ANNEX 75

EBC

Energy in Building and Communities Programme

International Energy Agency

Methodology for investigating cost-effective building renovation strategies at district level combining energy efficiency & renewables

Energy in Buildings and Communities Technology Collaboration Programme

May 2023

Technology Collaboration Programme

by iea

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

ISBN: 978-989-35039-6-6

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

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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 CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)

Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes
(*) completed working groups

Executive Summary

IEA EBC Annex 75 focuses on cost-effective building renovation at the district level combining energy efficiency & renewables. The present report defines the methodology the participating countries used in conducting building renovation assessments at the district level within the IEA EBC Annex 75 scope, which is mainly focused on residential buildings, both single and multifamily houses.

The objective of Annex 75 is to guide policymakers, companies working in the field of energy transition, as well as building owners to cost-effectively transform the existing building stock towards low-emission and low-energy solutions taking advantage of the synergies between energy efficiency and renewable energy measures at the district level.

The methodology defines the boundary conditions to be fixed for the assessments to be carried out, the research questions and hypotheses to be mainly investigated with the assessments, and the type of outputs to be generated with the assessments.

In light of the Paris Agreement and the objective to undertake efforts to limit climate change to a temperature increase of 1.5 °C above pre-industrial levels, it is of interest to investigate strategies that allow cost-effectively achieving zero emissions and 100% renewable energy-based solutions as pre-set targets.

Accordingly, some of the key questions to be investigated are the following:

- 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-effective balance between efficiency measures on the building envelopes and measures related to the use of renewable energy if far-reaching reductions in carbon emissions and primary energy use in urban districts are the objective?
- 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 a decentralised use of renewable energy sources for heating in each building?

The following Key Performance Indicators were selected for use within IEA EBC Annex 75 assessments: carbon emissions, primary energy use and annualised total costs indicated as values per square metre of conditioned gross floor area and per year.

The assessments were carried out based on matching the energy needs of buildings with the energy supply. The energy needs of buildings were calculated by considering the energy performance of the building envelope, outdoor climate, target indoor temperature/set-point temperature and internal heat gains. Both centralised and decentralised energy systems are considered options for the energy supply. District-based heating solutions are considered by distinguishing the following four elements of a district-heating system: heat source intake, centralised heat generator and circulating pumps, pipes, and individual heating substations for each building.

Each assessment compares various combinations of renovation measures, called renovation packages, with a reference case. The reference case is defined to comprise the type of renovation activities which would have been carried out *anyway* just to restore the building's functionality.

Carbon emission factors and primary energy factors are taken into account as country-specific factors. For calculating carbon emissions and primary energy use, upstream energy use and emissions for extraction and transport of fuel are included in the emission and primary energy factors.

A life cycle approach is chosen to indicate the costs for energy measures and *anyway measures*. The following cost elements are included: initial investment costs/replacement costs, energy costs, including existing energy taxes and CO_2 taxes, as well as maintenance and operational costs.

The following are among the relationships that are taken into account between energy efficiency measures and renewable energy measures:

- The better insulated a building is, the lower are typically its energy needs and therefore its energy use. Usually, this relationship has a stronger effect on reducing costs in the case of fossil fuel-based heating systems compared to renewable energy-based heating systems because renewable energy systems have lower operational energy costs than conventional fossil fuel-based systems.
- The more energy efficient a building is, the smaller the required capacity of the heating systems. Renewable energy systems typically have higher investment costs than conventional fossil fuel-based systems. Reducing the required capacity of the heating system due to insulation of the building envelope is, therefore, a factor from which renewable energy systems benefit more intensely than conventional fossil fuel-based systems.
- For heat pumps, there is an important synergy with efficiency measures on the building envelope because the lower the energy needs of a building are, the lower can be the flow temperature of the heat distribution system within a building. Accordingly, the temperature hub between the flow temperature of the heat distribution system and the temperature of the heat source becomes smaller. This increases the efficiency of heat pumps that provide heat from a heat source to the building.

While making related assessments, it is also important to consider the potential risks of overheating or increased demand for cooling in summer months if insulation is particularly heavy.

Investigating cost-effective strategies for achieving far-reaching reductions in carbon emissions and energy use in city buildings at the district level is a complex task. This methodology report provides a basis for investigating particularly the cost-effective balance between carrying out energy efficiency measures and deploying renewable energy measures in the renovation of buildings at the district level.

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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 combines definitions from the European legal framework, standard definitions of English dictionaries, related projects, research papers, and other professional publications.

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.

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

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

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 need (energy demand): The energy to be delivered to, or extracted from, a conditioned space to maintain the intended space conditions during a given period of time disregarding any technical building system inefficiencies (European Commission, 2021).

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 poverty: A set of conditions where individuals or households are not able to adequately heat or provide other required energy services in their homes at an affordable cost. (Pye et al., 2015). There are three main components: low household income; high/growing energy prices; and inefficient energy performance of buildings concerning thermal insulation, heating systems and equipment (Thomson and Bouzarovski, 2019) (EU Energy Poverty Observatory, 2020).

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

Energy use: The energy input to a technical building system providing an energy performance of buildings service intended to satisfy an energy need (European Commission, 2021).

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

Policymakers: All kinds of actors and stakeholders who define, develop, and implement policy instruments regarding building renovation or renewable energy projects. That includes all political levels: local, regional, national, and international, as well as all administrative levels and to a certain extent also administrative decision-makers.

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.

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.

1. Introduction

IEA EBC Annex 75 focuses on cost-effective building renovation at the district level combining energy efficiency & renewables. The present report defines the methodology the participating countries used in conducting building renovation assessments at the district level within the IEA EBC Annex 75 scope, which is mainly focused on residential buildings, both single and multifamily houses.

IEA EBC Annex 75 follows a similar approach as IEA EBC Annex 56, although now targeted to the district level, whereas IEA EBC Annex 56 referred only to individual buildings. Because of this similarity, reference is made here also to the methodology report provided within IEA EBC Annex 56 (Ott et al., 2017), which was developed by the same main authors of the present report. In case of similarities between the assessment of individual buildings and the assessment of groups of buildings in districts, the information presented in this report is kept rather short, as it is considered that related and detailed information has already been presented in depth in the mentioned report from IEA EBC Annex 56.

The topic of energy systems at the district level has been taken into account in various previous IEA projects, the results of which contribute to the methodology developed within this Annex.

In addition, the report takes into account and refers to the Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (European Commission 2012), as well as the related guidelines (European Commission 2012a).

2. Objectives

2.1 General objectives of IEA EBC Annex 75

IEA EBC Annex 75 aims to investigate cost-effective strategies for achieving far-reaching reductions of 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 for cost-effectively transforming the city's energy use in the existing building stock towards low-emission and low-energy solutions.

In light of the Paris Agreement and the objective of undertaking efforts to limit climate change to a temperature increase of 1.5 °C above pre-industrial levels, it is of particular interest to investigate strategies which allow achieving cost-effectively zero emissions and 100% renewable energy-based solutions as pre-set targets.

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

The project focuses on the following objectives:

- Give an overview of various technology options, taking into account existing and emerging energy efficiency technologies and renewable energy 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 evaluating the efficiency, impacts, cost-effectiveness, and acceptance of various strategies for renovating urban districts.
- Illustrate the development of such strategies in selected case studies, gather related best-practice examples, and explore, particularly, the interactions between energy efficiency and renewable energy measures.
- 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.

The present report focuses on the second of the indicated objectives in this list.

Through the work carried out in IEA EBC Annex 75, it is intended that accurate, understandable information, guidelines, tools and recommendations are provided 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.

2.2 Objectives of the methodology report

This report describes the methodology for identifying and assessing cost-effective strategies for renovating urban districts towards far-reaching objectives regarding reducing carbon emissions and energy use. The report proposes different scenarios considering boundary conditions and different interventions on building envelopes and thermal systems. The proposed methodology builds on the methodology previously developed for individual buildings in IEA EBC Annex 56 (developed by the same main authors of this report), extending it to the level of districts/groups of buildings. Furthermore, it also makes use of results from other related Annexes. The idea is that the methodology supports decision-makers in evaluating the efficiency, impacts, cost-effectiveness and acceptance of various strategies for renovating urban districts, and in identifying suitable renovation strategies.

The methodology defines the boundary conditions set for the assessments carried out, the research questions/hypotheses mainly investigated with the assessments, and the type of outputs generated from the assessments.

It is intended that, based on the methodology developed, existing tools can be identified, or existing tools can be adapted to support the application of the methodology in case-specific assessments. In addition, an online Calculation Tool (Annex 75 CT) was developed to support the application of this methodology, which is available at: https://annex75.bim.energy and at https://annex75.iea-ebc.org/publications.

Such tools were intended to support preliminary decisions in the early stages of an urban district renovation by facilitating the comparison of various strategic options. It is recommended that these tools consider fixed types of building typologies and that they can be adapted to reality with some simplifications. It is also recommended that the tools allow putting the results into perspective with existing targets or benchmarks.

Within IEA EBC Annex 75, the methodology is applied and tested in generic calculations and parametric calculations based on case studies. Through the application of the methodology in such a way, it is intended to identify and characterise factors affecting the cost-effectiveness of renovation strategies for urban districts. In addition, it is, in particular, intended to investigate synergies and trade-offs between renewable energy and energy efficiency measures and between individual and collective solutions.

All types of renewable energy carriers for heating or cooling can be considered with the proposed methodology: environmental energy from the ground, air or surface water harnessed by heat pumps, biomass energy or solar energy. For the assessments carried out, however, in IEA EBC Annex 75, it is recommended to focus on renewable energy carriers which are widely available, such as environmental heat made available through heat pumps.

Seasonal variations in the availability of renewable energy sources, particularly solar energy and related storage options, can also be included in the assessments. However, investigating the short-term intermittency of renewable energy carriers' availability and related solutions to address this is not the focus of the assessments.

2.3 Research questions

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

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

Distinguishing these starting situations, the following questions were investigated:

- What are 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 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, which are widely available renewable energy sources associated 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 associated 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, combined with energy efficiency measures on the buildings' envelopes, more advantageous?

The investigations focused on renovation scenarios that were fully based on using renewable energy combined with different energy efficiency measures on building envelopes.

The intention was that this focus allowed the investigation of the following questions:

- Which approaches, considering various possibilities for energy efficiency and renewable energy measures, allow districts to be fully supplied with renewable energy at the lowest cost?
- Which factors determine the cost-effective balance between efficiency measures on the building envelopes and measures that promote the use of renewable energy if far-reaching reductions in carbon emissions and primary energy use in urban districts are the objective?
- To what extent does the cost-effectiveness of building envelope renovation measures differ, comparing their association with a local district heating system based on renewable energy and with a decentralised use of renewable energy sources for heating in each building?

3. Scope, system boundaries and framework conditions

3.1 Districts

IEA EBC Annex 75 focuses mainly on residential buildings, both single and multifamily houses. Districts with other buildings having similar characteristics, such as schools or simple office buildings without complex HVAC systems, can be included by considering parameters specific to the related building type. Furthermore, other types of buildings can be included in case studies as long as relevant and useful information can be extracted from them related to the main objectives of this project. This project is developed in heating-dominated climate zones, with cooling being considered where appropriate. Including a mix of different uses could theoretically offer some additional options for optimizing solutions due to different energy use profiles. However, considering these additional uses makes the assessments also more complex and is unnecessary for investigating this Annexe's main research questions.

Regarding the definition of districts investigated, to apply the methodology developed in this project, it is suitable to define the district size according to the appropriate size of a possible district heating system. For practical purposes of carrying out cost optimizations and considering the limits in computational power, it is recommended to limit the number of buildings in a district to approximately forty. However, this number is only indicative and, especially with due simplifications, or by creating archetypes of similar buildings, each representing a different building typology, a larger number of buildings can be examined. In any case, it is considered appropriate to investigate at least four buildings together to examine questions related to districts rather than just individual buildings. District heating systems can be taken into account, even if they provide energy to more buildings than those of the district investigated, provided that the cost structure of the district heating system can be considered in such a way that allows assessing possible cost differences depending on the amount of energy used by the district.

Regarding the typology of the districts, several possible distinctions can be made. The first distinction is between urban, suburban and rural districts. In this project, it is proposed to focus on urban and suburban districts because, in these districts, the energy densities are higher than in rural districts, making district-based solutions potentially more attractive than in rural areas. A second distinction concerns the size of the buildings involved. It is proposed to focus on districts containing multi-family residential buildings rather than single-family buildings, also for reasons of potential attractiveness for district-based solutions. A third distinction concerns the number of available options for using renewable energy and carrying out renovation measures on building envelopes. It is proposed to focus assessments carried out within this Annex on districts where a large number of options are available, both in terms of renewable energy use and possibilities for thermal renovation of the building envelopes, allowing the comparison of various scenarios. In districts with buildings under monumental protection, it is considered necessary to consider related limitations in the options. However, it is not proposed that such districts be the focus of the assessments, even though they may be representative of a large part of the building stock in some countries. A fourth distinction concerns the starting situation regarding energy systems installed in the district. It is proposed to focus on districts that are currently heated/cooled mainly by fossil fuels because this is where the largest challenge is for reducing carbon emissions. The related heating/cooling system can be either a centralised system or a decentralised system. Starting situations based on district heating/cooling systems with a substantial share of renewable energy carriers are also part of the scope of this project.

In order to provide meaningful results, it is proposed to consider the country's building stock and investigate particular districts representative of a significant part of a country's building stock.

When selecting districts for case studies, it is worth checking whether this is a neighbourhood where energy consumption from the corresponding buildings' energy performance is lower than expected due to energy poverty situations. In the case of buildings where there is fuel poverty, relying on calculated energy needs typically leads to overestimating the potential energy-saving benefits of refurbishment measures, which will impact cost-effectiveness. This is not a reason to avoid refurbishing such properties, as it makes sense to make them a priority; however, it is important to recognise that the actual savings in energy costs are likely to be less than predicted in such cases. Nevertheless, also in these situations, it is recommended to carry out the assessments by relying on calculated energy needs.

3.2 Key Performance Indicators

A set of Key Performance Indicators (KPIs) is evaluated for each scenario to define the sustainability and cost-effectiveness of renovation projects. These KPIs help assess the extent to which project goals are achieved, providing means to measure and manage progress towards those goals for further learning and improvement (Kylili et al. 2016). In the mentioned review, Kylili et al. reviewed the KPIs approach in building renovation and classified the KPIs employed in the literature into different categories, as shown in **Figure 1**.

The following KPIs are considered the most important and therefore selected for use in IEA EBC Annex 75. They correspond to the «Environmental» category and its sub-categories «Atmosphere» and «Energy», as well as the «Economic» category in **Figure 1**:

- Carbon emissions, expressed as CO2-equivalents per square metre of conditioned gross floor area and per year
- Primary energy use, expressed as kWh per square metre of conditioned gross floor area and per year
- Annualised total costs, expressed as EUR per square metre of conditioned gross floor area and per year

Primary energy use refers here to total primary energy use, except for locally available low-grade renewable energy sources such as environmental heat or solar heat. The primary energy use of delivered renewable energy such as wood is instead accounted for in total primary energy use. The rationale is that wood is an energy carrier that could be used elsewhere if not used in a given investigated building. On the contrary, the use of environmental heat or solar heat by a given building, for the most part, does not influence other buildings' possibilities to use the same type of energy resources.

Additional Key Performance Indicators may be calculated depending on the specific features of each case study.

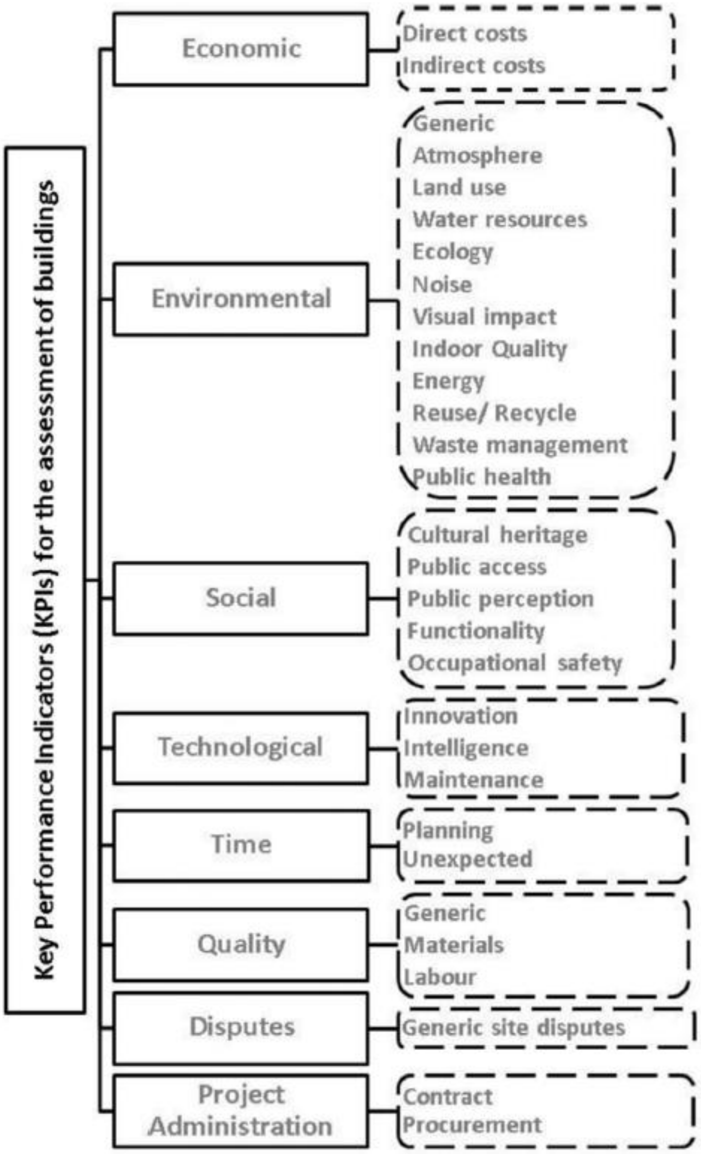

Figure 1. Overview of categories and subcategories of Key Performance Indicators (KPIs) (from A. Kylili et al. 2016).

3.3 Principle of matching the demand side and the supply side of energy

To assess the level of sustainability and cost-effectiveness of renovation projects, selected Key Performance Indicators are evaluated for each scenario investigated. Assessments are carried out based on matching the energy needs of buildings with the energy supply. Figure 2 illustrates this.

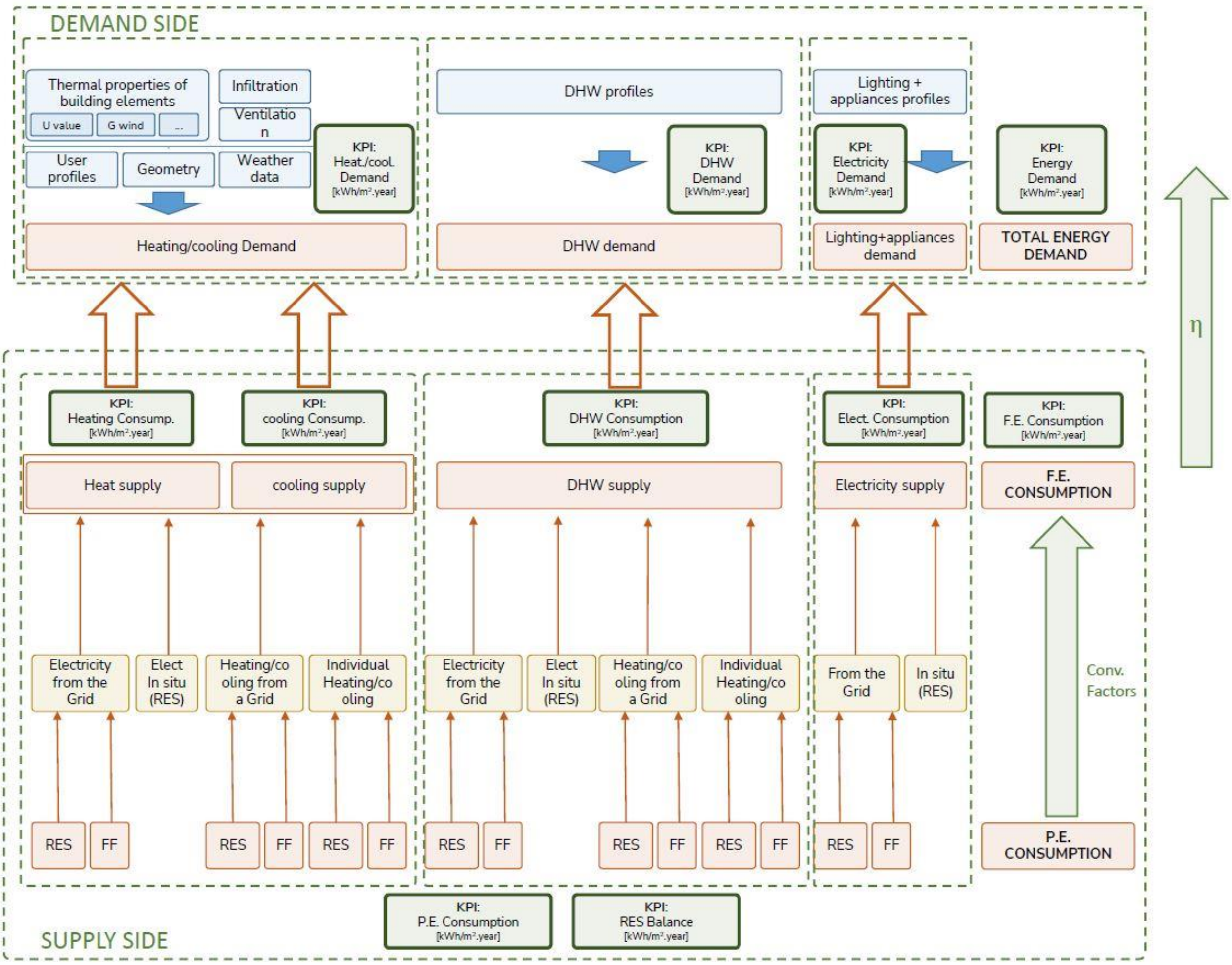

Figure 2. Overview of the principle of matching energy demand side and energy supply side when evaluating different assumed scenarios. In this figure, RES refers to renewable energy resources, FF to fossil fuels, F.E. to final energy, P.E. to primary energy, DHW to domestic hot water, and KPI to Key Performance Indicators (By the authors).

Districts can be evaluated using dynamic simulations or specific tools for evaluating the global performance of the whole system or considering the demand side on the one hand and the supply side on the other.

3.4 Characterisation of buildings - the demand side

The energy needs for heating and cooling of each building of the assessed district are calculated based on building dimensions and thermal properties. Energy needs are indicated as specific energy needs per m^2 gross heated floor area. Energy demand for domestic hot water, as well as electricity demand for appliances or ventilation, are calculated according to the standard profiles of each country.

Table 1 summarizes the data on building dimensions and thermal properties to be gathered or estimated for each building investigated in the district:

Table 1. Parameters necessary to be provided for each building in the district.

Parameter	Unit/value
Gross heated floor area	m^2
Position of building	Latitude / Longitude
Façade area	m^2
Roof area if flat roof	m^2
Roof area if pitched roof	m^2
In case of a pitched roof: Is the room below the roof heated or not?	Yes/No
In case of an unheated room below the pitched roof: area of the attic floor	m^2
Area of windows to North	m^2
Area of windows to East	m^2
Area of windows to South	m^2
Area of windows to West	m^2
Area of the ceiling of the cellar	m^2
Area of the basement floor, if no unheated cellar, floor adjacent to terrain	m^2
Number of floors	-
Average gross heated floor area per person	m^2
Indoor temperature to be maintained in the heating season, if applicable	°C
Indoor temperature to be maintained in the cooling season, if applicable	°C
U-value façade	$[W/(m^2 \cdot K)]$
U-value roof	$[W/(m^2 \cdot K)]$
U-value attic floor, if applicable	$[W/(m^2 \cdot K)]$
U-value windows	$[W/(m^2 \cdot K)]$
g-value windows	Factor 0.0 – 1.0
U-value ceiling of cellar, if applicable	$[W/(m^2 \cdot K)]$
U-value basement floor, if applicable	$[W/(m^2 \cdot K)]$
Is a ventilation system without heat recovery installed?	Yes/No
Is a ventilation system with heat recovery installed?	Yes/No
Efficiency of heat recovery, if applicable	%
Is an air conditioning system installed?	Yes/No
Energy need for hot water	$kWh/(m^2 \cdot a)$
Energy need for ventilation	$kWh/(m^2 \cdot a)$
Specific air flow rate	$m^3/(m^2 \cdot h)$
Average electricity consumption for appliances per year and m^2 excluding heating, cooling, ventilation	$kWh/(a \cdot m^2)$
Usage type	Categories
Construction type	Categories

In the detailed calculation method chosen for a given assessment, deviations from this table and on the related tools used can be justified on a case-by-case basis.

In districts, buildings have different starting situations regarding their building envelope. Another challenge is that the renovation cycles of the buildings' envelopes in a district are usually not synchronized. It is considered appropriate to consider such differences when providing recommendations on how to renovate a certain district.

3.5 Characterisation of energy systems - the supply side

Both centralised and decentralised energy systems are considered options for the energy supply side. Specific interactions amongst the different technologies, such as energy storage, are considered appropriate. Simplified methods can be applied, considering general parameters such as seasonal performances.

The following parameters characterise energy systems:

- Costs, as a function of capacity
- Service life
- Conversion efficiency, taking into account distribution losses. In the case of a heat pump, the conversion efficiency depends on the temperature hub between the source and the required output and, therefore, indirectly also on the energy needs of the building. The conversion efficiency may refer to the average yearly conversion efficiency; in addition, it is also possible to differentiate it according to the season
- Associated energy carriers

Energy from renewable sources is considered as energy from non-fossil sources, according to the definitions of EU directive 2009/28/EC, in particular solar, aerothermal, geothermal and hydrothermal energy, as well as biomass or biogas.

The assessments carried out within IEA EBC Annex 75 go beyond previous assessments conducted for individual buildings by considering district-based solutions.

To extend the assessment to district heating systems, it is, therefore, necessary that the cost structure of the district heating system considers the various elements of a district heating system as described in the following.

District-based heating solutions are considered by distinguishing the following four elements of a district heating system:

- Heat source intake
- Centralised heat generator and circulating pumps
- Pipes
- Individual heating substation for each building

This is graphically illustrated in Figure 3.

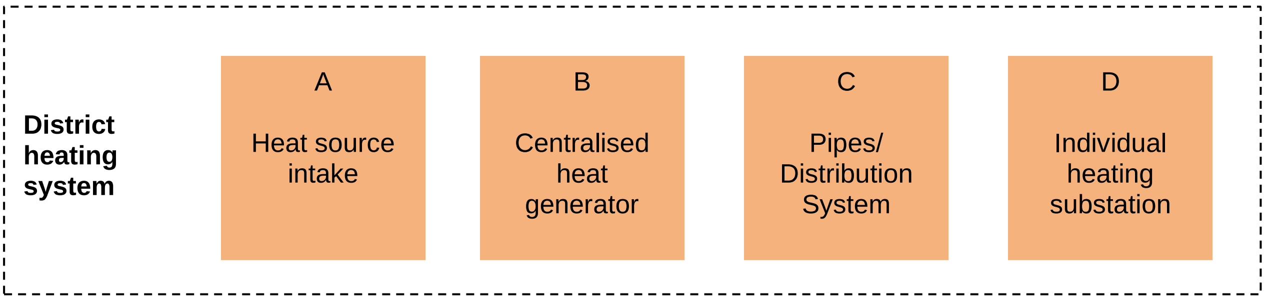

Figure 3. Overview of the main elements of a district heating system.

Such a system is applicable, for example, in the case of a district heating system based on heat from surface water such as a lake, a river or the sea, or from groundwater. In this case, the heat source intake includes the pipes connecting to the water body. It also applies to district heating systems with a centralised geothermal heat pump. In this case, the heat source intake includes the geothermal boreholes. A centralised geothermal heat pump may also be combined with solar collectors, from which heat is transferred into the ground. Furthermore, this scheme is also applicable in the case of solar collectors in connection with large-scale heat storage, which can be considered as a form of heat source intake combined with a centralised heat pump. In the case of a district heating system based on wood energy, the heat source intake can be understood as comprising the facilities for storing wood pellets or wood chips.

Alternatively, in the case of a low-temperature district heating system, the following can be distinguished:

- Heat source intake
- Circulating pump
- Pipes
- Decentralised heat pumps

In this case, instead of a centralised heat generator, there is a circulating pump, and instead of individual heating substations in each building, there are decentralised heat pumps.

Figure 4 illustrates a low-temperature district heating system graphically.

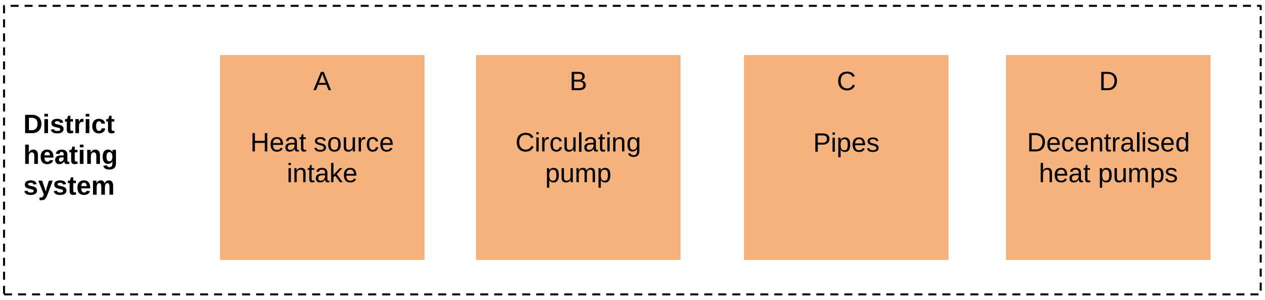

Figure 4. Overview of the main elements of a low-temperature district heating system.

In addition, in the case of seasonal solar thermal energy storage, it may be possible to provide all the necessary heat to buildings without further use of any heat pump. In such a case, the following elements can be distinguished in the district heating system:

- Solar thermal panels + storage
- Circulating pump
- Pipes
- Individual heating substations

Figure 5 illustrates a district heating system exclusively based on solar thermal energy storage graphically.

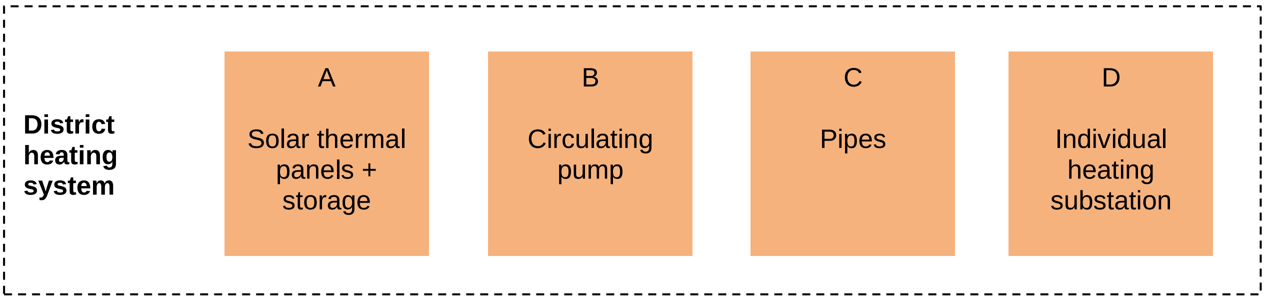

Figure 5. Overview of the main elements of a district heating system based fully on solar thermal storage.

When considering the costs of these various elements, it is necessary to ensure that the sum of the costs of the various elements leads to the total costs of the heating system; i.e. the pipes include all the work required to get them into the ground.

3.6 Other parameters for assessing the cost-effectiveness

There are other important parameters for assessing the cost-effectiveness of district heating systems. Among these is the temperature gap between supply and return temperatures. For a given performance, a high-temperature gap allows using smaller pipes, saving capital costs and distribution losses (Nussbaumer et al., 2018). Furthermore, an appropriate dimensioning of the diameter of pipes is important since implementing the smallest allowed diameter of the tubes saves costs. Capital costs, as well as the heat losses, are thereby reduced. However, electricity costs for pumping increase with smaller pipe diameters and therefore create a cap on the extent to which it makes sense to reduce the pipe diameter (Nussbaumer et al., 2018).

In this study, there is no specific focus on optimizing these parameters to create optimal systems. The focus is rather on parameters directly associated with the optimal balance between energy efficiency and renewable energy measures.

Regarding energy efficiency measures, the focus is on renovating building envelopes.

In addition, among other parameters that influence the balance between energy efficiency measures on the building envelope and renewable energy measures, is the insulation of the dwelling connections that connect the district heating system to the buildings, in combination with a low heat need. There are indications that heat losses in the dwelling connections can be reduced by 70% when compared to a traditional pipe system (Madson 2011). It may therefore make sense to include measures on the insulation of the dwelling connections as a renovation measure. However, as the present study focuses more on the balance between energy efficiency measures of the building envelope and renewable energy measures, it is considered to be appropriate that the possible insulation of pipes does not constitute the main measure to be investigated, even if it does make sense to take it into account.

It also makes sense to consider the reduction of heat losses in the district heating system associated with lowering the heating needs due to energy efficiency measures.

3.7 Measures undertaken anyway in the reference case and building renovation measures

For renovation measures on building envelopes, parameters are gathered to characterise the following properties for various types of materials:

- Thermal resistance/ thermal conductivity
- Costs for different insulation thicknesses/ U-values of windows
- Service life of renovation measures

As appropriate, related information is also gathered for measures that would have to be performed on building envelopes anyway and are, therefore, taken into account in the reference case. For such measures, the term «anyway measure» is also used.

Likewise, for a presumed replacement of the heating or cooling system to be carried out anyway, as well as for renovation measures on the energy system, parameters are gathered to characterise the following properties of the energy system:

- Conversion efficiency
- Costs, as a function of capacity
- Service life of the energy system
- Associated energy carriers

The concept of measures that would have to be carried out anyway in the reference case and a graph illustrating the meaning of «anyway measure» are described in chapter 5.2.

Concerning the costs, economies of scale can be considered when carrying out renovation measures in all or most of the buildings in a district.

3.8 Assessed energy needs and related energy use and emissions

The following types of energy use are taken into account, as well as related carbon emissions:

- Space heating
- Space cooling
- Domestic hot water
- Ventilation
- Auxiliary electricity consumption for building integrated technical systems such as fans, pumps, electric valves, control devices, etc.
- Lighting

In addition, it is considered appropriate to include the electricity consumption of appliances, as they contribute to electricity consumption and internal heat gains. Nevertheless, It is acknowledged that in some countries, including them in such assessments is not common.

When electricity consumption data covering lighting and appliances is available, as is often the case, this data can be used as such, provided that lighting is not modelled separately so that a possible increased lighting due to shading is detected as a measure for reducing cooling needs.

Energy use is assessed based on calculated energy needs. The norm EN ISO 52016-1:2017 is applied for calculating the energy needs of the building, taking into account the energy performance of the building envelope, outdoor climate, target indoor temperature/set-point temperature and internal heat gains.

The measured energy use of a building can be used to assess the plausibility of calculated energy needs, but it does not serve as a basis for the assessments.

3.9 Emission factors and primary energy factors

Carbon emission factors and primary energy factors are considered country-specific factors. The carbon emission factors and primary energy factors used for the assessment are shown in **Table 2**, based on the countries for which the assessments are carried out in IEA EBC Annex 75.

In the emission and primary energy factors, upstream energy use and emissions for extraction and transport of fuel are included.

Emission factors and primary energy factors are considered to be constant over time. The factors for electricity are supposed to refer to a future country mix based on renewable energy. In addition, however, it is possible to also consider, in specific scenarios, other types of electricity mixes corresponding more closely to today's electricity mix.

Where available, and unless there are specific justifications, it is recommended to apply official emission factors and primary energy factors. However, the factors must have a scientific basis and are not merely politically determined, including arbitrary weighting.

Carbon emissions and primary energy use are calculated by considering the conversion efficiencies of the heating systems and emission factors, as well as the primary energy factors of the energy carriers, including upstream emissions and energy use. It is proposed that national primary energy and carbon emission factors are used.

Table 2. Emission factors and primary energy factors of energy carriers; n.e. means not estimated.

Parameter	Unit	AT	CH	DK	ES	IT	NO	PT	SE
Carbon emission factors									
Current electricity mix	kg CO_{2eq} / kWh final energy	0.520	0.100	0.140	0.360	0.480	0.018	0.140	0.047
Future electricity mix	kg CO_{2eq} / kWh final energy	0.520	0.048	0.041	0.360	0.480	0.018	0.140	0.047
Wood pellets	kg CO_{2eq} / kWh final energy	0.027	0.027	0.042	0.018	0.030	0.014	0.045	0.044
Oil	t CO_{2eq} / kWh final energy	0.300	0.300	0.330	0.310	0.270	0.320	0.270	0.290
Natural Gas	kg CO_{2eq} / kWh final energy	0.230	0.230	0.250	0.250	0.250	0.260	0.200	0.230
Primary energy factors									
Current electricity mix	kWh per kWh final energy	3.180	3.010	2.150	2.400	2.420	1.540	2.500	1.600
Future electricity mix	kWh per kWh final energy	3.180	1.350	1.700	2.400	2.420	1.540	2.500	2.100
Wood pellets	kWh per kWh final energy	1.200	1.200	0.044	1.110	1.110	1.110	1.000	1.110
Oil	kWh per kWh final energy	1.240	1.240	1.280	1.180	1.070	1.110	1.000	1.110
Natural gas	kWh per kWh final energy	1.070	1.060	1.160	1.200	1.050	1.090	1.000	1.090

3.10 Cost elements

Overview

A life cycle approach is chosen to indicate costs for energy measures and anyway measures. The following cost elements are included:

- Initial investment costs/replacement costs
- Energy costs, including existing energy taxes and CO_2 taxes
- Maintenance and operational costs

The calculations for assessing life cycle costs and cost-effectiveness are carried out dynamically, either with the annuity or global cost methods, corresponding to the discounted cash flow method. It is proposed to use the annuity method for transforming investment costs into yearly costs, assuming typical service lives for the renovation measures in question. Alternatively, also the global cost method can be used.

The cost assessment is carried out from a private perspective. In doing that, it is assumed that the investments in the district heating system, decentralised energy systems and building envelopes are undertaken by the same energy actor. This means that the district is assessed as a unit. The reason is that what is intended to be investigated within this project is, at first, mainly what type of combination between energy efficiency measures and renewable energy measures is the most cost-effective while satisfying the boundary conditions. It makes more sense to investigate this question ignoring the fact that related investment decisions will, in practice, usually be taken by different energy actors, as this difference in energy actors does not affect the outcome of which combination of technology measures makes more sense in principle. Nevertheless, it is appropriate to investigate potential obstacles to implementing the overall most cost-effective solutions satisfying the boundary conditions because various energy actors are involved. However, this is not part of the assessment described within this methodology but a topic investigated in Subtask D of IEA EBC Annex 75.

Taxes on energy carriers are considered in the assessment according to the national framework conditions. This also includes CO_2 taxes, for which it may make sense to investigate various scenarios in the sensitivity calculations if a new tax or a change of related taxes is under discussion in the respective countries.

In principle, subsidies for energy-related measures are excluded from the cost assessment to allow providing information on what solutions make more sense without the effect of subsidies. To investigate the situation of a specific investor, subsidies may nevertheless be included in a specific assessment. External costs, benefits and co-benefits are not included, although policymakers should consider them for target setting and the design of energy and emissions-related programmes. The units of cost indicators are specific yearly values per m^2 conditioned gross floor area.

Additional comments on investment costs

Concerning investment costs, it is considered necessary for the assessment carried out that economies of scale are considered. In the absence of more precise data, this may be done by assuming, for example, a 10% reduction of costs when carrying out measures in buildings at a district level compared to the costs of related measures in a single building.

For new large district heating systems, it makes sense to consider that in the start-up phase, where new users need to be acquired and connected to an already functioning system, heat sales are lower than the capacity of the district heating system. These may be considered as one-off costs, in the sense of revenue reductions during the start-up phase, similar to investment costs.

Additional comments on energy costs and maintenance/operational costs

Regarding energy costs and maintenance/operational costs, **Figure 6** provides an overview of the related money flows. Energy costs refer here to the costs of energy carriers. Investment costs to the energy systems are not included in this overview.

The figure is further explained as follows.

Concerning the energy carriers' costs and maintenance/operational costs, three different subsystems are considered: «thermal subsystem», comprising heating or cooling systems and domestic hot water; «electricity grid»; and «*in situ* electricity generation».

Energy inputs in the thermal subsystem are mainly renewable energy, or fossil fuels in the reference case, as well as auxiliary energy for running the energy systems. The outputs are the energy for the heating and cooling supply and for the domestic hot water supply. In both cases, they comprise useful energy plus distribution losses. Thus, energy inputs equal energy outputs, including the energy losses due to the system inefficiencies. Similarly, the sum of energy costs and maintenance/operational costs of a specific system will be those related to the energy purchase of the energy carriers (€$_1$ and €$_2$) and costs related to maintenance, management and operation of the system (€$_3$). The sum of these costs is the total operational costs for the system associated with the thermal subsystem (€$_4$).

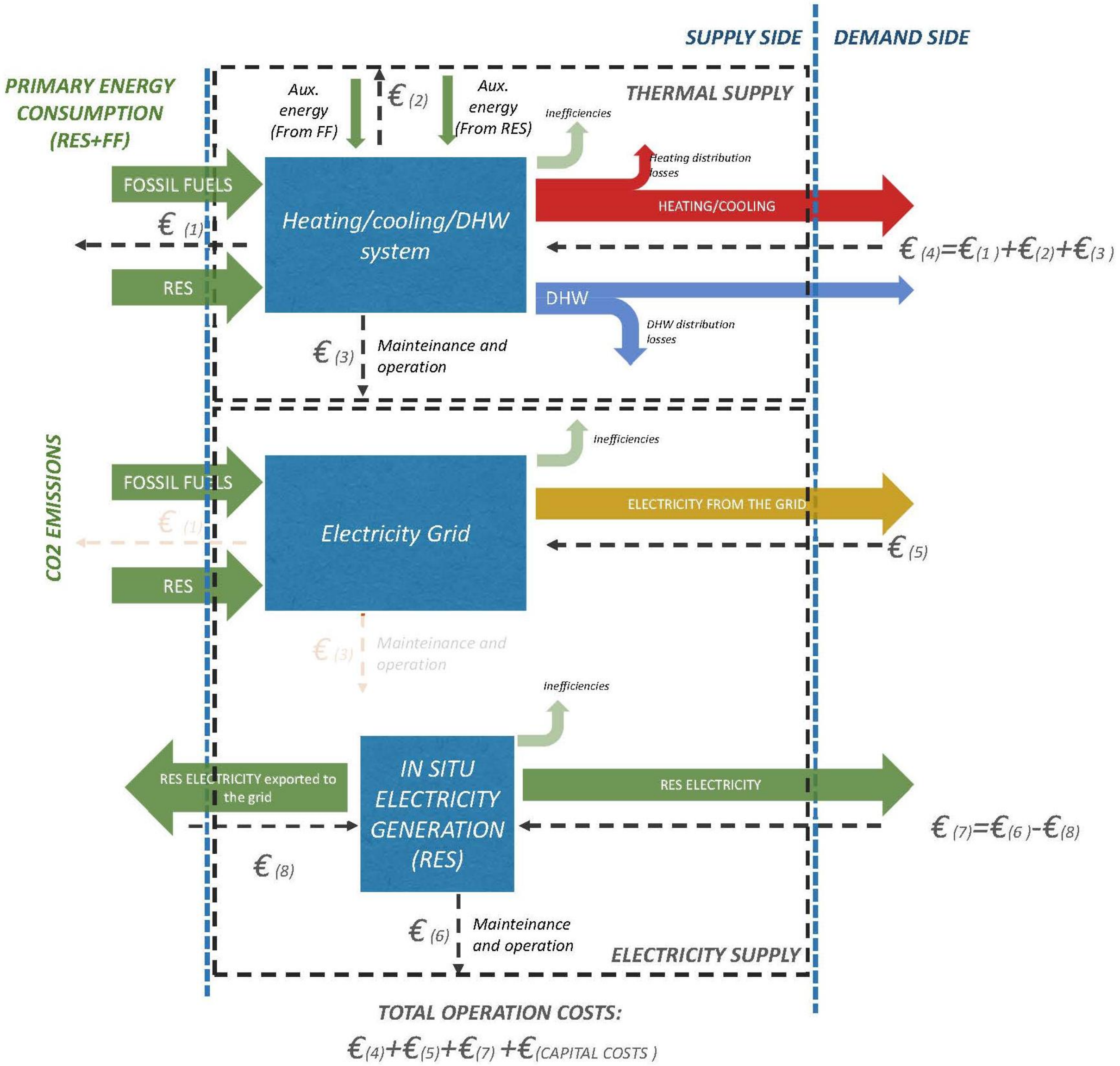

Figure 6. Overview of the elements of money flows related to costs for energy carriers and maintenance/operational costs. Investment costs are not included in this overview. RES refers to renewable energy sources, DHW to domestic hot water (By the authors).

Regarding electricity from the grid, only final electricity costs are taken into consideration (€$_5$).

Finally, in the subsystem «in situ electricity generation», which refers to the electricity generation from renewable energy sources, only energy outputs are considered: energy used in the evaluated district and energy exported to the grid. As far as money flows are concerned, the cost of maintenance and operation (€$_6$) and the benefit of electricity sold to the grid (€$_8$) are considered. The benefit or the deficit of this subsystem for end users is the difference between these two costs (€$_7$). Total costs for energy carriers and maintenance/operational costs for a related measure or set of related measures are the sum of €$_4$, €$_5$ and €$_7$.

In addition, there are costs associated with the investments in these systems and resulting capital costs, which are not shown in the figure.

3.11 Energy prices

It is recommended to take into account expected future increases in energy prices, in conformity with the report prepared by the European Union in 2016 on energy, transport and carbon emissions trends for 2015 (Capros et al, 2016). It is recommended to carry out the assessment with energy prices expected for 2030 to take into account future price increases. Concerning electricity prices, it is proposed to take the perspective of a future energy system fully based on renewable energy and related increases in electricity prices. It is assumed that in Europe, in the future, it will be necessary to store some of the summer electricity production through seasonal storage for making it available in the winter months. This is associated with costs for the related electricity storage and reconversion to electricity. It is proposed to assume that a third of the electricity consumption for heating purposes will have to be made available in this way, whereas the rest can be provided also in winter months, to the extent they are available, by renewable energy carriers such as wind, hydro, biomass, and solar energy. For this share of electricity consumption, including costs for storing electricity is considered appropriate. One of the related options that may be taken into account is, for example, the storage of electricity in the form of hydrogen by splitting water through electrolysis and regenerating electricity later on in winter months through fuel cells. It is considered appropriate to differentiate electricity prices and wood prices for operating a centralised district heating system and individual energy systems in single buildings. Such price differences may be taken into account for other energy carriers as well. Table 3 provides an overview of the energy prices applied in the assessments in the different target countries of this Annex. Further scenarios for the energy prices may be included as part of the sensitivity calculations.

Table 3. Current and future prices of energy carriers; n.e. means "not estimated".

Parameter	Unit	AT	CH	DK	ES	IT	NO	PT	SE
Current price for 2021									
Electricity	EUR/kWh final energy	n.e.	0.210	0.330	0.230	0.220	0.095	0.210	0.150
Wood pellets	EUR/kWh final energy	n.e.	0.080	0.074	0.064	0.067	0.040	0.050	0.040
Oil	EUR/kWh final energy	n.e.	0.100	0.200	n.e.	0.170	n.e.	0.140	n.e.
Natural Gas	EUR/kWh final energy	n.e.	0.100	0.120	0.089	0.081	n.e.	0.058	0.120
Electricity for district heating system	EUR/kWh final energy	n.e.	0.170	n.e.	0.230	0.150	0.052	n.e.	n.e.
Wood for district heating system	EUR/kWh final energy	n.e.	0.070	n.e.	0.064	0.060	0.027	n.e.	n.e.
Expected price for 2030									
Electricity	EUR/kWh final energy	0.200	0.340	0.410	0.230	0.260	0.120	0.270	0.038
Wood pellets	EUR/kWh final energy	0.050	0.100	0.092	0.064	0.070	0.040	n.e.	n.e.
Oil	EUR/kWh final energy	0.090	0.130	0.260	n.e.	0.190	n.e.	0.180	n.e.
Natural Gas	EUR/kWh final energy	0.090	0.130	0.150	0.089	0.091	n.e.	0.084	n.e.
Electricity for district heating system	EUR/kWh final energy	n.e.	0.280	n.e.	0.230	0.180	0.052	n.e.	n.e.
Wood for district heating system	EUR/kWh final energy	n.e.	0.090	n.e.	0.064	0.063	0.025	n.e.	n.e.

3.12 Interest rate

Applying a real interest rate of 3% is recommended unless more country-specific information is available.

3.13 Climate data

For the climate data, the following information is expected to be included, either on a monthly or an hourly basis:

- Average outside temperature, in °C
- Average global radiation from East, West, South, and North on a vertical surface, as well as on a horizontal surface in MJ/m^2

Alternative inputs can be used if required by the calculation tool applied for the assessment.

In addition, wind speed may also be considered in specific circumstances, as it may have a considerable impact, especially if the building is not airtight.

3.14 Embodied energy and embodied emissions

Embodied energy associated with the materials used in building renovations and the energy systems added and related embodied carbon emissions are taken into account. As we aim to investigate in particular what solutions make the most sense in a future energy system based 100% on renewable energy, it makes sense if embodied energy and embodied emissions also refer to such a future energy system. However, it is expected that the related data are not easily available. It is therefore considered adequate if embodied energy and embodied emissions data refer to the current energy system. Total embodied energy use and total embodied carbon emissions are transformed into yearly values by dividing embodied energy and embodied emissions by the years of expected service life of the renovated building element or the energy system concerned.

3.15 System boundaries, on-site electricity or heat production

The system boundary is set to correspond to «net delivered energy». Energy carriers delivered to the building are added up, and for on-site generated electricity or heat exported from the building to the grid, a benefit is granted, which improves energy performance and lowers the carbon emissions of the buildings. However, it is proposed to assume, in at least one of the scenarios investigated, that electricity in the grid is based on renewable energy so that upcoming changes in the electricity mix are considered, which then does not lead to any significant benefit of export of electricity to the grid other than potentially cost savings.

This focus on an energy system fully based on renewable energy is considered necessary to answer the research questions from a perspective that continues to be valid when the energy system is decarbonised, as required by the Paris Agreement to keep the 1.5 °C target within a relatively short period of time. However, to provide more comprehensive recommendations to policymakers, also referring to the transition period until an energy system fully based on renewable energy is reached, alternative scenarios that correspond more closely to today's electricity mix may also be investigated.

On-site electricity generation is considered when it is produced from renewable sources. The quantities of produced electricity consumed locally or exported to the grid must be distinguished.

The potential impact of switching from a fossil fuel heating system to heat pumps, in terms of the increased electrical peak demand on the electrical distribution system and potentially related incurring costs for the reinforcement of the electricity grid, is not considered. However, it is worth noting that this may be an issue to consider in some projects.

Revenues from exporting electricity or heat to the grid or an energy distribution system are considered. The tariffs for exporting electricity to the grid and consuming electricity from the grid are distinguished, as these tariffs are often different.

4. Hypotheses

The validity of several hypotheses is examined based on the investigation of the research questions mentioned in Chapter 2.3. The hypotheses can be understood as assumptions. Through the assessments, it is then determined whether the hypotheses can be validated.

The hypotheses focus, in particular, on comparing the cost-optimal level of energy efficiency measures on building envelopes in different scenarios. A main underlying question is to what extent energy efficiency measures on building envelopes make sense to promote a switch to renewable energy. 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 switch to a centralised renewable energy system, the hypothesis is as follows:

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

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

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

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

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

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

> «The cost-optimal level of the energy efficiency measures on building envelopes does not significantly differ 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 switch to a low-temperature renewable energy-based district heating system

When comparing decentralised fossil fuel systems with a switch to 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 significantly differ 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 the implementation of 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 low initial levels of thermal insulation

Regarding districts with a low initial 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 high initial levels of thermal insulation

Regarding districts with a high initial 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 the energy-efficiency measures on building envelopes» refers to the level of energy needs of the respective buildings considering energy-efficiency measures undertaken.

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

The indicated hypotheses are not completely independent of each other. If hypothesis 1 is confirmed, for example, it is likely that whatever the result is for hypothesis 3, the same result will be obtained for hypothesis 4.

Table 4 summarises the comparisons according to which differences in the cost-optimal energy-efficiency levels are assessed.

Table 4. Comparisons according to differences in the cost-optimal level of energy efficiency measures on building envelopes. Each hypothesis, from 1 to 6, is associated with a different comparison.

Hypothesis	First scenario for comparison	Second scenario for comparison
1	**District heating system based on renewable energy**	**Decentralised individual heating systems based on renewable energy**
2	Existing **district heating system based** fully or to a large extent **on fossil fuels**	A switch to a **centralised renewable energy system**
3	Existing **district heating system based** fully or to a large extent **on fossil fuels**	A switch to **decentralised renewable energy systems**
4	An existing district with **decentralised fossil fuel heating systems**	A switch to a **centralised renewable energy system**
5	An existing district with **decentralised fossil fuel heating systems**	A switch to a **low-temperature renewable energy-based district heating system linked to decentralised heat pumps**
6	A district where **a centralised renewable energy-based district heating system is newly installed**	**An existing district heating system switching centrally to renewables**

From the perspective that a transition towards a 100% renewable energy-based heating system is necessary in any case to meet the objectives to protect the climate, especially, hypotheses 1 and 6 are important, which compare two scenarios based on renewable energy.

The investigation of all hypotheses should also be considered to understand if, to promote energy systems based 100% on renewable energy, policy changes concerning the level of energy efficiency measures on the building envelopes are appropriate when compared with previous situations in which fossil fuels were predominant.

5. Assessment procedure

5.1 Definition and characterisation of investigated districts/groups of buildings

At the beginning of the assessment, the district or the group of buildings to be investigated is defined. This can either be a generic district based on reference buildings or a specific case study district.

The building parameters, as indicated in Chapter 3, are considered.

The dimensions of buildings can be determined through available datasets or blueprints of the investigated buildings.

One way to estimate the U-values of building envelopes is by applying top-down approaches involving GIS data information, such as the classification of each building according to its building period and latest renovation, and applying to them standard values corresponding to their building period or the time of their latest renovation, or, if available, based on data from building stock models. Other data sources that can be used for top-down approaches for estimating U-values are remote-detected energy use or estimates made based on measured energy use, for example, with data from the energy company.

In addition, a potentially helpful source of information is the energy performance certificates.

A more precise way to determine the buildings' U-values is by conducting site visits to each building by an energy advisor or building expert. With site visits, U-values can be measured, including new methods such as those reported by Scarpa et al. (2016), or estimated based on available building plans and the visible construction material.

5.2 Definition and assessment of reference case

At the beginning of the assessment, the reference case is defined, i.e. the type of renovation activities which would have been carried out anyway, just to restore the building’s functionality. This may include repainting walls or repairing the roof to make it waterproof again. It is assumed that these measures, which are to be undertaken anyway, do not increase the building’s energy performance but involve costs. If necessary, hypothetical cost assumptions are made for such measures.

For windows, as hypothetical anyway measures and associated costs, repainting and repairing windows can be assumed, even if windows are usually replaced entirely and not repaired.

A complicating factor is that new windows are often installed for other reasons than saving energy. These reasons may include, for example, noise protection and improvement of thermal comfort. It is theoretically possible to consider this in the assessment by attributing a factor which indicates to what extent investment costs can be attributed to energy-saving measures. However, it is considered that such factors are highly case-specific. Instead of constructing the reference case for windows in this way, it is therefore considered more suitable to estimate the measures to be undertaken anyway based on the hypothetical repainting and repairing of the windows.

For heating systems, a replacement is usually also considered in the reference case. This is necessary to assess the costs of installing a new heating system compared to a correct reference scenario. In the reference case, the replacement is considered to be of the same type as the original heating system. More modern heating systems, even if based on fossil fuels, usually have slightly higher conversion efficiencies than previous systems of the same type. The reference case usually considers an increase in the heating system energy efficiency.

The replacement cost of the energy system heat generation and individual heating substations are also considered for districts with an existing district heating system. However, if the district investigated corresponds only to part of the area covered by the district heating system, only a fraction of respective costs is allocated to the target area investigated.

If appropriate, replacement costs for cooling systems are also considered in the reference case.

Figure 7 illustrates what is meant by an «anyway renovation» (Ott et al. 2017).

For carrying out the reference case assessment, the following indicators are calculated: primary energy use, carbon emissions and costs on a yearly basis and per m^2 of conditioned gross floor area, as kWh/(m^2·a), kg CO_2 eq/(m^2·a), and EUR/(m^2·a), respectively.

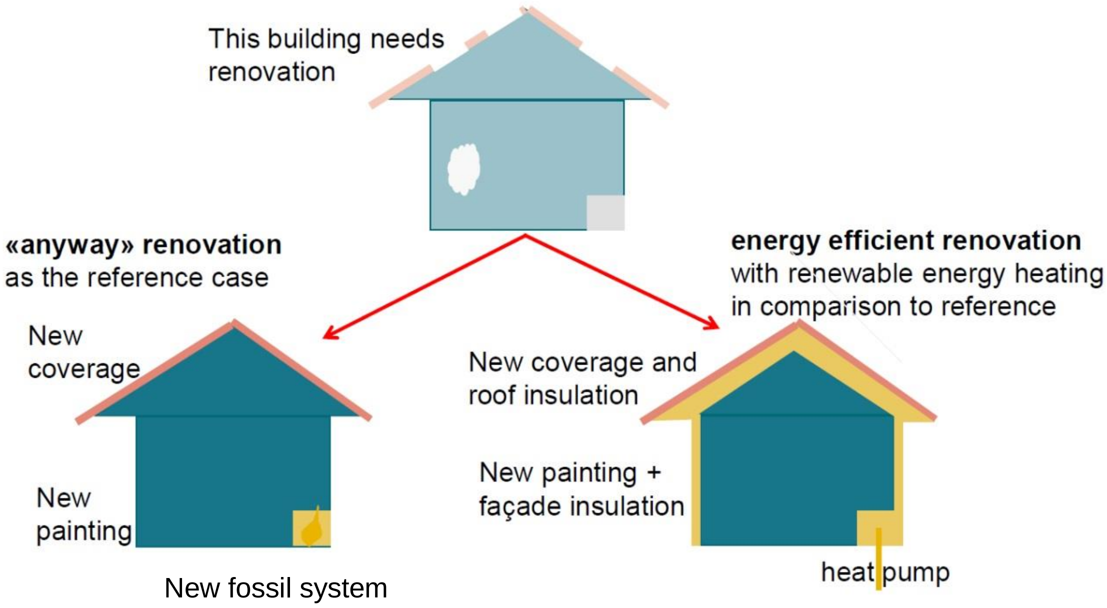

Figure 7. Distinction between anyway measures and energy efficiency measures. An anyway renovation, shown on the left side, restores a building's functionality without improving its energy performance. An energy efficiency renovation, as shown on the right side, restores a building's functionality while simultaneously improving its energy performance. Source: Ott et al. (2017).

5.3 Definition and assessment of building renovation scenarios

For each assessment, a set of building renovation measures is chosen and taken into consideration in building renovation scenarios.

Based on this set of renovation measures, either a limited number of combinations of renovation measures are identified as renovation packages for which the assessment is carried out or the optimal solutions are identified by choosing appropriate combinations through an optimization engine. With the optimization, the lowest cost combinations are sought to satisfy the boundary conditions.

For the investigated renovation packages, the costs and effects of renovation measures are determined.

In case of the identification of a limited number of combinations of renovation packages, the following procedure is recommended:

The reference case is chosen to include some rehabilitation measures, the so-called «anyway renovation» measures, without improving the energy performance. The exception is the replacement of the energy system, which is also assumed to occur in the reference caseleading, in many cases, to slightly higher conversion efficiencies.

For each building in the district, about ten renovation packages, denominated M1 to M10, with progressively higher ambition levels related to the resulting energy performance of the building envelope, are investigated. Renovation packages differ from each other both by the number of building elements included in the improvement of energy performance and the performance or efficiency level of the chosen insulation or the U-value of the chosen window. Furthermore, measures to improve the energy performance of the building by upgrading or installing technical systems such as ventilation with heat recovery or a PV plant can be considered. A replacement of the heating system is assumed in all cases, also in the reference case of an anyway renovation. The heat distribution system, including the radiators, can be assumed to remain the same or to be changed.

For each district, in all the renovation packages M1 to M10, combinations with at least one fossil fuel-based system, centralised or decentralised according to the initial conditions, and with both centralised and decentralised renewable energy systems are investigated.

The scenarios based on renewable energy are supposed to be fully based on renewable energy as a boundary condition.

Regarding the renewable energy systems investigated, it is considered to be more interesting to investigate options for using environmental heat, which is essentially available in most locations, such as solar energy, environmental heat from the air, from the ground, or surface water, depending on the country, unlike, for example, wood energy, which has a limited potential that does not allow to provide heat to all buildings.

For district-based systems, replacing the heating system is supposed to include central heat generation and individual heating substations.

If appropriate, cooling systems are considered in the renovation packages and related passive or active measures to reduce energy use for cooling. When cooling is considered, the potential risks of overheating or the increased demand for cooling in summer months, if insulation is particularly heavy, should be evaluated. Among the various buildings that are part of the district investigated, it is possible, yet not necessary, to apply the same type of building renovation measures to all buildings, if the situation permits. Alternatively, the measures can be distinguished separately for each building.

The renovation packages investigated are expected to be chosen in a way to be able to answer the research questions/check the validity of the hypotheses. To do this, varying levels of energy efficiency of the building envelopes must be investigated in combination with various types of heating systems.

It may be useful to align various renovation packages investigated with specific standards from a given country, making the results more easily interpretable.

The dimension of the heating system is calculated by determining the required peak capacity to maintain the indoor target temperature despite heat losses during winter time. It is considered that new heating systems can be downsized due to better insulation.

When choosing appropriate combinations of solutions through an optimization engine, there are various approaches to identifying the optimal solutions with multiple objectives.

In this Annex, it is proposed to consider as suitable solutions only combinations which result in an energy use fully covered by renewable energy; this includes electricity use with a combination of on-site electricity production and electricity imported from the grid. Once this condition is attended, the remaining carbon emissions are those associated with embodied emissions of the renovation measures and upstream emissions of the energy carriers. Among solutions that satisfy this condition, the optimal solution can then be chosen by taking into account primary energy use and costs.

The assessment is based on calculations and not on observed energy performance. In reality, it is sometimes observed that the energy efficiency performance levels do not reach the target values according to the calculation. Such a fact is referred to as a performance gap. It may occur due to deviations in the actual construction compared to design or user behaviour, including rebound effects. For carrying out the assessment, it is not necessary to consider these effects. It needs to be kept in mind, though, that this may potentially overestimate, to a certain degree, the cost-effectiveness of the renovation measures.

For assessing the renovation packages, the following indicators are calculated: primary energy use, carbon emissions and costs, on a yearly basis and per m^2 of conditioned gross floor area, as kWh/(m^2·a), kg CO_2 eq/(m^2·a), and EUR/(m^2·a), respectively.

5.4 Results to be obtained

To assess the cost-effectiveness of various renovation packages, a comparison is made between the reference case and the renovation packages.

The validity of the hypotheses is examined.

Results are illustrated with the following graphs:

- Specific carbon emissions [kg CO2eq/(m^2·a)] vs. costs [EUR/(m^2·a)].
- Specific primary energy use [kWh/(m^2·a)] vs. costs [EUR(/m^2·a)].

5.5 Sensitivity investigations

It is good practice to investigate the results by varying certain parameters to identify factors which strongly influence the calculation results. It may be particularly appropriate to consider, for example, varying assumptions regarding the future development of energy prices and various parameters characterising the district.

6. Relationships between energy efficiency measures and renewable energy affecting the project outcomes

6.1 Introduction

There are several relationships between energy efficiency measures and renewable energy measures that strongly affect project outcomes. They are indicated in a separate chapter to underline their importance for conducting the assessments.

6.2 Energy use as a function of the insulation of the building envelopes

Typically, the better insulated a building is, the lower its energy needs are and, therefore, its energy use. Usually, this relationship has a stronger effect on reducing costs in the case of fossil fuel-based heating systems compared to renewable energy-based heating systems because renewable energy systems have lower operational energy costs than conventional fossil fuel-based systems.

Similarly, increased insulation of pipes of a district heating system decreases energy use (Madson 2011).

When making related assessments, it is important to consider the potential risks of overheating or increased demand for cooling in the summer months if the insulation level is particularly heavy.

6.3 Costs of heating systems as a function of required heating capacity

To investigate the research questions concerning the balance between energy efficiency measures on building envelopes and renewable energy-based measures, the heating systems' costs must be modelled appropriately as a function of their necessary capacity. The latter is affected by energy efficiency measures carried out: the more energy efficient a building is, the smaller the required capacity of the heating systems. This relationship is important for assessing synergies or trade-offs between energy efficiency measures and renewable energy measures. It is a factor that creates synergies between energy efficiency and renewable energy measures.

Renewable energy systems typically have higher investment costs than conventional fossil fuel-based systems. Reducing the required capacity of the heating system due to insulation of the building envelope is, therefore, a factor from which renewable energy systems benefit more intensely than conventional fossil fuel-based systems.

Usually, the cost for a heating system is a logarithmic function of the installed capacity due to economies of scale. To facilitate the assessment, it is considered appropriate to approximate the cost function with a piecewise linear approximation based on a limited set of discrete capacity/cost relationships, as illustrated in **Figure 8**.

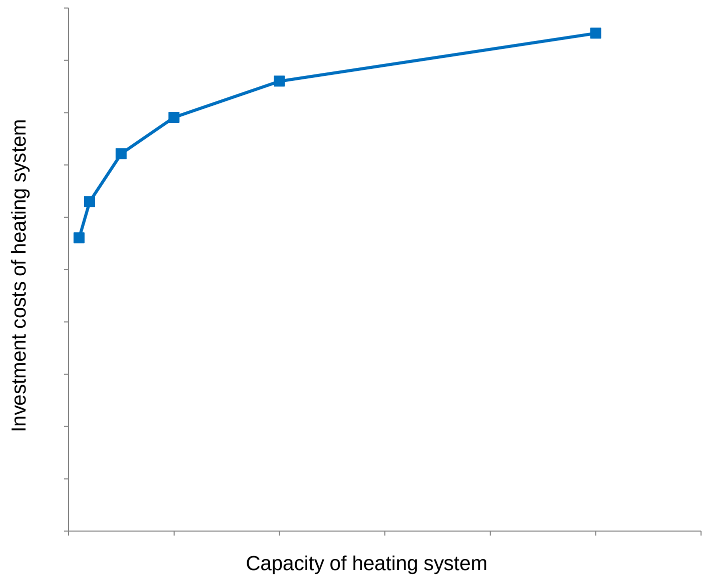

Figure 8. Example of a cost curve for a heating system (By the authors).

To apply the methodology to district heating systems, it is important to attribute to each of the elements of a district heating system its own cost curve, as a function of the necessary capacity of the heating system. For elements that are less dependent on the required capacity of the heating system, linear functions may be applied for simplification. It is considered that this is the case, for example, for the pipes.

When applying the cost curves, consideration should be given to whether there is already an existing district heating system or whether the assessment is made for investigating a possible new district heating system.

6.4 Conversion efficiencies of heating systems as a function of heat need

For heat pumps, there is an important synergy with efficiency measures on the building envelope because the lower the energy need of a building is, the lower can be the flow temperature of the heat distribution system within a building. Accordingly, the temperature hub between the flow temperature of the heat distribution system and the temperature of the heat source becomes smaller. This increases the efficiency of heat pumps operating to provide heat from a heat source to the building.

At the same time, for energy-efficient buildings, the average outdoor temperature during which any heating system is operating is lower than for less insulated buildings because in more insulated buildings, the outdoor temperature below which heating is required is lower than for less insulated buildings. This is a factor which decreases the average conversion efficiency of heat pumps in more energy-efficient buildings.

For the conversion efficiency of heat pumps, it is therefore considered to be important that their efficiency is modelled as a function of the heat need of the building, taking into account both of these factors.

In a district heating network that depends exclusively on a centralised heat pump, it has to be taken into account that benefits in terms of increased efficiency can only be achieved if all buildings in the network have a high-energy performance building envelope because otherwise, the operating flow temperature of the district heating system cannot be lowered.

Furthermore, when assessing potential synergies between energy efficiency measures and the conversion efficiencies of heat pumps in district heating systems, it is important to find an appropriate solution for generating domestic hot water. Synergies can only be achieved if it is ensured that the requirement for obtaining domestic hot water at a specific temperature level does not prevent the distribution temperature in the district heating system from being lowered. This may be achieved, for example, through a combination with separate decentralised heat pumps for locally generating domestic hot water with a higher temperature than the flow temperature of the district heating system.

Increased energy performance of buildings may have, in addition, an impact on reducing energy losses in a district heating system. It is, therefore, appropriate to consider the energy needs of connected buildings in relation to distribution losses, which influence the overall conversion efficiency of a district heating system (Madson 2011).

7. Concluding remarks

Investigating cost-effective strategies for achieving far-reaching reductions in carbon emissions and energy use in urban buildings at the district level is a complex task. There are numerous research questions that can be investigated in this context, and the level of detail that can potentially be examined is high. This methodology report provides a basis for investigating particularly the cost-effective balance between carrying out energy efficiency measures and deploying renewable energy measures in renovating buildings at the district level. It is recommended to keep a focus on this main idea of the methodology when applying it in generic calculations or real-world case studies.

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ANNEX 75

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