sEEnergies

QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST
PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

D3.4

Industry mitigation scenarios and IndustryPLAN tool results

Project

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Acronyms & Abbreviations

Term	**Description**
BAT	Best Available Technology
DH	District heating
EE	Energy efficiency
PBT	Payback time
HP	Heat pump
COP	Coefficient of performance
$T_{HighMean}$	Average DH forward temperature
$T_{LowMean}$	Average temperature of heat source
$T_{HighOutlet}$	Forward temperature from HP
$T_{HighInlet}$	Return temperature into HP
$T_{LowOutlet}$	Temperature heat source being cooled from
$T_{LowInlet}$	Temperature heat source being cooled to

1 Introduction

Industrial activity globally accounts for upwards of one-third of the global energy demand, making the industrial energy demand a critical part of the energy system. Despite this, energy system models have so far largely de-emphasised the importance of the industrial sector, leaving the industrial energy sector as an unknown black box. This may be for several reasons, including the lack of access to high-quality disaggregated industrial energy demand data, or due to the inherent difficulties of analysing the industrial sector as it is comprised of a multitude of technologies and processes. Future energy system models will, however, need to encompass all energy sectors, not only the electricity and heat sectors, to enable holistic and integrated energy planning for future renewable energy systems.

The IndustryPLAN tool targets the lacking middle ground between highly site-specific analyses of individual production facilities and generalized nationally aggregated analyses. The purpose of the IndustryPLAN tool is to open the black box of industry and provide a framework for developing sub-sector specific analyses on both a country-specific and European level. This is done by establishing both disaggregated industry energy demands for all countries of the EU and an extensive catalogue of potential mitigation measures for the future.

Applying the energy efficiency first principle, the IndustryPLAN tool provides a framework for investigating the industrial energy sector in the context of the renewable energy transition. The user is provided with a flexible platform for developing future industry energy scenarios based on a range of potential energy efficiency measure, electrification measures, and hydrogen fuel shift measures.

This report presents the scenarios resulting from the detailed analysis of the European industrial sector in the sEEnergies project. The scenario results provide the inputs necessary for representing the industry sector in further holistic energy system modelling in tools such as EnergyPLAN.

The scenarios included and presented in this report are based on two connected reports from the sEEnergies project, namely *"sEEnergies D3.1 Assessment of reference scenarios for industry"* [1] and *"sEEnergies D3.6 Energy efficiency potentials on top of the frozen efficiency scenario"* [2] which provide further documentation on the reference scenario energy demand and the included mitigation measures, respectively. Furthermore, this report is an extension of the previous report *"sEEnergies D3.2 Beta version of the model IndustryPLAN",* where a beta-version of the IndustryPLAN tool and expected scenarios were presented.

2 Tool overview

The following sections serve as an introduction to the IndustryPLAN tool, providing an overview of mitigation measures included with the tool, tool outputs, essential input data, and an overview of both the reference and mitigation scenarios explored in this report.

2.1 Schematic tool overview

IndustryPLAN is a tool for analysing industrial energy demands of European countries. The tool is developed as a Microsoft Excel spreadsheet using a combination of Excel functions and VBA coding, making the tool accessible to a wide audience.

Some of the main qualities of IndustryPLAN are:

- Providing easy access to sub-sector specific energy demand data for all countries of the European Union.
- Enabling the analysis of energy demands at a country level and European level.
- Allowing for analysis of excess heat potentials at different temperature levels.
- Providing a platform for the development of mitigation scenarios based on a range of mitigation measures.
- Providing data inputs for further integrated energy modelling in EnergyPLAN.

Figure 1 provides an overview of the main data inputs to IndustryPLAN and the main outputs.

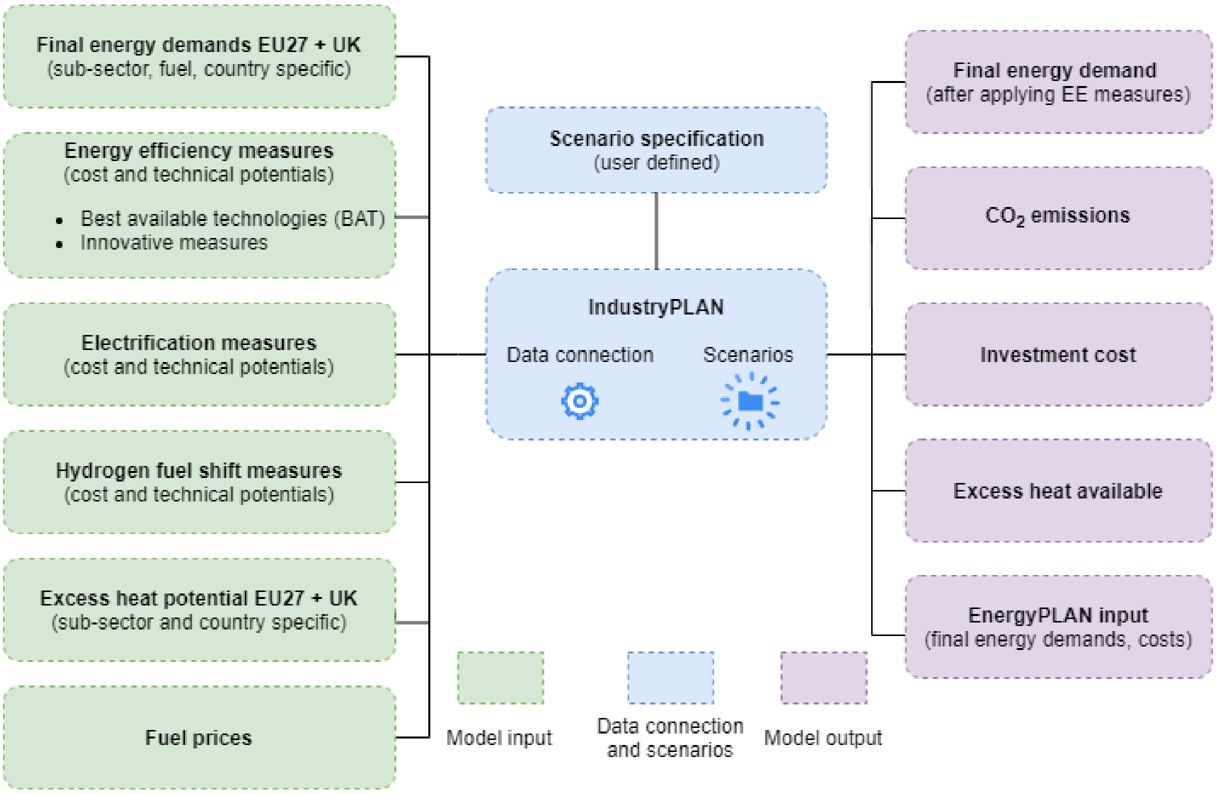


Figure 1: Overview of IndustryPLAN model.

As can be seen in Figure 1, IndustryPLAN provides many different results aimed at evaluating and quantifying future industrial energy demands. Combined with the included scenario design functionality, these outputs can aid in the investigation of a wide array of research questions. This may, for example, include analyses on the importance of energy savings, the impact of extensive electrification or conversion of fossil fuel-based processes to biomass and hydrogen-based processes. While such analyses and results specifically for the industry sector are interesting on their own, an important output of IndustryPLAN is an input provided for EnergyPLAN; a tool capable of encompassing complete national energy systems, including the heat, electricity, industry, and transport sectors. Thus, the disaggregated and detailed industry assessment from IndustryPLAN can provide a more thorough representation of the industry sector when investigating integrated energy systems in EnergyPLAN.

2.2 Mitigation measures

IndustryPLAN includes four main mitigation measures:

- Energy efficiency measures
    - Best available technologies (BAT)
    - Innovative measures
- Electrification measures
- Hydrogen-based fuel shifting measures
- Excess heat extraction for district heating

The user can decide the extent to which these mitigation measures are to be implemented, however subject to some technical boundaries such as what is technically feasible. The user may for example design one scenario where the full potential for BATs is implemented, to see how the energy demand compares to a scenario without further implementation of BATs, partial implementation, or sub-sector specific implementation levels (i.e. a higher/lower implementation rate in one or more sector). Likewise, scenarios can be designed with varying degrees of implementation of innovative measures, electrification, shift to hydrogen-based processes, excess heat extraction, or as a combination of all these.

In addition to the abovementioned mitigation measures, three different scenarios for projected development of material recycling are included:

- No extra recycling, compared to 2015 levels
- Incremental increase in recycling, same as in the EU reference scenario
- High increase in recycling

The recycling scenarios allow for an accounting of improved material efficiency through recycling (e.g. an increased share of steel production from scrap), but does not otherwise include implementation of energy-saving technologies – that would instead be included as BAT measures.

2.3 Data inputs and calculations

IndustryPLAN relies on a range of data inputs, most of which are included with the tool. By default, the tool includes final energy demands on sub-sector level for European countries and estimates of excess heat potential. The user will need to provide some inputs, mainly for excess heat utilisation, such as assumptions on district heating, forward and return temperatures for the country and or scenario investigated. Other assumptions, such as investment costs for heat pumps and heat exchangers, fuel emission factors etc. are included in the tool but can be altered by the user as needed.

IndustryPLAN applies a hierarchical prioritization of mitigation measures, with measures prioritized as follows:

0. Recycling scenario
1. Best available technologies (BAT)
2. Innovative measures
3. Electrification
4. Hydrogen-based technologies
5. Excess heat extraction for district heating

This principle means that measures are prioritized according to this order, i.e. first the selected recycling scenario is applied, then savings from implementation of BATs are subtracted from the updated energy demand, followed by savings from innovative measures being subtracted, etc.

After selecting one of the three recycling scenarios presented in 2.2, the user can select how large a share of the potential for BATs to implement followed by innovative measures, electrification, etc. Calculations are performed based on this prioritization principle as well, with BATs being implemented before innovative measures, and so forth.

It is possible to choose to implement between 0 and 100% of the estimated potential, with 100% being the maximum technical potential based on the range of measures included in the tool.

In the case that less than 100% of the potential is implemented, the tool will prioritise the measures with the lowest cost per saved energy. This principle is illustrated in Figure 2 showing a cost curve of the potential BAT measures for the chemicals sub-sector in Austria 2030.

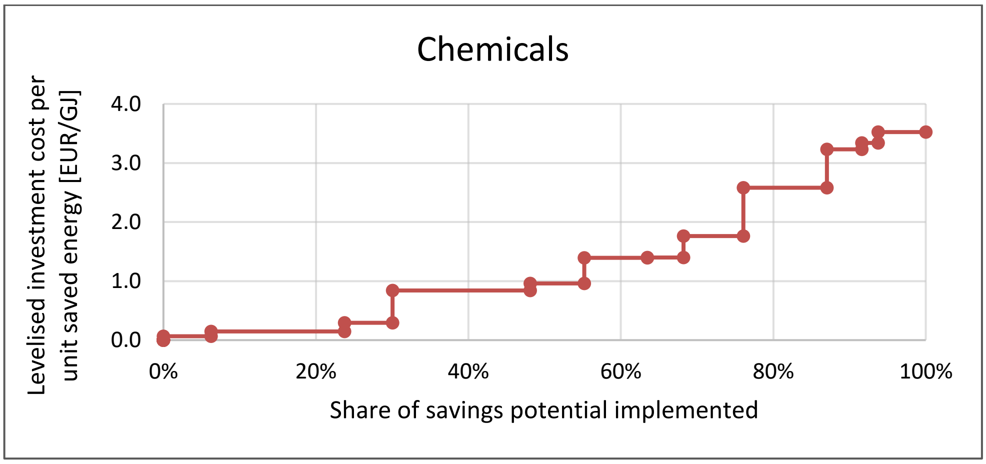


Figure 2: Example of cost-curve for BAT measures for the chemicals sub-sector in Austria 2030.

Cost curves are produced for every mitigation measure, sub-sector, and country. These costs curves do not include benefits from energy savings. By comparing the average industrial fuel price to the y-axis, one can see what share of the measures are economically efficient to implement. The array of available mitigation measures are the same for every country, however, because the production volume for every product varies for every country the total savings potential also varies and thus specific cost curves are produced for all countries.

2.4 Mitigation scenarios

A Reference scenario with 2015 as a base year has been established based on the industrial energy development in the EU Reference Scenario 2016 containing sub-sector specific energy demands [3], the fuel breakdown per industrial sub-sector from IEA [4], and temperature specific distribution of heating/cooling demands from Heat Roadmap Europe [5].

Based on the reference scenario a Frozen Efficiency scenario is established, assuming that the specific energy consumption for industrial processes remains unchanged (i.e. no efficiency improvements). Further details on the background for the Reference and Frozen Efficiency scenarios can be found in *"sEEnergies D3.1 Assessment of reference scenarios for industry"* [1] and *"sEEnergies D3.6 Energy efficiency potentials on top of the frozen efficiency scenario"* [2].

The mitigation measures mentioned in Section 2.2 can then be applied to develop mitigation scenarios. An overview of established scenarios can be seen in Table 1.

Table 1: Overview of mitigation scenarios.

Scenario	Mitigation measures	Recycling	Excess heat
1A	BAT	No extra recycling	All excess heat
1B	BAT	High recycling	All excess heat
2A	BAT + innovative	No extra recycling	All excess heat
2B	BAT + innovative	High recycling	All excess heat
3A	3A: BAT + electrification	No extra recycling	All excess heat
3B	3B: BAT + electrification	High recycling	All excess heat
4A	4A: BAT + hydrogen	No extra recycling	All excess heat
4B	4B: BAT + hydrogen	High recycling	All excess heat

For all the scenarios shown in Table 1, the mitigation measures included are implemented at their maximum potential. This means that all scenarios 1A-4B assume that all possible BATs are implemented. While the tool does allow for lower implementation rates, it is chosen to implement the maximum potential to align with the sEEnergies project scope of "energy efficiency first". Similarly, innovative measures, electrification measures, and hydrogen fuel shift measures are in all instances when included, included at maximum potential.

To illustrate the effect from the choice of recycling scenario, scenarios are tested for the scenario with no extra recycling, and the scenario with high recycling rates, respectively.

All scenarios are assumed to utilise the maximum potential for excess heat in district heating. While the utilisation of excess heat in district heating does not technically improve the energy efficiency of the industry sector, it is included from an energy systems perspective, where an increased utilisation of excess heat would improve the general energy system efficiency.

3 Input data description

The following describes the main input data and assumptions needed to use the IndustryPLAN tool and documents how these are incorporated into the tool. This report will only briefly introduce the underlying input data and the specific mitigation measures included, as these are already described in greater detail in the report *“sEEnergies D3.6 Energy efficiency potentials on top of the frozen efficiency scenario”* [2].

3.1 Energy demand

The main tool input is the final energy demand per industrial sub-sector distributed by fuel type. A baseline and reference scenario is established, as described in Section 2.4. This data is included with the tool for all EU27 countries and the United Kingdom, thus the user will simply need to select which country should be analysed, or opt to run the same scenario for all countries. The industrial energy demand is disaggregated into the following sub-sectors:

- Chemicals
- Foundries
- Iron and steel
- Non-ferrous metals
- Non-metallic minerals
- Paper and pulp
- Others

The energy demand included is calculated as final energy demand based on PRIMES 2016 data [3], using 2015 as a base year. The fuel-specific breakdown per sub-sector is based on the 2016 IEA Energy Balance [4]. Energy demands are included in 5-year intervals up to 2050.

Energy demands are included as final energy demands and are further disaggregated by the type of energy used according to the following energy types:

- Coal and coal products
- Oil products
- Peat and peat products
- Natural gas
- Biofuels and waste
- Heat
- Geothermal
- Electricity
- Hydrogen

CO_2 emissions are calculated based on the fuel emission factors shown in Table 2. For the results presented in this report, it is assumed that the energy from geothermal, biofuels and waste, heat, electricity, and hydrogen has a CO_2 emission factor of zero. That can however be changed in the IndustryPLAN tool by the user if needed.

Table 2: Fuel emission factors included in IndustryPLAN [6].

Energy type	CO_2 emission factor [tons/TJ]
Coal and coal products	94.04
Peat and peat products	107.3
Oil products	79.42
Natural gas	56.54
Geothermal	0
Biofuels and waste	0
Heat	0
Electricity	0
Hydrogen	0

Fuel costs in IndustryPLAN are calculated based on the fuel prices included in Table 3 and the fuel handling costs included in Table 4. Fuel handling costs are kept the same across all price levels. Three different fuel price levels are included to account for the uncertainties related to future fuel price projections.

Table 3: Fuel prices included in IndustryPLAN.

EUR/GJ	Low	Medium	High
Coal and coal products	2.28	2.28	3.42
Peat and peat products	2.28	2.28	3.42
Oil products	8.72	13.89	29.62
Natural gas	6.11	8.06	10.00
Geothermal	11.90	18.10	23.30
Biofuels and waste	5.61	7.00	8.02
Heat	11.90	18.10	23.30
Electricity	9.72	13.89	27.78
Hydrogen	30.56	47.22	116.67

Table 4: Fuel handling costs included in IndustryPLAN.

EUR/GJ	
Coal and coal products	0.00
Peat and peat products	0.00
Oil products	0.00
Natural gas	0.70
Geothermal	0.00
Biofuels and waste	0.67
Heat	0.00
Electricity	0.00
Hydrogen	0.00

3.2 BATs and innovative measures

In IndustryPLAN BATs are defined as internal (on-site) energy efficiency improvements, such as replacing older installations with state-of-the-art technologies, implementing integrated control systems, flue gas monitoring, or various heat recovery processes. This does not generally include the shifting of fuels from fossil fuels to electricity, as such measures will be included specifically as electrification measures. The potential for energy savings from implementing BATs is included for both 2030 and 2050, wherein general implementation rates and thus energy savings potential is higher for 2050.

Similarly, innovative measures are included for 2030 and 2050. However, the selection of available measures is smaller, and implementation rates are low for 2030 as these are emerging technologies that are not assumed to be widely available right now.

For both BATs and innovative measures, economic metrics such as investment cost and cost of conserved energy are included and are used to construct cost curves. If the user decides to only implement a part of the total savings potential IndustryPLAN will prioritise savings based on the cost of conserved energy.

3.3 Electrification

Electrification measures include technologies used for shifting previous fuel-based processes to electricity-based processes. This includes a wide range of technologies such as e.g. electric boilers, electric heat pumps, induction furnaces, etc.

3.4 Hydrogen

Hydrogen measures entail processes shifting previous fuel-based processes to hydrogen-based processes. The potential in 2030 is generally relatively low, as most technologies and measures are not expected to be widely available in the short term. Measures and technologies available include hydrogen boilers, direct reduction through hydrogen in the iron and steel sector, and various chemical processes based on using hydrogen as a feedstock.

3.5 Excess heat

IndustryPLAN includes a data set on excess heat potential for the industrial sub-sectors, enabling the user to define scenarios with varying excess heat utilisation in district heating. While this does not as such increase the energy efficiency of the industrial energy sector on its own, the increased use of excess heat improves energy efficiency in the scope of the entire energy system. As such, the utilisation of excess heat is defined as an external (off-site) energy efficiency improvement. The potential for excess heat in district heating estimated in IndustryPLAN can furthermore be translated to function as an EnergyPLAN input, and thus assist in quantifying the benefits of excess heat utilisation in a broader energy system perspective.

Estimations on the excess heat potential per sub-sector are included in the tool for three temperature levels; 25°C, 55°C, and 95°C. The excess heat potential does not include the potential for internal heat recovery i.e. using excess heat to improve the energy efficiency of industrial processes, as this potential is already included as part of the BAT measures.

The excess heat potential is coupled to the choice of recycling scenario mentioned in Section 2.3. However, a limitation of the model is that it does not update according to the mitigation scenario and any potential implications mitigation measures may have on the excess heat potential. The user would need to make adjustments outside the tool if this is to be assessed. Thus, the excess heat potential estimated could be considered as a "best case"-potential, as extensive energy efficiency improvements alongside electrification could likely result in a lower excess heat potential.

Further details on the methodology behind these estimations can be found in the sEEnergies D5.1 report *"Documentation on excess heat potentials of industrial sites including open data file with selected potentials"* [7].

IndustryPLAN includes both economic and technical assumptions used to estimate the required heat pump capacity in district heating as a function of the chosen level of excess heat extraction. The user decides whether to implement heat pumps along with the excess heat extraction, but if heat pumps are not implemented, it is assumed that the excess heat is used directly in district heating. In that case, the user needs to consider whether it is feasible to utilise the excess heat in practice. It may, for example, be impractical to use excess heat at 25°C and 55°C in district heating systems with significantly higher forward temperatures, without also including heat pumps to increase the temperature of the supplied excess heat.

If heat pumps are included, it is assumed that the excess heat will function as a heat source for the heat pump supplying heat at the designated district heating forward temperature. Heat pumps are assumed to be electric, which in turn increases the electricity demand. Based on the theoretical Lorentz efficiency and heat pump efficiency a COP value is calculated for the heat pumps. This is based on a range of technical assumptions. Based on assumed investment costs for heat pumps and heat exchangers and total thermal capacity an investment cost is calculated.

Technical and economic assumptions for the heat pump modelling in IndustryPLAN are based on three Danish examples where heat pumps for district heating were implemented together with excess heat recovery from industries. The examples cover excess heat temperatures ranging from 20°C-55°C, and three different industries; a paper factory [8], a biopharmaceutical factory [9], and a glass production factory [10]. Table 5 shows the primary economic assumptions included. These values can be changed as needed.

Table 5: Key economic assumptions for heat pumps in IndustryPLAN [8–10].

Technologies	[M€/MW]
Heat pump	0.66
Heat exchanger	0.10

The primary technical inputs needed for the Lorentz calculations can be seen in Table 6 and Table 7. These include district heating forward and return temperatures, with typical temperatures for district heating systems in Denmark being included as default values. Based on examples of excess heat utilisation in Danish district heating systems typical values for cooling of the excess heat source (Delta T) and heat pump efficiency is included; these can, however, be adjusted as needed.

Table 6: Technical specifications for district heating in IndustryPLAN [8–10].

Technical assumptions	Forward temperature [°C]	Return temperature [°C]	Operational hours [h/yr]
District heating	75	35	6,500

Table 7: Technical specifications for heat pumps in district heating relative to excess heat temperature [8–10].

Heat pump specifications	Excess heat 25°C	Excess heat 55°C	Excess heat 95°C
Delta T [°C]	10	30	60
Heat pump efficiency	45%	40%	30%

Figure 3 shows the functioning principle of the electric heat pumps as designed in IndustryPLAN.

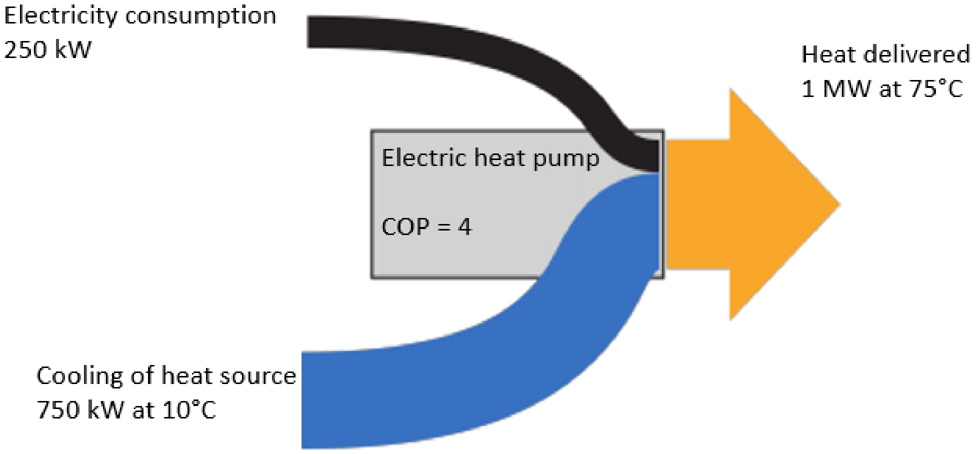


Figure 3: Principle of heat pump modelling [11].

A heat pump COP value is calculated for each of the three temperature levels (25°C, 55°C, and 95°C) based on a theoretical maximum Lorentz efficiency. Main inputs for this is the district heating forward and return temperatures along with the temperature of the excess heat source and the cooling of this. The Lorentz efficiency is calculated as seen in Eq. 1.

$$\boldsymbol{COP\ (Lorentz) = \frac{T_{HighMean}}{T_{HighMean} - T_{LowMean}}}$$

Eq. 1

Where $T_{HighMean}$ is the average forward temperature and $T_{LowMean}$ is the average temperature of the heat source.

$T_{HighMean}$ and $T_{LowMean}$ can be calculated as seen in Eq. 2.

$$\boldsymbol{T_{HighMean} = \frac{T_{HighOutlet} - T_{HighInlet}}{ln(\frac{T_{HighOutlet}+273{,}15}{T_{HighInlet}+273{,}15})}}$$

Eq. 2

Where $T_{HighOutlet}$ is the forward temperature from the heat pump and $T_{HighInlet}$ is the return temperature into the heat pump. In the same way, $T_{LowMean}$ can be calculated as seen in Eq. 3.

$$T_{LowMean} = \frac{T_{LowOutlet} - T_{LowInlet}}{ln(\frac{T_{LowOutlet}+273,15}{T_{LowInlet}+273,15})} \quad \textbf{Eq. 3}$$

Where $T_{LowOutlet}$ is the temperature the heat source is being cooled from, and $T_{LowInlet}$ is the temperature the heat source is being cooled to.

The output of the heat pump modelling is an estimation of the required heat pump capacity, annual heat production per temperature level a resulting increase in electricity demand, and an estimated investment cost. These can then function as inputs for EnergyPLAN and further analysis.

4 Tool scenario design functionality and outputs

This chapter describes the scenario design process from a user perspective and presents the main outputs that can be extracted from the scenario analysis. Finally, this chapter introduces EnergyPLAN and how industry scenario outputs may be included in EnergyPLAN for further integrated energy system analysis.

4.1 Scenario design

The process of designing a future scenario for the industry sector in IndustryPLAN is divided into two distinct processes; one for the implementation of mitigation measures, and one for excess heat utilisation in district heating. These two separate processes are illustrated in Figure 4.

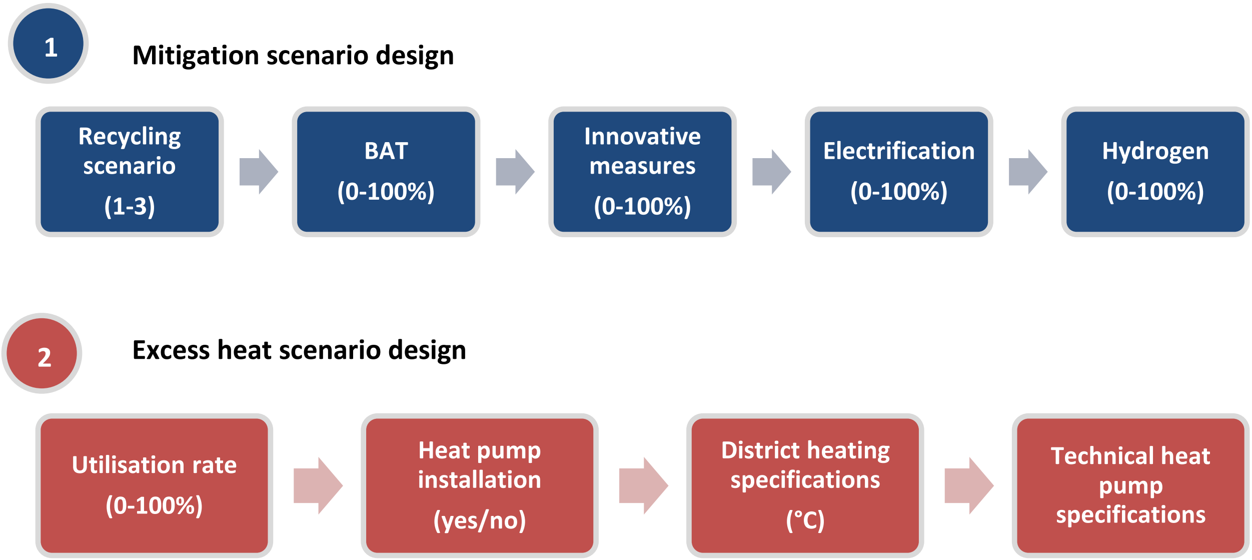


Figure 4: Overview of scenario design process from a user perspective.

For the process of mitigation scenario design, there are numerous steps:

- The first step is selecting a recycling scenario (no extra recycling, incremental recycling, high recycling), which will then update the production volumes for all products accordingly.
- The user can then specify how much of the technical potential for BATs should be implemented, ranging from 0-100%. To do so, the user is assisted by cost curves for all the industry sub-sectors as shown previously in Figure 2. The tool will automatically prioritise energy-saving measures based on their cost, with the lowest cost measures being prioritised first. This is done based on the user input, e.g. if the user would like to implement 50% of the savings potential from BATs, the tool will start with the cheapest option and continue until 50% savings or more have been obtained. This can lead to situations where the savings implemented is different from the value requested by the user. Typically, this would be due to a low number of savings measures, or cases where individual measures comprise a large share of the total savings potential. This process can then be repeated for the remaining mitigation measures (innovative measures, electrification, and hydrogen).
- After going through this for all mitigation measures, the user can initiate a VBA macro, making Excel repeat the process for all EU27+UK countries and export the results to a separate sheet where results for all countries are collected. The user will need to allow the user macros in the

Excel file for this to work. The process for the excess heat scenario design is similar to the mitigation scenario design. First, the user decides how much of the total potential for excess heat should be utilised in district heating from 0-100%.

- Then the user needs to decide whether heat pumps should be implemented to boost the temperature of the excess heat from industry. Whether this is relevant or not depends mostly on the temperatures in the district heating system where the excess heat will be supplied to.
- The user then specifies general characteristics of the district heating system like forward and return temperatures, and finally technical parameters for the heat pumps. Default values for both district heating and heat pumps are included with the tool based on Danish cases as described in Section 3.5, but these can be changed if so required.
- Lastly, the user can again initiate a VBA macro, which initiates a loop for all EU27+UK countries, and exports results to a separate sheet where results for all countries are collected.

4.2 Tool outputs

After designing a scenario and exporting results for all countries several different outputs can be extracted from the resulting data set. This section will introduce some of the main outputs and results established by the tool. A more practical illustration of the results is then included in Chapter 5, where the results for the selected scenarios are presented.

Final energy demands

Energy demands are available for all countries, sub-sectors, and fuel types. Energy demand in this context also includes electricity and hydrogen demand, and any potential increase in the demand that may have occurred as a result of increased electrification or shift to hydrogen-based processes. Energy demands are included for the base year 2015, the frozen efficiency scenario in 2030 and 2050, and the user-specified mitigation scenario in 2030 and 2050. The base year and frozen efficiency scenarios are included so that comparisons on both absolute and relative differences can be made. From the energy demand results, renewable energy shares can be calculated on both a country or sub-sector level.

CO_2 emissions

Based on the energy demands per fuel type and the fuel emission factors shown in Table 2, CO_2 emissions are calculated for every fuel type and sub-sector. Hence, CO_2 emissions can be aggregated either as desired by country, sub-sector, or fuel type as desired. Again, comparisons can be made to the base year and frozen efficiency scenarios.

Investment costs

Investment costs are calculated for the mitigation measures implemented and disaggregated per sub-sector. The investment costs for the mitigation measures are separated from the investment cost needed for excess heat utilisation in district heating.

Fuel costs

Annual fuel costs are calculated for each scenario for three different price levels (low, medium, high) based on the fuel prices introduced in Section 3.1. Fuel costs are separated by fuel type and include both the cost of fuel and, where applicable, fuel handling costs.

Excess heat

Results for excess heat production for district heating include the actual excess heat potential, the electricity demand for heat pumps if they are installed for boosting the temperature, and the investment costs for those heat pumps and the needed heat exchangers. Here it should be noted that the investment costs do not include any potential expenses for expanding the district heating grid.

4.3 EnergyPLAN integration

An important functionality of the IndustryPLAN tool is that the output can serve as an input for EnergyPLAN where further integrated energy system modelling can be conducted. This allows for analyses of how the industrial energy sector interacts with the surrounding energy system, and not only looking at the industrial sector in a vacuum. This section will briefly introduce how the IndustryPLAN outputs may be integrated into EnergyPLAN.

EnergyPLAN is a tool for simulating hourly energy balances for all energy sectors, including the heating, electricity, gas, transport, industry, and water desalination. In Figure 5 an overview of the technologies and sectors included in the EnergyPLAN tool can be seen, illustrating that the industrial sector is only a part of the energy system.

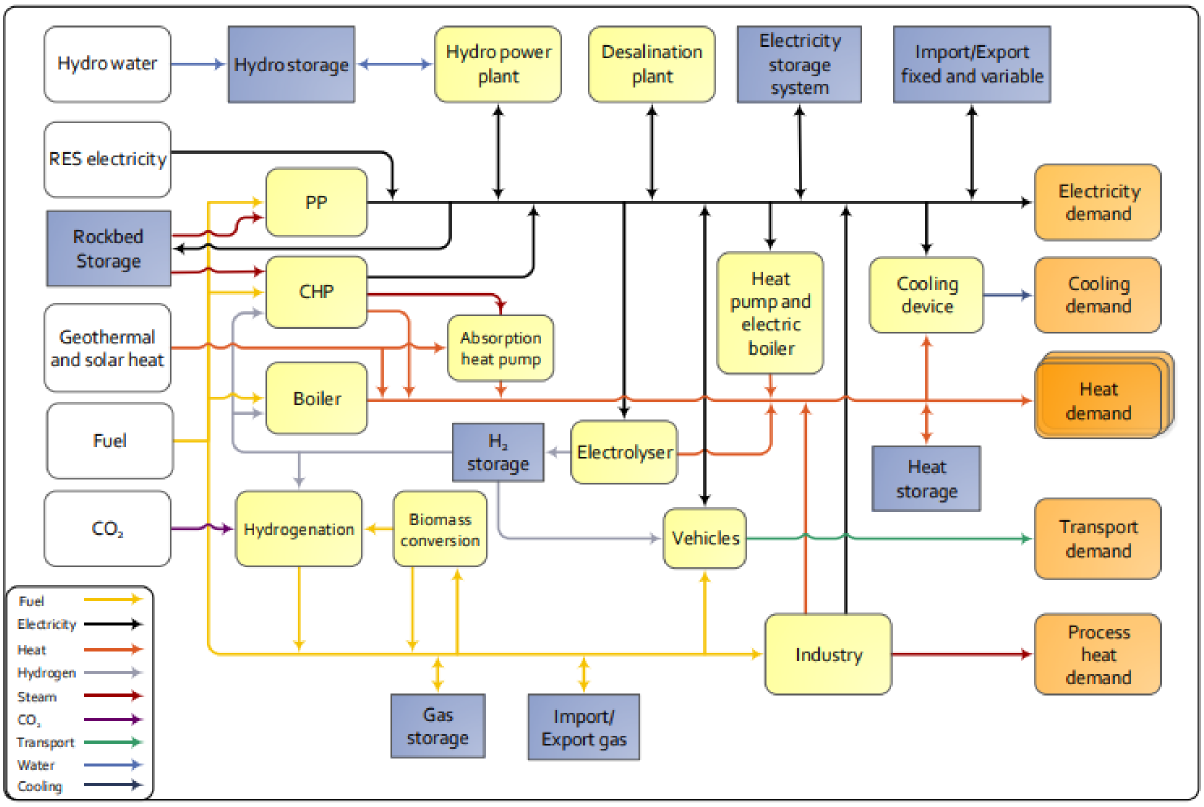
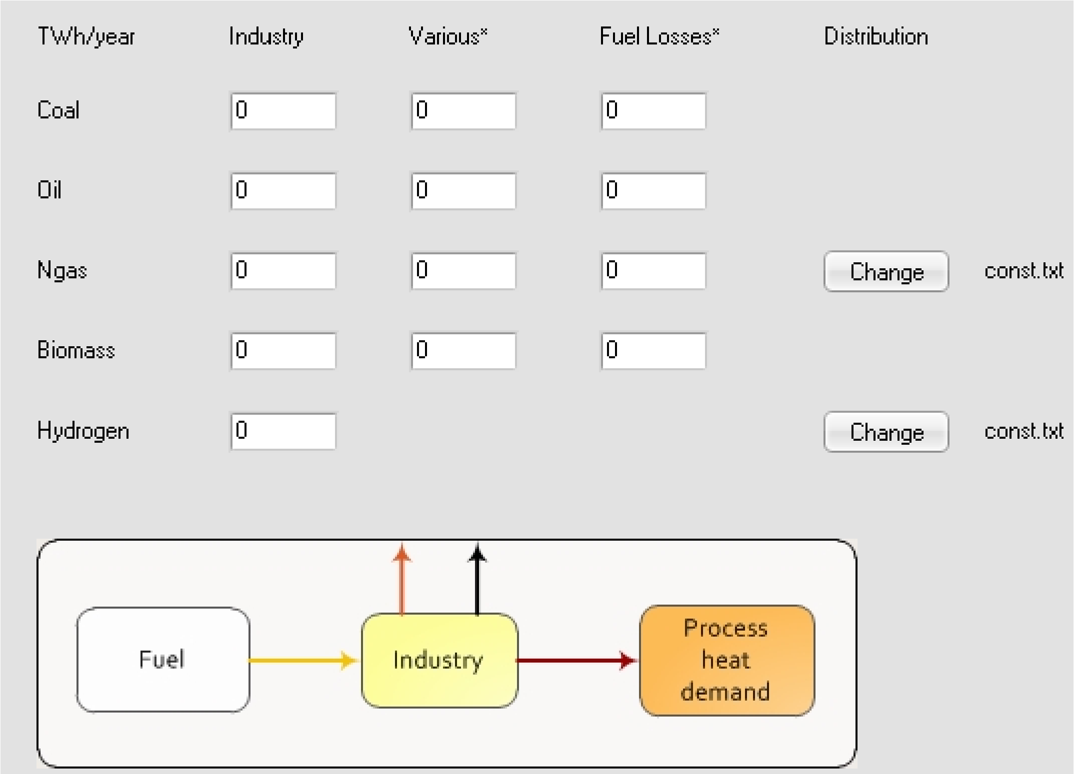


Figure 5: Overview of EnergyPLAN technologies and sector integration.

The purpose of this section is not to describe the functioning of the EnergyPLAN model in detail, but only how the outputs of the IndustryPLAN tool specifically could be integrated into EnergyPLAN.

Industrial energy demands are added in the “Industry and Fuel”-tab, as seen in Figure 6. Here a fuel demand for the entire industry sector is added separated by fuel type. EnergyPLAN does not distinguish by industry sub-sectors like it is done in IndustryPLAN, hence energy demands will need to be aggregated.

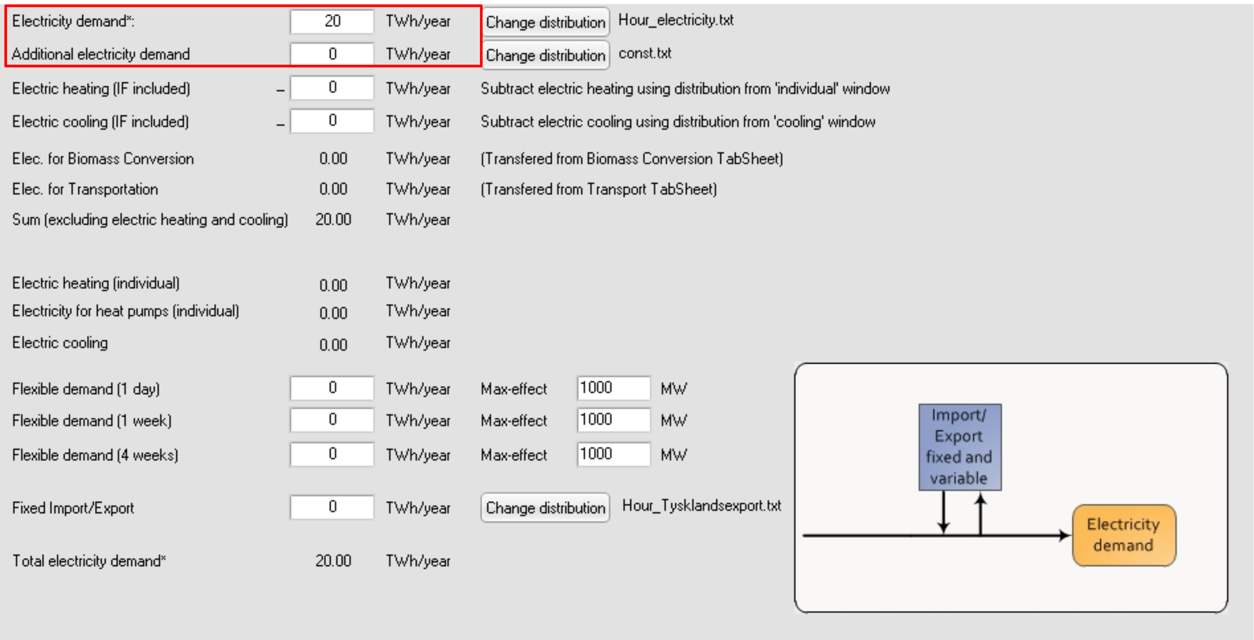


TWh/year	Industry	Various*	Fuel Losses*	Distribution	
Coal	0	0	0		
Oil	0	0	0		
Ngas	0	0	0	Change	const.txt
Biomass	0	0	0		
Hydrogen	0			Change	const.txt

Figure 6: Industry fuel inputs in EnergyPLAN.

It should be noted that not all the fuel types included in IndustryPLAN are represented in Figure 6. Hence they will need to be included elsewhere in EnergyPLAN.

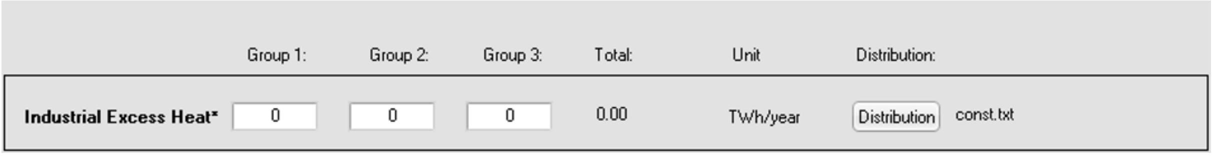
- Peat and peat products should be included either as coal or biomass demand depending on how it is sourced for the country being analysed.
- Geothermal energy can be included either specifically as geothermal production or added as production for district heating.
- Heat can be added either as a district heating demand or as industrial CHP.
- Electricity should be added on a separate tab for the electricity demand (Figure 7), and could be added either to the general electricity demand or added as an additional electricity demand. If added to the general electricity demand the hourly electricity distribution should be adjusted accordingly.



Electricity demand*:		20	TWh/year	Change distribution	Hour_electricity.txt	
Additional electricity demand		0	TWh/year	Change distribution	const.txt	
Electric heating (IF included)	–	0	TWh/year	Subtract electric heating using distribution from 'individual' window		
Electric cooling (IF included)	–	0	TWh/year	Subtract electric cooling using distribution from 'cooling' window		
Elec. for Biomass Conversion		0.00	TWh/year	(Transfered from Biomass Conversion TabSheet)		
Elec. for Transportation		0.00	TWh/year	(Transfered from Transport TabSheet)		
Sum (excluding electric heating and cooling)		20.00	TWh/year			
Electric heating (individual)		0.00	TWh/year			
Electricity for heat pumps (individual)		0.00	TWh/year			
Electric cooling		0.00	TWh/year			
Flexible demand (1 day)		0	TWh/year	Max-effect	1000	MW
Flexible demand (1 week)		0	TWh/year	Max-effect	1000	MW
Flexible demand (4 weeks)		0	TWh/year	Max-effect	1000	MW
Fixed Import/Export		0	TWh/year	Change distribution	Hour_Tysklandsexport.txt	
Total electricity demand*		20.00	TWh/year			

Figure 7: Electricity demand tab in EnergyPLAN.

The utilised excess heat in district heating should also be included in EnergyPLAN. This can be added specifically as industrial excess heat production, as seen in Figure 8. Here the actual excess heat utilised for district heating should be added, and not the technical potential.

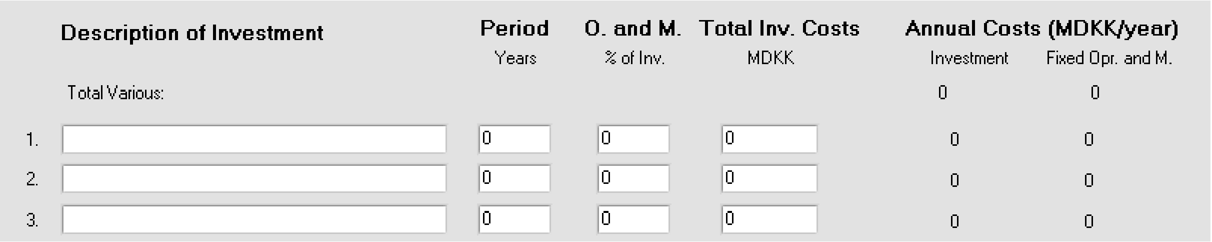


	Group 1:	Group 2:	Group 3:	Total:	Unit	Distribution:	
Industrial Excess Heat*	0	0	0	0.00	TWh/year	Distribution	const.txt

Figure 8: Industrial excess heat in EnergyPLAN.

As can be seen in Figure 8, it is possible to separate the excess heat into different district heating groups. This is mainly dependent on what type and size district heating system the excess heat is supplied to.

Lastly, EnergyPLAN requires inputs on the investment and O&M costs of the mitigation measures implemented in the industry, as seen in Figure 9. The investment cost should be the raw investment cost, i.e. before applying a discount rate or similar, as that is done within EnergyPLAN to calculate annual investment costs.



	Description of Investment	Period Years	O. and M. % of Inv.	Total Inv. Costs MDKK	Annual Costs (MDKK/year) Investment	 Fixed Opr. and M.
	Total Various:				0	0
1.		0	0	0	0	0
2.		0	0	0	0	0
3.		0	0	0	0	0

Figure 9: Investment and O&M costs in EnergyPLAN.

From this description of EnergyPLAN integration, it is clear that some of the details of the industry sector, e.g. the sub-sectorial level, is lost in the integration due to the more aggregate nature of industry modelling in EnergyPLAN. However, that is also the main purpose of the IndustryPLAN in the first place, as this now allows for more detailed and sub-sector specific analysis of the industry outside of EnergyPLAN. The tool also includes data on how O&M costs will change with new mitigation measures implemented and lifetimes for these measures, but these are not reflected in this report. For integration with EnergyPLAN, the user would need to review the list of mitigation measures included and from that establish an average O&M cost relative to the investment cost and average lifetime for the mitigation measures.

5 Results and scenario outputs

This chapter presents the results for the established mitigation scenarios. The mitigation scenarios are compared to the Baseline year and the Frozen efficiency scenario, and to further validate the results, comparisons to existing research on energy savings potential in the industrial sector are included. Scenarios are compared with regards to energy demands and fuel type, CO_2 emissions, investment costs for mitigation measures, and excess heat potential for district heating.

An overview of the established mitigation scenarios can be seen in Table 8.

Table 8: Overview of mitigation scenarios. Only the scenarios in bold are presented in detail.

Scenario	Mitigation measures	Recycling	Excess heat
1A	**BAT**	**No extra recycling**	**All excess heat**
1B	**BAT**	**High recycling**	**All excess heat**
2A	BAT + innovative	No extra recycling	All excess heat
2B	**BAT + innovative**	**High recycling**	**All excess heat**
3A	3A: BAT + electrification	No extra recycling	All excess heat
3B	**3B: BAT + electrification**	**High recycling**	**All excess heat**
4A	4A: BAT + hydrogen	No extra recycling	All excess heat
4B	**4B: BAT + hydrogen**	**High recycling**	**All excess heat**

The results and scenario outputs presented in this chapter will focus on the aggregated results for the EU 27 + UK countries, however, this is an aggregate of the results individual country modelling, and hence the results presented in this report are available for all countries for use in further country-specific modelling.

5.1 Energy demand

The Frozen efficiency scenario assumes that no energy efficiency improvements are done and that energy demands develop according to the population and GDP projections in the EU 2016 Reference scenario towards 2050 [3]. This results in a steadily increasing fuel and electricity demand when considering the entire industry sector across all EU27 + UK countries, as illustrated in Figure 10.

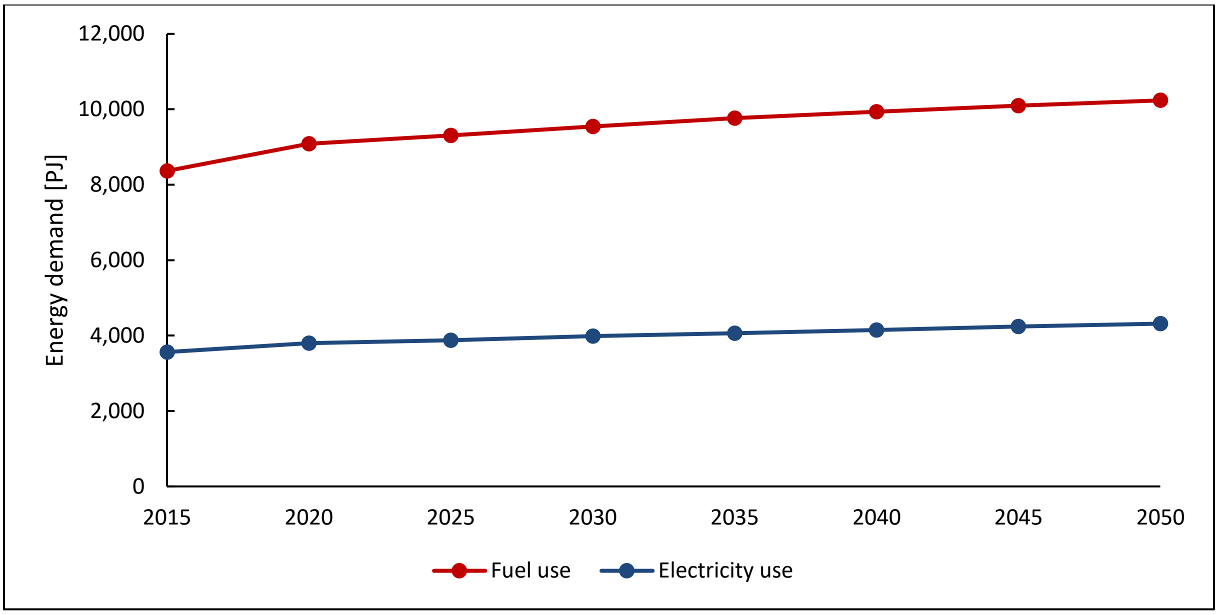


Figure 10: Fuel and electricity use in the Frozen efficiency scenario for EU 27 + UK.

In Figure 11 the fuel and electricity demands for the Base year and Frozen efficiency scenarios are compared to the mitigation scenarios.

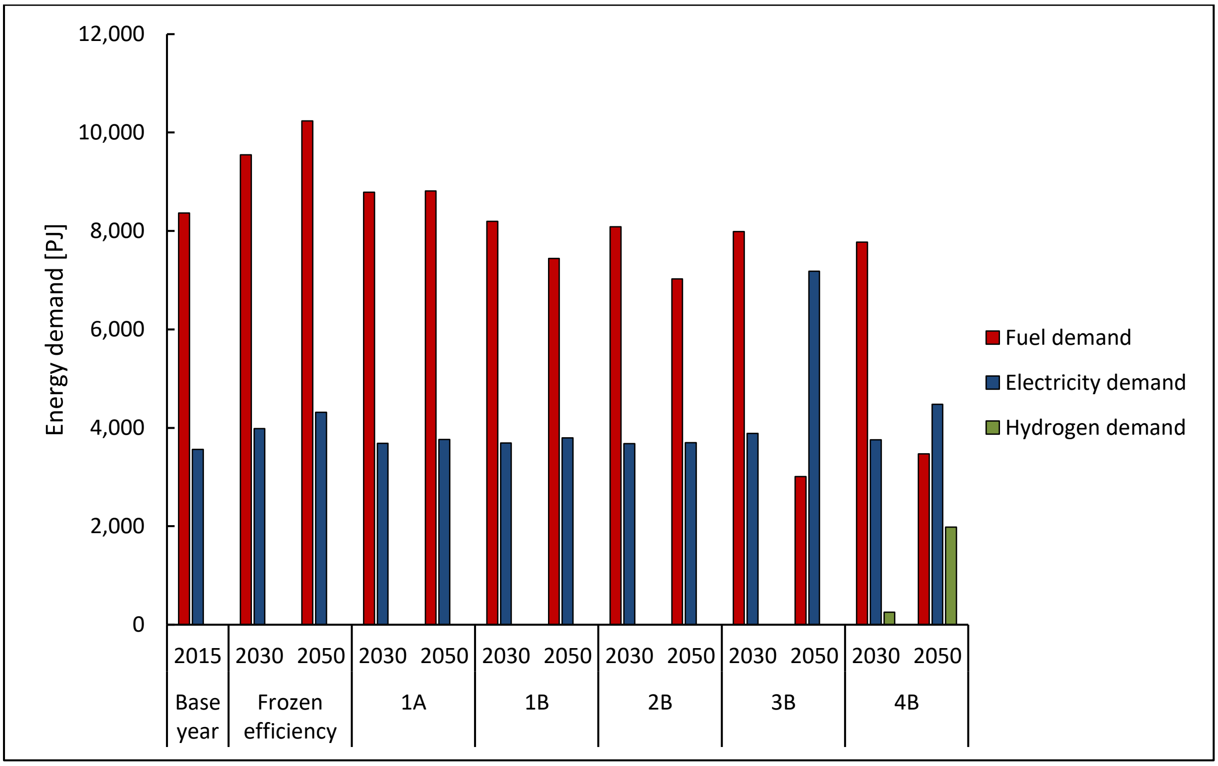


Figure 11: Energy demand by scenario for EU27 + UK.

The results shown in Figure 11 indicate that both the implementation of BATs and high recycling rates can lead to some significant energy savings (scenarios 1A and 1B). Further adding the innovative measures on top of the BATs as shown in scenario 2B lead to even more savings, especially for 2050 where these specific measures are expected to be more readily available. The electrification and hydrogen scenarios in 3B and 4B result in a shift of fuel demands to electricity and hydrogen respectively.

A more detailed distribution of fuel types per sub-sector can be seen in Figure 12.

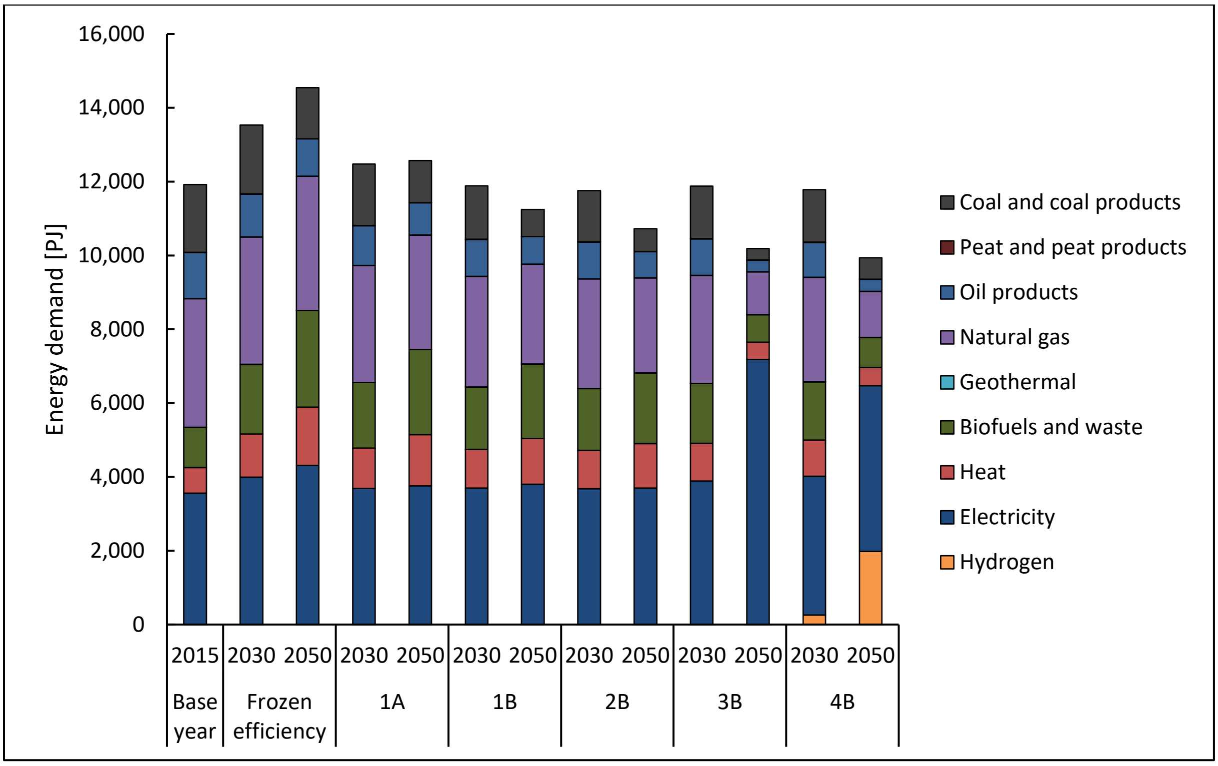


Figure 12: Final energy demand by energy type for selected scenarios for EU27 + UK.

The most drastic changes in terms of the fuel distribution occur for the 3B (Electrification) and 4B (Hydrogen) scenarios, where the electricity and hydrogen increases. It should, however, be noted, particularly for the hydrogen scenario, that the electricity demand does not account for the electricity required for hydrogen e.g. through electrolysis. The results shown in Figure 12 should be considered to represent the demand side of the industrial sector, and hence the electricity demand located outside of the industrial sector for this hydrogen production needs to be accounted for elsewhere when the energy system is analysed in an integrated manner. Furthermore, it should be noted that the electricity demand for all scenarios does not include the electricity demand needed for the heat pump operation in district heating related to the use of excess heat in district heating. This is however included later in Section 5.4.

An overview of energy demands per industrial sub-sector is seen in Figure 13.

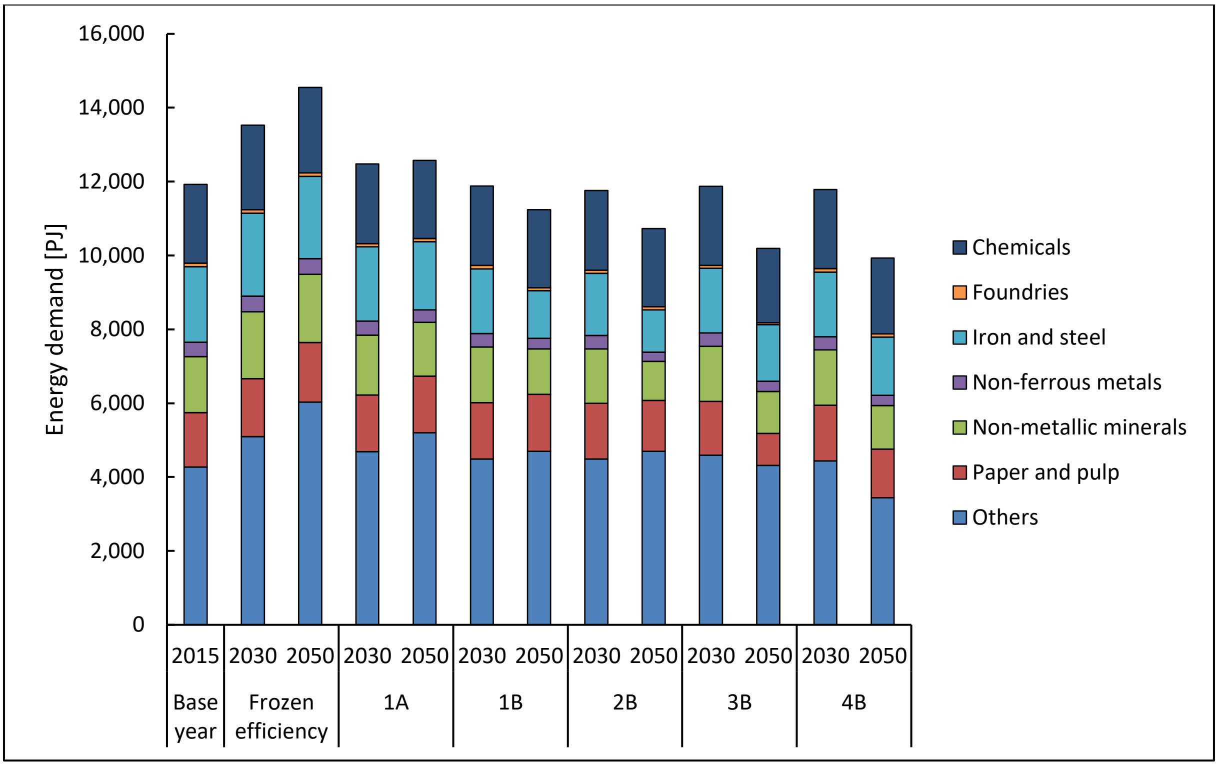


Figure 13: Final energy demand by industrial sub-sector for selected scenarios for EU27 + UK.

To validate the determined energy savings potential, the results are compared to an alternative study by European Commission Directorate-General Energy. In the report *"Study on energy efficiency and energy saving potential in industry and on possible policy mechanisms"* [12], estimates for energy savings are reported for industrial sub-sector in the EU in 2030 and 2050. The estimated savings potential is seen in Table 9.

Table 9: Energy savings potential estimated in [12].

Sub-sector	Year	2 yr PBT	5 yr PBT	Technical potential
Chemicals	**2030**	4.0%	4.9%	25.0%
	2050	7.9%	9.3%	22.0%
Iron and steel	**2030**	4.3%	4.6%	24.0%
	2050	8.6%	9.4%	26.0%
Non-ferrous metals	**2030**	5.5%	5.8%	22.0%
	2050	12.0%	12.7%	21.0%
Non-metallic minerals	**2030**	3.3%	3.6%	19.0%
	2050	6.6%	7.2%	18.0%
Paper and pulp	**2030**	2.9%	3.8%	19.0%
	2050	5.8%	7.1%	17.0%
Others[1]	**2030**	4.6%	5.5%	25.7%
	2050	9.5%	11.6%	17.0%

[1] Note: The "Others"-sector in this table is a weighted average from the savings potential of Machinery, Food and beverage, and Petroleum refineries from the original source.

In the report by European Commission Directorate-General Energy (DG Ener), the savings potential is categorized into three different categories. First, savings that can be implemented with an economic payback time of fewer than two years, savings with an economic payback time of fewer than five years, and finally the full technical potential. The technical potential may not result in the investment being paid back at any point.

As the scenarios established in this report also did not consider the economic payback as a critical criterion, e.g. evident from the implementation of the full potential for BATs and the energy efficiency first principle of the sEEnergies project, the technical potential presented in Table 9 will function as a basis for comparison.

In Table 10 and Table 11 the savings potential estimated in [12] is compared to the resulting savings from the scenarios established and presented in this report for 2030 and 2050 respectively.

Table 10: Energy savings obtained in mitigation scenarios for 2030 relative to estimated savings in [12].

2030	Chemicals	Foundries	Iron and steel	Non-ferrous metals	Non-metallic minerals	Paper and pulp	Others
Frozen efficiency	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
DG Ener (technical)	**25.0%**	**-**	**24.0%**	**22.0%**	**19.0%**	**19.0%**	**25.7%**
1A	5.8%	6.8%	10.5%	10.4%	10.4%	2.4%	8.0%
1B	5.8%	6.8%	21.7%	14.9%	17.0%	2.4%	11.9%
2B	5.8%	6.8%	24.9%	15.3%	18.6%	3.9%	11.9%
3B	6.4%	14.1%	21.9%	15.4%	17.9%	7.1%	9.8%
4B	6.4%	6.8%	21.9%	15.3%	17.7%	4.0%	12.9%

Table 11: Energy savings obtained in mitigation scenarios for 2050 relative to estimated savings in [12].

2050	Chemicals	Foundries	Iron and steel	Non-ferrous metals	Non-metallic minerals	Paper and pulp	Others
Frozen efficiency	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
DG Ener (technical)	**22.0%**	**-**	**26.0%**	**21.0%**	**18.0%**	**17.0%**	**17.0%**
1A	8.6%	15.3%	16.8%	22.0%	20.8%	4.6%	13.9%
1B	8.6%	15.3%	41.9%	33.6%	33.2%	4.6%	22.1%
2B	8.6%	15.3%	48.7%	39.5%	43.0%	14.5%	22.1%
3B	13.3%	43.8%	31.1%	35.4%	38.2%	46.7%	28.4%
4B	11.1%	15.3%	28.9%	34.8%	36.2%	18.4%	42.9%

A general tendency for 2030 seems to be that the energy savings potential determined for the sEEnergies scenarios is lower than that estimated by DG Ener, especially for the chemicals sub-sector and the paper and pulp sub-sector. Conversely, in 2050, the sEEnergies scenarios generally estimate a higher potential for energy savings, with the chemicals sub-sector and paper and pulp sub-sector being exceptions.

This is partly a result of the assumptions on recycling, as the estimated energy savings potential is similar in scenario 1A where no extra recycling is included, but higher for the other scenarios with assumed high recycling. This is especially apparent in the iron and steel, non-ferrous metals, and non-metallic minerals, where recycling is most prevalent.

5.2 Renewable energy and CO_2 emissions

In Table 12 the renewable energy share for the scenarios can be seen.

Table 12: Renewable energy share for EU27 + UK.

Scenario	Year	Renewable energy
Base year	2015	44.8%
Frozen efficiency	2030	52.1%
	2050	58.4%
1A	2030	52.5%
	2050	59.3%
1B	2030	54.1%
	2050	62.8%
2B	2030	54.4%
	2050	63.5%
3B	2030	55.0%
	2050	82.4%
4B	2030	55.8%
	2050	78.3%

The scenarios 1A, 1B and 2B do not include any fuel shifting measures or technologies but only fuel or electricity saving measures, and hence the fuel distribution and thereby renewable energy share is not highly affected by the changes implemented.

The 3B and 4B scenario includes extensive electrification and shift to hydrogen-based processes, resulting in the higher renewable energy share. It should be noted that the renewable energy share presented here assumes that the electricity and hydrogen used is from renewable sources, as an electricity emission factor of zero is included. This is perhaps an ambitious assumption, and especially for 2030 may be difficult to reach. However, limited electrification and hydrogen shift is expected to occur before 2030 and thus this does not influence the 2030 results much.

In Figure 14 the resulting CO_2 emission per sub-sector can be seen for each of the industrial sub-sectors.

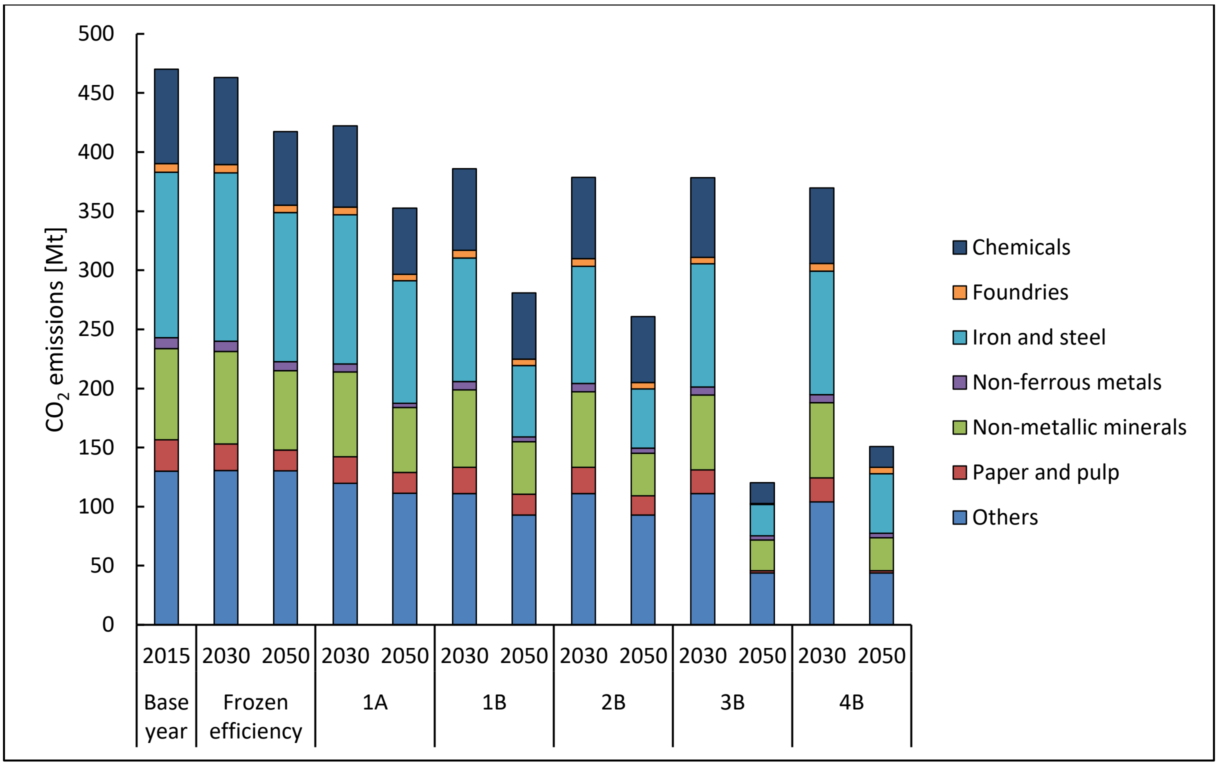


Figure 14: CO_2 emissions per sub-sector for EU27 + UK.

While the CO_2 emissions for the 3B (electrification) and 4B (hydrogen) scenarios appear very low, again it should be emphasised that this is based on the assumption of 100% renewable electricity. If hydrogen production is instead based on electricity from coal or natural gas-fired power plants, the CO_2 emissions will be higher.

5.3 Investment and fuel costs

In Figure 15 the investment cost for each of the mitigation scenarios can be seen, with investments allocated on a sub-sector level.

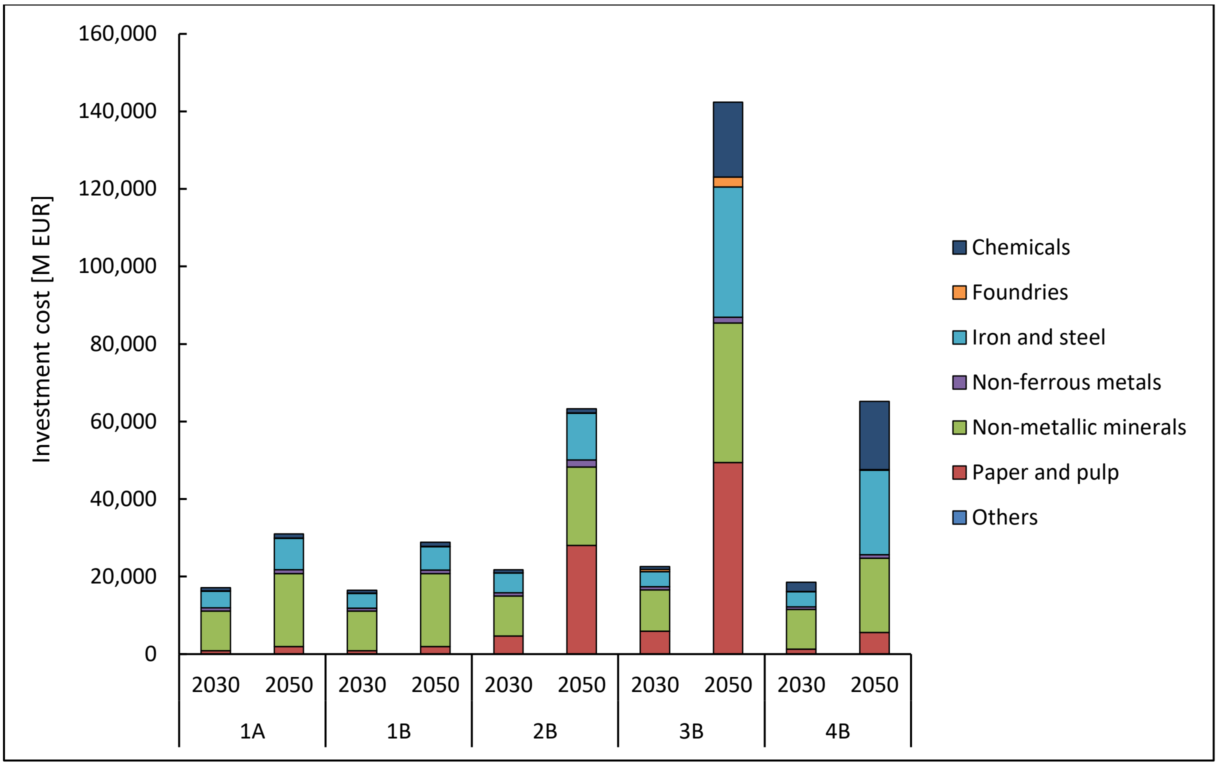


Figure 15: Investment cost per sub-sector for EU27+UK.

It is apparent that generally simply implementing the BATs (1A and 1B) is relatively inexpensive compared to some of the other measures such as implementing the more innovative measures (2B), or widespread electrification (3B). The scenarios developed also assume that the full technical potential is implemented. In reality, it may be more practical to exclude some of the most expensive measures at the end of the cost-curve, e.g. in the electrification scenario, where the top-end measures are very expensive. It should be noted that the hydrogen scenario (4B) only includes the investment costs for the industrial plant-side investments, i.e. investments needed for hydrogen production, e.g. in the form of electrolyzers, are not included. This is considered to be beyond the scope of this analysis as such hydrogen production capacity needs to be connected to the rest of the energy system, and hence should be included in more holistic energy system analyses

In FiguresFigure 16Figure 17Figure 18 the resulting annual fuel costs per fuel type can be seen, based on the three fuel cost price levels presented in Section 3.1.

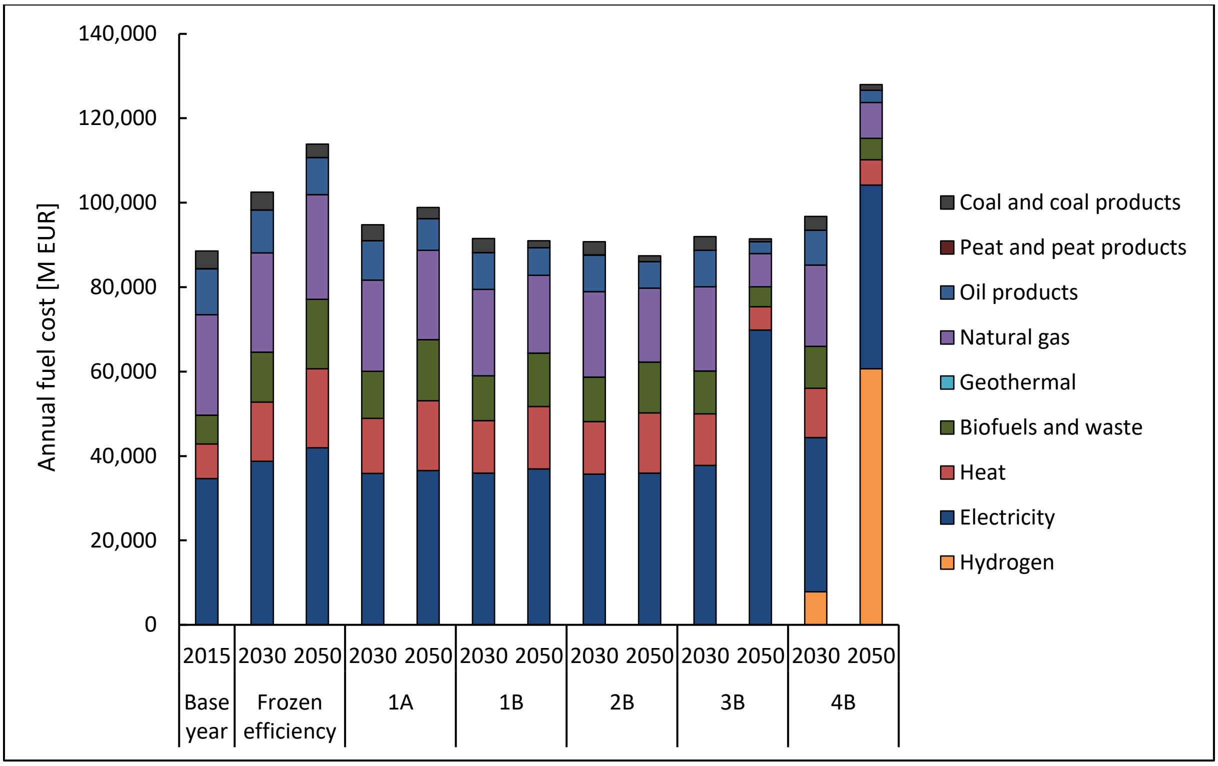


Figure 16: Annual fuel cost per fuel type for EU 27 + UK (low fuel prices).

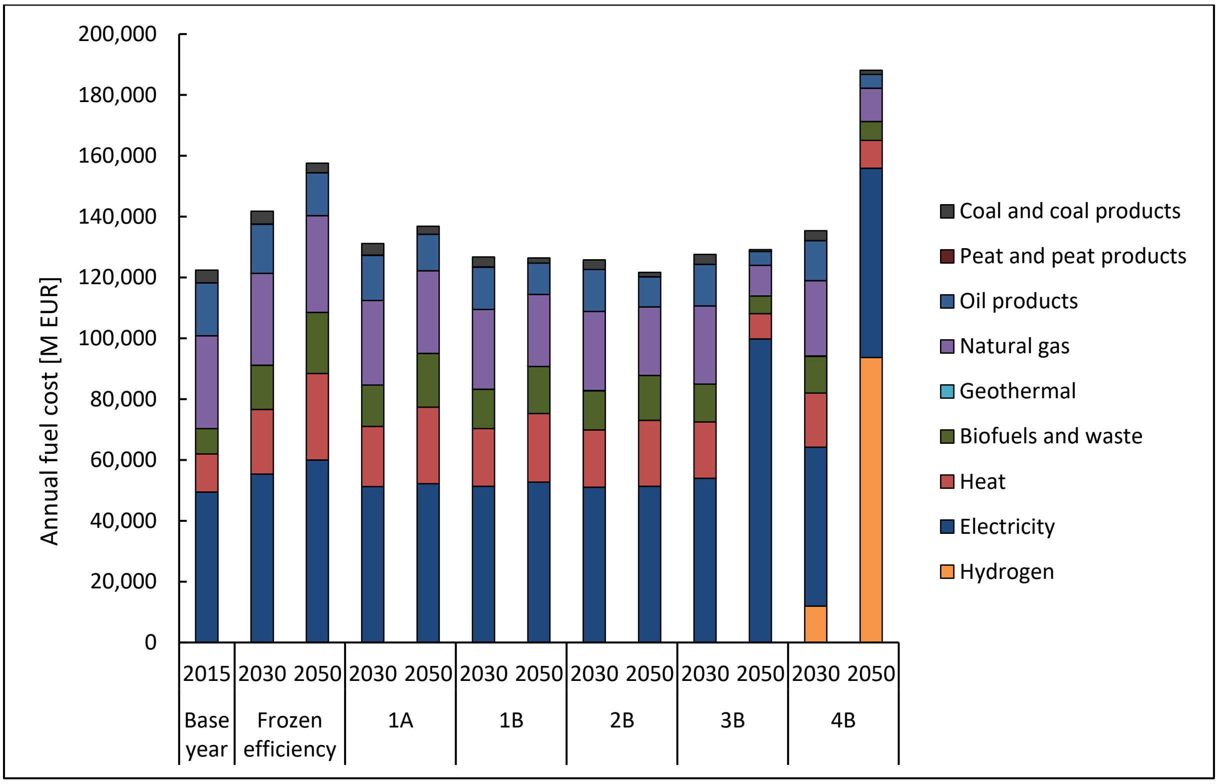


Figure 17: Annual fuel cost per fuel type for EU 27 + UK (medium fuel prices).

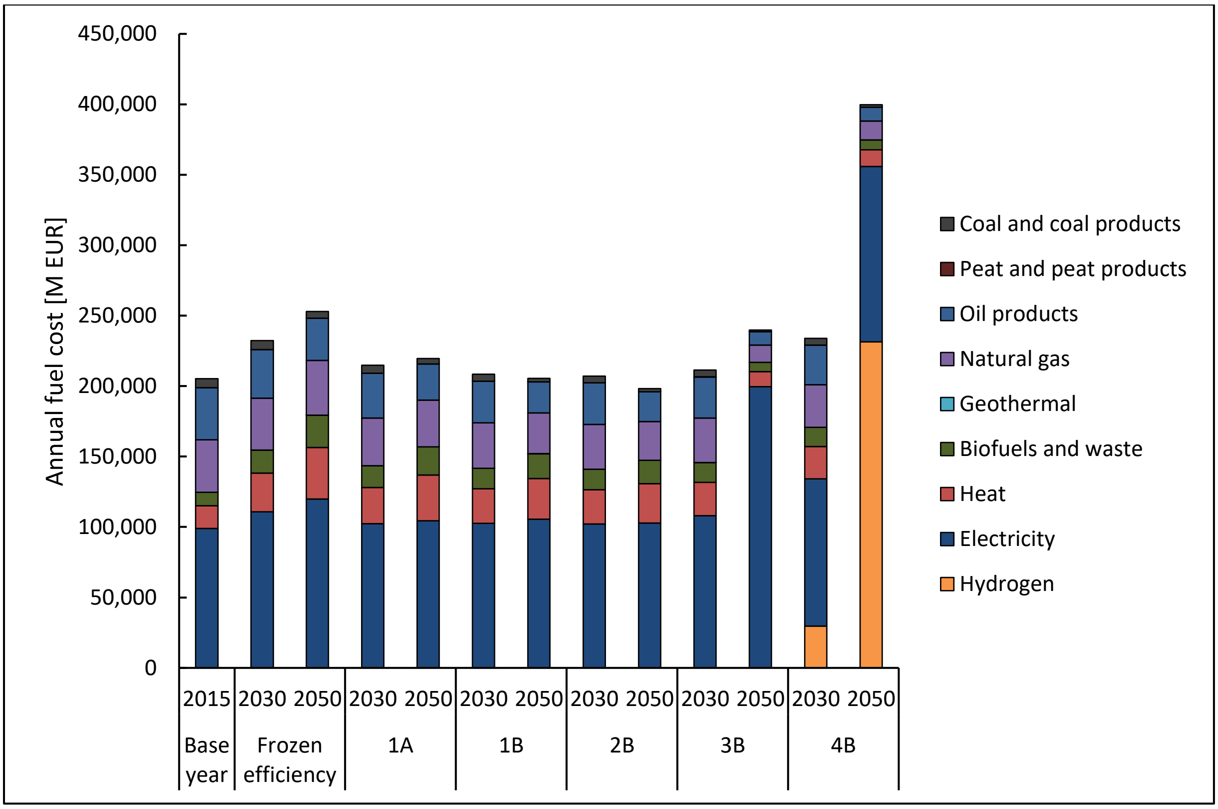


Figure 18: Annual fuel cost per fuel type for EU 27 + UK (high fuel prices).

It is apparent that the total annual fuel cost is highly dependant on future fuel prices. This is particularly the case for hydrogen for which the fuel price is high compared to other fuel types. Due to the high fuel costs connected to hydrogen, it is likely going to be necessary to prioritize the use of hydrogen specific sub-sectors and processes

5.4 Excess heat

This section presents results on the potential for excess heat extraction for use in district heating. Assumptions on district heating temperatures and heat pump efficiencies were presented in Section 3.5, forming the basis of the calculations estimating the required heat pump capacity. The results need to be prefaced with an important limitation of the tool, which is that the excess heat potential is not impacted by the mitigation measures, except for the recycling scenarios. This means that the implementation of BATs, innovative measures, electrification, and shift to hydrogen-based processes does not result in changes to the excess heat potential, while the recycling rate does change it. This is a limitation of the tool and the data available, as it is likely that extensive changes to the industrial sector such as those proposed in the mitigation scenarios would influence the excess heat potential. Because only the choice of recycling scenario influences the resulting excess heat potential, results are only shown for one scenario in the following.

Figure 19 illustrates the potential for excess heat and resulting electricity demand from electrical heat pumps. It is assumed that heat pumps are implemented to boost the excess heat supplied at 25°C and 55°C, while the excess heat supplied at 95°C does not require boosting.

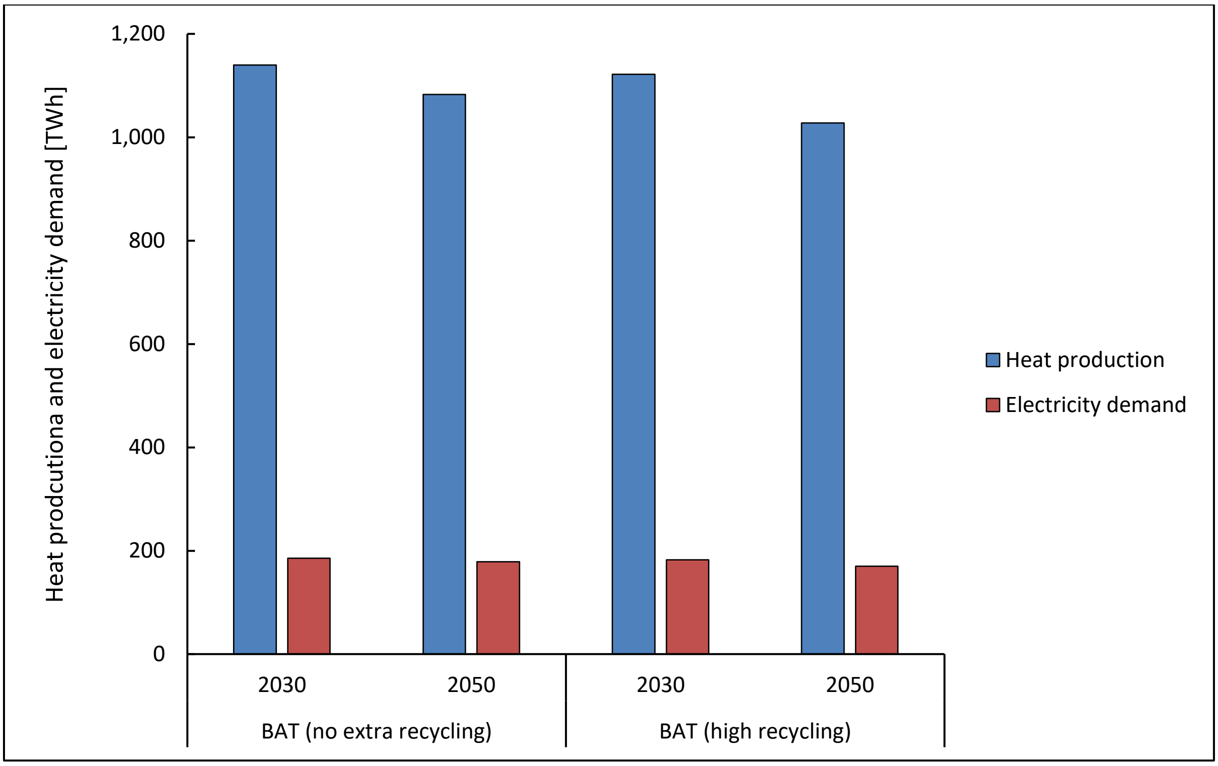


Figure 19: Excess heat production for district heating for EU 27 + UK.

A sub-sector specific overview of the excess heat potential is shown in Figure 20.

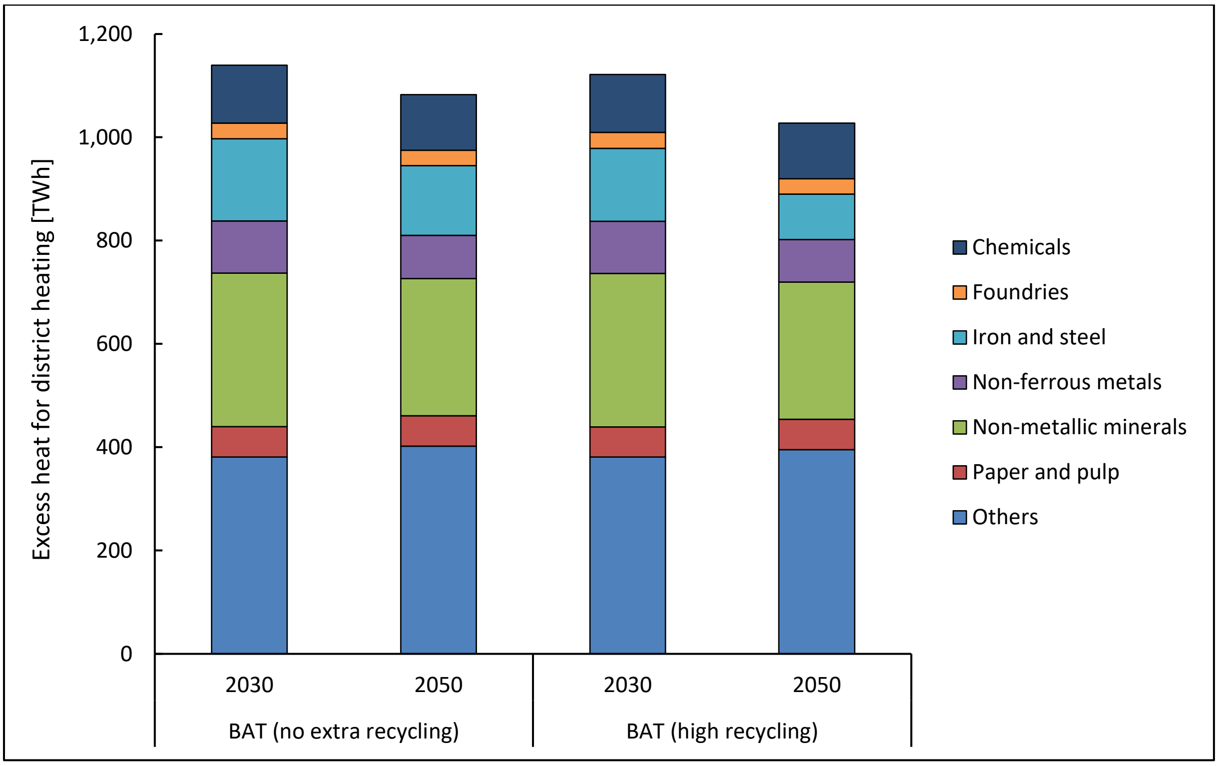


Figure 20: Excess heat potential for district heating for EU27 + UK.

The largest excess heat potentials are found in the others sub-sector, which mainly includes the food and beverage production, followed by the non-metallic minerals sub-sector, consisting of high-temperature processes such as cement production.

In Table 13 the resulting investment cost from the implementation of the excess heat potential in district heating is seen.

Table 13: Investment cost for heat pumps and heat exchangers needed for excess heat utilisation in district heating.

Scenario	Installed HP capacity [GW_t]	Sum of Investment cost [M EUR]
BAT (no extra recycling)		
2030	139.29	103,013
2050	133.65	98,826
BAT (high recycling)		
2030	137.10	101,393
2050	127.12	93,995

The investment costs shown in Table 13 is simplified to some extent, as this only includes the expected costs for heat pumps and heat exchangers. Other investments will, however, be needed to actually utilise and integrate this excess heat potential - most important being the extensions of the district heating grid. This is, however, depending on the location of current and future district heating areas to which the excess heat is to be integrated within, and estimating this would require more geographic and spatial analyses, beyond the scope of this specific task. A lower installed HP capacity (and thus investment cost) is found for 2050 due to an expected lower potential from some of the energy-intensive processes, particularly in the iron and steel and non-metallic minerals sub-sectors. This is exacerbated for the high recycling scenario, as high recycling rates lead to further reductions of the excess heat potential.

6 Conclusions

An Excel-based IndustryPLAN tool has been prepared, enabling the design of industrial mitigation scenarios. The tool provides access to energy demands for the EU27 countries and the United Kingdom for seven industrial sub-sectors further disaggregated by fuel type. This demand data functions as the foundation of the tool and baseline and frozen efficiency scenarios. The tool furthermore includes data on the potential for extraction of excess heat at temperatures of 25°C, 55°C, and 95°C, also disaggregated on a sub-sector level.

The tool enables the user to conduct country-specific as well as aggregated European analyses of mitigation measures such as the implementation of best available technologies (BAT), innovative measures and technologies, electrification, shift to hydrogen-based processes, and excess heat utilisation. Tool outputs are primarily: final energy demands after implementation of the specified mitigation measures, related investment costs, an input for EnergyPLAN where further integrated energy system analyses can be done.

Through the use of this tool four different mitigation scenarios are developed, where for each scenario two different recycling scenarios are applied – a scenario with no increase in recycling, and a scenario with a high increase in recycling. The scenarios developed are:

- a scenario where all BATs are implemented,
- a scenario with BATs and innovative measures,
- a scenario with BATs and extensive electrification, and
- a scenario with BATs and extensive shift to hydrogen-based processes.

This report has presented the established scenarios in terms of their resulting energy demand, CO_2 emissions, investment costs, fuel cost, and excess heat potential for district heating. The results indicate that final energy savings ranging from 4.6% to 48.7% per sub-sector can be obtained, depending on the extent to which BATs are implemented and the level of recycling assumed for future scenarios.

The IndustryPLAN scenario outputs can be integrated with EnergyPLAN for further holistic energy system modelling, and as an external tool, IndustryPLAN allows for much more detailed mitigation scenarios of the industrial sector than what is traditionally possible in the EnergyPLAN methodology. The scenarios and resulting outputs will be used at later stages in the sEEnergies project for representing the industrial sector in energy system modelling in EnergyPLAN.

7 References

[1] Kermeli K, Crijns-Graus W. sEEnergies D3.1 Assessment of reference scenarios for industry. 2020.

[2] Kermeli K, Crijns-Graus W. sEEnergies D3.6 Energy efficiency potentials on top of the frozen efficiency scenario. 2020.

[3] Capros P, De Vita A, Tasios N, Siskos P, Kannavou M, Petropoulos A, et al. EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050. 2016.

[4] International Energy Agency (IEA). Energy balances 2016 edition. Paris, France: 2016.

[5] D3.4 W 3. D. and. Heat Roadmap Europe (HRE) (2017): Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050. 2017.

[6] Danish Energy Agency. Standardfaktorer for brændværdier og CO2-emissionsfaktorer til brug for rapporteringsåret 2019. 2020.

[7] Fleiter T, Neuwirth M, Mildner F, Manz P, Persson U, Kermeli K, et al. sEEnergies D5.1 Documentation on excess heat potentials of industrial sites including open data file with selected potentials. 2020.

[8] Danish Energy Agency, Grøn Energi. Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet. 2017.

[9] HOFOR. Establishing an electric industrial excess heat pump at Novozymes. 2019.

[10] PlanEnergi. Case description excess heat in Fensmark. 2018.

[11] Grøn Energi. Drejebog om store varmepumpeprojekter i fjernvarmesystemet. 2017.

[12] European Commission Directorate-General Energy. Study on energy efficiency and energy saving potential in industry and on possible policy mechanisms. 2015.