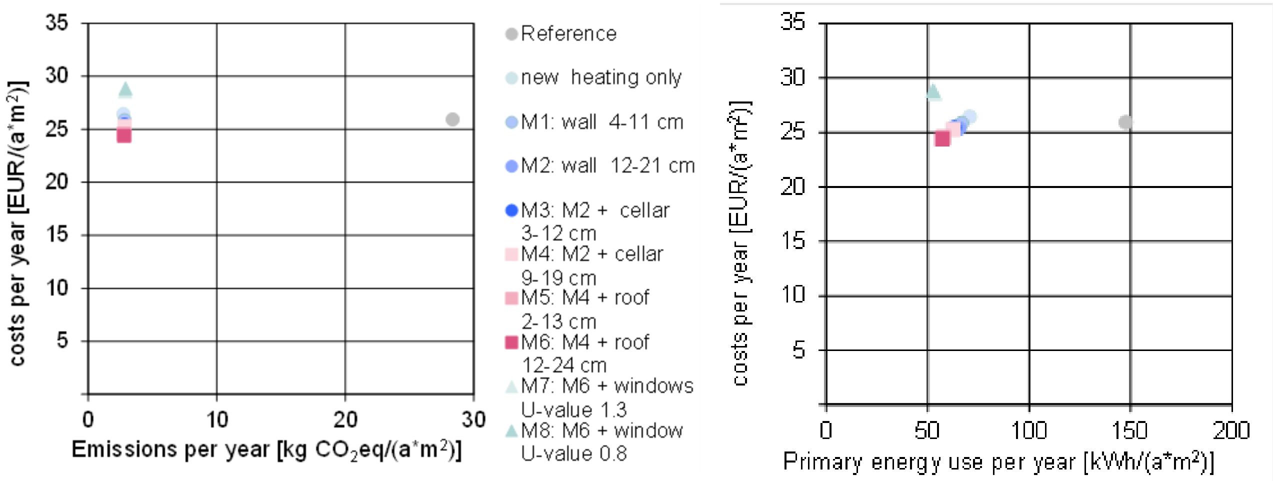

Figure 92: Heating system 2 – Decentralised air source heat pumps.

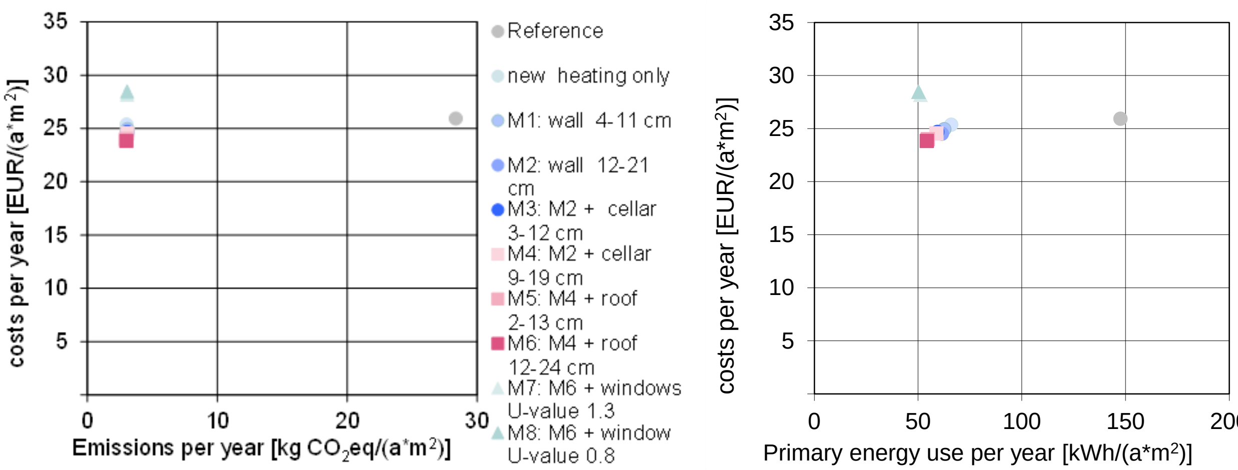

Figure 93: Heating system 3 – Decentralised ground source heat pumps.

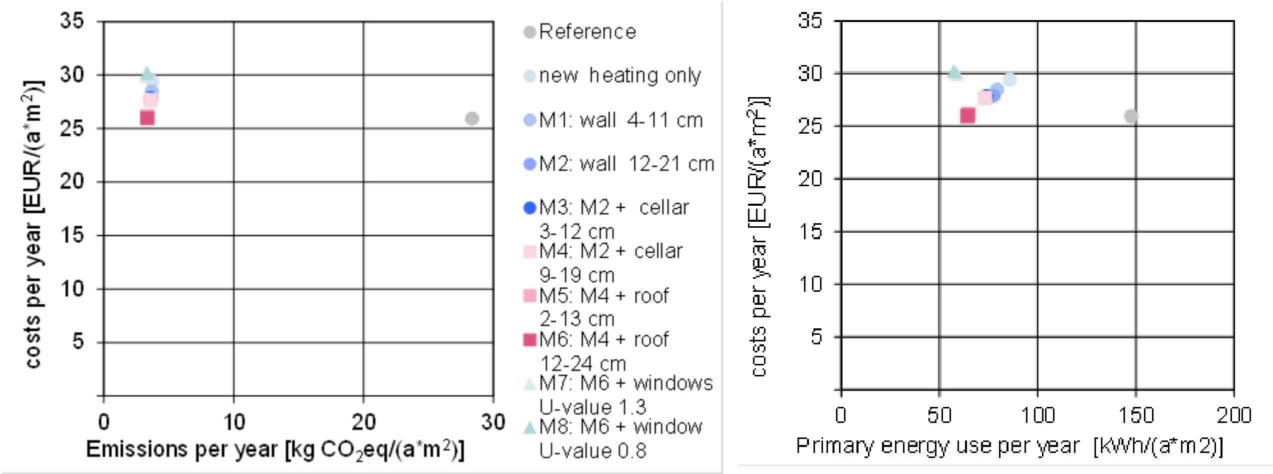

Figure 94: Heating system 4 - Lake water district heating with centralised heat pump.

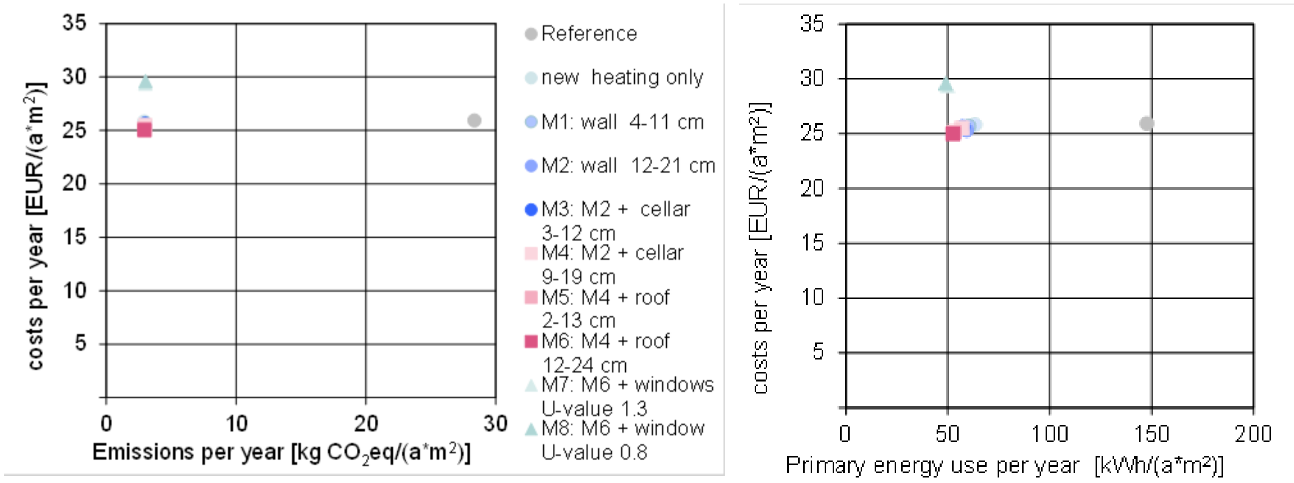

Figure 95: Heating system 5 - Cold lake water district heating with decentralised heat pumps.

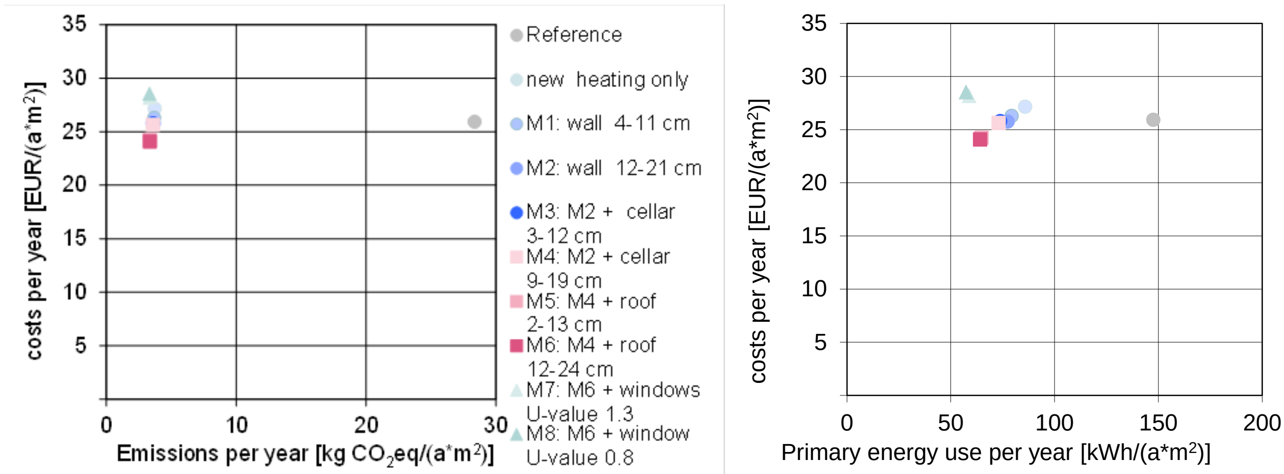

Figure 96: Heating system 6 - District heating with centralised ground source heat pump.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

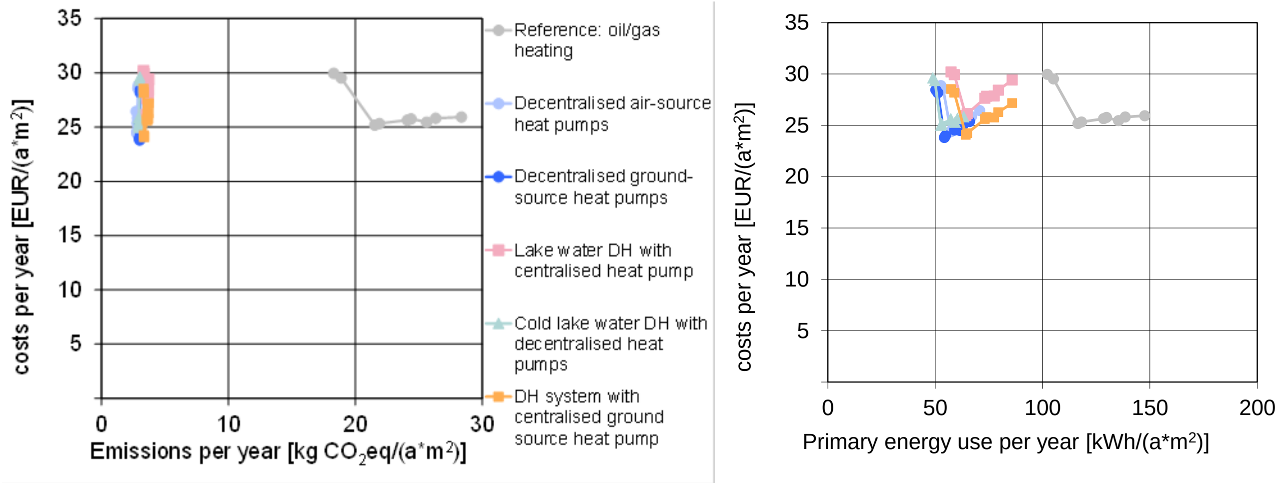

Figure 97: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

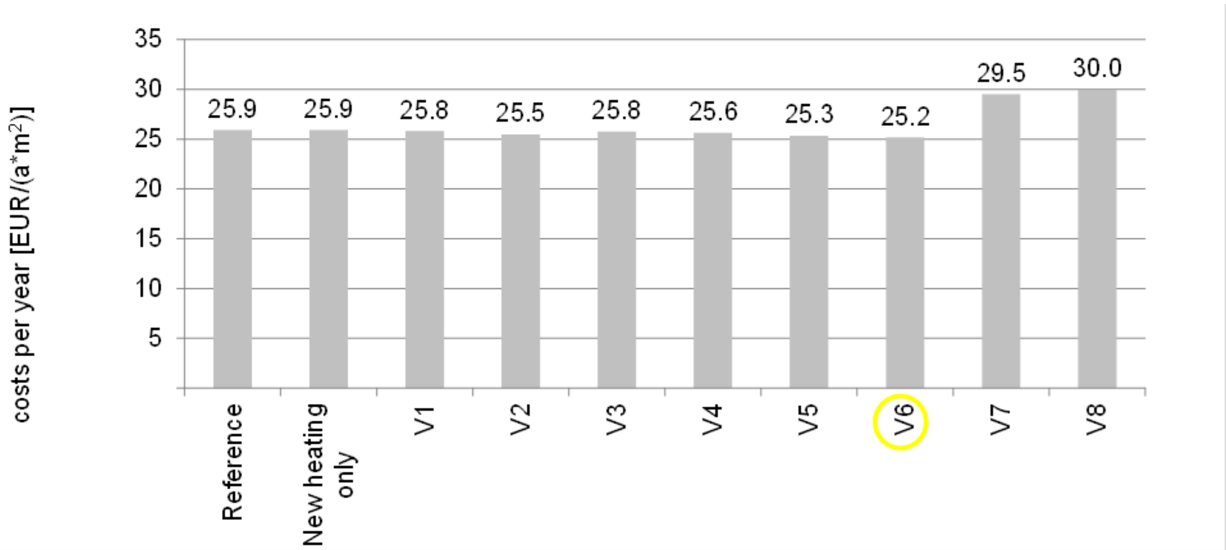

Figure 98: Reference heating system (decentralised oil/gas heating).

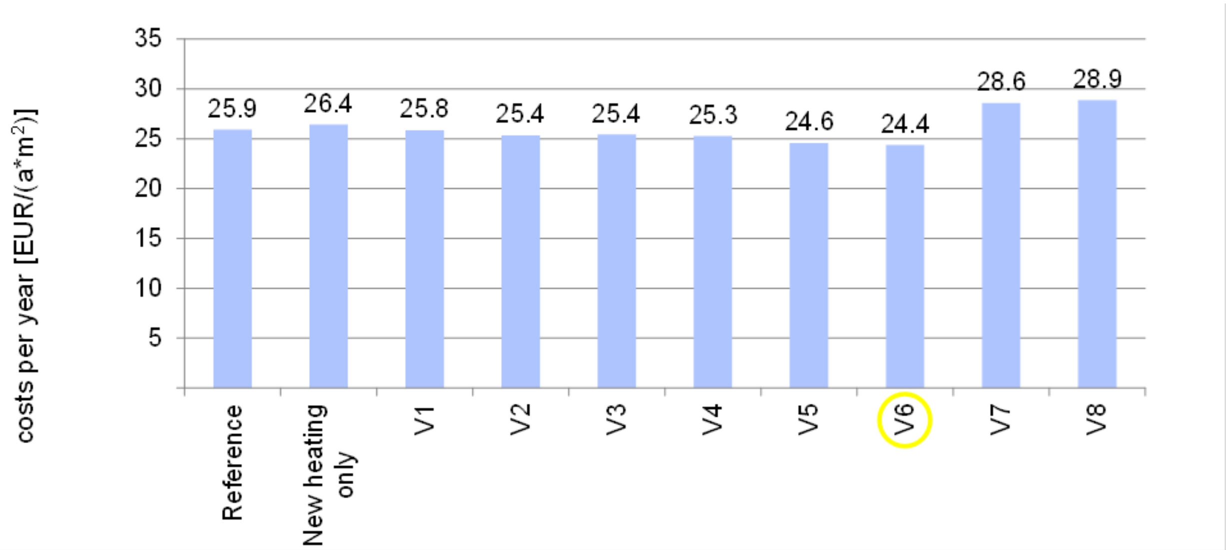

Figure 99: Heating system 2 - Decentralised air-source heat pumps.

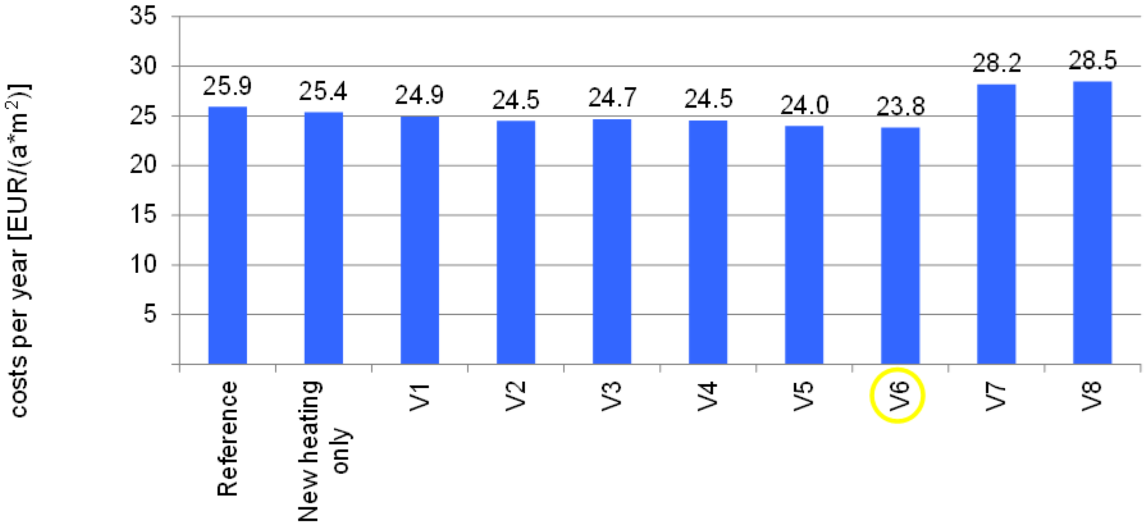

Figure 100: Heating system 3 - Decentralised ground-source heat pumps.

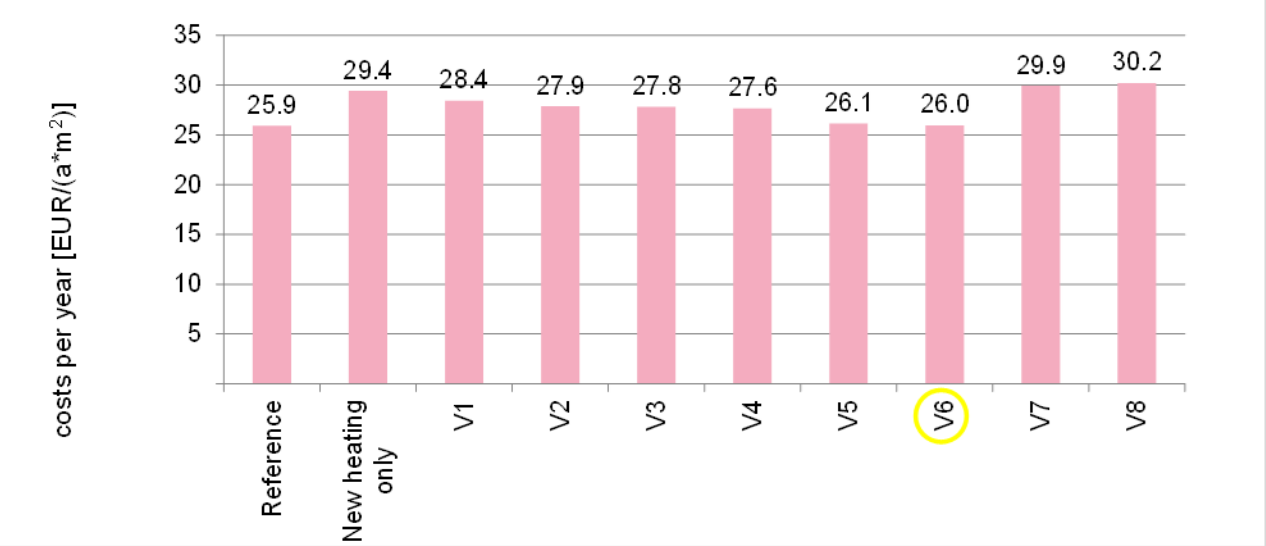

Figure 101: Heating system 4 – Lake water district heating with centralised heat pump.

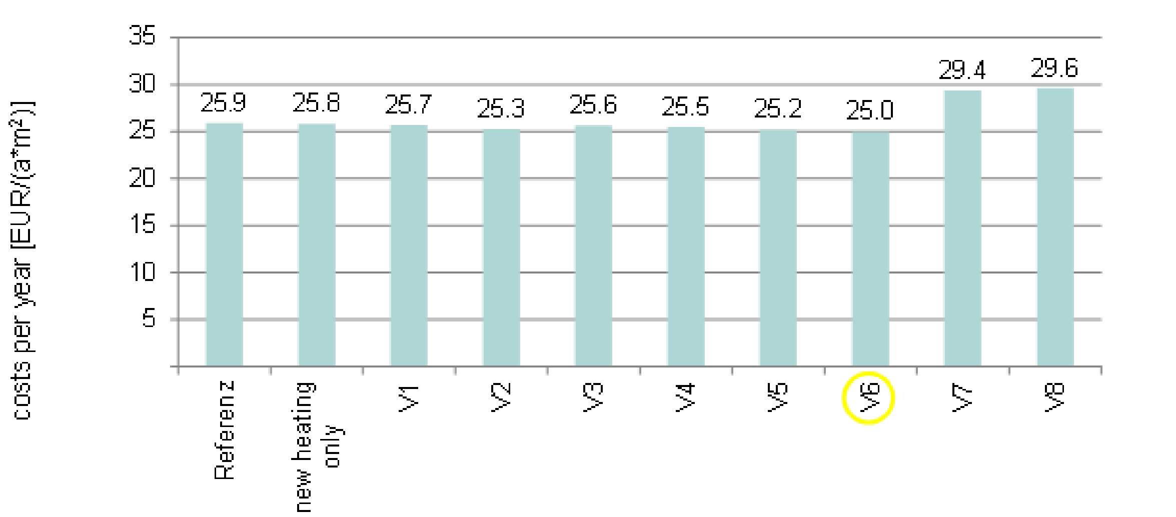

Figure 102: Heating system 5 – Cold lake water district heating with decentralised heat pumps.

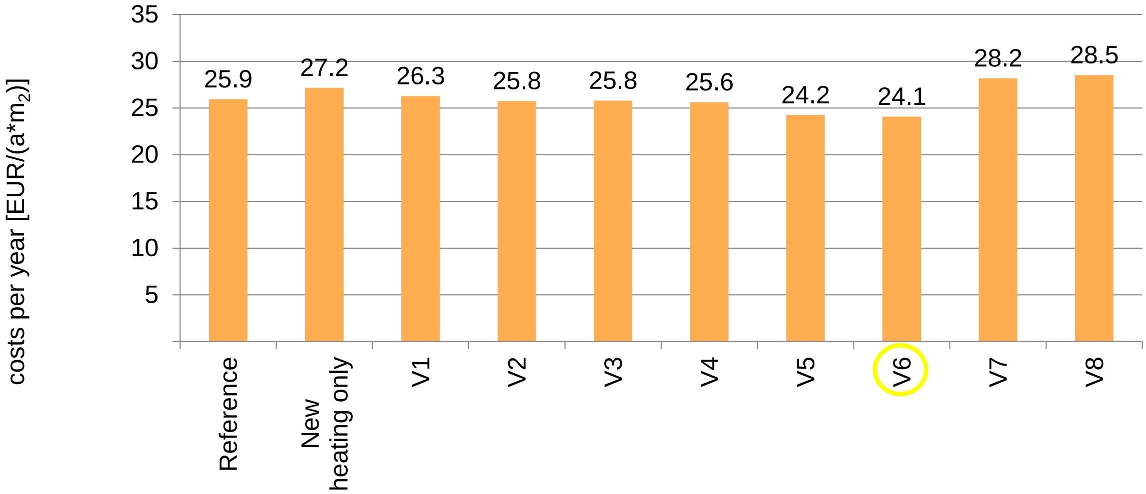

Figure 103: Heating system 6 – District heating with centralised ground source heat pump.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

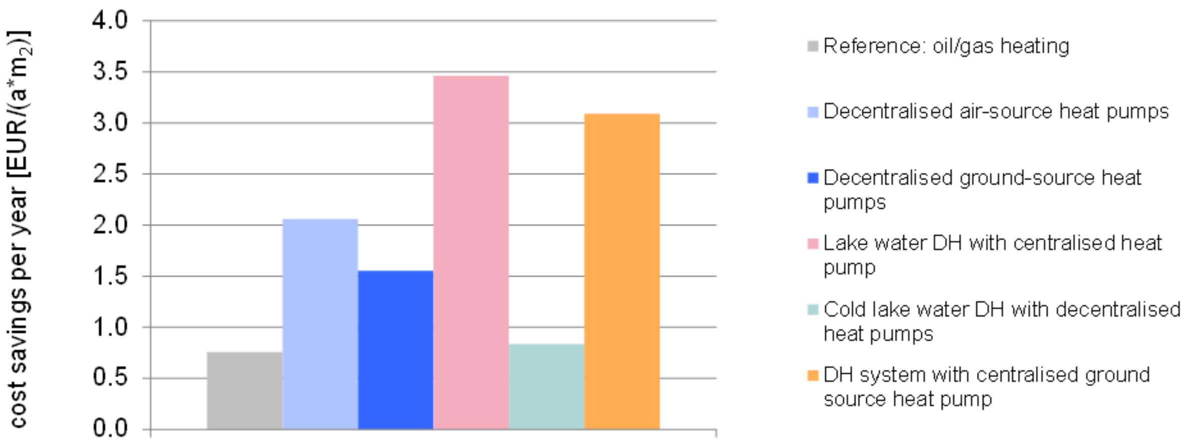

Figure 104: Cost-saving potential of the optimal scenario per energy supply variant.

In addition, the following graphs indicate the cost-effectiveness of various types of heating systems with and without the most cost-effective renovation package on the building envelope:

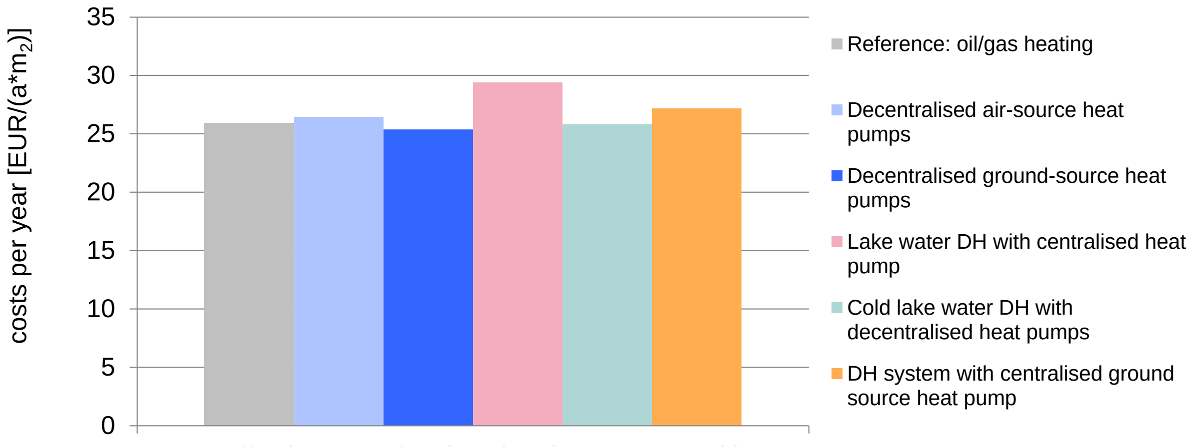

Figure 105: Cost-effectiveness of various heating systems without energy efficiency measures on building envelopes.

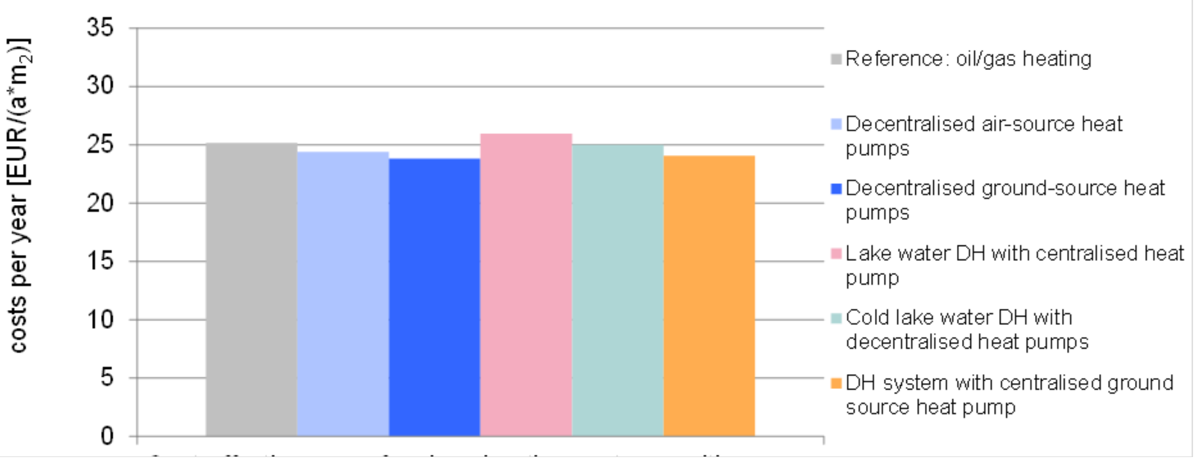

Figure 106: Cost-effectiveness of various heating systems with the most cost-effective renovation package on building envelope.

Based on these graphs, the following 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 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, there are scenarios with decentralised ground source heat pumps that offer cost advantages in comparison with heating systems based on fossil fuels. There are scenarios with a cold lake water district heating system with decentralised heat pumps that are equally cost-effective. With energy efficiency measures, there are also scenarios with decentralised air source heat pumps or a district heating system with a centralised ground source heat pump that are more cost-effective than scenarios with fossil fuel-based heating systems. Furthermore, with

energy efficiency measures, there are scenarios with a lake water district heating system with a centralised heat pump nearly as cost-effective as a fossil fuel-based system.
- Of the various types of heating systems investigated, decentralised ground source heat pumps offer the most cost-effective solution, combined with efficiency measures on the building envelopes.
- Other renewable energy source-based heating systems investigated, when combined with energy efficiency measures on building envelopes, are nearly as cost-effective: decentralised air source heat pumps, a cold lake water district heating system with decentralised heat pumps, a lake water district heating system with a centralised heat pump, a district heating with a centralised ground source heat pump.

All scenarios based on renewable energy sources have similarly low carbon emissions. The solution, which also causes the lowest amount of primary energy use, comprises a cold lake water district heating system with decentralised heat pumps and energy efficiency measures on the building envelopes. Combining decentralised ground source heat pumps with energy efficiency measures on building envelopes or decentralised air source heat pumps with such energy efficiency measures have similarly low primary energy use.

3.8.4 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 achieving climate protection targets. In addition, the results of the calculations show that a switch to renewable energy-based heating systems is also cost-effective or nearly cost-effective with several renewable energy-based heating systems investigated. This cost-effectiveness becomes even more pronounced when combinations with energy efficiency measures are considered. Carbon emissions are similarly low for all scenarios with renewable energy-based heating systems and significantly lower than in the case of heating systems with fossil fuels. Primary energy use is also lower for scenarios with renewable energy-based heating systems than with fossil fuel-based heating systems, but the difference is smaller. For heating systems based on a centralised heat pump, whether with lake water or the ground as the heat source, carbon emissions and primary energy use are higher than for decentralised air source heat pumps, decentralised geothermal heat pumps, or a cold lake water district heating system with decentralised heat pumps. The reason is that the overall efficiency of the former energy systems is somewhat lower 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 were heated decentrally; a district heating system has to deliver the highest temperature required by any of the connected buildings and, in addition, energy losses in the grid mean that, in the central heat generation location, 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 the case before 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, two effects 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 fossil fuel ones. The lower the energy needed, the lower the required capacity of the installed heating system. Therefore, renewable energy-based heating systems benefit 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, which increases the efficiency of the heat pump. 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 in the case of a combination with decentralised heating systems based on renewable energy than in combination 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. This happens because such district heating systems have a large share of costs, 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.

For a district heating system with a centralised ground source heat pump, the need to regenerate ground heat plays a role. Without energy efficiency measures on the building envelopes, a significant amount of heat regeneration is necessary, for example, through additional solar thermal systems as assumed in the case study. Energy efficiency measures reduce the need for such systems to regenerate heat in the ground. With an advanced level of energy efficiency measures, there is even no need at all for heat regeneration in the ground over an estimated period of use of 50 years. This effect accordingly contributes to strong synergies between energy efficiency measures on building envelopes and the switch to a renewable energy-based system at the district level.

Nevertheless, it was found that there are fewer economies of scale for decentralised renewable energy systems than for district heating systems. An explanation is that, even if there are economies of scale also in the case of smaller systems such as heat pumps, there are other factors - such as the necessity to comply with noise restrictions, challenges associated with the drilling of boreholes or the necessity to regenerate heat in the ground - that become more than proportionally higher in case the size of the heating systems increases. This can therefore cancel out any benefits that might be obtained from economies of scale that might be obtained just for the heat pumps. This reinforces the attractiveness of energy efficiency measures on building envelopes at the level of decentralised buildings in comparison with district-based solutions.

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

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

The cost-effectiveness of energy efficiency measures on building envelopes is slightly higher for air source heat pumps than for ground source heat pumps. A reason can be that ground source heat pumps already have a relatively high efficiency, and accordingly benefit in relative terms less 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 measures to improve the efficiency of the wall, the roof, and the cellar ceiling. The installation of new windows was not found to be cost-effective in combination with any type of heating system; a related renovation measure, therefore, requires a different type of motivation than saving costs.

Based on the calculations and related assumptions for the investigated heating systems, it was found that decentralised ground source heat pumps and a district heating system based on a centralised ground source heat pump are the most cost-effective solutions, in combination with energy efficiency measures.

Of the other systems investigated, decentralised air source heat pumps or a cold lake water district heating system are the next most cost-effective solutions, in combination with energy efficiency measures, with a slight advantage of the decentralised ground source heat pump compared with 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 the higher investment costs of ground-source heat pumps due to the drilling of boreholes.

Lake water-based district heating systems are a bit less cost-effective under the assumptions made, yet they continue to be cost-effective or nearly cost-effective in comparison with the fossil fuel-based reference case. 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 enough to serve all district buildings. This benefits the efficiency of the heat pumps involved. Furthermore, there are fewer heat losses associated with the grid because lake water is distributed at cold temperatures, which saves energy and makes the heat pumps run more efficiently in the 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 concerning 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 make use of energy resources that single buildings could not access. Lake water is, for example, a particularly attractive heat source, as its temperature is higher in winter than in the air, and heat exchange can be easily achieved with water. Often, lake water 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 of contamination of the environment. Other attractive energy resources are waste heat, water from rivers or the groundwater, 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 work, accordingly, most efficiently. This contrasts with a district heating system, which must 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 vital for making a centralised lake water-based heat pump and a centralised ground source heat pump cost-effective or nearly cost-effective.

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 energy prices of oil and gas of 30% until 2030 compared to 2021 was assumed. This might underestimate price increases in the case for example the war in Ukraine has a long-term impact on energy prices. In cases energy prices of fossil fuels increase more, 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 electricity will be provided in future 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 must 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 to obtain enough electricity in the future in winter months from other neighbouring countries instead, for example, through wind energy or solar energy from countries further South, energy 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 must 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 allowing rivers to flow naturally. In case such external costs were considered, the attractiveness of strategies with an amount of energy consumption as low as possible would increase.

In the case of drilling boreholes for decentralised or centralised ground source heat pumps, regeneration of heat in the ground is probably necessary in many cases if such a solution is implemented in an entire district. At least this was found to be necessary in the case study investigated and accordingly taken into account in the assessment. Such regeneration of the heat is often done through solar collectors. If this is done through this technology, this means that less roof area is available for electricity production through PV. This effect was not yet considered. Taking it into account might reinforce the attractiveness of energy efficiency measures in combination with ground source heat pumps and reduce to some extent the attractiveness of ground source heat pumps in comparison with other renewable energy technologies. However, there are also options to harvest simultaneously heat and electricity through solar panels, which might reduce the significance of this effect.

There is a potential advantage of a lake-water district heating system that was not yet considered: the assessment was only carried out for the specific district investigated; the option that the buildings concerned connect to a larger lake water-based district heating system was not yet into account. Connecting 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 to the cost-effectiveness of district heating systems in general, which were not yet considered:

- In calculations carried out, the same electricity price was applied for decentralised heat pumps as for district heating systems with centralised heat pumps, for the sake of transparency in the comparison of cost-effectiveness. However, from the perspective of investors or building owners, it must be considered that a centralised heat pump is a large electricity consumer which can obtain tariffs with lower electricity prices than this is the case for decentralised systems.
- If an electricity supply company has the possibility to operate a district heating system, it has the interest to do so and sell 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 calculate with even lower electricity costs, if necessary, to be cost-effective compared with other types of heating systems.

In case 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 the cost-effectiveness of various heating systems is relatively similar under current assumptions. These additional factors are, therefore, likely to have an important impact on the cost-effectiveness of district solutions, particularly lake-water-based district heating systems, compared with decentralised solutions.

The following table indicates whether the formulated hypotheses are confirmed or not confirmed for the investigated case study:

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.»	Yes
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.»	Not investigated
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.»	Not investigated
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 energy.»	Yes
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.»	Yes
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	Not investigated

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.»	Yes
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.»	Not investigated

3.9 Switzerland - Zürich

3.9.1 Description of the district

The case study is in Zürich in the Eastern part of Switzerland. The case study consists of 18 buildings constructed between 1949 and 1955. **Table 49** gives some general information on the district and its location, while **Figure 107** shows the aerial view of the case study.

Table 49: General information about the district.

Parameter	Explanation/definition
Location	Zürich
Latitude	E: 8.531443
Longitude	N: 47.33416
Climate zone	Dfb (Humid continental climate)
Number of buildings in total	18

Figure 107: Aerial view of the Case Study in Zürich in Switzerland (source: based on “Google Maps” by Google n.d.).

Based on the characteristics of the buildings, they were classified into 4 building typologies (see **Table 50**).

Table 50: Building typologies of the Swiss Case Study in Zürich, for building types 1-4; for one of the 8 buildings of type 3, an oil heating system was assumed as starting situation for the assessment for reasons of simplicity, even though the building is already equipped with a heat pump.

Parameter	Unit	type 1	type 2	type 3	type 4
Building information					
Number of buildings per typology		3	4	8	3
Construction period		1950	1950	1950	1958
Geometry					
Gross heated floor area (GHFA)	m^2	1875	535	535	1'100
Heated volume	m^3	n.a.	n.a.	n.a.	n.a.
Façade area incl. window area	m^2	964	276	303	880
Wall to unheated space	m^2	149	72	36	-
Area of attic floor	m^2	574	149	149	340
Additional roof area	m^2	35	12	12	-
Area of windows to North	m^2	-	30	30	10
Area of windows to East	m^2	88	-	-	60
Area of windows to South	m^2	16	48	48	20
Area of windows to West	m^2	50	-	30	60
Area of basement ceiling	m^2	593	103	103	340
Area of floor to ground	m^2	-	57	57	-
Area of floor to exterior	m^2	16	-	-	-
The average number of floors above ground	-	3	3	3	3
Usage					
Type of use		Residential	Residential	Residential	Residential
Average area per occupant	m^2 / person	40	40	40	40

Typical indoor temperature (for calculations)	°C	20	20	20	20
HVAC systems					
Type of existing heating system		Boiler	Boiler	Boiler	Boiler
Existing energy carrier		Gas	Oil	Oil	Oil
Is a ventilation system without heat recovery installed?	Yes/No	No	No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No	No	No
Ventilation rate	ach	0.7	0.7	0.7	0.7
Is a cooling system installed?	Yes/No	No	No	No	No
Hot water consumption	l/person/day	40	40	40	40

3.9.2 Calculation parameters and scenarios

Table 51: General parameters for the calculations of the Swiss Case Study.

Parameter	Explanation/definition
Date the calculations were made	2021-2022
Weather file used	Central Plateau
External shading (by surrounding buildings) considered	No

For the calculation of the energy performance, the weather file for the Central Plateau in Switzerland was used. The weather file is a standard climate that is included in the energy performance calculation tool. The external shading by surrounding buildings is not considered.

Eight renovation scenarios were investigated for the building envelope, including insulation of the exterior walls, the attic floors, new windows, and the cellar ceiling. Besides these scenarios that lead to a reduction of the energy need and an improvement of the thermal behaviour, a reference scenario was considered which restores the building’s functionality without any energy improvements.

The renovation measures include two energy standards: renovation to the Minergie standard and renovation to the Minergie-P standard, regarding insulation thickness and U-values of the building components. The insulation thickness required for each building type differs and depends on the energetic properties of the building before renovation. No measures on building envelopes were considered for buildings of type 4, which already have a high energy performance.

The following scenarios for building envelope measures were considered – the range in insulation thicknesses for the building types considered is indicated with a hyphen:

- Reference case: renovation of walls and windows to restore the building's functionality, yet without improving the efficiency.
- Scenario 1: Insulation of exterior wall with 16 cm of rock wool
- Scenario 2: Insulation of exterior wall with 22-23 cm of rock wool
- Scenario 3: Scenario 2 + insulation of cellar ceiling with 12-14 cm of PUR
- Scenario 4: Scenario 2 + insulation of cellar ceiling with 17-19 cm of PUR
- Scenario 5: Scenario 4 + insulation of attic floor with 7-10 cm of rock wool
- Scenario 6: Scenario 4 + insulation of attic floor with 14-17 cm of rock wool
- Scenario 7: Scenario 6 + new windows with U-value of 1.3 W/(m²K)
- Scenario 8: Scenario 6 + new windows with U-value of 0.78 W/(m²K)

Table 52 and Table 53 give an overview of the investigated scenarios and the assumptions for the measures on the building envelope and the energy supply system.

Table 52: Measures on the building envelope for the reference scenario ("Ref") as well as for scenarios 1 to 8; the range between the various building types is indicated with a hyphen; for buildings of type 4, which already have a high energy performance, no measures on building envelopes were considered.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8
Walls										
U-values	W/m²K	0.9 - 1.0	0.2	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Investment costs	EUR/m²building element	70	156	161 - 162	161 - 162	161 - 162	161 - 162	161 - 162	161 - 162	161 - 162
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	20	30	30	30	30	30	30	30	30
Cellar ceiling										
U-values	W/m²K	1.0 - 1.3	1.0 - 1.3	1.0 - 1.3	0.20	0.15	0.15	0.15	0.15	0.15
Investment costs	EUR/m²building element	-	-	-	163 - 165	174 - 175	174 - 175	174 - 175	174 - 175	174 - 175
Maintenance costs	EUR/m²building element. year	-	-	-	-	-	-	-	-	-
Service life	years	-	-	-	40	40	40	40	40	40
Roofs										
U-values	W/m²K	0.3 - 0.4	0.3 - 0.4	0.3 - 0.4	0.3 - 0.4	0.3 - 0.4	0.20	0.15	0.15	0.15
Investment costs	EUR/m²building element	-	-	-	-	-	89	100	100	100

Maintenance costs	EUR/$m^2_{building\ element}$. year	-	-	-	-	-	-	-	-	-
Service life	years	-	-	-	-	-	40	40	40	40
Windows										
U-values	W/m²K	1.6 - 1.9	1.6 - 1.9	1.6 - 1.9	1.6 - 1.9	1.6 - 1.9	1.6 - 1.9	1.6 - 1.9	1.31	0.78
Investment costs	EUR/$m^2_{building\ element}$	40	40	40	40	40	40	40	916	1038
Maintenance costs	EUR/$m^2_{building\ element}$. year	-	-	-	-	-	-	-	-	-
Service life	years	15	15	15	15	15	15	15	25	25

The following table shows the HVAC systems that were considered. For the eight scenarios of packages of renovation measures on the building envelopes, combinations with the following energy supply systems were investigated:

- At the building level:
  - decentralised oil or gas heating systems as the reference case
  - decentralised air-source heat pumps
  - decentralised ground-source heat pumps
- At the district level:
  - Lake water district heating with centralised heat pump
  - Cold lake water district heating with decentralised heat pumps, i.e., water is transported as the heat source to each building for use in decentralised heat pumps
  - District heating with centralised ground source heat pump

Table 53: Measures of the HVAC system; the detailed data for calculations of heating systems 4-7 was obtained under a confidentiality agreement and cannot be shared here.

Parameter	Unit	Ref	1	2	3	4	5	6	7	8
Decentralised oil or gas heating systems as the reference case										
Capacity	kW	568	404	394	331	328	304	300	283	259
Investment costs	EUR/kW	1 808	2 275	2 314	2 612	2 613	2 775	2 803	2 925	3 127
Mainte-nance costs	EUR/year	20 012	19 624	19 583	19 935	19 339	19 324	19 218	19 151	19 036
Service life	Years	20	20	20	20	20	20	20	20	20
Decentralised air-source heat pumps										
Capacity	kW	568	404	394	331	328	304	300	283	259
Investment costs	EUR/kW	3 350	3 844	3 888	4 227	4 250	4 426	4 459	4 607	4 855
Mainte-nance costs	EUR/year	15 014	14 595	14 549	14 295	14 283	14 162	14 145	14 070	13 936
Service life	Years	20	20	20	20	20	20	20	20	20

Decentralised ground-source heat pumps

Capacity	kW	568	404	394	331	328	304	300	283	259
Investment costs	EUR/kW	4 375	4 929	4 978	5 347	5 371	5 555	5 590	5 744	6003
Mainte-nance costs	EUR/year	12 451	12 347	12 344	12 324	12 322	12 321	12 319	12 315	12 295
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 2.6 and 3.1 depending on the level of the energy performance of the buildings for decentralised air source heat pumps, between 3.2 and 3.8 for decentralised ground source heat pumps, between 2.7 and 3.2 for a centralised ground source heat pump or a centralised water source heat pump, and between 3.3. and 4.1 for decentralised water source heat pumps in connection with a cold district heating system.

3.9.3 Case study results

The following graphs give an overview of the results obtained:

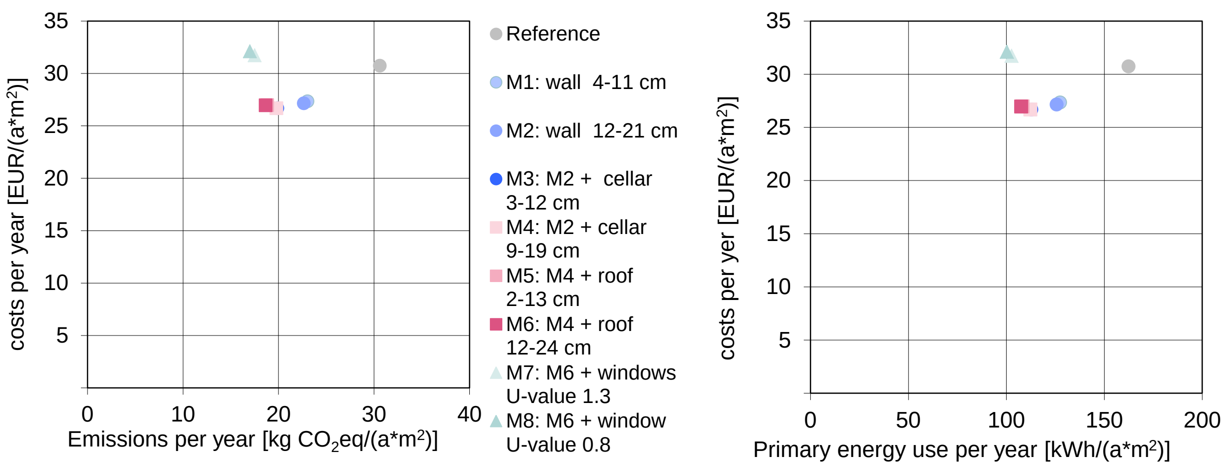

Figure 108: Reference heating system (decentralised oil/gas heating).

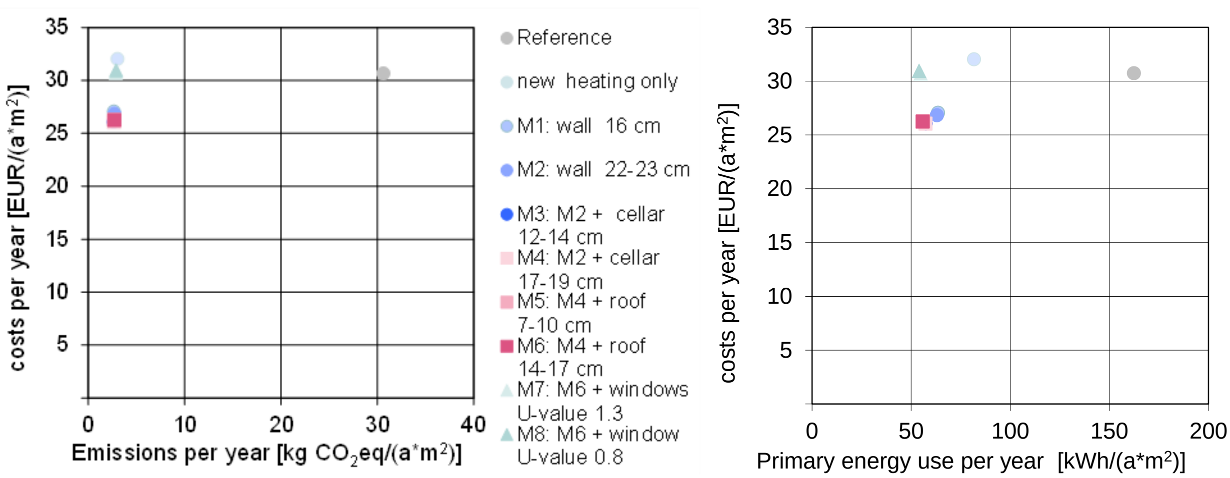

Figure 109: Heating system 2 – Decentralised air source heat pumps.

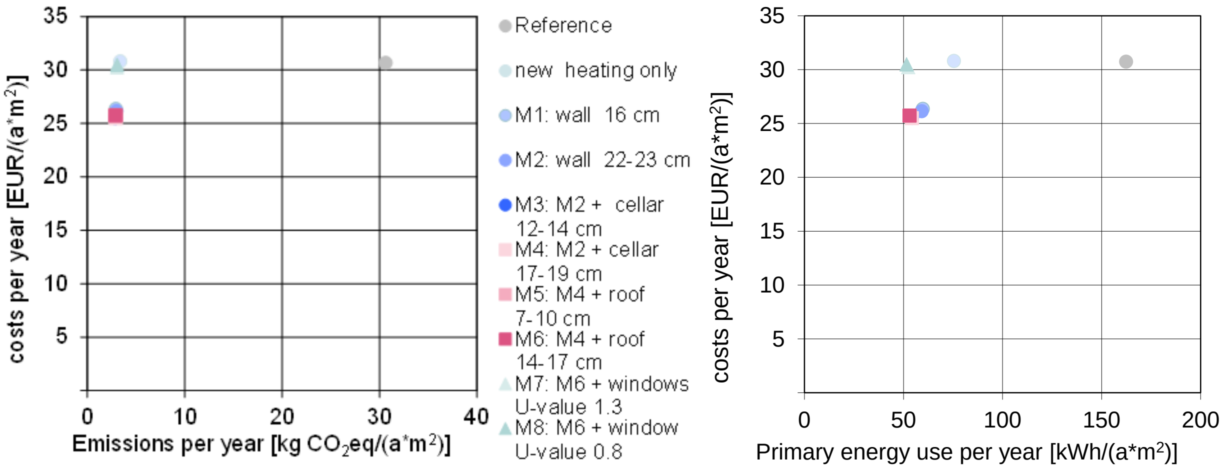

Figure 110: Heating system 3 – Decentralised ground source heat pumps.

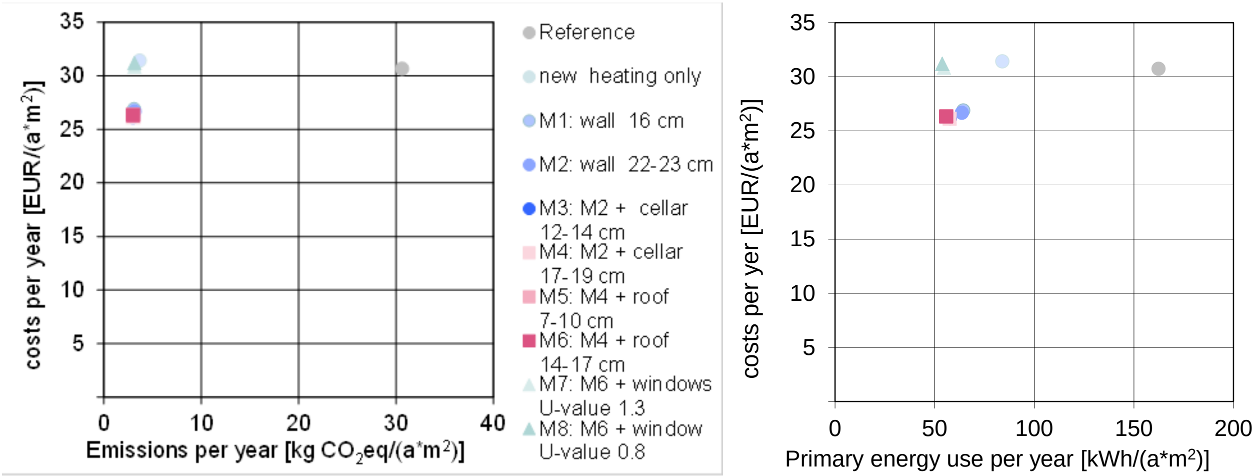

Figure 111: Heating system 4 - Lake water district heating with centralised heat pump.

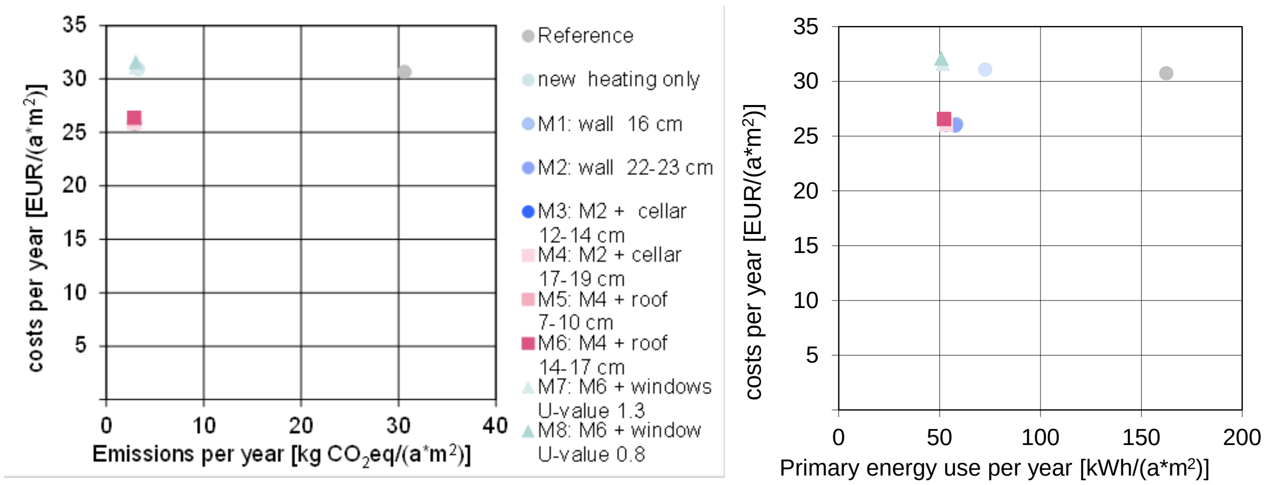

Figure 112: Heating system 5 - Cold lake water district heating with decentralised heat pumps.

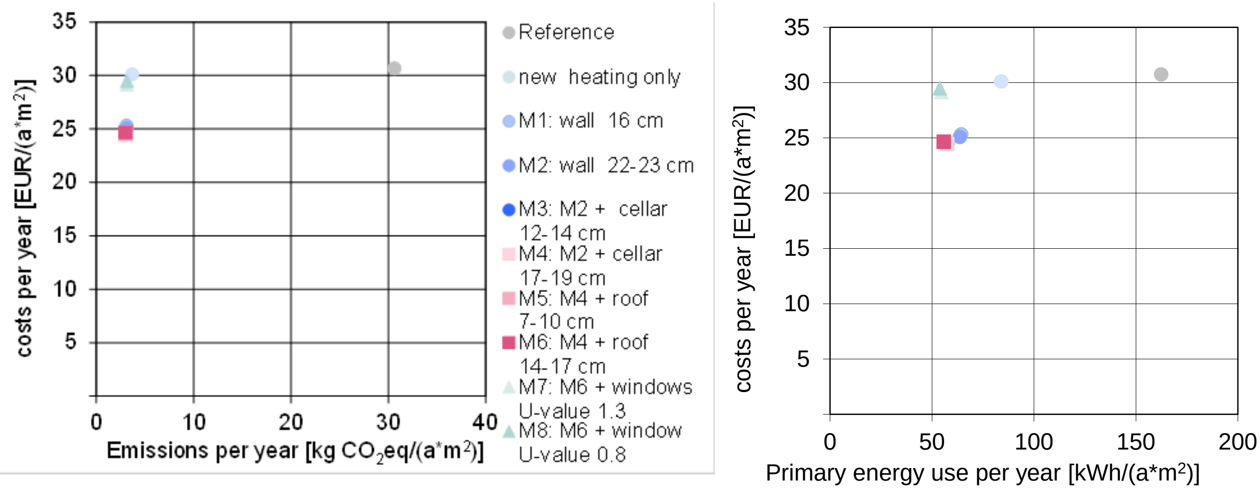

Figure 113: Heating system 6 - District heating with centralised ground source heat pump.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

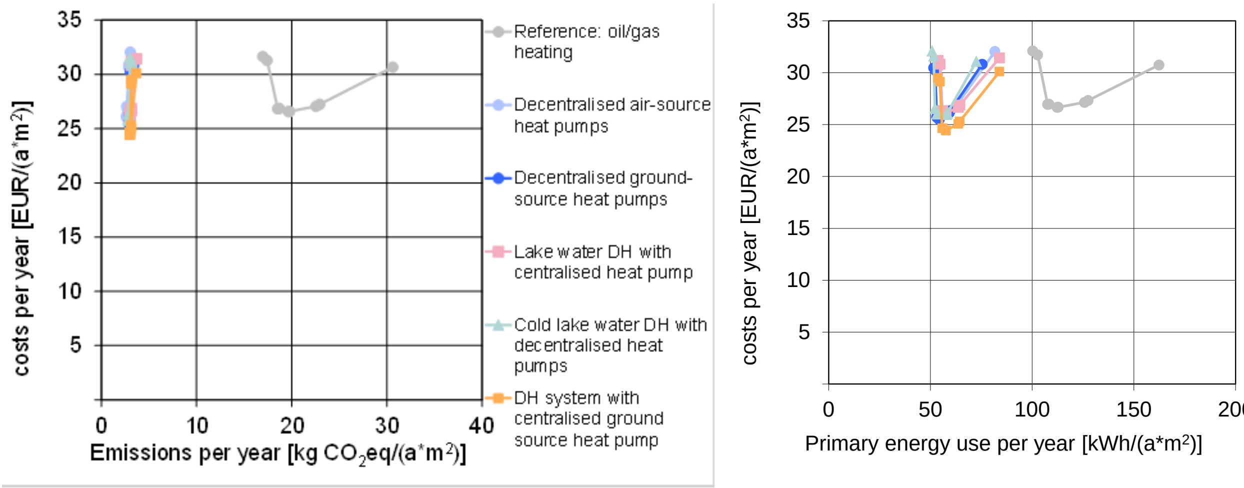

Figure 114: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated:

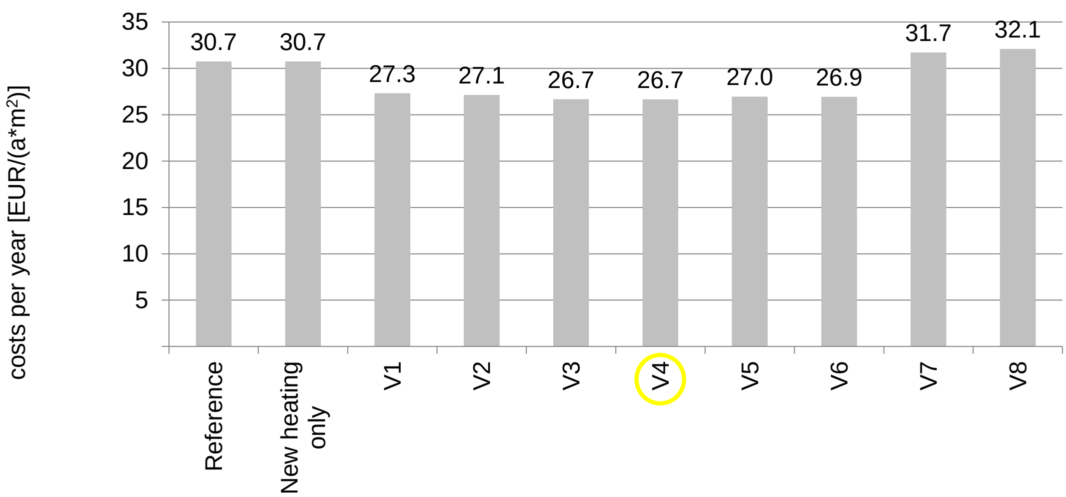

Figure 115: Reference heating system (decentralised oil/gas heating).

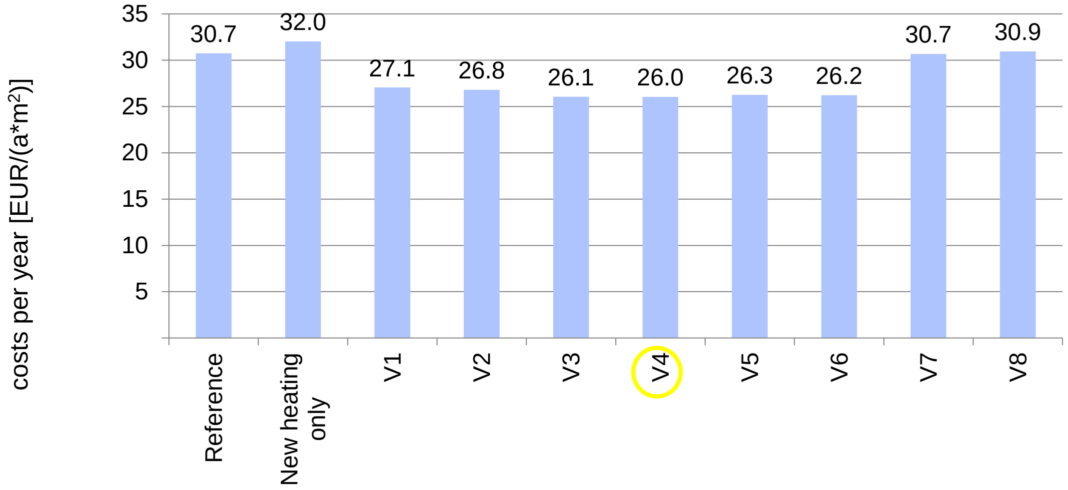

Figure 116: Heating system 2 - Decentralised air-source heat pumps.

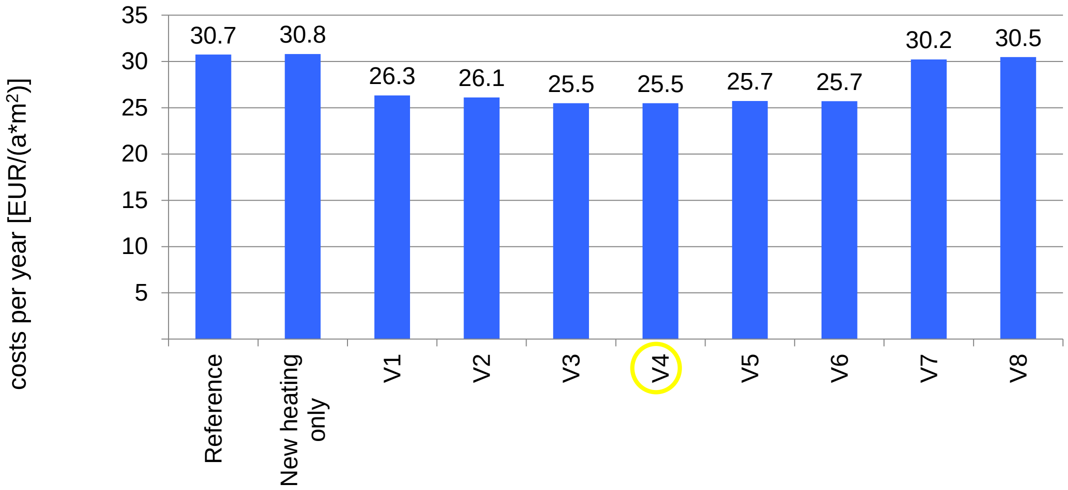

Figure 117: Heating system 3 - Decentralised ground-source heat pumps.

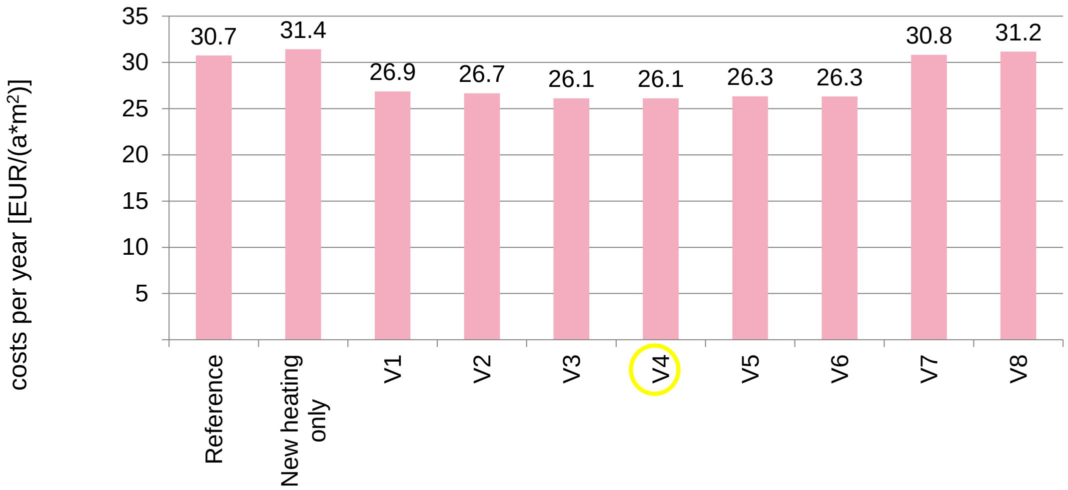

Figure 118: Heating system 4 – Lake water district heating with centralised heat pump.

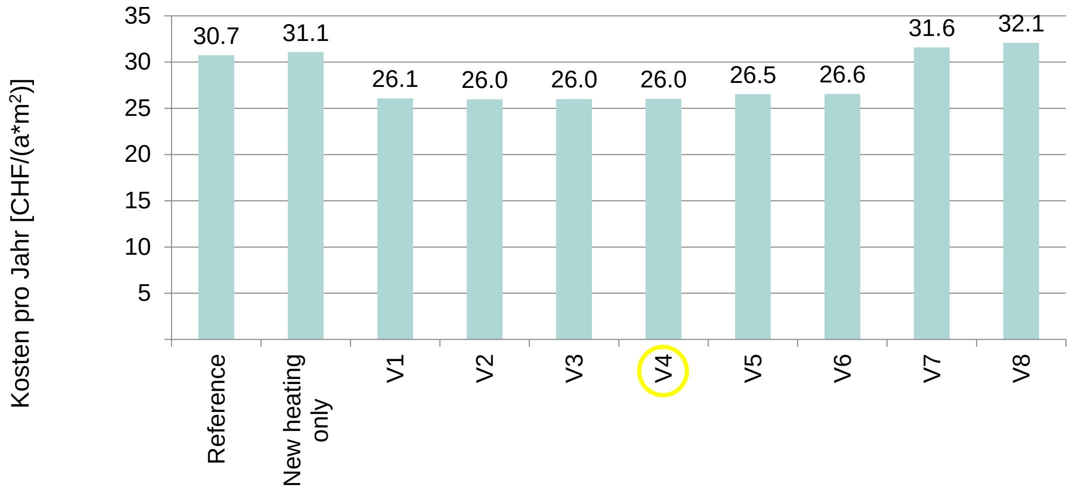

Figure 119: Heating system 5 – Cold lake water district heating with decentralised heat pumps.

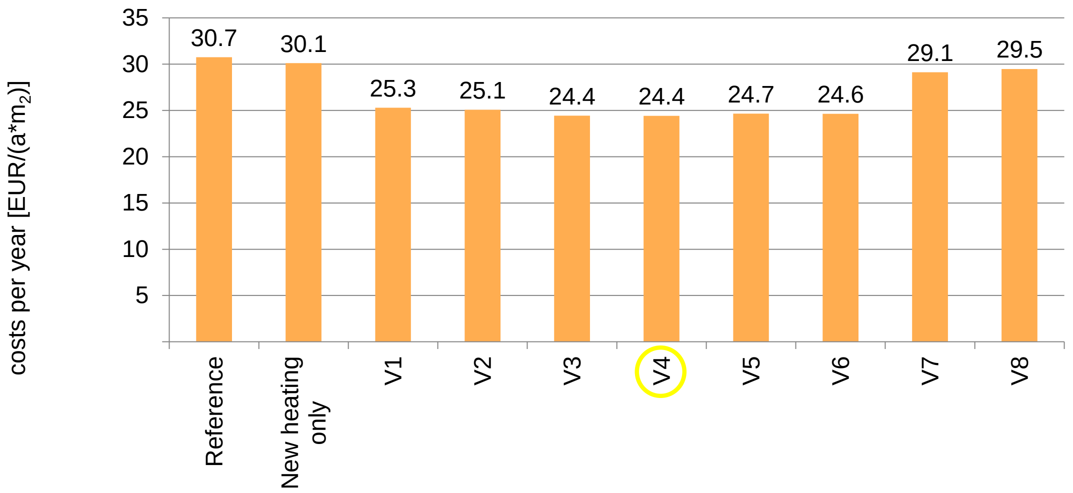

Figure 120: Heating system 6 – District heating with centralised ground source heat pump.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

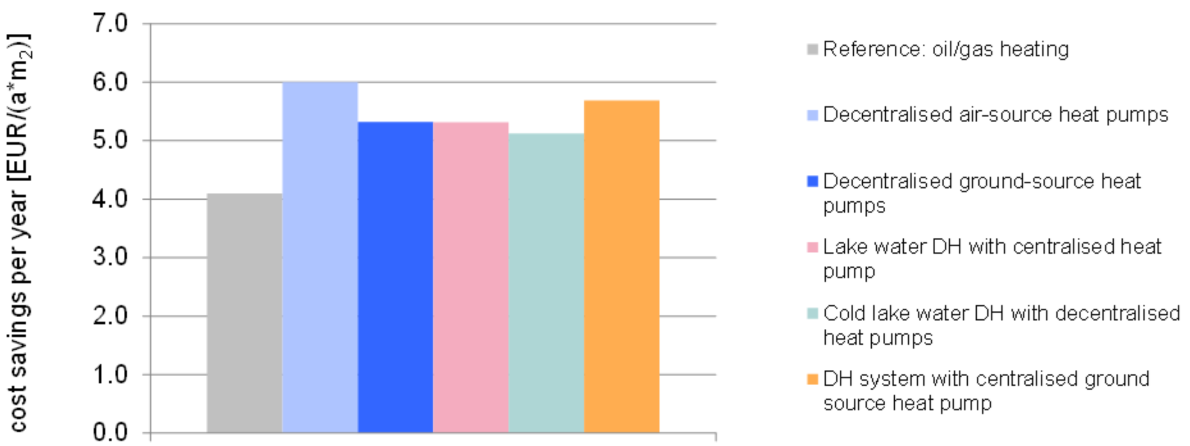

Figure 121: Cost-saving potential of the optimal scenario per energy supply variant.

In addition, the following graphs indicate the cost-effectiveness of various types of heating systems with and without the most cost-effective renovation package on the building envelope:

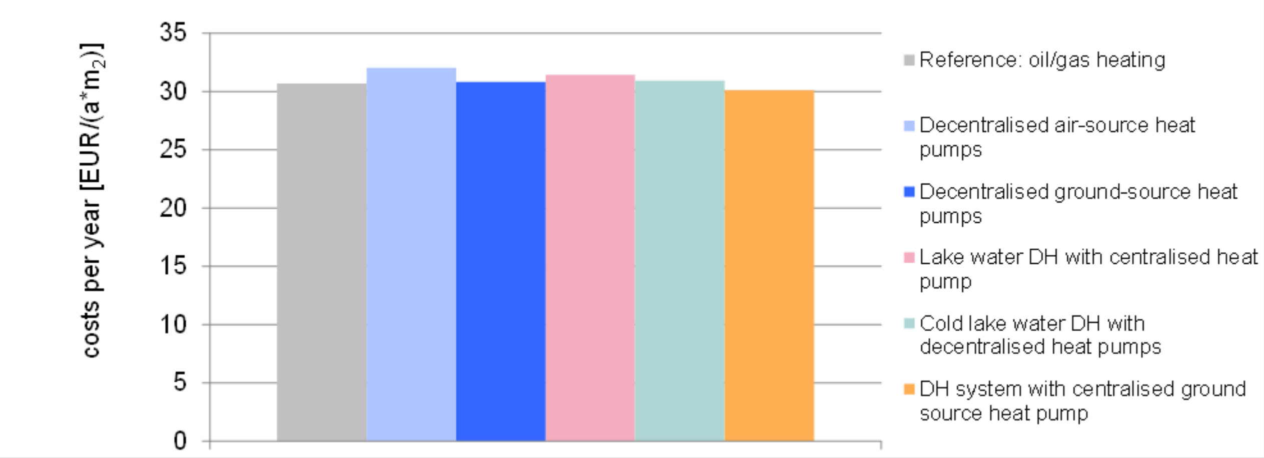

Figure 122: Cost-effectiveness of various heating systems without energy efficiency measures on building envelopes.

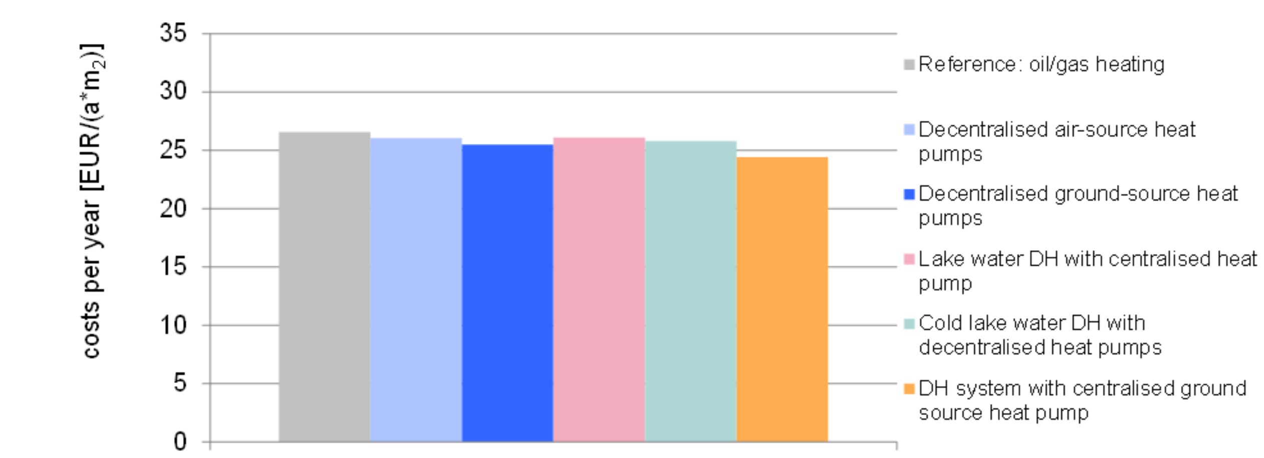

Figure 123: Cost-effectiveness of various heating systems with the most cost-effective renovation package on building envelope.

Based on these graphs, the following can be recognized:

- Energy efficiency measures on the building envelopes are cost-effective for all scenarios of heating systems considered.
- Package M4 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, when combined with energy efficiency measures on building envelopes; without such energy efficiency measures, only one of the renewable energy-based heating systems is cost-effective in comparison with the fossil fuel-based reference case.
- The installation of new windows was not found to be cost-effective in combination with any type of heating system. The reason for this is, that the existing windows are already in a rather good condition.
- 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 decentralised air-source heat pumps and for a district heating system based on a centralised ground source heat pump.
- Of the various types of heating systems investigated, the centralised ground source heat pump or the decentralised ground source heat pumps are found to offer the most cost-effective solution, in combination with efficiency measures on the building envelopes.
- Other renewable energy source-based heating systems investigated, when combined with energy efficiency measures on building envelopes, are nearly as cost-effective: decentralised air source heat pumps, a lake water district heating system with a centralised heat pump, or a cold lake water district heating system with decentralised heat pump.

All scenarios based on renewable energy sources have similarly low carbon emissions. The solution which in addition causes the lowest amount of primary energy use comprises the use of a cold lake water district heating system with decentralised heat pumps and energy efficiency measures on the building envelopes. Combinations of decentralised ground source heat pumps with energy efficiency measures on building envelopes have similarly low primary energy use.

3.9.4 Discussion

What stands out when interpreting the results?

Results are rather like those obtained in the case study in Luzern, and therefore, results are discussed here in a shorter form than in the case study in Luzern – see previous chapter.

The calculations show that a switch to renewable energy-based heating systems is cost-effective or nearly cost-effective with several investigated renewable energy-based heating systems. This cost-effectiveness becomes even more pronounced when combinations with energy efficiency measures are considered. Carbon emissions are similarly low for all scenarios with renewable energy-based heating systems, and significantly lower than in the case of heating systems with fossil fuels. Primary energy use is also lower for scenarios with renewable energy-based heating systems than with fossil fuel-based heating systems, but the difference is smaller. For heating systems based on a centralised heat pump, whether with lake water or the ground as the heat source, carbon emissions and primary energy use are higher than for decentralised geothermal heat pumps or a cold lake water district heating system with decentralised heat pumps. The carbon emissions and the primary energy use associated with centralised air source heat pumps are like heating systems based on a centralised pump. This is a difference from the case study in Luzern, which can be explained by the fact that in the case study of Zürich, the energy performance of some of the buildings is lower before renovation.

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 the case before with fossil fuel-based heating systems. It was even found that efficiency measures on the building envelopes benefit renewable energy systems more than they benefit fossil fuel-based systems. In this case study, this is even more clear than in the case study in Luzern. 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.

In this case study, synergies between energy efficiency measures and renewable energy measures are particularly high for decentralised air-source heat pumps. This may be due to several factors: some of the buildings in the case study in Zürich have a relatively low energy performance to start with, and air-source heat pumps benefit strongly if that energy performance is improved. Furthermore, for the district solutions, it was estimated that the conversion efficiency is higher in the case study of Zürich than in the case study of Luzern, making them benefit a bit less in relative terms of energy efficiency measures on the building envelopes.

For a district heating system with a centralised ground source heat pump, the need to regenerate ground heat plays a role. Without energy efficiency measures on the building envelopes, a significant amount of heat regeneration is necessary, for example, through additional solar thermal systems as assumed in the case study. Energy efficiency measures reduce the need for such systems to regenerate heat in the ground. With an advanced level of energy efficiency measures, there is no need for heat regeneration in the ground over an estimated period of use of 50 years. This effect contributes to strong synergies between energy efficiency measures on building envelopes and the switch to a renewable energy-based system at the district level.

The cost-effectiveness of energy efficiency measures on building envelopes is slightly higher for air-source heat pumps than for ground-source heat pumps. A reason can be that ground source heat pumps already have relatively high efficiency and accordingly benefit in relative terms less 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 measures to improve the efficiency of the wall and the cellar ceiling. The insulation of the attic floor was found to be nearly cost-effective. The installation of new windows was not found to be cost-effective in combination with any type of heating system; a related renovation measure, therefore, requires a different type of motivation than saving costs.

Based on the calculations and related assumptions for the investigated heating systems, it was found that decentralised ground source heat pumps and a district heating system based on a centralised ground source heat pump are the most cost-effective solutions, in combination with energy efficiency measures.

Of the other systems investigated, decentralised air source heat pumps, a lake water-based district heating system with a centralised heat pump, or a cold lake water district heating system are equally cost-effective solutions, in combination with energy efficiency measures. 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 the higher investment costs of ground-source heat pumps due to the drilling of boreholes.

The fact that the cost-effectiveness of a lake water district heating system based on a centralised heat pump and the one of a cold lake water district heating system with decentralised heat pumps is similar, is remarkable because the technological approach is rather different.

Where are the greatest uncertainties in the assumptions? How reliable are the results?
Uncertainties and reliability are like the case study in Luzern (see chapter 3.8.4).

The following table indicates whether the formulated hypotheses are confirmed or are not confirmed for the investigated case study:

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.»	Yes
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.»	Not investigated
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.»	Not investigated
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 energy.»	Yes
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.»	Yes
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.»	Not investigated
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.»	Yes
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.»	Not investigated

3.10 The Netherlands

3.10.1 Description of the district

Table 54: General information about the district

Parameter	Explanation/definition
Location	Haarlem
Latitude	52°3824″E
Longitude	4°6043″N
Climate zone	Cfb (Marine West Coast Climate)
Number of buildings in total	1152

Figure 124: Dutch Case Study map (source: www.nationaleenergieatlas.nl).

In the district, there are 1152 dwellings, 8 buildings with a retail function, 3 with a school function, 3 with a public function, 2 with an office function, and 2 with an industry function. In this case, the non-residential buildings were not considered. Only two typical residential buildings are used for the parametric assessment of this case study because those two building types are expected to have a decisive role.

Building typology 1 - in reality 55% of the dwellings of this neighbourhood, for simplicity reasons we assume this building type represents all dwellings built in this period and before this period, which is 66% in total – 760 dwellings (photo: Paula van den Brom).

Building typology 2 - in reality 24% of the dwellings of this neighbourhood, for simplicity reasons we assume this building type represents all dwellings built in this period and after this period which is 34% in total – 392 dwellings (photo: Paula van den Brom).

Table 55: Building typologies of the Dutch Case Study.

Parameter	Unit	Building typology 1	Building typology 2
Building information			
Number of buildings per typology		760	392
Construction period		1920-1939	1940-1959
Geometry (per dwelling)			
Gross heated floor area (GHFA)	m^2	122.4	123.12
Heated volume	m^3	262	333
Façade area incl. window area	m^2	73	75.5
Roof area if a pitched roof	m^2	57	59.7
Is the room below the roof heated or not?	Yes/No	Yes	Yes
Area of windows to North	m^2	15	17.2
Area of windows to South	m^2	16	20.6
Number of floors above ground	-	3	3
Usage			
Area per occupant	m^2 / person	0.02	0.02
Typical indoor temperature (for calculations)	°C	20	20
Average electricity consumption per year and m^2 (excluding heating, cooling, and ventilation)	kWh/(m^2.a)	-	-

Parameter	Unit	Building typology 1	Building typology 2
		HVAC systems	
Type of existing heating system		Combi gas boiler	Combi gas boiler
Existing energy carrier		Gas	Gas
Is a ventilation system without heat recovery installed?	Yes/No	No	No
Is a ventilation system with heat recovery installed?	Yes/No	No	No
Ventilation rate	l/s m^2	0.09	0.09
Is the cooling system installed?	Yes/No	No	No

3.10.2 Calculation parameters and scenarios

Table 56: General parameters for the calculations of the Dutch Case Study.

Parameters	Explanation/definition
Date the calculations were made	2020
Weather file used	De Bilt 2017 KNMI
External shading (by surrounding buildings) considered	No

Three scenarios for building envelope measures are developed for the Dutch case study. In the first scenario, the walls are not insulated, in the second scenario there is cavity insulation or inside wall insulation and, in the third scenario, the façade is very well insulated from the outside. For the roof, there is also a scenario with no insulation, a scenario with insulation from the inside, and a scenario with good insulation from the outside. For scenarios 1 and 3, the floors are insulated up to U-value 0.24, and for scenario 2 up to U-value 0.34. For the windows in each scenario, high-efficiency double glazing is assumed.

Table 57: Measures on the building envelope.

Parameter	Unit	Ref	1	2	3
		Walls			
U-values	W/m^2K	1.67	1.67	0.58	0.18
Investment costs	$EUR/m^2_{building\ element}$	-	-	29	86
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	-	-	-
Service life	years	40	40	40	40
		Roofs			
U-values	W/m^2K	0.45	0.45	0.28	0.18
Investment costs	$EUR/m^2_{building\ element}$	-	-	64	80
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	-	-	-

Parameter	Unit	Ref	1	2	3
Service life	years	40	40	40	40
		Floors			
U-values	W/m²K	1.37	0.24	0.34	0.24
Investment costs	$EUR/m^2_{building\ element}$	-	-	46	55
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	-	-	-
Service life	years	40	40	40	40
		Windows			
U-values	W/m²K	3.5	1.24	1.24	1.24
Investment costs	$EUR/m^2_{building\ element}$	-	141	141	141
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	-	-	-
Service life	years	40	40	40	40
		Ventilation system			
Investment costs	$EUR/m^2_{building\ element}$	-	20	20	37
Maintenance costs	$EUR/m^2_{building\ element}.year$	-	0.74	0.74	1.48
Service life	years	-	18	18	18

The buildings in the reference situation have natural ventilation. Scenarios 1 and 2 have natural supply and mechanical exhaust ventilation and scenario 3 has a fully mechanical balanced ventilation system with heat recovery. There are also three different scenarios for the heating system: gas boiler, individual heat pumps, and district heating. Both the gas boiler and the individual heat pumps refer to decentralised systems per building.

Measures on the HVAC system including renewable energy generation on-site average building typology 1 and 2. All numbers are based on individual buildings.

Table 58: Measures of the HVAC system including renewable energy generation on-site.

Parameter	Unit	1	2	3
		Gas boiler		
Capacity	kW	7.5 (per building)	6.8 (per building)	3.7 (per building)
Investment costs	EUR/kW	1257	1089	1187
Maintenance costs	EUR/year	80	80	80
Service life	Years	18	18	18
		Individual air-to-water heat pumps		
Capacity	kW	7.5 (per building)	6.8 (per building)	3.7 (per building)
Investment costs	EUR/kW	1677	1772	3277

Parameter	Unit	1	2	3
Maintenance costs	EUR/year	120	120	120
Service life	Years	18	18	18
		District heating		
Capacity	kW	7.5 (per building)	6.8 (per building)	3.7 (per building)
Investment costs	EUR/kW	489	517	956
Maintenance costs	EUR/year	350	350	350
Service life	Years	20	20	20

For the costs we made use of the ‘Arcadis kosten kengetallen 2020’. This is a document with key figures on construction costs developed by Arcadis in commissioned by the Dutch government. Although this document is regularly updated the number inevitably has some delay on the actual cost in the construction cost, especially in this period now the costs are increasing rapidly.

3.10.3 Case study results

The following graphs give an overview of the results obtained:

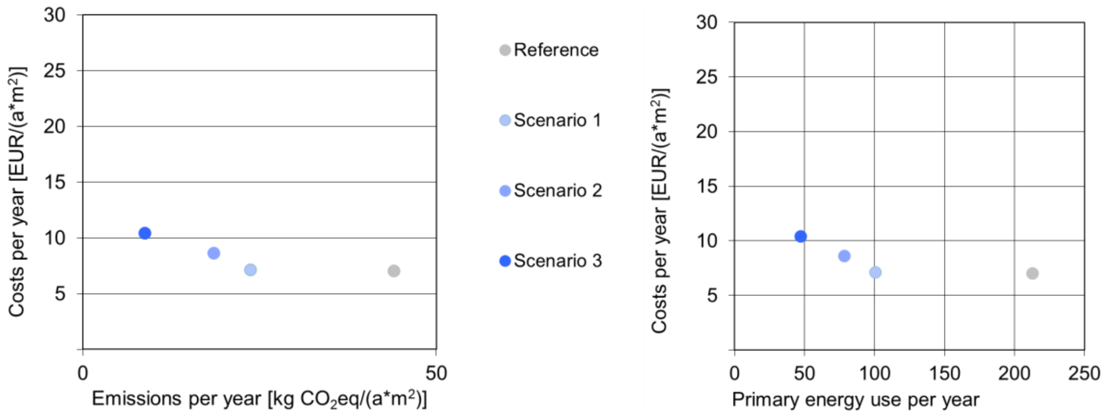

Figure 125: Reference heating system (individual gas boiler).

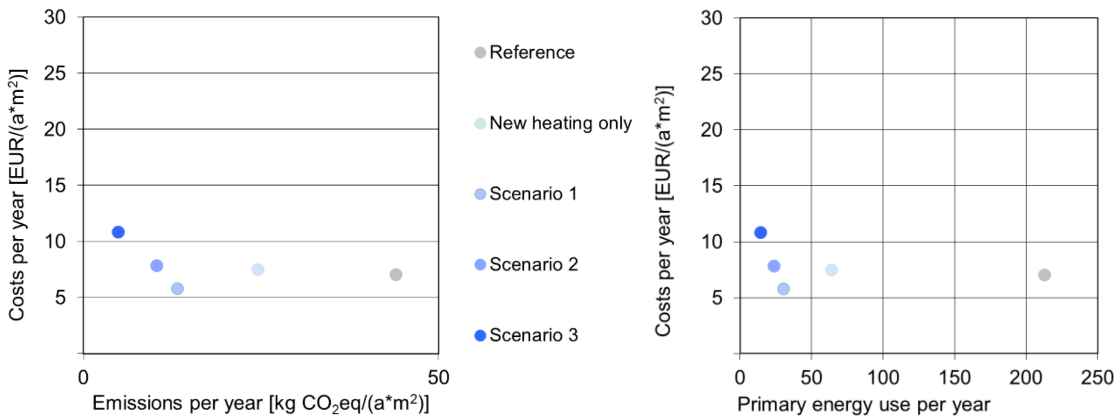

Figure 126: Heating system 2 - individual heat pump.

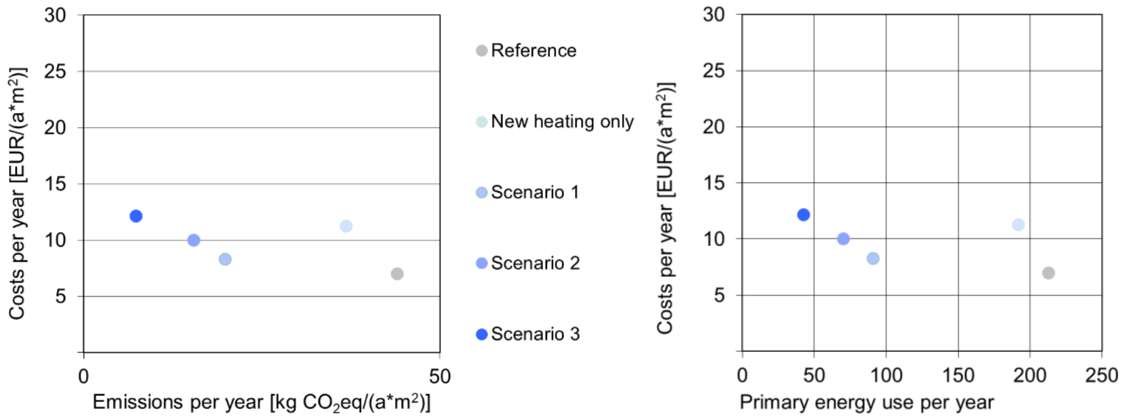

Figure 127: Heating system 3 – district heating.

The following graphs contain an overview combining the various renovation packages on the building envelopes with the various types of heating systems investigated:

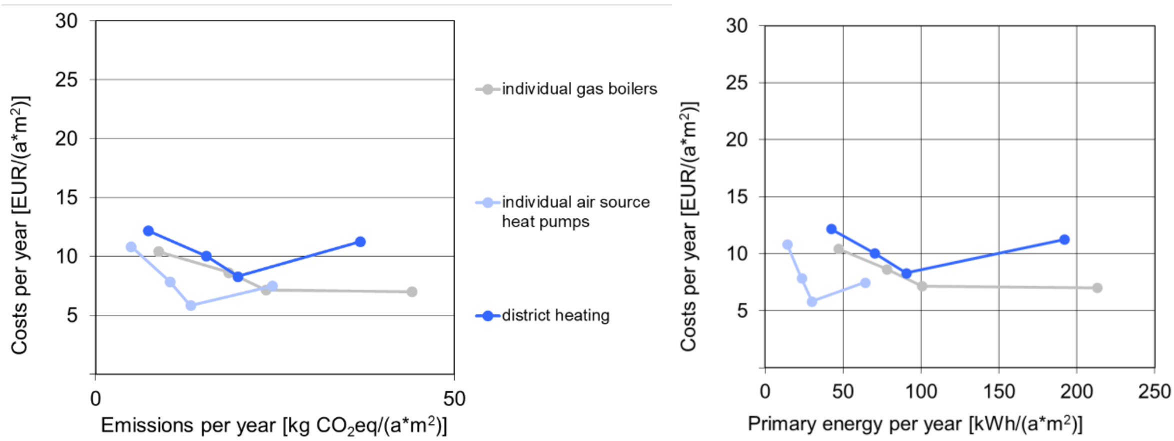

Figure 128: Combination of renovation packages on the building envelopes with the various types of heating systems.

The following graphs show more specifically which are the most cost-effective renovation packages for the various heating systems investigated.

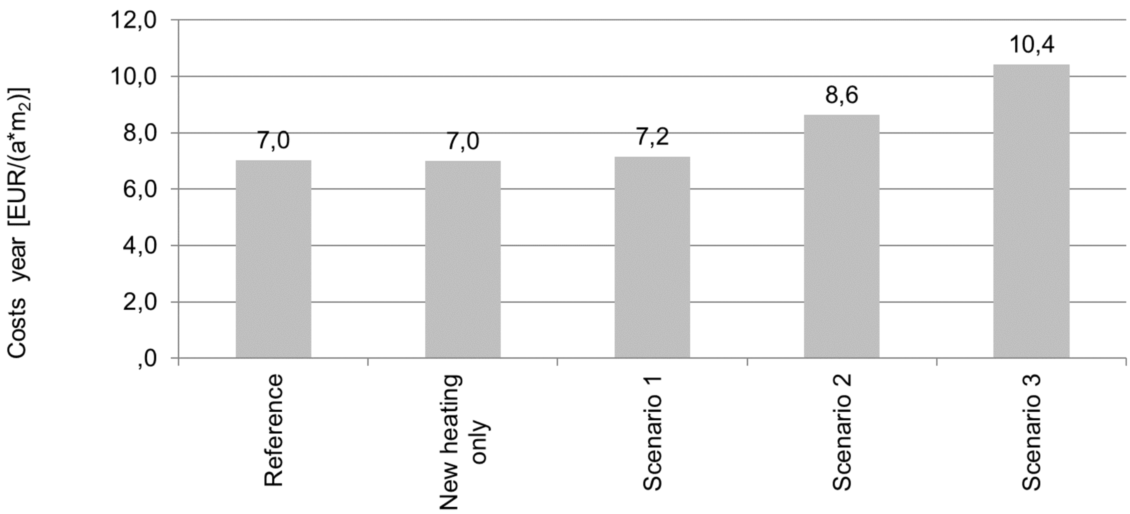

Figure 129: Reference heating system (individual gas boiler).

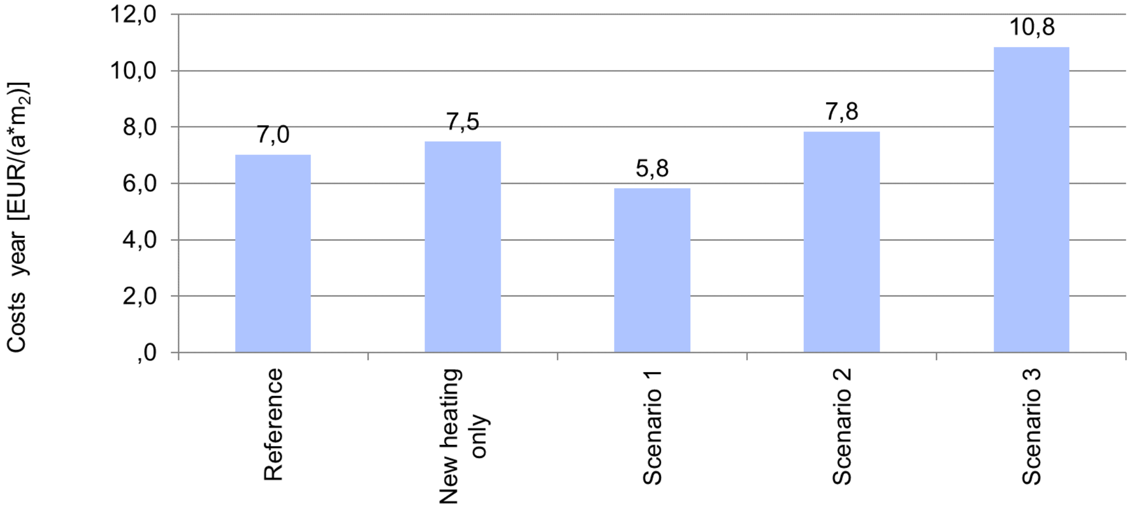

Figure 130: Heating system 2 - Individual ASHP.

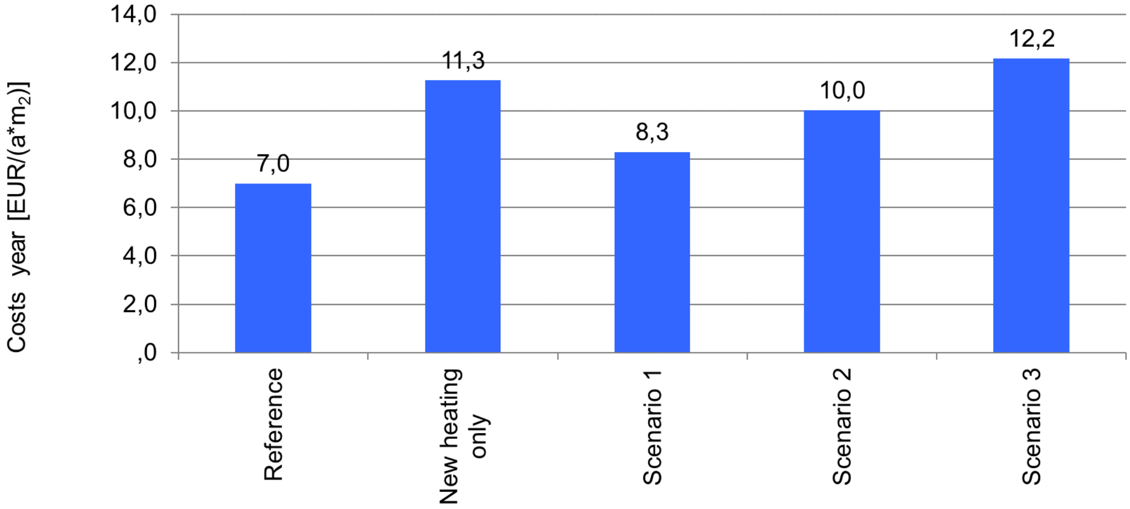

Figure 131: Heating system 3 - District heating.

The following graph summarizes the cost savings of the most cost-effective renovation package on the building envelopes investigated for various types of heating systems considered, in comparison with a scenario in which only the heating system is replaced.

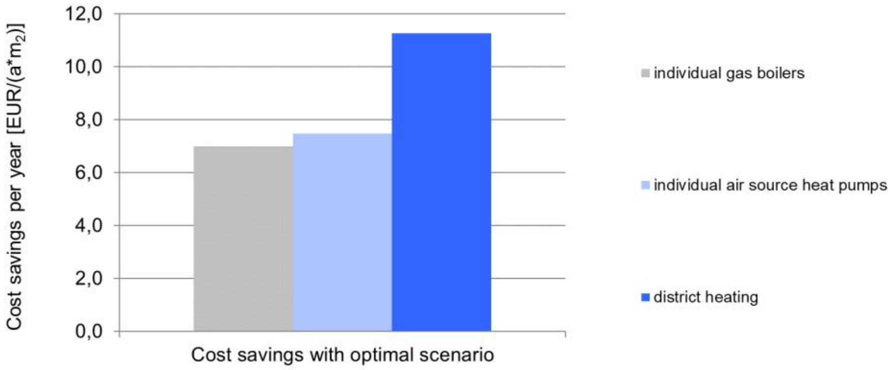

Figure 132: Cost-saving potential of the optimal scenario per energy supply variant.

Based on these graphs, the following can be recognized:

Considering the calculated options, intensive building renovation can save the most primary energy (insulation + balanced ventilation system with heat recovery). However, according to the calculations, this is often not the most cost-effective choice.

For the heating system, the air source heat pump is based on the calculations as the primary energy-saving solution. However, one must consider that the government determines the carbon conversion factors per energy source. They perfectly reflect reality because the government is also using those conversion factors to stimulate the use of electricity instead of natural gas.

The results also clearly show that it is important to renovate the building before a new heating system is installed. In the calculations, we did not consider that some heating systems will not be able to deliver an acceptable comfort level in the house if only the heating system in the building is changed and no renovation measures are applied. Because both, heating with a heat pump and heating using district heating, will lead to lower supply temperatures of the heating system it could sometimes happen that these low temperatures will not be enough to compensate for the cold draught in the building. It can also be that the current heat emitters (standard radiators) won't be sufficient to achieve an acceptable and comfortable indoor temperature. New heat emitters are currently not considered in the calculations but, if needed, they can play a significant role in the cost-effectiveness calculations.

The results show that the most costs can be saved by applying minimum insulation levels (see scenario 1), new windows and a district heating system.

One must consider that the costs considered in these calculations are the sum of annual maintenance and annual fixed costs for the heating system, investment costs for the energy renovation and the heating system, and the annual energy costs. The costs that must be paid by the governments/municipalities to provide the right infrastructure are not considered. That implies that district heating in this case from the viewpoint of the occupants is the most cost-effective solution. However, from the perspective of the municipality, this might be different. This is also why for example, the start analysis calculated with the Vesta MAIS model (a tool developed by the Dutch government that can help municipalities to determine the energy transition strategy for their neighbourhoods https://www.pbl.nl/modellen/vesta) more often considers heat pumps as more cost-effective than district heating. Also important to mention is the uncertainty of the energy price developments. Currently, the energy price of the district heating system is linked to the natural gas price. Depending on the price developments, this will influence the results.

3.10.4 Discussion

The following table indicates whether the formulated hypotheses are confirmed or are not confirmed for the investigated case study:

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.»	No
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.»	Not investigated

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.»	Not investigated
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 energy.»	No
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.»	No
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.»	Not investigated
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.»	Not investigated
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.»	Not investigated

4. Discussion of overall results

As the country contexts and the starting conditions in each district are highly diverse, so are the results of the case studies. This chapter mentions the most relevant findings from the parametric assessments in each country.

In Austria, it was found that the life cycle costs increase when only the energy supply system is changed, and no other measures are considered. This shows that heating system replacement should always be carried out in combination with renovation measures on the envelope. Furthermore, the results show, that the air-water heat pump achieves the worst result. Even if renovation measures on the building envelopes are considered, the primary energy demand, the carbon emissions, and the life cycle costs are the highest compared to natural gas heating, district heating, and pellet heating.

If the goal is to reduce carbon emissions, switching to district heating or pellets heating is advisable. The switch of the energy supply system reduces the carbon emissions more effectively than the measures on the building envelope.

Looking at the cost-effectiveness of the investigated renovation measures, the results show that the insulation of the roof and the façade are always cost-effective when compared to the reference case. The other investigated measures are only cost-effective when combined with the heat pump system.

In Italy, in all the investigated scenarios, the cost-optimal solution includes renovating the whole envelope (windows, façade, and roof). This is because savings can be achieved by decreasing the energy demand and improving the heat supply system.

Furthermore, cost-effective scenarios consider enhancing the heating system by substituting an existing single boiler for each flat with a centralised system at the district level with a geothermal heat pump. In terms of the installation of renewable energy systems, the installation of PV is advisable. A solar thermal installation for domestic hot water production would also bring benefits, but due to the bureaucratic situation in Venice, this measure is not considered feasible, affordable, and appropriate. The study further reveals that energy costs have the highest impact on global costs.

In Norway, the cost-effectiveness of measures on the building envelope is dependent on the energy supply system. So, for the central solution, the case with the best windows is the most cost-effective, while for the decentral and point source solutions, medium solutions on the building envelope are the most cost-effective. Still, it needs to be mentioned that the difference is very small and within the uncertainty of the calculations. The rest of the energy efficiency measures have too high investment costs to be cost-effective. The decentralised heat pump solutions are the most cost-efficient for heating systems. These solutions also have the lowest carbon emissions from a life cycle perspective. The district heating solutions have the lowest primary energy consumption.

From an LCC perspective, the installation of PV does not make sense in these calculations.

The solutions with district heating have the lowest emissions. Also, the cases with PV have lower emissions than those without.

In Portugal, all the investigated renovation packages are cost-effective compared to the reference case. Also, in terms of energy supply systems, all five systems selected for this case study proved to be cost-effective. The centralised systems also consistently show significantly lower emissions and primary energy demand than the decentralised systems.

Furthermore, this good performance is associated with reduced global costs, proving that district energy supply can be cost-effective in Portugal.

The centralised heat pump system shows the highest cost reductions compared to the reference case. Even if not the most cost-effective solution, the centralised biomass boiler and the heat pump system, in combination with the photovoltaic system, offer better environmental performance, leading to zero emissions and zero primary energy consumption for all the renovation packages analysed.

The investigations also show that, when looking at the renovation packages before and after adding their embodied energy to the analysis, there is a shift towards higher carbon emissions and primary energy consumption as expected. However, it is notable that there is no change in the results regarding the hierarchy from the smallest to the largest environmental impact of each renovation package.

In Spain, the window replacement costs significantly affect the cost-effectiveness analysis. Including the window replacement in the calculations lead to a reduced primary energy demand but at the same time, it almost doubles the LCC.

In addition, in this case study, it can be highlighted the weight that investment costs have on the overall economic analysis, compared to the energy-related costs during the lifetime of the building. This leads to a situation in which cost-optimality can be reached without deep renovating the building envelope. Four out of eight scenarios reach the optimal costs even without any measures on the building envelope. In these scenarios, only the energy supply system is replaced.

The Swedish investigations show that cost savings are mainly carried out by disconnecting the district heating system and installing a heat pump system. However, this can have negative effects on society at large.

The low carbon emissions numbers for all the investigated cases are due to the low environmental impact of district heating in Sweden.

In Switzerland, results of the calculations show that a switch to renewable energy-based heating systems is cost-effective or nearly cost-effective with all the renewable energy-based heating systems investigated: decentralised air-source heat pumps, decentralised ground source heat pumps, a cold lake water district heating system with decentralised heat pump, or a centralised ground source heat pump, and at least in one case study also for a lake water district heating system with a centralised heat pump. This cost-effectiveness becomes even more pronounced when combinations with energy efficiency measures are considered. 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. It was even found that efficiency measures on the building envelopes benefit renewable energy systems more than they benefit fossil fuel-based systems. The scope of cost-effective energy efficiency measures on the building envelopes comprises measures on the walls and the cellar ceiling in both case studies and in addition to that also measures on the roof in one of the case studies. It was shown that energy efficiency measures on building envelopes can be strong drivers for cost-effectiveness when combined with district heating systems operating with heat pumps, due to a lowering of the necessary temperature in the system and a reduced need for regeneration of heat in the ground.

In the Netherlands, the most primary energy can be saved by intensive building renovation (insulation + balanced ventilation system with heat recovery), however, this is according to the calculations often not the most cost-effective choice.

For the heating system, the air source heat pump is based on the calculations as the primary energy-saving solution.

The results also clearly show that it is important to renovate the building before a new heating system is installed. The results also show that the most costs can be saved by applying minimum insulation levels and a district heating system.

5. Conclusions

Based on the results of the case studies and their discussion in the previous chapter, as well as the specific hypotheses investigated, some general conclusions can be drawn:

- The renovation of the thermal envelope is generally recommended, although cost-effective renovation can vary. Sometimes it is only one measure, e.g., window replacement, and sometimes the renovation of the complete envelope. Sometimes, however, it can be in between. Which measures are cost-effective depends on several factors. Influencing factors are, for example, the initial situation (building already insulated or not), the climatic conditions (how much heating is required), and the prices (ratio of investment to energy costs).

- Concerning the energy supply systems studied, no clear recommendation can be derived about the heat generation system. Both decentralised, on the building level, heat pumps (air-water as well as geothermal) and district heating lead to good results and savings. This means that district projects are often likely to require a justification other than economic attractiveness. These were mostly not recommendable in the case studies investigating a supply on the apartment level.

- Results may differ if district heating systems are particularly large and benefit from substantial economies of scale. In such a case, district heating systems based on renewable energy may have clearer economic advantages. However, in a large district heating system, it would be much more challenging to benefit from energy efficiency measures in the building envelopes as it would be difficult to increase the energy performance of all buildings in the district.

- A common finding supported by results of most, although not all case studies, is that the cost-optimal level of energy efficiency measures on building envelopes does not differ significantly when comparing a combination of such measures with a district heating system based on renewable energy and a combination of such measures with decentralised heating systems based on renewable energy. This is an important finding as this indicates that energy efficiency measures are similarly attractive for the use of renewable energy at the district level as at the level of individual buildings.

- There are indications in various countries that energy systems based on heat pumps benefit from energy efficiency measures on building envelopes more strongly than fossil fuel-based systems. Concerning the balance between energy efficiency and renewable energy measures, there are above all synergies between the use of renewable energy measures and energy efficiency measures, and not trade-offs, at the district level.

- Energy efficiency measures on building envelopes may yield particularly strong synergies with renewable energy measures if these are carried out for all buildings in a district, allowing accordingly to reduce the temperature of the grid. This has benefits for increasing the efficiency of a centralised heat pump and to reduce thermal losses in the grid. Furthermore, in the case of using the ground as a heat source at the district level in connection with heat pumps, energy efficiency measures on building envelopes reduce the need to regenerate heat in the ground, which is another reason for synergies between energy efficiency measures and renewable energy measures.

- A finding supported by most case studies is that in 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's envelopes.

- In the case studies examined, photovoltaics was largely investigated as a renewable energy source on site. It has been shown that installing a PV system makes sense from an energy point of view (and thus also carbon emissions), but the economic viability is not always immediately given.

- Renovation measures on the building envelope, measures to replace the energy supply systems, and measures to use renewable energy sources can lead to CO_2 and primary energy savings but are not always cost-effective or cost-optimal. This is where the conflicting priorities become apparent. Savings to protect the environment vs. cost-effectiveness.

- Since the cost-effectiveness is determined by comparing the investigated scenarios with the reference case, the definition of the reference case plays a special role. The reference cases differ from country to country, but even within a country, districts can have different initial situations and, thus, different reference variants.

- Many assumptions must be made for the calculation of different scenarios. This concerns assumptions about costs, such as investment costs for the renovation of the building envelope, energy supply and renewable energy sources, maintenance and repair costs, and energy costs. But assumptions must also be made about user behaviour: what room temperature is used for calculations, what hot water consumption is assumed, and is active cooling also used? All these assumptions can influence the calculation results and, if individual parameters are changed, can also lead to different results or recommendations. Therefore, it is important to investigate not only different technical renovation measures but also the influence of such parameters. Also, the choice of the calculation software can influence the results. This must be considered as well.

- In addition to cost, carbon emissions, and primary energy savings, measures on the building envelope and the energy supply system also have other effects that were not part of the case studies but must nevertheless be considered (so-called “co-benefits”). For example, the thermal renovation of the exterior wall and the replacement of windows positively affect the thermal comfort in the interior. Likewise, the use of a PV system, for example, can reduce energy dependency.

Table 59 gives an overview of all investigated hypotheses and the findings from all countries. In the investigations, the focus was on hypotheses 1, 4, and 7. The other hypotheses could not be investigated due to the given starting situations or applicability of scenarios in the respective country.

In hypothesis 1, the focus is on the cost-optimal level of energy efficiency measures on the building envelope in combination with different energy supply systems. Based on the calculation results this hypothesis can be confirmed in five of the eight countries. Only in the Netherlands this hypothesis was not confirmed. In hypothesis 4, the starting situation is a decentralised heated district based on fossil fuels. It was investigated if the cost-optimal renovation measures on the envelope do not significantly change if the district is connected to renewable energy-based district heating. This is the case in Austria and Switzerland, where the cost-optimal level of renovation measures on the building envelope does not significantly change if the energy supply system is changed to district heating. In five other countries, this hypothesis cannot be confirmed, which means that the switch from decentralised fossil fuel-based heating to renewable energy-based district heating does lead in these cases to a change in the cost-optimum level of renovation measures on the building envelope.

In hypothesis 7, it was investigated if, 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’s envelopes. This can be confirmed in five of the eight countries. In two countries, this hypothesis was not investigated. In Sweden, it cannot be confirmed.

All other hypotheses cannot be confirmed or were not investigated.

Table 59: Overview of the hypotheses of all countries.

Hypotheses	AUT	ITA	NOR	POR	SPA	SWE	SUI1	SUI2	NED
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 energy.»	✓	✗	–	✗	✗	✗	✓	✓	✗
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	AUT	ITA	NOR	POR	SPA	SWE	SUI1	SUI2	NED
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

References

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., Matuška, T., Mlecnik, E., Mørk, O. C., Ott, W., Romagnoni, P., Rose, J., Säwén, T., Walnum, H. T., Venus, D., & Winkels, Z. (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

BPIE – Deep renovation (2021). Deep Renovation: Shifting from exception to standard practice in EU Policy. Retrieved 30/08, 2022, from: https://www.bpie.eu/ publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/

BPIE – Glossary of Terms (2021). Glossary of terms. Energy efficiency and building policies in the EU and US. Retrieved 30/08, 2022, from: https://www.bpie.eu/wp-content/uploads/2021/09/Glossary-of-terms%E2%80%93Energy-efficiency-and-building-policies-in-the-EU_rev3.pdf

Energy Performance of Buildings Directive (EPBD). EU Directive 2010/31/EU, European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union (2010): 13-35

European Commission DG Energy (2014). Financing the energy renovation of buildings with Cohesion Policy funding. Retrieved 01/04, 2020 from: https://ec.europa.eu/energy/sites/ener/files/documents/2014_guidance_energy_renovation_buildings.pdf

European Commission (2021). Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast) COM/2021/802 final, Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

IPCC (2007). IPCC Fourth Assessment Report: Climate Change. Retrieved 28/08, 2022 from: https://www.ipcc.ch/assessment-report/ar4/

Iturriaga E., Campos-Celador Á., Terés-Zubiaga J., Aldasoro U., Álvarez-Sanz M. (2021). A MILP optimization method for energy renovation of residential urban areas: Towards Zero Energy Districts; Sustain. Cities Soc., vol. 68, p. 102787, May 2021, https://doi.org/10.1016/j.scs.2021.102787

Kylili A., Fokaides P. A., Lopez Jimenez P. A. (2016). Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review, Renewable and Sustainable Energy Reviews, Volume 56, Pages 906-915

Lasvaux S., Favre D., Périsset B., Mahroua S., Citherlet St. (2017). Life Cycle Assessment for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56); University of Minho; ISBN: 978-989-99799-3-2

Sorensen, Å. L., Sartori, I., Lindberg, K. B., & Andresen, I. (2019). Analysing electricity demand in neighbourhoods with electricity generation from solar power systems: A case study of a large housing cooperative in Norway, in IOP Conference Series: Earth and Environmental Science, 2019, vol. 352, no. 1. https://doi.org/10.1088/1755-1315/352/1/012008

Terés-Zubiaga J., Campos-Celador Á., González-Pino I., and Escudero-Revilla C. (2015). Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain, Energy Build., vol. 86, pp. 194–202, Jan. 2015, https://doi.org/10.1016/j.enbuild.2014.10.018

Terés-Zubiaga, J., Bolliger, R., Almeida, M. , Barbosa, R., Rose, J., Thomsen, K. E., Montero, E., & Briones-Llorente, R. (2020). Cost-effective building renovation at district level combining energy efficiency & renewables – Methodology assessment proposed in IEA EBC Annex 75 and a demonstration case study. Energy and Buildings, 224, 110280. https://doi.org/10.1016/J.ENBUILD.2020.110280

ANNEX 75

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