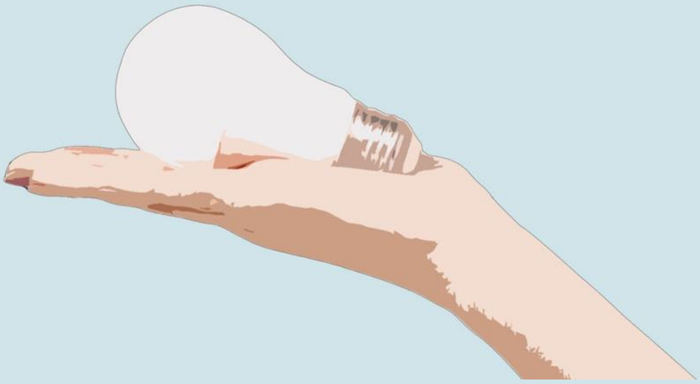
Nordic Energy Outlooks - Final report WP3

Energy efficiency and conservation

28. February 2023



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Abbreviations

BC	Black carbon
CO_2	Carbon dioxide
COP	Coefficient of performance
DHN	District heating network
DH	District heating
ECM	Energy conservation measures
ECEM	Efficiency and conservation of energy and materials
EE	Energy efficiency
ETS	Emission trading system
GHG	Greenhouse gas (emissions)
IEH	Industrial excess heat
KPI	Key performance indicator
LCOE	Levelised cost of energy
MAC	Mitigation abatement cost curves
MC	Material conservation
ME	Material efficiency
NCES	Nordic Clean Energy Scenarios
NEO	Nordic Energy Outlooks
NECP	National energy and climate plans
NVE	Norwegian Water Resources and Energy Directorate
OC	Organic carbon
ORC	Organic rankine cycle
SLCF	Short-lived climate forcers
SLCP	Short-lived climate pollutants
SME	Small and medium enterprises
UEH	Urban excess heat

1. Introduction

1.1. About the Nordic Energy Outlooks programme

Nordic Energy Outlooks [1] (NEO) is a programme organised by Nordic Energy Research, and financed jointly by Nordic Energy Research, the Swedish Energy Agency, the Research Council of Norway, and the Danish Energy Agency.

The main aim of the programme is to *Strengthen Nordic research competence and cooperation in the field of energy systems analysis, by building on existing national research programmes*. By creating a forum for collaboration between different research groups and institutions, NEO helps to synthesise the results of current national research and put these into a Nordic context, but also help to clarify how the choice of analytical methods can create different results.

An additional aim of the programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (NECP), and if the results can provide a regional perspective. Figure 1-1 illustrates the aims of the programme.

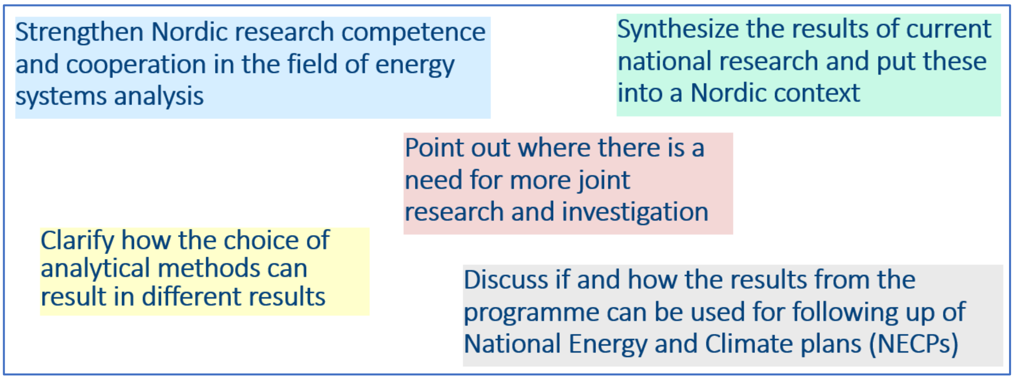

Figure 1-1: Aims of the Nordic Energy Outlooks programme

The programme is divided into four work packages (WPs), as shown in Figure 1-2, in addition to a separate WP for project lead. Each WP is carried out by selected research institutes in collaboration with SINTEF Energy – which is the project lead institution for the program. The outcomes from WP1 and WP2 are documented in [2], [3], whereas the outcome from WP3 is documented in this report.

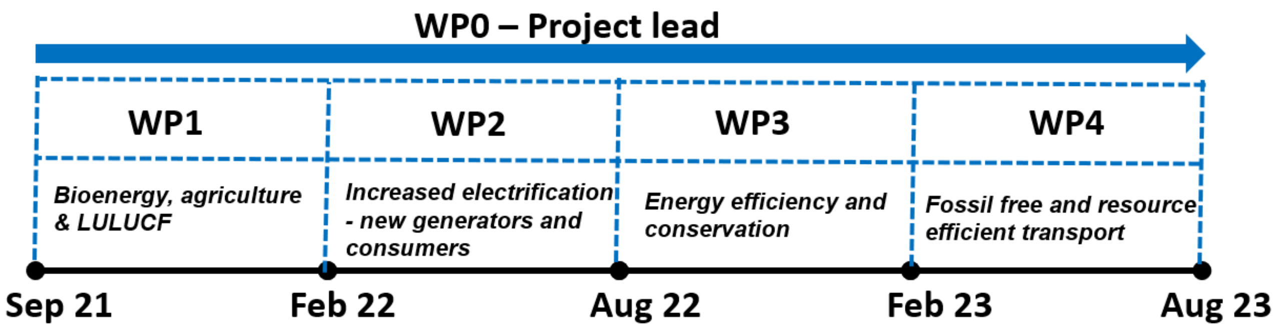

Figure 1-2: Overall structure and timeline for Nordic Energy Outlooks

1.2. WP3: Energy efficiency and conservation

This document is the final report from WP3, which addresses energy efficiency and conservation in the Nordic area. The framework for energy efficiency and conservation adopted in this WP3 is illustrated in Figure 1-3. National and EU targets for energy efficiency, as well as an increased focus on energy conservation and circularity, will affect the energy system transformation. *Conservation* reduces the energy need for different end-uses and services, while *efficiency* allows to supply these end-uses and services with a reduced energy supply. *Supply from renewable sources* reduces the share of energy coming from CO_2 emitting technologies e.g. fossil-fuel power generation. Given the urgent need to speed up decarbonisation of the energy system, it is important to consider all options available. It should also be noted that increased energy efficiency and conservation has positive synergies with other decarbonisation strategies, e.g. facilitating the integration of RES technologies, such as wind- and solar-power. In many cases, such as increasing the use of heat pumps, energy efficiency measures contribute to lower energy system costs. Finally, with focus on making the full energy conversion chain – supply-to-services – decarbonised and resource efficient, the material resources also become important, since the material-embedded energy demand and carbon footprint are not negligible. Therefore, WP3 sets out to work with the framework on Efficiency and Conservation of Energy and Materials (ECEM).

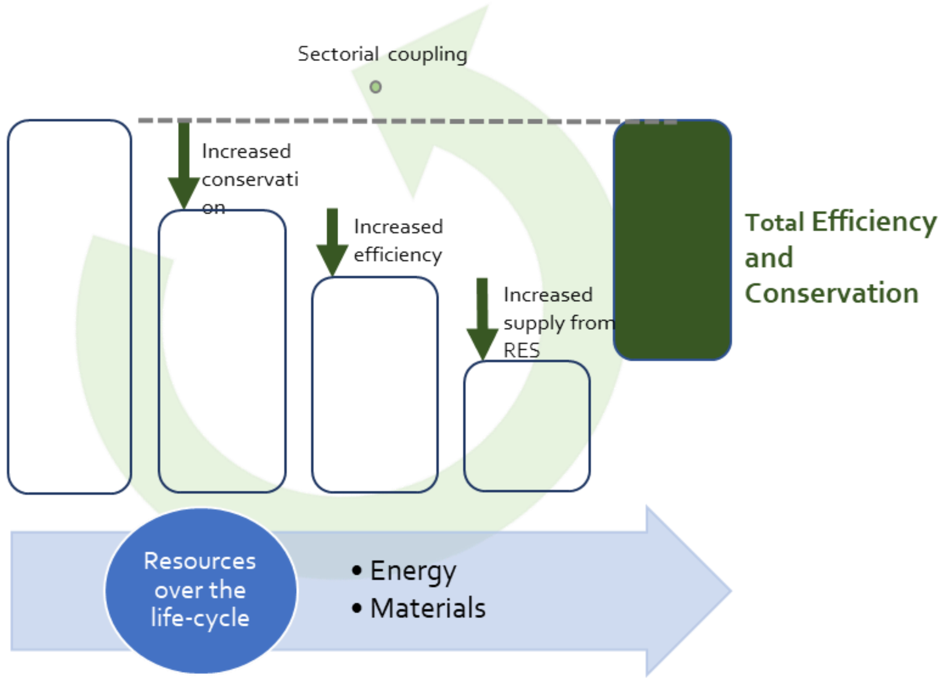

Figure 1-3: Framework for energy efficiency and conservation adopted in this WP3.

The research partners in WP3 are SINTEF Energy Research, IVL, IFE, KTH, and DEA. See also the corresponding short descriptions of the teams in Section 1.3. Each research partner has committed to specific tasks according to their contracts with their financing institution in NEO. The Research Questions (RQ) pursued are shown in Table 1-1. Even though they vary in many dimensions, we have grouped them into some main categories.

Table 1-1: Research questions in WP3

No	Research question
	Literature reviews and qualitative assessments of the role and potential for energy efficiency and conservation
RQ1	What is the existing knowledge on key aspects of Efficiency and Conservation of Energy and Materials (ECEM) in the Nordic area, from different methodological perspectives?
RQ2	To what extent do the most recent energy development scenarios in the Nordic countries explore the role of ECEM?
RQ3	What is the existing knowledge on the role of different energy-efficiency and conservation measures in the building sector?
	General energy system models: Improved representation of energy use, and simulations
RQ4	How can existing energy system models be improved to assess the role, and potentials for, ECEM in the Nordic context?
RQ5	How can datasets be improved to represent the Nordic industries, and what gains can be achieved from the increasing level of detail in the industrial sector?
RQ6	How can different energy efficiency and conservation measures in industry and buildings be included in energy system models?
RQ7	How large is the techno-economic potential of energy-efficiency and conservation measures in the building sector. How will uncertainty related to energy prices have impact on the estimated potentials?
	Utilisation of excess heat from industry, and expansion of thermal grid
RQ8	What is the cost-effective amount of excess heat that can be re-used through the coupling of the industry and building sectors?
RQ9	What will be the least-cost extension of the thermal grid in Sweden/Stockholm from spatial, and time point of view (i.e. where and when to invest)?
RQ10	How will the cost-effective reuse of excess heat reduce the energy intensity (MJ/GDP) on a national level?

A bouquet of mathematical models and methods has been involved to answer those research questions, including general energy system models (GENeSYS-MOD [4], OSeMOSYS [5], IFE-TIMES-Norway [6] and ON-TIMES [7]). Their use spans from new simulations carried out in WP3, via utilisation of simulation results for the REPowerEU scenario, which was specified and analysed in WP2, to link towards sector-specific models for energy use (PROFet [8], [9], RE-BUILDS model [10], Geo-Spatial tool [11], EnergyPlan [12]), to comparative studies of inputs to models and literature review of recent analysis. Each model is described in the appendix.

The applied methodologies are described in Section 2, focusing on the specific developments carried out in WP3. The corresponding findings for each of the research questions in Table 1-1 are described in Section 3. Section 4 discusses existing NECPs for Sweden [13]. Norway does not have an official NECP, but we discuss the document Meld.St.13 Klimaplan for 2021-2030 [14]. We also consider if the results from the project and the expertise from involved researchers can be used for following up NECPs by setting them into a Nordic perspective.

Some promising research topics for future cooperation between the research partners are described in Section 5. Within WP3, applied methodologies and plans for further developments, have been discussed in a process where all partners have shared information and provided mutual comments in workshops. Through this process, the research partners have gained enhanced increased mutual understanding of the corresponding energy system models. Section 6 concludes by providing a summary and key findings from the work.

1.3. WP3 Team

IVL

IVL Swedish Environmental Research Institute is an independent, non-profit research organisation owned by a foundation established by the Swedish government and industry. The institute comprises Sweden's largest groups of environmental experts and employs around 400 people, making IVL a leading institute for applied environmental research and consultancy services. IVL undertakes research projects and contract assignments in the areas of Natural resources, climate and environment, resource-efficient recycling and consumption, Sustainable production and environmental technology, sustainable urban development, and transport. The unit of Sustainable Cities and Society has participated in WP3, with a team that includes expertise in modelling the buildings and industry sectors, energy system optimisation and air pollution analysis.

IFE

The Institute for Energy Technology (IFE) is an independent research foundation located in Norway at Kjeller and Halden. IFE's research team in the Energy System Analysis department works with scenario analysis and transition studies that map out different pathways the Norwegian and European energy system could follow over the coming years, focusing on policies, investments, technologies, and other choices that policy makers and other decision-makers can influence.

KTH

KTH Royal Institute of Technology in Sweden participates via the division of Energy Systems (KTH-ES) who brings expertise on district energy solutions, industrial energy use, and regional energy systems modelling and optimisation. In combination, we have linked to this project our complementary expertise related to District Energy Systems; sector-coupling; the EMB3RS platform for the evaluation of alternatives and business cases for the re-use of industrial waste heat and cold [15]; the fully open-source energy modelling tool OSeMOSYS for long term planning of energy systems [5]; spatial and temporal aspects in optimisation problems including the geospatial tool for matching excess heat to demands in the least-cost connections.

SINTEF

SINTEF is a multidisciplinary, independent research organisation located in Norway. The research team consists of members from SINTEF Community working with sustainability in buildings, infrastructure, and mobility, and members from SINTEF Energy Research working with energy transition studies in energy systems, industry and infrastructure.

2. Progressing methods for analysing energy efficiency and conservation

This chapter provides a brief overview of the applied methodologies, while the outcomes from the work in WP3, including new simulation results and literature reviews, are presented in Chapter 3.

On modelling side, general energy system models have been linked with sector-specific models for energy efficiency and conservation. Furthermore, the representation of energy demand and corresponding data has been improved in several of the applied models. By doing so, we have developed and applied new methodology to study energy efficiency and energy conservation in the Nordic area. Literature reviews have been carried out to reveal the state of art for different aspects related to energy efficiency and energy scenarios, and findings have been a starting point for the modelling. Moreover, a comparative study assesses some of the main inputs and assumptions between a set of energy system models.

2.1. Linking PROFET – GENeSYS-MOD

GENeSYS-MOD is an energy system and capacity expansion model for Europe developed by a team at TU Berlin [16]. Such models have large datasets for which it is difficult to maintain high quality input data throughout. In this project, we have updated the input data for the building sector by linking it to outputs from a sector-specific model for the Norwegian building sector, the PROFet model. The advantage of this is that the outputs from the PROFet model are expected to be more accurate that the existing input data for GENeSYS-MOD, which will improve the outputs from GENeSYS-MOD. Furthermore, the RE-BUILDS model [10] calculates the building stock that is used in PREFet to generate energy demand projections. Each of the models is described in more detail in the appendix.

In PROFet model simulations, the development of the building stock in Norway towards 2050, and thus its energy demand, is compared in two scenarios, where one represents a Business-as-Usual development, and the other represents an ambitious promotion of energy efficiency; these scenarios are hereon referred to as the *Baseline* and *Energy Efficiency* scenarios, respectively. The building stock in Norway in 2020, representing the initial condition of the scenarios, is shown in Table 2-1. In both scenarios, the building stock grows by 18% from 2020 to 2050. The difference between them lies only in the energy efficiency of the new buildings and the rate of energy upgrading in renovations. In the *Baseline* scenario, all new construction is built according to the current building standard TEK17, considered in this study as *efficient* buildings. Also, only 20% of the renovated buildings are upgraded from *regular* to *efficient*. Construction at passive-house level is not promoted in this scenario, and thus *very efficient* buildings are not present in the building stock. In the *Energy Efficiency* scenario, it is stipulated that all new construction must adhere to passive-house standards and be considered *very efficient*. Furthermore, all renovated buildings must be upgraded to be more energy efficient. Table 2-2 summarises the development of energy efficiency in the building stock in the two scenarios.

Table 2-1. Building stock in the Norwegian electricity bidding zones in Norway in 2020, in m².

	Residential		Commercial	
	Regular	Efficient	Regular	Efficient
NO1	88 103 198	20 596 562	41 791 066	9 157 505
NO2	53 033 651	10 033 657	23 880 609	5 232 860
NO3	32 874 209	6 572 418	13 930 355	3 052 502
NO4	25 034 545	4 595 266	8 955 228	1 962 323
NO5	27 142 582	5 699 714	10 945 279	2 398 394
Total	**226 188 186**	**47 497 616**	**99 502 538**	**21 803 584**

Table 2-2. Development of the energy efficiency of the building stock in Norway in the Baseline and Energy Efficiency scenarios.

	Baseline			Energy Efficiency		
	Regular	Efficient	Very Eff.	Regular	Efficient	Very Eff.
2020	82 %	18 %	0 %	82 %	18 %	0 %
2030	71 %	29 %	0 %	64 %	25 %	11 %
2040	61 %	39 %	0 %	47 %	32 %	21 %
2050	51 %	49 %	0 %	32 %	38 %	30 %

The results of this sector-specific modelling can be used to update the previous residential heat demand assumptions included in the GENeSYS-MOD dataset. The baseline in 2020 is used for the current state of the system while the Energy Efficiency scenario is used for future periods.

2.2. Improved representation of the energy demand in industry for GENeSYS-MOD

Industrial energy demand in the GENeSYS-MOD dataset is represented solely as heat demand given annually, while the electricity demand per region is the combined electricity demand of all sectors. Furthermore, Norway is represented in five regions corresponding to the electricity market Nord Pool bidding zones.

In the original GENeSYS-MOD dataset, industrial heat demand is defined in three quality levels: low-temperature heat incorporates heat demands until 100˚C, medium temperature heat ranges from 100˚C to 1000˚C, and high temperature denotes heat above 1000˚C. However, the coarse resolution of modelled industrial heat demand does not allow for the accurate representation of the industrial sector nor the modelling of industrial energy efficiency measures such as high-temperature heat pumps, which are investigated.

In this work, in order to represent both industry and energy efficiency technologies more accurately, industrial heat demand in the medium temperature range is disaggregated into four qualities defined in the temperature ranges 100˚C-150˚C, 150˚C – 200˚C, 200˚C – 500˚C, and 500˚C – 1000˚C in the five modelled regions in Norway. The medium of heat transfer is not specified.

To quantitatively determine the industrial heat demand, the data must be inferred from several sources. The five branches in Norway, which are relevant to the medium temperature heat demand, are chemical, mineral products, food, pulp and paper, and metal. Furthermore, estimates of the relative and absolute heat demands in temperature ranges 60˚C-100˚C, 100˚C-150˚C, 150˚C-200˚C, 200˚C-500˚C, and above 500˚C per sector can also be found. [17] In order to spatially disaggregate the heat demands over the five modelled Norwegian regions, they are projected onto and scaled according to the locations of energy-intensive industries [18]. Available NVE statistics give the expected annual heat demand of 2018 with a total industrial heat demand of 19 TWh [19] to which the medium heat demand can be scaled when assuming that the low and high temperature heat demand of the original GENeSYS-MOD dataset remain unchanged. When disaggregating the temperature levels of the Norwegian heat demand, the modelled technologies that are able to provide industrial heat must be evaluated regarding their efficiency and availability as well.

As energy transition scenarios from 2018 to 2050 are considered in GENeSYS-MOD, the specified annual demands are projected into 2050. In this work, the projected growth in demand is kept according to the original input data assuming no new industrial development in the region. If new developments for potential new industries should be modelled, such as data centres, battery production, and hydrogen, a market equilibrium model is then required to project the future growth of these industries in the global context as input to GENeSYS-MOD.

2.3. Linking Geo-Spatial tool – OSeMOSYS – EnergyPlan for Energy Conservation through Sector-Coupling

Overview of model linking

The study aims to analyse the development of district heating systems while considering the techno-economic feasibility of extending existing thermal grids to integrate excess heat from industrial and urban activities – a concept for resource efficiency more broadly known as Sector-Coupling. The study is applied to the Swedish national context, but the insights can also inform the other Nordic countries when using the methodology for their case-specific contexts.

The method used for this part considers the linking of three tools: a geospatial tool to determine the least distance network connection to potential excess heat sources and the corresponding costs; a long-term energy system model to determine the investment pathways for inclusion of excess heat; and lastly, a dispatch model to determine the feasibility of the investment pathways. See Figure 2-1 for an overview.

The linking of models was preceded by a detailed literature review to analyse the use of similar tools in previously reported cases. The literature review has also been used to set up the background for the case applications studied, and to collect data for implementing the model in the different tools. The following sections provide a brief overview of the literature review and explain each tool and the linking of these tools.

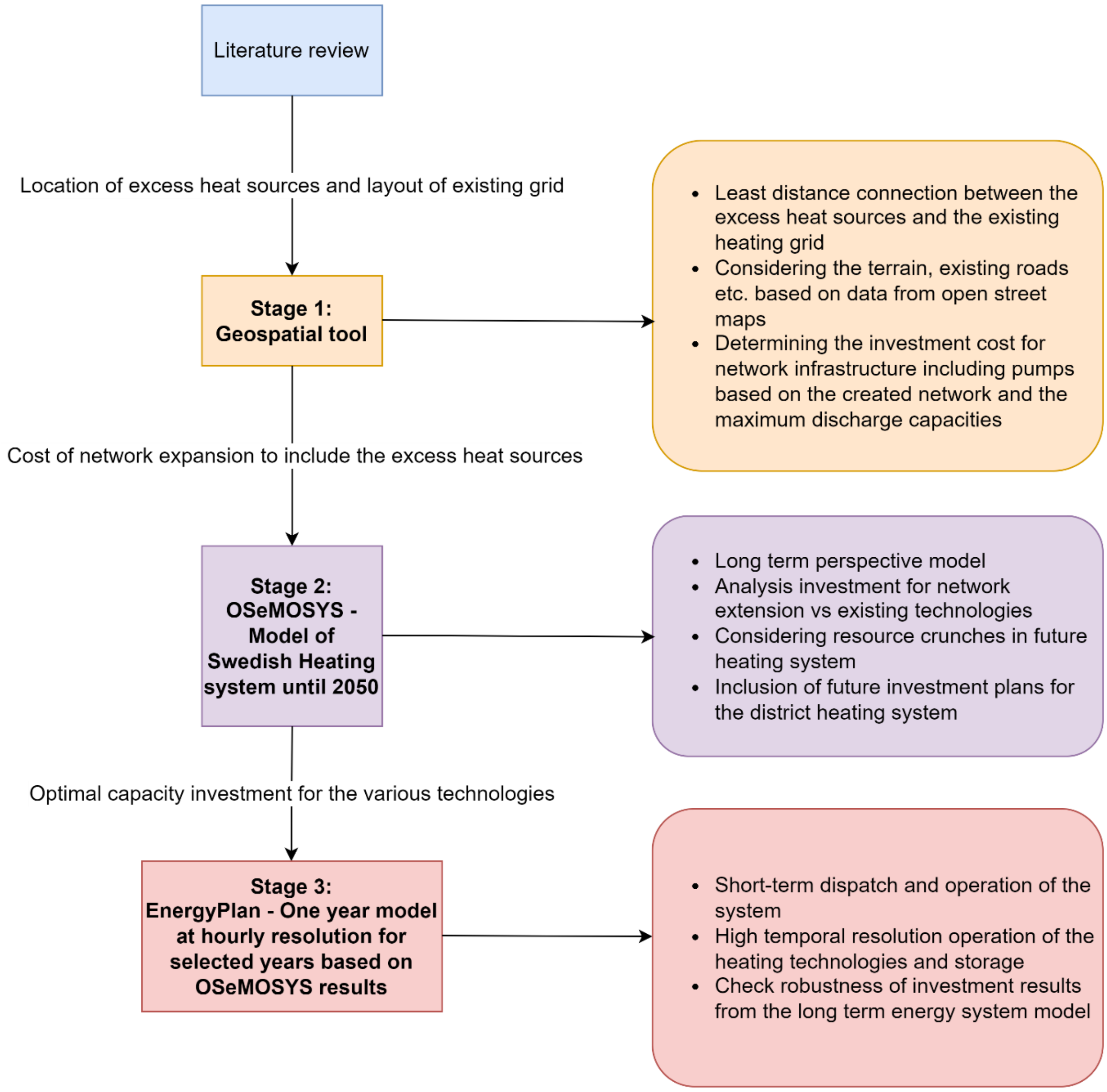

Figure 2-1: Model linking

Literature review – setting the stage for analysing excess heat integration in district energy networks

This section presents the results of a literature review on tools for analysing the long-term development of a district energy system, along with background review for some select cases to model including relevant input data for these cases. Several methods have been applied for the techno-economic analysis of excess heat integration.

Broberg et al. collected energy audits and potential for excess heat recovery in industries in Östergötland and Örebro counties in Sweden through surveys [20]. The survey consisted of three parts. The first part concerned the availability of excess heat and whether the possibility of using this heat internally and/or externally had been investigated. The second part addressed the amount of excess heat available in various energy carriers while the third part concerned energy management within the industries. The results indicated presently unused primary heat potentials of approximately 2 TWh/year and total unused heat potential (including secondary) of 21 TWh/year on a national level. The estimation of the heat potential has further been updated in the WP3 report of the Stratego project, where 123 energy and industry sector facilities were mapped out in Sweden and their total excess heat potential is projected to be around 60 TWh (217 PJ) per year [21]. The map also indicates the geographical location of these excess heat sources and their capacities. The mapping from this study is used to determine cases for the application in the current study. The spatio-techno-economic dimension of excess heat was analysed in Manz et al. This study mapped 1608 industrial sources of excess heat in Europe and determined the potential of industrial excess heat in Sweden to be 12.6 PJ per year from 70 sources which exist within 10 Kms of existing heating grids [22]. The potentials were shown to rise up to 41.3 PJ while considering low-temperature district heating systems. This study also provides a map of the existing sources within Sweden which were used to determine sources for the current study. Su et al. mapped out clean sources of urban excess heat within the city of Stockholm [23]. A higher solution mapping of sources along with a technical potential evaluation determines a potential of 7504 GWh per year. The data in this study is used to build the model of the district heating systems in Stockholm as a case for the NEO WP3. Over 250 sources of urban excess heat within the Stockholm city are analysed. Low and high temperature sources have been analysed. Low-temperature sources in the city are expected to be connected to low-temperature district heating islands as a part of the local utility's effort towards 5th generation district heating systems.

Geo-spatial tool

Spatial mapping of excess heat sources is obtained from the European Heat Atlas [24]. Based on the available data, the cost of extending the network to sources of industrial excess heat is calculated using an open-source geospatial optimisation tool developed within the horizon 2020 project EMB3RS [15] [11]. The location of each source of industrial excess heat and the corresponding connection point in the district heating network is input to the geospatial optimisation tool. The EMB3RS-tool then calculates the network connection with the least distance using data about existing roads, terrains, etc. from open street maps. The tool also calculates the costs of network construction and the thermal losses in the network.

OSeMOSYS – Long-term energy system analysis

The calculated costs and losses are then fed into the long-term energy system optimisation model OSeMOSYS to determine the long-term, up to 2050, plan for integrating excess heat into the district heating and cooling systems [5]. The PULP version of OSeMOSYS in python was used for this study [25]. The long-term scenarios consider the current and future policies in the Swedish energy context, as well as the impact of the resource availability in the future. This includes the availability of biomass, which is a key resource for district heating, as well as other energy needs such as transportation and electricity generation. The long-term optimisation provides the guiding pathways for the development of district heating and the integration of excess heat into the future system. However, the temporal resolution of such a case is rather low, with 288 intra-annual timesteps. The temporal resolution is kept low to reduce the computational complexity of the model. The output from the OSeMOSYS model is the annual least-cost capacity to satisfy a demand, providing insights into when investment is cost-optimal for integrating a particular excess heat source.

EnergyPlan – Dispatch model

Excess heat availability profiles tend to vary on an hourly basis, so it is essential to consider a high temporal resolution for the operation of industrial excess heat and associated thermal storage in the heating systems. Therefore, a short-term dispatch model is used to study the intra-annual operation of the heating technologies. The dispatch model uses the capacities calculated from the long-term optimisation and verifies the feasibility of the solutions by analysing the hourly supply-demand match. The linking is explained in more detail in the following section. The short-term energy system optimisation tool EnergyPlan is used for this purpose [12]. EnergyPlan has been used in previous studies to model excess heat and DHN [26] [27].

Model linking: Geo-spatial tool – OSeMOSYS – EnergyPlan

The three models are soft-linked in a series, with the result of one tool being input to the next. In the first step, the location of the sources and the network connection point is input to the geospatial tool. The capital cost of expanding the network to connect to the excess heat source is determined from the geospatial tool. These capital costs are then fed into OSeMOSYS along with the techno-economic characteristics of other heat generation technologies in the district heating system, to determine the optimal capacity of excess heat that can be integrated into the system from a long-term perspective. OSeMOSYS then determines the optimal investment capacities and operation of all technologies in the DHS. The determined capacities for certain key years are input to EnergyPlan to determine the detailed intra-annual operation of the technologies and the storage. The results from EnergyPlan are used to determine the feasibility of the energy mix solution at a higher temporal resolution and compare the dispatch of the different heat generation units between the temporal resolutions. The soft link between the tools and the main outputs are shown in Figure 2-1.

2.4. Improved building module in IFE-TIMES-Norway

Inclusion of new buildings standards and new energy efficiency measures

As a part of the Nordic Energy Outlooks WP3 work, the representation of energy efficiency (EE) measures in the building sector in Norway was improved in the IFE-TIMES-Norway model [6]. The IFE-TIMES-Norway model is a linear programming model to analyse the long-term development of the Norwegian energy system. The model is described in more detail in Appendix A1. This work was limited to including energy renovation rate-based growth rates and private discount rates in the modelling of EE measures in the building sector in Norway.

In this work, the end-use demand projections for the Norwegian building stock are based on the data from previous work in the FlexBuild project[1] (see Figure 2-2) [28]. New buildings are assumed to be built according to the current building standard TEK17. Furthermore, in 2050, 20 percent of the construction is assumed to be built according to the passive-house standards. In this regard, the improved energy efficiency in the new buildings is included in the demand projections, while the EE measures in the existing buildings and end-use technologies (e.g., heat pumps) are modelled as technology options. This enables more detailed analysis of the cost-effectiveness of the building sector EE measures in the Norwegian energy system-wide context. The endogenous approach of

[1] The end-use demand projections represent the “Energy Nation” scenario.

modelling EE measures includes data regarding investment cost, technical lifetime, and upper limit for energy savings potential for each modelled measure, building standard/age, bidding area, and year. The growth rate for implementing the EE measures is assumed to be 0.2 %/year and 0.3 %/year in the residential and commercial buildings, respectively. The growth rates are based on the building stock renovation rates (with energy performance upgrade) in Norway as estimated in [28]. The growth rates applied for implementing EE measures are listed in Figure 2-3. The behavioural aspects are analysed by using a private discount rate of 14.75% and 11% for energy efficiency investments in the residential and commercial buildings, respectively [29]. The value of the discount rate is influenced by factors such as the interest rate in the capital markets, the degree of access to such markets, and mostly by the value that each individual associates to own funding resources (e.g., equity capital or savings of individuals). Therefore, the individual behaviour in the energy efficiency investments is illustrated with a comparative analysis by using a social discount rate of 4% and the aforementioned private discount rates. The private discount rates are applied to the EE measures and end-use technologies (e.g., heat pump, building-applied solar PV) in the building sector.

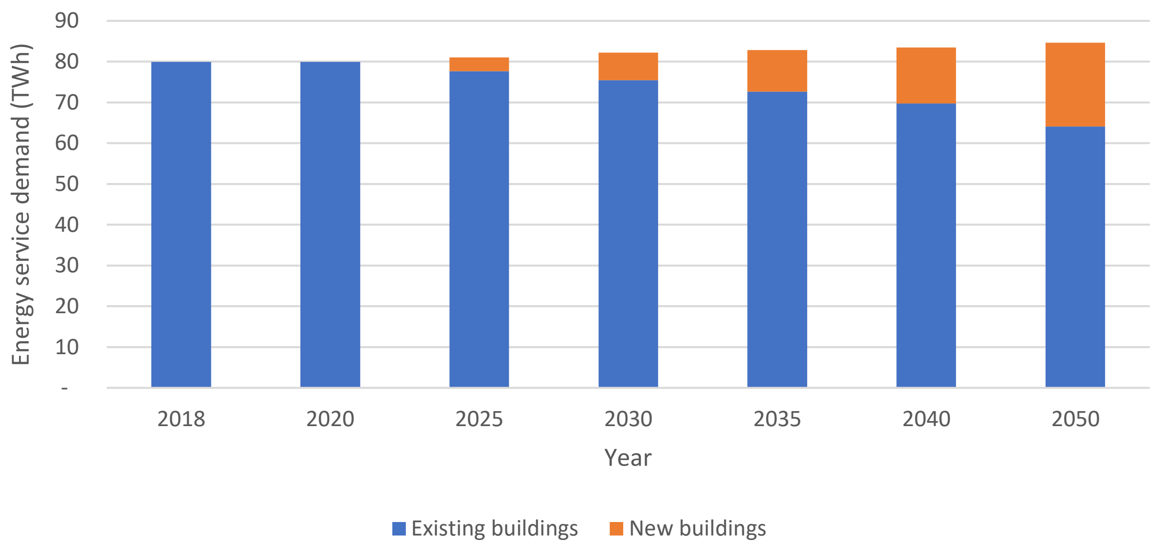

Figure 2-2: Energy service demand projections for the building sector in Norway until 2050

Estimating the technical potential for the EE measures in the Norwegian building sector is not within the scope of this work, and was therefore based on previous studies presented in [30] and [31]. The considered technical potentials and costs cover 13 EE measures in 13 different building categories. The existing building stock is further disaggregated based on the four different building standards and the five climatic zones, representing the bidding areas in Norway. The categorisation of the EE measures and the existing building stock is illustrated in Figure 2-3.

Energy efficiency measures:

1. Insulation of walls
2. Insulation of roof
3. Insulation of floor
4. New windows and doors
5. Reduced indoor temperature at nights and weekends
6. Improved heat recovery in ventilation
7. Improved power efficiency
8. Improved ventilation regulation
9. Lighting regulation
10. Energy efficient lighting
11. Automatic sun protection
12. Demand controlled ventilation (DCV)
13. Energy management systems

Building categories:

Residential buildings:

1. Single-family houses
2. Multi-family houses

Commercial buildings:

3. Kindergarten
4. Offices
5. Schools
6. University/higher education
7. Hospitals
8. Nursing homes
9. Hotel
10. Sports
11. Wholesale and retail
12. Culture
13. Light industry / workshop

Building standards:

1. TEK97
2. TEK87
3. TEK69
4. TEK49 or older

Climate zones:

1. Bergen
2. Kristiansand
3. Oslo
4. Tromsø
5. Trondheim

Figure 2-3: Energy efficiency measures and building categories

The technical potentials for the EE measures are estimated individually, for each measure, both as savings in kWh/building (or m^2) and as a percentage share of energy demand, as presented in [31]. The individual measures are aggregated based on the areas of different building types, standards, climate zones, and end-use demands (heat, hot water, electric specific use). The estimated energy-saving potentials are corrected in cases where the building standard of already renovated buildings is improved and further calibrated based on Norwegian energy statistics. For example, the energy-saving potential in a renovated building is assumed to be lower than the potential in a building based on the original building standard. Moreover, when a measure is implemented, the energy-saving potential of the next measure is reduced as the end-use demand is reduced. In this study, preliminary data from the Behaviour project is used [32], however the technical potential is adjusted based on the previously implemented measures. The order in which the EE measures are implemented is based on the levelised cost of energy (LCOE), as it is done in optimisation models such as IFE-TIMES-Norway. The technical energy-saving potential in the building sector in Norway is estimated to be at around 37 TWh annually in 2025. This potential varies depending on the building type: 17.7 TWh/year in single-family houses (see Figure 2-4), 2.7 TWh in multi-family houses (Figure 2-5), and 17 TWh/year in commercial buildings (Figure 2-6). Moreover, the technical energy-saving potential is estimated to decrease in the future due to demolition of existing buildings – reaching around 30 TWh annually in 2050.

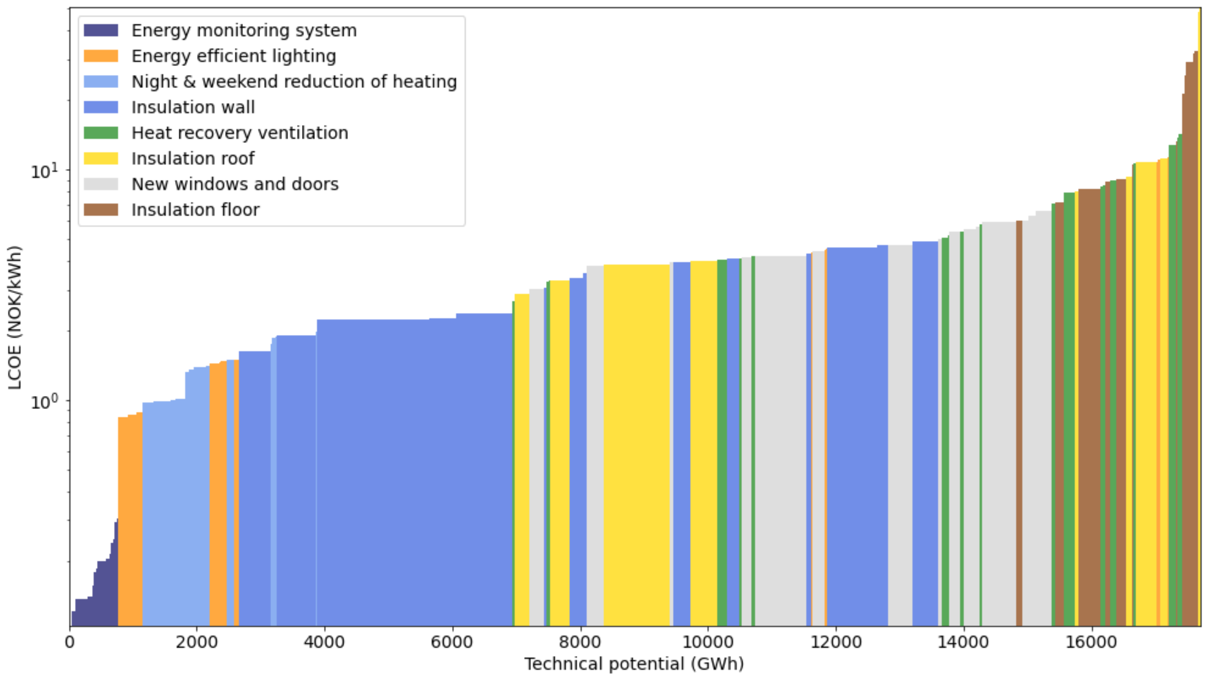

Figure 2-4: Technical energy efficiency potential by levelised cost of energy in single-family residential buildings in Norway in 2025

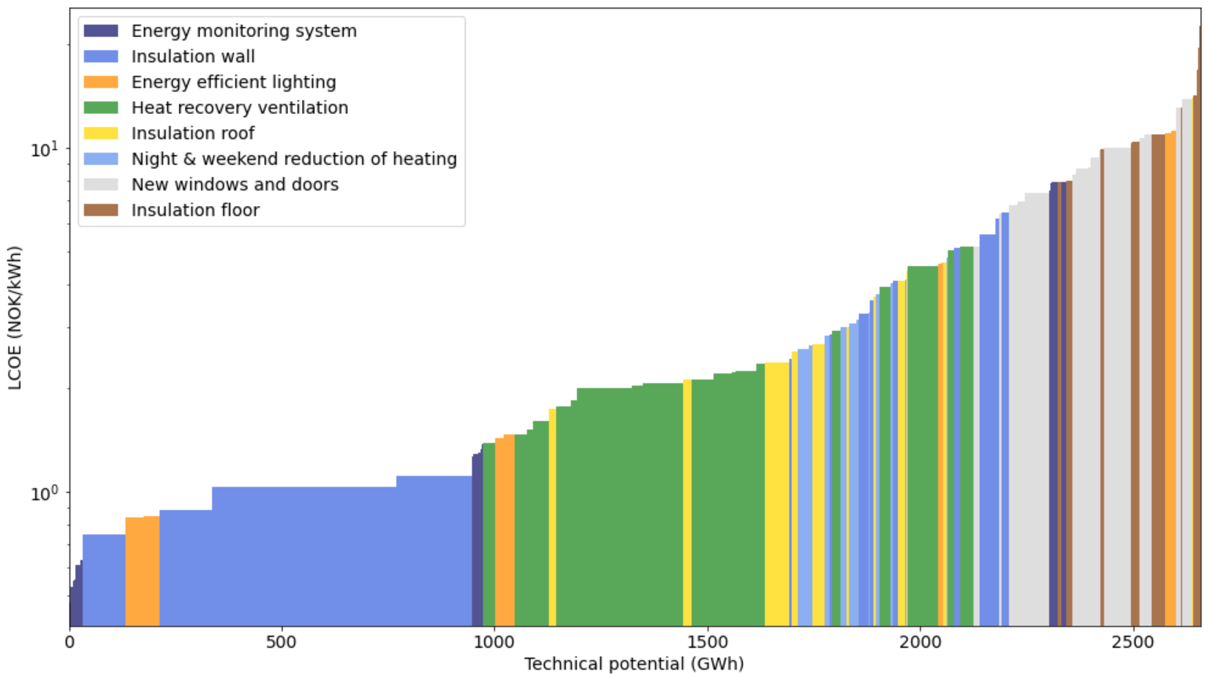

Figure 2-5: Technical energy efficiency potential by levelised cost of energy in multi-family residential buildings in Norway in 2025

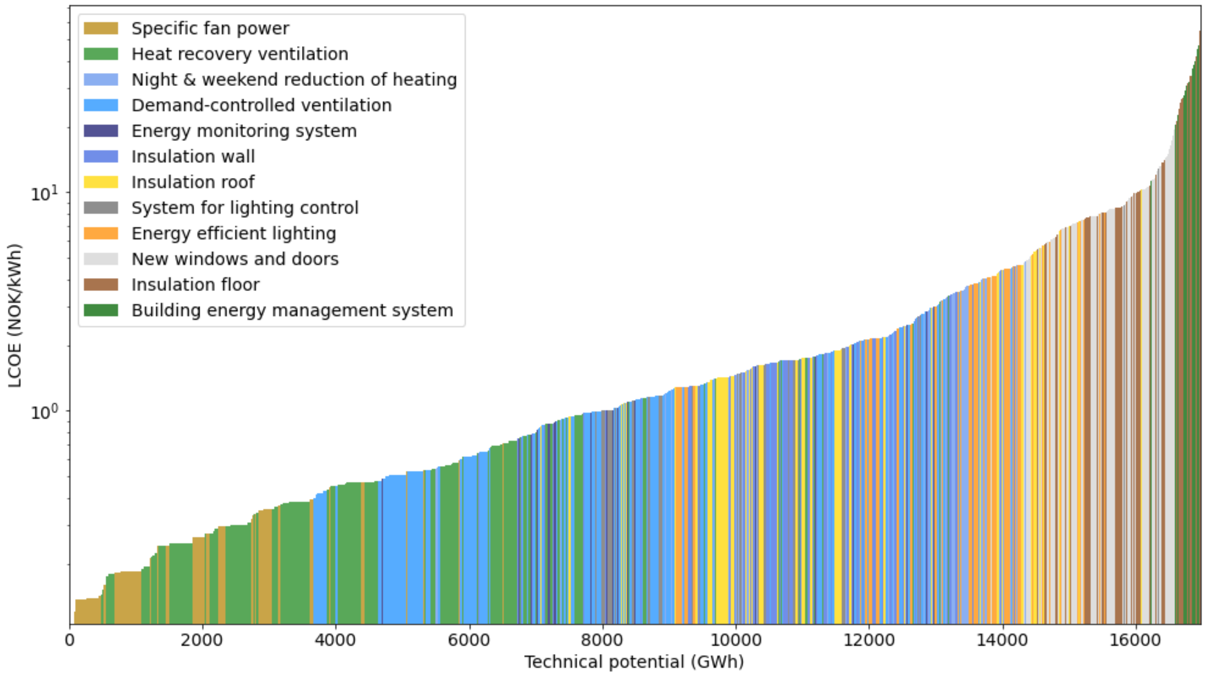

Figure 2-6: Technical energy efficiency potential by levelised cost of energy in commercial buildings in Norway in 2025

Building sector representation in IFE-TIMES Norway

The building sector module in the IFE-TIMES-Norway model is divided into residential single-family and multi-family houses and commercial buildings for each of the model regions, representing the bidding areas in Norway. The building stock is further divided into existing and new buildings, with the existing buildings having a stock of equipment in the reference year. The end-use demand is divided in central heating, point source heating, hot water, and electricity specific demand. The demand for energy services in the building sector can be met by both existing and new technologies using energy carriers such as electricity, district heat, biomass, and oil, as well as energy efficiency and conservation measures. Consequently, the use of energy carriers is a model output rather than exogenous input, which makes sector coupling a part of the optimisation problem. For example, endogenous investments in heat pumps couple the power sector with the building sector. A detailed description of the building module representation in the IFE-TIMES-Norway model is presented in [6].

2.5. Literature reviews

A number of assessments performed in several other projects in which the researchers of this WP3 have collaborated with other Nordic researchers using energy systems development scenarios as a base, i.e. national and international initiatives that include the Nordic countries, have been reviewed. The assessment includes previous and ongoing quantitative and qualitative projects that use energy system modelling (with ON-TIMES, IFE-TIMES Norway, IntERACT, GENeSYS-MOD, OSeMOSYS, EnergyPlan), sector specific models (with ECCABS, PROFet, Geo-Spatial tool) as well as modelling to estimate emissions to air and cost-effective emission control strategies (with GAINS).

Additionally, a focused review has been performed on potentials for increased conservation and efficiency for both energy and materials in the Nordic buildings sector. The review focuses on studies that aim for a sustainable energy transition, which is not only technically possible, but also socially and institutionally feasible, meets energy and climate targets while also delivers social and economic benefits, contributing to competitiveness in the Nordic countries. It includes social sustainability by incorporating socioeconomic aspects to empirical and modelling analyses. Therefore techno-economic scenario pathways are complemented with socio-institutional approaches. This broad methodological approach results in more robust assessments and in a deeper understanding of uncertainties, alternatives, and contextual frameworks.

For both the cross-sectoral and the sectorial reviews, the following steps have been followed. Firstly, a list of 10-15 ongoing or recently performed projects that provide quantitative or qualitative insights from different perspectives (societal, energy system, sector, private consumer) and methods (simulation/optimisations with energy system/sectorial models, economic modelling or experiments, qualitative) is made. A template for systematic categorisation was derived, including key data (e.g. energy-saving potentials, investment costs, MAC-curves, LCOE comparisons, environmental and health impacts, adoption rates, key policies) to be compiled. The output of this first step is a catalogue of ECEM solutions, including their individual characterisation as well as an analysis of synergies, overlaps and gaps. A summarised analysis of this output is presented under RQ1, whereas all background materials compared are presented in the appendices, and include:

- Results of the RePowerEU scenario run for WP2, with the models ON-TIMES (Appendix A3.1.3), SINTEF's model (Appendix A4.1), IFE's model (Appendix A5.1).

Secondly, a new portfolio of projects – which may not entirely overlap with those above – has been gathered, presenting Nordic energy scenarios either as framework conditions and storylines, modelling results, or visualisation frameworks. Scenarios aligned with energy, climate and socio-economic goals have been collected and analysed for critical parameters that may impact pathways. The compilation is comparatively analysed to identify relevant storylines that have not yet been modelled. The combination of methods allows for better estimates of consequences if key assumptions develop differently than expected in any of the studied scenarios. A template for systematic categorisation has been derived and filled in. The output of this second step is a catalogue of Nordic scenarios for ECEM. Conclusions based on this output are presented under RQ2, whereas the background materials compared are presented in the annexes, including specifically:

- Scenarios with ON-TIMES for NCES project (Appendix A3.1)
- The RePowerEU scenario run for WP2, with the models ON-TIMES (Appendix A3.1), SINTEFs model (Appendix A4.1), TIMES-IFEs model (Appendix A5.1).
- Scenarios of building sector models (Appendix A3.2: PROFet and ECCABS), dispatch models (Appendix A3: Energy Plan) heat recovery models (Appendix A3.1.3) and air pollution (Appendix A3.3: GAINS)

2.6. Comparative studies

The up-to-date knowledge gathered in the review and the studies on the role of ECEM for sustainable energy transition pathways in the Nordic countries, performed in this WP3, have been comparatively analysed. Differences between models and results have been identified, along with corresponding potentials causes and effects. The output is a qualitative and quantitate characterisation of the role of ECEM in the Nordic energy transition, an analysis of synergies between measures, overlaps, and gaps, suggestions to put the results together to provide a more comprehensive assessment.

More specifically, the comparison of varying aspects (spatial and temporal resolution, input assumptions and data sources, outputs and visualisations) of different existing different models is summarised in Appendix A1. The comparison has been used to identify how existing energy system models can be improved to assess the role and potentials for ECEM in the Nordic context. The conclusions of this review are presented under RQ4.

3. Results

As described in Section 1.2, this work has divided into a number of Research Questions (RQs) which have been pursued by the participating research institutes, with their portfolio of tools. The RQs are grouped into the following three categories:

- Literature reviews and qualitative assessments of the role and potential for energy efficiency and conservation (RQs 1-3)
- General energy system models: Improved representation of energy use, and simulations (RQ4-7)
- Utilisation of excess from industry, and expansion of thermal grid (RQs8-10)

In this chapter, the key findings for the RQs are presented and discussed, to inform on the most recent opportunities for efficiency and conservation of energy and materials in the Nordic context.

3.1. RQ1: What is the existing knowledge on key aspects of Efficiency and Conservation of Energy and Materials (ECEM) in the Nordic area, from different methodological perspectives?

We have assessed the key aspects of ECEM following the framework described in Section 1.2, for all the existing and new modelling works of this WP3 (see Table 3-1 for an overview).

How do the models/literature generally define and represent ECEM?

Models for long-term energy system optimisation included in WP3 generally use demand from various sectors as a constraint/input, and the demand can be met by existing and new technologies. The models minimise the total discounted cost of an energy system to meet the demand for energy services, and consequently, energy-saving measures which are cost-effective from a system perspective are implemented by the model. In the models, various ECEM and existing/future policies affecting the cost-efficiency can be implemented in the scenario modelling.

For the buildings sector, e.g. in ON-TIMES there are new investment options for existing buildings such as heat-saving measures, new heat devices and connection to the DH systems during the model time horizon. Simultaneously, some existing buildings are demolished and replaced with new and more efficient buildings. In the model, all the buildings in Sweden constructed before 2012 have the possibility of adopting energy saving measures corresponding to different cost levels. All the buildings also have the possibility to invest in individual heat devices (heat pumps, boilers, etc.) if it is cost-effective from a system perspective. Not all the buildings have the possibility of investing in a connection to district heating (i.e., a district heating substation).

For the industry, existing technologies are gradually replaced with new technologies (due to either reaching their lifetime or constraints on CO_2 emissions) given as new investment options in the model. For the Nordic Clean Energy Scenarios (NCES) there are key performance indicators (KPIs) including future energy intensity in heavy industry for Sweden, Norway, Denmark, and Finland.

In this project, OSeMOSYS is used to analyse the development of district heating networks while considering the techno-economic feasibility of extending existing thermal grids to integrate excess heat. The model is soft linked with the short-term energy system optimisation tool EnergyPlan to consider the intra-annual operation of the heating technologies. This allows the investigation of new energy efficiency measures, such as high-temperature heat pumps and new resources such as industrial waste heat.

In summary, as shown in Table 3-1, we conclude that:

- The reviewed sectorial models provide valuable insights.
- The reviewed energy system models of the Nordic countries have a simplified representation of ECEM, which could be relatively easily improved based on existing knowledge from bottom up and sectorial models. More specific suggestions are given under RQ4-6.
- The GAINS model provides additional knowledge on key themes (health impacts and their economic evaluation) for which the integration in energy system models is not apparently straightforward.

Table 3-1. Summary of the ECEM measures considered in the modelling works reviewed.

	Total (cross- sectorial)	Buildings	Industry
MC: Reduced demand of materials		Shared spaces	
EE: Reduced final energy consumption		Switch to on-site HP. Increased efficiency of on-site HP	Use of excess-heat sources
ME: Increased material efficiency			Material recyling
EE: Reduced primary energy consumption	high temperature heat pumps (OSeMOSYS); new resources such as industrial waste heat (OSeMOSYS)	Switch to DH	

ME, material efficiency; EE, energy efficiency; MC, material conservation; EC, energy conservation.

What overall key measures have been identified? Which contributions are expected by country?

In the NCES, direct electrification is emphasised as a cornerstone for all scenarios, not only to reduce carbon emissions, but also as one of the key solutions to obtain energy efficiency in the coming decades. Electricity as energy carrier has attractive characteristics; it can supply almost any energy service demand with little loss. Switching to electric heating, engines, or pumps, for example, is often a central solution when implementing energy saving solutions in industries and buildings. For the transport sector, the shift from traditional combustion engines to electric vehicles is expected to significantly reduce energy consumption. In NCES, results presented in the appendix show that an increase in electricity demand will reduce demand for other energy carriers as large-scale direct electrification delivers significant overall efficiency gains.

The Nordic total primary energy supply of 2020 compared to year 2050 for all three NCES scenarios is shown in the appendix. In scenarios CNN and CNB, the primary energy supply decreases for the Nordics from 2020 to 2050. In the NPH scenario, it increases slightly. For the same level of CO_2 emissions reduction in the Nordic region, under the assumptions made in the CNB scenario, the power demand in the Nordic countries would be 5% lower in 2050 and final energy demand would be 17% lower in 2050 compared to the CNN scenario (cf. illustration in appendix). For the RePowerEU scenario, the differences in final energy consumption in the residential and industry sectors compared to the CNB base case are very small (+0.8% for the residential sector and -0.3% for the industry sector, for the Nordic area) and these is no change in energy savings for these sectors.

For the industry, in NCES, there are key performance indicators (KPIs) including future energy intensity in heavy industry for Sweden, Norway, Denmark, and Finland. The results show a strong improvement compared to 2015 values for Denmark and Finland, with around 40% decrease in energy intensity. For heavy industries in Sweden and Norway however, improved energy intensity lags, with a 10% decrease for Norway and a slight increase for Sweden (0-5% depending on the scenario). There are two main reasons for this development. Firstly, heavy industries in Sweden and Norway are already very efficient in their use of electricity to supply their processes. Secondly, for some industries, the least-cost option in the model is to keep using fossil fuels by incorporating CCS, resulting in a stable or slightly higher final energy demand in the CNN. In contrast, in the NPH scenario, the Swedish steel industry is assumed to instead switch away from coal, towards hydrogen and electricity, following a power-to-X pathway. This currently seems to be the path favoured by industry, exemplified by projects like HYBRIT and H2 Green steel.

For the building sector, the above-mentioned modelling features in ON-TIMES (area demand, heat-saving measures, replacing old buildings with new) can all contribute to lower final energy consumption in the scenarios modelled.

Adding to the energy system modelling, sectorial studies regarding ECEM in the building sector target both electricity for appliances and space heating demand (increased insulation, replacement of windows, installing ventilation with heat recovery, lowering indoor temperature, etc.). The review on material efficiency includes efficient and circular use of building materials (utilising waste products in building materials, urban mining and recycling of building components and elements, etc.) and efficient use of buildings (sharing offices, flexible architecture). See results in detail in appendix, which are further discussed under RQ3.

Air pollutants

A GAINS project evaluated the implementation of mitigation measures and assessed the impacts of short-lived climate forcers (SLCFs), specifically black carbon (BC), organic carbon (OC), CO_2 and O_3 precursors. The Swedish abatement costs for different SLCF abatement options varied widely, but the same abatement options appeared as the most cost-effective in all scenarios. The most cost-effective measures, decreasing BC emissions from power production and renewing domestic fuelwood boilers, were found to be in the same range as the CO_2 ETS price projected for Sweden in 2020.

Research project SunHorizon, analysed the implementation of innovative and reliable heat pumps coupled with advanced solar panels (PV, hybrid, thermal) that provide heating and cooling to residential and tertiary buildings with lower emissions. For most substances, emission factors are lower than for conventional technologies, compared to the baseline development in 2030 and 2050.

This resulted in lower concentrations of primary and secondary PM2.5 and ground-level ozone and, subsequently, in reduced negative health effects.

Measures to reduce emissions of short-lived climate pollutants (SLCPs) in the Nordic countries were analysed in a project with combined SLCP analysis using the GAINS model. The measures in the model aimed at residential combustion can reduce BC emissions in 2030 by 3.7 kt, which is about 79% of the estimated total technical BC emission reduction potential in the Nordic countries. Part load combustion in boilers increased the emissions between 2– 6 times, while moist fuel increased the emission by a factor of 1.5–2. Modern stoves are sensitive to moist fuel, where emissions of PM2.5 and OC increased in the order of 5–8 times, likely due to limited air capacity. To improve the national emission inventories, the large sensitivity to operational conditions needs to be taken into consideration.

3.2. RQ2: To what extent do the most recent energy development scenarios in the Nordic countries explore the role of ECEM?

In the review presented in the appendix, we have found 25 scenarios that look at ECEM in one or several of the Nordic countries. Furthermore, new modelling results obtained in this WP3 deliver 12 additional scenarios. All included, the following scenarios have been identified:

- For Nordic countries, four scenarios with a focus on energy system development. Buildings and industry are included in all four scenarios, but no scenarios for all Nordic countries focus specifically on these sectors.
- For Sweden, four scenarios with a focus on energy system development, 16 with a focus on buildings and two with a focus on the sector-coupling of industry with excess heat to buildings. No scenarios focus specifically on industry, as this was not the focus for the participating institutions.
- For Norway, four scenarios with a focus on energy system development, five scenarios with a focus on development of the building sector. No scenarios focus specifically on industry, as this was not the focus for the participating institutions; however, work has been done to investigate possible improvements in representing the industrial sector in energy system models.
- For Denmark, four scenarios with a focus on energy system development, all of which include buildings and industry, although no scenarios were found for all Nordic countries that focus specifically on these sectors.

Most of these scenarios have a techno-economic approach to ECEM, with different focus:

- Change in energy demand over time for different sectors.
- Potentials for energy-saving measures in existing buildings (retrofitting measures, efficient appliances etc.) and the cost-effectiveness of implementing such measures.
- Sensibility of implementation of measures in buildings to variations in energy prices and interest rates.
- The potential for overall increase of energy efficiency in the building sector through existing buildings being demolished and replaced with new and more efficient buildings.
- Increased use of excess heat through sector-coupling.
- Measures to increase use of RES by for example introducing heat pumps in buildings and industry.

- The potential for overall increase in energy efficiency in industry based on existing technologies gradually being replaced with new technologies given as new investments.
- Potential energy savings from user flexibility/demand response and price mechanisms which can influence the extent to which such measures are taken.
- Price elasticity and macro-economic determinants of buildings' future energy demand.

In all cases, the four scenarios focusing on energy system development come from ON-TIMES, i.e., three scenarios from the NCES project and the RePowerEu scenario run for this project.

All the three scenarios of the NCES project (Carbon Neutral Nordic, CNN; Nordic Powerhouse, NPH; and Climate Neutral Behaviour, CNB) include ECEM in all sectors, however the CNB scenario sees politicians and citizens adopting additional ECEM measures in all sectors, ultimately leading to lower demand for both. It also assumes higher public acceptance for energy infrastructure development. The RePowerEU scenario is based on the CNB scenario, with the alteration that 30 TWh of additional net electricity export from the Nordics is assumed in year 2030. These are, however, simply exogenous assumptions (summarised in the BOX below) in which the different components of ECEM are mentioned, and only serve to see the effects of ECEM broadly.

BOX: Exogeneous assumptions related to ECEM from ON-TIMES scenarios, see Appendix A3.1.

In the CNB scenario, demand projection for heavy industry is the same as CNN up until 2030, and then reduces by 10% compared to CNN until 2050. For passenger transport, with an assumed increase in shared mobility, no growth is assumed for national passenger km from 2030 onwards. Freight transport sees 10% lower growth in tonne-kilometre (tkm) projections from 2025 onwards due to more efficient logistics and lower consumption. For international transport, 10% lower freight in aviation and navigation from 2030 onwards is assumed compared to CNN. In terms of technology development, a breakthrough in autonomous vehicles and shared mobility results in more efficient private transport.

The CNB scenario, besides the energy demand reduction, examines where behaviour changes could reduce energy demand. For instance, for low-carbon electricity production, the CNB models higher acceptance of expanded onshore wind power capacity. In addition, the model analyses the potential impact of dietary changes, lowering agricultural Green House Gas (GHG) emissions by 10%. These changes do not have a direct effect on energy demand in CNB but do make the transition easier.

Industry – The decrease in energy intensity for different sectors is also driven by a general improvement in the efficiency of technologies using other energy carriers.

Buildings – Area demand for buildings, based on national forecasts, is the main driver of energy demand in the buildings sector. Energy use per m^2 decreases with the assumption that some existing buildings are demolished and replaced with new and more efficient buildings.

At the same time, several scenarios investigate socio-demographic perspectives, institutional issues or trade-offs and synergies of energy efficiency measures, that is:

- Corresponding air pollutant emissions (PM2.5, SO_2, NOx, black carbon etc.) from different sectors (transport, buildings, industry) and the health benefits and following financial benefits of lower levels of air pollutants. Such scenarios point that energy efficiency measures in several sectors (e.g. electrification, scrapping of old vehicles and machinery) show important synergies with lower emissions of air pollutants.

- The robustness of building retrofitting measures against climate uncertainties: such scenarios point that energy conservation is the most resilient measures, such as improvements in the building envelope (insulation, windows) and lowering indoor temperatures.

Whereas key components and findings from the scenarios above with cross-sectorial and industrial focus are presented in the appendix and summarised above under RQ1, the results of the scenarios that focus on the buildings sector will be further presented below under RQ3.

Finally, we have not found scenarios that focus on the topics below, which can be concluded as a gap and topic for further research:

- If new developments for potential new industries should be modelled, such as data centres, battery production, and hydrogen, a market equilibrium model is then required to project the future growth of these industries in the global context as input to GENeSYS-MOD.
- No scenarios were found that include all Nordic countries and focus specifically on ECEM in the buildings and industry sectors, on circularity or on material conservation and efficiency.

3.3. RQ3: What is the existing knowledge on the role of different energy-efficiency and conservation measures in the building sector?

The European Union (EU) member states have committed to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 (compared to 1990 levels) and to be climate neutral by 2050 [33]. Norway has also updated its national climate targets with plans to reduce GHG emissions by 90-95% compared to 1990 levels by 2050, excluding carbon sinks. Improving the energy efficiency of buildings is seen as a key tool to achieve these targets.

The building sector accounts for 40% of final energy consumption and 36% of energy related emissions in the European Union (EU) [34]. Therefore, the building sector holds considerable potential for energy conservation and for mitigating energy-related GHG emissions. The newly proposed energy efficiency directive nearly doubles the annual obligation to save energy from 0.8% to 1.5% of final energy consumption from 2024 to 2030 [35]. Energy efficiency and conservation measures in the building sector are driven mainly by the Energy Performance of Building Directive (EPBD) 2010/31/EU, the revised Energy Efficiency Directive (EED) 2012/27/EU, the Ecodesign directive 2009/125/EC, and the Energy Labelling Regulation 2017/1369 [36]. In addition, substituting energy sources from fossil fuels to electrification and renewable energy sources is driven by the Renewable Energy Directive (2009/28/EC). Although Norway is not an EU member state, it has chosen to collaborate with the EU in the adoption of EPBD [37].

A summary of the reviewed literature on energy efficiency (EE) measures in the building sector is presented in the appendix. In this regard, the considered EEMs in the building sector can vary significantly in different studies from:

- Increased energy performance of building envelope, insulation of cellar/basement, facades, attics/roofs, energy-efficient windows and doors (see e.g., [38]–[40])

- Upgrade of ventilation systems with heat recovery, demand-controlled ventilation, specific fan power, night and weekend reduction of heating (see e.g., [41]–[44])
- Installation of energy efficient lighting and appliances, systems for lighting control (see e.g., [45]–[47])
- Installation of energy monitoring system, building energy management system (see e.g., [48])
- Integration of renewable energy (e.g., building-applied solar photovoltaics (PV)), electrification (e.g., heat pumps) (see e.g., [49]–[51])

The literature on EE measures on the building sector is also wide in terms of methodologies, perspectives, and the scope of the research (e.g., building or country level). Gonzales-Caceres et al. [38] evaluated cost-effective measures for the renovation of an existing dwelling in Norway, reporting energy savings between 14.4% and 41.6% for the considered EE measures. Mata et al. [52] studied 12 different EE measures (including increased insulation, replacement of windows, upgrade of ventilation systems with heat recovery) in the Swedish residential sector. According to the results, a 53% reduction of energy use in the Swedish residential sector can be achieved when all the considered EE measures are implemented. The authors also conclude that the effectiveness of different energy efficiency measures can differ for different parts of the country. For example, improving the building envelope was seen to be a more effective measure in Northern Sweden. Therefore, considering the regional climate differences in energy renovations is recommended to provide optimal solutions appropriate for local conditions [53]. Several studies have also highlighted that the energy performance (and the size) of the existing building stock varies significantly among EU countries, resulting in differing energy savings potentials (see e.g., [54]–[56]). In a study on EE measures in the residential and non-residential buildings in different European countries, Mata et al. [56] report a total technical energy savings potential of 30–60% for the different member states.

In addition to energy savings, building sector energy efficiency improvements can contribute to achieving national GHG emissions reduction targets. Hirvonen et al. [57] studied optimal energy retrofit scenarios of the Finnish building stock by 2050. According to the results, district heating demand can be reduced by 25–63% and CO_2 emissions by 50–75% by 2050, depending on how extensive the retrofits would be. In a study of bottom-up energy-supply optimisation of the German building stock, Kotzur et al. [49] report that the key technologies for reducing the GHG emissions in the building stock are building-connected solar PV and heat pumps. The time distribution of implementing EE measures can affect the cumulative emissions of the building stock over the long-term. Hirvonen et al. [58] reported that around 66% more emission can be reduced with early retrofitting actions compared to delayed actions. The absolute GHG emissions reduction potential in the building sector can be strongly dependent on the development of the used energy carriers' emission intensity factors (e.g., for electricity, district heat) [10].

Several studies show that there are a large number of measures that can be applied to improve the energy performance of existing buildings, which can contribute to the decarbonisation of the energy system. On the other hand, the effectiveness of different EE measures can vary and the actual energy savings potential can be lower than expected [59]. Mata et al. [60] report that the technical potential for energy-saving measures in buildings can differ from the potential based on cost-efficiency. The cost-effectiveness of different EEMs can also depend on the energy performance of the building being renovated [38], [54]. Cozza et al. [61] used a Monte Carlo method for the Swiss residential buildings to study the uncertainty in the potential energy savings from improving the energy label. According to the results, considering the energy performance gap between labelled and actual energy consumption can lead to reduced energy (and emissions) savings with the business-as-usual renovation rate. Similarly, Cholewa et al. [62] show, in a long-term field evaluation of multi-family buildings, that the actual energy savings range between 8.8 to74.8 % of the calculated energy savings, depending on the different renovations. The energy performance gap in the building sector can partly be explained by socio-technical factors, such as prebound- and rebound effects [63], [64]. For example, income is found to be a clear determinant of total and space heating demand for European households, however residential energy consumption could also be affected with energy prices [65].

Furthermore, the energy efficiency gap is the observation that although energy efficiency is perceived to be economically and environmentally advantageous, the level of investment in energy efficiency fails to be adequate [66]. In this regard, the European Commission estimates that every year, only 1% of the buildings in the EU undergo energy renovations [34]. The energy efficiency gap is often explained with market failures (e.g., imperfect information), principal-agent problems, split incentives, capital market failures, and behavioural factors [67]. It has also been argued that investments in energy efficiency are uncertain, and as the stakeholder (e.g., households, building owners) are risk-averse, they tend to choose risk-adjusted optimal investments [68]. This can result in building owners cancelling their planned renovation projects [69].

Regarding material efficiency, the potential is clear for the global housing sector [70]. From a Nordic perspective, policy instruments that can accelerate a circular transition of the Nordic construction sector have been suggested by actors representing sector stakeholders in Denmark, Norway, Finland and Sweden through interviews [71]. Suggestions mainly focus on rules and regulations, with a lesser focus on economic incentives, agreements, or providing supplementary information. According to the interviewees, the resource consumption could be reduced by approximately 20% compared to the current consumption of building materials, which would result in a decrease of greenhouse gas emissions of approximately 10 million tonnes in total for all four Nordic countries. For Sweden, the resource savings potential in office sharing has been estimated to be 24.4 to 34.4 Mt mass of materials, which is obtained through requirement reduction of 14-19.6 million m^2 of office space [72].

In summary, although the literature is clear that one-step renovations of existing buildings are not sufficient to transform the existing built environment in line with environmental, economic and social targets, and that only a comprehensive uptake of ECEM over the buildings' life-cycle would lead to achieving such targets [73]–[76], our review does not find examples of studies for the Nordic countries in which the uptake of ECEM measures is at the transformative levels suggested in global studies. Instead, the energy system studies with focus on the Nordic area rely on decarbonisation of the energy production and increased network flexibility and connections, for which the feasibility is only assumed and, therefore, deserves further study.

3.4. RQ4: How can existing energy system models be improved to assess the role, and potentials for, ECEM in the Nordic context?

From our attempt to analyse the role, and potentials for, ECEM in the Nordic context, based on results from current national and international research that use both energy system modelling and sectorial approaches, a number of possibilities for improving the existing energy system models were apparent. We have grouped these in two main themes below.

First, it has been challenging to compare varying aspects of efficiency and conservation between different models and scenarios. Although the models can rapidly generate many scenarios and address a complex set of indicators (e.g., technology choices, primary and final energy use, costs, and emission levels), understanding the selection among all these options is far from straightforward. In agreement with recent research emphasising the need to pursue such selections in a systematic and policy-relevant manner, we identify a need to better understand the opportunities, risks, synergies, and trade-offs within each modelled scenario if energy systems modelling results are to be used as a basis for decision making. This can be achieved by using both various Key Performance Indicators (KPIs), i.e. ECEM in this WP3, as well as other visualisation tools.

Of particular interest is the comparison over time, as the knowledge generated from energy system models can support climate policy decision making processes, e.g., when introducing and/or revising specific policy instruments. Other significant challenges associated with the understanding of the results require attention, which relate to both the input and outputs of the models.

For example, in terms of outputs, for the industry and building sectors, we have identified that the presence of changes in primary energy use in fulfilling the corresponding energy demand is a critical KPI. This KPI could enable a comparison between scenarios regarding the cost-effectiveness of ECEM measures in the long term. From the ON-TIMES model results for the NCES scenarios it was not straight forward to see the results for this KPI. Instead, for the heavy industry, for each scenario and model year, it was possible to divide the "Heavy Industry Energy Service Demand" result by the "Heavy Industry Fuel Consumption" result to get some insights on changes in energy efficiency in this sector. For the residential sector, it was possible to add the "Residential Heating" and "Electric Appliances Consumption" results and divide them by "Residential Fuel Consumption" to get some insights into changes in energy efficiency in the sector. Energy intensity in the buildings sector [kWh/m^2] could also be presented as a KPI. It enables a comparison between scenarios regarding cost-effectiveness of ECEM measures in the sector in the long term. From the current results provided for the NCES scenarios some extra calculations are required to get insights for this purpose. For the calculations, the data assumptions in the model for area demand for buildings [in m^2] for each scenario need to be known, so that intensity could be derived using that and energy consumption. Currently, the following assumptions were made in the ON-TIMEs model in term of area demand for buildings, and these are scenario independent.

Table 3-2- Households' floor area demand in ON-TIMES [M m^2].

Scenario\Period		2015	2020	2025	2030	2035	2040	2045	2050
CNN, CNB and NPH	DK	321	333	345	355	364	371	378	384
	NO	324	341	357	372	385	397	409	420
	SE	466	488	541	555	566	576	586	595

In terms of inputs, several key drivers of energy system transformation could be disaggregated to facilitate their understanding, as it will be further discussed below in this section. In any case, the KPIs need to be clearly described, documented, and provided to the model users, e.g., policy makers, academia, and decision makers. For instance, for the NCES scenarios' results, "fuel consumption" and "energy demand" results are presented for the building and industry sectors, without clarification on whether these illustrate similar or different things.

A second broad area for improvement relates to how energy conservation, energy demand reductions, and materials use are modelled. For the buildings sector, in the energy system models, the demand is typically linked to floor area development, which, in turn, is often exogenous and based on national forecasts and projections. An improved description of demand disaggregated by measures that lead to less floor area (i.e., reduced population growth, increased space sharing) and fewer new buildings (i.e., increased renovation of existing buildings, or caps the on use of virgin materials). Consequently, this could affect the energy and material use in the industry sector with a direct impact on less energy and material use for cement and steel production. The less building area demand leads to lower energy demand in the residential sector (fewer m² to heat etc.). This will have direct impact on the heat sector and, therefore, on the development of the energy system (more specifically, the power system that interacts with the heat sector) over time.

Along these lines, material recovery processes and their associated energy use have not been explicitly represented in the energy system models. Such a representation would require the techno-economic parameters of the recovery processes as well as data assumptions on availability potential of waste materials being recovered in the recovery processes. For the assumptions of the amount of waste materials, a linking between energy system model and macro-economic models could be useful. Similarly, the industry sector is often represented by energy flows for the industrial process in the energy system models. Thus, some of the material flows are represented implicitly through the energy flows. This is one simplification in the models, however, representing the material flows for the industrial processes could open opportunities to study material efficiency measures and CO_2 emissions that originates from the material use within the industries.

More detailed suggestions are given below in terms of improvements of the datasets (RQ5), and on how different energy efficiency and conservation measures in industry and buildings can be included in energy system models (RQ6).

3.5. RQ5: How can datasets be improved to represent the Nordic industries, and what gains can be achieved from the increasing level of detail in the industrial sector?

Multi-sectoral integrated energy system models at the European level such as GENeSYS-MOD have large datasets which can be difficult to create and handle. Maintaining and performing quality checks on existing datasets is demanding but necessary to ensure the quality and robustness of the results. The methodology of improving industrial datasets will be illustrated in this section with respect to GENeSYS-MOD. In this work, the primary approach taken to improve the sectorial representation in GENeSYS-MOD is the disaggregation of industrial heat demand, which yields a more accurate representation of the industrial sector in Norway, and in turn will aid the implementation of technologies (such as heat pumps) in GENeSYS-MOD.

In the original GENeSYS-MOD dataset, the energy demand in the industrial sector is specified by their heating demand aggregated to three different temperature levels: low temperature industrial heat (<100˚C), medium temperature industrial heat (100˚C – 1000˚C), and high temperature industrial heat (>1000˚C). Norway is split in five regions corresponding to the Nord Pool bidding zones, while Denmark, Sweden, and Finland are modelled as one region respectively. The medium temperature industrial heat demand (100˚C – 1000˚C) is disaggregated into four temperature levels (100˚C – 150˚C, 150˚C – 200˚C, 200˚C – 500˚C, and 500˚C – 1000˚C). Furthermore, for energy efficiency technologies, industrial waste heat is modelled as a resource at four temperature levels (25˚C – 40˚C, 40˚C – 60˚C, 60˚C – 140˚C, >140˚C).

The methodology in disaggregating industrial heat demand for other countries will depend on the format of the available data; nonetheless, the procedure of disaggregating Norwegian industrial heat demand is discussed for transparency and reproducibility. The total annual industrial heat demand is scaled according to NVE statistics to 19 TWh [19]. The disaggregation of heat demand according to the different temperature levels and regions in Norway is calculated. We assume Norwegian industry to fall into the categories: chemical, mineral products, food, pulp and paper, and metal for which the temperature specific amount of heat demand is known [17]. Assumptions on the spatial distributions of these industries are made based on [18]. The industrial waste heat availability at the defined waste heat temperature levels and the disaggregated regions in Norway is modelled according to [77]. When disaggregating the heat demand, the technologies modelled that can provide heat must be re-evaluated with regards to their efficiency and availability.

It is assumed that waste heat is available within each region, as only energy transport between regions is modelled. Therefore, it could be of interest in further works to consider intra-regional energy transport, such as local district heating networks also as a coupling technology between the industrial and building sector.

As energy transition scenarios from 2018 to 2050 are considered in GENeSYS-MOD, the specified annual demands are projected into 2050. In this work, the projected growth in demand is kept according to the original input data assuming no new industrial development in the region. If new developments for potential new industries should be modelled, such as data centres, battery factories, and hydrogen production, a market equilibrium model is then required to project the future growth of these industries in the global context as input to GENeSYS-MOD.

The approach to improving industrial datasets in this work focuses on the modelling framework GENeSYS-MOD in which industrial demand was represented solely as heat demand of three temperature levels. The heat demand is disaggregated into six temperature levels. The modelled technologies providing heat are re-evaluated with respect to their availability and efficiency. The achieved effects of improved industrial datasets are a more realistic representation of the industrial landscape in Norway. Furthermore, many energy-efficiency promoting technologies, such as heat pumps, require a finer definition of temperature levels to model these accurately. Therefore, improving the heat demand representation will also aid in the modelling and evaluation of new technologies.

3.6. RQ6: How can different energy efficiency and conservation measures in industry and buildings be included in energy system models?

Modelling and results in GENeSYS-MOD

Multi-sectoral integrated energy system models at the European level such as GENeSYS-MOD highlight the importance of including the full spectrum of potential technologies to obtain the most accurate results. This also means including energy efficiency and conservation measures. This section investigates the modelling of different energy efficiency and conservation measures in the building and industrial sectors.

Energy efficiency measures can, in practice, be included by adding technology options with higher efficiency or technologies utilising waste heat for instance. Energy conservation measures can be more difficult to model as they also include behavioural changes (reduction of temperature setting, switching off light, shorter showers, etc.) that can be hard to represent in such models. One possibility that does not require significant modifications to the model is to use a set of scenarios with different assumptions regarding those behavioural aspect or broader parameters. One example of such an approach (or storylines) was developed to explore the energy transition in Europe. The four storylines include various assumptions to represent the combination of the level of policy exertion, technology novelty and societal changes. A disadvantage of this approach is that it does not allow for endogenously considering these measures.

In this work, we consider the inclusion of energy efficiency measures in the industrial sector and in the building sector in GENeSYS-MOD, IFE-TIMES-Norway and OSeMOSYS with different approaches.

In GENeSYS-MOD, in the building sector, the improved representation is handled mainly on the input data. As described, in Section 2.1, two scenarios describing the evolution of the future Norwegian building stocks are used in the RE-BUILDS model [10] . In one scenario, new buildings stocks are built at the current building standard and only 1 in 5 renovations include an upgrade in energy efficiency. In the other scenario, all new buildings must be built at the passive house standard and renovations must include energy aspects (e.g., building envelopes, windows) to increase the energy efficiency and decrease energy demand of the building. In both cases, an increase of the building stock is considered.

The building stocks resulting from these two scenarios are used in the PROFet tool to generate demand profiles for the Norwegian areas in the model. PROFet allows for a finer representation of the building sector in Norway and updating of the assumptions from the dataset. The PROFet tool [8], [9] is an aggregated load profile generator that can predict hourly load profiles of space heating demand, domestic hot water demand, and electric-specific demand for a given mix of building floor area and temperature profile. It considers different building types – houses, apartments, and nine types of service buildings – and efficiency levels ranging from the average of the national stock to buildings with energy efficiency equivalent to passive houses. The tool consists of a regression model based on measured data from 2.5 million m^2 of heated area in existing buildings in Norway. In this study, the energy demand of the building stock has been calculated separately for each of the five energy market areas in Norway (NO1 to NO5), using representative weather data for the cities of Oslo, Kristiansand, Trondheim, Tromsø and Bergen.

The tool can be combined with information about the existing building stock in the different Norwegian regions and projections on the evolution of the building stock (an increase in floor area, improvement of the buildings' envelope, etc.) to create a projection of the heat demand profiles from the residential and commercial sector in Norway towards 2050. As mentioned above, the RE-BUILDS model is used for calculating the building stock at the different time periods of the study. RE-BUILDS addresses the development of the complete building stock, including both residential and non-residential buildings. It calculates the long-term development of the building stock by estimating the demand for floor area, based on population, lifestyle parameters, demolition rates and renovation rates. See [10] for a detailed description of RE-BUILDS. The energy demand profiles generated with the combination of RE-BUILDS and PROFET replace the existing demand profiles for Norway in the GENeSYS-MOD model.

The old and new loads are shown on Figure 3-1:

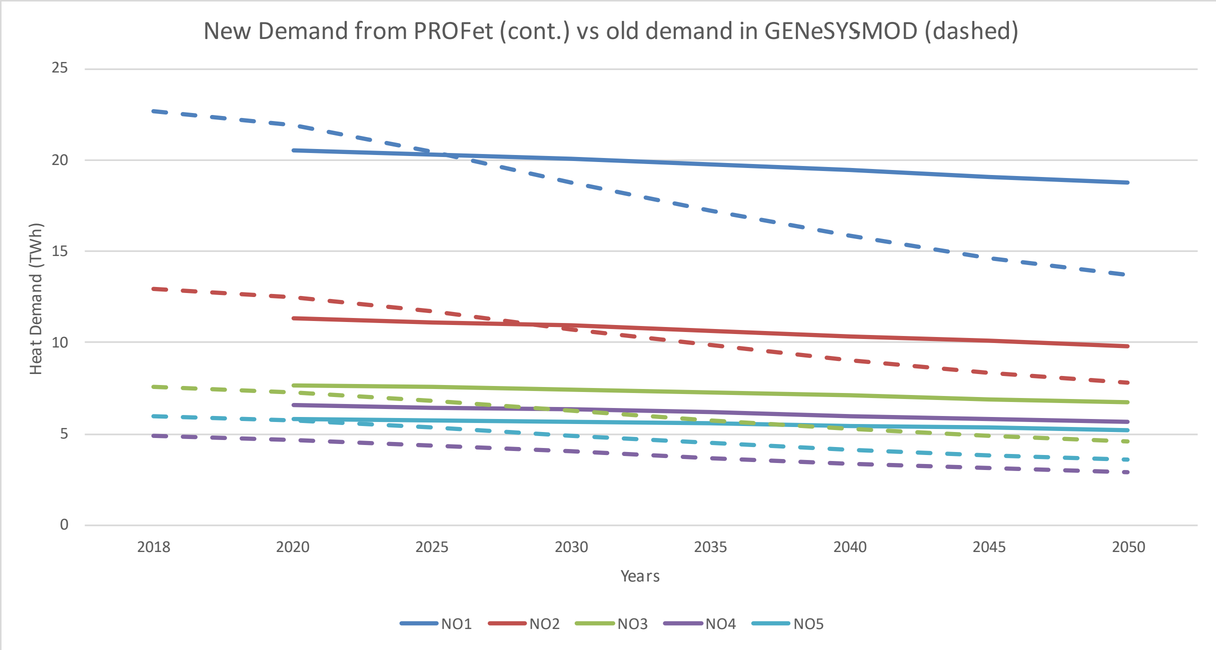

Figure 3-1 Comparison of the residential (and commercial) heat demand from the sector-specific modelling done in PROFet (full line) and the demand used in the model in the original dataset for GeneSys-Mod (dashed line).

The figure shows that the detailed sector-specific modelling is not as optimistic as the assumptions used in GENeSY-MOD. Indeed, the demand reduction assumed earlier is much lower in the detailed modelling (37.5% vs. 8.5% reduction). This difference could be explained by several factors such as an overestimation of the renovation rate or an underestimation of the increase in the building stock in the original dataset. The sector-specific modelling is crucial to the correct representation of the future expected loads. This work was done for Norway, but sector specific modelling should also be used to validate the assumptions on the loads for other countries.

The residential heat demand of the other Nordic countries was also compared to the residential heat demand from the NCES project with ON-TIMES. Despite deviations, the original data from GENeSYS-MOD were kept consistent between runs, and due to differences in scope with the source, as the ON-TIMES dataset considers the Nordic countries while GENeSYS-MOD considers the European context.

In the industrial sector, heat pumps and heat-to-power technologies are implemented. Both of these technologies use industrial waste heat and provide heat at the disaggregated temperature levels. High-temperature heat pumps are assumed to be able to provide industrial heating at temperature levels below 100˚C, at 100˚C – 150˚C, 150˚C – 200˚C, and 200˚C – 500˚C. High-temperature heat pumps providing industrial heat up to 150˚C are assumed to be available from 2018. Industrial heat pumps up to 200˚C are assumed to be available from 2025 onwards, whereas high-temperature heat pumps capable of providing heat up to 300°C are assumed to be available from 2030 onwards. The coefficient of performance (COP) is then modelled as half the Carnot efficiency, with the temperature levels calculated as the mean temperature of the available waste heat and the heat demand satisfied.

Heat-to-power technologies also aim to utilise available waste heat to generate electricity for example through ORC cycles or steam bottoming cycles. Their conversion efficiency is assumed to be half of the calculated Lorentz efficiency. Due to waste heat being mostly available at low temperature levels, the conversion efficiency is low, leading to no investments by the model into heat-to-power technologies.

To assess the impact of the changes to GENeSYS-MOD described in RQ5 and 6, we compared results from the version of the model used in WP2 of Nordic Energy Outlooks, with the original data for energy demands, to this new version of the model. We refer to the results obtained using the model as used in the base case of WP2 as WP2 and the results obtained with the changes performed under WP3 as WP3.

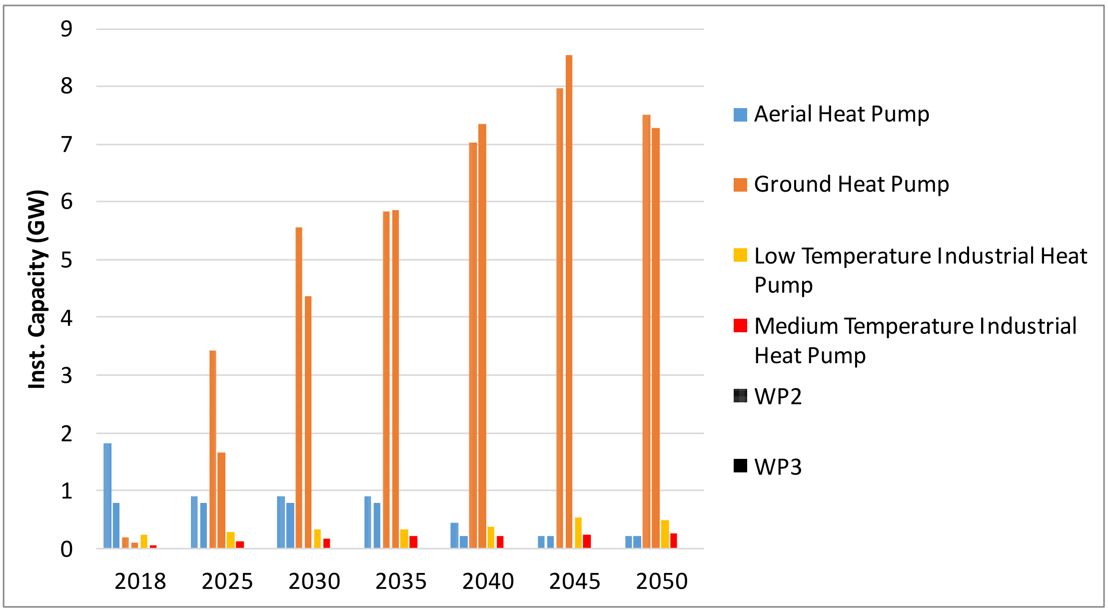

Figure 3-2 Investment in heat pumps in GENeSYS-MOD in Norway between WP2 (hatched) and WP3 (filled).

Figure 3-2 shows the investment in heat pumps in Norway by the GENeSYS-MOD in WP2 and WP3. The initial decrease in demand from the more detailed sectoral modelling (cf. curve levels e.g. for year 2020 in Figure 3-1) leads to a decrease in air source heat pump investment in 2018. For ground source heat pumps, the investments in WP3 happen at a slower rate until 2030 before catching up in 2035. Despite the higher load in WP3 in 2050 in Norway, the heat pump capacity is similar to the numbers from the WP2 report [3]. In addition, there is some investment in industrial heat pumps. For the low temperature industrial heat, it corresponds to the identified potential using the waste heat. For medium industrial temperatures, we see a use of the potential up to 200˚C but no heat pump for temperatures above.

The generation of residential heat is presented in Figure 3-3. The starting point in 2018 is similar in WP2 and WP3. From 2025, the rate of decrease of direct electric heating is lower in WP3, resulting in twice the amount remaining in 2050. The installation rate of ground source heat pumps is higher in WP3, resulting in about 30% more heat pumps in the latest periods. Hydrogen boilers appear simultaneously in both cases but are more prominent in WP3 where they account for three times as much heat production.

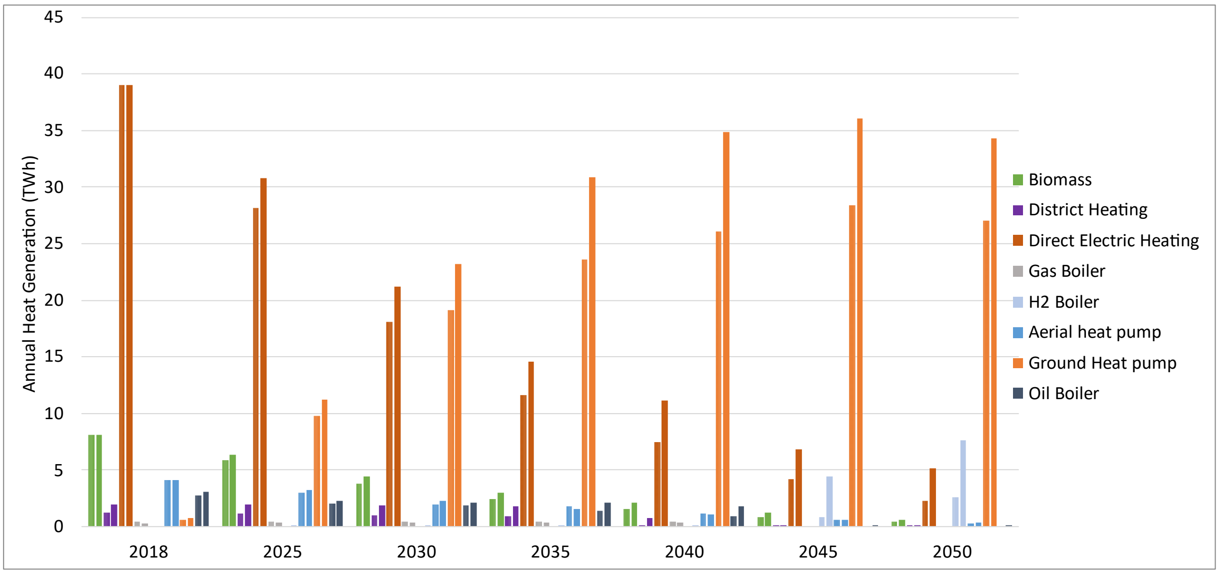

Figure 3-3 Residential heat generation by sources in GENeSYS-MOD in Norway in WP2 (hatched) and WP3 (filled).

These differences reflect the assumptions of the residential loads in WP2 and WP3. The loads in WP2 decrease faster, resulting in lower demands. The additional demands when considering the detailed sector-specific modelling of WP3 are met with more ground heat pumps and a better utilisation of the heat pumps as well as a smaller phase out of direct electric heating and a heavier reliance on hydrogen for heating.

For the low-temperature industrial heat (Figure 3-4), the more detailed modelling of industrial heat introduced in WP3 leads to a decrease in direct electric heating and gas use. The industrial waste heat pumps are built up to the identified potential of the corresponding waste heat and replace some of the gas and direct electric heating. Among other minor changes from WP2 to WP3, biomass is slightly reduced between 2030 and 2045 and district heating is used more although still marginally.

For the medium industrial temperature range (Figure 3-5), the results are aggregated for WP3, and not presented for each of the four sub levels introduced, to facilitate the comparison. Medium temperatures heat pumps appear in 2018 and are phased in gradually, contributing from 1TWh heat in 2025 to slightly under 2 TWh in 2050. The more detailed modelling of the different temperature levels has an impact on the results, with a slightly higher production of heat being observed. This can be explained by the separation into different heat levels. In details, this means around twice as much hard coal, until it is phased out in 2030; somewhat higher oil use in 2018; slightly more biomass throughout; marginally higher use of gas, except in 2040 before being phased out where it has a 25% share of the medium temperature heat instead of 7%; and a larger amount of steam. The improved representation of the medium level industrial heat has as its main consequence an increase of the amount of fossil fuels used before their phase out, despite the introduction of the heat pumps. The more detailed modelling is thus important to quantify fossil fuel use more precisely during the energy transition.

For the high-temperature industrial processes, no changes to the modelling have been implemented in this work and only minor changes are observed (slight reduction in use of scrap electric arc furnace and corresponding increase of use of traditional blast furnace in 2025 and 2030, which disappear in 2035).

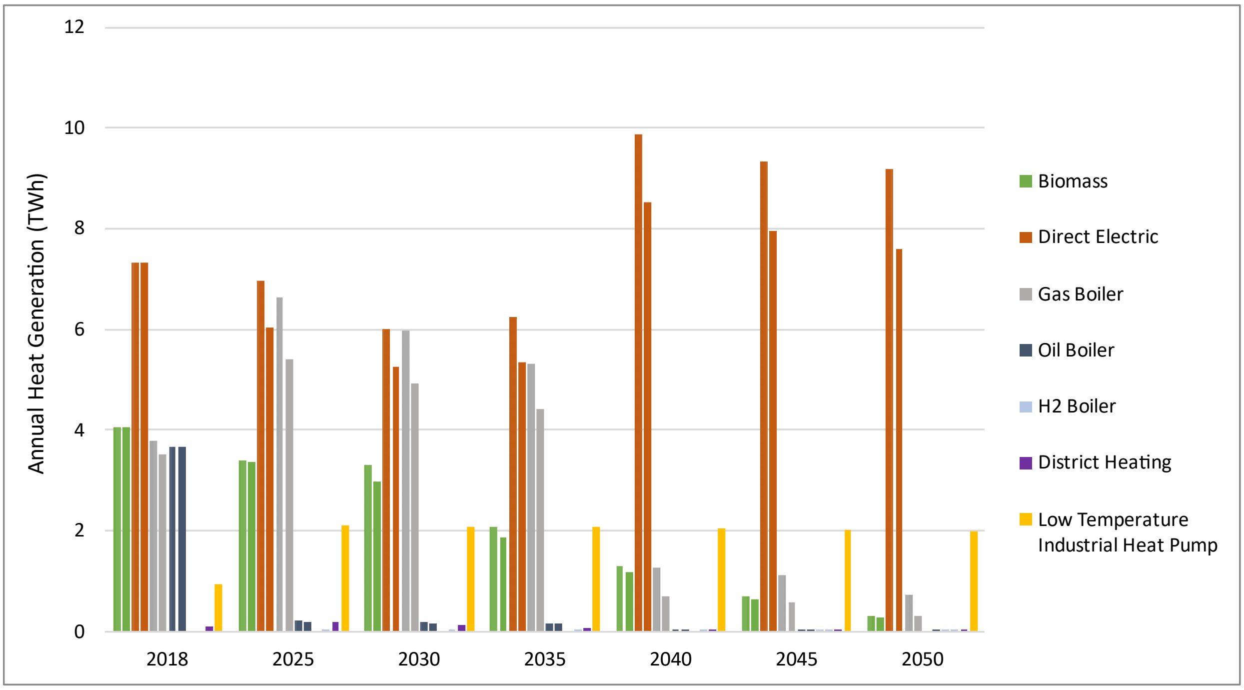

Figure 3-4 Low-temperature industrial heat generation by sources in GENeSYS-MOD in Norway in WP2 (hatched) and WP3 (filled).

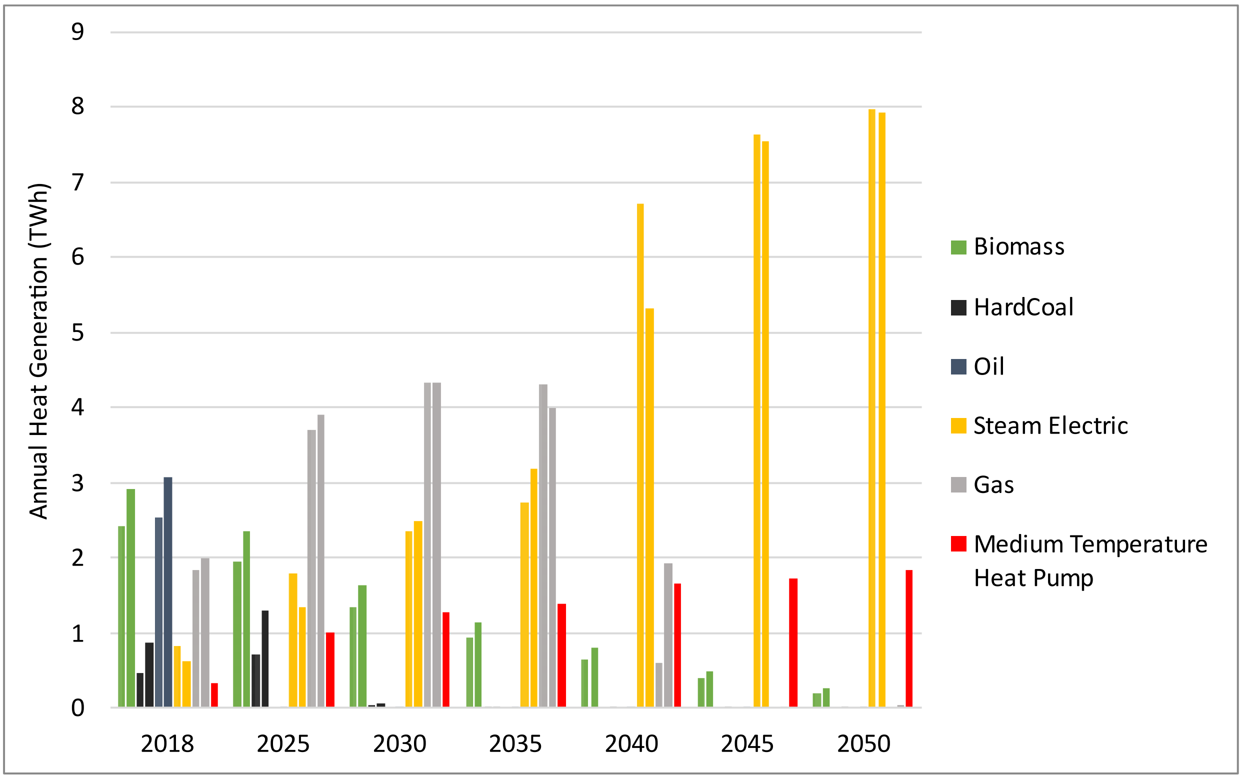

Figure 3-5 Medium-temperature industrial heat generation by sources in GENeSYS-MOD in Norway in WP2 (hatched) and WP3 (filled).

Figure 3-6 presents the average efficiency of the heat production in the industrial and residential sector, calculated as the ratio of the total heat produced by the total energy (fuel) consumption to produce it. It represents a weighted average of the efficiency of the technology used to produce the heat. We see a decrease of the efficiency going from WP2 to WP3 for the residential sector, especially from 2040. This can be explained by a larger reliance on direct electric heating and hydrogen boilers with the overall higher loads in WP3. For industry, we do not see a major change in the efficiency, only a marginal decrease.

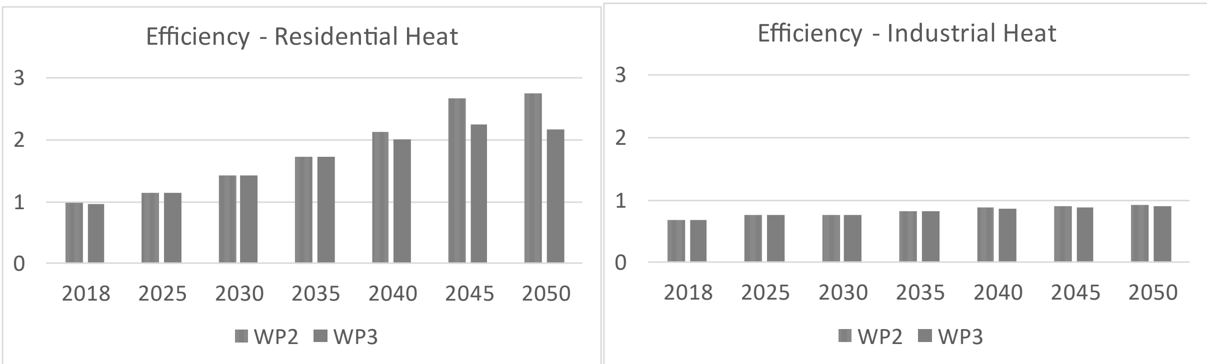

Figure 3-6 Efficiency of heat production for the residential and industrial sectors in GENeSYS-MOD in Norway. Results from WP2 (hatched) and WP3 (filled).

It is crucial to consider carefully the assumptions made for the input data to the model as they can significantly impact the model results. To illustrate this, we run the case with the improved representation of the industrial sector but without limiting the amount of available waste heat. We can then compare to the results we obtained with our assumption of the availability of waste heat.

Figure 3-7 shows the investment in heat pumps in the case where we have unlimited and limited access to waste heat. As seen in our previous results, with our limited access to waste heat, the model invests in residential heat pumps, as well as some low and medium temperature industrial heat pump. Those investments in residential heat pumps remain unchanged but we see increased investments in low temperature industrial heat pumps with about four times more in 2050 when the waste heat limitation is removed. Despite removing the limitation on the waste heat availability, we only see a marginal increase in medium temperature heat pump capacity.

The investment in the low temperature industrial heat pumps results in changes in the low-temperature industrial heat production, as shown on Figure 3-8. Indeed, from 2025, the heat pump replaces almost entirely the use of gas. It also significantly reduces the use of biomass in later periods, with about 50% reduction between 2030 and 2045. As more heat pumps are installed through the periods and gas is phased out as in the base case, it also replaces the direct electric heating that was replacing gas in the case with limited waste heat availability. These results points towards a potential for waste heat in industry applications that could allow a more rapid diminution of gas usage. Simultaneously, they highlight the importance of an accurate representation of the availability of waste heat resources in order to accurately predict its future role. Finally, it spotlights the need for an extension of the work done to the other countries included in the model and in particular a detailed assessment of the potential of waste heat.

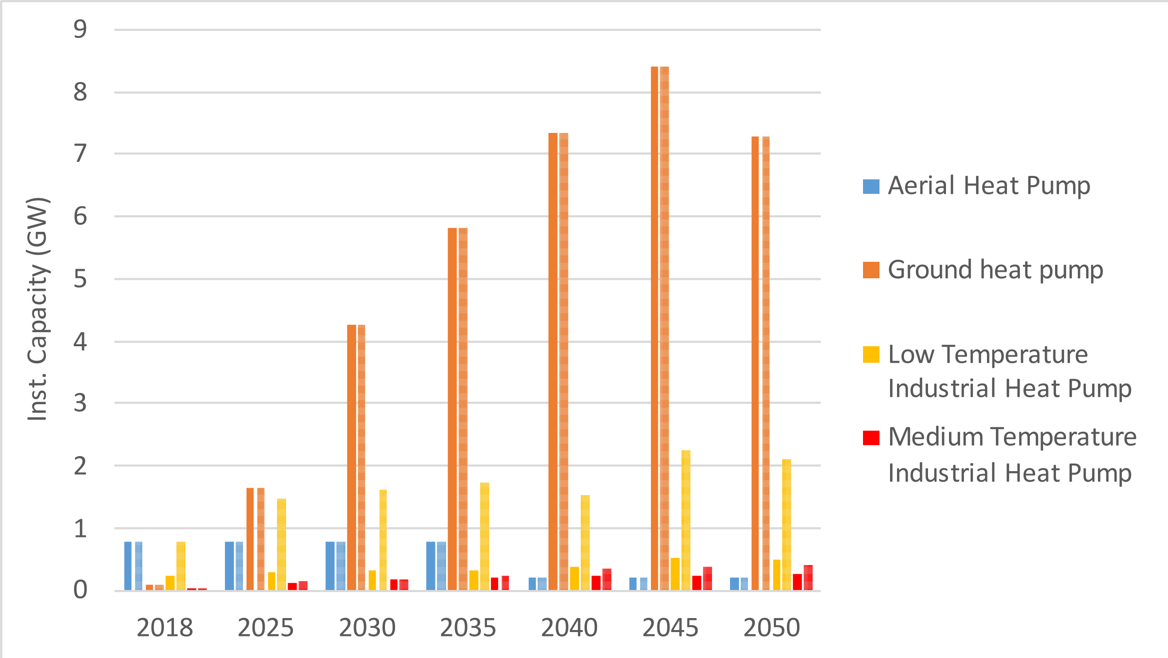

Figure 3-7 Investment in heat pumps in GENeSYS-MOD in Norway in WP3 with (filled) and without (dotted) waste heat availability limit.

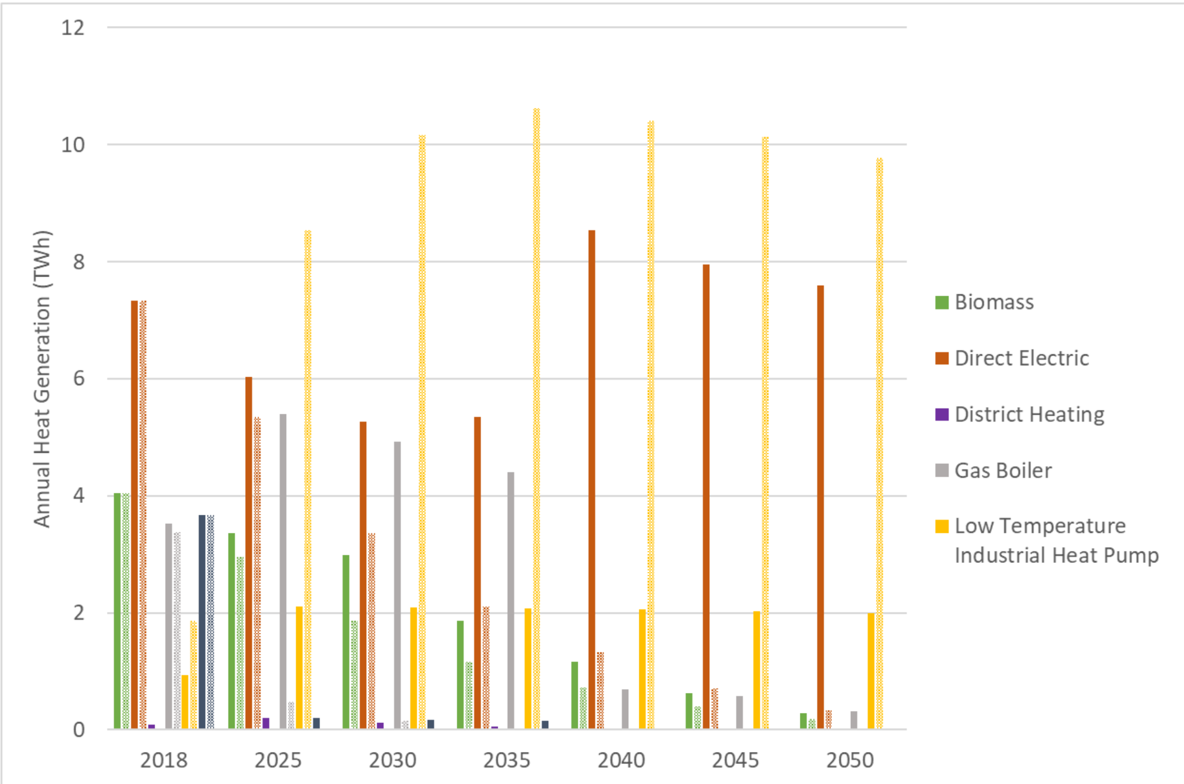

Figure 3-8 Low-temperature industrial heat generation by sources in GENeSYS-MOD in Norway in WP3 with (filled) and without (dotted) waste heat availability limit.

High-temperature heat pumps and heat-to-power technologies are only examples of industrial energy efficiency measures. Numerous studies in literature assess the techno-economic potential for heat integration utilising various technologies in different industrial processes [78], [79]. These energy efficiency measures are assessed depending on the specific industrial process at hand and are rarely generalisable. To implement such technology options in a global energy systems model such as GENeSYS-MOD requires detailed knowledge, or strong assumptions of the industrial processes within the modelled regions.

This section gives an overview of how energy efficiency and conservation measures of the building and industrial sector can be modelled in GENeSYS-MOD. For the building sector, the residential heat demand is re-evaluated using PROFet and RE-BUILDS, where two energy efficiency scenarios are considered. The updated residential energy demand shows a more gradual demand decrease from 2020 to 2050 than the original GENeSYS-MOD dataset. In the industry sector, energy efficiency measures such as heat pumps and heat-to-power technologies are modelled. Finally, this section discusses the optimal investment strategy quantitatively.

Modelling in IFE-TIMES-Norway model

In the IFE-TIMES-Norway model, the modelling of energy conservation measures (e.g., energy-efficient building envelope) in the existing buildings is handled by including the measures as endogenous technology options, which are part of the energy system optimisation problem. The growth rate for implementing the different energy conservation measures is considered, and it is based on the estimated energy renovations rates in the buildings sector in Norway. In the new buildings, the improved energy efficiency is included in the energy service demand projections (see Figure 2-2). The energy efficiency measures related to the buildings sector end-use technologies (e.g., heat pump, building-connected solar PV) are included also as endogenous technology options. The individual behaviours in the undertaking of energy efficiency investment are illustrated by considering different discount rates (i.e., social and private). The modelling of energy efficiency and conservation measures in the IFE-TIMES-Norway model is described in Section 2.4.

Modelling in OSeMOSYS

OSeMOSYS has been used in previous studies to model energy efficiency and conservation measures. These can be modelled both exogenously and endogenously within the OSeMOSYS framework. Most exogenous representation of energy efficiency and conservation measures are made by varying the final energy demand in the model. The variation in energy demand due to the implementation of these measures is determined exogenously using specific models. The exogenously calculated demand is then used by OSeMOSYS to determine the effect of these measures on the supply side. Smeureanu et al. [80] used OSeMOSYS to model the residential space heating demand in Romania, considering various financing modes. The investments in heating technology are weighted against investment in thermal insulation to determine the cost-optimal mix for meeting the domestic heating demand. There are also exogenous implementations where a technology representing energy efficiency measures (with a cost and an energy cascade corresponding to the efficiency measure) have been used to evaluate cost-effectiveness of these efficiency measures and potentially even have a comparison between the different efficiency measures.

In the current study, OSeMOSYS was used to represent sources of excess heat and relevant technologies for excess heat recovery. The energy conservation measures have been incorporated as an energy cascade such that excess heat from the industrial sector has been reused in the district heating systems. The heat sources, relevant technologies and the connection to the district heating network have been implemented as endogenous technologies. Therefore, the energy conservation measure representing the recovery of excess heat is a part of the energy system optimisation problem and the model determines the cost-effective implementation of the energy conservation measure.

3.7. RQ7: How large is the techno-economic potential of energy-efficiency and conservation measures in the building sector in Norway?

The results from the IFE-TIMES-Norway model provide insight into the cost-effective deployment of energy efficiency (EE) measures in the building sector in Norway until 2050. The main model assumptions used in the IFE-TIMES-Norway model are based on the REPowerEU scenario, as defined in NEO WP2 [3]. The techno-economic potential[2] for the energy efficiency measures in the building sector in Norway until 2050 is presented in four different scenarios that highlight the effects of different modelling assumptions:

- Base: The baseline scenario – Only energy efficiency improvements related to end-use technologies can be implemented when economically feasible; energy service demand development as presented in Section 2.4 in Figure 2-2.
- Sce1: The unlimited growth energy efficiency scenario – Additional EE measures are implemented when economically feasible using a social discount rate, as described in Section 2.4.
- Sce2: The behaviour energy efficiency scenario – Additional EE measures are implemented when economically feasible using a private discount rate for energy efficiency investments in the building sector, as described in Section 2.4.
- Sce3: The limited growth energy efficiency scenario – Additional EE measures are implemented when economically feasible, taking into account the growth rate for implementing EEMs as described in Section 2.4.
- Sce4: The target growth energy efficiency scenario – Additional EE measures are implemented when economically feasible using a private discount rate. The growth rate for implementing EE measures is assigned based on the 10 TWh end-use energy demand reduction target for 2030 [81].

According to the results from the IFE-TIMES-Norway model, significant techno-economic potential for the different EE measures can be identified in the building sector, in both existing residential and commercial buildings. The estimated total techno-economic energy savings potential is up to 30 TWh in 2025 and 27 TWh in 2050 (Sce1). In the existing residential buildings, the most cost-effective measures with the highest estimated energy savings potential are post-insulation of walls, post-installation of energy-efficient windows and doors, post-insulation of roofs, and changing to energy-efficient lighting, as presented in Figure 3-9 and Figure 3-10. In the commercial buildings, the corresponding measures with the highest estimated energy savings potential are ventilation heat recovery, demand-controlled ventilation, and specific fan power, as presented in Figure 3-11.

The estimated total techno-economic potential decreases to 20 TWh in both 2025 and 2050, when private discount rates are imposed for the energy efficiency investments in the building sector (Sce2). The private discount rate is observed to affect energy efficiency investments especially in

[2] The technical potential is an input to the model, whereas the techno-economic potential is the output from the IFE-TIMES-Norway model.

single-family residential buildings where the capital expenditures of different EE measures are already higher due to the value-added tax.

The assumed rate of energy renovations in the existing buildings is observed to significantly affect the techno-economic potential for the EE measures during the whole modelling horizon. If the growth rate for implementing EE measures follows the renovation rates (with improving energy efficiency) of the residential (0.2 %/year) and commercial building stocks (0.3 %/year) in Norway, the estimated total energy savings potential decreases to 0.5 TWh and 2.2 TWh in 2025 and in 2050, respectively (Sce3). Moreover, when the growth rate for implementing EE measures is considered for all residential building types, the energy renovations are observed to be more cost-effective in the multi-family residential buildings.

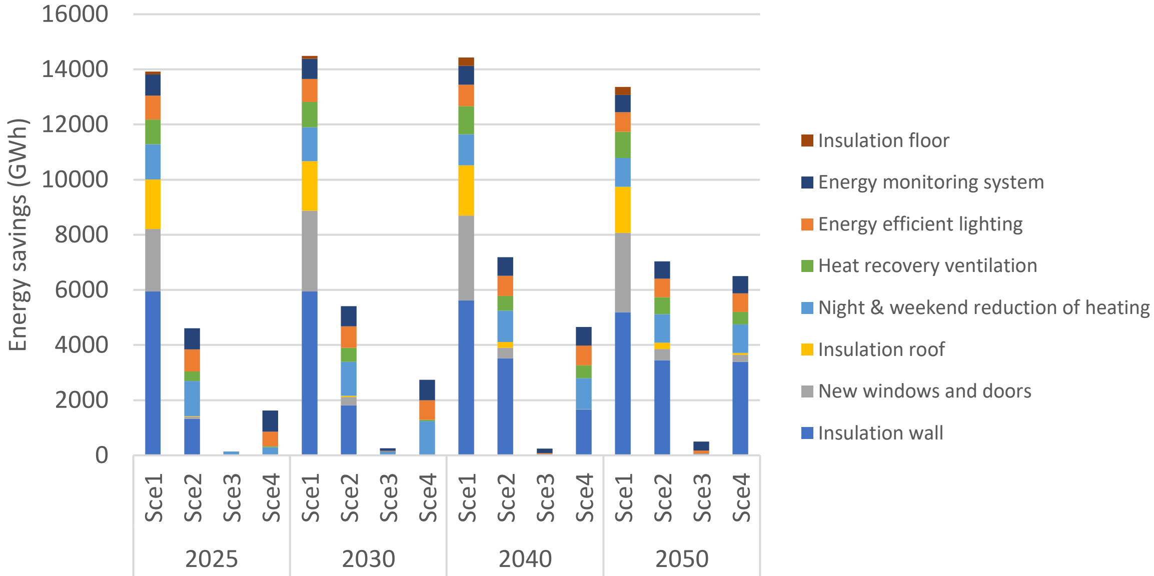

Figure 3-9: Techno-economic energy efficiency potential in the existing single-family residential buildings in Norway until 2050

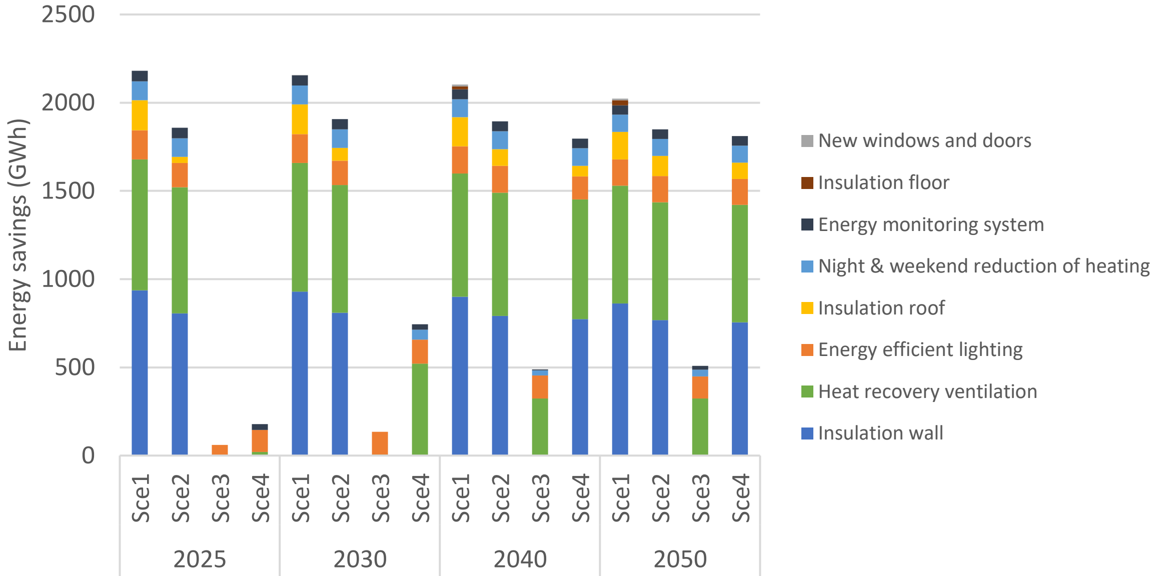

Figure 3-10. Techno-economic energy efficiency potential in the existing multi-family residential buildings in Norway until 2050

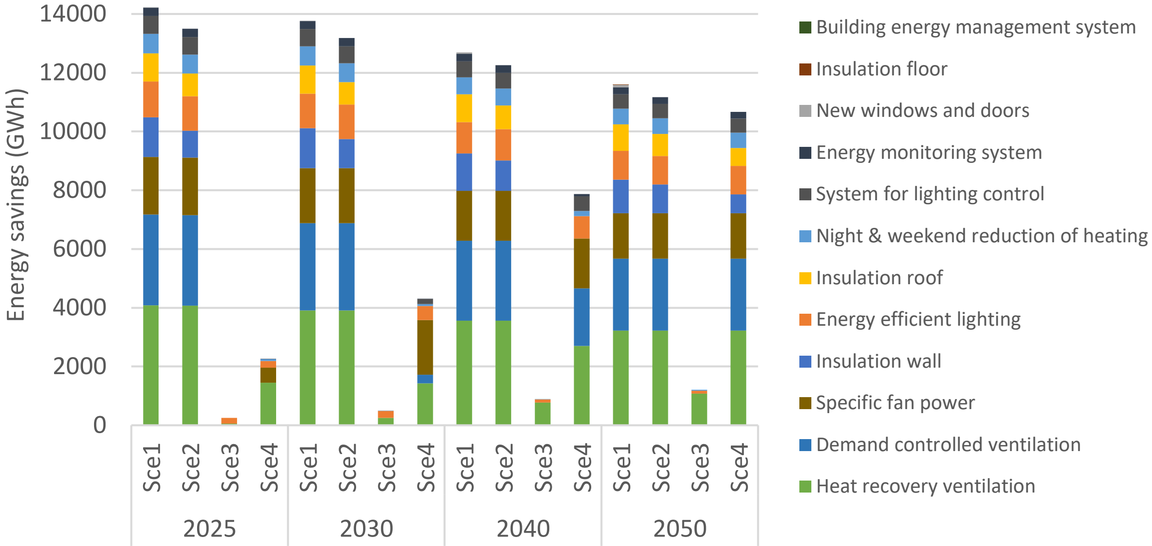

Figure 3-11. Techno-economic energy efficiency potential in the existing commercial buildings in Norway until 2050

Energy efficiency in the building sector is also assumed to improve through the integration of renewable energy technologies, such as heat pumps (e.g., water-water, air-water, and air-air heat pumps) and building-applied solar PV. The estimated total local renewable energy (RE) generation from heat pumps and building-applied solar PV in the building sector in Norway until 2050 is presented in Figure 3-12, Figure 3-13, and Figure 3-14.

The local energy generation increases over time in most scenarios (when lower discount rates are used). The highest local RE generation is observed in the baseline scenario, where no other EE measures are implemented in the existing buildings. Conversely, the local RE generation decreases in the scenarios, where the investments in local RE technologies compete with other energy efficiency investments. The lowest levels of local RE generation are observed in the scenarios where a higher private discount rate is applied to the energy efficiency investments (Sce2, Sce4). This affects especially the more capital-intensive energy efficiency investments. For example, in single-family residential buildings, the higher discount rate affects the cost-effectiveness of building-applied solar PV, whereas in multi-family buildings, the cost-effectiveness of heat pumps (water-water) is reduced. A similar effect can also be observed in commercial buildings, although to a lesser extent.

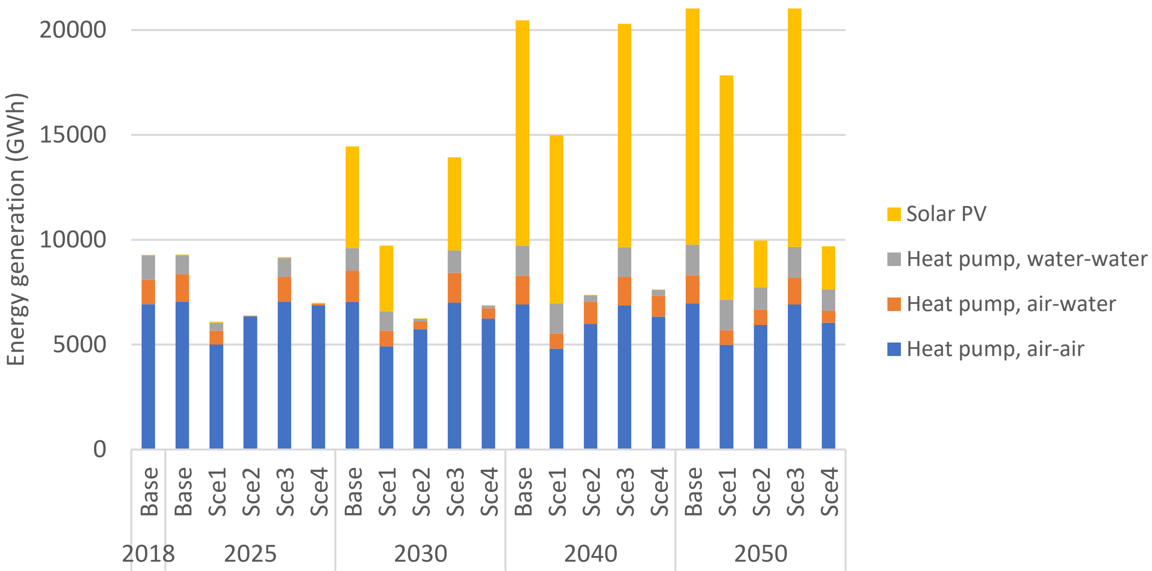

Figure 3-12: Local renewable energy generation in single-family residential buildings (incl. existing and new)

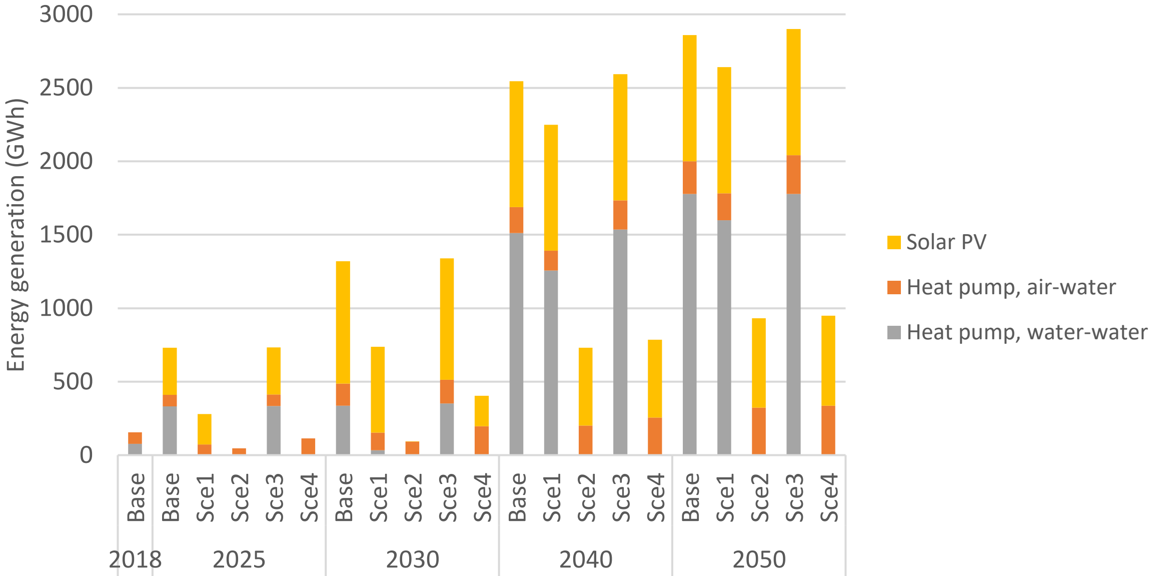

Figure 3-13: Local renewable energy generation in multi-family residential buildings (incl. existing and new)

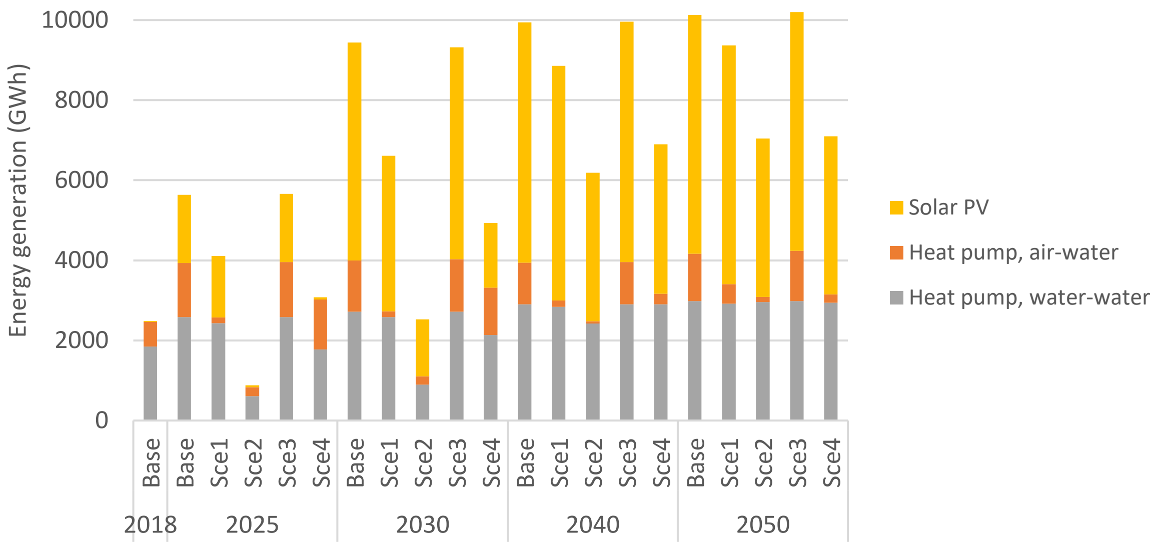

Figure 3-14: Local renewable energy generation in commercial buildings (incl. existing and new)

The estimated total energy use in the building sector in Norway until 2050 is presented in Figure 3-15, Figure 3-16, and Figure 3-17. The estimated total energy use is observed to decrease over time in all energy efficiency scenarios, being around 1–23 TWh and 3–22 TWh lower in 2030 and 2050, respectively. The current political goal is to reduce energy use by 10 TWh in existing buildings by 2030, compared to the 2016 level [81]. In this work, it is estimated that reducing energy use in existing buildings by 10 TWh in 2030, compared to the 2018 level, would require an energy renovation rate of about 1.8 and 2.7% (1.6 and 2.4% with a social discount rate) in residential and commercial buildings, respectively. Residential and commercial buildings account for 49% and 51% of this energy use reduction target, respectively. In this scenario, energy renovation rates in the residential and commercial building are assumed to increase at even rate.

The results show that electricity will continue to be the dominant energy carrier in the Norwegian building sector in the long-term, varying between 79–90% in different scenarios at various times. Furthermore, most of the total energy savings come from reduced electricity consumption in the building sector. District heat has a share of 5–10% between the scenarios and years. The use of district heat is observed to increase especially in multi-family residential buildings. Furthermore, district heat becomes an economically more feasible heating source when a higher private discount rate is applied to the energy efficiency investments (Sce2, Sce4). As a result, district heat is observed to substitute electricity use. The use of biomass for heating increases over time in scenarios where implementing the EE measures is limited by the growth rates (Sce3, Sce4), especially in commercial buildings. Biomass has a share of 4–12% between the scenarios and years.

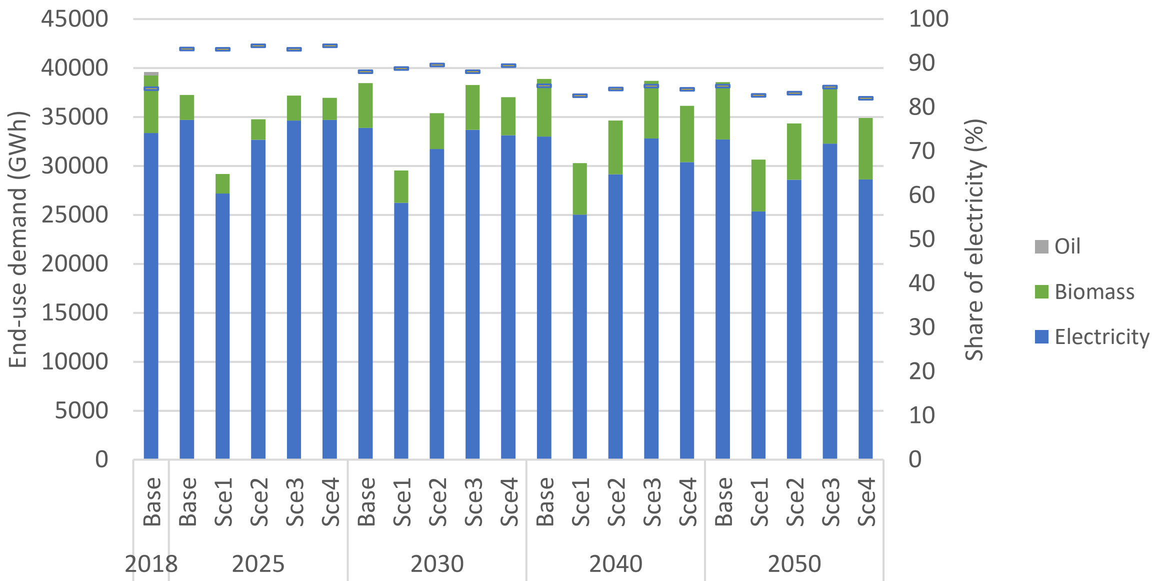

Figure 3-15: Energy use in single-family residential buildings in Norway until 2050

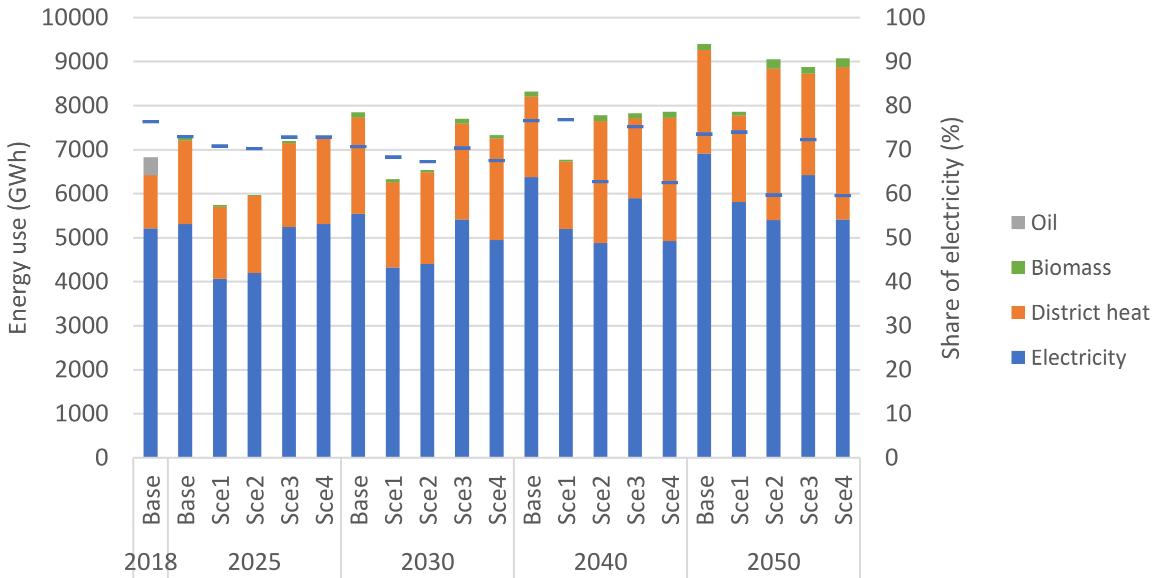

Figure 3-16: Energy use in multi-family residential buildings in Norway until 2050

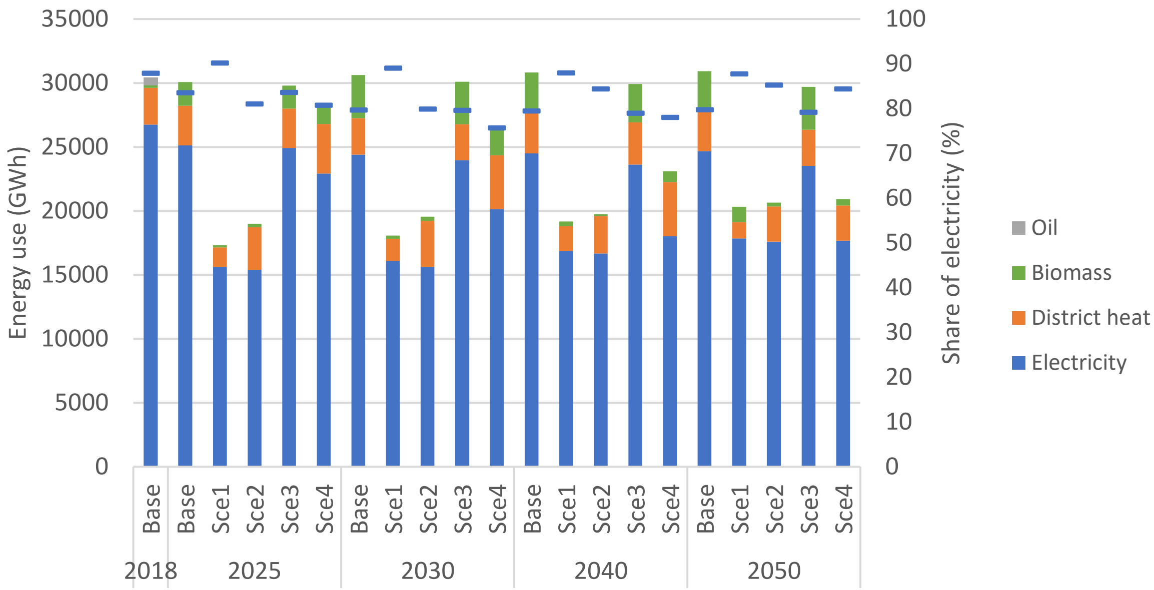

Figure 3-17: Energy use in commercial buildings in Norway until 2050

3.8. RQ8: What is the cost-effective amount of excess heat that can be re-used through the coupling of the industry and building sectors?

In the Nordic Countries at least 100 TWh per year is rejected from industrial processes – a number that is based on a very "generous" assumption of 40% overall energy efficiency on an estimated annual 250 TWh energy use in this sector combining Denmark, Finland, Norway, and Sweden. The heat rejected comes in various forms (radiated heat, effluent streams, and some flared gas) and naturally, not all of it is "useful" from a techno-economic point of view. For example, in a recent report, the Swedish Energy Agency presents results on the techno-economical potential for increasing the use of industrial surplus heat for heating and cooling of buildings, from 6 TWh in 2015 to 9 TWh 2050 [82]. Here, the largest potential was suggested as recovering low-grade heat – a result in line with that of one other recent study by Manz et al who matched locations for surplus heat sources and District Heating Networks (DHN) in EU27+UK [22]. At the same time, the Swedish Energy Agency projected a growth in the use of biomass in DHN of 25 TWh until 2050, which, combining the two, results in a net increase of primary energy use. Questions arise from these estimates since they considered the heating demand in isolation:

a) what happens to the biomass projection if we also take into consideration the fact that biomass is a resource with merging attractiveness to many other sectors including transportation and bio-based products for non-energy purposes; and
b) what happens if the increased demand for cold is treated together with the heating demand, so that the sound shortcut to generate cooling from industrial surplus heat can be used.

In addition, it is necessary to find out more about optimum locations for WHERE to invest, along with the timing aspect as to WHEN to invest.

Here, results from a transparent (using open tools as described in Section 3.2) long-term (until 2050) assessment of excess heat integration in District Heating Network (DHN) is presented for Sweden as a whole, as well as the city of Stockholm. The two cases give some complementary perspectives as detailed in Figure 3-18. For the national level Sweden Case, conventional industrial heat sources have been considered, whereas for the Stockholm Case, the focus was on urban heat sources from e.g. data centres. The spatial resolution is lower for the national case, and more detailed for the Stockholm case.

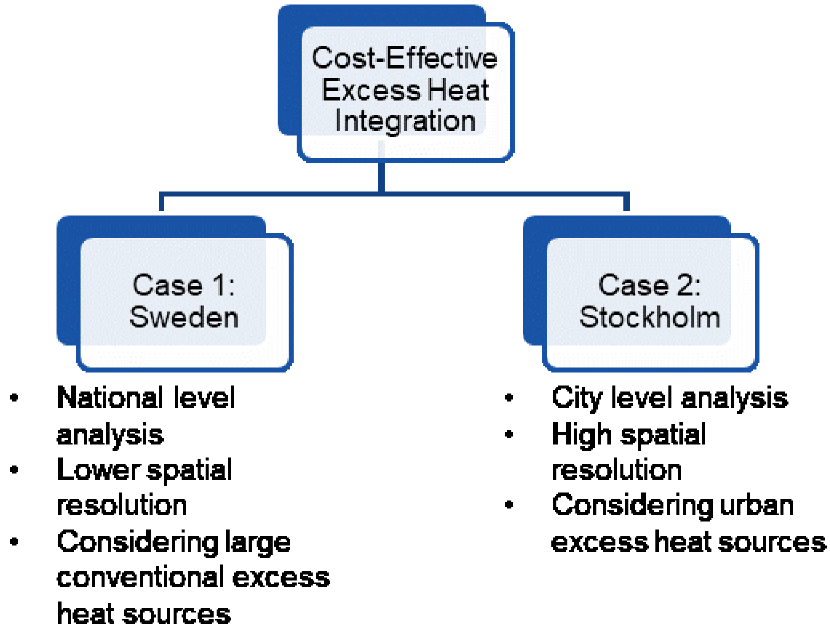

Figure 3-18: Cases for the analysis of excess heat utilisation in the Swedish context.

Case Sweden – Industrial Excess Heat

For this case, the starting point was the existing heat atlas provided by the Heat Roadmap Europe, indicating 45 Industrial Excess Heat sources and their proximity to existing DHNs [21], [83] amounting to a total of 19 TWh. Table 3-3 summarises some information about the 10 largest sources in this pool. These 45 sources are all resources not presently used, so that, for example, the IEH from the steel mills in Oxelösund and Luleå, and refinery in Gothenburg, are not included.

Based on this information, the cost of connecting to the grid was calculated as described in Section 2.3 of this report, using a fully open-source geospatial tool [11] to estimate the least distance between the IEH source and the DHN, and based on this the connecting cost was calculated. The results of this assessment are summarised in the capacity-distance-cost map shown in Figure 3-19.

Here, the capacity of each source (each circle) is mapped with respect to the distance to the DHN. The size of the circle represents the specific cost of network extension, ranging from 0.1 to 1 MSEK/MW. The results from the geospatial analysis indicate that several small and medium sources under 100 MW are located close to the district heating system, i.e. within a distance of 1 to 10 kilometres. The costs of these connections tend to vary depending on the distance. There are a few small sources between 100 and 150 MW located 10 to 60 kilometres from the existing heating grids with high costs for connections.

Table 3-3: Example Industrial Excess Heat Sources considered (10 largest out of a pool of 45).

IEH source type	Size [GWh/year]	Distance IEH source-DHN [km]	Chosen in cost-optimal mix for Sweden 2050 [yes/no]
Refinery	3108	11.5	No
Pulp and paper	1158	25.5	No
Pulp and paper	1044	0.65	Yes
Pulp and paper	1006	9.3	No
Pulp and paper	792	2.2	Yes
Pulp and paper	778	11.1	No
Pulp and paper	772	1	Yes
Pulp and paper	753	2	Yes
Pulp and paper	739	1.1	Yes
Fertilizer	647	1.3	Yes

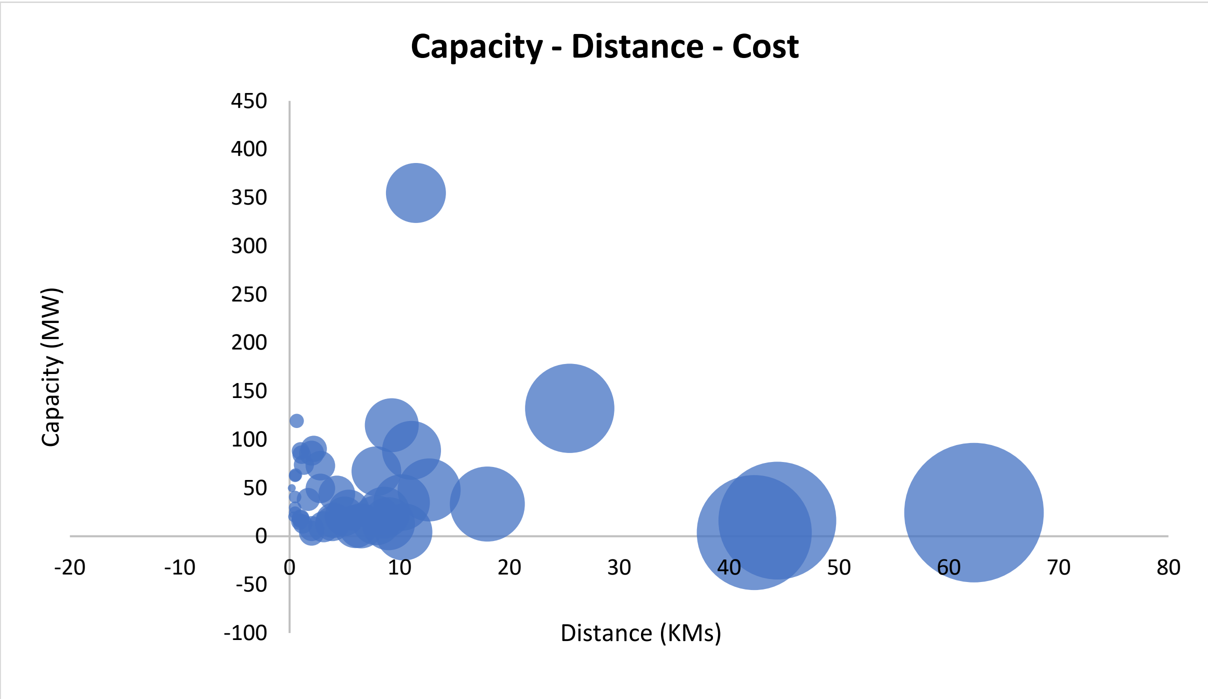

Figure 3-19: Capacity-Distance-Cost Map in relation to utilising Industrial Excess Heat in District Heating Networks

Next, using these cost-distance-results, our long-term energy optimisation model OSeMOSYS (fully open-source, as explained in Section 2.3) was used to compare the network extension for using the IEH, as compared to other existing options to produce district heating and satisfy the demand. A cost-optimal mix for satisfying the annual heating demand from base year 2022, through 2050, was computed. Some key results of this optimisation are highlighted further.

Distance and volume (size) of the connections were the determining factors, with large sources not being possible to use to their full capacity. Most of the sources chosen for connection were located less than 10 km from a DHN. In total, 37% of the technical potential, that is 7 TWh, was also economically feasible. In Figure 3-20, the results for the installed capacity of the excess heat sources are shown.

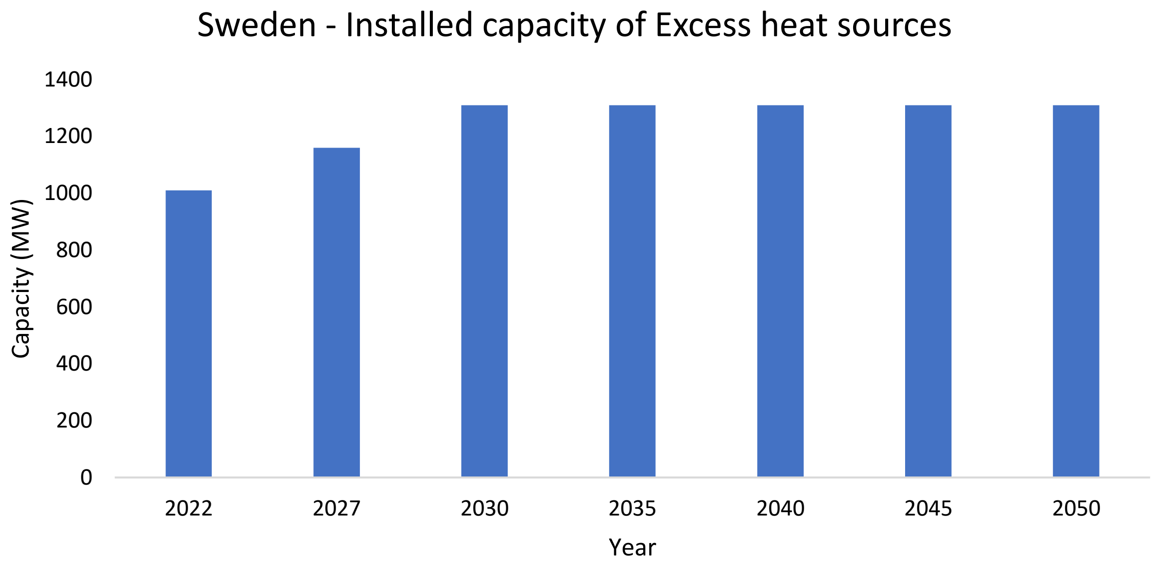

Figure 3-20: Case Sweden – Installed capacity of excess heat sources in MW

The results indicate that there is a potential for 1000 MW of capacity from excess heat sources in the base year of 2022, which is significantly greater than the actual installed capacity today. Also, we see that there is a constant increase in the installed capacity until the year 2035 due to the constant increase in demand. The capacity addition stops in the year 2035 meaning that, despite the higher prices of biomass in the future years, sources with high connection costs are not installed.

Figure 3-21 shows how the installed capacity mix to meet the heating demand varies between 2022, and 2050, based on the cost-optimal mix for satisfying the district heating demand in Sweden.

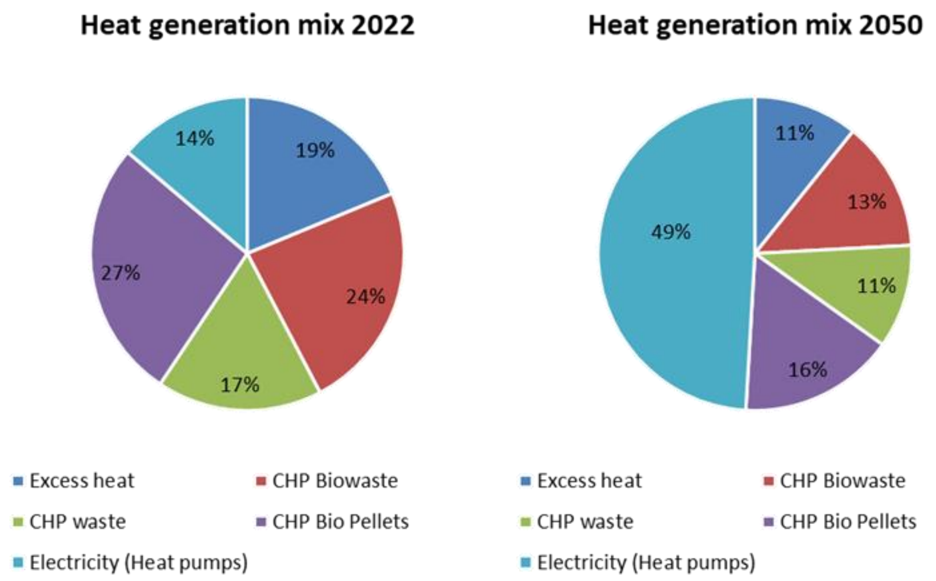

Figure 3-21: Optimal source and technology mix for satisfying the Swedish DH demand: (a) 2022; and (b) 2050

Starting from close to "12 o'clock", we have excess heat (EH), biowaste-based combined heat and power (CHP), waste CHP, bio pellet-based CHP, and heat pumps (electricity for). Focusing on EH, we see that for 2022, the cost-optimal mix includes 19% EH corresponding to 1010 MW installed capacity for 5 TWh generated. The corresponding number for 2050 is "only" 11%, but since the total demand has risen, this fraction corresponds to 1310 MW installed capacity, generating 7 TWh. Again, this capacity is in addition to the already operational capacity of 4-5 TWh/year that is used today in the Swedish DHN.

Some key insights from the Sweden Case are:

- A cost-optimal mix for district heating in Sweden can contain almost 20% IEH already for the base year 2022, which is far more than what is installed today.
  - ➢ Incentives to strive for such resource efficiency could both improve the national energy intensity and alleviate the electric grid to some extent.
- Large sources of IEH can be better utilised if they are closer to existing (or planned) DHN.
  - ➢ For efficient systems, think sector-coupling from the planning stage, and analyse opportunities for co-locating industrial activities with DHN.
- Distance and connection volume are factors determining the feasibility.

Case Stockholm – Urban Excess Heat

The Stockholm case has been developed based on a previous study which conducted a high-resolution spatial mapping of urban excess heat (UEH) sources in the Stockholm city. Su et al. [23] identified and mapped out both the geographical locations and the technical potentials of the clean non-fossil fuel heat sources available for district heating in Stockholm city. Based on this data, 49 large sources of UEH in Stockholm city have been identified and classified as shown in Table 3-4.

Table 3-4: Example Urban Excess Heat Sources considered

Source Type	Annual Heat (GWh)	Temperature (°C)
Data Centres	3200	Condenser: 20 - 80 °C
Ice Rink	200	Condenser: 20 - 80 °C
Sewage Plant	360	Air cooled: 20–45 °C Water cooled: 20–60 °C Two-phase cooled: 50–60 °C

Similar to the Swedish case, the network connection cost has been calculated using the geospatial tool, considering their geolocation, capacities and the approximate layout of the DHN as shown in Figure 3-22.

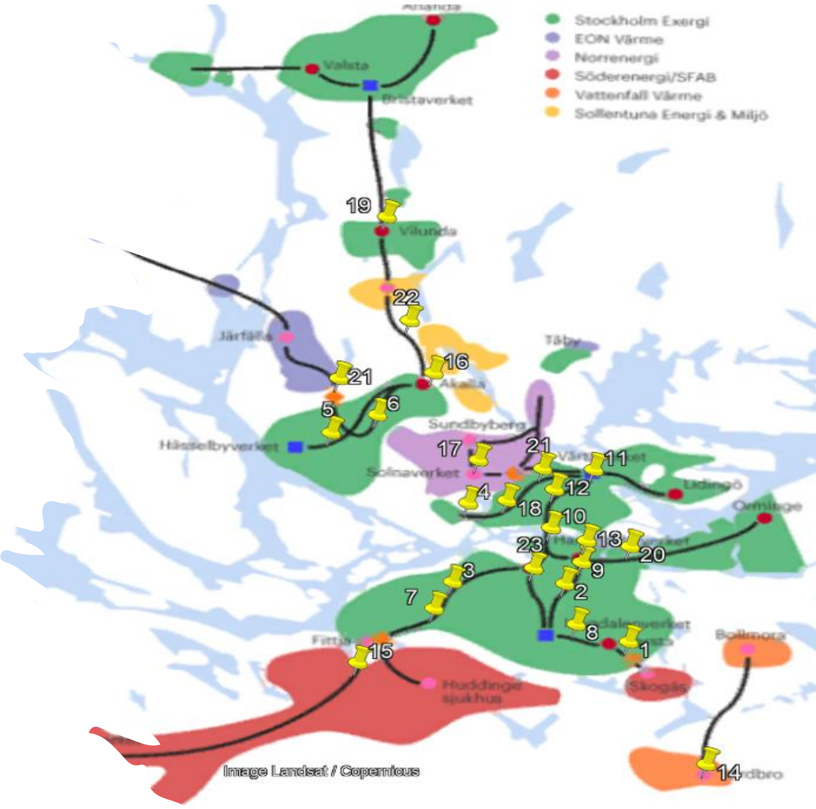

Figure 3-22: Urban excess heat sources in Stockholm

The geospatial tool determines the connection costs and losses for these different sources which have then been used as input to the long-term optimisation using OSeMOSYS. The results from the long-term optimisation indicate that ***98% of the technical potential is also economically feasible***. Similar to the results of the Swedish case, these results also indicate that 268 MW of UEH capacity can already be connected to the system in the base year as shown in Figure 3-23.

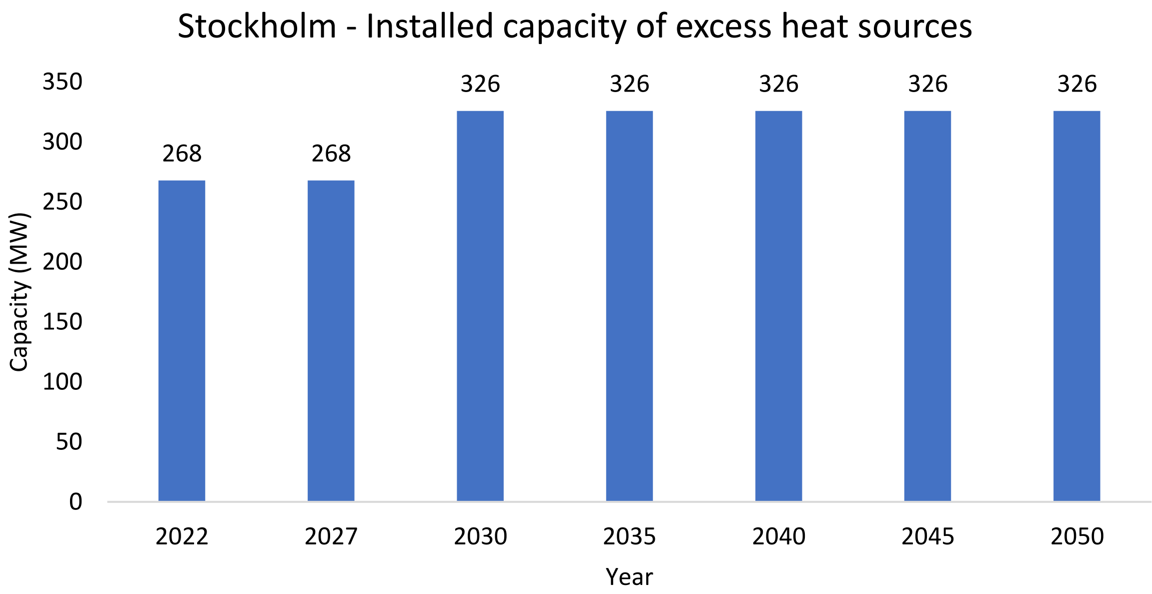

Figure 3-23: Stockholm - Installed capacity of excess heat sources in MW – cost optimal results, base case.

The capacity addition continues until 2030 where 98% is used, and then remains the same until 2050.

Examining the dispatch feasibility of the integration of UEH shows that it is a sound integration that forms a base load in the Stockholm system (Figure 3-24 and Figure 3-25 for 2022 and 2050, respectively). As demand is lowered, first the CHP is phased out, followed by most of the electric heat pumps during the summer months.

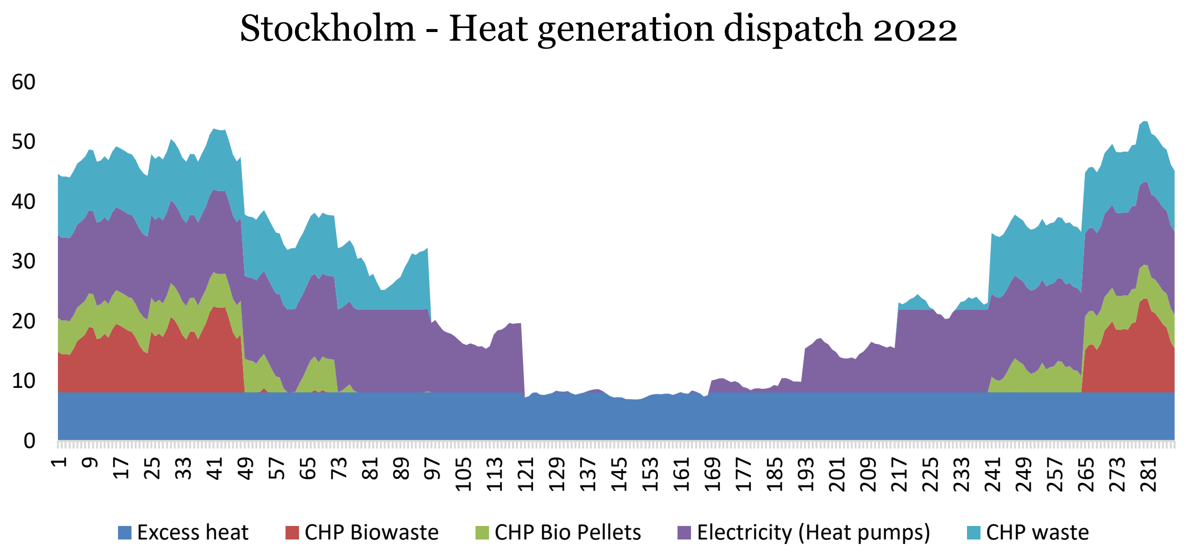

Figure 3-24: Stockholm – Heat generation for 2022

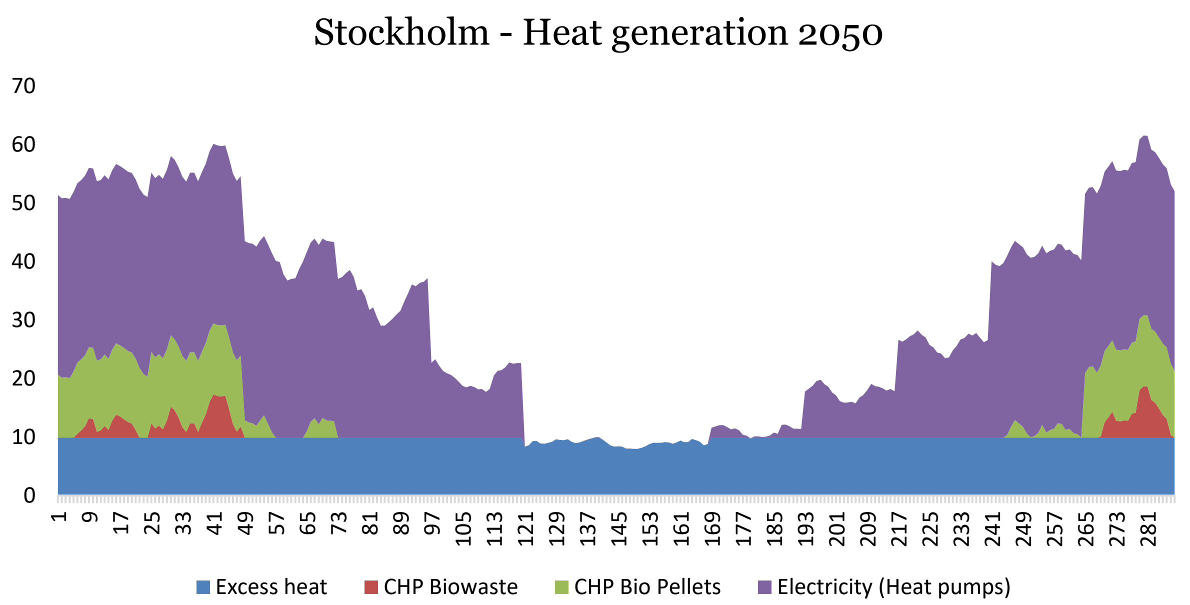

Figure 3-25: Stockholm – Heat generation for 2050

For the Stockholm case, Figure 3-26 shows the cost-optimal mix obtained from the analysis, for 2022 and 2050.

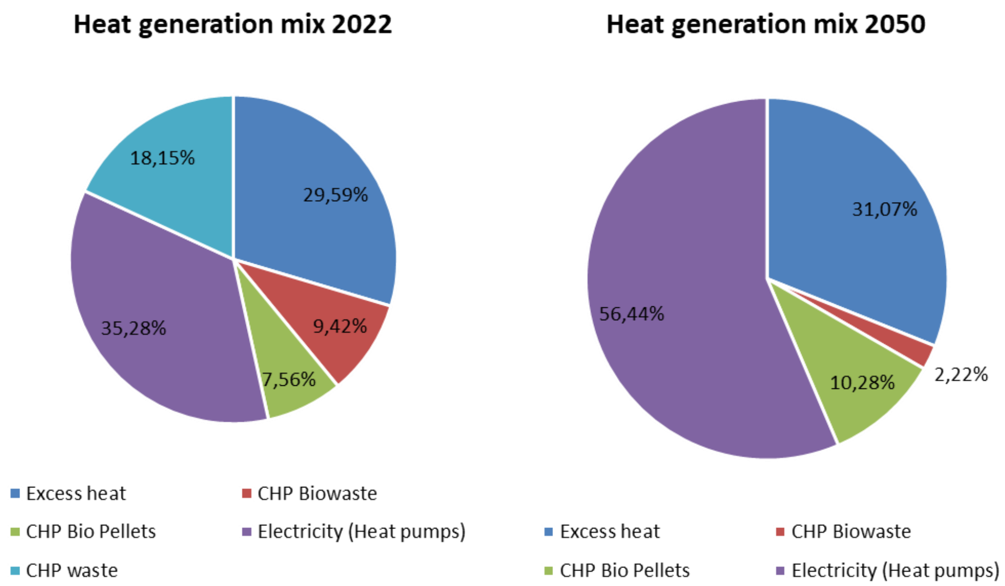

Figure 3-26: Optimal source and technology mix for satisfying the Stockholm DH demand: (a) 2022; and (b) 2050

As compared to the national case, the shares of excess heat obtained in the cost-optimal mix are higher, based on the fact that the sources are close to a large demand – the cost of connection is much lower here, ranging from 0.07 to 0.1 MSEK/MW. We also see that UEH could already today be a significant part of a cost-optimal mix – a result that is not represented in reality yet, but highlights the importance of utilities assessing whether this resource efficiency, theoretically cost-effective, shouldn't be part of immediate updates to investment plans.

3.9. RQ9: What will be the least-cost extension of the thermal grid in Sweden/Stockholm from a spatial and temporal point of view (i.e. where and when to invest)?

From the analysis of the national scale potential, focusing on industrial excess heat, we see a clear connection between cost and distance between sources. In cost-optimal energy mixes, only the sources within 10 km of an existing network were chosen to become part of a cost-optimal energy mix.

The results from the long-term optimisation for both the cases present the exact least-cost investment for each excess heat source. The results show which source to invest in and, thereby, the network extension. The capacity investments for each source in both cases are presented in Figure 3-27 (Sweden) and Figure 3-28 (Stockholm).

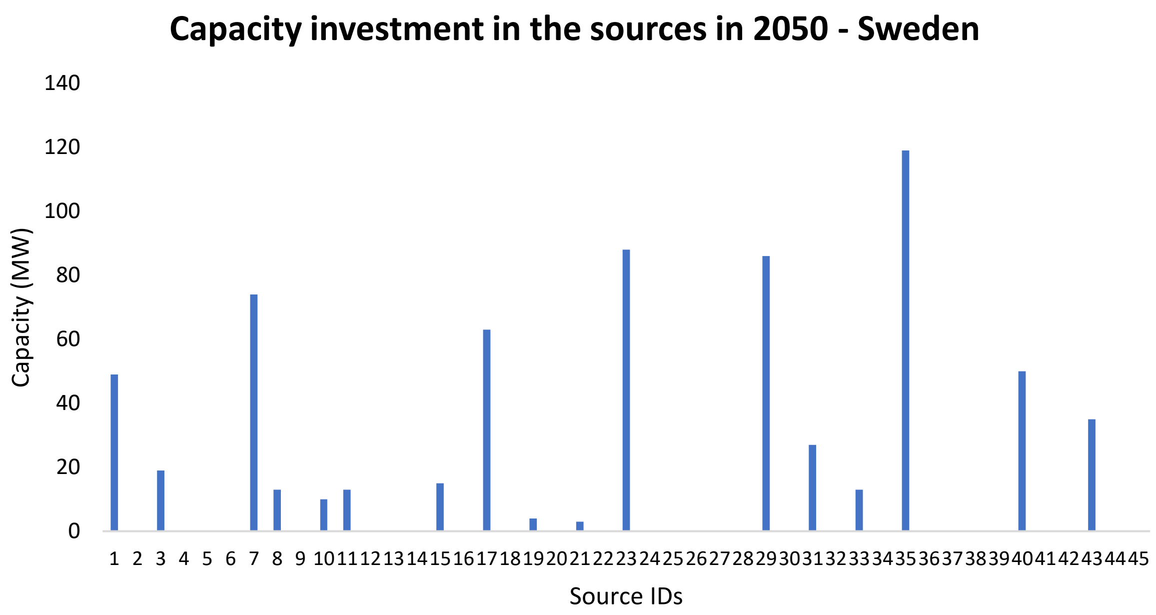

Figure 3-27: Sweden – Capacity investment for different sources – Where to invest

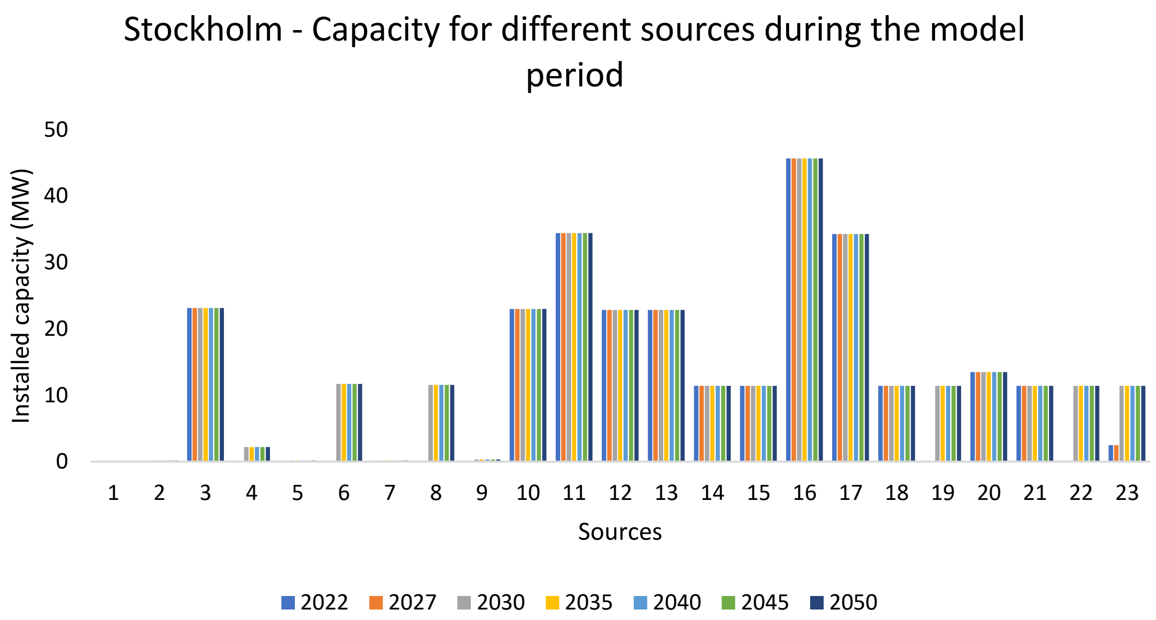

Figure 3-28: Stockholm - Capacity for different sources during the model period – When and Where to invest.

When and where to invest, can be summarised as follows:

- Most economically feasible sources are located within 10 km of a DHN.
- For the Swedish-IEH sources case, the investment is gradual until 2035, after which remaining IEH sources are not feasible due to the long distance and, in some cases, due to the volume being too large for a low demand.
- For the Stockholm-UEH sources case, most of the sources are economically feasible already today, while remaining sources become interesting from 2030 onwards.

3.10. RQ10: How will the cost-effective reuse of excess heat reduce the energy intensity (MJ/GDP) on a national level?

One of the important objectives of the Nordic Energy Outlook WP3 is, as previously described, to inform on the potential of lowering the national energy intensity – the one measure for assessing energy and resources efficiency in line with the Swedish NECP.

For this, we must make an assessment for the national level as to how much additional IEH and UEH is available, and techno-economically feasible. This work has contributed to that as summarised in Table 3-5.

Table 3-5: Unutilised potential of IEH and UEH

Case	Amount of heat technically available [TWh/year]	% of technically available heat that is also economically feasible	Amount of heat economically feasible [TWh/year]
Sweden – IEH	19	37	7
Stockholm- UEH	2	98	Approx. 2

Naturally there are assumptions, e.g. about cost-developments on fuel and electricity prices and also on heat demand, that make these figures only indicative. However, by considering presently unused sources of IEH and UEH, and UEH for only one city (albeit the largest in Sweden) we see that we can come close to the cost-effective use of almost 10 TWh per year EH, which is equivalent to 2 percent of the Swedish national energy supply (which 2020 was 508 TWh). Then, we can present here that cost-effectively integrating excess heat into the district energy system has the ability to impact the energy intensity by the order of a few percent. The main conclusion from this finding must be to consider this in planning onwards, to couple sectors from the start, and to plan for either co-locating heat generating activities with existing DHN, or to plan new developments in combination – industrial activities in proximity to expanding societal heat sinks such as new, potentially 5th generation district heating networks.

3.11. Discussion: insights from all WP3 research questions.

In this work, it has been important to benchmark the development of the modelling tools included, and new results produced, to the existing knowledge base related to energy efficiency and conservation measures, and to the Nordic context. As such, this report summarises and concludes on the incoming knowledge base, and presents some additional and new insights to support planning and decision-making for energy efficiency and conservation, e.g. for work related to updating the National Energy and Climate Plans.

Through an extensive review of the literature, the status of efficiency and conservation of energy and materials ***related to the build environment*** can be summarised as follows:

- When considering ECEM for the building sector, a large variety of measures should be included, from improving the thermal performance of the building envelop itself, to upgrading the heating and ventilation systems including monitoring and control, to integrating modern technological solutions such as PV + heat pumps.
- The technical energy saving potential can be as high as 60% when adopting a multitude of ECEMs, however cost-effectiveness varies and depends on factors like climatic condition (improvements on the building envelop more effective in the far north), market dynamics, and behavioural factors.
- Energy efficiency has a great opportunity to come with also lowered GHG emissions, and to maximise the benefits of retrofitting on the emissions. These should be done as soon as possible (front-loaded renovation plan) rather than operating with delayed actions, to minimise the cumulative emissions over a building's lifetime.
- Material efficiency is another important part of the overall efficiency and conservation ambitions, with published work showing that material resources could be reduced by 20% in the overall Nordic region, amounting to 10 million tonnes of CO_2 emissions saved. One example for Sweden has shown that just the practice of shared office space can reduce the required office area by up to 20 million m^2, saving 30 + million tonnes of material.

With these insights as a basis, additional modelling within this project has used ***Norway as a case application*** to further explore the potential. In this work, a number of scenarios have been assessed (representing various growth and economic conditions to evaluate economic feasibility). The results show that the greatest potential for the residential sector comes from post-insulation of walls, changing to energy-efficient lighting, and post-installation of energy efficient windows and doors. For commercial buildings, the highest potential come from heat recovery and control strategies in the ventilation systems, and from changing to energy-efficient lights. In total, ***the annual energy demand for the building sector in Norway can be reduced by about 30 TWh in 2025 and 2050, despite the annual increase in the built area.*** Additionally, the rate of innovation was found to significantly affect cost-efficiency. When applying the constrained growth rate of energy efficiency improvements of 0.2% per year and 0.3% per year for the residential and commercial sectors, respectively, the savings are reduced by one order of magnitude. As Norway presently has a target of ***10 TWh reduction*** in annual demand for this sector, this study shows that ***the rate of energy efficiency improvement must be increased to 1.5 and 2.3% for residential and commercial buildings, respectively.*** The final insight to highlight is that for Norway, electricity continues to be the dominating energy carrier in the building sector until 2050, and at the same time, the energy saved throughout this period is also due to reduced electricity demand. While these findings are for the Norwegian case application as stated, the work is also relevant for a wider Nordic context. Firstly, ***the IFE-TIMES-NORWAY model has been improved with the inclusion of new building standards and energy efficiency measures, and its implementation opens up the possibility of adapting the model to the other Nordic national contexts as needed.*** Secondly, the general insights on which efficiency measures come with the largest potential (post-insulation and post-installation of windows and doors, efficient lighting, and adaptation of ventilation systems) can serve as a guide in general.

In this work, long-term energy systems optimisation modelling tools like GENeSYS-MOD, OSeMOSYS, and IFE-TIMES-Norway were examined for their capability to serve planning and decision-making with quantitative results on the potential of various energy efficiency and conservation measures. These measures have been incorporated in the models in various ways, such as adding technology options with higher efficiency, integrating excess heat from other sectors as a resource for another sector, and specifically addressing the load generator, the demand, and how it is affected by measures on the demand side. One sub-part of this project addressed the evolution of the building stock for the GENeSYS-MOD tool, with a particular focus on Norway. By combining a PROFet tool, that predicts refined hourly load profiles for a given mix of building floor area, with the RE-BUILDS model, that estimates the long-term development of the building stock (accounting for parameters like population, lifestyle, demolition rates and renovation rates), the estimated demand reduction until 2050 went down to 8.5 % compared to previous estimations of 37.5%. In this specific case, reasons for the large deviation are for example over-estimating the rate of renovation and under-estimating the growth in building stock. ***This result highlights the importance of constantly working with sector-specific data to better represent input to the long-term energy models, and this is relevant for all country contexts.***

One other conservation measure integrated and explored in the long-term energy modelling tools *is* ***the reuse of excess heat from the industrial sector*** (approximately 100 TWh per year for the Nordic countries combined***) in the building sector*** via the concept of sector-coupling. Using a combination of geospatial modelling tool (to locate excess heat sources in relation to existing district heating networks, as well as cost-estimating a connection) and the long-term optimisation energy modelling tool OSeMOSYS, one sub-part of this project assessed the potential of integrating industrial as well as urban excess heat sources (data centres, ice rinks, large chillers, waste water) with district heating, as applied to ***the Swedish case application***. As one additional methodological feature, these results were cross-checked for operational functionality using the unit-dispatch model, checking for supply-demand compatibility at an hourly resolution. Not only do the results show that ***at least an additional 10 TWh of excess heat can be cost-effectively integrated by 2050, in addition to the 6 TWh presently used,*** but also that this can be cost-effectively implemented already by 2030. The main aspect influencing the cost-effectiveness is the distance between the source and the district heating network, which means that urban excess heat especially is a very attractive heat source for the future. Via this sub-part, the modelling tools, which are all fully open-source, are ready to be implemented also in other Nordic countries.

Finally, regarding efficiency measures directly implemented in the modelling of industries (such measures could lower the amount of excess heat generated), additions to the GENeSYS-MOD tool have been implemented, compared to the advancements previously reported in the WP2 of the Nordic Energy Outlook series. Here as well, ***a more detailed industry sectorial model*** was introduced, with particular attention given to the use of heat pumps at various temperature levels. Results showed that for low-temperature industrial heat demand, electricity and gas is replaced by heat pumps making use of excess heat in the industry. For medium-temperature industrial heat, the detailed modelling showed that despite the introduction of heat pumps, fossil fuel demand still increases at first. For example, ***coal demand in 2025 is at almost twice the amount with this detailed modelling, compared to modelling with a lower level of detail about temperature levels***.

4. Inputs to the update of National Energy and Climate Plans (NECPs)

4.1. Norwegian NECP

The Ministry of Climate and Environment (Klima- og miljødepartementet) informs that Norway is not obligated to submit any NECP to the EU. However, in 2019 the Government submitted a voluntary plan [84] for the non-ETS sectors and LULUCF. This plan has not been updated, but in 2021, a more comprehensive climate plan for Norway for the period between 2021-2030 [85] was issued. This climate plan is not an updated NECP, but it is the more relevant plan, as it is newer and includes more detailed plans across the different energy sectors and technologies. We comment that plan in the following section.

Energy efficiency and conservation in the building sector

The building sector accounts for 36% of domestic energy use in mainland Norway [86]. Therefore, the building sector can significantly contribute to energy conservation and GHG emissions mitigation via energy efficiency and conservation measures and decarbonisation of the energy supply. The Norwegian Government has decided to integrate its 2030 climate policy with the EU targets [87]. In this regard, the Norwegian Government has concluded that the Energy Efficiency Directive (2012/27/EU) should be incorporated into the EEA agreement with the necessary adaptations. The Norwegian Government has also introduced a regulation banning the use of mineral oil (fossil oil) for heating buildings from 2020. According to current regulation, it is not permitted to install heating systems using fossil fuels (both fossil oil and gas).

The main energy efficiency measure-related policies in the building sector are based on standards for new buildings, investment subsidies, metering systems and energy performance labelling and certificates. The climate plan also underlines the need for utilising the existing building stock via refurbishment, which also contributes to material efficiency through recycling and re-using materials. In this regard, the current political goal is to reduce energy use by 10 TWh in the existing buildings by 2030, compared to the 2016 level [81].

According to the results from the IFE-TIMES-Norway model, significant techno-economic potential for different energy efficiency and conservation measures can be identified in the building sector, both in residential and commercial buildings. However, the rate of energy renovations in existing buildings can significantly impact the degree and pace at which this potential can be realised. In Norway, around 0.2–0.3% of the residential and commercial building stocks are renovated each year, with improved energy efficiency [28]. The estimated required energy renovation rate of the existing building stock is 1.8–2.7% (1.6–2.4% with a social discount rate) to achieve the 10 TWh energy use reduction target by 2030[3]. Therefore, more stringent energy efficiency policy planning that addresses the historically low energy renovation rates (including clear energy renovation targets, monitoring and supporting measures) can be beneficial for the Norwegian Government to realise the estimated energy savings potential in the building sector. Moreover, the results show

[3] The reader should note that in the IFE-TIMES-Norway model, the reference year for the energy reduction target is 2018 instead of 2016.

that financial barriers (e.g., access to capital, lack of profitability and high investment requirements) can also limit the adoption of energy efficiency and conservation measures, especially in residential buildings. Energy efficiency policies related financial support (including information, improved awareness of available funding, low-interest loans) for energy renovations can increase the adoption of energy efficiency measures.

Energy efficiency and conservation in industry

The climate plan provides few details on how to achieve the national goals to reduce emission by 50-55% in 2030 and 90-95% by 2050 in comparison to emissions in 1990. Prosess21 [88] states that the process industry was responsible for 11.5 million tonnes CO_2 equivalent emission in 2019, which represents about 23% of the total Norwegian Emissions. CCS is identified as the most important implementation towards a green industry, with hydrogen being the second most important, followed by electrification and the use of biomass.

The most important policy measure to accelerate the transition to a zero-emission society is the CO_2 emission tax, which is recommended to be increased to 2000 NOK per tonne of CO_2 in 2030. In addition, it is recommended to ban the burning of fossil fuels in industry. Klimakur 2030 [89] mapped the emissions reduction potential of different emitters (sectors), as well as the impact of the CO_2 price, and recommends further actions to meet targets.

The Norwegian government recognises that the transition to a zero-emission industry requires advanced technology development and large investments. There are several governmental measures that stimulate investment and research into energy efficiency measures in industry:

- Norwegian Research council: In the period between 2010-2017, the Research Council of Norway supported projects with a volume of NOK 1 715 million. Norwegian industry is a central part of the projects supported by the Council to make them relevant for industry.
- Gassnova: Its main purpose is the realisation of carbon capture and storage, which will enable more actors in the process industry to intensify their work on CCS.
- Enova: Supports implementation of innovative climate-friendly investments so that the risk is reduced for industry partners. The support should allow investments in technologies which are today not economically feasible for industry actors. It accelerates the implementation of new technologies in the market. Enova received a budget of NOK 4.5 billion in 2023.
- Innovasjon Norge: Supports industry to implement environmentally friendly technologies. The main focus lies on technologies that can replace and improve existing ones.
- Norwegian Catapult and Innovation Centres: These centres invest in infrastructure and support long-term innovations and cooperation in the regional economic system. They invest in prototypes, offer expertise and equipment for testing.
- Pilot-E: A programme established by the Research Council of Norway, Innovasjon Norge and Enova to quickly establish new products and technologies in the market.
- Grønn platform: Established in 2020 to improve collaboration between different government programmes. In the first round, the focus was on establishing a complete green value chain with large number of partners in granted projects.

The EU set a target of 300 GW of installed capacity of offshore wind by 2050. The Norwegian Government recently announced a target of 30 GW of offshore wind by 2040 [90]. However, how these new electricity generators are distributed and deployed is not specified. Moreover, the electricity demand by industry is largely uncertain, which can be seen by the large deviation of energy demand between low (14 TWh) and high (53 TWh) scenarios [91]. The process industry, which is the largest user of electricity in Norway, currently uses about 42 TWh, which indicates how large the uncertainty in the projection is.

The climate plan indicates that excess heat should be used as an energy source for district heating systems to increase flexibility and lift the burden on the power grid. However, how to connect producers and users of excess heat is not addressed. It is mentioned that heat pumps can be a viable alternative in same cases.

In addition to energy efficiency and conservation, Norway has a strong focus Carbon Capture and Storage (CCS) for CO_2 mitigation in industry, and with Longship, initiated a full-scale demo project. CCS can be viable for some industry to reduce their emissions. Hydrogen production is identified as an area where Norway has a large potential. It can be used as a substitute for fossil fuels and also reduce emission in industry. However, no specific production volume goals for hydrogen are mentioned. Moreover, the consequence on consumers of increased variable renewable penetration in the electricity production is not addressed.

For energy system modelling, it is increasingly important to recognise that different sectors will have to cooperate more closely with each other. Additional aspects such as hydrogen and CCS must be included in the modelling of energy systems, since those technologies affect energy demand, energy supply, and emissions. The climate plan [85] identifies that access to renewable energy to allow for a circular economy and reduce emissions is important. However, energy system modelling has had little focus on achieving a circular economy. Collecting data is important for being able to represent the circular economy in energy system models, and this must be addressed.

Energy efficiency measures, like use of excess heat, require a connection between source and sink, which must be represented in the energy system models. Our results show that a more detailed analysis of waste heat reutilisation enables a correct assessment of its potential. Heat pumps play an important role in utilising this potential. Improved information about excess heat in the industry is needed. A common standard in the Nordic countries for reporting heat demand, excess heat and possibly material streams would help making future predictions more accurate and comparable between countries.

4.2. Swedish NECP

What the current NECP says: Sweden was obligated to present an integrated NECP to the European Commission by 31 December 2019, in accordance with the Governance Regulation [13]. The NECP summarises key targets for decarbonisation, energy efficiency and energy security. Regarding overall targets for energy efficiency and conservation, which are the focus of this WP, there is a target set by the Swedish Parliament for 50% improvement in energy efficiency by 2030 (with 2005 as the baseline for comparison) [92]. This target is also mentioned in the NECP. The target is expressed as primary energy supplied in relation to real GDP, and, therefore, does not have a fixed absolute level of primary energy consumption for the target to be achieved. According to the NECP, assuming the economy grows at a rate of 2% per year, the target in 2030 would translate to 461 TWh of primary energy consumption and 339 TWh of final energy consumption.

Within this WP3, research related to the Swedish national context has been conducted within the conceptual framework "Conservation and Efficiency of Energy and Materials" defined in Section 1.2, which considers both energy and materials over a life cycle and includes sectorial coupling.

The key concept in sector coupling is to think “multi-level energy systems”, where the investment in one sector can have cascading benefits to connected sectors. Its implementation on a large scale supports the circular economy, including resource efficiency [93]. Below, insights for the NECP are presented related to the opportunities for ECEM and towards resource efficiency presented by coupling industrial activities with excess heat generation to sectors with heat demand.

Conservation and efficiency in the buildings sector

What the NECP says: Regarding buildings, the NECP mentions a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings. This strategy was not finalised when the NECP was released and is therefore not included in the NECP, but the basis for the strategy can be found in a separate report by the Swedish National Board of Housing, Building and Planning and the Swedish Energy Agency [82]. It states that there is a large potential for increased energy efficiency in the existing building stock of Sweden, but that the renovation rate must increase to exploit this potential. An analysis is presented comparing energy declarations for multi-family buildings from 2008 and 2018, which shows an average improvement of specific energy use, and an estimation is made of 1.1 % improvement of energy efficiency yearly. Applying this rate of energy efficiency on all multi-family buildings with an energy declaration, the report shows that specific energy use could be halved from 2005 to 2056, implying that the current rate of energy efficiency is not enough to reach the target of 50% improved efficiency by 2030. In the same report, scenarios for increased energy efficiency by 2050 have been developed and compared, showing how energy efficiency can be almost doubled compared to today's improvement rate if every renovation opportunity is used and if all cost-effective energy efficiency measures are realised. The NECP concludes that further contributions are needed to bring about more ambitious renovations and increase energy efficiency. It suggests that the following financial policy instruments should be further investigated: rent allowance after renovation, tax-free maintenance funds and adaptations of the support for renovation.

Insights from this project: A study on roadmaps for zero and low energy carbon buildings found that roadmaps often suffer from the following deficiencies: (1) lack of specific, quantitative metrics on goals (2) lack of enforcement mechanisms to ensure goals are met, (3) lack of technical analysis for identifying pathways to meet the goals, and (4) weaker goals for building renovations [74]. We find that this is also applicable to the Swedish NECP. Also in agreement with the literature [52], [65], [73], [76], the NECP and renovation strategy state that current policies are not sufficient to realise the larger share of the renovation potential required in order to reach the energy efficiency target.

Whereas implementation of energy efficiency measures dictated solely by technical renovation needs leads to a very low energy demand, with some buildings becoming energy producers by 2050, implementation strictly driven by cost-efficiency (from the perspective of the property owners) only reduced the energy demand by 5% during this time and would not fully utilise the investment capacity of the property owners. Furthermore, the current limitations of reaction capacity for the market shares allowed for a reduction of the energy demand of only 15% during the same period. Workmanship capacity was more constraining than investment capacity and is thus identified as a local imperative need and suggests co-benefits related to job creation within the construction sector [60]. Although the literature shows high variability for the cost-efficiency of the ECMs between and within the national building stocks, the potential application of complete ECM packages generally appears to be more profitable than the application of individual ECMs [56].

Recommendations: Existing policy needs to be more ambitious and include enforcing mechanisms for energy efficiency in renovation could be part of the solution to the currently insufficient measures. Adding specific, quantitative metrics to the NECP to follow up on the progress could be another recommendation. This could also include adding monitoring processes to ensure that renovations are contributing to increased energy efficiency. A further recommendation is to ensure compliance of the NECP with the EU Energy Efficiency Directive. These requirements could be defined more specifically, so as to address the identified information gaps, thereby facilitating the implementation and monitoring of energy savings in existing buildings.

Energy efficiency and conservation in industry

What the NECP says: While there are general measures that aim to reduce GHG emissions in industry, such as the energy and carbon dioxide tax, the EU ETS and "Industriklivet"[4], there are also policies aimed specifically at improving energy efficiency and conservation. For example, large companies in Sweden are obligated to map their energy consumption and suggest ways to reduce it. The can apply for financial support to help this process. Moreover, there is a network for energy efficiency that small and medium enterprises (SME) can participate in to exchange knowledge and identify key success factors. Businesses can also apply for EU-level financial support directed towards investments that improve efficiency . However, as previously mentioned, no enforcement or monitoring mechanisms are tied to these instruments.

The NECP foresees an increased electricity demand from industry, although without using concrete figures in their prognosis. The increased demand for electricity is linked in the NECP to an increased risk of capacity shortage. However, there are no connections made between conserving energy in industry and reducing the risk of insufficient capacity. Meanwhile, demand flexibility is considered in the NECP to have an important role in a future energy system with a large share of variable production and high demand for electricity, but with no subsequent targets set within this dimension.

Insights from this project: As previously mentioned, the Swedish NECP suffers from a lack of specific targets, which is a common NECP pitfall [74]. Although modelling results from the Nordic Clean Energy Scenarios suggest a limited ability of Swedish industry to contribute to improved national energy efficiency, energy conservation could still be expected if demand for the products of Swedish heavy industry decreases (see scenario CNB in appendix A3.1.2). This could in turn be expected if material recycling is increased, which further points to the interlinkage of energy conservation and material conservation.

Recommendations: Addition of clearly defined targets for the industry, keeping track of both efficiency and conservation over the long term, with indicators that allow for monitoring of progress. Furthermore, consider adding mechanisms to enforce actions.

Material conservation and efficiency[5]

What the NECP says: The NECP mentions the establishment of the Sustainable Building Information Centre with a mission to "promote energy-efficient renovation and building, using sustainable materials while minimising the impact on the environment from a life-cycle point of view". While such an establishment can provide information to increase knowledge of sustainable buildings, the NECP lacks references to enforcement mechanisms to ensure a transition of the sector towards increased circularity.

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[4] Eng: The climate leap for Industry.

[5] As explained in Section 1.2, we follow an approach to efficiency in this WP3 that considers resources more generally and thus materials are included in the analysis in addition to energy.

Insights from this project: In the literature, policy instruments which can accelerate a circular transition of the Nordic construction sector have been suggested by actors representing sector stakeholders in Denmark, Norway, Finland and Sweden [71]. The main policy instruments suggested are supplementary requirements for documentation of the content and quality of the building materials and new requirements for (1) waste and building demolition plans and (2) documentation of the use of reused building products and building products containing recycled resources.

Recommendations: Addition of clearly defined targets for the use of materials, keeping track of both efficiency and conservation over the long term, with indicators that allow for monitoring of progress. A suggestion for the updated NECP is to consider implementing the policy instruments suggested in the literature, and to coordinate the implementation of such policy instruments for all Nordic countries to increase the possibility of a simultaneous circular transition and cooperation between the countries.

Sector-coupling – moving from sector-siloed considerations to lowering the national energy intensity.

What the NECP says: With the wider scope of WP3 of the Nordic Energy Outlook being energy efficiency AND conservation, it is of relevance to point out that in the present NECP, there is only one relevant indicator: the energy intensity per GDP. Specific measures are further discussed by sector, such as "industriklivet", promoting energy audit in industries and potential investment support in this sector, as well as new building codes, and refurbishment targets for the building sector. These are all sector-siloed policies and will *not capture the opportunities we have to significantly lower the Swedish Energy Intensity by coupling industrial activities with heat surplus to the building sector.*

Insights from this project: Conservation of resources, and transitioning to a circular economy is of importance for reaching the UN sustainable development goals and adhering to Agenda 2030, but also for keeping Swedish businesses and industrial activities competitive on a global market [94]. However, a circular economy is not only about closing the cycles of material flows, but also about conserving energy and making the most of end-use energy services from available natural resources. This is recognised, for example, by the EU's Strategy for Energy System Integration, where a circular energy system is described as one where no energy is wasted [95]. An important strategy to employ here is the concept of cascading, or simply put, for the energy context, using surplus energy from one activity or sector to supply demand in another activity or sector. This is what is called sector coupling.

Results from the Nordic Energy Outlook WP3 have shown, via previously published heat mapping combined with new, geospatial, and long-term system optimisation modelling, that Sweden holds an opportunity for cost-effectively integrating up to 10 TWh of heat into the district heating system, heat that is presently "wasted". This is based on current industrial activities.

Looking into the future, with emerging industrial initiatives, the opportunity is even larger. For example, we can expect some emerging technology trends to enter our national energy system at a large scale: green hydrogen production via electrolysis, and small modular reactors for nuclear power. Both concepts come with additional generation of excess heat.

To elaborate, Green Hydrogen is under rapid development, for example to support fossil-free steel production, like the HYBRIT process mentioned in the present NECP [96]. Hydrogen production comes from electrolysis where the electricity input for green hydrogen is of renewable origin [97] and with heat produced in the stack. Thus, there is a potential to recover this heat to provide heating and cooling to the building sector. Aside from being techno-economically feasible, the integration with energy utilities can provide additional benefits since the ultra-pure water needed for the electrolysis can be cogenerated in this integration. In a recent study, a combined hydrogen and heat set-up was showed to produce roughly 630 kW of hydrogen, and 300 kW of useful heat for a local heat network, for every MW of electricity provided to the electrolyser [98].

As a result of the 2022 Swedish election results, a new government has come in place consisting of the Moderate Party, the Christian Democrats, and the Liberal Party, and cooperating with the Swedish Democrats as set forth in the so-called 'Tidöavtalet' [99]. Related to climate and energy, these parties, in this agreement, push for new nuclear power-based infrastructure through, for example: government-based credit guarantees; changes in Swedish law that currently prohibits placement of nuclear reactors in places other than those presently used, and a speedy framework to allow for small modular reactor permits. If this development is realised, *cogeneration is the most resource efficient* way to do it – it links nicely to Sweden's well-developed district energy systems, and the coupling of electricity, heating and cooling sectors is logical. Indeed, SMR is listed as suitable for cogeneration in district heating by the IAEA [100]. Therefore, planning for the SMR and cogeneration in combination is warranted already from the start to effectively consider placement of generation capacity in this context and present a clear Environmental Impact Assessment.

Recommendations: Based on the findings from this work, the recommendation is for Sweden to promote the use of the unique and world-leading know-how the country has in DH and integration of HP technologies – from components, to planning, and delivering resilient and robust heating and cooling solutions for buildings – to facilitate sector-coupled planning and make use of industrial and urban excess heat as a resource for DH. To not plan for the use of the surplus heat from these emerging concepts already from the beginning would be a lost opportunity, in terms of sound economics as well as developing a robust national energy system that rests on the principles of circular economy.

The role of Nordic cooperation

Energy conservation and resource efficiency consist of local measures, for example for industrial activities and buildings. Therefore, at first sight, there may not be an obvious benefit from Nordic cooperation, as in the case of e.g. the electricity market [3]. Nevertheless, there are a few areas where Nordic cooperation could be highly beneficial.

Collaborative actions on demand-side-management and resource efficiency will facilitate this and should be an integral part of Nordic collaboration. For example, demand-side management, improving efficiency, and conserving resources at national levels could facilitate the collaboration on electricity, considering that:

- insulated buildings, for example, will be less affected by changes in temperature
- loads will be less aggregated to a specific time in the morning and evening
- heat pumps, compared to direct electric heating, will decrease peaks

Despite the potential economic, technical, and behavioural benefits of implementing flexibility measures, there are also recognised risks such as higher peaks and congestions in low price-hours. Other examples are difficulties in designing electricity tariffs because of conflicts with CO_2 intensity and potential instability in the entire electricity system caused by tariffs coupling to wholesale electricity pricing. In all cases, it seems that the current regulatory framework would need to change to facilitate participation [101].

5. Needs for more joint research and investigation

5.1. Long term modelling and optimisation of ECEM in the Nordic Energy System

Rationale:

Combined results and insights from the first three work packages in the overall Nordic Energy Outlooks programme on the one hand update the list of available resources (biomass, biogas, industrial and urban excess heat, and sources for decarbonisation of the electricity system), and on the other, here in WP3, provide new facts on the opportunity for efficiency in industry and buildings to manage the demand side. In addition, regarding the various countries' NECPs, results have identified the importance of collaboration on a Nordic electricity sector for a robust and secure electricity supply, as well as the importance of integrating the principles of a circular economy in the overall energy sector for economic and environmental benefits. Here, the work in WP3 has specifically shown the ability of efficiency measures in building and industry to manage peak demands and conserve resources as sectors are coupled in cost-optimal ways. However, the studies are still national, which means that the dynamics of a future integrated Nordic energy system (where electricity is the main carrier, but not the only one) are pending.

Expected outcome:

A collaborative long-term study (until 2050) is proposed, that would include all Nordic countries for optimising energy infrastructure investment over time and also from a spatial point of view. The expectation is that new knowledge can be generated regarding how synergies among the Nordic countries can be maximised as each national demand (in the specific national context) is managed: what should be the technology mix, where (in what country) and when should investment be done? What cost benefits can be achieved by collaborating in the decarbonisation of the electricity system, and what trade-offs would be the most important to manage? What specific policies, e.g. around demand-side-management through efficiency, would need to be harmonised between countries for such a collaboration to thrive?

Scope:

For Denmark, Finland, Norway and Sweden, a connectedness in the electricity supply and demand is modelled using a long-term optimisation model such as OSeMOSYS, previously described in Section 2.3. Demand profiles and their expected development until 2050 are taken per country depending on the national context (industrial activities, population, etc), but the investment for a decarbonised electricity supply by 2050 is taken in the Nordic context, examining "in what", when and where to invest from a cost-optimal point of view. The starting point for the work is all the new insights developed on resources and demand from the four Nordic Energy Outlook WPs in combination, anticipating that WP4 about to start in early 2023 will come with important information related the transportation sector.

5.2. Sector-coupling Industry with Excess Heat to Buildings with Heating and Cooling Demand – the Nordic Potential

Rationale:

Conservation of resources is necessary for managing the carbon footprint of the energy sector and reaching the UN sustainable development goals. In EU's Strategy for Energy System Integration, a circular energy system is described as one where no energy is wasted. Results from the present study in WP3 have shown how making use of excess heat from industrial activities, as well as urban sources like computer server rooms, ice rinks, and more is already cost-effective today. This work was based on Sweden.

With important and emerging trends in society, like electrifying the heating and cooling sector using heat pumps, and setting up large scale production of hydrogen which results in much surplus heat, we now have an opportunity to start valuing excess heat as a resource, and applying sector-coupled planning and investment to make use of this resource excess in the building stock across the Nordic countries.

Expected outcome:

While the work generates knowledge on the cost-optimal integration of excess heat per country, the primary objective of the study is to use these national potentials to formulate best-practices on supporting policies and conditions, and define applications with the highest opportunities for successful integration of excess heat in district energy systems. Results per country are assessed in relation to the policy landscape, with a special focused work package addressing policies that support the use of excess heat as a resource, while also supporting integration of new renewable energy capacity. This means that conflicting trade-offs between excess heat and new renewable capacity are minimised and that the two options can co-develop and support each other.

Scope:

In this work, all Nordic countries explore their national opportunity for using industrial, as well as urban, excess heat as part of the heat supply to a district energy network.

5.3. The integration of techno-economic and socio-technical approaches in the energy system modelling: The case of energy efficiency gap in the Nordic region

Rationale:

As demonstrated in this project and supported by the literature, the energy renovation rates in the buildings sector can have a significant effect on the adoption of different energy efficiency and conservation measures, even when they are cost-effective. This can lead to underutilisation of the energy savings potential that is perceived economically and environmentally advantageous. This is often referred to as energy efficiency gap, which can stem from behavioural factors that are often omitted or included with a narrow interpretation in energy system modelling.

Expected outcome:

Key factors contributing to and consequences of the energy-efficiency gap are identified in the Nordic context. A novel method of including behavioural factors related to the adoption of energy efficiency and conservation measures in the energy system modelling is proposed. The improved method for including behavioural factors can eventually lead to a more accurate representation of energy savings potential that can be achieved by adopting energy efficiency and conservation measures in the Nordic region. In addition, a better understanding of the key behavioural factors and their consequences can be essential for policy purposes to design policy measures targeted at mitigating the causes of energy efficiency gap.

Scope:

The research should include interdisciplinary work between social scientists and energy system modellers: (i) to identify factors and parameters that can contribute to the successful implementation of energy efficiency and conservation measures; (ii) to formulate a framework to account for these socio-technical factors in energy system modelling. Sectoral scope can be defined based on the perceived magnitude of the energy efficiency gap in different sectors as identified in the literature.

5.4. Model Agnostic Evaluation: Data Sets and KPIs for the Nordic countries

In addition to ensuring transparent and accurate data sets, a common quality assurance framework could be investigated. Sensitivity analysis demonstrates how uncertainty of the input propagates to variations in the model output. It is an important meta-analysis tool that will highlight the robustness and differences between Nordic energy system models.

Common KPIs regarding energy and material efficiency for different sectors enables comparison of efficiency changes over time between different models and scenarios.

Models can now rapidly generate many scenarios and address complex sets of indicators, such as technology choices, primary and final energy use, costs, and emission levels. Nevertheless, selecting among all these options is far from straightforward, and recent research in the field has emphasised the need to pursue such selections in a more systematic and policy-relevant manner that is typically done today. The knowledge generated from energy system models can support climate policy decision-making processes, for example, when introducing or revising specific policy instruments. At the same time, though, there are significant challenges associated with which results (KPIs) to devote attention to.

Moreover, to avoid confusion in interpretation of the KPIs, a clear description of KPIs need to be documented and provided to the model users (e.g., policy makers, academia, decision-makers, etc.).

5.5. Training courses - open access tools and models

Nowadays, many useful energy system models and tools are developed as open access by universities and the research institutions in the Nordic countries. In order to introduce and use them in the research projects, it will be important to transfer existing knowledge about them within the

Nordic region, through holding training courses, workshops or webinars. This will open opportunities for further development of the models and tools as well as their application to other different cases (at the national or sub-national level).

6. Concluding remarks

6.1. Summary

The work carried out in WP3 of Nordic Energy Outlooks consists of many different parts, including several literature reviews, assessments of existing models, improved modelling of energy efficiency measures, model linking between general models and sector-specific models, as well as analyses of the cost-efficiency of energy saving measures in energy system scenarios.

The reviews and assessment of previous work focus on:

1) How are energy conservation and material efficiency represented in energy system models (general and sector-specific) in the Nordic countries?
2) What are the theoretical potential and costs of better energy conservation and material efficiency in the buildings sector?
3) What are the drivers, barriers, motivations, risks, and uncertainties for the realisation of energy efficiency measures in the buildings sector?

The improvements in modelling and data related to energy efficiency includes:

4) IFE-TIMES-Norway model: Energy efficiency has been included as an integrated part of the optimisation (endogenously) instead of only being scenario-dependent (exogenously).
5) GENeSYS-MOD: The number of different industrial heat products was increased, and a separate representation of waste heat was added. In addition, new heat technology, notably heat pumps, and corresponding efficiencies, costs and processes have been added – thereby utilising the new heat levels represented in the model.

The following linking between general energy system models and sector-based models has been carried out:

6) Two sector-based tools for buildings, PROFet and RE-BUILDS, have been used to provide new input data from the residential sector to GENeSYS-Mod.
7) Soft-linking of fully open-source geospatial tool for cost optimisation of excess heat integration to OSeMOSYS (long-term energy optimisation model) and hourly unit-dispatch model using EnergyPLAN.

The cost-efficiency of energy saving measures in energy-system scenarios has been assessed by:

8) Comparing existing energy system scenarios in the ON-TIMES model,

whereas new simulations accounting for the updated modelling and data have been carried out with:

9) IFE-TIMES-Norway
10) GENeSYS-MOD
11) OSeMOSYS model

6.2. Main findings

Cross-sectorial

1) The cost-effective utilisation of energy efficiency measures is estimated to be between 30 and 40 TWh for Norway.
2) If additional energy and material efficiency measures are taken in all sectors in the Nordic area, on top of existing plans, this will lead to a 17% reduction in final energy demand. Power demand is reduced by 5%, whereas energy system costs are reduced by 10% (when not considering the cost of the extra energy efficiency measures).
3) Utilisation of an additional 10 TWh of excess heat from industrial and urban activities can cost-effectively reduce the Swedish energy intensity by 2% until 2030.
4) ECEMs result in clear positive synergies with various SDGs, e.g. in terms energy security, clean air, health impacts, job creation and climate mitigation.
5) Although the literature is clear that only a comprehensive uptake of ECEM can transform the energy system in line with environmental, economic, and social targets, our review does not find examples of studies for the Nordic countries in which the uptake of ECEM measures is at the transformative levels suggested in global studies. Instead, the energy system studies with a focus on the Nordic area rely on a decarbonisation of the energy production and increased network flexibility and connections, for which the feasibility is only assumed, and therefore deserves further study.

Buildings

6) The potential for energy efficiency measures is significant for buildings for a wide range of measures for energy saving and flexibility. For Norway, it is estimated to between 27 and 30 TWh.
7) Some of the investments are cost-effective only when applying a social discount rate. If a higher private discount rate is applied, investments are reduced especially for single-family residential buildings.
8) The potential for efficiency measures to increase material efficiency is high. Barriers include product lifecycles, technical challenges for material recovery, and lack of a clear vision in industry.
9) A majority of the ECEM potentials in the buildings sector are related to the energy renovation of existing buildings, implying a potential focus area for incentives.
10) The time distribution of implementing ECEMs affects the cumulative emissions of the building stock over the long-term and would lead to substantially higher emission reductions if retrofitting actions are implemented in the near term. Absolute GHG emissions reduction potential in the buildings sector strongly depends on the development of the used energy carriers' emission intensity factors (e.g., for electricity, district heat).

Industry

11) Investments in heat pump technology for the industrial sector is cost-effective for some temperature levels, but results are sensitive to the waste heat availability assumptions which highlights the importance of accurate estimation of waste heat potential for different regions.
12) For Sweden, at least an additional 10 TWh of excess heat can cost-optimally be used to satisfy the heating demand in the network, which is considerably higher than previous estimates. Also, 10 TWh of primary fuel saved (e.g., biomass at approximately 200 M EURO)

that can be used for something else is worth pursuing in terms of circular economy and sustainable development.

Data and model improvements

13) The reviewed sectorial models provide valuable insights. The reviewed energy system models of the Nordic countries have a simplified representation of ECEM, which could be relatively easily improved based on existing knowledge from bottom up and sectorial models. The GAINS model provides additional knowledge on key themes (health impacts and their economic evaluation) for which the integration in energy system models is not apparently straightforward.
14) No scenarios were found that include all Nordic countries and focus specifically on ECEM in the buildings and industry sectors, in circularity or on material conservation and efficiency. These are key areas that require further study.
15) There is a need to better understand the opportunities, risks, synergies and trade-offs within each modelled scenario if energy system modelling results are to be used as a basis for decision-making. This can be achieved by using both various KPIs that reflect the implications of the scenarios in the focus issues for which they have been developed, as well as by linking modelling results to other visualisation tools.
16) On the fully open-source energy analysis tools, soft-linking the EMB3RS geo-spatial optimisation tool, to the long-term planning tool OSeMOSYS has been implemented for the case of excess heat integration in district heating. The results are verified for operational functionality with the unit-dispatch model EnergyPLAN.
17) For the GENeSYS-model
    - Residential heat demand input data used for Norway in the past should be updated with new values from this project.
    - The improved representation of the industrial sector leads to more accurate results and allows to draw a more precise estimation of the use of fossil fuels before their phaseout.
18) If new developments for potential new industries should be modelled, such as data centres, battery manufacturing, and hydrogen production, a market equilibrium model will be required to project the future growth of these industries in the global context as input to GENeSYS-MOD.

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Appendix

A1 Model descriptions

A1.1 ON-TIMES

Introduction to ON-TIMES

The ON-TIMES (Open Nordic - TIMES) model includes the five Nordic countries in detail (Denmark two regions, Sweden four regions, Norway two regions, Finland two regions, Iceland one region), whereas the surrounding countries are represented by trade-links and price profiles for traded commodities. Sectors represented in the model are upstream/ fuel production, power and heat, heavy industry, residential, transport and other (i.e., manufacturing industries, services and agriculture). The model has a time horizon between 2015 and 2050, in 5-year time steps. Each model year is divided into 32-time slices. ON-TIMES can be soft-linked to the BALMOREL model, which analyses dispatch and operation focusing on the electricity system. The BALMOREL model covers power systems in 18 European countries, including Denmark, Finland, Norway and Sweden [102]. The main model inputs to ON-TIMES are techno-economic data of existing energy conversion technologies, current and future resource and LULUCF potential, fuels prices and (if relevant) the associated CO_2 emissions, demands projections for different energy services, techno-economic data of new conversion technologies, which are used as investment options, and model constraints, e.g., CO_2 emissions cap. The entire ON-TIMES energy system model is available on GitHub – Nordic Energy Research NCES [103]. It contains all sector-level technology data and all demand projections with the associated references. The current version of the model contains three main scenarios designed to meet the carbon neutrality target by balancing carbon emissions and sinks in the Nordic countries as below (for more detail description of the scenarios please see Appendix A3):

- Carbon Neutral Nordic (CNN) seeks the least-cost pathway, considering current national plans, strategies, and targets. This scenario is used as base scenario in this report.
- Nordic Powerhouse (NPH) explores the opportunity for the Nordics to play a more prominent role in the broader European energy transition by providing clean electricity, clean fuels, and carbon storage.
- Climate Neutral Behaviour (CNB) reflects Nordic societies adopting additional energy and material efficiency measures in all sectors, ultimately leading to lower demand for both.

For each scenario and model year, the primary model outputs are installed capacities of energy conversion technologies, fuel use, production per conversion technologies and marginal energy and CO_2 prices. The model also generates results for primary energy supply by energy source, CO_2 emissions, investment capacities, carbon capture level, final energy consumption by energy source, final energy consumption by sector.

Building sector in ON-TIMES

The building sector is represented in ON-TIMES by exogenously giving current demand area for single-family and multifamily buildings, divided (based on heat supply technology) into individual, decentralised, and centralised buildings, in total in six main groups. Buildings not connected to district heating (DH) are assumed to have an individual heating system; buildings connected to DH are divided into centralised and decentralised based on connection to a corresponding DH system[6]. The existing technologies (heat devices) in the buildings with individual heating systems are boilers (fuelled by oil, natural gas, biomass or electricity), heat pumps and solar thermal collectors. During the model time horizon there are new investment options for the existing buildings such as heat-saving measures, new heat devices and connection to the DH systems. Simultaneously, some existing buildings are demolished and replaced with new and more efficient buildings. For the buildings, electricity demand for appliances is also included in the model per number of appliances for current and future single-family and multifamily buildings.

Figure A- 1 shows schematic representation of the buildings sector with regards to heat demand for the case of Sweden in the ON-TIMES model. Buildings' area demand has been represented in the same way for Denmark and Norway, but buildings' construction year may differ from the ones in Sweden. **Figure A- 1** also illustrates that:

- all the buildings constructed before 2012 have the possibility for making energy saving measures corresponding to different cost levels.
- all the buildings have the possibility to invest in individual heat devices (e.g., heat pumps, boilers, etc.) if it is cost-effective from a system perspective.
- not all the buildings have the possibility to invest in a connection to district heating (i.e., a district heating substation)

The area demand projection for buildings (in Mm^2) for the case of Sweden, for instance, follows the methodology outlined in the Swedish Energy Agency (SEA) report [104]. From 2020, for the new buildings, the shares of single-family houses and apartments are assumed to be 42% and 58 %, respectively. For 2020-2025, the demand projection for new buildings is based on the forecast from the National Board of Housing, Building and Planning (Boverket) [105]. From 2026 on, the projection has been calculated by extracting population forecast from Statistics Sweden (SCB) [106]. Then, it is assumed that the average number of people per household remains unchanged while single-family houses and apartments have an area of 149 m^2 and 65 m^2, respectively.

[6] Centralised DH systems are assumed to have annual heat deliveries of more than 400 GWh, decentralised otherwise.

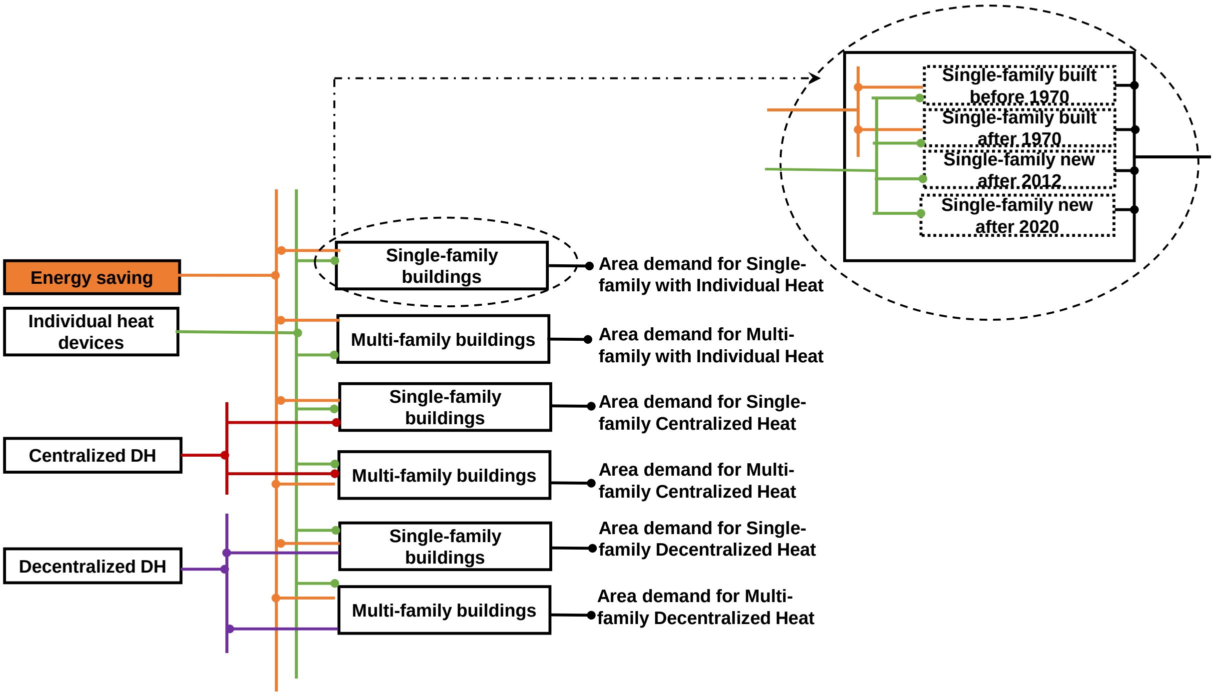


Figure A- 1 Schematic representation of heat demand and energy saving measures in the buildings sector (the case of Sweden) in ON-TIMES

Energy demand in new buildings is based on regulations from Boverket, in which the buildings were constructed before 2020 are based on "BBR22 from 1 July 2015" standards [107], whereas the ones built after 2020 are based on "Near zero energy buildings" standards [108].

Representation of appliances demand (per number of appliances for single-family and multi-family buildings) is shown in Figure A- 2.

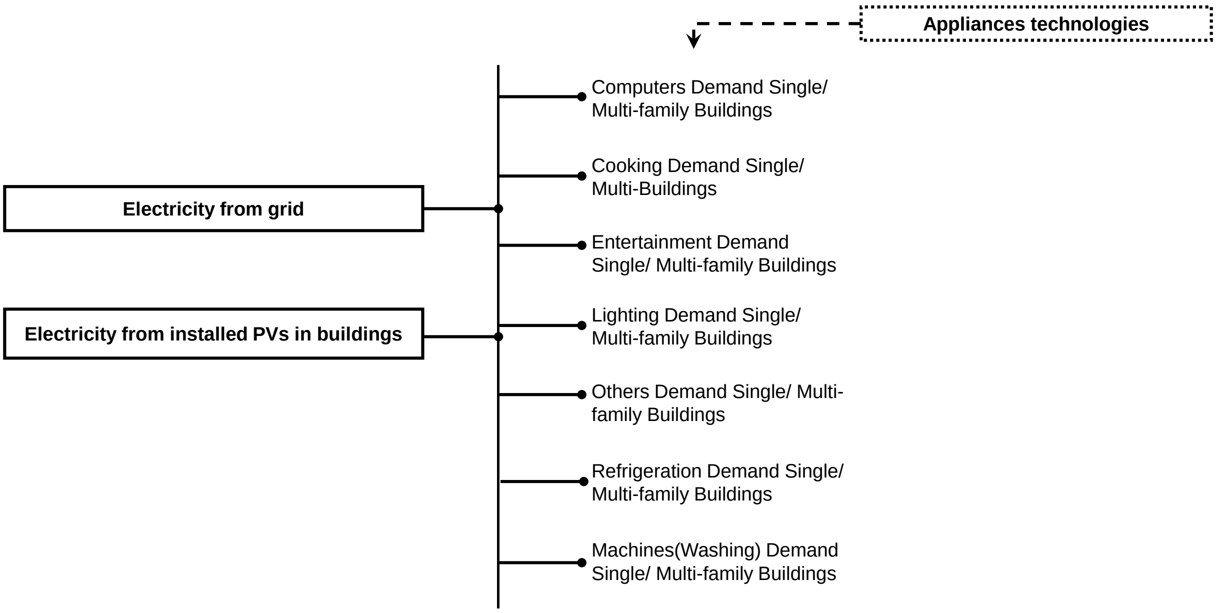


Figure A- 2 Schematic representation of the buildings sector for appliances demand in ON-TIMES.

Heavy industry in ON-TIMES

In the ON-TIMES model, industries are divided into Heavy industry (Pulp and paper, Mining, Iron and steel, Aluminium, Cement) and Manufacturing industries (Food, Chemical, Machinery, Wood products). Industries dealing with fuel production (Exploration/mining of fossil energy, Fossil and renewable refineries, PtX) is represented in the category Upstream/fuel production.

The energy demand in the industrial sector is represented by annual electricity demand and several conversion technologies that currently fulfil the sector's heat demand. There are different types of heat pumps, centralised and decentralised district heating, and heat-only boilers represented in detail. Fuel input to the heat-only boilers includes natural gas, coal, diesel, biogas, heavy oil, LPG, waste, and electricity. In addition, current diesel-fuelled tractors, trucks, fishing boats, forestry machines, LPG-fuelled forklifts, electric light appliances, and motors are also considered. Like for the buildings sector, the existing technologies are gradually replaced with new technologies (due to either reaching their lifetime or constraints on CO_2 emissions) given as new investment options in the model. These investments include hydrogen-based technologies in the iron and steel industry, woodchips boilers, heat pumps with waste heat recovery, electric boilers, mechanical vapor recompression, booster heat pumps, infrared heating, oil, gas and coal boilers, solar, centralised, and decentralised district heating. See Figure A- 3 for a schematic representation of the industry sector in the ON-TIMES model.

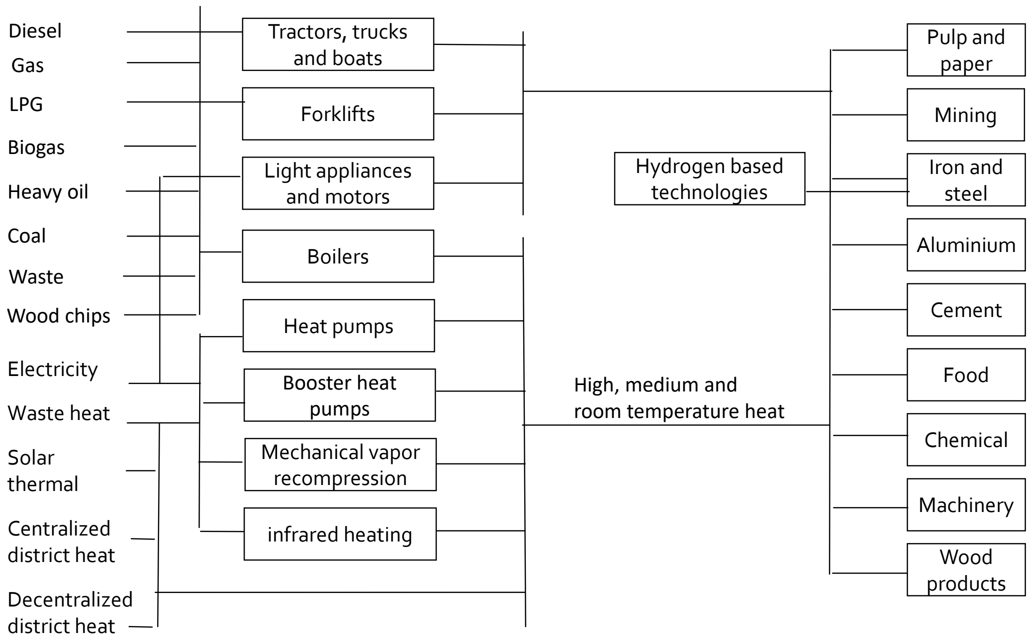


Figure A- 3 Schematic representation of the industry sector (the case of Sweden, Denmark and Norway) in ON-TIMES.

In terms of technology options in the industry sector, the technology catalogue from the NCES project [109] analysed levelised cost of heat (LCOH) for direct and indirect heating at space heating temperature levels, at medium temperature (MT) levels below 150 °C and at high temperature (HT) levels above 150 °C. It was found that heat pumps offered a low-cost and high-efficiency option for space heating and low-temperature process heating. Both conventional and absorption-based heat pumps could moreover be used, although to a limited extent, in MT heating applications: up to 22% of the service demand depending on sector: among them the cement industry, aluminium industry and pulp and paper industry. Meanwhile, mechanical vapor recompression technology (MVR) instead showed an even greater potential: 31-41% of service demand in food and beverage production, in the chemical industry and in the cement and concrete industry. The deployment of these technologies offers the potential to reduce the use of input energy thanks to their higher conversion efficiency. The LCOH analysis of HT services showed that electric boilers would result in high costs for the generated heat because of high electricity prices and that electrification is therefore not expected to be the main pathway to decarbonise HT heating processes. Instead, HT processes might instead rely on conventional boilers and direct-fired furnaces. Compared to conventional boilers and direct-fired furnaces, electrical boilers proved more efficient but also more expensive and were thus not favoured by the model.

A1.2 IFE-TIMES-Norway

The IFE-TIMES-Norway model [6] is a linear programming model to analyse the long-term development of the Norwegian energy system, which is generated by TIMES (The Integrated MARKAL-EFOM System) modelling framework [110]. TIMES is a bottom-up modelling framework, providing a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand from a social welfare perspective. The TIMES model minimises the total discounted cost of an energy system to meet the demand of energy services for the regions over the period analysed. The total energy system costs include investments in both supply and demand technologies, operation and maintenance costs, and income from electricity export and cost of electricity import from European countries.

Spatially, the model covers the five geographical regions in Norway, representing the current bidding areas. The model provides strategic investment (long-term) and operational (short-term) decisions for model periods starting from 2018, until 2050. Each model period is divided into 96 sub-annual time slices, where four seasons are represented by 24 chronological hours.

The IFE-TIMES-Norway model has detailed description of end-use energy, with demand for energy services divided into several end-use categories within industry, buildings, and transport sectors. The demand can be met by both existing and new technologies using energy carriers such as electricity, district heating, bioenergy, hydrogen, and fossil fuels. Consequently, the use of energy carriers is a model output and not a model input, hence making the sector coupling a part of the optimisation problem. Other input data include fuel and CO_2 emission prices, exogenous electricity prices in regions outside Norway[7], renewable energy resources, and technology characteristics such as capital and operational expenditures, efficiencies, technical lifetime, and learning curves.

Existing transmission capacity, both within Norway and to neighbouring regions, is modelled exogenously and is based on the current transmission capacities (TC) and ongoing capacity expansion. The model allows new investment to TC, both on existing and new connections. First year of investment is fixed to 2030 due to the long lead time of new transmission line projects. The electricity spot prices in the bidding areas in Norway are endogenous, as those are the dual values of the electricity balance equation, while the electricity prices in the European countries with TC to Norway are exogenous. The IFE-TIMES-Norway model has been soft linked to various European power system models, such as the EMPIRE model [111], to capture the characteristics of the European power market under different future pathway scenarios.

[7] Countries with transmission line capacities to/from Norway include Denmark, Sweden, Finland, United Kingdom, Netherlands, and Germany.

In terms of renewable energy sources, the model differentiates between run-of-river and reservoir hydropower plants, onshore and offshore wind power, as well as building-applied photovoltaics (PV) on commercial and residential buildings. For new investments, several technology options are available with different costs, operational conditions, and technical potentials for each bidding area.

A1.3 GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) is an open-source, linear energy system model, minimising total system cost, including the different energy sectors transportation, electricity, and heat [112]. Through an optimisation procedure to minimise costs, the model outputs scenario pathway results for how the energy system could evolve to meet predefined demand and emission targets. Results from the model for four different European decarbonisation scenarios are openly available through the open Platform of the H2020 project openENTRANCE [113]. openENTRANCE investigates different pathways for the transition to a reduced-emission and low-carbon future. The GHG emission budgets for Europe needed for the 1.5°C and 2°C goals are results obtained from MESSAGE-Globium [114]. Data from the SET-Nav project is used as input to the demand projections for the scenarios. The quantitative scenario descriptions and simulation results are available in the openENTRANCE scenario explorer (https://data.ece.iiasa.ac.at/openentrance/#/login) and provide important information for companies and decision makers to support them in making more informed choices and investments on the way to reaching a climate neutral Europe in 2050.

GENeSYS-MOD is based on the Open-Source Energy Modelling System (OSeMOSYS) [115] framework. Energy demands for transport, final electricity and heat are exogenously defined over the modelled timeframe, e.g. for each five-year timesteps from today to 2050. The details of the current energy system (2018) provide the starting point to the model, together with resource potentials, emission intensities and costs associated with the different fuels and technologies. GENeSYS-MOD finds the cost-efficient way to satisfy the provided energy demand over the years, respecting a set of constraints. In openENTRANCE, GENeSYS-MOD has been linked to various open source and proprietary models, among others the power-market simulator EMPS [116]. The current version of the openly available European dataset is developed within the openENTRANCE project and contains 4 different scenarios through which Europe can reach a decarbonised energy system in 2050, see [113] for details.

Initiated with a central European focus, the Nordic hydropower production has not been the focus of GENeSYS-MOD and its description is more simplified there than in the sector-specific models like EMPS. Despite this limitation, transmission and generation of electric power are included in the model and the endogenous investment in infrastructure will be adapted to the emission reduction targets and the electrification associated. In GENeSYS-MOD, the demand for heating and transport can be covered by different energy sources, and model will calculate the optimal combination of sources and infrastructures. Hydropower from reservoirs is modelled in a simplified manner, not accounting for the inflows, restrictions on water levels or reservoir size, cascaded systems etc..

Industrial Sector in GENeSYS-MOD

The industrial sector in GENeSYS-MOD is modelled in form of regionally and temporally aggregated energy demands. Industrial demand is modelled as power, low-temperature heat (<100˚C), medium-temperature heat (100˚C - 1000˚C), and high-temperature heat demand (>1000˚C).

To meet the demands of decarbonisation and utilise existing waste heat streams high temperature heat pumps (HTHP) are recommended. HTHPs can cut down on the use of fossil fuels in boilers and improve the energy efficiency. Heat pumps utilise electricity and heat at a lower temperature level to produce heat at a higher temperature level. For efficiency reasons, the difference between these respective temperature levels of the input heat and output heat cannot be too large.

The focus of this study lies on incorporating high-temperature heat pumps for industrial waste heat utilisation in the Norwegian industry sector. Other efficiency measures such as power-to-heat applications and hydrogen as feedstock as well as the implications for the Nordic energy system are investigated.

As industrial heat demand is heavily aggregated over a broad temperature spectrum, the first step is to disaggregate the heat demand. Then the relevant data for the efficiency measures need to be gathered, that includes the current conversion efficiency and realistic projections until 2050.

A1.4 ECCABS

The building-stock model ECCABS [60], [117], was initially created to investigate potential reductions of energy use in Swedish residential buildings [118] and has since been further developed to map effects (in terms of energy demand, final energy consumption and corresponding CO_2 emissions) and costs of transforming the building sector through different actions (changes in consumption patterns, energy efficiency, installation of renewable energy), as well as to include the non-residential buildings. The model has been used to assess the transformation of Swedish residential [60] and non-residential [119] buildings (including urban applications [120], [121]), as well as that of several European countries [56].

Figure A- 4 shows the model structure. Input data includes physical building data (e.g., heated floor area, window area, heat loss coefficients, ventilation); climate data (outdoor temperature and solar radiation); existing energy system data; and further details to decide on scenarios and energy saving measures (ESMs) (e.g., constraints on costs, human labour).

In the simulation module, the energy performance of the building stock is calculated together with the potential energy savings, associated CO_2 emissions and costs. The module takes into account the thermal mass of the building at each time step (one-hour resolution) and extends the results to the building stock modelled (e.g. a building portfolio, city, region or country depending on the implementation). In the optimisation module, selected ESMs are implemented over a timeline following various technical and economical reasoning. The output from optimisation includes demands by end-uses and demands by fuels.

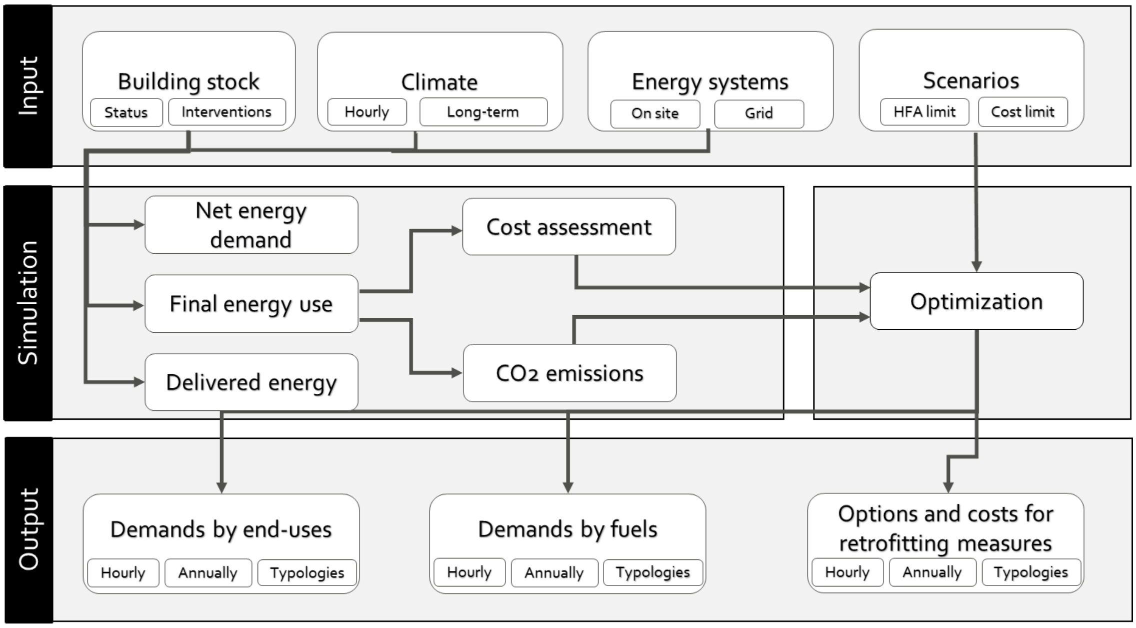


Figure A- 4 Structure and workflow of ECCABS Model [60].

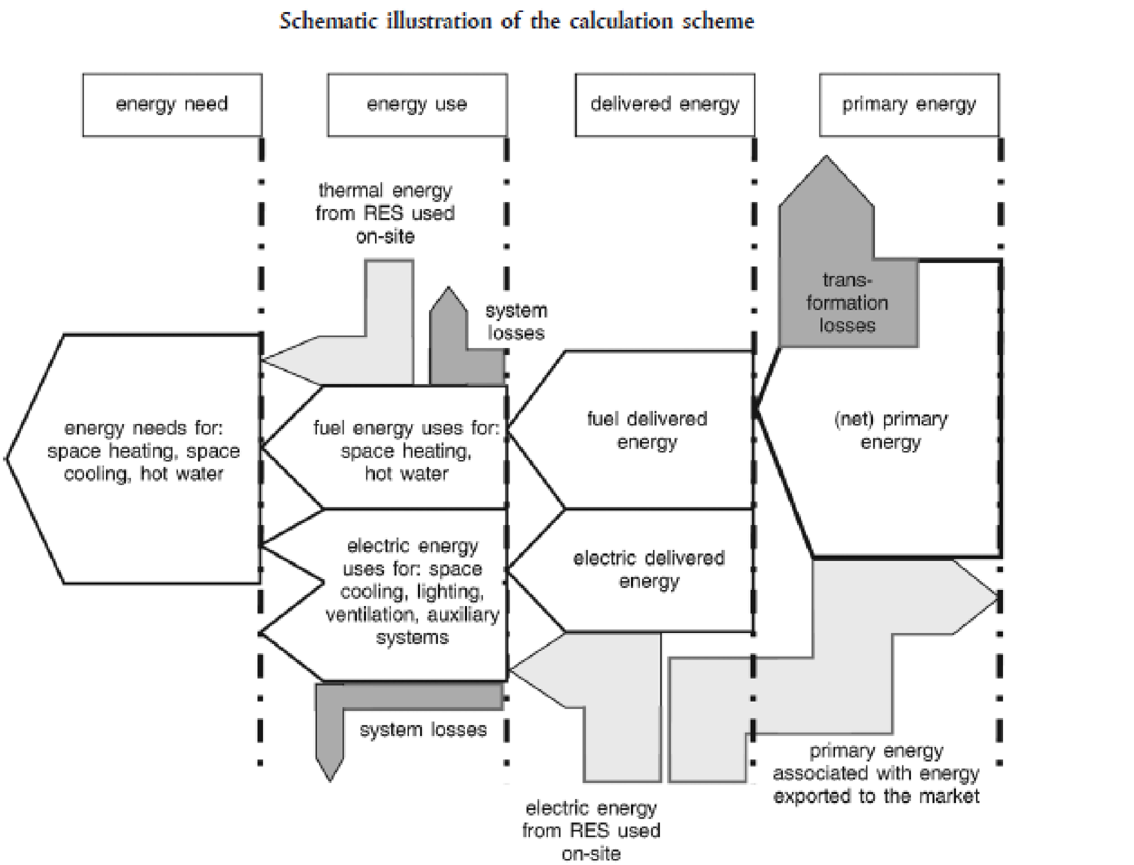


Figure A- 5 Schematic illustration of the calculation scheme used in ECCABS Model.

The model follows the calculation scheme suggested in the Energy Performance of Buildings Directive (Figure A- 5). The representation of electrification in ECCABS includes:

- At the energy need level, demands for hot water, and space heating and cooling are calculated.

- At the energy use level, the model calculates fuel uses for hot water, and space heating and cooling; electric uses for space cooling, lighting, ventilation, auxiliary systems; and thermal energy from RES used onsite.
- At the delivered energy[8] level, the model calculates fuel delivered energy, electric delivered energy, and electric energy from RES used on-site, e.g. PV panels.

As the modelling approach is dynamic and detailed, it allows to investigate DSM and other smart energy solutions, which are key for electrification of the buildings sector. Thus, the modelling approach enables input of hourly patterns, the same resolution as real-time pricing, of heat gains (occupants, lighting and appliances), and accounts for the thermal inertia of the building, while also allowing calculation of the indoor temperature.

A1.5 GAINS

In the 1990's, IIASA developed the RAINS model (Regional Air Pollution Information and Simulation) to study cost-efficient strategies to control air pollution in Europe, which was later extended to include greenhouse gases in the GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) model [122]. The current model contains an emission to air and abatement cost database, which is used to estimate environmental and health impacts and explores cost-effective emission control strategies. These strategies aim to simultaneously improve local air quality and reduce climate gases emissions, and at the same time maximises economic and environmental benefits. The model offers three ways of assessment:

Simulation of the costs, health and ecosystems benefits of user-defined packages of emission control measures,

Cost-effectiveness analysis to identify least-cost packages of measures that achieve user-defined policy targets; and

Cost-benefit assessments that maximise net benefits of policy interventions.

The model allows users to explore emission mitigation strategies by modifying activity levels, emission factors, as well as the reduction efficiency and application rates of emission control technologies. The emission abatement costs are assessed either through treatment- or new technology, or by exchange of materials, fuel, or methods. If run in optimisation mode, the model specifies cost-efficient mitigation strategies for each country that enable it to meet policy targets.

The emission projections are based on basically two different control scenarios:

• CLE - Current legislation. This scenario incorporates full implementation of national legislations as of 2013, including known implementation failures.

• MTFR - Maximum technically feasible reductions. This scenario incorporates all currently available control technologies and is subject to site-specific application limits. It disregards all kinds of implementation barriers, costs and institutional issues.

GAINS covers emissions of ten air pollutants as well as six climate gases. The model simultaneously addresses health and ecosystem impacts of particulate pollution, acidification, eutrophication, and tropospheric ozone, as well as consider greenhouse gas emission rates and the associated value per

[8] *Delivered energy* is otherwise referred to in this report as *final energy* in this report.

ton of CO_2 equivalence. Historic emissions of air pollutants and climate gases are estimated for each country and assess emissions on a medium-term time horizon, emission projections are specified in five-year intervals through the year 2030. The model is applied to conduct integrated assessment model analysis in support of the Gothenburg Protocol. IVL has jointly with IIASA developed a Nordic version of GAINS.

A1.6 PROFet

PROFet is described as the following in [8], [9]: PROFet is an aggregated load profile generator which can predict hourly load profiles for both thermal loads and electric loads, based solely on outdoor temperatures and building area. Identifying the energy efficiency level is based on the building temperature dependency, i.e. the typical energy signature curves (ESC), which has been extracted from trEASURE, a database of monitored buildings mostly connected to district heating [41]. After the identification of efficiency level, PROFet uses fixed-effects panel regression analysis[49] to provide representative load profiles within each category, in Wh/h per m^2 [42]. The load profile considers the outdoor temperature, the hour of the day, the type of day (weekday vs. weekend), and the season. As the representative load profiles indirectly account for the coincidence factor1, the aggregated load profile for an area is simply found by multiplying it with the building area in m^2 [38]. PROFet estimates the typical load profile of an area based solely on building area input (for 11 building categories and 3 energy efficiency levels as described in the categorisation) and outdoor temperatures.

A.1.7 OSeMOSYS

OSeMOSYS is an open-source energy system model that can be used for the optimisation of long-term energy system investments and operation. OSeMOSYS was primarily designed to fill an existing gap in the analytical tools available to energy researchers and energy planners in developing nations. OSeMOSYS has been developed over the years with the addition of various functionalities, both general and application-specific making it a full-fledged energy system optimisation tool. OSeMOSYS was the first energy system optimisation modelling framework where the solver, code and solving environment were all open-sourcee. The source code of OSeMOSYS is available in several different languages, GNU mathprog, GAMS, Pyomo package in python, and PULP package in python.

OSeMOSYS has been structured in a way that is easy to understand and modify. It has been developed as a series of operational blocks. In the OSeMOSYS framework, a model is built by connecting these different blocks using the input data. Each block is further divided into different levels of detail. The different blocks of detail in OSeMOSYS are costs, storage, capacity adequacy, energy balance, constraints and emissions. OSeMOSYS is formulated as a linear optimisation problem to reduce the total investment and operate costs in a region [19]. OSeMOSYS also has a very large community of users which is a major advantage for the tool. The large community of users helps in the comprehensive development of the tool for various applications.

OSeMOSYS is an open-source tool and has been proven to be flexible and easy to link with other tools, and provides a platform to conduct a long term analysis of the development of an energy system. It has been previously used to model both the heating sector and scenarios from the decarbonisation of industries. The tool has a low spatial resolution. While it is possible to represent trade and energy flow between different regions in OSeMOSYS, the spatial energy flow cannot be mapped. This presents a huge challenge in modelling district heating systems where the spatial mapping of the network is crucial in optimal energy investment and planning. Though the spatial aspects of the energy system cannot be represented using it, the tool has been linked to various GIS-based spatial models to account for the lack of spatial resolution. While it is possible to build models with very high temporal resolution in OSeMOSYS, the required computational effort increases significantly and thus leading to very long simulation times. Thus, it needs to be supplemented with a geo spatial tool and a dispatch modelling tool.

A.1.8 EnergyPlan – Dispatch Modelling tool

EnergyPlan is a deterministic tool that optimises an energy system based on a set of inputs given by the user. This tool was developed in 1999 and has since been used to model national or regional energy systems including electricity, heating, transportation and industrial sectors. Similar to other energy system optimisation models, the inputs in the model are demands, renewable energy sources, and capacities of different energy generation technologies, costs and different policy and regulating measures as inputs. The source code of EnergyPlan has to be programmed in Delphi Pascal [33]. The model can be used for three different types of analysis which are listed below:

- Techno-economic analysis: This analysis consists of the optimisation of an energy system and provides an optimal investment mix and dispatch of the different energy generating technologies.
- Market exchange analysis: The market economic simulation strategy in EnergyPlan is based on a short-term marginal price market model which focuses solely on bids to the market while minimising short-term consumer costs. Price elasticity can also be modelled in such an analysis.
- Feasibility studies: The model calculates the feasibility of the different investments in the system by optimising the total annual cost of the system. The model also determines the socio-economic consequences of the system in this case.

EnergyPlan has been used in various previous studies to model the district heating system (DHS). A review of energy plan simulation and performance indicators by Østergaard et al. [34] in 2015 showed that the tool had been used to model in District heating system in at least 6 studies. Modelling a DHS in this tool includes:

- Heating demand: District heating demand divided into:
  - District heating demand in systems without CHP (Boiler systems)
  - District heating demand in decentralised CHP systems
  - District heating demand in centralised CHP systems (Typically extraction plants or similar).
- Heat generation technologies: CHP, heat pumps and boilers
- Industrial waste heat for district heating: This is given priority in the heat generation mix
- Heat storage
- Heat pumps and electric boilers in Individual houses: This can be used to analyse a case of centralised vs decentralised production.

The model runs at an hourly resolution and can optimise the system for a year. However, it can only be used to simulate for a modelling period of a year.

A.1.9 EMB3Rs Geo Spatial tool for District Heating Network Connections

The EMB3RS Geospatial model analyses the network dimension and brings the spatial dimension between excess heat sources and sinks into the overall modelling framework. The main functionalities of the spatial analysis module are pipe routing, thermal loss, and network cost calculation.

The spatial analysis model is a network optimisation model that considers the analysis region, heat sources and sinks, as well as economic and environmental factors like investment costs, and ground and ambient temperature. The network solution is determined using a road network graph retrieved from Open Street Maps (OSM). Every road segment of the OSM network represents a potential path for the installation of a pipe. It is possible to add new road elements, restrict or force the use of roadways, and add an existing grid network.

The spatial analysis model consists of two mixed integer linear programming models as shown in Figure A- 6. The main goal of the models is to minimise the length of the grid while connecting all sources and sinks and matching their heat exchange capacities. The models try to use the existing grid (if any) as much as possible and then expand these existing pipes if their capacities are insufficient. The optimisation output is the least-distance grid network, including the lengths and capacities of each pipe. The capacities of the pipes are converted into diameters, and the thermal losses and network costs are calculated. The optimisation of the network distance (which has the largest share in the capital costs) along with the design of pipe diameters based on optimal dispatch leads to a least-cost network solution from the modelling framework.

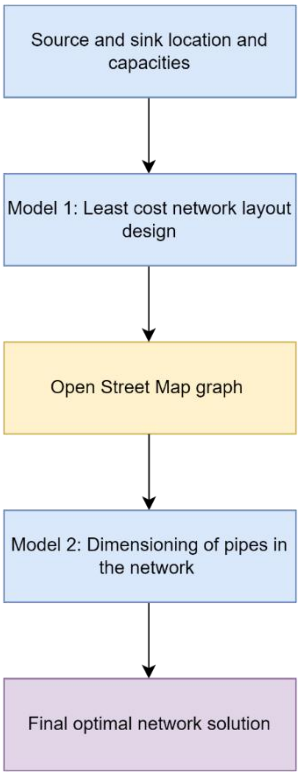


Figure A- 6 Illustration of the modelling process in the spatial analysis tool

Network costs consist of digging and piping costs. Two surface classes are considered to reflect the digging cost differences between different surfaces: street and terrain. The piping costs are independent of surface type. Thermal losses are also calculated based on the type of pipes, namely surface and underground pipes. The ambient or underground temperatures are used depending on the type of pipe. Outputs of the spatial analysis model are the individual and cumulative pipe lengths, losses, installed pipe capacities, the network costs between source-sink pairs, and a graphical representation of the network solution.

A2 KTH

A2.1 Existing knowledge on potentials for excess heat integration

The methodology for the techno-economic analysis of excess heat integration has been applied using several cases. These cases have been determined based on a literature review that presents excess heat potential within Sweden and their spatial overlap with heating demands. The summary of the literature is presented in Table A- 1 with the most important articles and the key takeaways.

Table A- 1 Existing knowledge on potentials for excess heat integration – summary of literature

1.	
Title	Industrial excess heat deliveries to Swedish district heating networks: Drop it like it's hot
Link	https://doi.org/10.1016/j.enpol.2012.08.031
Summary	Broberg et al. collected energy audits and potential for excess heat recovery in industries in Östergotland and Örebro counties in Sweden through surveys. The survey consisted of three parts. The first part concerned the availability of excess heat and whether the possibility of using this heat internally and/or externally had been investigated. The second part addressed the amount of excess heat available in various energy carriers while the third part concerned firm energy management. The results indicated that on a national level indicates unused primary heat potentials of approximately 2 TWh/year and total unused heat potential (including secondary) of 21 TWh/year.
2.	
Title	Quantifying the Excess Heat Available for District Heating in Europe
Link	https://heatroadmap.eu/wp-content/uploads/2018/09/STRATEGO-WP2-Background-Report-7-Potenital-for-Excess-Heat.pdf
Summary	The Wp32 report of the Stratego project indicates that 123 energy and industry sector facilities were mapped out in Sweden and their total excess heat potential is 217 PJ per year. The map also indicates the geographical location of these excess heat sources and their capacities. The mapping from this study is used to determine cases for the application in the NEO WP3
3.	
Title	Accessible urban waste heat
Link	https://www.reuseheat.eu/wp-content/uploads/2021/02/D1.4-Accessible-urban-waste-heat_revised-compressed.pdfhttps://www.reuseheat.eu/wp-content/uploads/2021/02/D1.4-Accessible-urban-waste-heat_revised-compressed.pdf
Summary	Deliverable 1.4 of the ReUseHeat project presents geographical mapping od several urban excess heat sources such as data centres, metro stations, food productions, supermarkets, cooling of service sector buildings, cooling of residential sector

	buildings and wastewater treatment plants. 45 datacentres were shown to be located within 2kms of district heating systems in Sweden with a recoverable heat potential of 13.3 PJ and 2332 wastewater treatment plants were located within 2 kms of heating grids with a potential of 20.3 PJ of heat supply. A total excess heat potential of 40.6 PJ per year has been determined for Sweden along with a spatial mapping of the existing sources. These have been used to design cases for the NEO WP3.
4.	
Title	Decarbonising District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites?
Link	https://doi.org/10.3390/su13031439
Summary	Manz et al. mapped 1608 industrial sources of excess heat in Europe and determined the potential of industrial excess heat in Sweden to be 12.6 PJ per year from 70 sources which exist within 10 Kms of existing heating grids. The potentials were shown to rise up to 41.3 PJ while considering low temperature district heating systems. This study also provides a map of the existing sources within Sweden.
5.	
Title	High-resolution mapping of the clean heat sources for district heating in Stockholm City
Link	https://doi.org/10.1016/j.enconman.2021.113983
Summary	Su et al. mapped out clean sources of urban excess heat within the city of Stockholm. A higher solution mapping of sources along with a technical potential evaluation determines a potential of 7504 GWh per year. The data used in this study is used to build the model of the DHS in Stockholm as a case for the NEO WP3. Over 250 sources of urban excess heat within the Stockholm city is analysed.

A2.2 Model – Inputs and Assumptions

This appendix describes the main inputs and the key assumptions in the model. The appendix is divided into several subsections with each subsection providing details about a specific input to the model.

Time period and time resolution

The structure of the model is shown in Table A- 2. The model is setup with a base year of 2022 and analyses a period until 2050. The 29 years are split as 5-year timesteps in order to reduce the computational complexity of the model. Each year is split into 288 intra annual timesteps to represent both seasonal and hourly variations. The year is split into 12 aggregate days (each representing one month) with 24 hours per aggregate day.

Table A- 2:Time resolution and analysis period of the model

Time period	2022 – 2050 split as 5 years timesteps – 2022, 2027, 2030, 2035, 2040, 2045, 2050
Time resolution	288 TimeSlices – 24 hours * 12 months

Technologies and Techno-economic parameters

The technologies in both cases have been set up based on the existing types of power plants within the corresponding district heating systems. The considered technologies and their techno-economic parameters are shown in Table .

Table A- 3: Techno-economic parameters of the technologies in the model

Technology	Capital cost (SEK/kW)	Efficiency (%)	Fixed costs (SEK/GW)
Waste incineration CHP	52000	70	1560
Bio waste CHP	52000	86	1560
Bio Pellets CHP	52000	88	1560
Heat Pumps[9]	12308	COP of 3	125
Bio oil boilers	32920	89	225
Bio pellet boilers	32920	89	225

Fuels and Fuel costs

The fuel costs in SEK/kWh for the different years are shown in the Table A- 4. The costs for all fuels except municipal waste have been assumed to increase in the future. The price of bio-based fuels is assumed to increase due to an increased demand for biomass in the electricity and transport sectors. International energy agency's report on the use of biomass within Sweden indicates a steady increase in the use of biomass based energy carriers in transport and electricity sector over the last decade to around 10% and 18% respectively. A large proportion of the heating supply, roughly 65% heat generated directly and indirectly from biomass. However, the supply of biomass in Sweden is limited and it is expected that the biomass will be imported to meet the energy demands. Therefore, the prices of bio-based fuels are assumed to increase 2% every year until 2050.

The increase in electricity prices have been projected in several previous studies. The electricity demand is projected to grow by 17% between 2020 and 2050. The increase in demand is due to the growth in population and the increased electrification of transport and industrial sectors. The rate of increase in demand is quicker than the rate of increase in electricity generation from renewable sources in the near term. Therefore, it is assumed that the electricity prices will increase significantly 2020-2040 and thereafter stagnate due to higher production from renewable sources. The prices are assumed to increase by 12 % between 2022 and 2030 and by 6% between 2030 and 2040. These have been based on estimates from the Swedish energy agency and the energy analyst firm 'Energy Brainpool' [123].

[9] Some of the considered heat pumps are considered to use existing excess heat sources as heat input, while outside air heat pumps and ground source heat pumps have also been considered. The heat pumps with different sources have been grouped together with a weighted average of the COPs.

Table A- 4: Fuel costs in the model

Year / Fuel	2022	2027	2030	2035	2040	2045	2050
Electricity	440	475	490	505	520	520	520
Bio oil	600	662	731	808	892	984	1087
Bio pellets	250	276	305	336	371	410	453
Bio waste	200	221	244	269	297	328	362
Waste	153	153	153	153	153	153	153

Capacity factors for excess heat sources

The heat availability at various excess heat source have been considered using generic heat availability profiles from industrial and urban excess heat sources. The data has been obtained for an online open source database. These profiles indicate typical operation of large industrial excess heat sources and data centres. These profiles have been assumed to be representative of all the excess heat sources considered in this study. The generic profiles for excess heat sources are obtained from [124].

For the Stockholm case, all the excess heat sources are connected only to the district heating systems of Stockholm. However, in the Swedish case, the heat demand is aggregated and represented as a single national heat demand and the different district heating systems are not represented separately. Therefore, the excess heat from the industrial sources is used to meet the demand on a national scale.

Temperature levels in the district heating system

The study also considers the development of 4th and 5th generation district heating systems in the long-term optimisation. Based on this, the temperature levels in the district heating systems are changed and therefore, the COPs of the heat pumps are also increased. The study considers current district heating temperatures of 75°C supply and 50 °C return until the year 2030. It is assumed that the supply and retune temperatures are reduced to 60°C and 40°C respectively by 2030. Low temperature district heating with supply temperature of 50°C and return temperature of 30°C is assumed to be integrated by 2040. Therefore, there is a steady increase in the COP of the heat pumps due to the reducing supply temperature in the network. The COP is 3 until 2030, 4 between 2030 and 2040 and the COP is assumed to be 5 after 2040.

A3. IVL Swedish Environmental Research Institute

The aim of IVL's work is to support the sustainable transformation of the Nordic energy system, in line with climate and socio-economic goals. From an energy system perspective, the efficiency and conservation of energy and resources will reduce the pressure on the energy system, contribute to increased share of renewables, security of supply and avoided network expansions. From a climate perspective, as current action remains insufficient to meet the goals of the Paris agreement or stabilise the climate, solutions related to conservation, services and social aspects of climate change mitigation can close the gap while reducing the risk associated with negative emission technologies. Socially such measures considered as overall beneficial, and mostly associated with no or moderate risks of harmful side effects, and to support the provision of decent living conditions for all. In all cases, the development scenarios driven by efficiency and conservation of energy and materials have clear economic, social and environmental benefits over technology-driven scenarios [125].

The specific objectives are:

1. To identify, gather and share, up-to-date knowledge on key aspects of cross- sectorial measures for Energy and Conservation, as well as Material Efficiency (ECEM) in the Nordic countries.
2. To identify and analyse the role of ECEM in the most recent energy development scenarios (narratives, modelling results, visualisation frameworks) in the Nordic countries, from different methodological perspectives.
3. To assess the role, and potentials for, ECEM in the Nordic context based on results from current national and international research and provide suggestions to improve and put together these results.
4. To inform Nordic energy researchers and policy makers about the relevance of considering ECEM when assessing energy system developments in the Nordic countries.

The work in this WP builds on, and links to, the comprehensive number of assessments performed in several other projects, i.e. national and international initiatives that include the Nordic countries. This includes energy systems modelling but also assessments of policy, economic outlook, social and market acceptance, developments in other countries, and other societal changes that impact the Nordic region. This broad methodological approach will result in more robust assessments, and in a deeper understanding of uncertainties, alternatives and contextual frameworks.

Given the set-up of the NEO program with specific WPs for Land use (WP1) and transportation (WP4), IVLs work in this WP3 will focus on Energy and Conservation, as well as Material Efficiency (ECEM) in the sectors of buildings and industry.

A3.1 ON-TIMES scenarios and results

A3.1.1 Description of the ON-TIMES Scenarios

Carbon Neutral Nordic (CNN)

<u>Climate and energy policy</u>

It develops according to the Nordic countries' national plans, strategies, and targets to reach carbon neutrality. The Nordic countries become climate neutral by 2050. Rest of Europe also see a strong cut in CO_2-emissions leading to approximately 80% reduction in emissions by 2050. The green transition in this scenario is driven by high CO2 prices equal to those applied in the Sustainable Development scenario of the IEA's World Energy Outlook 2020. This creates a need to transform the power system by applying renewable energy sources such as solar PV panels and wind turbines.

<u>Technology</u>

Decarbonisation of energy consumption will require fast actions in all sectors. The amount of renewable power and heat production must increase to provide clean energy to end-use sectors. BECCS will compensate some of the most expensive CO_2 emissions abatement options. Onshore wind development will be limited below the technical potential due to acceptability and land use issues.

In the Nordic countries we see a significant increase in the demand for PtX to decarbonise long-distance transport and industries. In the rest of Europe PtX demand is more modest reflecting a lower willingness to pay for GHG reductions.

Fuel / energy use

Nordic countries will increase electricity exports to Central Europe, but the amount will not increase much above current projections as electrification of Nordic heating, transport, and industry will require a large supply of low carbon electricity. Biomass imports from outside the Nordics will be limited to current or slightly higher levels to ensure sustainability of bioenergy use.

Nordic Powerhouse (NPH)

Climate and energy policy

All activities increase demand for electricity and/or other energy products.

Technology

In addition to their efforts to reduce Nordic emissions, the Nordic countries host larger number of data centres, produce more batteries, and manage to increase the exports of electricity, electro fuels, and carbon free steel and aluminium. The Nordic economy would benefit from the export of new products. The additional electricity and electro fuels would be produced by offshore wind hubs, continuing the lifetime of nuclear power plants, ground-based PV power plants, and by onshore wind, assuming high acceptance for onshore wind.

Fuel / energy use

The Nordic countries can provide cheaper clean energy than Central Europe and manage to host more low carbon services and industries and increase their exports of low carbon products and energy carriers. There would be more excess heat from industry and services that can be used in district heating generation.

Climate Neutral Behaviour (CNB)

Climate and energy policy

Strong political and citizen engagement. politicians and citizens adopt additional energy and material efficiency measures in all sectors that lead to lower energy demand. Focus of society is not on GDP but on sustainability, circular economy, and securing biodiversity.

Technology

A rapid decrease in costs of distributed energy generation and other low carbon technologies. decentralised generation technologies become much more common, and they further cut the energy delivered through grids and lead to prosumers and districts as energy suppliers.

Fuel / energy use

Energy demand for transport decrease due to modal changes, remote working, car sharing, and lower and more efficient heavy transport of goods.

A3.1.2. Results for the NCES project on the ON-TIMES (all sectors)

All the three main scenarios of the NCES analyses include ECEM in all sectors, however the CNB scenario sees politicians and citizens adopting additional ECEM measures in all sectors, ultimately leading to lower demand for both. It also assumes higher public acceptance for energy infrastructure development. The differences in ECEM measures in the scenarios are summarised as following.

The CNN scenario, for the heavy industry, households, and national and international transport, the demand projection follows the national projections in the Nordic region. Compared to the CNN scenario, in the NPH scenario, the production of aluminium, and iron and steel is assumed to increase by 10% in 2050. In addition, the power transmission capacity between the Nordic countries and from the Nordics to mainland Europe is increased. In terms of technology development, H2 and fuel (power-to-X) production are increased.

In the CNB scenario, demand projection for the heavy industry is the same as CNN up until 2030, thereafter reduces by 10% compared to CNN until 2050. For passenger transport, with an assumed increase in shared mobility, no growth is assumed for national passenger km from 2030 onwards. Freight transport sees 10% lower growth in tkm projections from 2025 onwards due to more efficient logistics and lower consumption. For international transport, 10% lower freight in aviation and navigation from 2030 onwards is assumed compared to CNN. In terms of technology development, a breakthrough in autonomous vehicles and shared mobility result in more efficient private transport.

The CNB scenario, besides the energy demand reduction, examines where behaviour change could reduce energy demand. For instance, for low-carbon electricity production, the CNB models higher acceptance of expanded onshore wind power capacity. In addition, the model analyses the potential impact of dietary changes, lowering agricultural GHG emissions by 10%. These changes do not have a direct effect on energy demand in CNB but do make the transition easier.

The model results for the primary energy supply in the three scenarios are shown in Figure A- 7. The share of fossil fuels in Nordic primary energy supply falls from 42% in 2020 to 6-9% by 2050 in the NCES scenarios, while export of electricity and power-to-X fuels rises (negative values indicate exports to non-Nordic countries).

As Figure A- 7 shows, wind power dominates new electricity investments while the share of fossil fuels falls to below 5% by 2050 in all the three scenarios. This pattern is constant even as generation increases substantially from 455 TWh in 2020 to 710 TWh (CNN), 615 TWh (CNB) and 980 TWh (NPH) in 2050. At the same time, domestic Nordic electricity demand increases from 370 TWh in 2020 to 450-680 TWh in 2050 in the three scenarios. Production of power-to-X fuels, 'upstream fuel production', is the single largest growth driver.

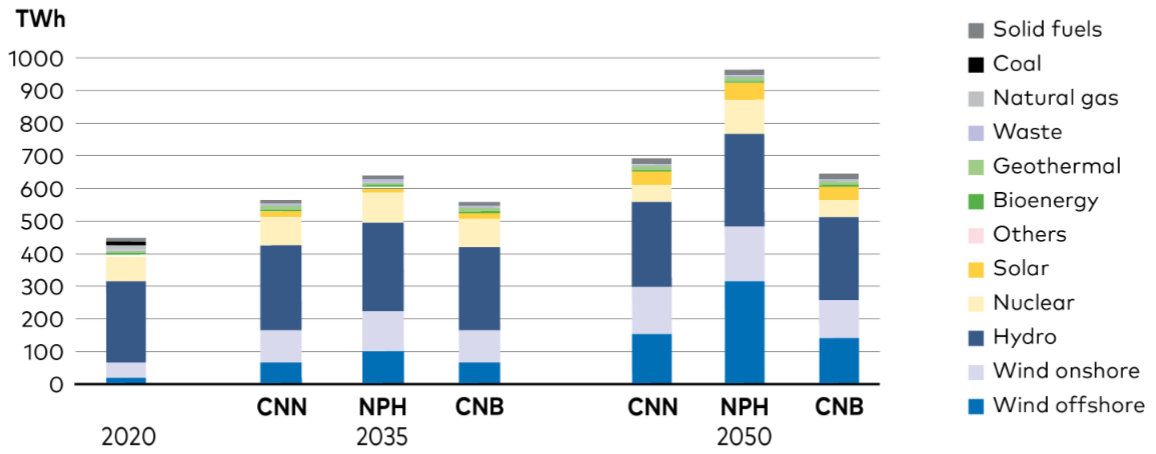


Figure A- 7 Nordic electricity generation in 2020 and in the CNN, NPH and CNB scenarios (Source: Figure ES.3, Nordic Clean Energy Scenarios 2021 [126]).

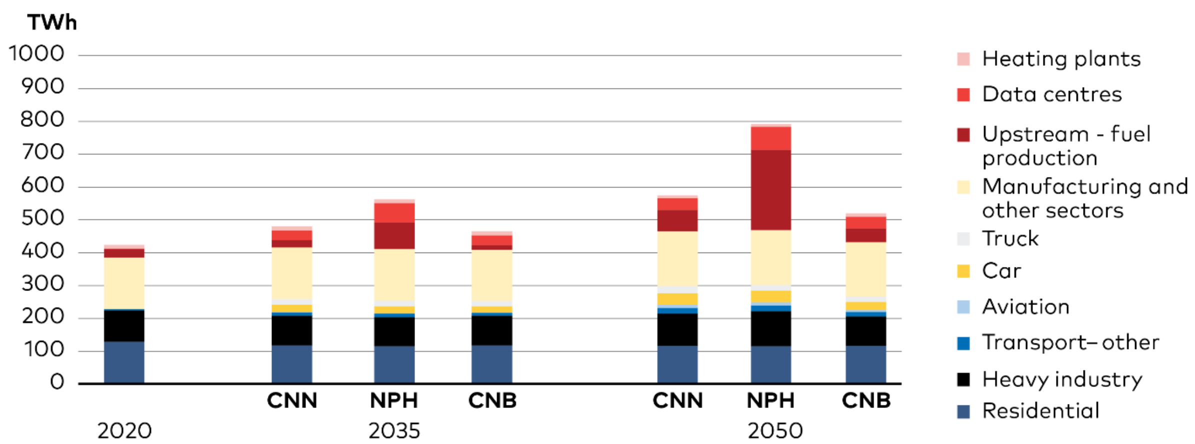


Figure A- 8 Domestic Nordic electricity demand in 2020 and in the CNN, NPH and CNB scenarios (Source: Figure E2.4, Nordic Clean Energy Scenarios 2021 [126]).

For the same level of CO_2 emissions reduction in the Nordic region (Figure A- 8) under the assumptions made in the CNB scenario, the power demand in Nordic countries would be 5% lower in 2050 and final energy demand would be 17% lower in 2050 compared to the CNN scenario (Figure A-9). Total system costs would also decrease by about 10% over the period.

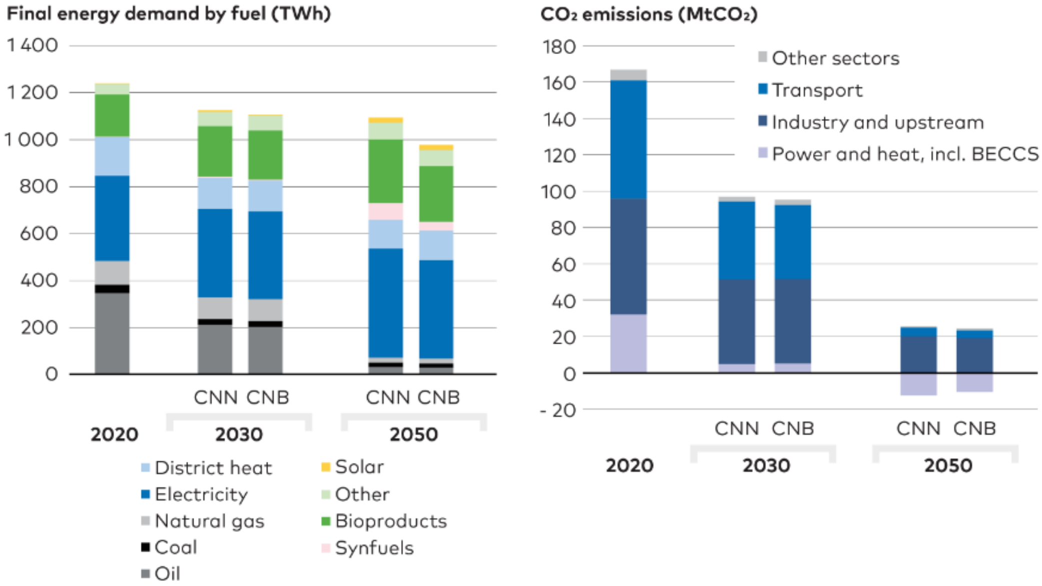


Figure A- 9 Final energy demand (left) and CO2 emissions (right) in CNN and CNB scenarios (Source: Figure 7.1, Nordic Clean Energy Scenarios 2021 [126]).

Electricity as energy carrier has attractive characteristics, with little loss it can supply almost any energy service demand. Switching to electric heating, engines, or pumps for example is often a central solution when implementing energy saving solutions in industries and buildings. This is why we see that an increase in electricity demand will reduce demand for other energy carriers as large-scale direct electrification delivers significant overall efficiency gains. Heat pumps for space heating can, by utilising 1 kWh electricity, deliver 2.5-4 kWh heat, while a boiler at maximum could deliver 1 kWh heat from 1 kWh fuel.

The decrease in energy intensity for different sectors is also driven by a general improvement in the efficiency of technologies using other energy carriers. For heavy industries in Sweden and Norway however, improved energy intensity lags. There are mainly two reasons for this development. Firstly, heavy industry in Sweden and Norway are already very efficient in their use of electricity to supply its processes. Secondly, for some industries the least-cost option in the model is to keep using fossil fuels by incorporating CCS, resulting in a stable or slightly higher final energy demand in the CNN. In contrast, in the NPH scenario the Swedish steel industry is assumed to instead switch away from coal using hydrogen and electricity, following a power-to-X pathway. This currently seems favoured by industry, exemplified by projects like HYBRIT and H2 Green steel.

A3.1.3. RePowerEU scenario

This section compares results for a decarbonised Nordic energy systems in 2050 between the different models. As shown in Table A- 5 and Table A- 6 , the focus is on energy and material efficiency in the industry and buildings sectors.

The model results for the ON-TIMES scenarios illustrate carbon neutrality pathways in all the energy sectors in the Nordic region by 2050. For our analysis, among the three main ON-TIMES scenarios, we select the Climate Neutral Behaviour (CNB) scenario as our base case. The reason is that Energy and Conservation, as well as Material Efficiency (ECEM) in all sectors are considered specifically in the CNB scenario (see *A3.1.1 Description of the ON-TIMES Scenarios* for the full description of the CNB scenario). The primary assumptions of the CNB scenario for the industry and buildings sectors are summarised in Table A- 5.

Table A- 5 The key assumptions of the CNB scenario. Source: Table 2.7, Nordic Clean Energy Scenarios 2021.

Key assumptions	Climate Neutral Behaviour (CNB)
Low bioenergy sensitivity variant	Biomass imports are linearly reduced from today's levels to zero in 2050 for all Nordic countries. 25% lower domestic bioenergy potentials.
GHG targets	National targets
Heavy industry	Sectoral production volumes from national projections until 2030, thereafter reduces by 10% compared to national projections until 2050.
Production industry	Sectoral production volumes from national projections.
Trade and commerce	Sectoral Gross Domestic Product (GDP) from official economic projections.
Households	Private consumption projections from official economic projections.

The results of the CNB scenario in 2050 for the parameters that are of importance of WP3 are provided in Table A- 6.

Table A- 6 Base case (CNB scenario from NCES project) results for the Nordic area, 2050.

Model	Unit	ON-TIMES				
		Nordic area	Denmark	Finland	Norway	Sweden
Industrial excess (waste) heat use in district heating	TWh/yr	27	7.2	0	8.6	11.1
Urban excess (waste) heat* use in district heating	TWh/yr	9.3	0.5	0	4.6	4.3
Final energy consumption in the residential sector	TWh/yr	203	34	45	53	71
Share of district heating of total fuel/ energy consumption in the residential sector	%	31	49	35	1	40
Energy saving in the residential sector	TWh/yr	0	0	0	0	0
Final energy consumption in the industry sector	TWh/yr	531	49	175	117	190
Share of district heating of total fuel/ energy consumption in the industry sector	%	11	30	5	3	16
Energy saving in the industry sector	TWh/yr	22.2	0.3	5	4.7	12.2

* e.g., sewage system, data centre, metro station, cooling system of buildings, supermarkets, etc.

As Table A- 7 shows with the assumptions in the RePowerEU scenario, the impacts on the chosen ECEM parameters in 2030 are very little. The reason is that similar to the base scenario (i.e., CNB), in the RePowerEU scenario, ECEM measures in the industry sector are considered after 2030.

Table A- 7 Impact of RePowerEU scenario (run for this project based on the NCES scenario CNB+30Twh) for the Nordic area, 2030 [TWh/yr] (delta values +/-, not absolute values).

Model	Unit	ON-TIMES				
		Nordic area	Denmark	Finland	Norway	Sweden
Industrial excess (waste) heat use in district heating	TWh/yr	0	0	0	0	0
Urban excess (waste) heat* use in district heating	TWh/yr	0	0	0	0	0
Final energy consumption in the residential sector	TWh/yr	+0.8	+0.25	0	0	+0.5
Share of district heating of total fuel/ energy consumption in the residential sector	%	0	0	0	0	0
Energy saving in the residential sector	TWh/yr	0	0	0	0	0
Final energy consumption in the industry sector	TWh/yr	-0.3	+0.5	-0.5	-0.3	-0.5
Energy saving in the industry sector	TWh/yr	0	0	0	0	0

* e.g., sewage system, data centre, metro station, cooling system of buildings, supermarkets, etc

A3.1.4. Results from ON-TIMES (Nordic Clean Energy Scenarios) for the industry sector

The energy use in heavy industry in the modelled scenarios in the Nordic Clean Energy Scenarios are measured by two metrics: one for the *energy service demand* and one for *fuel consumption*. The difference between the two metrics is that the energy service demand describes how much energy is needed to produce the output product from a certain industry, while the fuel consumption describes what energy carriers are used to supply the energy services.

To explore the potential for energy efficiency in the Nordic Clean Energy Scenarios, a new metric, the *energy efficiency change*, was defined:

$$Energy\ efficiency\ change\ = \frac{Energy\ service\ demand_{2050}/fuel\ consumption_{2050}}{energy\ service\ demand_{2020}/fuel\ consumption_{2020}} \quad \text{(Equation A3.1.4.)}$$

In other words, equation A3.1.4 and the energy efficiency change could be explained as *the change in the ratio between the energy service demand and fuel consumption over the period 2020-2050*, where a positive value for the energy efficiency change indicates a more efficient use of energy in 2050 compared to 2020, i.e., an energy efficiency improvement. The reason to define a new indicator from the two existing ones was to be able to determine whether any decrease in fuel consumption in a sub-sector of heavy industry related to improved efficiency of the processes and technologies or if it was rather caused by a decrease in demand for the output product of the industry.

In Figure A- 10, the energy efficiency change according to the model is represented by a colour gradient, where the darkest green represents the largest potential for a more efficient use of energy presented in relative numbers. According to the figure, the industry showing the largest potential for energy efficiency improvement is the cement industry, where the ratio between input energy and useful energy in the sector could improve by 16-45%, depending on country and scenario. In all cases, the improvement is due to the mid-temperature technologies with high energy and cost efficiency, that are expected to be increasingly used in the coming decades [109]. The same technologies are also able to improve the efficiency in the aluminium industry, thanks to its mid-temperature energy service segments. Another industry showing potential for an improvement in energy efficiency is the mining industry, which has the potential of being further electrified. The pulp and paper industry seems to have improved its efficiency in 2050 compared to 2020 in Finland only. The reason is that, in Finland, the model selects an increased use of district heating as the energy carrier to supply the pulp and paper industry with energy, meaning that any conversion efficiencies are hidden upstream. Thus, energy efficiency in the pulp and paper industry mainly caused by shifting energy conversion losses to the heat sector. In the rest of the pulp and paper industry, the dominating technology supplying the energy services is biomass boilers, which have a significantly low energy efficiency, also in comparison to the existing fossil energy conversion technologies [109]. The iron and steel industry also shows limited potential for improved energy efficiency and this is due to the need for high temperature heat in the sector, which heat pumps and mechanical vapor recompression (MVR) technologies cannot supply [109]. The efficiency actually decreases in the CNN scenario, while it remains unchanged in the NPH and improves in the CNB scenario. A further reason for the decline in efficiency in the CNN scenario is the increased need for CCS technology compared to the CNB scenario and thus more energy is required to produce the same amount of output product, due to the high energy intensity of CCS. However, in the NPH scenario it is instead assumed that break-through technologies like HYBRIT (i.e., use of hydrogen in the steel production processes) will be available. As the result, the model finds them more cost-optimal to reduce carbon emissions. The use of hydrogen for steel production means that the energy conversion losses occur in upstream processes. The NPH scenario therefore appears to have a larger potential for energy efficiency improvement in the iron and steel industry, but this is merely a matter of in what sector energy is converted. Therefore, the use of primary energy as an indicator instead of fuel consumption (referring to the use of energy carriers, not just fuels) would be helpful in showing the full image of the actual efficiency of the entire energy system.

In Figure A- 11, the change of fuel consumption between 2020 and 2050 is presented for the same countries, scenarios and sectors. Here, a positive value indicates an *increase* in the fuel consumption, meaning that the amount of energy used to supply the energy demand is increased. The colour coding is therefore the opposite of the previous figure: the green values highlight the potential for a decreased fuel consumption, while yellow and red cells indicate an increased use of energy.

Energy efficiency change 2020–2050 [%]		All sectors	Cement	Aluminium	Iron and steel	Mining	Pulp and paper
Nordics (excluding Iceland)	CNB	14	19	10	8	12	15
	CNN	13	22	9	-1	11	17
	NPH	16	25	9	0	9	22
Denmark	CNB	44	44				
	CNN	43	43				
	NPH	41	41				
Finland	CNB	8	36	-2	9	4	8
	CNN	13	47	0	9	0	13
	NPH	15	50	0	-2	0	15
Norway	CNB	13	24	16	13	12	-1
	CNN	9	22	14	6	10	-1
	NPH	5	21	12	-5	9	-2
Sweden	CNB	-4	17	2	-1	3	-5
	CNN	-6	16	2	-16	3	-4
	NPH	-3	16	2	-5	3	-5

Figure A- 10 - Gradient over potential for efficiency improvements, according to the Nordic Clean Energy Scenarios. The energy efficiency is in this case defined as the relationship (ratio) between the input energy (fuel consumption) and output energy (energy service demand). The darkest green represents an energy efficiency *improvement* over 40%, while the most saturated yellow represents a *decrease* in energy efficiency by 10-20%. The only heavy industry in Denmark is the cement industry, hence the grey colouring (denoting N/A) of the other sectors.

Change of fuel consumption [%]		All sectors	Cement	Aluminium	Iron and steel	Mining	Pulp and paper
Nordics (excluding Iceland)	CNB	-14	-28	-28	-2	24	-17
	CNN	-8	-22	-22	-6	35	-9
	NPH	2	-17	-17	30	45	-4
Denmark	CNB	-39	-39				
	CNN	-32	-32				
	NPH	-24	-24				
Finland	CNB	-31	-11	2	-17	110	-38
	CNN	-26	-9	13	-8	114	-33
	NPH	-23	-11	13	23	114	-35
Norway	CNB	-13	-36	-24	13	24	-10
	CNN	0	-28	-15	34	40	0
	NPH	15	-13	-5	63	56	11
Sweden	CNB	1	-27	-7	0	3	3
	CNN	15	-19	3	25	15	14
	NPH	22	-11	14	17	26	25

Figure A- 11 Gradient graph representing the percentual change in fuel consumption in the time period 2020-2050. A *decrease* in fuel consumption is expressed as a negative number and indicated by a green hue, while an increased fuel consumption is expressed as a positive value and a yellow, orange or red colour.

From Figure A- 11, the cement industry still stands out with its large (relative) potential of a reduced fuel consumption in 2050 compared to 2020, amounting to a reduction of 17-28% in the Nordic countries, depending on scenario. Other industries, like the iron and steel industry and the mining industry, instead see an increased fuel consumption by 2050. However, this is explained by how the scenarios are formulated, where the production in heavy industry is set to increase by 10% in the NPH scenario CNN scenario and to decrease by 10% compared in CNB scenario compared to the CNN scenario, see [126]. Thus, CNB is, unsurprisingly, the scenario where the largest reduction of fuel consumption is foreseen.

Similar to Figure A- 11, Figure A- 12 presents the change of fuel consumption but instead in absolute numbers (TWh). As figure 14 shows, the energy efficiency potentials in some industries contribute to a small share of the total potentials in all the sectors. For example, the change in fuel consumption in the mining industry is very small when comparing with the total amount of fuel used in Nordic heavy industry. The potential for reduced fuel consumption in the cement industry also presents as somewhat limited: only 2.4-4 TWh for all the studied Nordic countries.

Change of fuel consumption [TWh]		All sectors	Cement	Aluminium	Iron and steel	Mining	Pulp and paper
Nordics (excluding Iceland)	CNB	-35	-4.0	-5.5	-0.84	1.5	-26
	CNN	-10	-3.1	-2.7	-2.7	2.1	-14
	NPH	6.0	-2.4	-0.20	12	2.7	-6.5
Denmark	CNB	-1.6	-1.6				
	CNN	-1.3	-1.3				
	NPH	-0.98	-0.98				
Finland	CNB	-29	-0.45	0.05	-2.1	1.0	-27
	CNN	-24	-0.38	0.41	-0.98	1.0	-24
	NPH	-21	-0.45	0.41	2.7	1.0	-25
Norway	CNB	-5.3	-1.0	-5.3	1.3	0.28	-0.59
	CNN	-0.14	-0.80	-3.2	3.4	0.46	0.02
	NPH	6.3	-0.37	-1.0	6.4	0.64	0.64
Sweden	CNB	0.72	-0.97	-0.26	-0.08	0.13	1.9
	CNN	15	-0.68	0.12	5.0	0.58	10
	NPH	22	-0.39	0.50	3.3	1.0	18

Figure A- 12 - Gradient graph representing the absolute change in fuel consumption in the time period 2020-2050. A *decrease* in fuel consumption is expressed as a negative number and indicated by a green hue, while an increased fuel consumption is expressed as a positive value and a yellow, orange or red colour.

In these above presented three figures, two out of three scenarios display a potential for the Nordic countries to reduce the fuel consumption in heavy industry: 35 TWh in the CNB scenario and the 10 TWh in the CNN scenario. Contrastingly, the fuel consumption increases in the NPH scenario. More specifically, the fuel consumption is assumed to decrease regardless of scenario in Denmark and Finland, while in Norway, the fuel consumption decreases in two out of three scenarios. In Sweden, heavy industry is not expected to reduce its fuel consumption at all, but is instead expected to increase its fuel consumption. Meanwhile, the energy efficiency (as described in equation A3.1.4) of heavy industry, aggregated for all the studied countries, improves in all three scenarios. The pulp and paper industry presents potential for reductions in fuel consumption (not in Sweden and Norway, but in Finland), although the energy efficiency will actually decrease over time when all countries are aggregated. However, Finnish pulp and paper industry increases its energy efficiency (between 8 and 15 %) while also decreasing its total fuel consumption significantly (25-27 TWh). This is in large part thanks to district heating being able to supply an increasing share of the energy, while biofuels are phased out. The large reduction of consumed fuel also relates to the demand on the products from the Finnish pulp and paper industry: the energy service demand decreases in Finland over the period, which would imply a decrease in activity level in the pulp and paper industry. On the contrary, the fuel consumption and energy service demand in Swedish pulp and paper industry increases throughout the same period.

Another metric used to capture energy in the Nordic Clean energy scenarios is the energy *intensity*, indexed with a base year of 2015. The energy intensity connects the economic value (GDP) to the energy required to produce the output. The further the economic decoupling, the more product could be produced using the same, or less, amount of energy. Figure A- 13 presents the energy intensity between 2015-2050, relative to 2015 values. From the model results, in all the countries, except Sweden, the energy intensity in the heavy industry decreases compared to 2015. In Sweden, the energy intensity instead increases during the same time horizon according to the model.

Table A- 8 Primary energy consumption (temperature corrected) per GDP, percent (base year 2005), 2005–2015

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Primary energy consumption, per GDP [%]	**0.0%**	-6.0%	-10.8%	-10.2%	-13.0%	-12.3%	-14.5%	-13.0%	-16.2%	-26.0%	-26.8%

**Excl. international transport and non-energy use*
Source: [127]

The model results of Swedish heavy industry show a limited potential for heavy industry's contribution to the Swedish energy intensity target [92] of a 50% reduction in 2030 compared to the energy intensity in 2005.

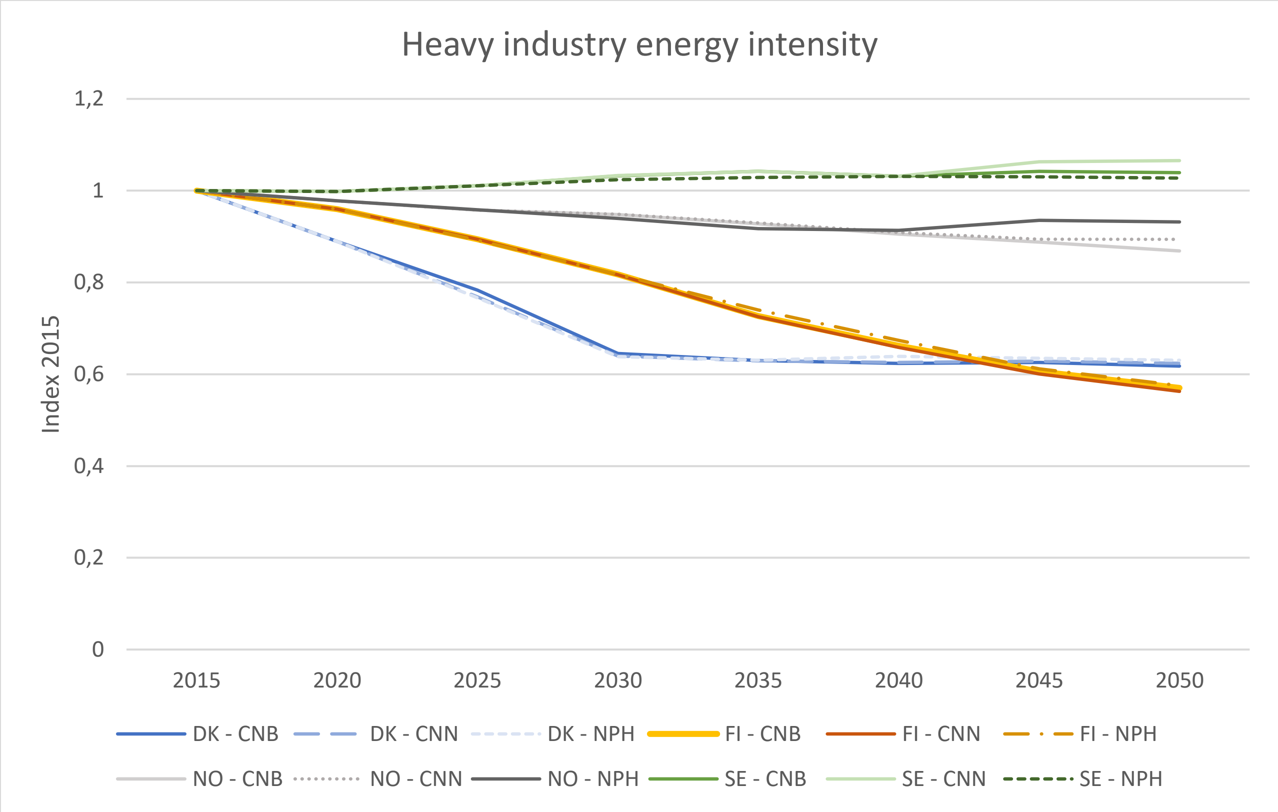
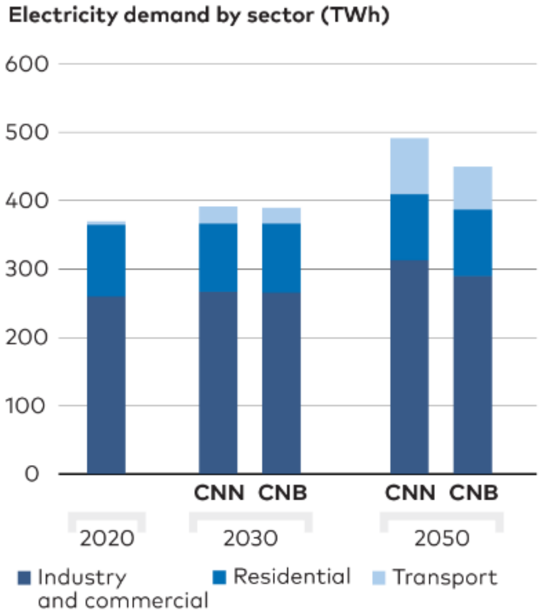


Figure A- 13 The energy intensity of heavy industry, indexed with 2015 as a base year.

A3.1.5. Results for the buildings sector in ON-TIMES model

In the Nordic Clean Energy Scenarios, the energy demand for the residential sector includes energy for appliances (computers, cooking equipment, lighting etc.) and heating (both, individual and district heating). For the CNB scenario (see Table A- 6) the final energy consumption in 2050 for the residential sector is expected to be 203 TWh/year for the Nordic area. The results for the different Nordic countries are 34 TWh/year for Denmark, 71 TWh/year for Sweden, 45 TWh/year for Finland and 53 TWh/year for Norway. Comparing with the consumption in 2020 of 233 TWh/year, this means the sector is expected to slightly decrease its energy consumption for the Nordics as a whole. The development is very similar for all three NCES scenarios. For Denmark the total residential fuel consumption decreases with about 25% from 2015 to 2050. In residential heating natural gas, diesel and wood pellets are phased out and replaced with increased amounts of biomethane, solar power. For Norway the total residential fuel consumption is expected to increase slightly with about 5%, and for heating diesel is replaced by mainly by wood pellets and solar power. For Finland the total residential fuel consumption decreases with about 25%, phasing out diesel and lowering the use of biofuels. For Sweden the fuel consumption stays fairly stable, as diesel, wood pellets and biodiesel are phased out and mainly replaced with increased amounts of solar power [128].



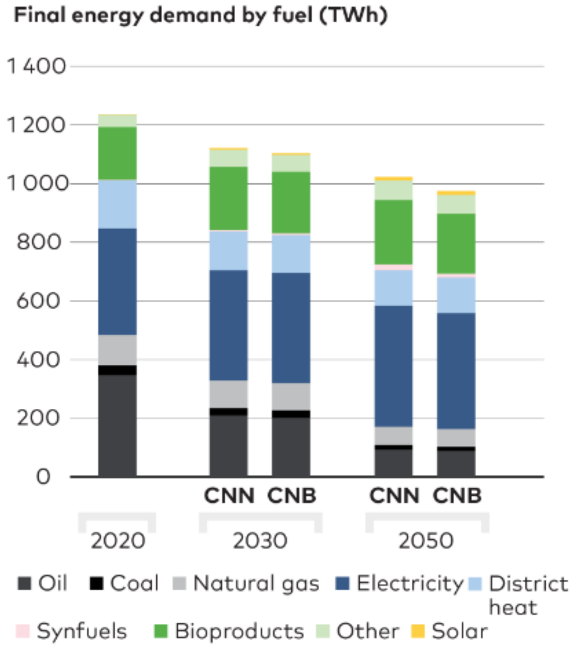


Figure A- 14 Results of model runs of quantified assumptions of behaviour changes (ECEM) on electricity demand in the industry, residential and transport sectors (left) and on final energy demand (right) in Nordic countries in TWh per year. (Source: Figure 7.1, Nordic Clean Energy Scenarios 2021 [126])

In the Nordic Clean Energy Scenarios, electrification is emphasised as one of the major ways to obtain energy efficiency in the coming decades, since switching to electric engines or pumps can deliver significant overall efficiency gains and lower the total energy demand. For buildings energy efficiency can be obtained by for example replacing boilers or direct electric heating with heat pumps for space heating in individual buildings. During the model time horizon there are new investment options for the existing buildings such as heat-saving measures, new heat devices and connection to the DH systems. Simultaneously, some existing buildings are demolished and replaced with new and more efficient buildings. The total floor area also increases over time. Since all these factors influence the NCES modelling results, it is difficult to specify exactly how much energy efficiency measures influence the overall energy consumption. Figure A- 14 shows the electricity demand by sector, including the residential sector, in the years 2020, 2030 and 2050 for the CNN and CNB scenarios. The results show that the electricity demand of the residential sector is expected to remain relatively stable with a slight decrease over the coming decades. Electricity consumption for lighting or appliances generally remain flat to 2050 in all NCES scenarios. This is because the expected growth in service demand for traditional electricity consumption is being counteracted by improved efficiency for different appliances, mainly driven by EU regulation [126].

Today district heating systems deliver 35% of residential heating in the Nordics, on average, divided between countries: Norway 2%, Denmark 40%, Iceland 75%, Finland 40%, and Sweden 48%. In all NCES scenarios district heating and cooling become increasingly important. In the CNN base scenario, increased energy efficiency is achieved by introducing large scale heat pumps utilising different heat sources (ambient heat, seawater etc.). Replacing biomass boilers and combined heat and power plants with heat pumps reduces the reliance on biomass which can then be used elsewhere. [126]

According to Table A- 7, for the RePowerEU scenario (run for this project based on NCES scenario CNB + 30 TWh) the final energy consumption in 2030 for the residential sector is expected to increase with 0.8 TWh/year for the Nordic area (compared to the CNB base case). The results for the different Nordic countries are 0.25 TWh/year for Denmark, 0.5 TWh/year for Sweden and 0 TWh/year for Finland and Norway. No change in energy saving for the residential sector is observed for the RePowerEU scenario compared to the base case.

In the ON-Times model, for all the scenarios, the cost curves for energy efficiency measures in each type of building have been included. The cost curves are represented by an upper bound constraint on heat efficiency capacity (PJa) and the associated cost and economic lifetime.

A3.2. Insights from sectorial models – ECEM in the buildings sector

This section summarises findings from previous projects on energy conservation and material efficiency in the building sector. Some of the studies focus mainly on the Swedish building sector, while others also include a Nordic and/or European perspective.

The studies on energy conservation show significant potentials for a wide range of measures for energy saving and flexibility. Regarding energy-saving measures for the Swedish building sector, the technical potential to reduce energy demand is high (53% reduction of energy use) when implementing a wide range of measures including improved U, replacement of windows, upgrade of ventilation systems with heat recovery etc. [52]. However, the technical potential for energy-saving measures in buildings is shown to differ from the potential based on cost-efficiency [129]. This implies that while the theoretical possibility for lowering the total energy demand from the building sector over the coming years is high, especially for older buildings, the pace of renovation and introduction of energy-saving measures based on economic incentives is not expected to match the technical potential by far. It is possible that changing energy prices will affect the development. In one study price sensitivity of energy demand in Europe was shown to be intermediate to high [65].

Table A- 9 presents a summary of the reviewed previous studies on energy efficiency and conservation in the building sector.

Table A- 9 Previous studies - measures studied, estimated potentials and conclusions related to energy efficiency and conservation.

Ref	Country, sector	Energy efficiency and conservation measures	Estimated potentials and conclusions
Mata et al. 2015 [52]	Sweden, residential buildings	Twelve energy-saving measures (ESMs) including: • Improved U value of facades, cellar/basement, attics/roofs • Replacement of windows • Upgrade of ventilation systems with heat recovery • Reduction of power for lightning, appliances • Reduction in power used for production of hot water • Replacement of water pumps • Lowering the indoor temperature	**Technical potential energy saving:** 51.0 TWh/year (53% reduction of energy use in the Swedish residential sector compared to 2005) assuming all ESMs assessed are implemented. **Potential change in energy demand from installing heat recovery:** Single-family dwellings: 12.7 TWh reduction in net energy demand for space heating (increased electricity demand 0.7 TWh) Multi-family dwellings: 9.65 TWh reduction in net energy demand for space heating (decreased electricity demand 0.25 TWh)
Mata et al, 2018 [56]	UK Sweden Spain Germany France, residential and non-residential buildings	Ten energy conservation measures (ECM) including: • Increased insulation of cellar/basement, facades, attics/roofs • Replacement of windows • Upgrade of ventilation systems with heat recovery • Installation of efficient lighting/appliances • Hot water production with solar panels • Replacement of oil and gas boilers with biomass boilers/more efficient oil and gas boilers	**Energy conservation potential (average) from** • **Increased insulation and replacement of windows:** Residential buildings: 31% Non-residential buildings: 20% • **Upgrade of ventilation systems with heat recovery** Residential buildings 14% Non-residential buildings: 19% • **Doubling the efficiency of lighting and appliances, installing solar panels for hot water, replacement of boilers** All below 8% for both residential and non-residential buildings
Mata et al, 2020 [130] (Review)	France Germany Sweden UK, building sector	A wide range of flexibility measures, e.g.: • Price mechanisms • User-centred control strategies for space heating and water heating • Automated shifting of appliances' use • Electric vehicle charging algorithms • Consumer feedback	**Potential energy savings in TWh/yr (and % of total residential energy consumption)** Space heating – All fuels, Germany: 8.7 - 29.1 TWh/yr (1.3%-4.3%) Electricity - Appliances, Germany: 38.4TWh/yr (5.6%) Electricity All, UK: 2.6 TWh/yr (0.5%)

Table A – 9 continued

Ref	Country, sector	Energy efficiency and conservation measures	Estimated potentials and conclusions
Mata et al. 2015 [52]	Sweden, residential buildings	Twelve energy-saving measures (ESMs) including: Improved U value of facades, cellar/basement, attics/roofs Replacement of windows Upgrade of ventilation systems with heat recovery Reduction of power for lightning, appliances Reduction in power used for production of hot water Replacement of water pumps Lowering the indoor temperature	**Technical potential energy saving:** 51.0 TWh/year (53% reduction of energy use in the Swedish residential sector compared to 2005) assuming all ESMs assessed are implemented. **Potential change in energy demand from installing heat recovery:** Single-family dwellings: 12.7 TWh reduction in net energy demand for space heating (increased electricity demand 0.7 TWh) Multi-family dwellings: 9.65 TWh reduction in net energy demand for space heating (decreased electricity demand 0.25 TWh)
Mata et al, 2018 [56]	UK Sweden Spain Germany France, residential and non-residential buildings	Ten energy conservation measures (ECM) including: Increased insulation of cellar/basement, facades, attics/roofs Replacement of windows Upgrade of ventilation systems with heat recovery Installation of efficient lighting/appliances Hot water production with solar panels Replacement of oil and gas boilers with biomass boilers/more efficient oil and gas boilers	**Energy conservation potential (average) from Increased insulation and replacement of windows:** Residential buildings: 31% Non-residential buildings: 20% **Upgrade of ventilation systems with heat recovery** Residential buildings 14% Non-residential buildings: 19% **Doubling the efficiency of lighting and appliances, installing solar panels for hot water, replacement of boilers** All below 8% for both residential and non-residential buildings
Mata et al, 2020 [130] (Review)	France Germany Sweden UK, building sector	A wide range of flexibility measures, e.g.: Price mechanisms User-centred control strategies for space heating and water heating Automated shifting of appliances' use Electric vehicle charging algorithms Consumer feedback	**Potential energy savings in TWh/yr (and % of total residential energy consumption)** Space heating – All fuels, Germany: 8.7 - 29.1 TWh/yr (1.3%-4.3%) Electricity - Appliances, Germany: 38.4TWh/yr (5.6%) Electricity All, UK: 2.6 TWh/yr (0.5%)

Table A- 9 continued

Ref	Country, Sector	Energy efficiency and conservation measures	Estimated potentials and conclusions
Mata et al, 2020 [129]	Sweden, Multifamily buildings	Eleven ESMs including: • Increased insulation of floor/basement, facades, attics/roofs • Replacement of windows • Upgrade of ventilation systems with heat recovery • Installation of efficient lighting/appliances • Reduction of power used for hot water production • Installation of PV panels	**Energy-saving potential in reduced energy demand (by 2050)** Driven by technical renovation needs: 85% Driven by cost-efficiency:15%. "current limitations of reaction capacity to implement these cost-effective measures would only allow a reduction in the energy demand by 4%–23% during the same period." "In both scenarios, workmanship capacity was more constraining than investment capacity…"
Nik et al, 2015 [40]	Sweden (Stockholm, Gothenburg, Lund), Residential buildings	Nine energy retrofitting measures including: • Increased insulation of cellar/basement, facades, attics/roofs • Replacement of windows • Upgrade of ventilation systems with heat recovery • Installation of efficient lighting/appliances • Installation of thermostats to set the minimum indoor air temperature to 20 ◦C	**Most effective measures to reduce heating demand:** Stockholm: Retrofitting packages to (1) improve building envelope and (2) include all measures (mean 30.4% for each) Gothenburg and Lund: Lowering the indoor temperature. **Upgrading the ventilation system decreases the heating demand** on the hourly scale between 6% to 12%.
Mata et al, 2020 [130] (Review)	France Germany Sweden UK, Building sector	A wide range of flexibility measures, e.g.: • Price mechanisms • User-centred control strategies for space heating and water heating • Automated shifting of appliances' use • Electric vehicle charging algorithms • Consumer feedback	**Potential energy savings in TWh/yr (and % of total residential energy consumption)** Space heating – All fuels, Germany: 8.7 - 29.1 TWh/yr (1.3%-4.3%) Electricity - Appliances, Germany: 38.4TWh/yr (5.6%) Electricity All, UK: 2.6 TWh/yr (0.5%)

Table A -9 continued

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Mata et al, 2018 [56]	UK Sweden Spain Germany France, residential and non-residential buildings	Ten energy conservation measures (ECM) including: Increased insulation of cellar/basement, facades, attics/roofs Replacement of windows Upgrade of ventilation systems with heat recovery Installation of efficient lighting/appliances Hot water production with solar panels Replacement of oil and gas boilers with biomass boilers/more efficient oil and gas boilers	**Energy conservation potential (average) from Increased insulation and replacement of windows:** Residential buildings: 31% Non-residential buildings: 20% **Upgrade of ventilation systems with heat recovery** Residential buildings 14% Non-residential buildings: 19% **Doubling the efficiency of lighting and appliances, installing solar panels for hot water, replacement of boilers** All below 8% for both residential and non-residential buildings
Mata et al, 2020 [130] (Review)	France Germany Sweden UK, building sector	A wide range of flexibility measures, e.g.: Price mechanisms User-centred control strategies for space heating and water heating Automated shifting of appliances' use Electric vehicle charging algorithms Consumer feedback	**Potential energy savings in TWh/yr (and % of total residential energy consumption)** Space heating – All fuels, Germany: 8.7 - 29.1 TWh/yr (1.3%-4.3%) Electricity - Appliances, Germany: 38.4TWh/yr (5.6%) Electricity All, UK: 2.6 TWh/yr (0.5%)

Table A- 9 continued

Ref	Country, Sector	Energy efficiency and conservation measures	Estimated potentials and conclusions
Nyholm et al, 2015 [131]	Sweden, Single-family dwellings	Demand response (DR) of electric space heating using: • electric boilers (with hydronic system) • direct electric heating (without hydronic system) • four types of heat pumps with different coefficients of performance (COP)	**Technical potential for DR from all electrical space heating systems** in Swedish single-family dwellings: 7.3 GW. **Increase in electricity demand for space heating**: 0.9% (152 GWh/yr)
Österbring et al, 2019 [120]	Sweden, Multi-family buildings	Eleven ESMs (see Mata et al, 2020 [129] above). Scenarios with different renovation logics (end-of-life of components or cost-effectiveness) and limitations for investment and renovation capacity.	**Highest reduction of energy use with the renovation logic end-of-life**, high investment and renovation capacity: (23%)
Mata et al, 2019 [121]	Sweden, Residential buildings	Thirteen retrofitting measures (nine single ESMs and four packages of ESMs, see Nik et al, 2015 [40]) Five climate scenarios.	**Potential energy demand reduction** (variations induced by climate scenarios) Insulating building envelope (different parts): 2.0% (+/- 0.2%) to 8.2% (+/- 1.0%) Thermostats for indoor temp. control: 8.3% (+/- 0.7%) to 14.6% (+/- 0.9%) Ventilation with heat recovery: 21.3% (+/- 1.9%) to 34.8% (+/- 4.8%) Lowering the indoor temperature to 20 °C: 8.3% (+/- 0.7%) to 14.6% (+/- 1.5%)
Ewald et al, 2021 [132]	European Union, Residential buildings	Changes in energy prices and income, effects on residential energy demand	"We find a long-run price elasticity of −0.5. The total long-run income elasticity is around 0.9, but if we control for the increase in income that goes towards larger homes and other factors, the income elasticity is 0.2. These findings have practical implications for climate policy and the EU buildings and energy policy framework."
Nik et al, 2015 [133]	Gothenburg, Sweden Residential building stock	Four retrofitting measures: • Change in U-value of cellar/basement, facades, attics/roofs • Replacement of windows Five climate scenarios.	**Reduction heating demand** (average) is highest for replacement of windows, on all the time scales. Conclusions: • Uncertainties induced by different climate scenarios and different time periods (20-year periods) do not affect the relative performance of the considered retrofitting measures.

Regarding efficient use of building materials in circular and sharing economy, the following strategies have been found and included:

- Efficient and circular use of building materials (utilising waste products in building materials, urban mining and recycling of building components and elements etc.)
- Efficient use of buildings (sharing offices, flexible architecture)

The potentials for increased efficiency in the use of materials are clear. Globally, combined circularity interventions can almost double the current global Circularity Metric of 8.6% and bringing it to 17% [70]. For the housing sector, potentials for material mass reduction until 2050 are 3.5 Gt for circular construction materials, 8.4 Gt for reducing floor space and 4Gt in resource efficient construction, interventions which combined can contribute to a reduction of emissions of 7.7 Gt CO_2e. Core interventions include banning construction with virgin materials and introducing policies to cap residential stock expansion which will be constrained by the availability of secondary materials from construction and demolition waste [70]. In a virtual special issue on climate mitigation from circular and sharing economy in the buildings sector with a geographic scope of Europe, North and South America [134] the improved management and production of concrete found to be of central importance in achieving climate mitigation, while reuse and recycling of other materials (wood waste, facades and urban mining) is also shown to contribute with significant reductions of GHG emissions.

In the scientific literature, barriers and enablers of a circular economy within the built environment have been identified. Both barriers and enablers are found to be of cultural, regulatory and financial character. A few examples of identified barriers are lack of collaboration, both within and between businesses, lack of consistent regulatory framework, high upfront investment costs and low virgin material prices. Moreover, sectorial barriers are also identified with long product lifecycles, technical challenges regarding material recovery and the absence of coherent vision for the industry. Among identified enablers are clear leadership, policy support for skills and innovation and new valuation techniques incorporating environmental, social and governance dimensions. [135]

From a Nordic perspective, policy instruments which can accelerate a circular transition of the Nordic construction sector have been suggested by actors representing sector stakeholders in Denmark, Norway, Finland and Sweden through interviews [71]. According to the interviewees, the resource consumption could be reduced by approximately 20% compared to the current consumption of building materials, which would result in a decrease of greenhouse gas emissions by approximately 10 million tonnes in total for all four Nordic countries.

Suggestions mainly focus on rules and regulations, with a lesser focus on economic incentives, agreements or providing supplementary information. The main policy instruments suggested are supplementary requirements for documentation of the content and quality of the building materials and new requirements for (1) waste and building demolition plans and (2) documentation of the use of reused building products and building products containing recycled resources [71]. Harris et al. [72] have evaluated de sustainability of several sharing solutions including office sharing. The estimated resource savings potential in office sharing is 24.4 to 34.4 Mt mass of materials, which is obtained through requirement reduction of 14–19.6 million m2 of office space. This could significantly reduce requirements to construct new offices as well as maintenance.

Modelling in ON-TIMES is performed by exogenously adding current building demand area for different types of buildings. Area demand is then one of the determinants of energy system solutions chosen by the model. Modelling results used for analysis in this report (NCES and

RePowerEU scenarios) therefore have a predetermined area demand, and do not give indications of possible efficiency gains of for example office sharing interventions. On order to get such results, area demand would have to be modelled according to potentials of area reduction like those mentioned above.

A summary of the studies can be found in Table A- 10.

Table A- 10 Previous studies on material efficiency in buildings.

Ref	Country, Sector	Measures investigated	Results/Potentials
Høibye & Sand 2018 [71]	The Nordic Construction Sector	Policy instruments to accelerate transition to circular construction sector.	The interviewees expect that the resource consumption can be reduced by approximately 20% compared to the current consumption of building materials in the buildings and construction sector today (a decrease of GHG emissions by approx. 10 million tonnes in total for all four Nordic countries). The policy instruments interviewees mainly suggest: 1. Supplementary requirements for documentation of the content and quality of the building materials. 2. New requirements for documentation of the use of reused building products and building products containing recycled resources in buildings. 3. New requirements for waste and building demolition plans.
The Circularity Gap Report 2021 [70]	Global, all sectors (incl. construction and housing)	Housing and construction: Limiting construction with virgin materials, policies to cap residential stock expansion and constraining it by the availability of secondary materials.	For the housing sector, potentials for material mass reduction until 2050 are 3.5 Gt for circular construction materials, 8.4 Gt for reducing floor space and 4Gt in resource efficient construction, interventions which combined can contribute to a reduction of emissions of 7.7 Gt CO2e.
Hart et al. 2019[135]	Built environment	Identifying barriers and enablers for the circular economy within the built environment.	Both barriers and enablers of cultural, regulatory and financial character. Examples of identified barriers: lack of collaboration within and between businesses, lack of consistent regulatory framework, high upfront investment costs and low virgin material prices. Sectorial barriers: long product lifecycles, technical challenges regarding material recovery, absence of coherent vision for the industry. Examples of identified enablers: clear leadership, policy support for skills and innovation and new valuation techniques incorporating environmental, social and governance dimensions. "Technological and regulatory developments alone will not suffice, a shift is required in business models and stakeholders' behaviours and attitudes."

Table A- 10 continued

Ref	Country, Sector	Measures investigated	Results/Potentials
Kyrö 2020 [136]	Existing buildings	Framework of circular economy in the built environment, focusing on existing buildings.	This paper suggests a literature-based framework comprising three complementary approaches to implementing circularity in the context of existing buildings: 1) Share; 2) Preserve; 3) Adapt, and; 4) Rethink. Sharing of spaces carries with it both technological and cultural prerequisites, and a paradigm shift from ownership to access. Preserve relates to the ongoing maintenance of buildings, while Adapt is related to more intrusive changes to maintain functionality and optimise use. These two elements are more technical and related to a required paradigm shift from producing new to maintaining old. Rethink comprises all novel circular business models, which challenge the existing paradigm of ownership and new production.
Harris et al. 2022 [134]	Nine studies covering Europe, North and South America Building sector	Concrete: Modelling quantities (current/future), assessing impacts of reuse and recycling. Waste recovery: construction waste, wood waste for bio-concrete, urban mining.	Significant reductions in greenhouse gas (GHG) emissions are demonstrated for utilising waste wood in bio-concrete, sharing offices, urban farming and recycling building facades. The need for planning and circular management to enable recycling of concrete is highlighted. Potential trade-offs are identified in terms of limited improvements in the climate footprint and increased water use. This suggests a need for improved design and recycling processes to reap the environmental benefits of recycling concrete. Going beyond concrete and metals in an assessment of over 350 components and materials, urban mining is shown to be economically beneficial, and with significant prospects for savings of embodied carbon. There is a need for increased awareness, quantification of benefits, support for demolition contractors and separation methods for façade components.
Harris et al. 2021 [72]	Sweden, Office buildings	Sustainability implications of sharing offices in Sweden.	Sharing offices could lead to a significant reduction in total required floor area and lead to substantial reductions in GHG emissions. The estimated resource savings potential in office sharing is 24.4 to 34.4 Mt mass of materials, which is obtained through requirement reduction of 14–19.6 million m2 of office space. This could significantly reduce requirements to construct new offices as well as maintenance.

Table A- 11: Scenarios in previous studies – aim and features.

Ref	Scenario name and number of scenarios	Country, region	Baseline/ Final year	Aim	Scenario narrative
Nik et al, 2015 [133]	Five climate scenarios RCA3 (regional climate model) 50 km horizontal resolution.	Sweden	1961/ 2100	Assessing efficiency and robustness of retrofitting measures against climate change	Retrofitted vs. non-retrofitted buildings compared in different climate futures
Mata et al, 2019 [121]	Five climate scenarios (see Nik et al. 2015)	Sweden		Assess the impact of input uncertainties on future climate scenarios in the evaluation of different retrofitting measures, particularly the (1) criteria potential for CO_2 mitigation (2) economic feasibility	Uncertainties of future climate (and other uncertainties such as geographical location and energy prices) and possible effects on evaluation of retrofitting measures.
Mata et al, 2018 [56]	Two scenarios for each of five EU member states: 1.Reference 2. Implementation of energy conservation measures	EU	2009-2012/2030, 2035, 2050	Provide homogenous mapping of the potential for energy savings in EU buildings.	Potentials of lowering energy demand and CO_2 emissions through implementation of energy saving measures.
Camarasa et al, 2022 [76]	Two scenarios (for all regions and countries): 1.Reference scenario 2.Decarbonisation scenario.	Global	2020/ 2050	Share insights from national building sector models to describe carbon mitigation scenarios by 2050 and compare them to results from global models in line with 1.5°C–2°C scenario goals.	Investigating scenarios for building sector decarbonisation on country, regional and global level.
Mata et al, 2020 [130]	3 scenarios for carbon intensity of electricity	EU	-	Assessing how digitalisation of the grid edge contribute to climate mitigation from residential buildings	Scenarios for carbon intensity of electricity influencing potential reduction in CO_2 emissions from load shifting

Table A- 11 continued

Ref	Scenario name and number of scenarios		Baseline/ Final year	Aim	Scenario narrative
Mata et al, 2012 [118]	Two scenarios: 1. Baseline 2. Implementation of energy saving measures	Sweden	2005/-	Assessing the effects of applying a set of energy saving measures to all residential buildings in Sweden.	Reduction of final energy demand of the Swedish residential sector by application of energy saving measures
Mata et al, 2020 [60]	Two scenarios to account for renovations driven by (1) solely technical renovation needs (end-of-life of building components) (2) cost efficiency	Sweden	2015/ 2050	Incorporate the realities of the decision-making process for building renovations in building-specific stock modelling. Identify locally optimal renovation strategies and key determinants of the long-term deployment of renovation strategies.	Renovation is driven by either (1) technical renovation needs or (2) cost-efficiency. Renovation scenarios (incl. future energy demand) are presented based on the two decision-making strategies.
Österbring et al, 2019 [120]	Two scenarios for renovation logic: (1) end-of-life and (2) cost-effectiveness	Sweden	2015/ 2050	Explore the environmental impact of future development of an urban housing stock.	Renovation logic (end of life, cost-efficiency) effects on potential in energy savings and reduction in greenhouse-gas emissions
Mata et al, 2014 [52]	Three energy price development scenarios: 1.Baseline 2.High-price-increase 3.Low-price-increase	Sweden	2010/ 2020, 2030, 2040, 2050	Explore how the cost-effectiveness of different energy-saving measures in buildings is dependent upon assumptions of energy prices and discount rates.	The scenarios are a description of possible future development of the energy system in terms of energy prices for the different energy carriers used in the buildings.
Nyholm et al, 2015 [131]	Two demand response (DR) scenarios: 1.No DR occurs. 2.Optimisation of DR by minimising electricity cost.	Sweden	Normal-price year (2012)/ High-price year (2010)	Investigating the demand response potential, (for electric space heating in Swedish SFDs using the thermal inertia) in terms of influence on the electricity load curve and reduction of electricity costs.	Potential monetary savings in load shifting through optimisation of demand response. Range of savings potential through comparison normal/high-price year.
Ewald et al, 2021 [132]	Varying energy price	Europe	1990/ 2018	Examine the importance of changes in energy prices and income on residential energy demand.	Investigating economic determinants of energy demand for future modelling and policymaking.

A3.3. Insights from GAINS model - Summary of studies

Comparing differences between emissions in the GAINS Swedish scenario and in the emissions in the official Swedish national reporting, showed that emissions were generally suitably aligned for SO_2, while NOx and PM2,5 emissions differed. The identification of data sources and the use of a systematic method for transferring data from Swedish sources to the GAINS model format allows for sensitivity analysis on alternative futures.

According to the Swedish emission projections, the national total emissions of all short-lived climate pollutants (SLCP) will be lower in 2030 compared to today. Emissions from residential combustion of biomass are expected to remain at about the same level as at present. The most cost-effective measures in the analysis were an increased proportion of pellets as biomass fuel replacing wood logs in residential combustion. The technically possible total potential, as a sum of all the analysed SLCP actions, is equivalent to 0.1-3% of Sweden's total estimated GHGs 2030. The measures analysed were relatively expensive from a climate perspective when compared to average cost levels to abate CO_2. As a result of reduced emissions of air pollutants, also provide important synergies such as a reductions of adverse health effects.

A project was performed that estimated potential impact on air emissions and abatement costs. The analysis implicates that scrapping of old units might be more important to reduce emissions of air pollutants than an increased share of new technologies. For example, small-scale wood combustion in residential buildings, scrapping of very old units would give a large effect on emissions of PM2,5 in 2030.

A GAINS project evaluated the implementation of mitigation measures and assess impacts of Black carbon (BC), Organic carbon (OC), CO_2 and O_3-precursors short-lived climate forcers (SLCF). The Swedish abatement costs for different SLCF abatement options varied strongly, but the same abatement options show up as the most cost effective in all scenarios. The most cost-effective measures decreasing BC emissions from power production, and renewing of domestic fuel wood boilers, are found to be in the same range as CO_2 ETS (EU Emissions Trading System) price projected for Sweden in 2020.

In the research project SunHorizon, implementation of innovative and reliable Heat Pumps coupled with advanced solar panels (PV, hybrid, thermal) that provided heating and cooling to residential and tertiary buildings with lower emissions, were analysed. For most substances, emission factors are lower than for conventional technologies, compared to the baseline development in 2030 and 2050. This result in lower concentrations of primary and secondary PM2.5 and ground-level ozone. The total monetised health and climate benefits in EU-28 from implementation of SunHorizon technologies are about 30 billion € year 2030 and about 80 billion € in year 2050. If monetised health effects in the entire Europe, the total human health-related benefits become 6 – 7% higher.

Measures to reduce emissions of SLCP in the Nordic countries were analysed in a project with combined SLCP analysis using the GAINS model. The measures in the model aimed at residential combustion can reduce BC emissions in 2030 by 3.7 kt – which is about 79% of the estimated total technical BC emission reduction potential in the Nordic countries. Part load combustion in boilers increased the emissions between 2– 6 times, while moist fuel increased the emission by a factor of 1.5–2. Modern stoves are sensitive to moist fuel, where emissions of for example PM2,5 and OC increased in the order of 5–8 times, likely due to limited capacity of the air. To improve the national emission inventories the large sensitivity to operational conditions needs to be taken into consideration. Country-specific assessments on shares of "bad combustion conditions" are essential to properly weigh bad combustion.

Table A- 12 Previous studies *GAINS*

Ref	Country , Sector	Measures	Estimated potential	Main conclusion
Åström et. al. 2013 [137]	Sweden, All sectors	Air pollution control	Cost-effective reduction of emissions of air pollutions	The purpose was to create a robust system for development of national emission scenarios in the GAINS model that are consistent with Swedish official emission inventories and emission projections. Comparing and analysing differences between emissions in the Swedish scenario in the GAINS model and the emissions in the official Swedish national reporting, showed that emissions were suitably aligned for SO_2, while NOx and $PM_{2.5}$ emissions differed. Further development of the approach used during re-allocation and re-aggregation of data is needed, as well as increased national knowledge regarding the current and expected use of air pollution emission control technologies in Sweden. The identification of data sources and the use of a systematic method for transferring data from Swedish sources to the GAINS model format allows for sensitivity analysis on alternative futures. This allows Sweden to have easy access to decision support material for Swedish negotiators on international air quality issues calculated by using the same model as is used by the CLRTAP secretariat and the CLRTAP Centre for Integrated Assessment Modelling (CIAM) in the negotiations. The project results can also, given further development, allow for decision support under the EU negotiations for burden agreements of non-CO_2 GHG.
Åström et. al. 2016 [138]	Sweden, road transport, Non-road mobile machinery, small scale wood heating	GHG, air pollutions: Eight different measures within the current sectors, with focus on subsidies and technology exchange	Potential impact on air emissions and abatement costs	The project has been performed on commission from the All Party Committee on Environmental Objectives estimated potential impact on air emissions and abatement costs. The best impact on emissions of greenhouse gases and air pollutants was found following a large transition of the entire transport system. Such a transition requires a combination of different measures, both with respect to reduced transport demand as well as reforms that stimulate new technologies (such as electric vehicles). Electrification might prove to have a tangible impact on emissions of air pollutants. Some climate measures such as biofuels can give small or no effects with respect to air pollution. A quota for biofuels is however income neutral for the governmental budget. The effect of subsidies for purchasing low-emitting heavy vehicles and machinery on emissions is mainly influenced by how many old vehicles and machinery that will be in use year 2030. The analyses implicate that scrapping of old vehicles and machinery might be more important to reduce emissions of air pollutants than an increased share of new vehicles and machinery. The same effect applies for small-scale wood combustion, for which a scrapping of very old units would give a large effect on emissions of $PM_{2.5}$ in 2030.

Table A- 12 continued

Ref	Country , Sector	Measures	Estimated potential	Main conclusion
Åström et. al. 2011 [139]	Sweden, Transport	CO_2: Increase share of biofuels	Insignificant	The use of ethanol and biodiesel in the transport sector is increasing in line with the latest legislation, stimulating use of biofuels in efforts to reduce CO_2 emissions. Calculation results indicate that introducing emission factors for biofuels does not have a significant effect on air pollutant emissions from the transport sector in Sweden. Reported emission factors for vehicles using biofuel vary considerably. An important prerequisite for obtaining reliable emission results in the GIAINS model is properly quantified emission factors. Despite the small influence of biofuel use on the road and total national emissions of NO_x and PM, the availability of the developed approach, enabling emission calculations with respect to emission factors for biofuels, contributes to better reflection of $_x$s and trade-off between air pollution and greenhouse gas mitigation in the GAINS model.
Hellsten, 2017 [140]	Sweden, Agriculture	Ammonia: Low nitrogen feed, low ammonia application of manure, and low emission manure storage.	Up to 26% reduction of ammonia emissions between year 2005 and 2030	The aim of this study was to compare ammonia emission estimates and projections from the national Swedish inventory (SMED) and the GAINS model. A further objective was to identify the most promising policy options and best available techniques to reduce ammonia emissions from agricultural practices in Sweden, and thus reducing their harmful environmental effects. The most cost effective ammonia abatement measures in Sweden are low nitrogen feed, low ammonia application of manure, and low emission manure storage. Measures to reduce housing emissions, e.g. designing the stable to reduce the surface and time manure is exposed to air, are also rather cost effective, particularly for new stables. An important policy challenge with a great potential to reduce overall emissions of ammonia is measures to reduce meat and dairy consumption and measures to reduce food waste. An important policy challenge with a great potential to reduce overall emissions of ammonia is measures to reduce meat and dairy consumption and measures to reduce food waste. In this context it is also important to consider the effect of emissions derived in other countries due to increased import.
Yaramenka et al., 2017 [141]	Sea transport	Help guide actions to reduce emissions of particulate matter that are also effective in reducing black carbon emissions.		

Table A- 12 continued

Ref	Country , Sector	Measures	Estimated potential	Main conclusion
Kindbom et. al. 2015 [142]	Sweden, All sectors	SLCP: Increased proportion of pellets as biomass fuel replacing wood logs in residential combustion, and anaerobic digestion of manure.	0.1-3% of Sweden's total estimated greenhouse gas emissions in 2030	Compilation current and expected future Swedish emissions of SLCPs until 2030, based on recent official Swedish emissions inventory reporting and emission projections. focus of the study is on the time period 2010-2030 and emissions of black carbon (BC), methane (CH_4) and volatile organic compounds (NMVOC).The focus was the years 2010-2030 and emissions of black carbon (BC), methane (CH_4) and volatile organic compounds (NMVOC). According to the Swedish emission projections, which take current legislation into account, the national total emissions of all SLCPs will be lower in 2030 compared to today. The trend, however, is different for different sources. Emissions from road traffic are expected to decline significantly. From other mobile sources reductions are also expected, but to a lesser extent than from road traffic. Emissions from residential combustion of biomass are expected to remain at about the same level as at present. CH_4 from the agricultural sector, as well as NMVOC from product and solvent use, are both reduced only slightly to 2030. Emissions of CH_4 and NMVOC from other sources are projected be reduced to a greater extent. The most cost-effective measures, is an increased proportion of pellets as biomass fuel replacing wood logs in residential combustion, and anaerobic digestion of manure in the agricultural sector. The technically possible total potential, as a sum of all the analysed SLCP actions, is equivalent to 0.1-3% of Sweden's total estimated GHGs 2030. The measures analysed are relatively expensive from a climate perspective when compared to cost levels usually discussed for measures to abate CO_2. The measures analysed result in a reduced climate impact but, as a result of reduced emissions of air pollutants, also provide important synergies such as a reductions of adverse health effects.
Yaramenka et al., 2014 [143]	Sweden, Long Heavy Duty Vehicles	Energy efficiency in Transport and Traffic work, emission mitigation	One conventional Eouropean vehicle would consume 22 % less fuel per traffic work but 30% more fuel per transport work than one long heavy duty vehicle.	The objective was to explore possible approaches to explicitly incude long heavy duty vehicles in the GAINS model to assess their fuel efficiency. The main conclusion is that it is possible to develop an integrated assessment model method for presenting long heavy duty vehicles as a fuel efficiency option in the transport sector in the GAINS model.

Table A- 12 continued

Ref	Country , Sector	Measures	Estimated potential	Main conclusion
Hansson et al. 2012 [144]	Sweden	Implementation of mitigation measures and assess impacts f Black carbon (BC), Organic carbon (OC), CO_2, O_3-precursors	The three most cost effective options covered about 30% of the present emissions. Fuel efficiency improvements, fuel shifts, as well as scrapping schemes.	Techniques involving combustion should be reviewed concerning emissions.It is clearly shown that regulation of SLCF can give co-beneficial effects on climate, health and ecosystem. However it cannot replace the abatement of long-lived climate forcers but rather increase the climate response to the abatements. The reductions needed for 2050 and beyond have to be large. Combustion is the basic process in the major common sources 6 for CO_2, O_3-precursors and particles including BC. Combustion has to be questioned as a part of future sustainable transport systems, energy and heat production.The Swedish abatement costs for different SLCF abatement options varied strongly. The same abatement options show up as the most cost effective in all scenarios. The most cost effective measures found, e.g. decreasing BC emissions from power production and renewing of domestic fuel wood boilers, are found to be in the same range as CO_2 ETS price projected for Sweden in 2020. The cost estimates were in line with other studies. The measures studied represent only a very small fraction of all options available to reduce BC emissions. The cost effectiveness of more alternatives in both the mobile and stationary sectors should be assessed. In conclusion, the options analysed in this study are found to be effective complements, both from health and climate point of view.
Sun Horizon 2020 [145]	EU Members States	Implementation of inovative and reliable Heat Pumps coupled with advanced solar panels (PV, hybrid, thermal) that can provide heating and cooling to residential and tertiary buildings with lower emissions, energy bills and fossil fuel dependency.	For most substances, emission factors are lower than for conventional technologies, compared to the baseline development in 2030 and 2050. This result in lower concentrations of primary and secondary $PM_{2.5}$ and ground-level ozone, and, subsequently, in reduced negative health effects.	The total monetised health and climate benefits in EU-28 from implementation of SunHorizon technologies are about 30 billion € year 2030 and about 80 billion € in yesr 2050. If monetised health effects in the entire Europe, including non-EU countries, are considered in the analysis, the total human health-related benefits become 6 – 7% higher. Estimating country-specific benefits from implementation of SunHorizon technologies in the EU Members States, and expressing them in monetary terms, are aimed at providing investors and strategic decision-makers with additional analysis for further justification of SunHorizon technologies' wider deployment in the coming years.

Table A- 12 continued

Ref	Country , Sector	Measures	Estimated potential	Main conclusion
Economic Commission for Europe [146]	First region: EU, Second region: non-EU Eastern Europe, Third region: Norway, Switzerland, UK	First region: Control of agricultural waste burning and replacement of older wood-fuelled stoves. Second region: controlling emissions from cement production, cleaner coal-fuelled, heating stoves and bans on trash burning. Third region: ban on agricultural waste burning, and increased utilisation of new wood-fuelled stoves and pellet stoves.	See Main Conclusion	The baseline scenario results for the first region indicate that, between 2020 and 2030, implementation of emission control measures in industry would abate 7 kilotons of PM2.5 emissions, but almost no BC emission abatement is anticipated. A technical potential to further control 2030 emissions with more than 300 kilotons of PM2.5 with measures that ensures high priority to BC emission control. for the second region indicate that 22 kilotons of PM2.5 emissions would be abated between 2020 and 2030 through controlling emissions from cement production, without much BC emission abatement. Measures technically available by 2030 that also ensure high priority to BC emission abatement include cleaner coal-fuelled heating stoves and bans on trash burning. All in all, between 2020 and 2030, the scenarios suggest a technical potential to further control 128 kilotons of PM2.5 emissions whilst still ensuring high priority to BC emission control. The scenario results for the third region. about 20 per cent of the total modelled 246 kilotons of PM2.5 emission reduction for the period 2020–2030 does not imply any noticeable change in BC emissions. There is significant remaining technical potential for measures ensuring high priority to BC emission reduction. A full-scale effective ban on agricultural waste burning, and increased utilisation of new wood-fuelled stoves and pellet stoves, are two important measures ensuring high BC priority.
Kindbom et al., 2018 [147]	Nordic countries	Moist fuel or part heat load conditions. Drier fuel, higher heat loads, or entering other sizes batches of wood than prescribed in the standards.	See Main Conclusion	Part load combustion conditions in the boilers increased the emissions between 2– 6 times, while moist fuel generally increased the emission levels by a factor of 1.5–2. The modern stoves were sensitive to moist fuel, where emissions of for example PM2.5 and OC increased in the order of 5–8 times compared to when fired with standard fuel. The higher impact from moist fuel in the modern stoves is likely due to limited capacity of the air systems in many modern stoves. For the stoves, part load conditions generally increased the emission levels by 1.5–3.5 times. To improve the national emission inventories the large sensitivity to operational conditions needs to be taken into consideration, where "real life" emissions are estimated. Countryspecific assessments on shares of "bad combustion conditions" are essential to properly weigh bad combustion.

Table A- 12 continued

Ref	Country, Sector	Measures	Estimated potential	Main conclusion
Yaramenka et al., 2018 [148]	Belarus, Nordic countries	End-of-pipe solutions (electrostatic precipitators, high-efficiency dedusters) for industrial furnaces and residential boilers, replacement of conventional boilers with improved devices.	Emission reduction potential is estimated at 35.2 ktonnes for PM2.5 and 2.5 ktonnes for BC. High emission reduction potentials are observed in sectors with the largest contribution to the total emissions, implying that mitigation efforts should be taken in the key source sectors.	The most cost-effective measures for BC emissions in Belarus according to this analysis are end-of-pipe solutions (electrostatic precipitators, high-efficiency dedusters) for industrial furnaces and residential boilers, as well as replacement of conventional boilers with improved devices. These measures would result in significant black carbon emission reductions at relatively low costs. The total (brutto) societal benefits from full implementation of the MFR scenario in Belarus are estimated at between EUR 600 (VOLY – Value of a Life Year lost) and 2,100 (VSL – Value of Statistical Life)) million annually. About half of it corresponds to avoided negative impacts on population health in the neighbouring countries. Particle emissions in each of the considered countries affect population in the other countries, with the exception of Belarus-to-Denmark and Finland-to-Denmark cases.

A4 SINTEF

A4.1. Results of the RePowerEU scenario

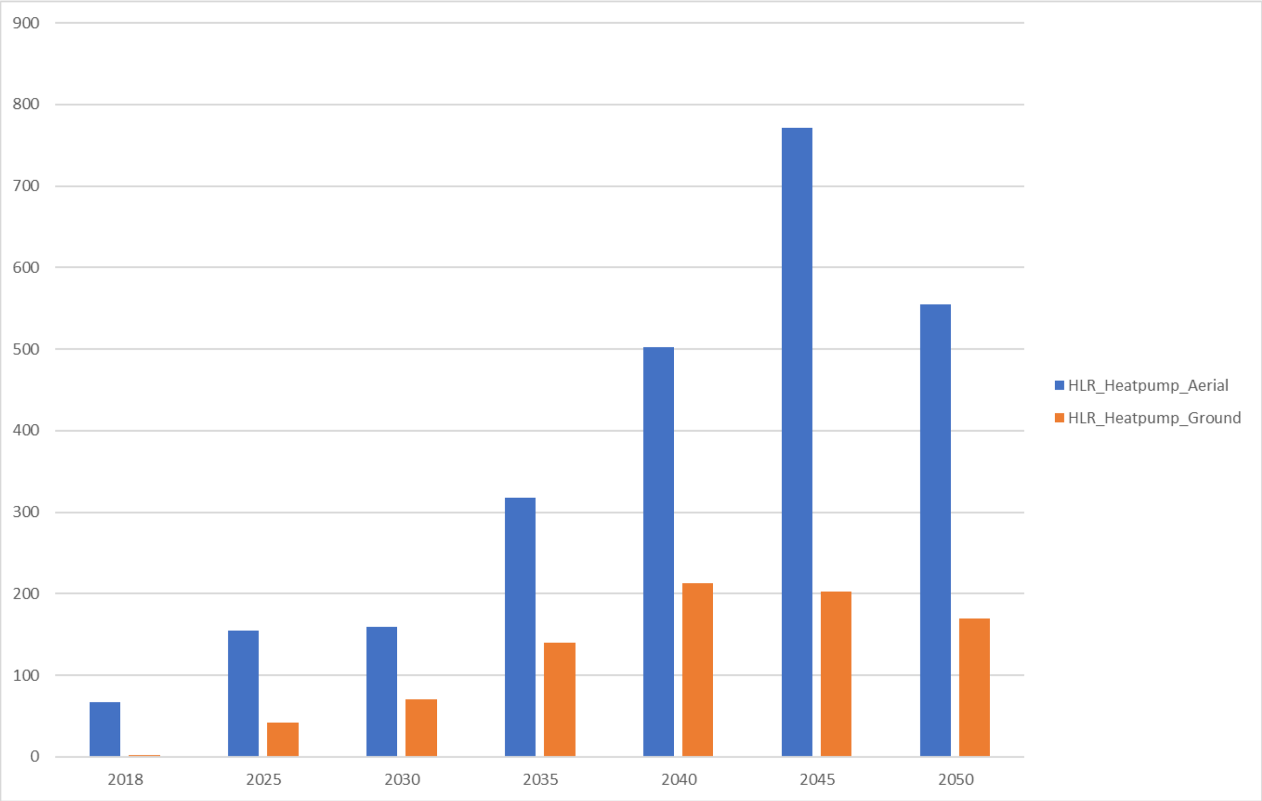


Figure A- 15: Heat pumps in residential sector

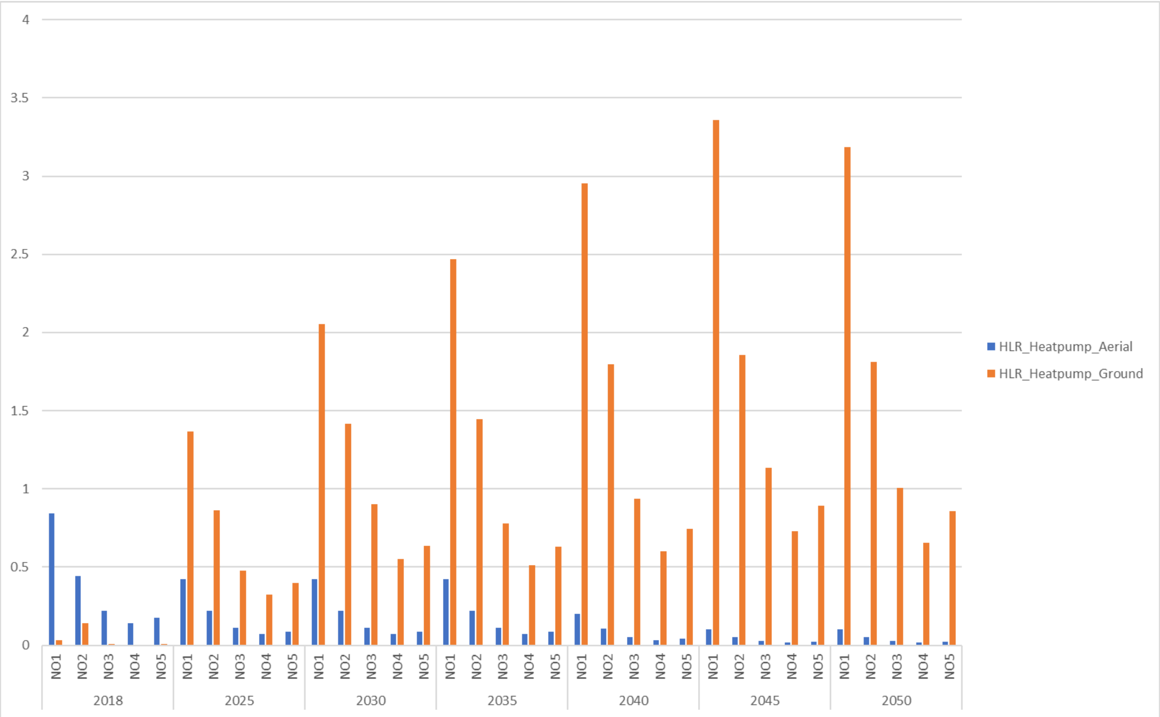


Figure A- 16: Heat pumps in industrial sector

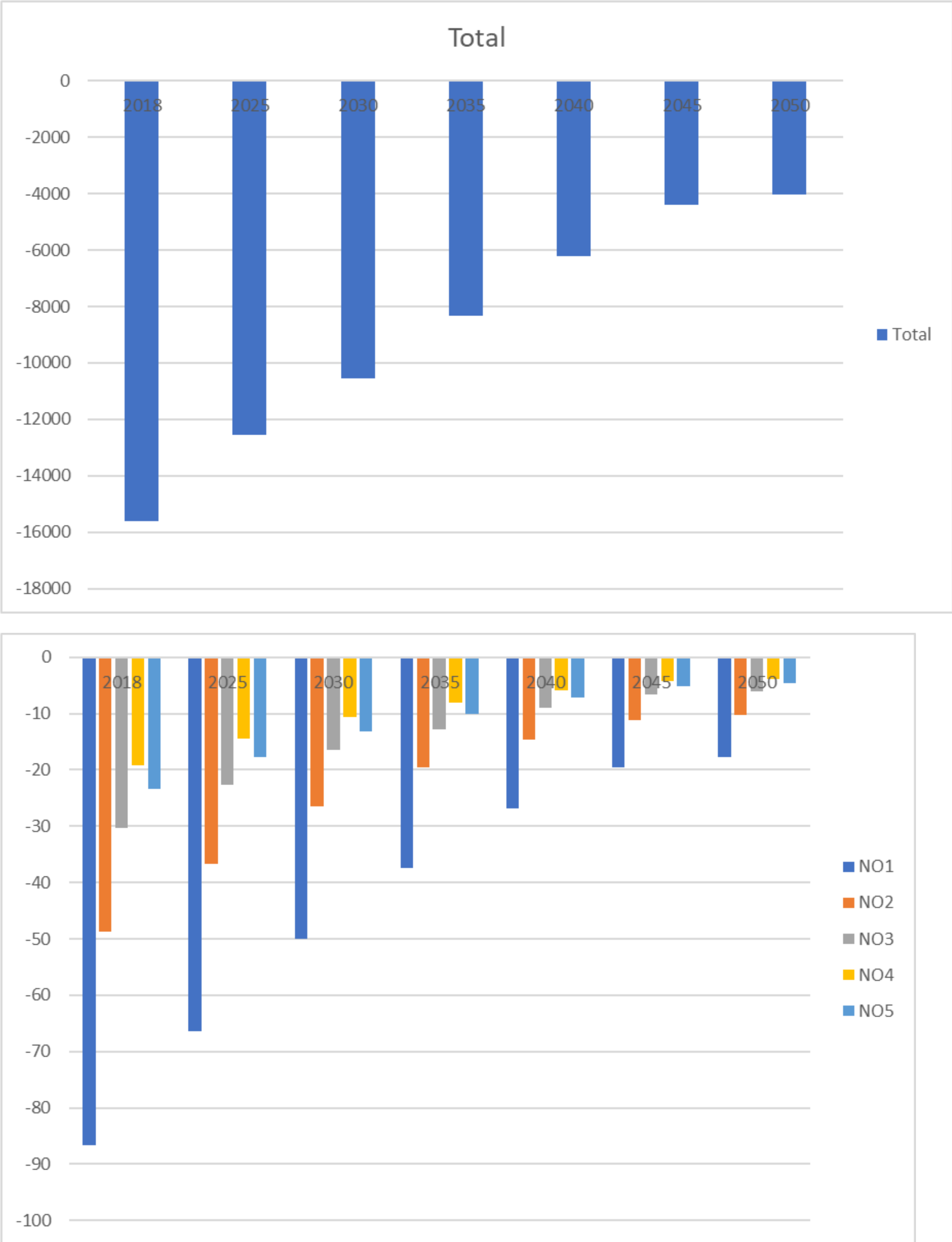


Figure A- 17: Energy used for heating in buildings

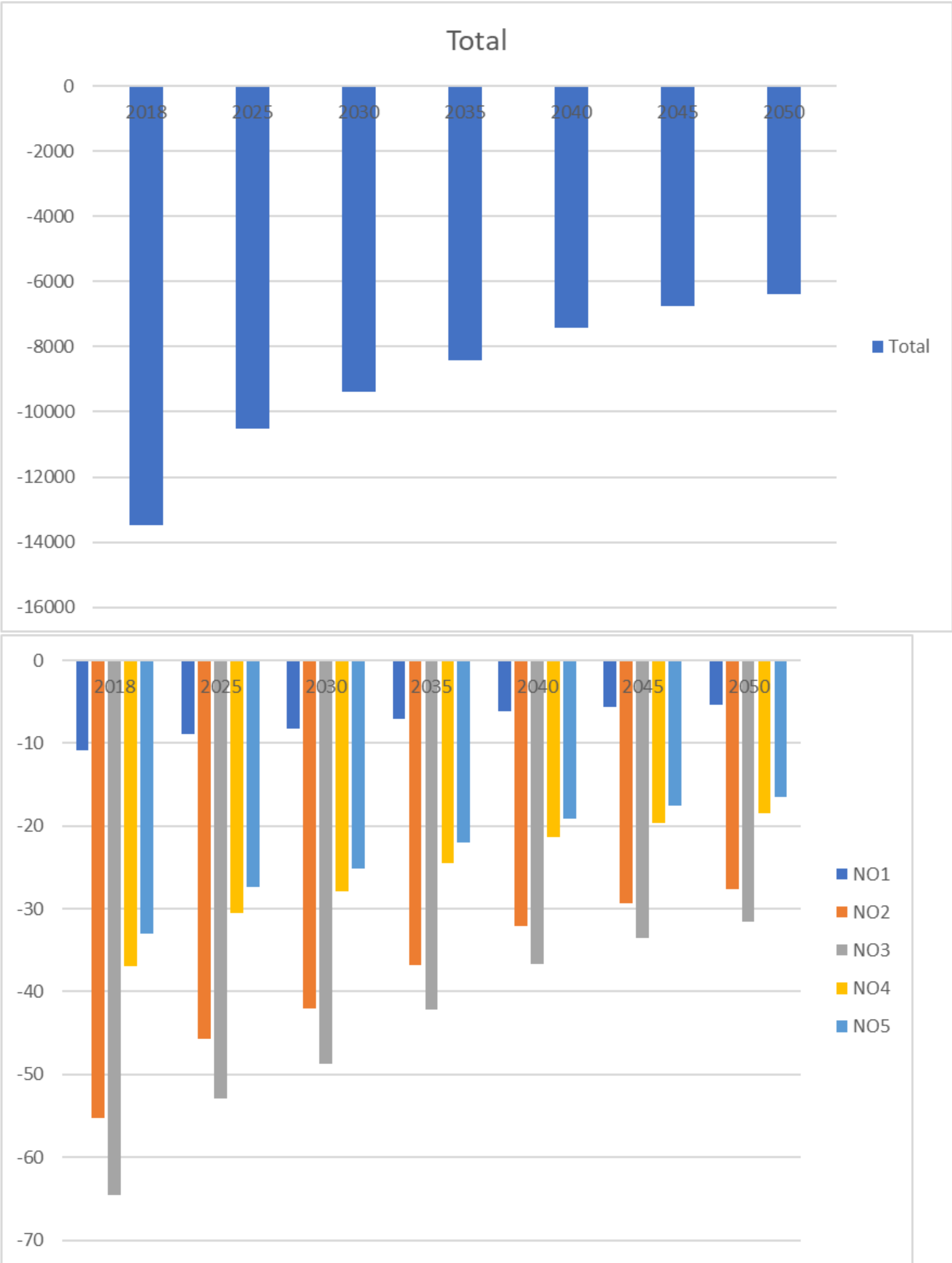
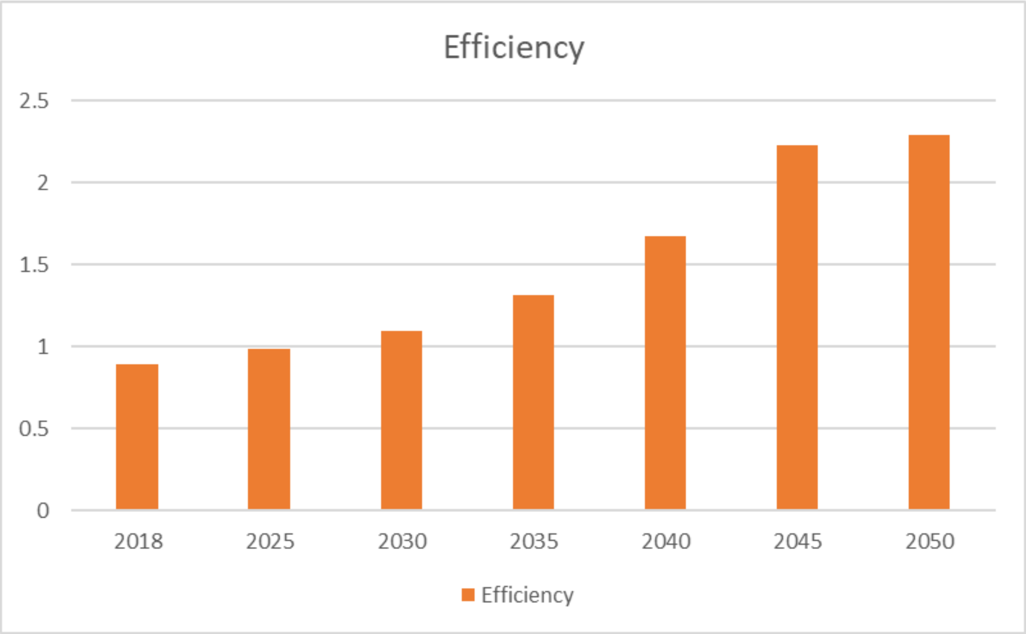


Figure A- 18: Energy used for Industrial heat



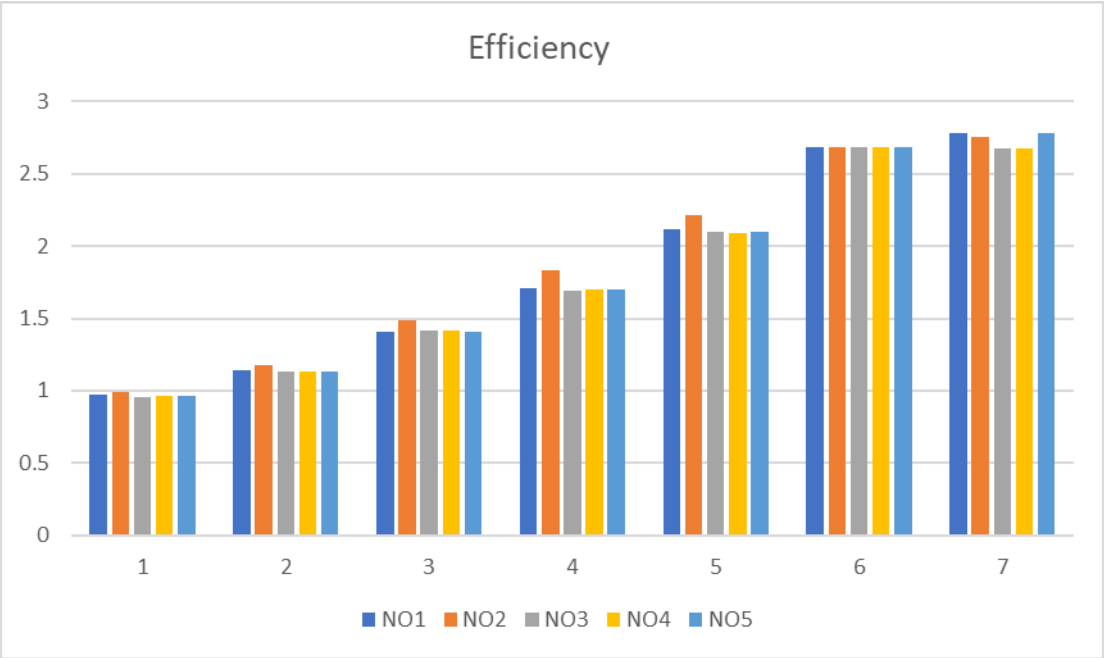
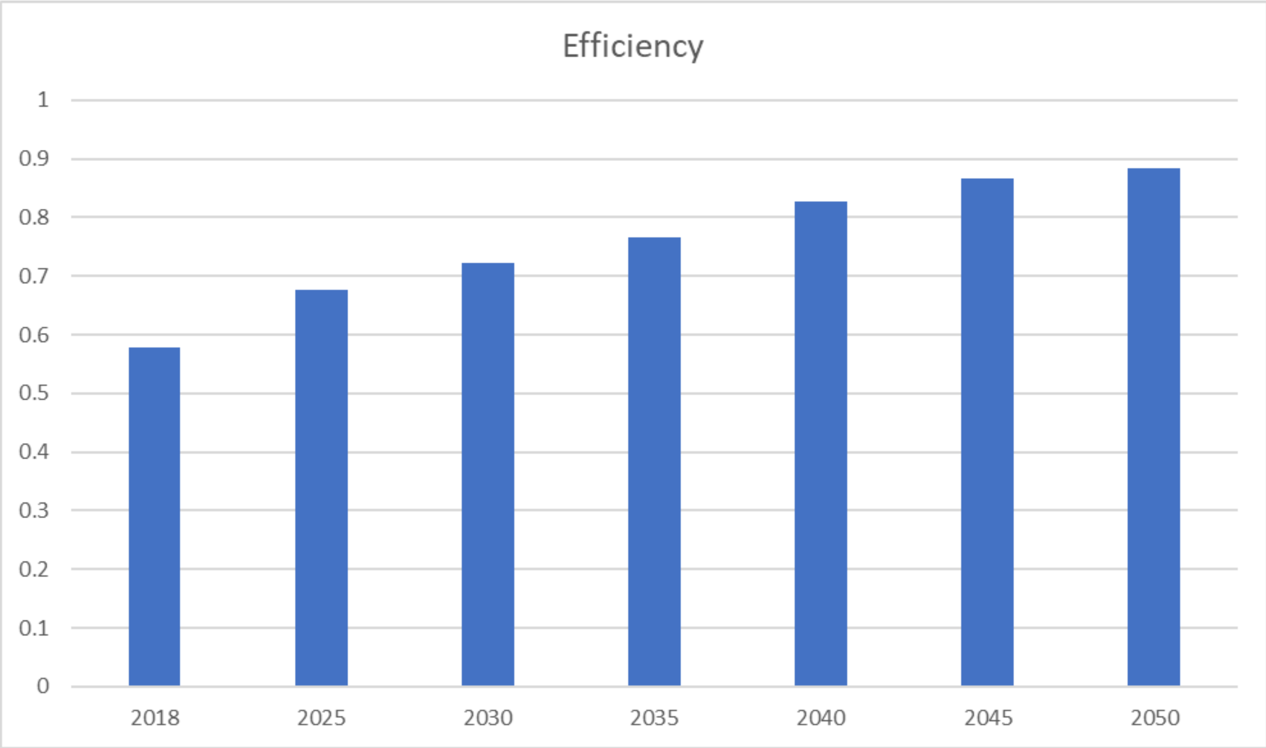


Figure A- 19: Energy efficiency residential sector



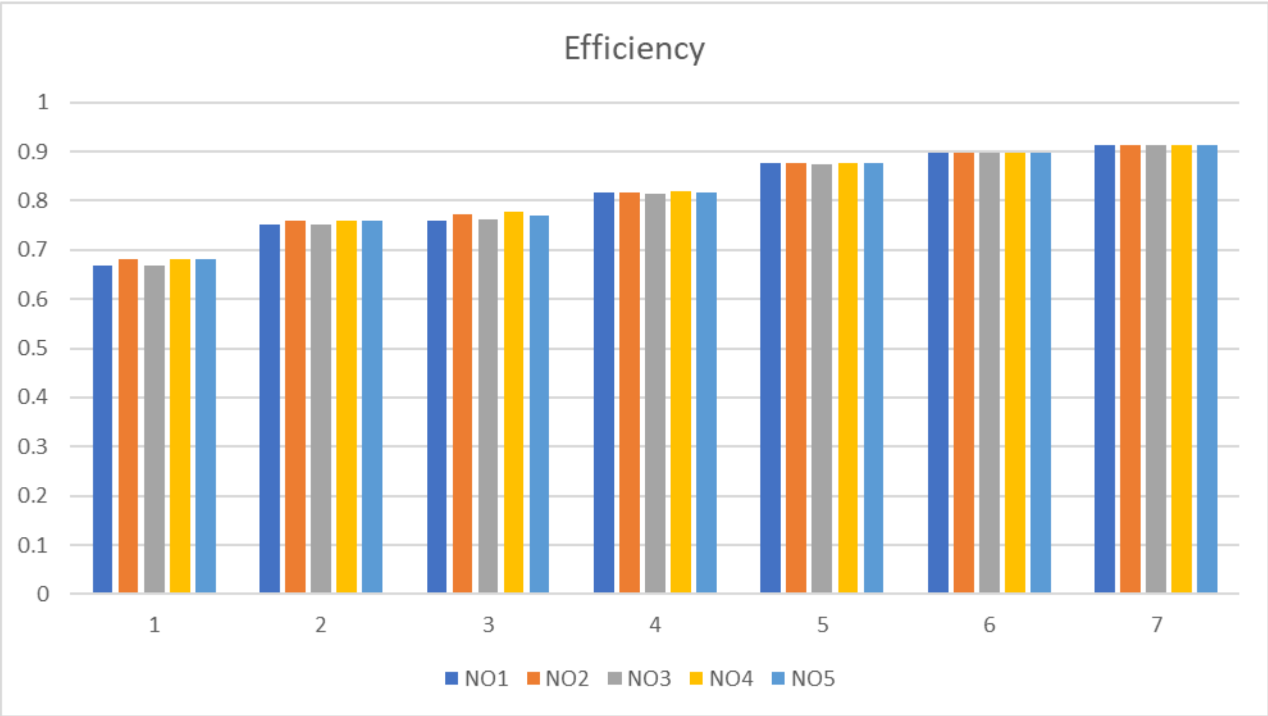


Figure A- 20: Energy Efficiency industry

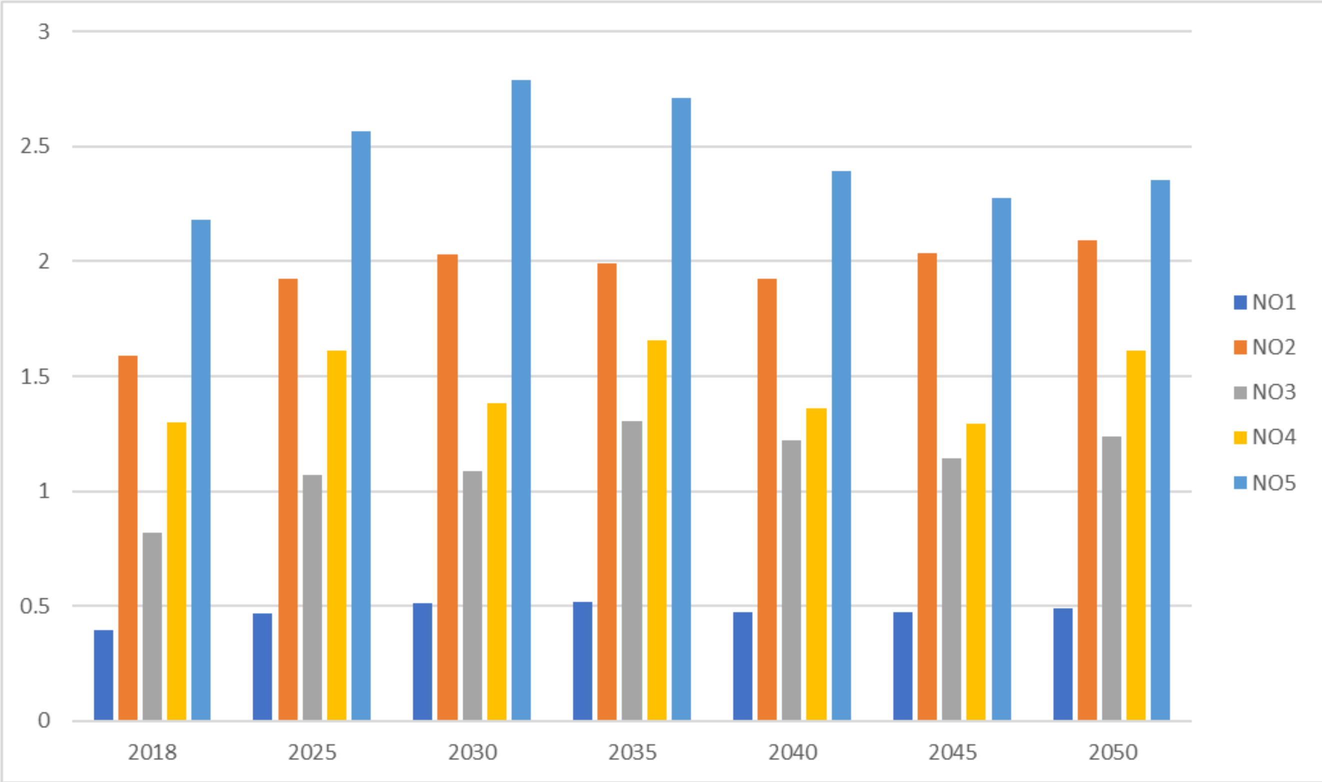


Figure A- 21: Self-sufficiency rate

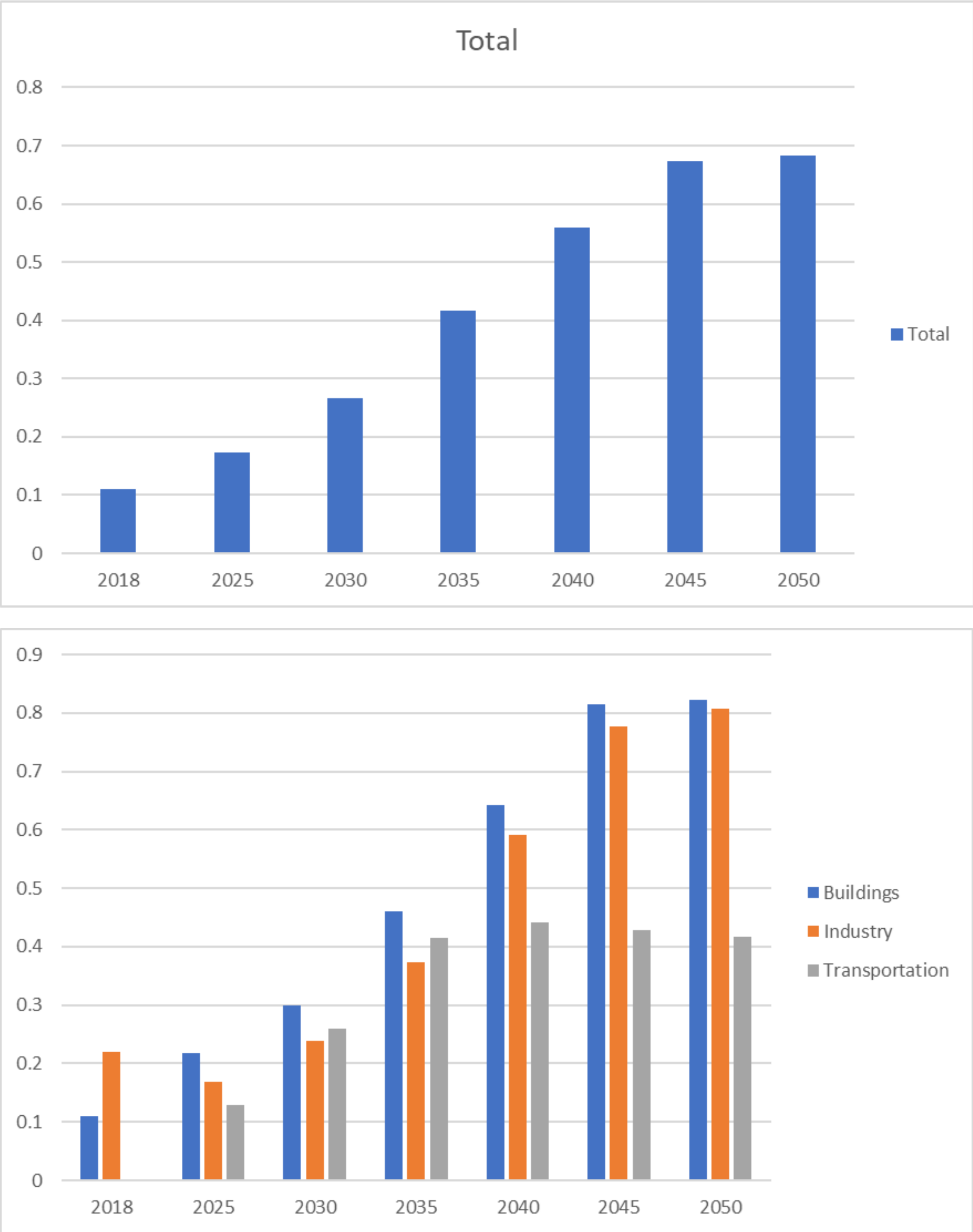


Figure A- 22: Electrification rate

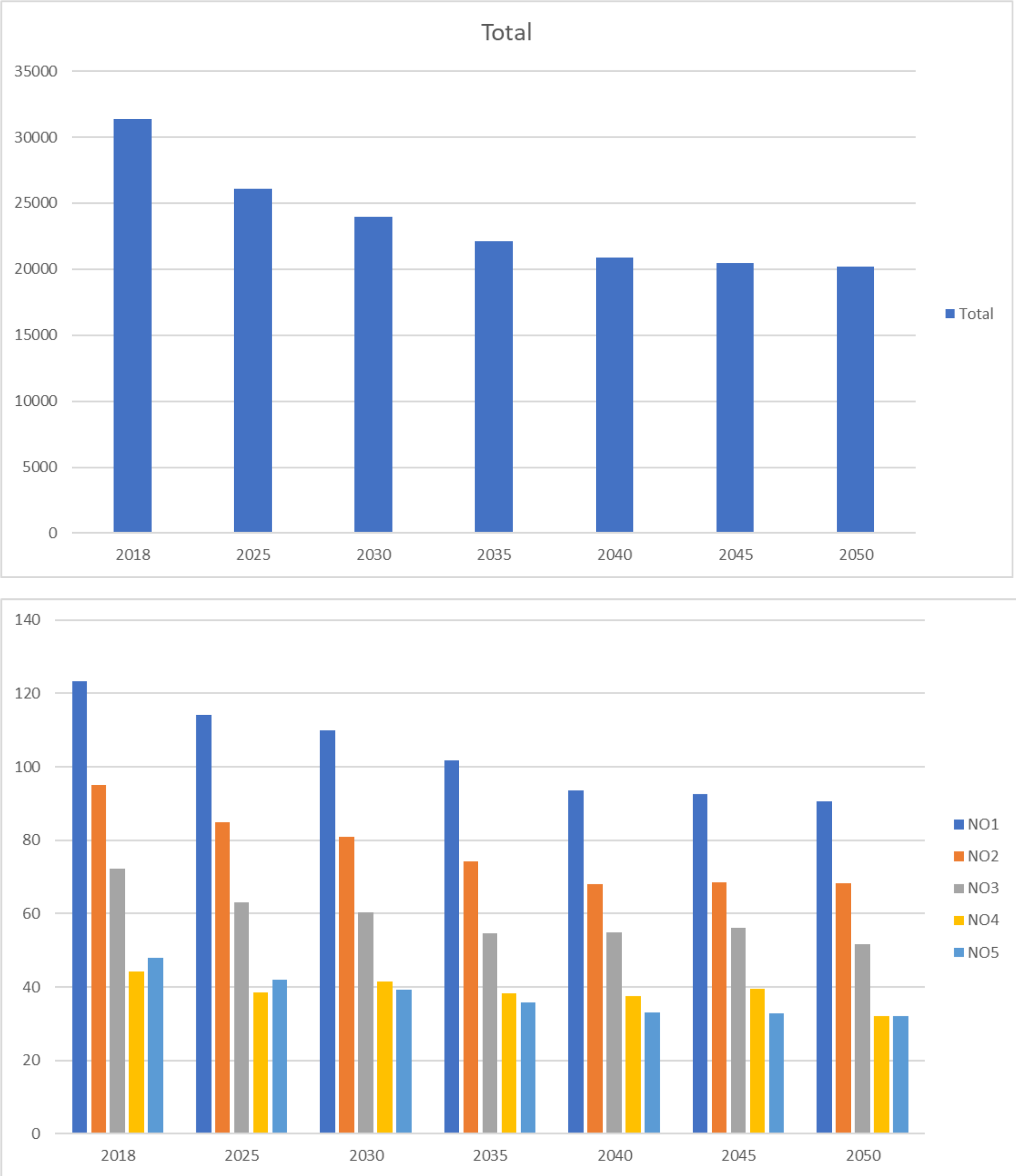
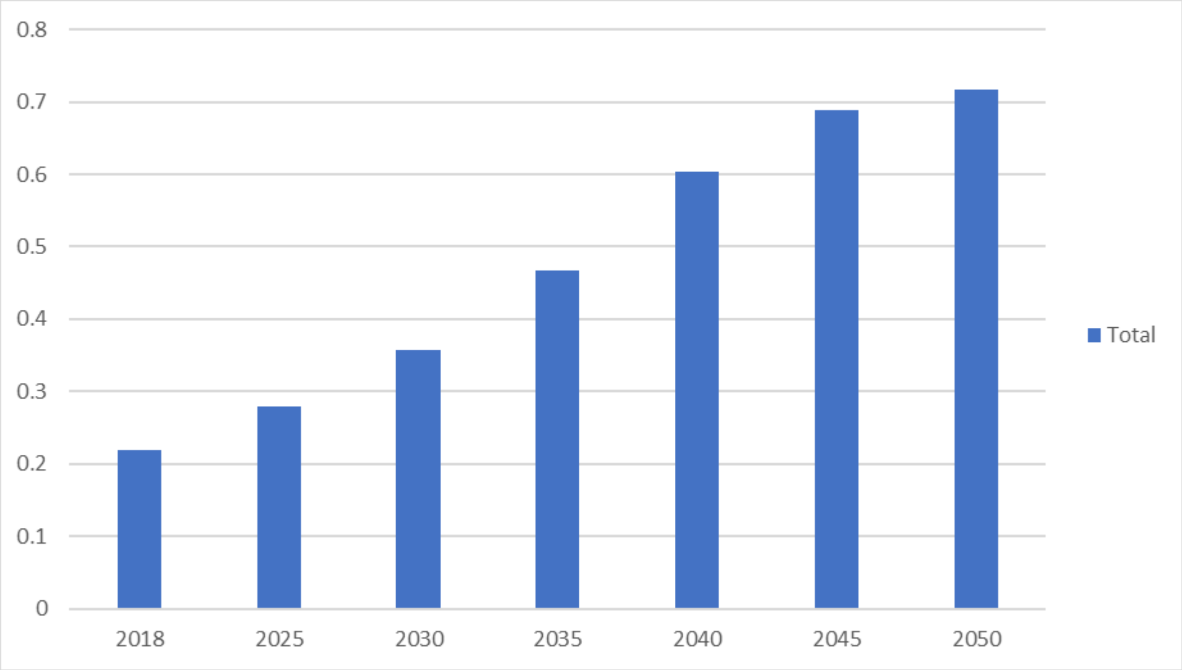


Figure A- 23: Final energy consumption



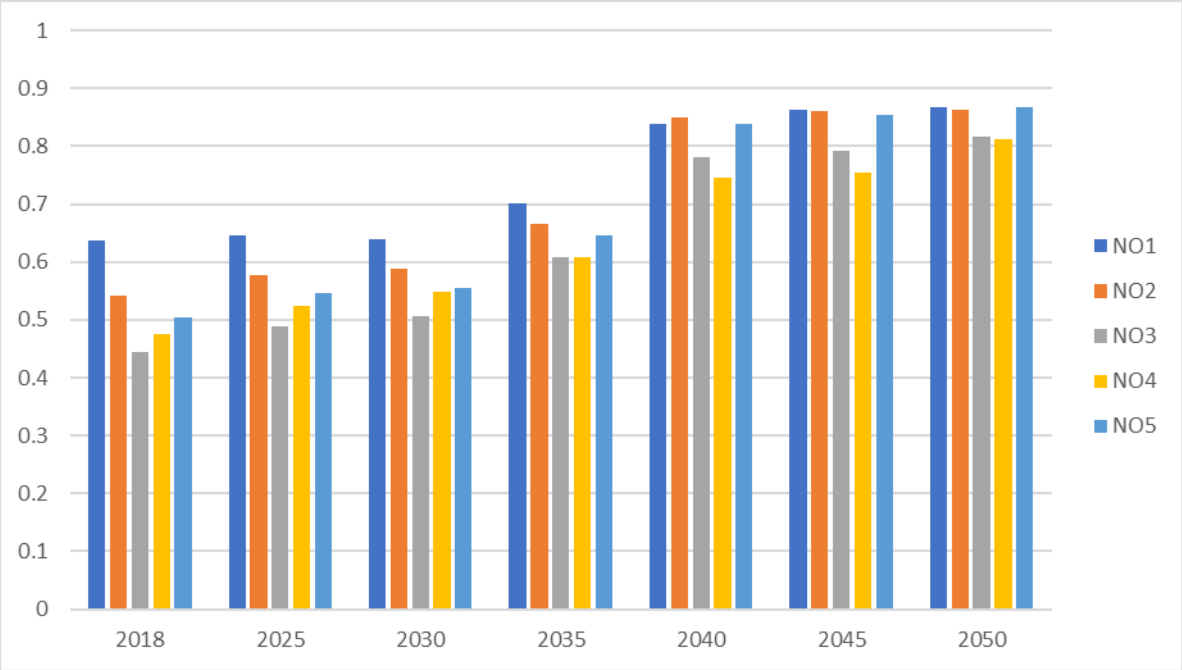


Figure A- 24: Electricity share of final energy consumption

A5 IFE

A5.1. Results of the RePowerEU scenario

The WP3 modelling results are presented in the Section 3.7. The WP2 RePowerEU scenario is used as a baseline.

A6 DEA

Table A- 13

Consumption in households – Denmark	2022	2030	2050
Electricity (TWh)	9.0	8.5	7.5
District heating (TWh)	19.9	22.0	21.7
Gas (TWh)	6.6	2.2	0.6
Total	35.5	32.7	29.8

Total consumption of electricity, district heating and gas in households decreases with 16% from 2022 to 2050.