H2020 Work Programme

D3.2 - REPORT ON THE CBA OF INDUSTRIAL WASTE HEAT AND COLD AND RES IN INDUSTRY INVESTMENTS IN EUROPE

Lead Contractor: IVL Svenska Miljöinstitutet (IVL)

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Executive summary

In this report (D3.2) a cost-benefit analysis (CBA) of the socio-economic costs and benefits from using industrial excess heat and cold is presented. The calculations include techno-economic costs of investments and operation & maintenance, as well as socio-economic benefits from reduced air emissions of greenhouse gases and local air emissions. In addition to the cost-benefit analysis on industrial excess heat and cold recovery investment, integration of renewable energy sources (RES) was also analyzed, considering both new installations and local area RES potential for three of the demo sites. The results were incorporated into the cost-benefit analysis by assessing the impact of RES integration on the CBA results. The result in this report gives some interesting insights into how the environmental benefits of some investments are offset by large techno-economic costs, and also how some investments seem profitable from a techno-economic perspective but could lead to more emissions. In addition, there are also investments that are both environmentally and economically beneficial. In general, the greatest national potentials seem to derive from the waste-to-energy and district energy sectors.

A CBA could be an important method to integrate in the SO WHAT software in order to assess the welfare effects of industrial excess heat and cold exploitation scenarios. The ability to assess the net welfare through a CBA could be useful for making decisions on large public sector investments and to attract financial support, among other things. However, it is important to note that to be able to integrate a cost-benefit analysis in the SO WHAT software the input data to the CBA is just as important as the CBA method itself. To be able to perform a similar analysis to the one in this report a number of inputs are required, such as emissions factors linked to fuel combustion and electricity mixes, scenario specifications, technology options, technical specifications, external costs from emissions, investment costs and costs for variable inputs, the estimation of excess heat and RES potential etc. If possible to include such input data, a CBA module could be a powerful tool to assess the net welfare of an investment scenario.

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Abbreviations

BC	black carbon
CBA	cost-benefit analysis
CE	choice experiment
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CV	contingent valuation
DH	district heating
DHC	district heating and cooling
EFLH	equivalent full load hours
EU	European Union
GHG	greenhouse gas
GWh	giga watt hour
H_2	hydrogen
IEH	industrial excess heat
kt	kiloton
kW	kilowatt
M€	million Euro
MWh	megawatt hour
MWh_{th}	megawatt hour thermal energy
N_2O	nitrous oxide
NH_3	ammonia
NOx	nitrogen oxides
NVP	net present value
O&M	operation and maintenance
OC	organic carbon
PJ	peta joule
$PM_{2.5}$	fine particulate matter
PMres	non-BC, non-OC $PM_{2.5}$
R&D	research and development
RES	renewable energy sources
SO_2	sulfur dioxide
TWh	terawatt hour
VOC	volatile organic compounds
VOLY	value of a life year
VSL	value of a statistical Life
WTP	willingness to pay

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TABLE OF CONTENTS

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1 INTRODUCTION

1.1 Background

The main objective of the Horizon 2020 project SO WHAT is to develop and demonstrate an integrated software which will support industries and energy utilities in selecting, simulating and comparing alternative industrial excess heat (IEH) and cold[2] exploitation technologies that could cost-effectively balance the local forecasted heating and cooling demand, and also via renewable energy sources (RES) integration. The objective of WP3 "SO WHAT tool outcomes: business model analysis" is to generate important information for attracting investments and for realizing industrial excess heat and cold recovery investments.

One such important set of information is whether the investments will increase human welfare or not. Since all economic activity is related to some, but varying, degree of environmental impact, it is not at all certain that an investment increases human welfare. To analyze this, one need to make a full assessment of the social costs as well as the social benefits of an investment: one need to make a cost-benefit analysis (CBA). By considering both the costs that could be directly imposed on the parties taking part in the economic transaction, and the costs imposed on a third party not taking part in the transaction (referred to as externalities in economics), the cost-benefit analysis can assess the total impact on human welfare. CBA is mandated prior to making large changes in legislation and large public sector investments in the EU [1]. Besides this, the CBA can also be considered a useful support material when companies address the finance sector for financial support to investments.

In this report (D3.2) a cost benefit analysis of the socio-economic costs and benefits from using industrial excess heat and cold is presented. The calculations include techno-economic costs of investments and operation & maintenance, as well as socio-economic benefits from reduced air emissions of carbon dioxide (CO_2), nitrous oxides (N_2O), methane (CH_4), nitrogen oxides (NO_x), sulfur dioxides (SO_2), fine particulate matter (PM2.5), non-methane volatile organic compound (NMVOC), and ammonia (NH_3). Due to the fact that environmental and health effects from greenhouse gases and air pollutants are relatively well researched compared to effects of emissions to water and soil, or of toxins only emissions to the atmosphere are considered in this report. The calculations were made on the demo sites of the SO WHAT project, and costs and benefits were scaled up with existing data on the potential for industrial excess heat and cold recovery per demo site country. The CBA shows the aggregated, societal benefits of undertaking all the identified, potential industrial excess heat and cold recovery investments in the countries of the demo sites. The work has been performed by IVL.

In addition to the cost-benefit analysis on industrial excess heat and cold recovery investment, RES integration was also analyzed, considering both new installations and local area RES potential for a number of the demo sites. The integration with the identified excess heat and cold sources was also considered. The analysis considers the technical feasibility and barriers while the CBA is assessing the profitability of the investment. The work has been performed under RINA-C guidance, and the results was incorporated into the cost-benefit analysis performed by IVL by assessing the impact of RES integration on the CBA results.

[2] Could also be referred to as waste heat and cold

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1.2 Previous studies

Previous work, analyzing the economic and environmental benefits of an increased use of industrial excess heat, are mainly case studies analyzing costs and benefits through different energy system models, such as [2] and [3], and energy market scenarios, as in [4] and [5]. The main focus in the published work is on Sweden, but [6], [7] and [8] are examples on studies from other European countries. Some of the studies take a business economic perspective, such as [8], while others have a more socio-economic perspective, as in [7]. None of the studies found include the costs of negative externalities; costs associated with the effects on health and environment from emissions.

The integration of excess heat in district heating (DH) systems could have both economic and environmental benefits. In [6] both economic and environmental benefits prevails when using the IEH with flexibility options such as connecting several cities to the same DH grid and to integrate thermal storage to facilitate a large utilization of the excess heat.

A case study from Gävleborg county in Sweden [9] illustrates the impacts on greenhouse gas (GHG) emissions from the use of recovered heat from pulp and paper and steel industries in a DH system or for electricity generation. The results illustrate the impact on GHG from different scenario assumptions such as build margin technology for heat and electricity and margin user of the fuels.

The Gothenburg district heating grid, which is also participating in the SO WHAT project, is part of two previous studies analyzing the economic and environmental benefits of using industrial excess heat. In [4] a framework, differentiating between unavoidable excess heat and avoidable excess heat that could be avoided by increased heat recovery at the plant site, is presented. The authors emphasize that the larger GHG emissions reductions are achieved when using unavoidable excess heat. In [2] the system profitability of the use of industrial excess heat from a cluster of chemical industries in the same Kungälv/Gothenburg DH grid is analyzed. The results show network profitability under most assumptions and the economic viability increases with biomass competition, phase-out of natural gas and higher CO_2 emission charges, but decreases if other industrial excess heat sources than from the chemical industries contribute to a large share of the base load in the DH grid.

In [5] the trade-off between internal (on the industrial site) and external use (in a district heating grid) of excess heat is investigated for an energy system model consisting of a pulp mill and an energy company. The study shows that external use of the excess heat is always preferred to reduce the CO_2 emissions, while the optimal use of the excess heat from an economic perspective depends on the energy market price if the district heating loads is medium or large. For small district heating loads, external use of excess heat is always the most favorable.

In [3] the economic and environmental benefits on a specific district heating system in Hofors, Sweden, with a jointly operated CHP plant and supplied by excess heat from a nearby steel industry, is evaluated. The results show advantages for a DH system to utilize industrial excess heat for the delivery of DH, process steam and cogeneration of electricity. The study presents a decrease in total system cost, less use of fuel and electricity and reduced CO_2 emissions. The authors of the study emphasize that the integration of industrial excess heat may facilitate different kinds of energy cooperation, but that it is difficult to generalize the potential of such cooperation due to the specific local circumstances.

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Many of the studies that have been performed to assess economic and environmental benefits of industrial excess heat recovery highlights the large impact from the assumptions about the costs (e.g. energy market prices [7] [8] [5] [4] and CO_2 prices [7]) as well as the environmental impact from the substituted energy generation (e.g. from build margin power generation technology [4] and substituted marginal electricity production [3]). To summarize the experiences from previous work it is important to emphasize the impacts from assumptions of what the IEH is replacing and how it is used in the energy system, just as the other assumptions done for the energy system analyzed, both the present one and the future.

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2 METHOD AND MATERIAL

The CBA presented in this report includes the socio-economic net-present economic value of various types of investments necessary to utilize excess heat. The CBA considers techno-economic costs associated with investments as well as non-market costs of climate change and poor air quality. It covers a 50-year time span (2020-2069) and considers seven demo sites in five European countries. The SO WHAT MPI demo site in the United Kingdom is a research pilot plant and not a full-scale demo site and the required data for the site was very limited, hence it was excluded from the analysis. This chapter first presents an overview of CBA as a concept, the Impact Pathway Approach used to identify climate change and human health effects, the scenario technique, and how the upscaling has been done. Following this, we present the part of the analysis related to estimating the potential of renewable electricity. Examples of the material used for the CBA is found in the appendices to this report. The publicly available version is redacted with respect to investment costs as well as operation and maintenance costs due to these items being classified as proprietary information.

2.1 Cost Benefit Analysis

The CBA approach was developed in the 19th century in France [10]. Over the years, CBA practices have been developed by both applied and theoretical researchers and many guidelines have been written on how to do a CBA. In a typical manual, a CBA should include the following steps (adapted from Boardman, Greenberg [11]):

- A specification of the alternatives to be evaluated,
- A decision on whose benefits and costs that should be considered,
- Identification of effects and how to measure them,
- Prediction of the quantitative change of the effects,
- Monetization of the changes,
- Discounting of the monetized values if they occur over a period and not only in a single year,
- Computing Net Present Value (NPV) of all the alternatives,
- Sensitivity analysis,
- Recommendation on policy action.

Measurement and monetization of the changes induced on non-tradeable goods and services is done by either creating hypothetical markets in which respondents can express their willingness to pay (WTP) for goods or services (stated-preference method) or by studying existing markets for other related goods and services (revealed preference method). The stated preference method has several alternative designs. The choice experiment (CE) and the contingent valuation (CV) methods are the two most common designs. In the CE method the respondents are asked to choose a level of environmental quality from a set of varying environmental qualities, called choice set. In the CV method the respondents are asked to imagine an environmental market situation and then asked how he/she would act in that given situation. CE and CV attempts to find the WTP for a good or service by asking individuals direct questions about their preferences. Alternatively, researchers can ask the respondents for their WTP. The main criticism towards the stated preference method is that the conclusions are drawn from a hypothetical survey, where the respondents who state they would pay a certain amount do not actually have to pay at all.

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The revealed preference method observes the real choice between money and the environmental goods. Methods often include observations of consumers' or producers' behavior or actions, such as the hedonic price method and the production function method. The hedonic price method determines values from actual market transactions. These transactions are used to see how the price of a market commodity varies when the quantity or quality of a related environmental good changes: such as the effects of noise or air pollution on housing prices. The production function method is used to estimate the value of the environmental effects on production. This method is suitable when consumption or production of a private good is affected by the environmental good. An example is the valuation of ground-level ozone levels by valuing the impact on the production of wheat or timber, which has market prices [12].

A case-specific monetization of the environmental changes is usually prohibitively expensive to analyze, and many environmental policy CBAs have come to rely on benefits being assessed with the benefit transfer method. Benefit transfer basically implies that either the benefit value or the benefit function from an existing state-of-the-art economic valuation study is transferred to a study on other populations, geographical regions, or policies [13]. The transfer of benefit values can be done through different levels of sophistication where the least sophisticated – the direct transfer of values – has been shown to often be the least accurate. Preferably, the transfer of benefit values involves either adjustments for economic parameters such as GDP per capita and purchase power parity, studying the trends in values from different studies, or the use of value ranges from prior studies. Transferring benefit functions implies that explanatory variables observable in both the original study and the ongoing study are used to derive a function that explains the benefit value in the original study. The function is then transferred to the ongoing study and used to calculate new benefit values [14]. In this study the benefit transfers are adjusted with respect to differences in purchase power parity between the region in which the original study was made and Europe. Further, EU average values of benefits from improved human health and reduced climate change are used for all demo site countries.

There are two main versions of CBA applied for policy analysis, one version based on optimization and one version based on scenario comparisons (as in this report). In the optimization version the CBA searches after a cost-efficient solution: a solution that gives human health and environmental effects so that net socio-economic benefit of emission reduction is maximized (adapted from OECD [15]). In such CBAs it is presumed that the demand for environmental quality and human health is dependent on the cost of satisfying the demand, and most often it is assumed that each incremental improvement is worth less than the previous. It is also assumed that emission control costs increase with increasing policy ambition. If this is the case, there is a solution in which the marginal cost for achieving an incremental reduction in emission levels is equal to the marginal benefits of that incremental change. This resulting total emission level is then cost-efficient (optimal) for society.

The second main version of CBA is to identify which of the available options (or policies) that would give highest available net socio-economic benefits for society. The results from such a CBA often show the ratio of total benefit over costs (B/C ratio). If the B/C ratio is above one, the solution gives net socio-economic benefits. This latter version of CBA can be considered useful if many options are available to reach the same target or if the control options studied are non-additive.

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2.2 Impact Pathway approach

The impact pathway approach (IPA) [16] describes the currently considered appropriate steps of air pollution policy analysis. These steps include modelling of emissions, emission dispersion, environmental & human health impacts, as well as the economic modelling of emission control costs and corresponding economic benefits. It highlights that air pollution policy also needs to adapt to regional circumstances since population densities and demographics varies over Europe and since the ecosystems of Europe are varying with respect to their sensitivity to deposition of acidifying pollution, eutrophying deposition, and ozone damages. Furthermore, since air pollutants are transported over country borders, and European winds have a general annual average direction, it is also important to know where a potential emission reduction should take place. The impact pathway approach takes all these matters into account and is used as a guidebook for the key analytical steps when doing air pollution CBA. An important concept formalized within the IPA is the use of dose-response functions and concentration-response functions. These functions describe in a formalized way the relation between air pollution exposure and the impacts on human health and the environment (Figure 1).

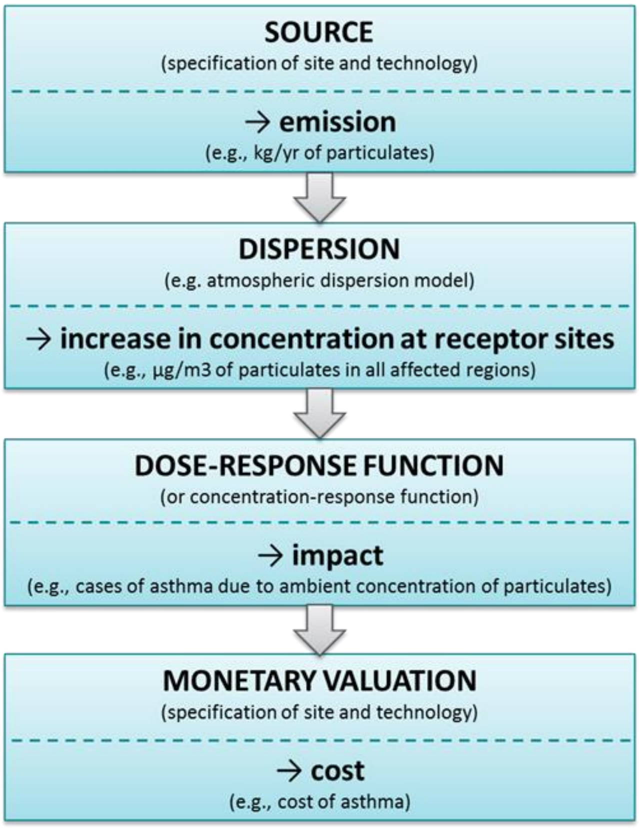

Figure 1 The principal steps of an impact pathway analysis, for the example of air pollution. Adapted from Bickel and Friedrich [16]

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2.3 Scenario analysis

The foundations for this CBA are the scenarios that are created within the framework of the SO WHAT project. A scenario is usually described as a "*coherent, internally consistent, and plausible description of a possible future state of the world*" [17]. In other words, in order to use the term 'scenario' on a description of a potential future, a bit more than two historical data-points, a pen and a ruler is necessary. In this report, the demo site-specific scenarios are based on data and expertise from the SO WHAT project partners representing the respective sites. Interviews have been made and data collection has also been performed via mail correspondence with the demo site representatives. The scenarios on fuel prices and emissions from electricity production are taken from recent scenario analyses made for the European Commission [18, 19]. The scenario period is 2020-2069, although with air pollution legislation kept constant after 2030 and energy and climate policies kept constant after 2050. Emissions, costs and benefits are calculated for all these years.

2.4 Scenario specification

The scenarios explored for the demo sites were developed in cooperation with the demo site representatives of the SO WHAT project. At first, interviews were performed by IVL to get a better understanding of the excess heat and cold investment plans of the demo sites. In the next phase the technology investment options were collected from the demo sites, these options are the building bricks of the scenarios. Additional meetings were held by RINA with representatives for Umicore, LIPOR and RADET demo sites to also formulate several RES scenarios that was used in the sensitivity analysis. In cases where no information could be attained, assumptions have been made. The limitations and assumptions are presented more in detail in Chapter 3 of this report, assumptions made for the demo site-specific scenarios are presented in Chapter 4.

In brief, each **scenario** explored in this report is defined by:

i) a set of technology investment options (from now on called option/s);
ii) the investment and reinvestment years of these options and;
iii) the years during which these options are in operation

For each demo site there is a **reference scenario**; a combination of the technology options that are in operation today and which will be replaced in the other scenarios. For example, if a heating customer today uses a natural gas boiler as a source for heating but will be using industrial excess heat supplied by a district heating network in one future investment scenario, the reference scenario contains the technology investment option natural gas boiler and the future investment scenario contains the option excess heat recovery technologies and the option district heating network.

The options are important building bricks of the scenarios. Each **option** contains information about the following:

a) Type of technology
b) Year of investment [Year]
c) Technical lifetime [Years]
d) Installation size [kW]
e) Annual heat production [MWh,thermal]
f) Investment cost [€/kW]
g) Maintenance costs, fixed [€/kW] and variable [€/MWh,thermal]

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h) Variable input demand [x/MWh,thermal], where x can be different units depending on the input (e.g. liter for water, kg for material, hours for work etc.)
i) Variable fuel demand [MWh,fuel/MWh,thermal]
j) Variable electricity demand [MWh,electricity/MWh,thermal]
k) Emissions from fuel combustion [kg/MWh,thermal]

Furthermore, linked to the above technology options are also the following data which is specific for the country in which the demo site is located:

a) Emissions from the electricity production, table A.II.1-A.II.5 [kg/MWh,electricity]
b) External costs of the emissions, table A.II.6-A.II.10 [€/kg]
c) Costs of the variable inputs, fuel and electricity, table A.II.11-A.II.15 [€/unit]

The data used for the above mentioned information included in the scenarios was primarily based on information provided by the demo site representatives, but additional sources have also been consulted. For the type of technology and year of investment the demo site representatives have been the primary sources. For the technical life times, the information provided by the demo site representatives has been complemented by technology data from the Danish Energy Agency provided in [20, 21] and a report on EU projections of technology developments in the heating and cooling sector [22]. The demo site representatives have also provided data on installation sizes and the annual heat production. In the cases where this data has not been available, as for existing natural gas installations of the heat customers, the assumptions presented Chapter 3 was made. For the investment and maintenance costs, [20, 21] and [22] have been valuable resources in the cases where the demo site representatives have not been able to deliver these data. The same applies to the variable inputs and fuel demands.

Emission data for the technology options and electricity production, as well as emission dispersion patterns between regions, has been extracted from the GAINS model database[3] and from the scenarios presented in [19]. The GAINS model [23, 24] is an air pollution integrated assessment model developed by the International Institute for Applied Systems Analysis (IIASA). It is a bottom-up model developed to analyze how future air pollution emissions can be reduced to achieve specified positive effects on the environment and human health to the lowest cost. The model is based on the following main components: i) exogenous scenario data on polluting activities; ii) database information on emission factors, control options, and emission control costs; iii) linear form calculations of emission dispersion and deposition over Europe; and iv) exogenous data on ecosystem sensitivities and on population demographics. These components enable calculation of scenario-specific results on emissions, emission control costs, as well as environmental and human health effects. Several separate research disciplines and models feed into the GAINS model. Exogenous scenario data on polluting activities is taken either from European scale energy system models and agricultural models such as POLES, CAPRI, and PRIMES [25-27], or from national scenarios supplied by national experts. The linear form calculations of emission dispersion are based on calculations with the chemical transport model EMEP [28] and the exogenous data on ecosystem sensitivities is based on [29, 30]. The GAINS model utilizes a rich description of control options when minimizing control costs [31-35]. Compared to for example some economic equilibrium models, one can consider the GAINS model to

[3] https://gains.iiasa.ac.at/gains/EUN/index.login?logout=1&switch_version=v0 , scenario: CEP_post2014_CLE_v.Dec.2018

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use a techno-economic approach to costs of emission reductions, which ensures physical consistency of modelling results. All data and scenarios are publicly available after registration.

As can be seen in Figure 2 - Figure 6 below, developed from the latest EU long-term energy projection [18], the fuel and primary energy mixes for the power production in the five countries vary both between the countries and years.

The Belgian electricity mix is characterized by large shares of nuclear and natural gas today but increasing shares of natural gas and renewables in the long term, see Figure 2.

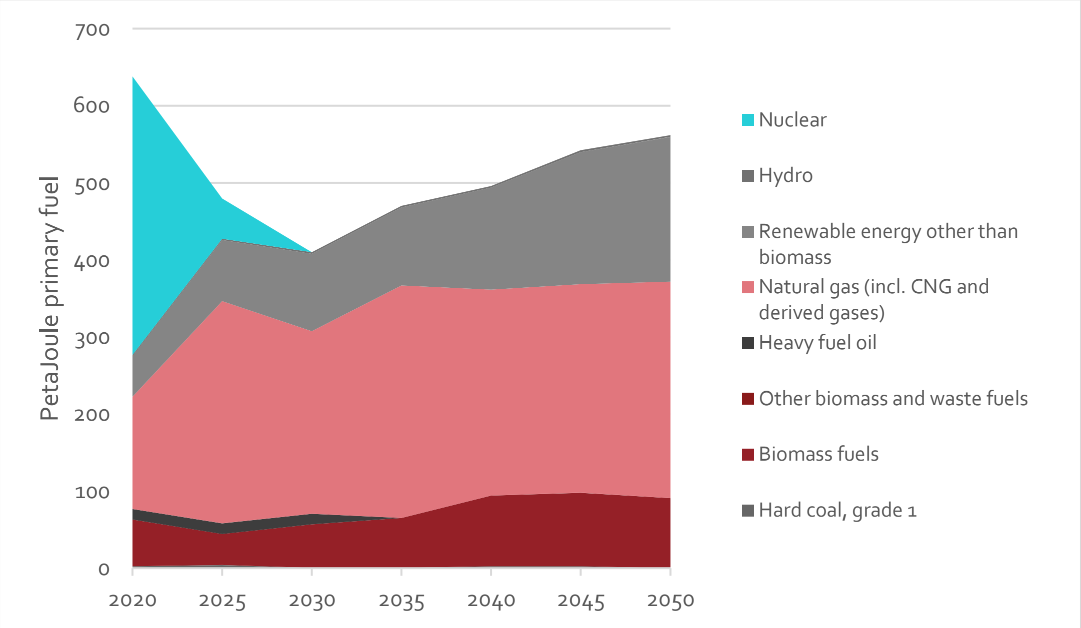

Figure 2 Fuel input to power plants, Belgium 2020 - 2050

The Spanish fuel input to electricity production is somewhat more diversified than the Belgian mix, see Figure 3, with the major shares being of nuclear, natural gas and coal today but a domination of renewables in the long term.

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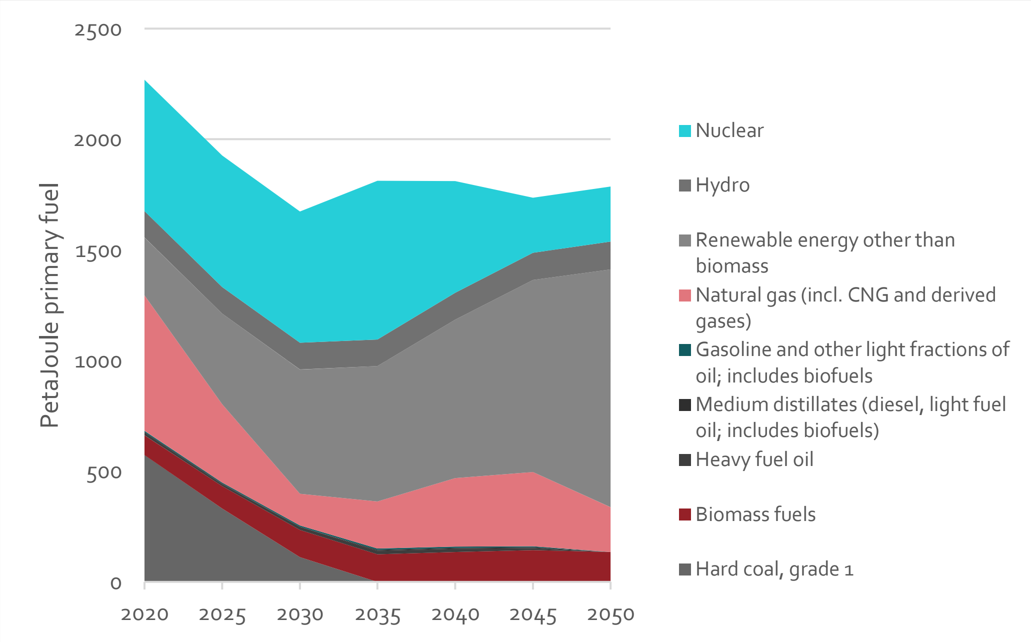

Figure 3 Fuel input to power plants, Spain 2020 – 2050

The Italian fuel mix is primarily natural gas today, but in the long-term renewables will also contribute with an increasing share as could be seen in Figure 4.

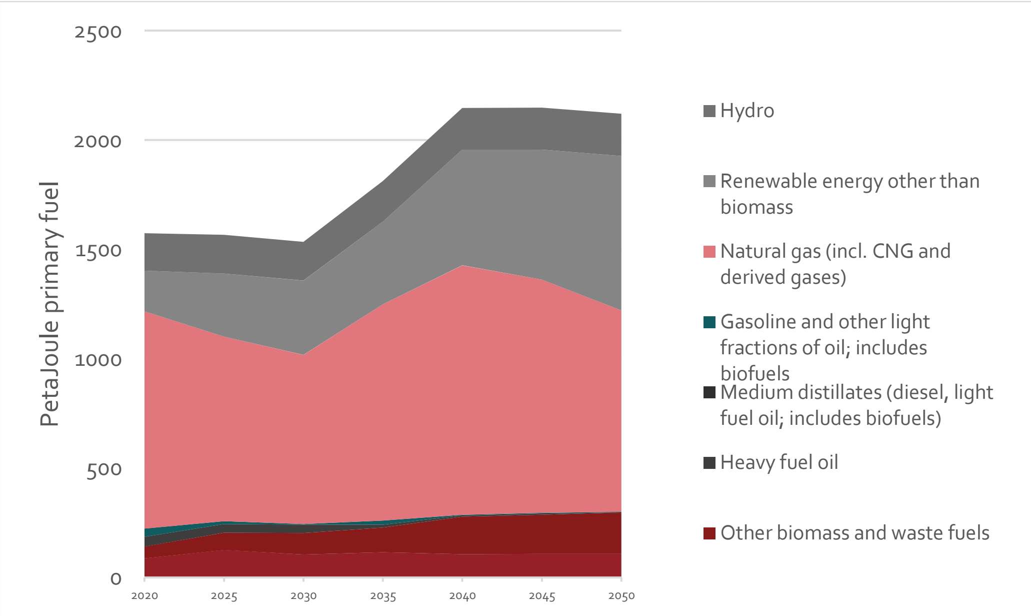

Figure 4 Fuel input to power plants, Italy 2020 – 2050

In Portugal hydro, renewables, natural gas and biomass each contributes with large shares today, see Figure 5, but in the long-term the renewables seem to increase at the expense of natural gas and coal.

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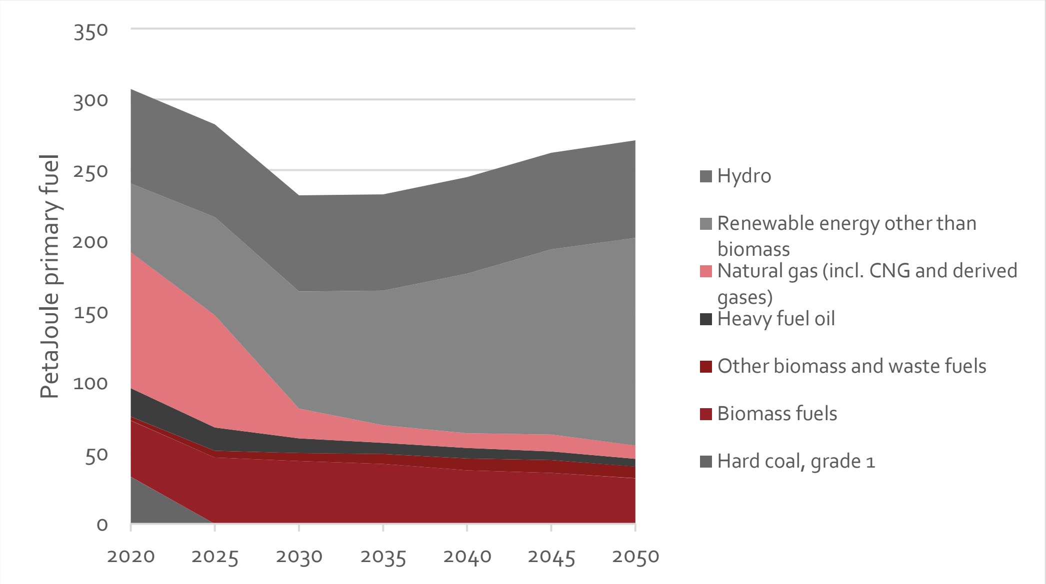

Figure 5 Fuel input to power plants, Portugal 2020 – 2050

Romania has large shares of nuclear, natural gas and coal in the electricity mix today, see Figure 6. However, in the long run the share of nuclear will increase and coal will be phased out and replaced by renewables.

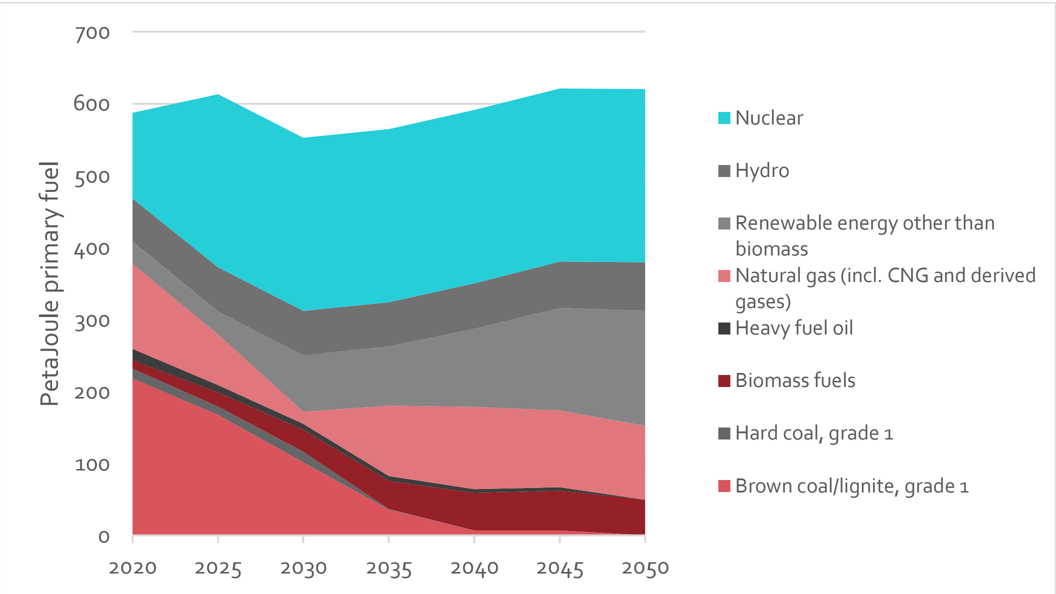

Figure 6 Fuel input to power plants, Romania 2020 – 2050

The costs for variable inputs, fuels and electricity have been collected for each of the countries to the extent possible. The data sources used are provided in Table 1.

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Table 1 Data sources for variable input costs

Variable input	Source	Demo sites used for
Person hours	Estimated hourly label cost 2019, Eurostat [36]	RADET, ISVAG, RADET
Water	Total charges for 198 Cities in 2017 for a Consumption of 200 m^3 in USD, International Water Association [37]	UMICORE, RADET
Material	Price of chemical reactant, demo site representative of RADET	RADET
Electricity	Average price of electricity in final demand sectors 2020-2050, EU Reference Scenario 2016 [38]	ENCE, UMICORE, IMERYS, LIPOR, PETROMIDIA, RADET, MARTINI&ROSSI
Crude oil	Import price in JRC-EU-Times reference scenario 2015, 2030 and 2050, Heat Roadmap Europe [39]	PETROMIDIA
Natural gas	Import price in JRC-EU-Times reference scenario 2015, 2030 and 2050, Heat Roadmap Europe [39]	ENCE, UMICORE, IMERYS, LIPOR, ISVAG, RADET, MARTINI&ROSSI
Biofuel	Average biomass price with a low labour share 2015, 2030 and 2050, Heat Roadmap Europe [40]	ENCE, RADET
Waste	Gate fees for household waste, bulky waste and municipal waste in Flanders in 2018, OVAM [41]	ISVAG

Historical costs have been recalculated into 2020 Euro-area real values using the following inflations: 6 % (from 2013 and 2015 to 2020), 4 % (from 2017 to 2020), 3 % (from 2018 to 2020). For the cost of electricity, a prognosis for the average prices of electricity in final demand sectors per EU country for the years 2020 – 2050 developed in the EU Reference Scenario 2016 was used [38]. As this data source only contain costs for every fifth year, the values were interpolated in order to get values for every single year. The 2050 value was used for 2051 – 2069. For the cost of natural gas, the JRC-EU-Times reference scenario in [39] was used. This baseline scenario is aligned with the EU Reference Scenario 2016. For the cost of biomass the average costs of biomass, assuming a low labor share, presented in [40] as part of the Heat Roadmap Europe, was used. For natural gas and biomass, only values for 2015, 2030 and 2050 were given. The values in between these years were interpolated and for 2051 – 2069 values, the 2050 value was used. In cases where no published prognosis exists, as for the cost per work hour and for water, a constant value has been used for the years 2021 to 2069. For the work hour costs the estimated hourly costs EU country for 2019 per was used [36]. For the cost of water the total charges for a consumption of 200 m^3 in USD for 2017 in Antwerp (Belgium) and Constanta (Romania) were used [37] and the EUR/USD exchange rate was assumed to be 1.13.

The external costs for the emissions included both climate change and air pollution. All emissions considered in this report are known to have radiative forcing properties, and we used the latest available and comparable indicator values for the climate metric 'Global Warming Potential' integrated over 100 years (GWP100) to achieve comparable climate change effects of the emissions [42-45]. To put an economic value of climate change we used social cost of carbon-estimates from a revised version of William Nordhaus' DICE model [46]: 88 €$_{2020}$/ton in 2020 and rising to 322 €$_{2020}$/ton $CO2_{eq}$ by 2069.

The effects of emissions to the atmosphere are for long-lived greenhouse gases such as CO_2 not specifically dependent on emission source region, and for short-lived climate pollutants such as SO_2

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the effect on climate change is only possible to estimate per continent. The human health effects of emissions however are varying within much smaller geographical regions. It is therefore not suitable to use average monetary values of emissions, and at least a country-specific estimate is necessary. To estimate external costs of air pollution we used the GAINS model to calculate the effect of a country's air pollution emissions on population-weighted exposure to PM2.5 in ambient air in the affected countries. These exposures were then transferred into the ARP model [47]. The ARP model is a tool for health impact assessment and monetary evaluation of air pollution emissions. By using age group specific population data projections from United Nations [48], together with data on health impact incidence rates and data on concentration-response functions from WHO, Henschel [49] the ARP model calculates the health impacts from air pollution. Impacts on mortality are in this study calculated as the aggregate reduction in life expectancy across the population. In this study we excluded any direct health impact from exposure to NO_2 [50] or the suspected relatively high importance of black carbon particles for health impacts [51] due to risk of double-counting with health impacts from exposure to PM2.5. Neither were the health impacts from exposure to ozone included. The economic value of a life-year lost, which constitutes the large majority of the economic value of air pollution, is based on willingness-to-pay studies [52] and should therefore be adjusted with increased income in the future [53].Here we inflate the original value with 2% per year as a proxy for increase in disposable income. All together, we calculate country-specific and year-specific external costs for emissions of CO_2, N_2O, CH_4, SO_2, PM2.5 (including sub-species), NO_x, NMVOC and NH_3 and use these as input to the CBA.

All data for the technology options used in the scenarios is presented in Appendix I, all other data used for the analysis is presented in Appendix II. The actual calculations were made in the free software Python (v. 3.7), using the plugins Pandas (v. 1.1.3) and Numpy (v. 1.16.5). The python code is available at https://github.com/IVL-Research and the repository: "SO_WHAT_CBA".

2.5 Upscaling from demo site to country

To scale up the welfare effect results for the individual demo sites to a national level the method described in Appendix III was used. Assessments on excess heat potential in SO WHAT D1.2 [54], excess heat potentials assessed in [55] and Romanian district heating data from [56] and [57] were used to estimate the national potentials for industrial excess heat, and for RES in district heating in the case of Romania. To calculate the potential net welfare effect in each country and industry sector the following parameters were used:

- The industrial excess/RES heat production of the individual demo site, P_{demo} *[TWh]*
- The welfare effect of the individual demo site for the preferred scenario, W_{demo} *[€]*
- The industrial excess/RES heat potential of the industry sector and country, $P_{sector,country}$ *[TWh]*

Two different methods (Method 1 and Method 2) to attain the excess heat potential of each industry sector and country, described in [54], were used. In short, the first method uses a top-down approach and is based upon a calculation of the percentage of heat demand that is recoverable from surplus heat output from major industrial processes. The second method uses a bottom up study of all the technologies that are used in each industry to estimate surplus output energy streams with recoverable waste heat at three temperature levels. For Romania it does not differ anything between Method 1 and Method 2 as district heating networks were not part of these methods and the national

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potential has been assessed based on other assumptions. This also applies to the Portuguese case, as well as the upscaling of Belgian demo site ISVAG results, as waste-to-energy facilities were not part of the two methods developed in [54].

To calculate the welfare effect for each sector and country, $\boldsymbol{W_{sector,country}}$, the following formula was used:

$$\boldsymbol{W_{sector,country}} = \frac{\boldsymbol{W_{demo}}}{\boldsymbol{P_{demo}}} \boldsymbol{P_{sector,country}}$$

Finally, the welfare effect for each demo site country, $\boldsymbol{W_{sector,country}}$, was obtained by summarizing the result for all sectors:

$$\boldsymbol{W_{country}} = \sum \boldsymbol{W_{sector,country}}$$

The result of the upscaling is presented in Chapter 5.

2.6 Profitability analysis

The profitability analysis was carried out in order to evaluate the profitability of the investments in the technologies that exploit the renewable energy sources for electricity and thermal production. This evaluation was applied to the demo sites (Radet, Lipor and Umicore) in which the electrical RESs are considered in order to cover the electrical energy consumed by the thermal plant auxiliaries, to sell the electricity surplus to the national grid or, in the case of Radet, introducing an heat pump to provide heat to the DHN.

The indexes that have been used to highlight if the investment produces an economical advantage at the end of the plant technical life are the payback period and the net present value (NPV). The payback period is equal to the number of years that are necessary to obtain the return of the total investment done for the technologies and it is expressed by the following equation:

$$PBP\ [year] = \frac{Total\ investment\ [€]}{Annual\ revenues\ [€/year]}$$

Where the total investment is the sum of the investment cost for the installation of the technologies and the O&M cost over the technology lifetime years, while the annual revenues in this case is considered as follow:

$$Annual\ revenues\ \left[\frac{€}{year}\right] = El_{cost} * El_{dem} + El_{price} * \left(El_{prod} - El_{dem}\right) + H_{cost} * H_{prod}$$

Where:

- El_{cost} is the cost of the electricity bought from the national grid [€/kWh];
- El_{dem} is the electrical demand of the thermal plant auxiliaries that will be satisfy by the electrical RES technologies that will substitute the electrical consumption from the national grid [[kWh];
- El_{price} the electrical price at which the electrical energy is sold to the grid [€/kWh];

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- $(El_{prod} - El_{dem})$ is the difference between the electrical energy produced by the electrical RES technologies and the electrical auxiliaries demand [kWh];
- H_{cost} is the price at which the heat is sold the end user [€/kWh];
- H_{prod} is the heat that is produced by the thermal RES technologies [kWh].

The net present value allows for comparison of cash flows in different periods and is defined as the difference between the total investment and the sum of revenues obtained during the technology's lifetime actualized at the investment year. It is expressed by the following expression:

$$NPV\ [€] = -Total\ investment\ [€] + \sum_{t=1}^{N} \frac{Annual\ revenues[€]}{(1+i)^t}$$

Where:

- i is the discount rate (assumed equal to 4%);
- t is the reference year;
- N is the technologies lifetime.

The investment is considered economically advantageous if the PBP is lower than the technology's lifetime or if the NPV assume a positive value before the year in which it is planned to decommission the plant.

The formulas of the PBP and the NPV were applied to the different demo sites in order to evaluate the profitability of the investment in the electrical RES technologies. The scenarios taken into account are presented in the sensitivity analysis in Section 5.3.

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3 LIMITATIONS AND ASSUMPTIONS

The CBA and RES calculations are subject to limitations and require some assumptions. These can relate both to economic perspectives, environmental effects and technical circumstances. In this chapter we present the most important of the limitations and assumptions, grouped into excess heat and cold recovery on one side, RES on the other. Demo site specific assumptions are presented in Chapter 5.

3.1 Economic limitations and assumptions

The CBA of excess heat recovery is of a standard format, albeit with an extended consideration of the climate change effects of air pollution. As such, it has certain limitations. The time frame for the analysis is 50 years. This is a reasonable assumption since some of the technology investments have a maximum lifetime of 50 years. That CO_2 emissions have a much longer climate perturbation time than 50 years is to our understanding accounted for in the social cost of carbon used in the analysis. Therefore, the time span of the analysis doesn't have to cover the entire climate perturbation time of all emissions. Even if the time frame for the analysis is 50 years, the input data only covers the period up until 2050 for fuel prices (oil, natural gas and biomass), electricity costs and external costs. In the main analysis we therefore assumed that prices and costs remain constant, at the 2050 level, between 2051 and 2069. Further, the CBA is a socio-economic CBA that accounts for costs for society, not the individual firm. The potential profit from selling heat or electricity for the firm is thus not accounted for, since the firm's profit is another firm's loss. Also, in relation to this, the analysis assumes that the investment will be so small that it does not affect market prices of fuel electricity and heat. Investment costs and benefits are given as EU-average values for all demo-sites, reflecting the existence of an effective EU-internal market for environmental technologies and that transboundary pollution affects many countries.

3.2 Limitations and assumptions with respect to emissions and effects

When calculating emissions, we have assumed emission factors for electricity corresponding to average national electricity mixes of the demo site countries. Emissions from the demo site technology options and their associated fuels are assumed to be constant over the years as it is assumed that the technology installed are in line with the current emissions control policies for the year when it is installed, and that no retrofit will take place. In contrast, the emissions from electricity varies over time in response to changes in demand, climate change policy and air quality policy. The analysis is also limited with respect to the environmental and human health effects considered. Environmental and human effects from emissions of greenhouse gases (CO_2, CH_4, N_2O) and air pollutants (PM2.5, NO_x, SO_2, NMVOC, NH_3) are relatively well researched, at least compared to effects of emissions to water and soil, or of toxins. Due to this, only emissions to the atmosphere are considered in this report. This implies that we assume that the investments only will have effects on air quality and climate change, and only via atmospheric processes. Further, given that we base the emission dispersion on the GAINS model, we implicitly assume that the emissions from the demo sites have a geographical dispersion pattern identical to the average dispersion pattern for the entire country.

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3.3 Limitations and assumptions with respect to technology

The waste heat recovery potentials for the demo site in MWh annually were assessed by the demo site representatives. The temporal resolution is one calendar year. This implies that potential differences between daily peak-load and annual average emissions are ignored. The most important data gaps relate to lack of data for facilities other than the demo sites. The availability of technology data on the current thermal supply and technologies of utilities not part of the SO WHAT project, e.g. when a demo site plans to share excess heat with another facility such as an airport, has been limited and assumptions have been made on what type of technologies they are currently using. The availability of data on current thermal systems of the demo sites have in some cases also been very limited. As some of the demo sites have performed detailed feasibility studies of excess heat recovery and recovery technologies, while others are in the process of valorizing the excess heat streams, there are also variations in the quality of data.

As the installation sizes of some of the technologies used for space heating or cooling in the reference cases were not known, but the annual heat or cold supplied is known (assumed to be the same as the size of the excess heat or cold that will be replacing it), these have been calculated as:

$$Installation\ size\ [kW] = \frac{Annual\ thermal\ energy\ production\ [kWhthermal]}{Equivalent\ full\ load\ hours\ [hours]}$$

This approach was applied to LIPOR, ENCE, IMERYS and ISVAG demo sites (the demo sites are further described in Chapter 4). The equivalent full load hours (EFLH) values for heating or cooling was taken from [58], a study presenting the values for some of the cities in the USA. To find US cities that were similar in climate to the demo sites of SO WHAT a weather comparison tool provided by Codeminders [59] was used. For LIPOR and ENCE, the EFLH values for San Francisco were used. For IMERYS and ISVAG the Seattle value was applied. These two U.S. cities have a 99 % weather similarity with cities in the vicinity of the demo sites.

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4 TECHNICAL DESCRIPTION OF SCENARIOS

The technical description of the scenarios explored for the demo sites in the SO WHAT project are presented below as well as scenario specific assumptions. First the reference scenario, describing the current system, is described. Then the alternative scenarios, are presented.

4.1 RADET

RADET (Regia Autonoma de Distributie a Energiei Termice Constanta) is operating the Constanta municipality district heating grid and supplies 70% of the urban heating demand. Currently there is no industrial excess heat or renewable heat integrated in the district heating grid, but the company would like to explore the potentials of these sources to become less dependent on fossil fuels, e.g. natural gas. Data for the technology options and scenarios have been supplied by Medgreen, but some assumptions have also been made. The heat supply in the two different scenarios are presented in Figure 7 and a full description of the scenarios follows.

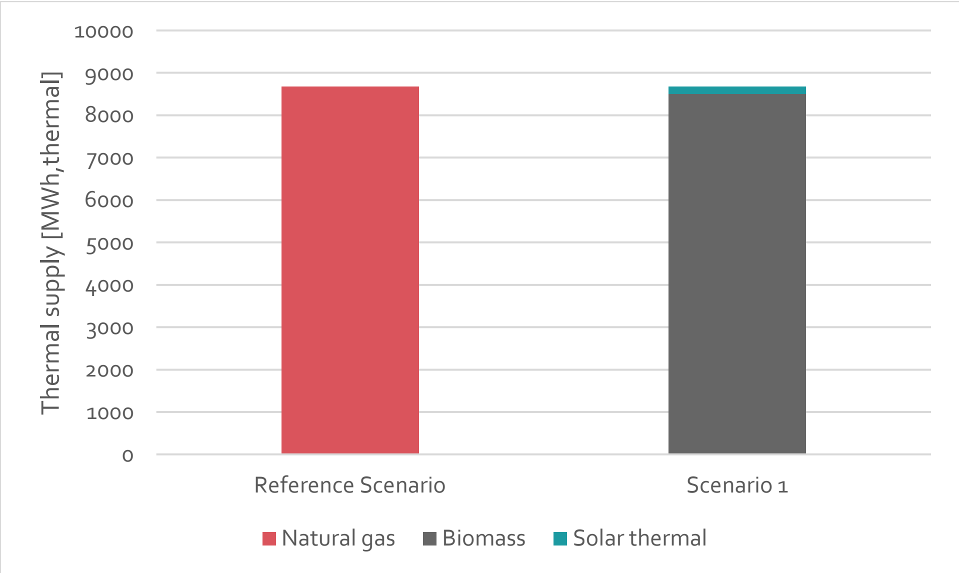

Figure 7 Heat supply in the different scenarios, RADET

4.1.1 Reference scenario

In the reference scenario the heat customers of RADET district heating grid is primarily getting their heating from natural gas fueled heat only boilers. There are both boilers owned by RADET and boilers owned by another company supplying the district heating grid.

Scenario assumptions:

- The natural gas boilers have been in operation for 10 years in 2020.
- The natural gas boilers are natural gas district heating boilers with an electricity demand of 0.14 % per MWh of heat generated, given by [21].
- The financial lifetime of the natural gas boilers is 25 years, based on information provided in [57].

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- For the cost of chemical reactants in Romania, RADET provided a value with the assumption that the LEU/EUR exchange rate was 4.7. The cost is constant for 2020 – 2069 as no prognosis exist for the cost development.

4.1.2 Scenario 1: Renewable district heating

In scenario 1 some of the heat in the district heating grid is replaced by heat produced by solar thermal (168 MWh annually) and from biomass pellets boilers (8,500 MWh annually). The investments are planned for 2020.

Scenario assumptions:

- The financial life time of the pellets boilers and solar thermal in RADET, Romania is 25 years [57].
- The fixed operation and maintenance cost of the solar thermal plant is 0.09 €/kW of thermal energy, given by data provided in [21].
- The solar thermal plant has an electricity demand of 0.3% per MWh of heat generated and the pellets boiler has an electricity demand of 0.5% per MWh of heat generated, given by data provided by the demo site representative.

4.2 PETROMIDIA

The Rompetrol Petromidia refinery is the largest Romanian oil refinery [60]. The refinery is primarily processing Ural crudes and the main products are fuels, mainly gasoline and diesel [61]. As a way to improve the efficiency of the refinery processes, Petromidia would like to explore the potential of industrial excess heat recovery for internal use. Data for the technology options and scenarios have been supplied by Medgreen, but some assumptions have also been made. The energy supply of the scenarios is not presented here, as Scenario 1 is leading to efficiencies rather than a new energy supply.

4.2.1 Reference scenario

In the reference scenario Petromidia Refinery is not recovering any excess heat from the hot condensate from the amine unit (140 °C).

4.2.2 Scenario 1: Internal use of excess heat

In Scenario 1 there are 15,215 MWh of excess heat recovered from the processes by investment in heat recovery technologies, such as heat exchangers, that will recover heat primarily from hot condensate at 140°C. This is leading to efficiency improvements in the oil refinery processes which decreases the CO2 emissions and crude oil consumption.

Scenario assumptions:

- The financial lifetime of the heat exchangers is 15 years. This number was given by the Belgian demo representative in the Belgian cases and assumed to be the same in Romania.
- The efficiency improvement as a result of the heat recovery, is quantified as a reduction in crude oil consumption. This reduction has been calculated by using the CO_2 reduction value given by Medgreen and the CO_2 emission factor for Romanian oil refining given by the GAINS model. The total 3,640 kt reduction in CO_2 is assumed to be directly from the reduction in the combustion of crude oil. The CO_2 emission factor of crude oil in refineries is 76.7 kt /PJ crude

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oil. Through calculations this means that the consumption of crude oil is reduced by 0.86 MWh crude oil for each MWh of industrial excess heat recovered.

- For the cost of crude oil, values for 2015, 2030 and 2050 were obtained from the JRC reference scenario in [39]. The values in between these years were interpolated and for 2051 – 2069 values the 2050 value was used.

4.3 LIPOR

Lipor is responsible for the management, recovery and treatment of the municipal waste in eight associated municipalities, among them the Maia municipality. The energy recovery plant in Maia was taken into operation in 2000 [62]. In 2019, 74 % of the municipal waste sent to Lipor was used for energy recovery generating approximately 170,000 MWh electricity. Nearly 90 % of the electricity produced is sent to the grid, while the rest is being consumed internally. Data for the technology options and scenarios have been supplied by 2GO OUT Consulting and AdE Porto, but some assumptions have also been made. The heat supply in the two different scenarios are presented in Figure 8 and a full description of the scenarios follows.

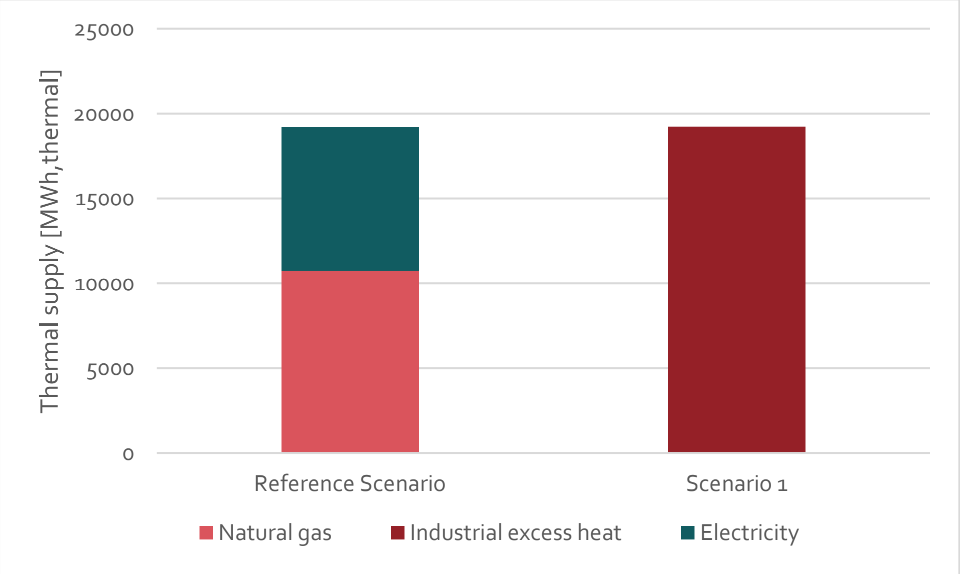

Figure 8 Heat supply in the different scenarios, LIPOR

4.3.1 Reference scenario: Natural gas boilers and electric chillers

In the refence scenario the Lipor Maia waste-to-energy plant is only producing steam for electricity production and the excess heat is released to the air. As there was very little information on the current thermal supply of the Francisco Sá Carneiro Airport the reference scenario has been based on the most likely supply for a Portuguese airport.

Scenario assumptions:

- The airport is using natural gas boilers for heating and electric chillers for cooling.
- The natural gas boilers and chillers need to be reinvested in 2020.

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- EFLH (equivalent full load hours) for cooling is 493 hours and for heating it is 1189 hours, assumed to be the same as for San Francisco, USA [58]. Porto has similar climate to San Francisco, according to [59].

4.3.2 Scenario 1: Excess heat recovery from waste incinerator

In this scenario 40,8 GWh heat will be recovered from the waste incinerator and shared with Porto Airport. The heat will be used for space heating and space cooling at the airport, in total 19,2 GWh of thermal energy. For the purpose of this there will be an investment in 3 absorption chillers with in total 12,000 kW cooling power capacity, pumps and heat exchangers as well as a hydraulic district heating network totaling 4 km.

Scenario assumptions:

- The absorption chillers have an efficiency (heat to cold) of 0,7, given by [63].
- The year of investment is 2020.
- There will be no additional waste incinerated to supply the heat.

4.4 ISVAG

The Belgian demonstrator ISVAG is an inter-municipal partnership company for waste management [64]. ISVAG operates a waste incineration plant close to the city of Antwerp, Belgium. The waste incineration plant is a superheated steam power plant that is currently focusing on producing electricity. There are plans to recover heat for a district heating network. The first step is to construct a small district heating network to the waste-to-energy plant, and later expand the network. Data for the technology options and scenarios have been supplied by Kelvin Solutions, but some assumptions have also been made. The heat supply in the three different scenarios are presented in Figure 9 and a full description of the scenarios follows.

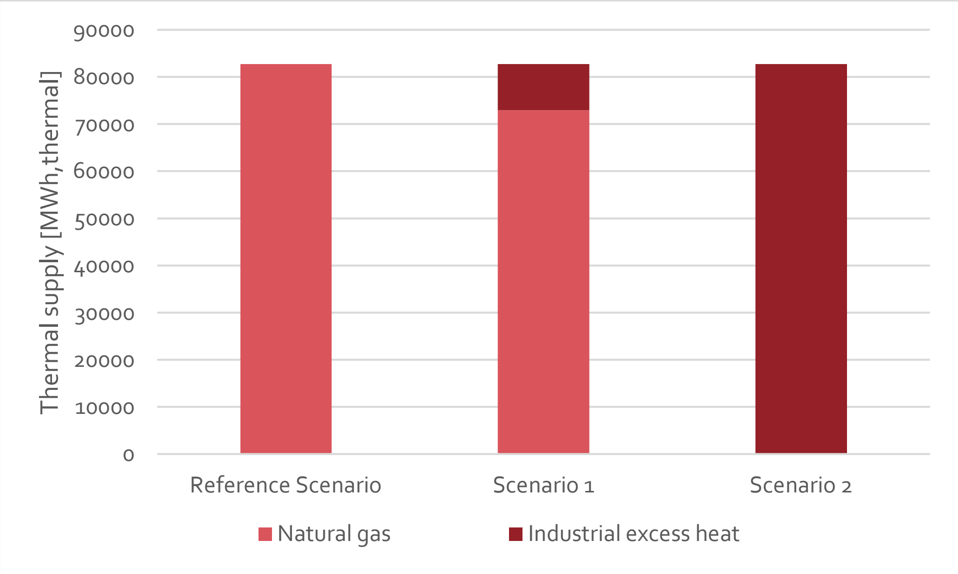

Figure 9 Heat supply in the different scenarios, ISVAG

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4.4.1 Reference scenario

In the reference scenario no heat is recovered from the waste-to-energy plant. The existing steam power plant is focusing on generating electricity, thus it is not included in the overall emission count. The potential excess heat customers use individual natural gas boilers to provide space heating and process heating.

Scenario assumptions:

- The natural gas boilers need to be reinvested in in 2020.
- The technical and financial lifetime of the natural gas boilers are both 25 years.
- The EFLH (equivalent full load hours) for heating is 2569 hours, assumed to be the same as for Seattle, USA [58]. Antwerp has similar climate to Seattle, according to [59].
- The technical and financial data for the natural gas boilers were given from the values of a natural gas boiler in an apartment complex, existing building, 400 kW/unit, 2020 numbers in [20].

4.4.2 Scenario 1: Small district heating network

In this scenario 9,749 MWh of excess heat is recovered from the flue gases of the existing waste-to-energy plant and from the boilers. The heat recovery investment includes heat exchangers that are connected in parallel to the individual natural gas boilers. The excess heat is distributed to the heat customers through a small-scale district heating network that will be taken into operation in 2020.

Scenario assumptions:

- The waste incinerated in the plant to produce heat has a lower heating value (LHV) of 10 MJ/kg, given by data used by the IPCC [65].
- For waste combusted in the ISVAG waste incinerator it was assumed that ISVAG was paid a gate-fee to handle the waste, hence the cost of waste was assumed to be negative. The gate-fee was taken from a report by OVAM, the Public Waste Agency of Flanders [41]. The fee was assumed to be constant between 2020 – 2069.
- The natural gas boilers of the remaining customers contribute with 72,954 MWh, which is the difference between the small and large (see Scenario 2) district heating network.
- The air pollution emission control of the waste incinerator is only for $PM_{2.5}$ (2-field electrostatic precipitator). There is no emission control for SO_2, NO_x nor NH_3. This is derived from the national average as expressed in [19], while existing and future waste-to-energy plants of ISVAG which are fully equipped the abatement technology, in correspondence with the concerned Flemish legislation).

4.4.3 Scenario 2: Large district heating network

In this scenario the new waste-to-energy plant as well as a larger district heating network is taken into operation in 2026, before that the small district heating network has been running since 2020 (the new installation will replace the old one). The total annual excess heat distributed to the customers will now be 82,703 MWh.

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Scenario assumptions:

- There will be no changes in the type of waste combusted per MWh heat recovered in this scenario compared to Scenario 1. The amount of waste is higher as a result of an expected increase of the Flemish population.
- The gate-fee for waste, e.g. the revenue that ISVAG gets to manage the waste, remains the same as in Scenario 1.
- The air pollution emission control of the waste incinerator is only for $PM_{2.5}$ (2-field electrostatic precipitator). There is no emission control for SO_2, NO_x nor NH_3. This is derived from the national average as expressed in [19], while existing and future waste-to-energy plants of ISVAG which are fully equipped the abatement technology, in correspondence with the concerned Flemish legislation).

4.5 UMICORE

Umicore is a high-tech materials recycling and production plant. The site in Olen, Belgium is focusing on recycling, clean technology, R&D and production of high-tech materials based on cobalt and germanium [66]. The industrial plant is currently using a steam heat network powered with natural gas to supply all the facilities on the site. However, they would like to invest in an internal heat grid that would use excess heat from some of the exothermic industrial processes.

Data for the technology options and scenarios have been supplied by Kelvin Solutions, but some assumptions have also been made. Please note that the excess heat streams and recovery plans might change due to changes in the production at the Olen site as was indicated in a press release on September 30, 2020 [67]. However, for the purpose of this CBA the excess heat analysis of the current production site, not taking the production changes into account, has been used. The heat supply in the two different scenarios are presented in Figure 10 and a full description of the scenarios follows.

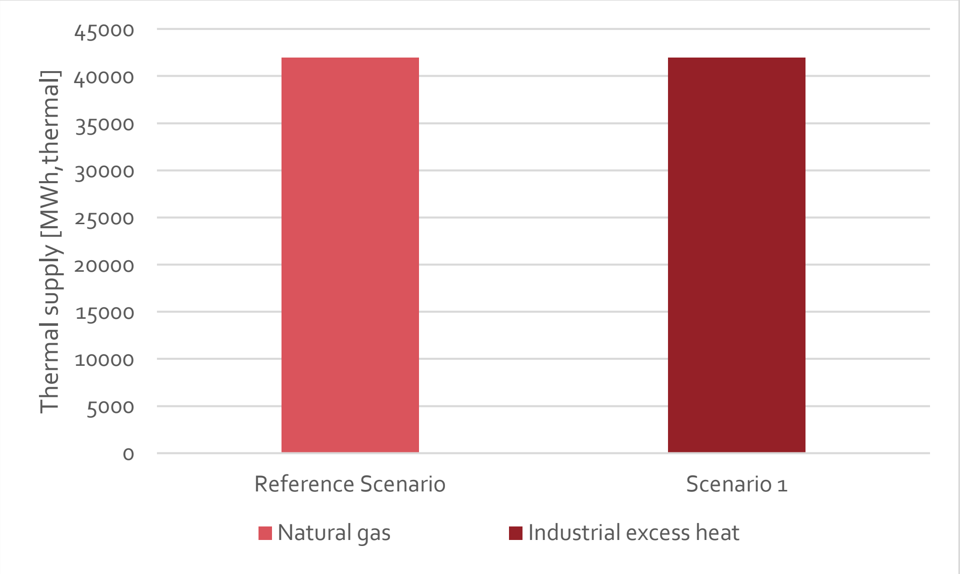

Figure 10 Heat supply in the different scenarios, UMICORE

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4.5.1 Reference scenario

In the reference scenario no heat is recovered from the industrial processes and an internal steam grid is supplying all the facilities on the industrial site. The steam used is produced using natural gas in multiple natural gas boilers, and two cogeneration turbines, that also produces electricity, are used on site.

Scenario assumptions:

- The cogeneration turbines of the steam grid contribute with electricity production; hence the electricity consumption is assumed to be negative for the current technology.

4.5.2 Scenario 1: Internal use of excess heat

In this scenario 41,960 MWh of industrial excess heat is recovered mainly from the hydrogenation and pyrogenation processes, in total from seven heat recovery points. The heat recovery investment includes heat exchangers installed in the chimney and in connection to process streams. There is also an investment in a heat grid onsite to distribute the excess heat internally. The investment is planned for 2022. The heat recovered will be used internally for process heating and space heating. The heat grid is not replacing the steam grid entirely so some facilities on site will continue to use steam for the processes.

4.6 IMERYS

The Belgian demonstrator Imerys Graphite & Carbon belongs to the multi-national Imerys Group, which is focusing on mineral specialties for the industry. The carbon black plant in Willebroek, Belgium produces a specialty-type of carbon black, mainly used by the conductive polymer and battery industries. The industry produces a mixture of hydrogen (H_2) and carbon monoxide (CO) as a by-product and this is currently burned in a furnace from which excess heat could be recovered. Currently, no heat is recovered from this furnace but there are opportunities to recover heat and share it externally. Data for the technology options and scenarios have been supplied by Kelvin Solutions, but some assumptions have also been made. The heat supply in the two different scenarios are presented in Figure 11 and a full description of the scenarios follows.

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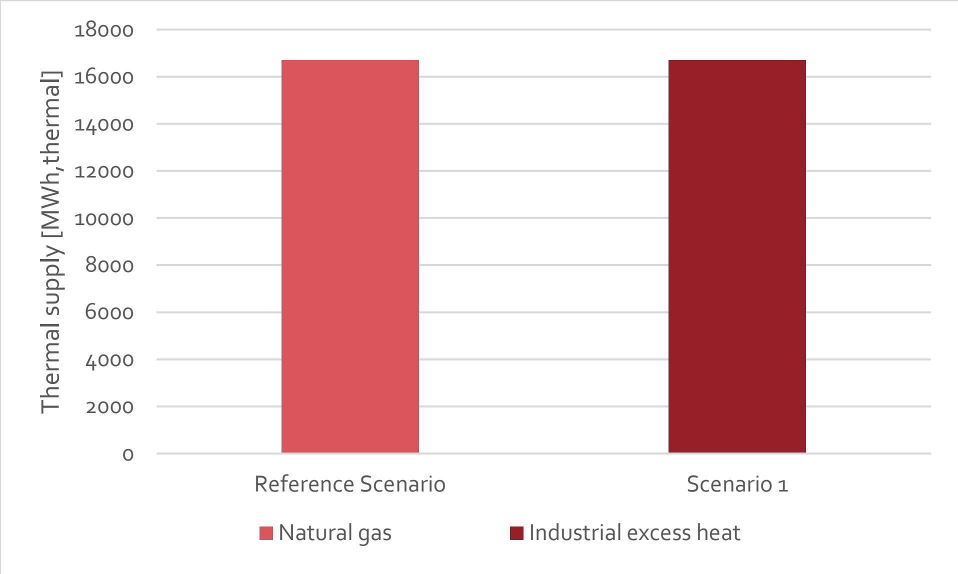

Figure 11 Heat supply in the different scenarios, IMERYS

4.6.1 Reference scenario

In the reference scenario no heat is recovered from the furnace and the potential excess heat customers use individual natural gas boilers to cover their space heating demand.

Scenario assumptions:

- The natural gas boilers will be reinvested in during 2023.
- The natural gas boilers have an 85 % fuel efficiency. This assumption was made by the demo site representative.
- The EFLH (equivalent full load hours) for heating it is 2569 hours, assumed to be the same as for Seattle, USA [58]. Willebroek has a similar climate to Seattle, according to [59]
- The technical and financial lifetime of the natural gas boilers are assumed to be 25 years. This assumption was made by the demo site representative.
- The technical and financial data for the natural gas boilers was given by [22], assuming that the boilers were natural gas fired hot water tube boilers. These boilers are relatively large and hence are primarily used by industrial heat customers, the type of customers that would primarily make use of IMERYS' excess heat.

4.6.2 Scenario 1: External use of excess heat

In this scenario 16,700 MWh of heat is recovered from the chimney gases of the furnace and shared with 37 heat customers through a heat grid of a total of 7.5 km that will be constructed. The heat recovery investments include chimney heat exchangers and plate heat exchangers. The planned year of investment is 2023. The heat customers will use the heat for space heating.

Scenario assumptions:

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- The heat grid represents 2/3 of the investment cost, the rest of the investment cost was allocated to the heat recovery equipment. This assumption was made by the demo site representative.

4.7 ENCE

The Ence pulp mill in Navia, Spain is not only producing eucalyptus pulp but is also a major producer of renewable electricity from biomass. Ence is today recovering heat from the bleaching stage to use in a biomass dryer and in other parts of the process. Ence has identified that excess heat could also be recovered from the causticization process to be used for the biomass dryer. That would also increase the capacity of the dryer. There is also a possibility to share additional excess heat from the bleaching stage and the effluent treatment stage with nearby public buildings. Data for the technology options and scenarios have been supplied by Eleukon, but some assumptions have also been made. The heat supply in the three different scenarios are presented in Figure 12 and a full description of the scenarios follows.

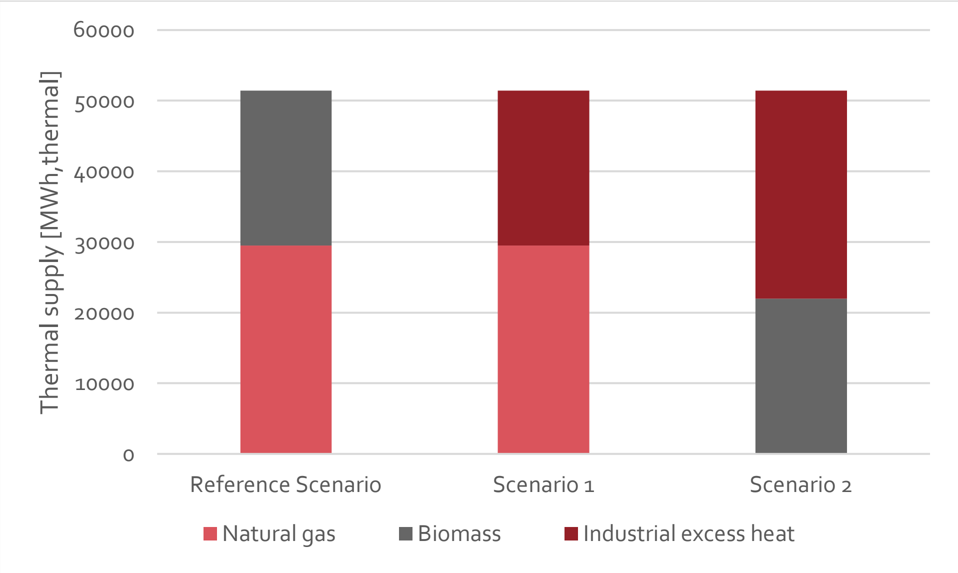

Figure 12 Heat supply in the different scenarios, ENCE

4.7.1 Reference scenario

This scenario describes the current situation at the pulp mill and for potential external users of excess heat. There has already been some internal heat recovery from the bleaching stage since it used for the biomass dryer and other internal processes. However, in the reference scenario the biomass dryer runs on a lower capacity than the nominal power, meaning that 18,000 kg biomass is dried each hour. Due to the already existing heat recovery the biomass boiler is hence saving 6 tons/hour of eucalyptus bark which is biproduct of the pulp production process and used as a fuel for the biomass boiler. The potential external customers of the excess heat, a townhall and a hospital, use individual natural gas boilers for space heating.

Scenario assumptions:

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- The biomass dryer operates 8,500 hours annually. This assumption was made by the demo site representative.
- The costs and emissions of the biomass boiler used to produce heat for the biomass dryer is not included in this scenario but will appear as a reduced biomass fuel cost in Scenario 1.
- The current natural gas boilers at the customer side are from 2010.
- The EFLH (equivalent full load hours) for heating it is 1189 hours, assumed to be the same as for San Francisco, USA [58]. Navia has a similar climate to San Francisco, according to [59].
- The technical and financial parameters associated with the individual natural gas boilers of the potential heat customers have been estimated using [22] and [20].

4.7.2 Scenario 1: Internal use of excess heat

In this scenario an additional 21,956 MWh/year of excess heat is recovered from the causticization stage in the pulp process and used internally in the biomass dryer. The biomass dryer runs on a higher capacity, 25,000 kg biomass/hour, which will lead to a 2 tons/hours efficiency improvement from reference scenario, equivalent to 200 MWh of biomass savings per year. The heat recovery investment includes gas/water heat exchanger in the causticization stage. The investments will be made in 2022.

Scenario assumptions:

- The biomass dryer operates 8,500 hours annually. This assumption was made by the demo site representative.

4.7.3 Scenario 2: External use of excess heat

In this scenario 29,487 MWh of excess heat from the effluent treatment stage and the bleaching stage is shared with nearby public buildings, such as a town hall and a hospital. The heat is used externally as space heating. The investments in new water/water heat exchangers and a total of 5 km heat grid will be made in 2022.

Scenario assumptions:

- The configuration of the new heat exchangers in relation to existing ones may impact how much energy that could be recovered and shared with external users. For simplicity, it is assumed that the installation of these do not affect the previous installations.
- The annual full load hours of the new heat exchangers and heat grid would be 1,189 hours, assuming these would run on full capacity as much time as the natural gas boilers in the reference scenario.
- The district heating substations are assumed to be in industry size and the technical parameters and costs associated with the heat grid and substations have been estimated using [22].

4.8 MARTINI & ROSSI

Martini & Rossi is an Italian multi-national company with one of the headquarters located in the village of Pessione of Chieri, Italy. The distillery in Pessione is producing sparkling wine and liquors. The company has looked into several options for internal thermal energy recovery, especially from the cooling processes of the beverage production. Data for the technology options and scenarios

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have been supplied by EnviPark, but some assumptions have also been made. The heat supply in the two different scenarios are presented in Figure 13 and a full description of the scenarios follows.

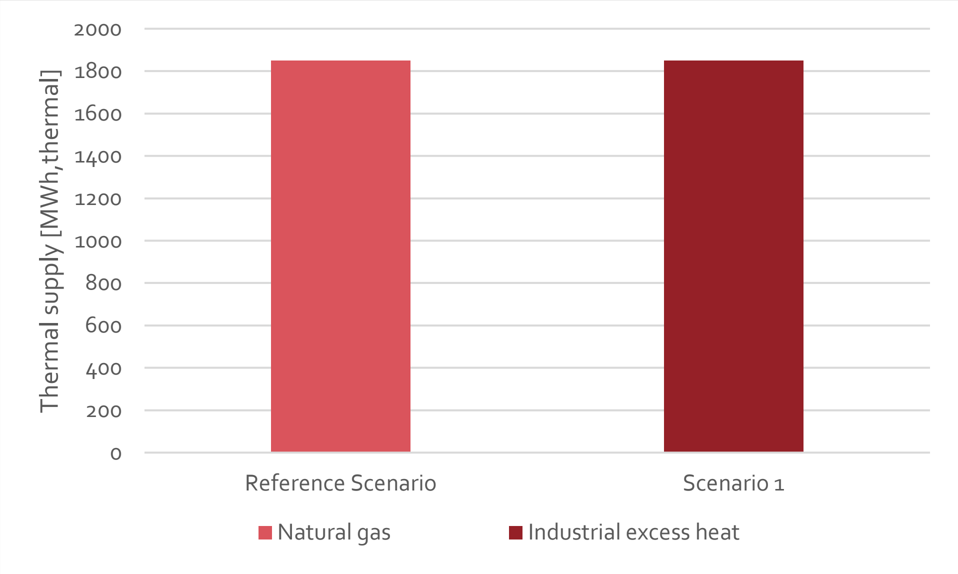

Figure 13 Heat supply in the different scenarios, MARTINI&ROSSI

4.8.1 Reference scenario

Currently three natural gas boilers each with a 4 MW capacity (total 12 MW) are used to produce hot water used internally at the Martini & Rossi site in Pessione.

Scenario assumptions:

- There are three natural gas boilers: one that was taken into operation in 2011 and two in 2008. For simplicity, the investment year used is 2010.
- The technical lifetime of the natural gas boilers is 25 years.
- Technical and financial data for the natural gas boilers was taken from, using 2020 values [20].

4.8.2 Scenario 1: Internal use of excess heat

In this scenario 1,848 MWh of excess heat from the sparkling wine process is recovered and used internally at the site for producing hot water. The heat recovery investment includes heat exchangers that will be used as water-cooled fluid condensers.

Scenario assumptions:

- The new heat exchangers have a technical lifetime of 10 years, and 5 years financial payback time. These assumptions were made by the demo site representative.
- The investment will be made in 2021.
- The fixed operation and maintenance cost for the heat exchangers is 1 €/kW,thermal installed, taken from [68].

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5 RESULTS

5.1 Emissions

The resulting emissions for the demo site scenarios have been indexed with the Reference scenario time series as the base for all demo sites, except PETROMIDIA as there were no reference data available for this site but only the changes in emissions and efficiency. The GHG emissions contains the emissions of CO_2, CH_4 and N_2O recalculated into CO_2 equivalents using 28x the CH_4 and 265x the N_2O [42]. In addition to the GHG emissions, the PM2.5, NO_x, SO_2 and VOC air emissions are presented below for each of the demo sites and scenarios. These are the major air emissions that have an impact for the environmental and health effects in the CBA.

5.1.1 RADET

The changes in emissions for RADET are primarily due to differences in the use of natural gas, biomass and auxiliary electricity between the Reference Scenario and Scenario 1 when changing from natural gas to solar thermal and biomass boilers. As can be observed in Figure 14 the GHG (in CO_2 equivalents) and VOC emissions are decreasing, much thanks to the decrease in the use of natural gas. The VOC emissions also decrease until 2034 thanks to emissions reductions in the Romanian electricity grid. The rest of the emissions, PM2.5 and NO_x, are however increasing due to an increased use of electricity for the biomass boiler and the solar thermal plants in comparison to natural gas, as well as the combustion of biomass. In Figure 15 the effects from the biomass combustion is also very much apparent on the large increase in SO_2 emissions.

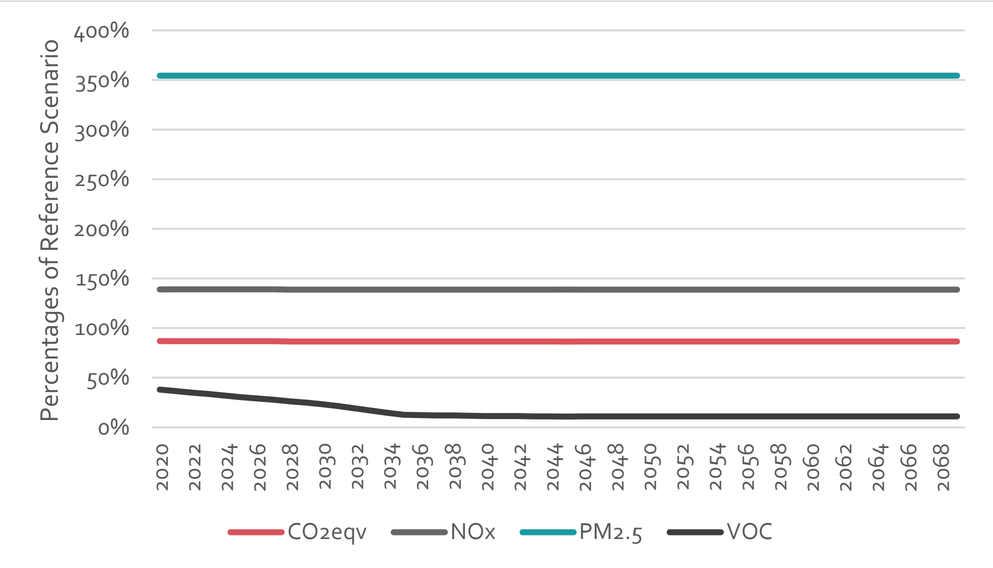

Figure 14 Emission changes (excl. SO2) in Scenario 1 with Reference Scenario as index, RADET

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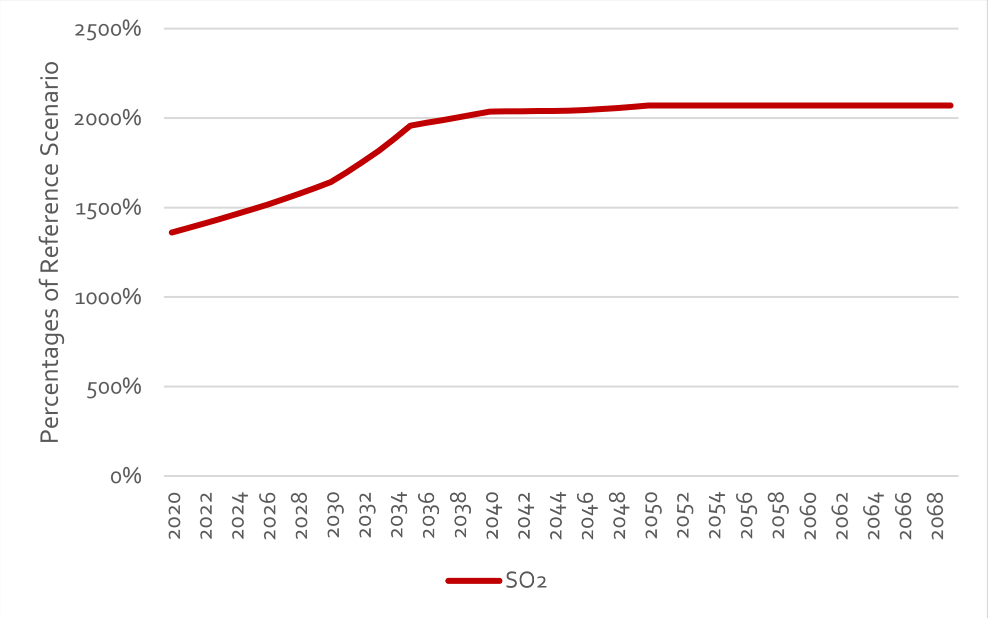

Figure 15 SO_2 emission changes in Scenario 1 with Reference Scenario as index, RADET

5.1.2 PETROMIDIA

In Scenario 1 assessed for Petromidia, industrial excess heat is recovered to improve the refinery process. For Petromidia there were little information about the current emission levels from the refinery processes and the emissions are presented as the annual mass (kg) change in emissions relative to the Reference Scenario. As a result of the more efficient oil refining process there are emissions decreases for all the emissions analyzed, see Figure 16 - Figure 20. The marginal change in emissions with time is due to the assumed efficiency improvement in the crude oil combustion technologies.

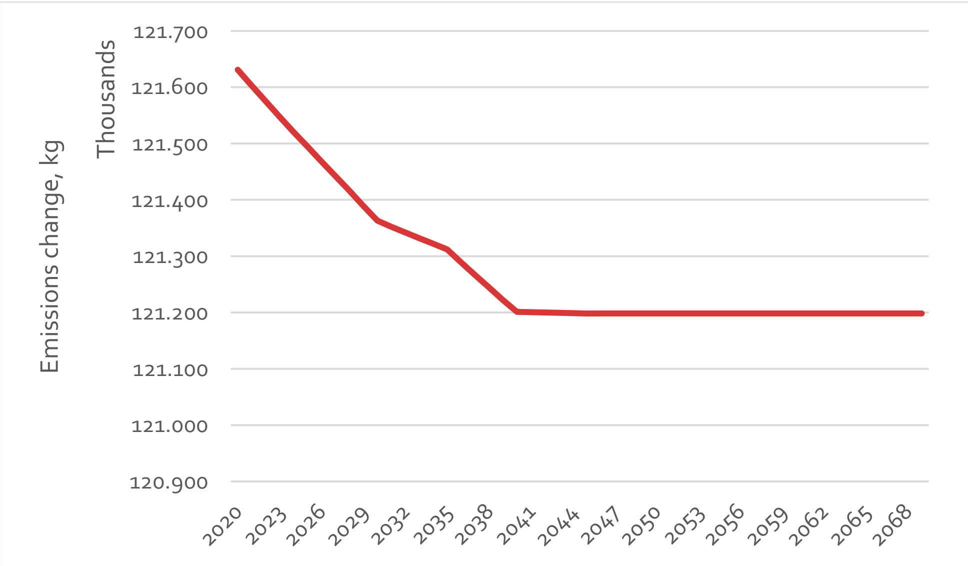

Figure 16 CO2eq (CO2, CH4 and N2O) annual emissions change, PETROMIDIA

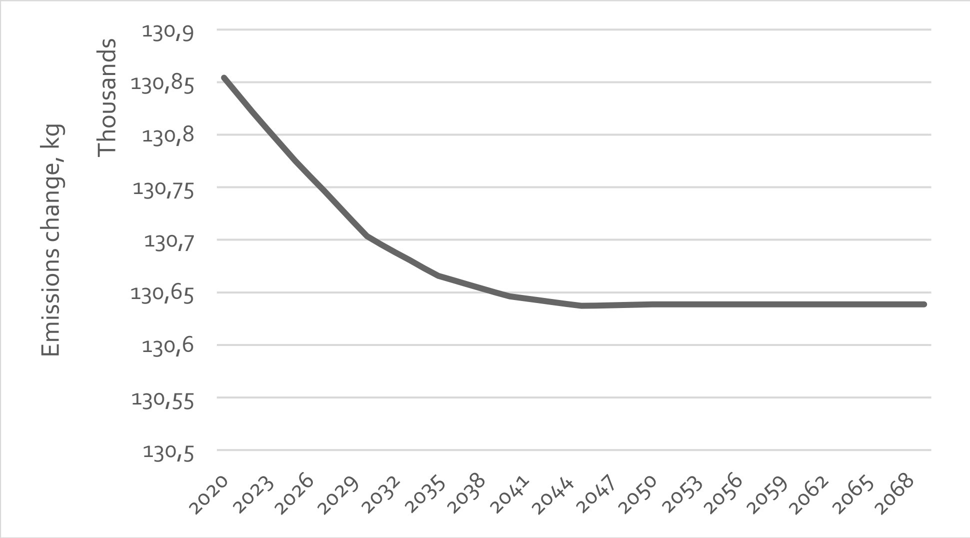

Figure 17 NOx annual emissions change, PETROMIDIA

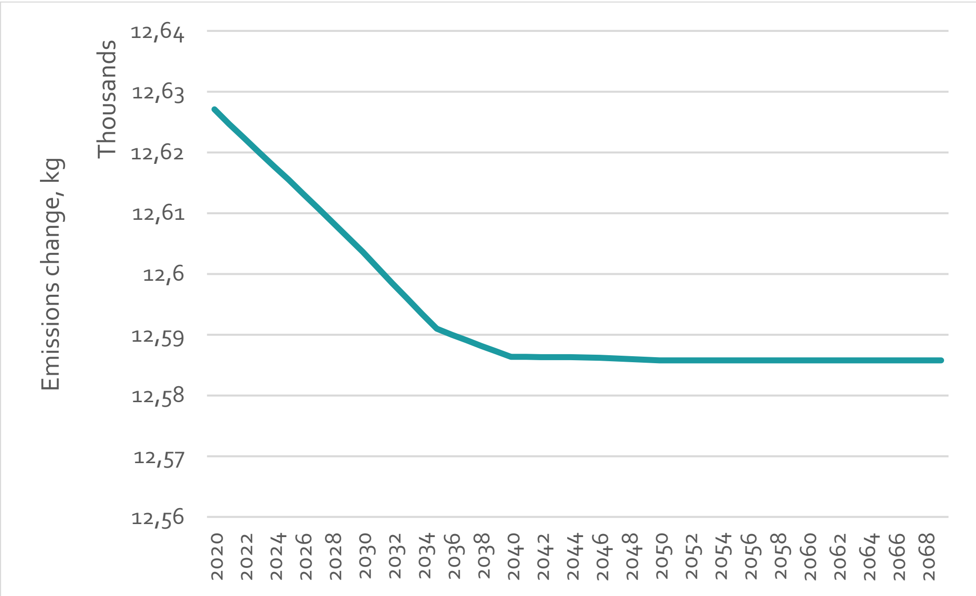

Figure 18 PM2.5 annual emissions change, PETROMIDIA

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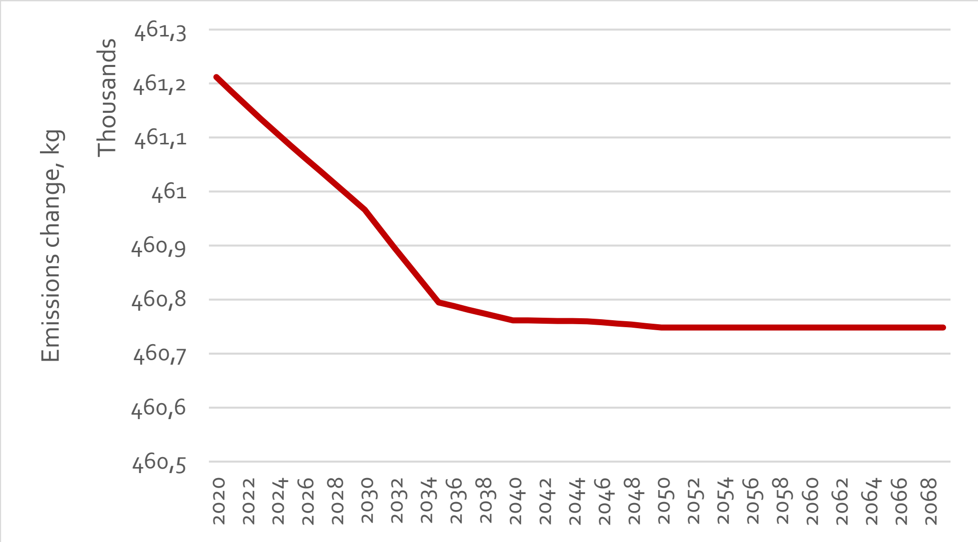

Figure 19 SO2 annual emissions change, PETROMIDIA

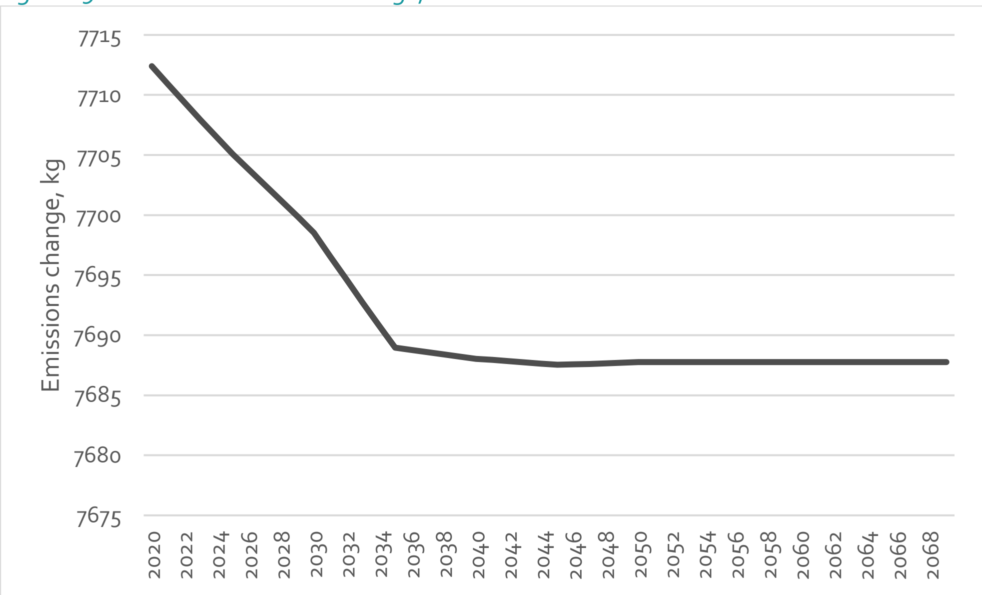

Figure 20 VOC annual emissions change, PETROMIDIA

5.1.3 LIPOR

In the LIPOR demo site excess heat recovery from the waste incinerator replaces natural gas combustion at the heat customer sites. As there is no additional waste used for generating this heat there will not be any additional emissions from the waste, hence the differences between the two scenarios are the reduction in natural gas and electricity consumption in Scenario 1. As could be seen in Figure 21, the largest impact the shift from natural gas to excess heat is on the GHG (CO_{2_eqv}), NO_x and VOC. These three types of air emissions are closely linked to natural gas combustion. There are also some changes in PM2.5 and SO_2 emissions, mainly thanks to a decrease in electricity consumption in Scenario 1 compared to the Reference Scenario.

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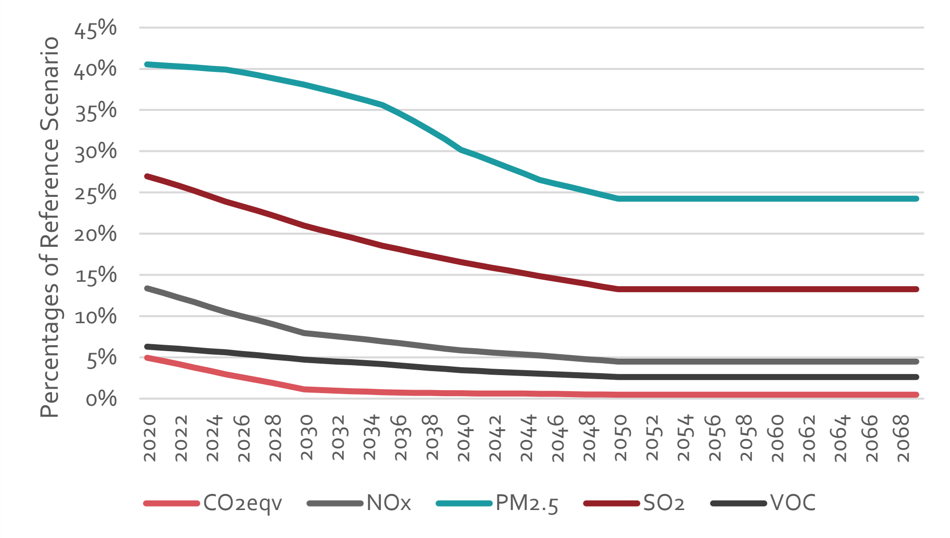

Figure 21 Emission changes in Scenario 1 with Reference Scenario as index, LIPOR

5.1.4 ISVAG

In the ISVAG scenarios natural gas consumed by the heat customers is replaced by an increasing amount of municipal waste combustion for heat generation (existing, scenario 1 and new, scenario 2), which is leading to more emissions in Scenario 1 and Scenario 2 for all the emissions accounted for. This increase in emissions need to be considered as hypothetical as the reference scenario assumes the current waste-to-energy plant of Isvag does not exist. The emissions increase with the amount of waste combusted, as could be seen in Figure 22, where VOC, PM2.5 and NO_x in particular, increases with 200-500% in Scenario 2. For SO_2 the increase is even larger; in Figure 23 an increase with between about as much as 4000-6000% can be observed for Scenario 2. Please note that these results are based on a reference scenario with natural gas boilers.

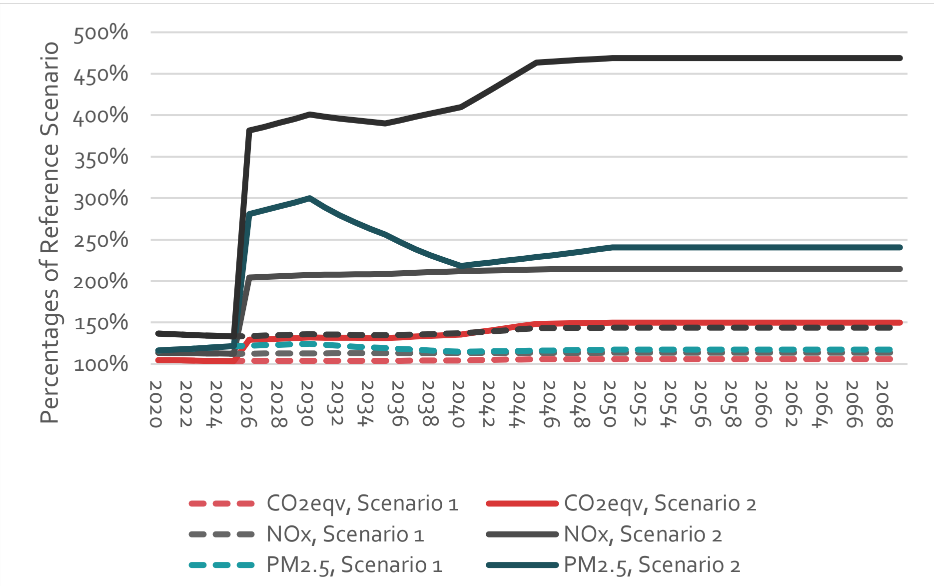

Figure 22 Emission changes (excl. SO2) in Scenario 1 and Scenario 2 with Reference Scenario as index, ISVAG

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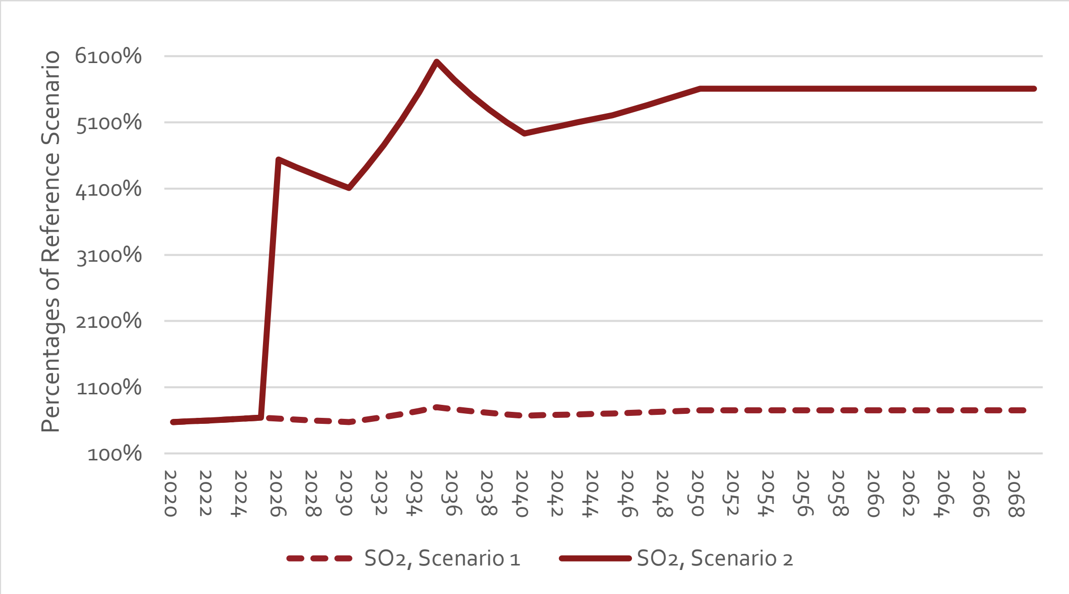

Figure 23 SO2 emission changes in Scenario 1 and Scenario 2 with Reference Scenario as index, ISVAG

5.1.5 UMICORE

UMICORE Scenario 1 means that the demo site is replacing the use of a natural gas fueled CHP and steam grid with an internal heat grid fed by industrial excess heat from the internal industrial processes. With this shift there is also an increase in the electricity net consumption, which in the Reference Scenario is negative thanks to the production from the CHP. The emissions linked to natural gas decrease in Scenario 1 compared to the Reference Scenario due to a decrease in the use of natural gas, see Figure 21. This particularly applies to GHG (in CO_2 equivalents), NOx and VOC emissions that decreases slightly. However, as the electricity consumption from the national grid is increasing in Scenario 1 and is not negative as in the Reference Scenario due to CHP electricity production, some of the emissions associated with the electric energy from the national grid will increase. The SO_2 emissions will also increase with a factor 4-5 due to an increased use of electricity, which in addition has a larger SO_2 emission factor than the natural gas, and the PM2.5 emissions are also increasing due to the same reason.

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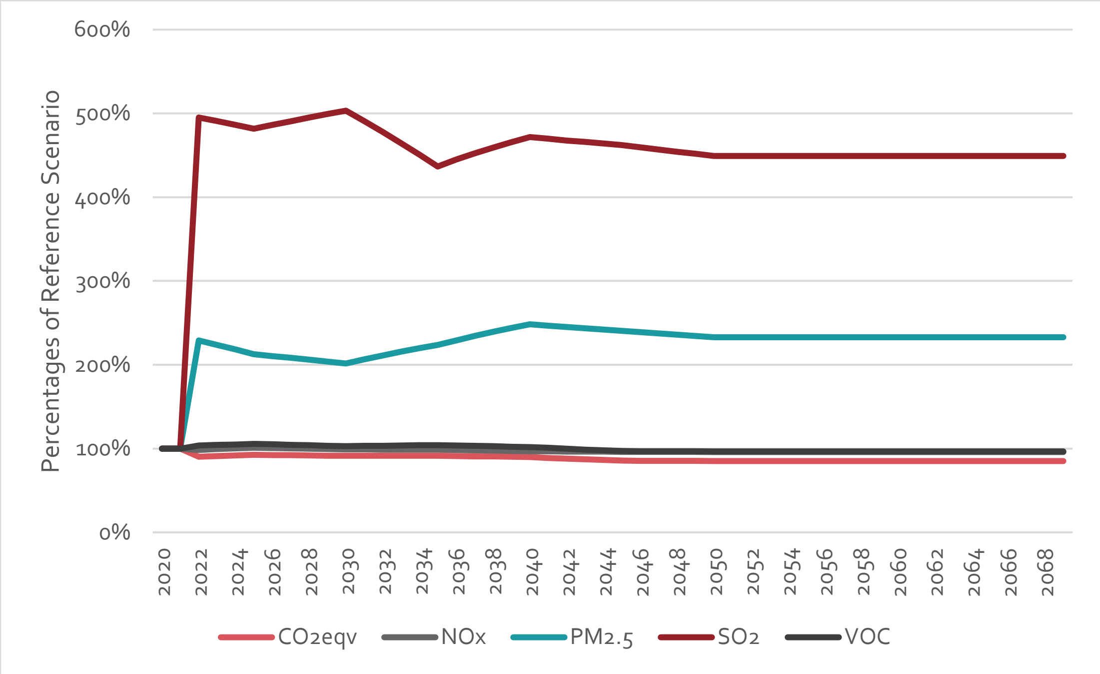

Figure 24 Emission changes in Scenario 1 with Reference Scenario as index, UMICORE

5.1.6 IMERYS

In IMERYS Scenario 1 the individual natural gas boilers of the heat customers are replaced by a heat grid supplying industrial excess heat from IMERYS' processes. Implementing IMERYS Scenario 1 would lead to emission decreases compared to the Reference case, see Figure 25, mainly due to a decrease in the use of natural gas. In comparison with UMICORE, IMERYS is not experiencing such large changes in electricity consumption. The only emissions remaining in Scenario 1 is the emissions from the electricity consumption, but these are also reduced compared to the Reference Scenario.

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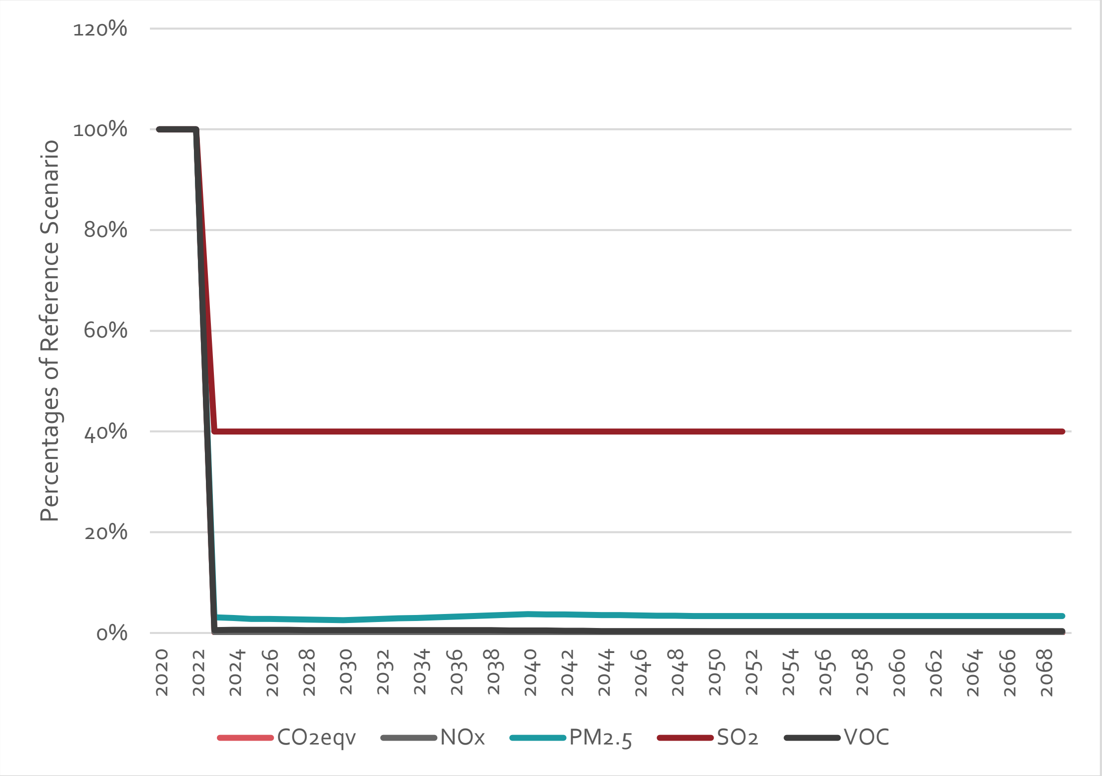

Figure 25 Emission changes in Scenario 1 with Reference Scenario as index, IMERYS

5.1.7 ENCE

For the ENCE scenarios the main differences between the scenarios are the uses of biomass and natural gas. In Scenario 1 the recovered excess heat is replacing biomass combustion and in Scenario 2 industrial excess heat is replacing natural gas consumed by heat customers. In addition to changes in fuel used, there are also some slight changes in the electricity consumption that affects the emissions. As could be seen in Figure 26, the emissions decreases the most for Scenario 2 compared to the Reference Scenario, specifically the emissions of GHG (CO2eqv in the figure), VOC and NO_x. For PM2.5 and SO_2 the emission decreases are more apparent in Scenario 1 thanks to the changes in biomass combustion and electricity consumption relative to the Reference Scenario. In Scenario 2 the SO_2 emissions are somewhat larger than in the Reference Scenario due to the larger auxiliary electricity usage of the heat grid compared to the natural gas boilers.

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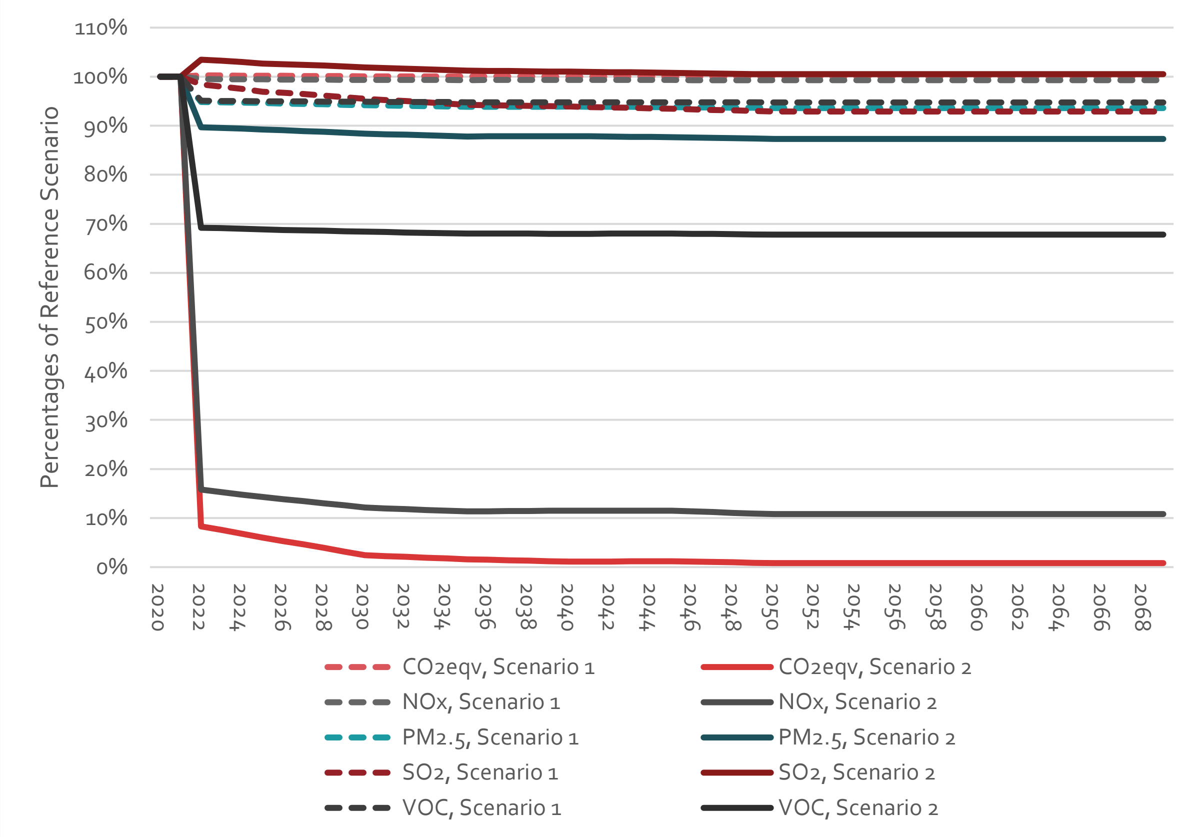

Figure 26 Emission changes in Scenario 1 and Scenario 2 with Reference Scenario as index, ENCE

5.1.8 MARTINI & ROSSI

In Martini&Rossi Scenario 1 industrial excess heat is replacing natural gas boilers to supply heat for internal industrial processes. As the heat recovery technologies does not demand any fuel or electricity, there are no emissions linked to this scenario from 2021 and onwards. Hence only the initial emissions in 2020 is presented in Table 2. A graph showing the emission change would not provide any additional information as these emissions are eliminated completely. To get a better understanding of how much emissions that were eliminated by replacing natural gas with excess heat Table 2 provides the emissions in 2020 in the Reference Scenario. Please note that these levels change during the years in the Reference Scenario, mainly due to the changes in the Italian electricity mix.

Table 2 Emissions in 2020, MARTINI&ROSSI Reference Scenario

Emissions	Amount [kg] of emissions in 2020
$CO_{2\ eqv}$ (CO_2, CH_4 and N_2O)	407,359.5
NO_x	364.3
PM2.5	0.7
SO_2	0.8
VOC	13.4

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5.2 Socio-economic costs and benefits

The socio-economic costs and benefits of the different options are presented in terms of net welfare effect. The net welfare effect is calculated as the difference between the change in external costs, e.g. decreases in impact on environment and health, and the change in techno-economic costs, e.g. changes in CAPEX and OPEX. The net welfare of the different demo site scenarios, compared to the reference scenarios, are presented in Figure 27 below. The two ISVAG scenarios are special cases as the environmental benefits are negative while the techno-economic costs are also negative. However, the cost reductions exceed the environmental and health benefit decrease as could be seen in the net welfare graph.

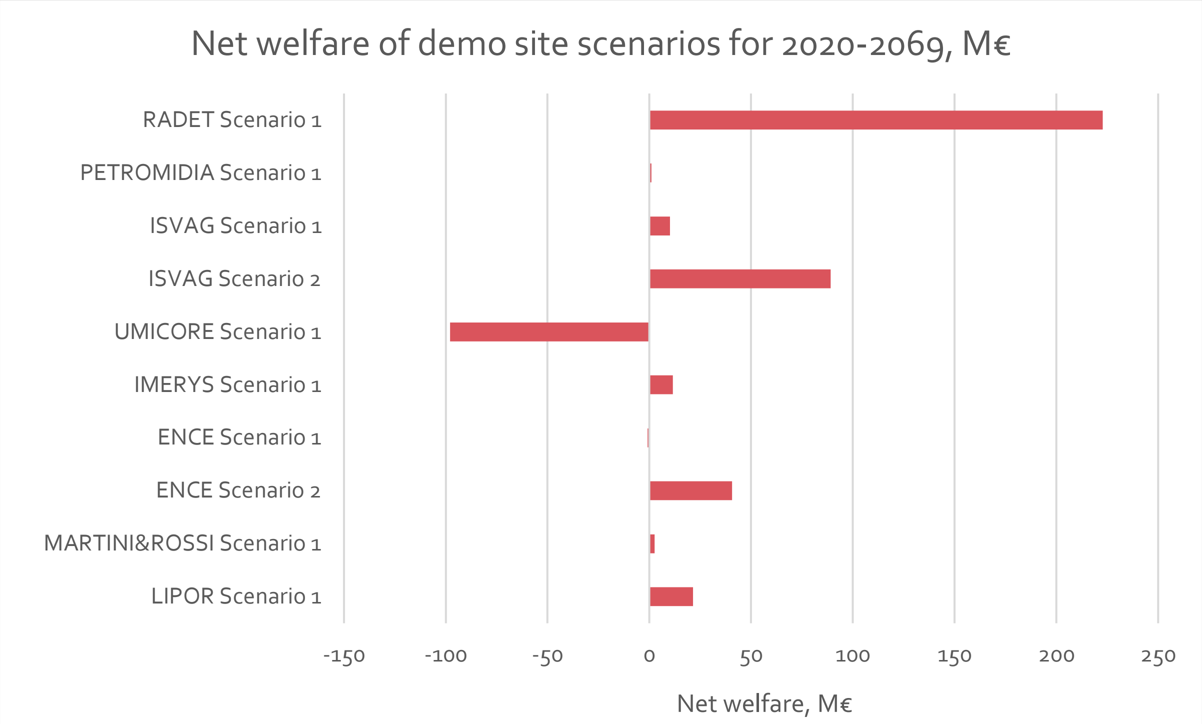

Figure 27 Net welfare of the demo site scenarios relative to the reference scenarios for 2020-2069, (NPV M€$_{2020}$)

The benefit/cost (b/c) ratios of the different demo site scenarios, compared to the reference scenarios, are presented in Figure 28 below. Investments where the b/c ratio exceeds 1 could be considered a profitable investment. UMICORE Scenario 1 and ENCE Scenario 1 have been excluded as these two have negative net welfare. Please note that the b/c ratio for RADET Scenario 1, ENCE Scenario 2, MARTINI&ROSSI Scenario 1 and LIPOR Scenario 1 have been excluded from the figure as their costs were negative while the benefits positive, meaning that there were both gains for the environment and cost reductions - hence an analysis of the b/c ratio is redundant. Bear in mind that in the special case of the ISVAG scenarios, the actual benefits are reduced techno-economic costs, whilst the costs are from increased environmental burden via increased emissions of greenhouse gases and air pollutants.

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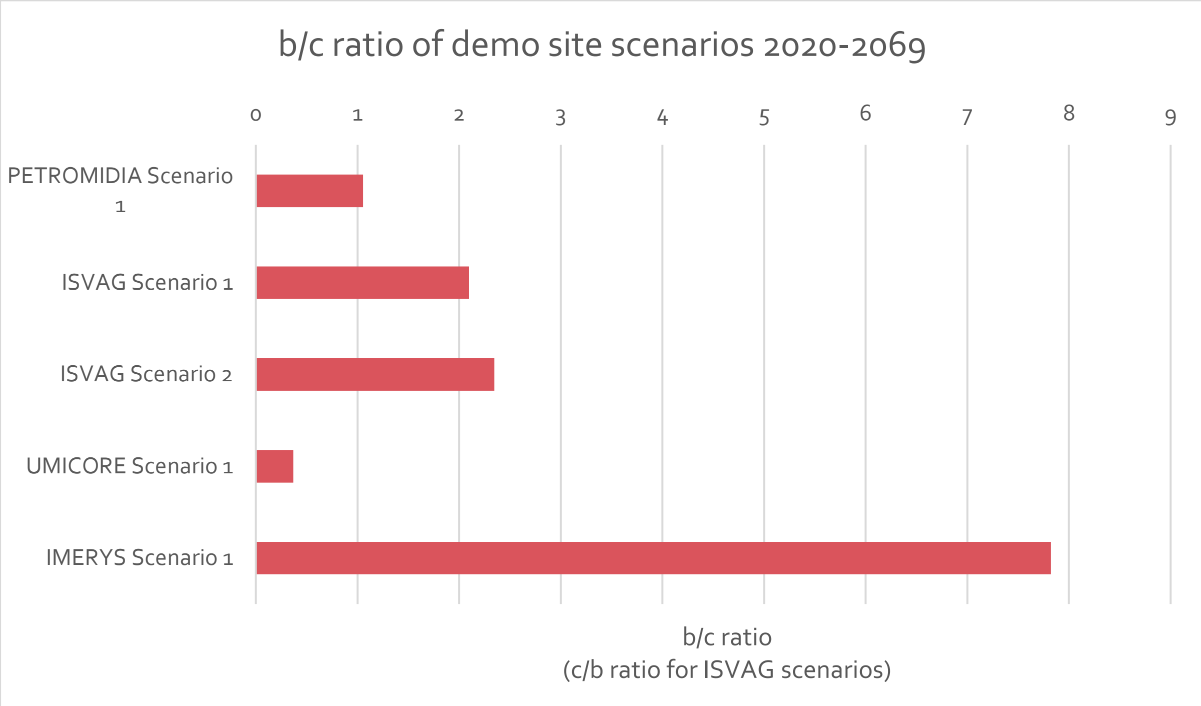

Figure 28 b/c ratio for the applicable demo site scenarios. Scenarios implying negative techno-economic costs and positive benefits are not applicable for calculation of benefit-cost ratios or cost/benefit ratios and are therefore excluded.

5.2.1 RADET

With an increased integration of renewables in the district heating grid, replacing natural gas combustion, RADET would see a net welfare gain due to reductions in some of the major emissions (in particular N_2O and VOC) and also in terms of decreases in the variable costs. The investment costs for biomass boilers and solar thermal are relatively high, but as the variable costs for natural gas are high, the renewable investment would lead to cost reductions in the long run. Even though some of the emissions would increase with biomass being introduced and with an increasing auxiliary electricity demand for the renewable boilers, the savings in GHG emissions would also lead to climate benefits. All in all, the net present value of the socio-economic welfare improvement of the RADET scenario would for the entire period be some 220 million€$_{2020}$, with almost the entire welfare improvement coming from savings for RADET.

5.2.2 PETROMIDIA

With internal heat recovery from the oil refining process, crude oil consumption reduction in the Petromidia refinery would lead to net welfare benefits. Even though there would be initial investments costs and operating costs associated with the heat recovery equipment, the investment would be paid back in terms of emission reductions from a more efficient oil refining process. The net welfare improvement is however small, with a benefit/cost-ratio just above 1.

5.2.3 LIPOR

By replacing natural gas boilers with excess heat recovery from the waste incinerator, while not combusting additional waste, the LIPOR demo site would contribute with lower emissions. However,

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there would still be some emissions associated with the heat recovery equipment as some auxiliary electricity is needed. The negative techno-economic costs indicate that there are cost savings related to the heat recovery investments, this is mainly due to the high variable costs of the natural gas boilers and electric chillers as well as high reinvestment cost of the electric chillers. Even though the investment cost in the hydraulic heating network is relatively high, the costs of the natural gas and electric chillers is much higher. In addition to this, the emissions savings contribute to a profitable socio-economic investment. In total for the timespan analyzed, the net present value of the welfare improvement is some 20 million $€_{2020}$, and savings for LIPOR constitute 60% of the welfare improvement.

5.2.4 ISVAG

The two scenarios analyzed for ISVAG includes an increasing share of waste combustion (note the difference to the LIPOR case where additional waste will not be used) to replace natural gas heating. Both scenarios lead to cost reductions but at the same time also increases in emissions - the environmental benefits of the investments are negative. Despite the fact that the scenarios have undesirable environmental effects, the cost reductions are exceeding the negative environmental benefits and hence the net welfares for the two scenarios are positive. As ISVAG receives a gate fee for the waste received and incinerated, the more waste that is used for heating the more revenues and hence a larger district heating system also seems to be even more profitable than a smaller one despite the fact that the emissions are increasing. There are also high variable costs associated with the natural gas boilers in the reference scenario. In total the net present value of techno-economic savings are ~20 and 155 million $€_{2020}$ respectively for the two scenarios, whilst the net present value of the damages to human health and climate change is 9 and 66 million $€_{2020}$ respectively. Both scenarios have benefit/cost ratios above two, with the second scenario providing 'biggest bang for the buck'. Again, it needs to be stressed that both scenarios are negative for human health and climate change. Please note that these results are based on a reference scenario with natural gas boilers.

5.2.5 UMICORE

Just as in many of the other demo sites, the changes in emissions for UMICORE with investment in excess heat recovery technologies is mainly linked to decreases in natural gas combustion. As some of the emissions are not as clearly associated with natural gas, such as $PM_{2.5}$ and SO_2, there will also be increases in these emissions due to increases in electricity consumption with the new heat grid. The internal heat grid and heat recovery technologies have relatively high investment cost (five times the reinvestment cost of the steam grid) compared to the cost saving from reductions as well as relatively high O&M costs of the heat grid, meaning that the net welfare is affected negatively despite the emissions savings. The benefit/cost ratio is around 0.4.

5.2.6 IMERYS

When heat exchangers, enabling heat recovery from the internal processes of IMERYS, are replacing natural gas and some of the electricity demand there are large environmental benefits deriving from cuts in emissions. Heat exchangers also have relatively low variable costs compared to natural gas and electricity, hence there are cost reductions in Scenario 1 compared to the Reference Scenario. Despite the fact that the investment costs for heat exchangers and heating grid is larger than the investment cost for natural gas boilers, the total cost increase is small. All in all, the IMERYS scenario

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implies a benefit/cost-ratio of 7 and a net present value of the welfare improvements corresponding to 11 million $€_{2020}$.

5.2.7 ENCE

In the ENCE demo two different uses of recovered excess heat are compared, one scenario with internal use (Scenario 1) and one with external use (Scenario 2) of the heat. The net welfare is largest for Scenario 2, indicating that the environmental and economic gains are largest when excess heat is replacing natural gas externally rather than when it is leading to a reduction in biomass usage internally. However, one should note that the investment costs and operating costs of the biomass boiler was excluded from the analysis and only the reduction in biomass fuel use due to the internal excess heat recovery has been considered. In total with the data available in this CBA, the net present value of the welfare improvement of scenario 2 is 40 million $€_{2020}$, out of which 50% originates from techno-economic savings.

5.2.8 MARTINI & ROSSI

With an increased excess heat recovery Martini&Rossi can achieve reductions in both emissions and costs, leading to a positive net welfare. As there are no fuel nor electricity use associated with the heat exchangers the emissions will be eliminated when replacing natural gas with recovered excess heat. The cost savings are mainly a result of reduced costs from reinvestments, O&M and variable costs associated with the electricity and natural gas consumption of the boilers. As these costs are relatively large compared to the costs of the heat exchangers, there would be cost savings if implementing excess heat recovery at the demo site in Pessione. In total the net present value of the welfare improvements would be some 2.5 million €2020, with 45% originating from techno-economic savings.

5.2.9 Net welfare potential per sector and country

The potential effects on the national net welfares during 2020-2069 were calculated based on the method presented in Appendix III. To scale up the demo site results to a national level, it is assumed that only the investments made that have a positive net welfare and a b/c ratio (or c/b for ISVAG) above 1 would be realized. This means that the Umicore scenario would not be realized and only one scenario for each demo site would become reality. Method 1 and Method 2 are referring to two different ways to estimate the national excess heat potential. For more details on these methods and the detailed calculations, see Appendix III. The largest net welfare potential could be observed in Belgium where both the waste-to-energy sector and non-ferrous metals sector have large potentials, see Figure 29 and Figure 30.

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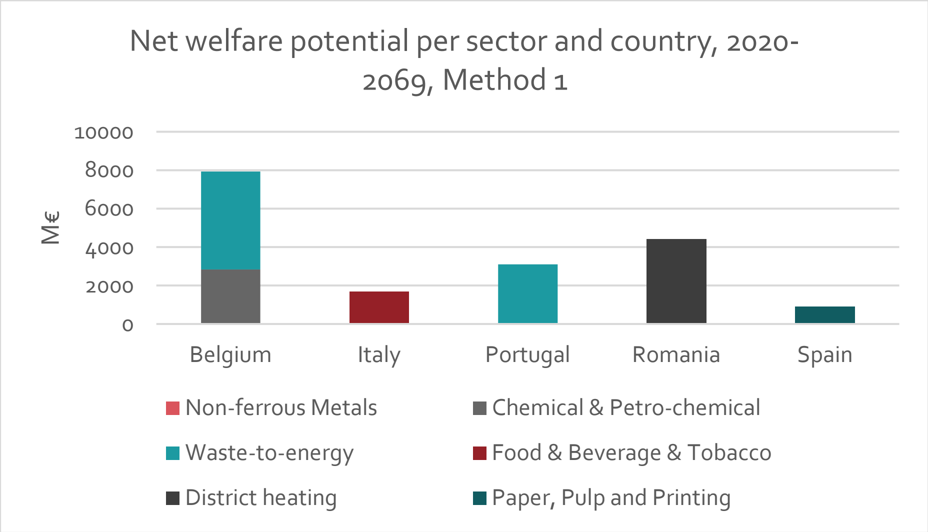

Figure 29 Net welfare per sector and country, 2020-2069, Method 1

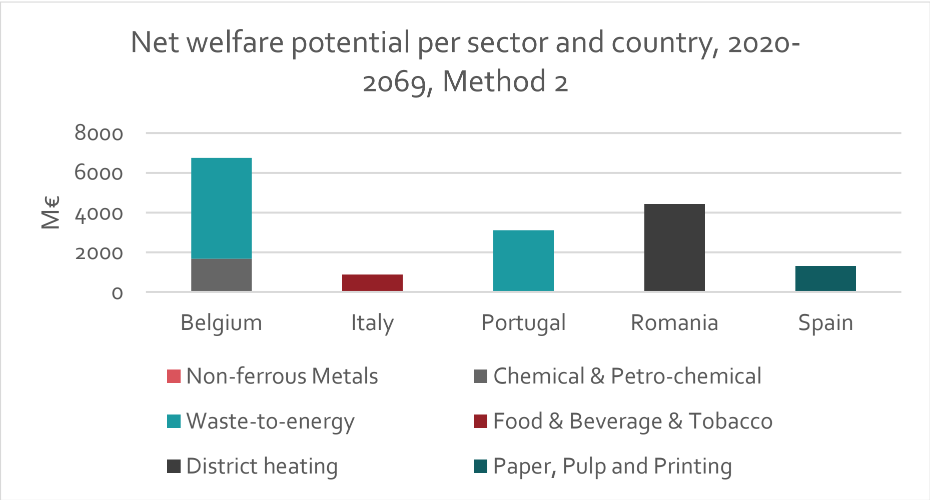

Figure 30 Net welfare per sector and country, 2020-2069, Method 2

As Method 1 and Method 2 did not include different assessments of district heating and waste-to-energy facilities the results for these two methods does not differ much for Portugal and Romania where these types of sectors contributed to the main net welfare potential, this could be observed in Figure 31. For the other three countries there were differences depending on which method that was used. The differences between the two methods are described more in detail in SO WHAT D1.2 [54].

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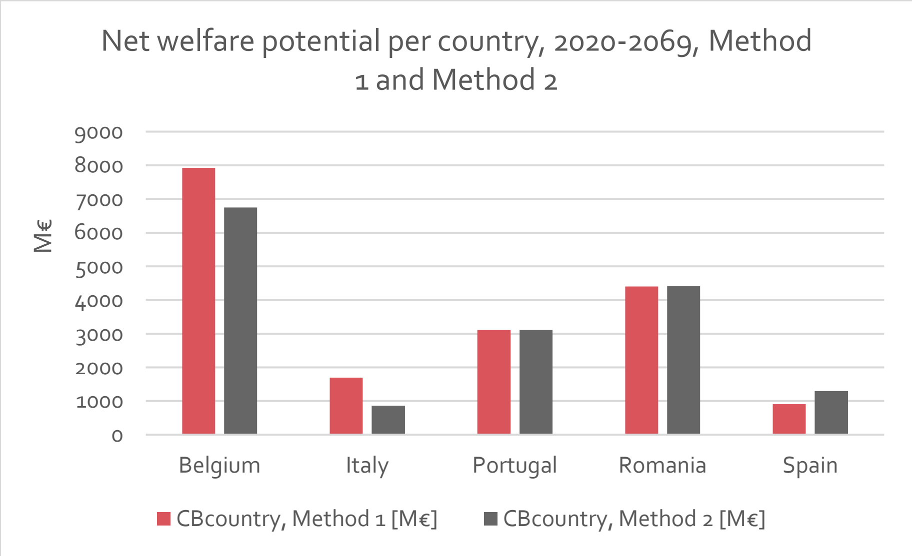

Figure 31 Net welfare per country, 2020-2069, Method 1 and Method 2

5.3 Sensitivity analysis

5.3.1 Discount rate

The discount rate used for this CBA is 3.5%. Two alternative discount rates have been tested to assess the impact of the discount rate: 2% and 5%. These alternative discount rates do not have a significant general impact on the result, e.g. change the net welfare from negative to positive or the b/c ratio from below 1 to above. However, for the Petromidia case a discount rate on 5% would lead to a b/c ratio just below 1, compared to a when the discount rate is 3.5% or 2% and the b/c ratio is just above 1. The Petromidia case is different from the other demo site scenarios in the sense that the b/c ratio is very close to 1 and minor changes in cost and benefits will change the outcome of the b/c ratio. For the other demo sites, there are small changes in net welfare and b/c ratio but this does not affect the profitability of the investment drastically as the b/c ratios are relatively far away from 1 or the net welfare does not hoover around zero.

5.3.2 Hyperbolic discounting

With hyperbolic discounting, it is considered that the time preference is quickly declining during the first years after year t, after which the decline far into the future is small. In effect, the discount rate is high during the first years and low in the long term. The impact of such a discounting method was tested. The hyperbolic discount function 1/(1+at) had a discount factor equal to that of the standard exponential 3.5% rate at t=15. Just as the case with the discount rate, using hyperbolic discounting does not change the result drastically and it is only for Petromidia the hyperbolic discounting shifts the b/c ratio from being just below 1 to just above 1. For the other demo sites the impacts are that the net welfare increases or decreases even more with the use of hyperbolic discounting, e.g. a negative net welfare gets even more negative and a positive even more positive. The effects on the b/c ratio for the scenarios with positive welfare are that the it improves for all, while the c/b ratio decreases for ISVAG.

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5.3.3 RES scenarios for RADET, LIPOR and UMICORE

To model the impact from RES integration on the CBA results three new scenarios was developed for UMICORE, RADET and LIPOR. These scenarios have been based on the RES potential assessments of these three sites, presented in Appendix IV, but some changes have been made to better match the electricity demand of the heat recovery investments. The scenarios are presented below, followed by a short summary of the results of the RES integration on the net welfare effect.

5.3.3.1 RADET RES integration

The auxiliary electrical consumption of the RES heat installations in Scenario 1 is covered by electricity produced by photovoltaics (PV) on site. To cover this need, 27 kW of installed PV power and 43 MWh produced solar electric energy annually is needed. It is assumed that the consumption matches the production of solar electricity. RADET makes the investments in this technology. The year of investment is the same year as the biomass boiler and solar thermal, 2020. The technical and financial lifetime of the PVs are assumed to be 25 years. The efficiency of the panels is assumed to be 17%.

For the profitability analysis there were slightly other assumptions made for the biomass boiler electricity demand (2.1 % instead of 0.5%), impacting the dimensioning of the photovoltaics. The area covered by the panels would then be equal to 635 m^2 and the installation size, assuming the peak irradiance equal to 1,000W/m^2, is approximatively 108kW. This leads to a total annual electricity production of 171 MWh. Both this size and the size presented in the paragraph above, with biomass boiler electricity demand 0.5%, were analyzed in the sensitivity analysis but the differences between the results of two were insignificant (<1%).

Moreover, two other scenarios are included in the profitability analysis: one where the heat demand is covered by heat from water source heat pumps and their electrical consumption is covered by small wind turbines; the other one where the technology configuration is the same, however in this case with ground sourced heat pumps. More details on the assumptions are presented in Appendix IV.

Profitability of RES scenarios applicable to RADET

The installation of small wind turbines (coupled with heat pumps) or of photovoltaic panels was considered for the RADET demo site. The characteristic parameter linked to the country are listed in Table 3. The selling price is evaluated considering the Quota system in force in Romania [69] and the heat cost is assumed equal to the heat price from natural gas for the household consumers.

Table 3 Electricity price and cost of electricity and heat for Romania

	Value	**Reference**
El_{cost} [€/MWh]	89	[70]
H_{cost} [€/MWh]	20.4	[71]
El_{price} [€/MWh]	22.05	[69]

The lifetimes of the wind turbines and the heat pumps are assumed to be 20 years [21]. The results obtained in these scenarios are listed in Table 4 and

Table 5, in addition to the data about the nominal power and the energy produced. The trends of the NPV across the years are shown in Figure 32 and Figure 33.

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Table 4 Wind turbines coupled with water source heat pumps scenario for RADET

	Values
Small wind turbines nominal power [kW]	335
Small wind turbines electrical energy produced [MWh/year]	17,558
Heat pumps (water source) power [kW]	1000
Heat pumps (water source) thermal energy produced [MWh]	8667
Investment cost [€]	2,104,460
O&M cost [€/year]	55,482
Total investment [€]	3,214,099
Revenues [€/year]	575,382
PBP [year]	5.58
NPV after lifetime [€]	4,918,308

Table 5 Wind turbines coupled with ground source heat pumps scenario for RADET

	Values
Small wind turbines nominal power [kW]	335
Small wind turbines electrical energy produced [MWh/year]	17,558
Heat pumps (ground source) power [kW]	1000
Heat pumps (ground source) thermal energy produced [MWh/year]	8667
Investment cost [€]	1,659,460
O&M cost [€/year]	46,582
Total investment [€]	2,591,099
Revenues [€/year]	575,382
PBP [year]	4.50
NPV after lifetime [€]	5,541,308

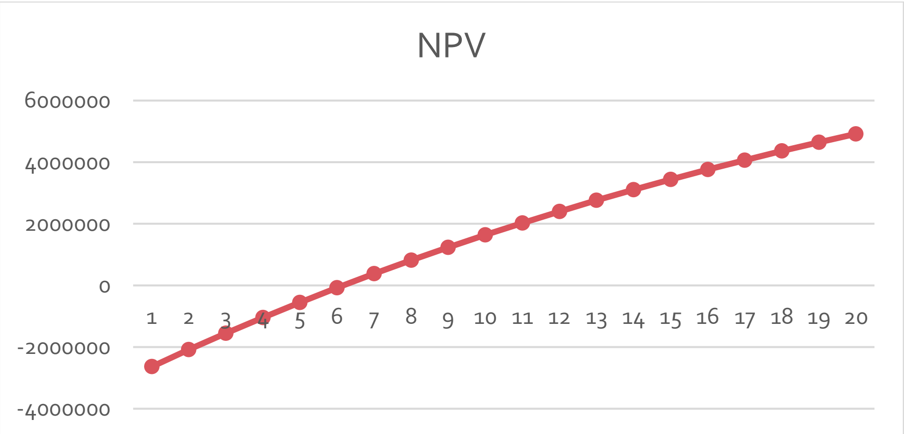

Figure 32 NPV trend for wind turbines coupled with water source heat pumps scenario for RADET

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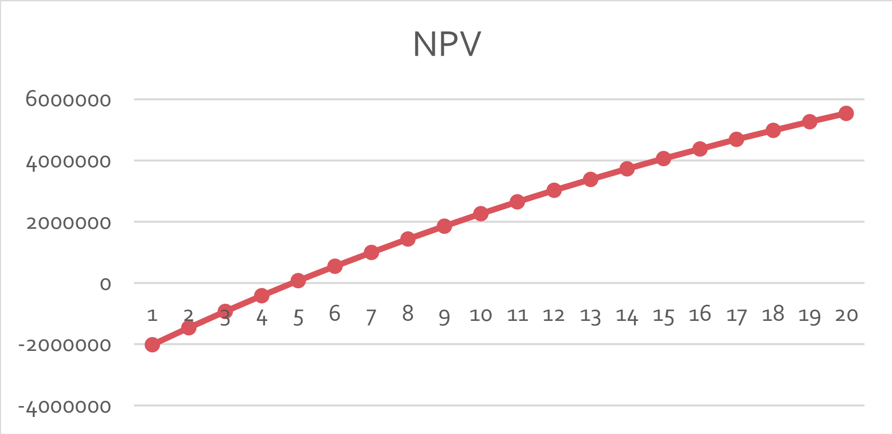

Figure 33 NPV trend for wind turbines coupled with ground source heat pumps scenario for RADET

The lifetime of the photovoltaic solar panels is assumed equal to 25 years [21]. For this scenario the results are listed in Table 6, in addition to the data about the nominal power and the energy produced by the panels. The trend of the NPV across the years is shown Figure 34.

Table 6 Photovoltaic panels scenarios for RADET

	Values
PV panels nominal power [kW]	108
PV panels electrical energy produced [MWh/year]	171
Investment cost [€]	86,419
O&M cost [€/year]	1,026
Total investment [€]	112,075
Revenues [€/year]	15,174
PBP [year]	7.39
NPV after lifetime [€]	144,724

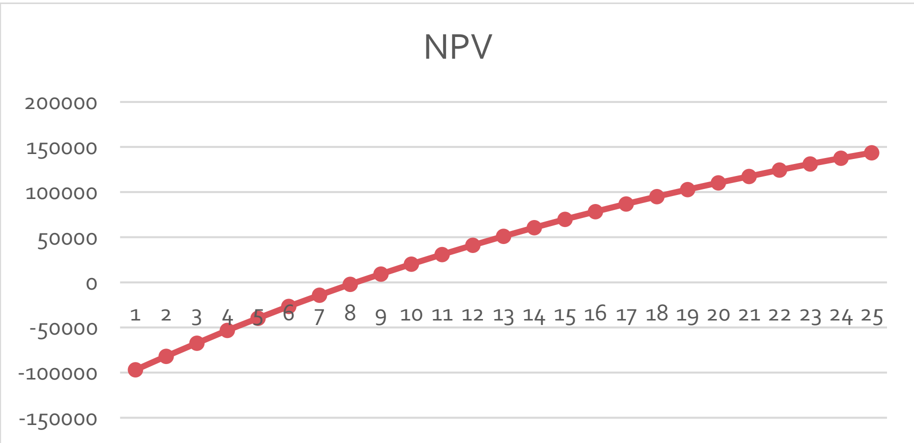

Figure 34 NPV trend for photovoltaic panels scenarios for RADET

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5.3.3.2 UMICORE RES integration

Umicore produces electricity from wind turbines on site and this is used to satisfy the electrical demand on site in Scenario 1. There are two wind turbines, but for this sensitivity analysis only one of the turbines were assessed. The wind turbine has 3.5 MW of installed capacity and 6.7 GWh of electric energy produced annually. Out of this 298 MWh are used to cover the auxiliary electricity demand of the heat grid. It is assumed that the consumption matches the production of wind power electricity. UMICORE makes the investments in this technology. The year of investment in the wind turbines is the same as the heat grid, 2022. The technical and financial lifetime of the wind turbine is assumed to be 20 years. The hub height is 116.5 m and the rotor diameter is 117 m. The rated power of the wind turbines type considered for this site is 3,450 kW and wind speed used to evaluate it is 11.5 m/s. More details on the assumptions are presented in Appendix IV.

It is assumed that the wind turbines will produce far more than what is required to cover the auxiliary electricity demand of the new heat grid, and the excess electricity will be fed into the national grid. The effect in the national grid and the revenues from selling the electricity is however not considered.

Profitability of RES scenarios applicable to UMICORE

The installation of wind turbines is considered for the Umicore demo site. The characteristic parameter linked to the country are listed in Table 7. The selling price is evaluated considering the Quota system in force in Belgium [69].

Table 7 Electricity price and cost for Belgium

	Value	Reference
El_{cost} [€/MWh]	80	[70]
El_{price} [€/MWh]	65	[69]

The lifetime of the wind turbines is assumed equal to 20 years [21]. The results obtained in these scenarios are listed in Table 8, in addition to the data about the nominal power and the energy produced by the two aerogenerator installed. The trends of the NPV across the years are shown in Figure 35 and Figure 36. In this demo site the PBP and the NPV are both evaluated considering that the electrical production could replace all the demand or considering that the whole production will be sold to the grid at the electricity price; this solution is adopted in order to evaluate the two extreme cases because the total electrical consumption of the firm is not defined.

Table 8 Wind turbines scenario for Umicore

	Values
Total wind turbines nominal power [kW]	6970
Total wind turbines electrical energy produced [MWh/year]	134.082
Investment cost [€]	13,244,149
O&M cost [€/year]	285,304
Total investment [€]	18,950,229
Revenues considering the electricity cost [€/year]	10,726,601
Revenues considering the electricity price [€/year]	8,715,364
PBP considering the electricity cost [year]	1.77
PBP considering the electricity price [year]	2,17

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NPV after lifetime considering the electricity cost [€]	132,658,906
NPV after lifetime considering the electricity price [€]	104,232,193

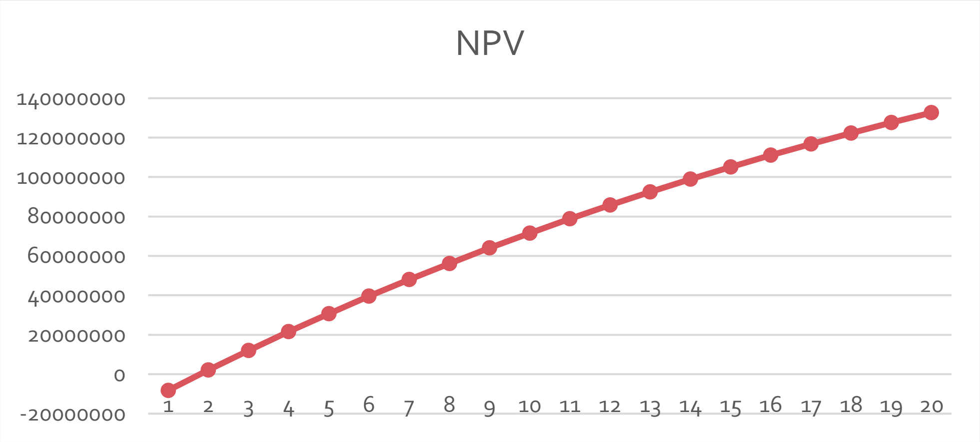

Figure 35 NPV trend for wind turbines scenario for Umicore considering the electricity cost

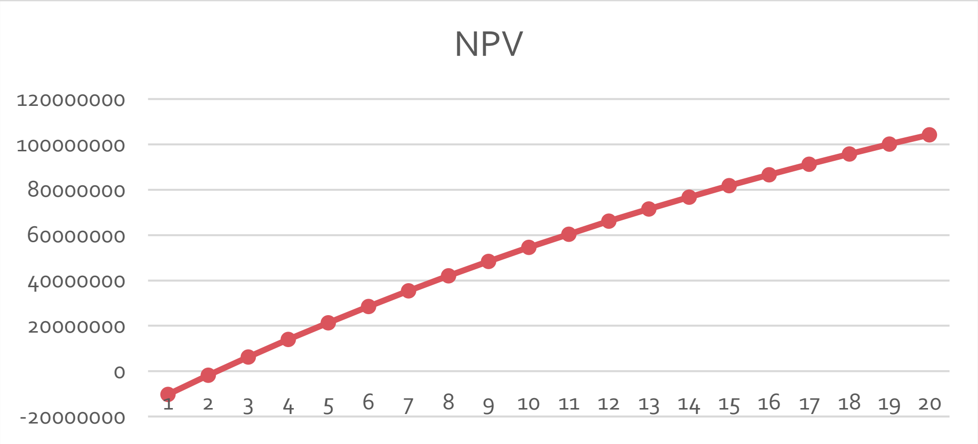

Figure 36 NPV trend for wind turbines scenario for Umicore considering the electricity price

5.3.3.3 LIPOR RES integration

The electrical consumption of the absorption chillers and the hydraulic heat network in Scenario 1 is covered by electricity produced by photovoltaics (PV). To cover this need, 441 kW of installed PV power and 793 MWh produced solar electric energy annually is needed. It is assumed that the consumption matches the production of solar electricity. LIPOR makes the investments in this technology. The year of investment is the same as the heat grid, 2020. The technical and financial lifetime of the PVs are assumed to be 25 years. The efficiency is assumed to be equal to 17%. The area covered by the panels is equal to 2,595 m^2 and the installation size, assuming the peak irradiance equal to 1,000 W/m^2, is approximatively 441 kW. Moreover, for the profitability analysis a scenario in which only the consumption of the absorption chillers is covered by the PV production is also considered. In this scenario the area covered by panels is equal to 1280 m2 and the installation size, assuming the peak irradiance equal to 1,000W/m2, is approximately 218kW. More details on the assumptions are presented in Appendix IV.

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Profitability of RES scenarios applicable to LIPOR

The installation of photovoltaic panels was considered for the Lipor demo site. The characteristic parameter linked to the country are listed in Table 9; in this case the whole electrical energy amount was used to satisfy the auxiliaries electrical consumption.

Table 9 Electricity price and cost for Portugal

	Value	Reference
El_{cost} [€/MWh]	79	[70]

The lifetime of the photovoltaic panels was assumed equal to 25 years [21]. Two configurations were considered: in the first one the photovoltaic panels satisfy only the absorption chiller electrical consumption and in the second the electricity produced by the PV panels is delivered also to the pumps of the heat grid. The results obtained in these scenarios are listed in Table 10 and Table 11, in addition to the data about the nominal power and the energy produced by the panels. The trends of the NPV across the years is shown in Figure 37 and Figure 38.

Table 10 PV panels (absorption chillers consumption) scenario for Lipor

	Values
PV panels nominal power [kW]	218
PV panels electrical energy produced [MWh/year]	391
Investment cost [€]	174,012
O&M cost [€/year]	2,066
Total investment [€]	225,672
Revenues [€/year]	30,885
PBP [year]	7.31
NPV after lifetime [€]	276,128

Table 11 PV panels (absorption chillers and hydraulic network pumps consumption) scenario for Lipor

	Values
PV panels nominal power [kW]	441
PV panels electrical energy produced [MWh/year]	793
Investment cost [€]	352,938
O&M cost [€/year]	4,191
Total investment [€]	457,717
Revenues [€/year]	62,644
PBP [year]	7.31
NPV after lifetime [€]	560,055

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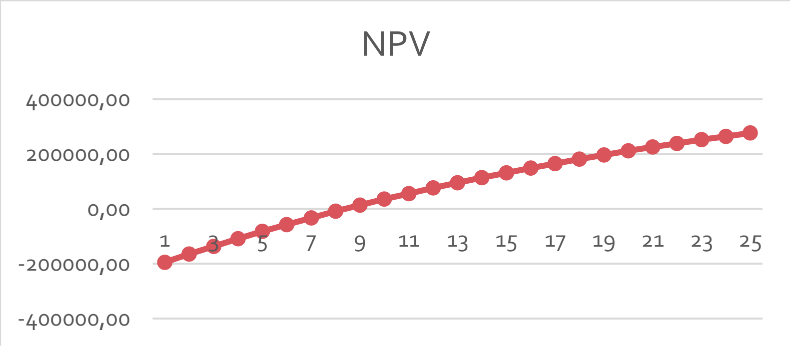

Figure 37 NPV trend for PV panels (absorption chillers consumption) scenario for Lipor

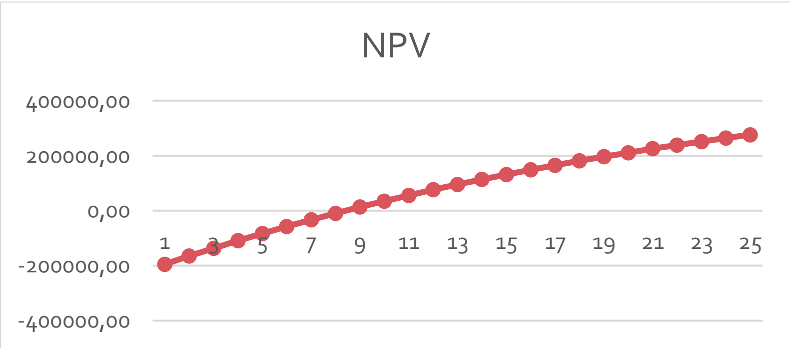

Figure 38 NPV trend for PV panels (absorption chillers and pumps consumptions) scenario for Lipor

5.3.3.4 Impact from RES integration on net welfare effect

The net welfare increases for RADET by approximately 0.1% and for LIPOR by 11.4%, given the sensitivity scenarios chosen, which suggests that there are positive impacts from integrating RES and excess heat recovery. The techno-economic costs remain negative for RADET and LIPOR, meaning that there are still cost reductions despite the fact that there are investments in RES technology in addition to the excess heat recovery technologies. The emissions, and thus environmental and health costs, also decrease when electricity taken from the national grid is replaced by RES. For UMICORE an integration of wind turbines will lead to increased techno-economic costs of 8% while the environmental and health benefits will only increase with 0.2%; as a result, the net welfare will decrease by 13%. Once again it shall be noted that it has not been considered that the UMICORE wind turbine has not been dimensioned to only supply the heat recovery technologies, and in reality there could also be revenues from selling the electricity surplus to the grid.

5.3.4 Alternative Reference Scenario for LIPOR

As there was very little information on the current thermal supply of the airport the reference scenario has been based on the most likely supply for a Portuguese airport, but there might be other alternatives for heating supply. In the alternative refence scenario analyzed as part of the sensitivity analysis the LIPOR Maia waste-to-energy plant is only producing steam for electricity production and the excess heat is released to the air. The Porto Airport is using heat pumps for heating, instead of natural gas boilers as in the primary reference scenario, and electric chillers for cooling, just as in the primary reference scenario.

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As the investment cost for and variable costs for heat pumps are assumed to be larger than the costs for the natural gas boilers, the techno-economic costs would increase in the Alternative Reference Scenario. However, the electricity used for the heat pumps is assumed to lead to less emissions than the heat produced in natural gas boilers. This means that the Alternative Reference Scenario would have a smaller environmental impact than the original Reference Scenario. Comparing Scenario 1 with the Alternative Reference Scenario instead of the original Reference Scenario, Scenario 1 would lead to even larger techno-economic cost reductions (85 % larger cost reduction) but smaller effects on the environmental benefits (93% the size of the environmental benefits). The cost reduction is however having a larger impact on the net welfare, meaning that when comparing Scenario 1 and the Alternative Reference Scenario it would have a net welfare effect 16% higher than when comparing Scenario 1 with the original Reference Scenario. This is indicating the importance of the reference system one compared the investment with.

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6 DISCUSSION

In relation to previous work assessing the economic and environmental impacts of an increased use of industrial excess heat, out of which some is presented in Chapter 1, this report widens the perspective by combining the economic and the environmental impacts and assessing the net welfare of such investments. By monetarizing the environmental and health impacts from the emissions, the environmental and the techno-economic spheres does not have to be managed in isolation from each other.

The result in this report gives some interesting insights into how the environmental benefits of some investments are offset by large techno-economic costs, and also how some investments seem profitable from a techno-economic perspective but could lead to more emissions. In addition, there are also investments that are beneficial for both the environment and the financial departments of public and private companies.

In the ENCE demo site interesting findings are seen when comparing the internal use of excess heat (replacing the combustion of biomass), with the external use (replacing natural gas). With the net welfare in mind, the external use of the excess heat appeared as the most profitable option in most cases. The increased use of biomass in the RADET scenario also showed how the change in energy source might increase some types of emissions, while decreasing others. For the ISVAG waste-to-energy demo sites it was also shown how the combustion of waste does not lead to environmental benefits compared to natural gas combustion. In this case it should however be noted that an alternative waste management method, such as a landfill, was not part of the system analyzed. It should also be highlighted that the result was based on the reference scenario with natural gas boilers, but the demo site representative have emphasized that there will only be a shift in the location of activities and air emissions within Flanders as waste will be incinerated in the ISVAG incinerator rather than in other areas of Flanders.

As shown by previous studies, the increased use of industrial excess heat can have both economic and environmental benefits, but it is highly dependent on the nature of the heat source it replaces. As has been highlighted in previous studies, the assumptions about the investment and O&M costs and what the IEH will replace and how it is used will have an impact on the result. This was shown by the LIPOR sensitivity analysis. In this report there have been a bias in reference systems where natural gas have been the main energy source for heating, and to some extent also in the electricity mixes of the five countries. The electricity demand of the heat recovery equipment may be just as important for the emissions as the heat source the recovered heat replaces. In a system where more RES is integrated, both in the heating and electric system, the net welfare gains from excess heat recovery will not be as large. An alternative interpretation of the results is that it is important to ensure that clean electricity is used in the facilities when recovering excess heat.

The upscaling of the net welfare showed particularly large potentials for the waste-to-energy sectors in Belgium and Portugal as well as the district energy sector of Romania. This could be due to the fact that the method to assess the potential in these countries was somewhat different than for the other sectors, or simply that the potential is large. For Romania there are a large amount of district heating grids, meaning that the potential when upscaling would be large regardless of the size of the demo site potential. In the case of Belgium and Portugal, the potentially recoverable heat in the individual

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demo sites ISVAG and LIPOR were large in comparison to the other demo sites assessed, meaning that an upscaling on a national level could have a large impact.

It is important to note that the demo site results are very site specific and it could be hard to apply them to the industry sectors in general. The challenge to generalize the results has also been highlighted by the previous studies performed on industrial excess heat, as presented in 1.2 of this report. This should be kept in mind when looking at the result for the upscaling to a national level. The task was explicitly to apply a bottom-up approach of the cost-benefits of industrial excess heat using the demo sites as study objects - generalization should be treated with caution.

There are some uncertainties that haven't been possible to consider given the project constraints. The most important omitted uncertainties relates to the social cost of carbon, the choice of using the value of statistical life or the value of a life year lost to monetize health effects of air pollution, and the choice of using EU-average values for human health valuation in all case studies. None of these omitted uncertainties are expected to flip the results of the CBA, only widen the variance. The literature on the social cost of carbon comes with quite a variation, but there is little indication on how the variation is explained and how this should be considered in uncertainty analysis. What we do know is that the variation to a large extent is dependent on economic growth, a parameter that affects all values in our analysis, in the same direction. The choice between Value of a Statistical Life (VSL) and Value of a Life Year (VOLY) can be seen as a choice between valuing old and sensitive persons as much as the average person, or not. The choice of using EU-average values for human health and climate change effects is due to the transboundary nature of both climate change and air quality. Emission reduction in one country will affect climate change and air quality in a neighboring country, and that country can be richer or poorer than the emitter country. There is little possibility to find an ethically defensible strategy for separating values between countries, and we therefore stick to global average values for climate change and EU average values for air quality.

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7 CONCLUSIONS

The main objective of the Horizon 2020 project SO WHAT is to develop and demonstrate an integrated software which will support industries and energy utilities in selecting, simulating and comparing alternative industrial excess heat and cold exploitation technologies that could cost-effectively balance the local forecasted heating and cooling demand, and also via RES integration.

Given the limitations and assumptions made in this CBA, the analysis suggests that most of the scenarios studied will improve welfare, with the exception of the UMICORE scenario. However, also the ISVAG scenarios should be further scrutinized since they imply increased emissions of air pollutants and greenhouse gases. Four of the sites have presented scenarios that would imply techno-economic cost savings. These scenarios should be considered interesting for investments, even if ignoring their associated emission reductions. The upscaling of results showed particularly positive net welfare potentials for the waste-to-energy and district heating sectors, indicating the large impacts of these sectors when integrating both IEH, as for ISVAG and LIPOR, and RES, as for RADET. Integrating IEH and RES could also generate additional gains in net welfare, as was shown in the sensitivity analysis.

A CBA could be an important method to integrate in the SO WHAT software in order to assess the welfare effects of industrial excess heat and cold exploitation scenarios. The ability to assess the net welfare through a CBA is useful for making decisions on large public sector investments and can also be useful to attract financial support, among other things. However, it is important to note that to be able to integrate a cost-benefit analysis in the SO WHAT software the input data to the CBA is just as important as the CBA method in itself. In the CBA reported here, a number of inputs were required, such as emissions factors linked to fuel combustion and electricity mixes, scenario specifications, technology options technical specifications, external costs from emissions, investment costs and costs for variable inputs, the estimation of excess heat and RES potential etc. If it would be possible to include such input data, a CBA module based on the code developed for this particular CBA could be used as a powerful tool to enable the assessment of the net welfares of different investment scenarios in the SO WHAT software.

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Appendix I
Demo site technology options and scenario

(2020-11-20) The inform given below is what we estimate to be publicly available information. Some data used in the analysis have been removed out of confidentiality reasons.

A.I.1. – ENCE Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Electricity demand	Natural gas demand	Biofuel demand
Units			[kW thermal]	[MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	ele	nat_gas	biofuel
Investment made before 2020: Individual natural gas boilers	01	2	24800	29487.2	0.005	0.990099	0
Biomass dryer runs on 3713 kW gas/water heat exchanger in the causticization stage (high capacity, 25 t biomass/h)	02	15	3713	21955.5	0.003871	0	-0.00911
Bleaching effluent water/water heat exchanger	03	15	11630	13828.07	0	0	0
Cooling tower effluent water/water heat exchanger)	04	15	13170	15659.13	0	0	0
Heat grid to town hall (2 x 2.5 km)	05	30	24800	29487.2	0.01	0	0
Substation for heat grid	06	20	24800	29487.2	0	0	0
Reinvestment made after 2020: Individual natural gas boilers	07	25	24800	29487.2	0.005	0.990099	0

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A.I.2. – ENCE Emission factors per option

	CO_2 emissions	CH_4 emissions	N_2O emissions	SO_2 emissions	NO_x emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH_3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Investment made before 2020: Individual natural gas boilers	198.8909	0.712871	0.000356	0	0.213861	0.000356	0.00025	7.13E-05	3.56E-05	0.00082	0.007129
Biomass dryer runs on 3713 kW gas/water heat exchanger in the causticization stage (high capacity, 25 t biomass/h)	0	-0.000361	-0.00013	-0.00123	-0.00246	-0.00024	-9.5E-06	-0.00021	-1.87E-05	-9.8E-05	-0.001574
Bleaching effluent water/water heat exchanger	0	0	0	0	0	0	0	0	0	0	0
Heat grid to town hall (2 x 2.5 km)	0	0	0	0	0	0	0	0	0	0	0
Substation for heat grid	0	0	0	0	0	0	0	0	0	0	0
Reinvestment made after 2020: Individual natural gas boilers	198.8909	0.712871	0.000356	0	0.213861	0.000356	0.00025	7.13E-05	3.56E-05	0.00082	0.007129

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A.I.3. – IMERYS Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Electricity demand	Natural gas demand
Units			[kW thermal]	[MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	ele	nat_gas
Old investment: Individual natural gas boilers	o1	3	6500.584	16700	0.005	1.18
Heat recovery from furnace chimney gases	o2	10	7000	16700	0	0
Heat grid	o3	40	7000	16700	0.002	0
Reinvestment: Individual natural gas boilers	o4	25	6500.584	16700	0.005	1.18

A.I.4. – IMERYS Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Old investment: Individual natural gas boilers	237.0382	0.4248	0.000425	0	0.2124	0.000425	0.000297	8.5E-05	4.25E-05	0.000977	0.008496
Heat recovery from furnace chimney gases	0	0	0	0	0	0	0	0	0	0	0
Heat grid	0	0	0	0	0	0	0	0	0	0	0
Reinvestment: Individual natural gas boilers	237.0382	0.4248	0.000425	0	0.165672	0.000425	0.000297	8.5E-05	4.25E-05	0.000977	0.008496

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A.I.5. – ISVAG Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Work hours demand	Electricity demand	Natural gas demand	Waste demand
Units			[kW thermal]	[MWh thermal]	[h/MWH thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	man_hours	ele	nat_gas	waste
Individual natural gas boilers	o1	25	32192.68	82703	0	0.289	1.176471	0
Waste heat from boiler and W2E plant, Heat exchangers/pumps/instrumentation	o2	20	4776	9749	0.00286	0.085	0	1.112
Mini district heating grid	o3	40	4776	9749	0.0115	0	0	0
Waste heat from boiler and NEW W2E plant, exchangers/pumps/instrumentation (including replacement investments after 15 years)	o4	20	16000	82703	0.0076	0.06	0	1.112
Large scale district heating grid	o5	40	16000	82703	0.027	0	0	0
Natural gas boilers as backup	o6	25	32192.68	72954	0	0.289	1.176471	0
Natural gas boilers as backup - only until 2026	o7	6	32192.68	72954	0	0.289	1.176471	0
Waste heat from boiler and W2E plant, Heat exchangers/pumps/instrumentation	o8	6	4776	9749	0.00286	0.085	0	1.112
Mini district heating grid	o9	6	4776	9749	0.0115	0	0	0

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A.I.6. – ISVAG Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Individual natural gas boilers	236.3292	0.423529	0.000424	0	0.211765	0.000424	0.000296	8.47E-05	4.24E-05	0.000974	0.0084706
Waste heat from boiler and W2E plant, Heat exchangers/pumps/instrumentation	373.3902	0.120096	0.016013	0.5004	0.520416	0.005925	4E-05	0.005564	0.00032	0.006005	0.060048
Mini district heating grid	0	0	0	0	0	0	0	0	0	0	0
Waste heat from boiler and NEW W2E plant, exchangers/pumps/instrumentation (including replacement investments after 15 years)	373.3902	0.120096	0.016013	0.5004	0.520416	0.005925	4E-05	0.005564	0.00032	0.006005	0.060048
Large scale district heating grid	0	0	0	0	0	0	0	0	0	0	0
Natural gas boilers as backup	236.3292	0.423529	0.000424	0	0.211765	0.000424	0.000296	8.47E-05	4.24E-05	0.000974	0.0084706
Natural gas boilers as backup - only until 2026	236.3292	0.423529	0.000424	0	0.211765	0.000424	0.000296	8.47E-05	4.24E-05	0.000974	0.0084706
Waste heat from boiler and W2E plant, Heat exchangers/pumps/instrumentation	373.3902	0.120096	0.016013	0.5004	0.520416	0.005925	4E-05	0.005564	0.00032	0.006005	0.060048
Mini district heating grid	0	0	0	0	0	0	0	0	0	0	0

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A.I.7. – LIPOR Technical information per option

	Option	Technical life time	Installation size	Annual waste heat production / heat production	Electricity demand	Natural gas demand
Units			[kW thermal]	[MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	ele	nat_gas
Natural gas boiler for airport heating	o1	25	9040.01	10748.57	0.005	0.990099
Electric heat pump for airport heating	o2	20	9040.01	10748.57	0.277778	0
Electric chillers for cooling airport (Compression chiller, air cooled, electricity fuelled)	o3	20	12000	5916	0.232558	0
Hydraulic heating network	o4	30	12000	19200	0.020938	0
Heat exchangers	o5	10	12000	19200	0	0
Absorption chillers	o6	25	12000	19200	0.020363	0
Pumps	o7	20	12000	19200	0	0

A.I.8. – LIPOR Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Natural gas boiler for airport heating	198.8909	0.08198	0.028515	0.008911	0.071644	0.000356	0.000321	0	3.56E-05	0.007129	0.0160396
Electric heat pump for airport heating	0	0	0	0	0	0	0	0	0	0	0
Electric chillers for cooling airport (Compression chiller, air cooled, electricity fuelled)	0	0	0	0	0	0	0	0	0	0	0
Hydraulic heating network	0	0	0	0	0	0	0	0	0	0	0
Heat exchangers	0	0	0	0	0	0	0	0	0	0	0

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Absorption chillers	0	0	0	0	0	0	0	0	0	0	0
Pumps	0	0	0	0	0	0	0	0	0	0	0

A.I.9. – Martini Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Electricity demand	Natural gas demand
Units			[kW thermal]	[MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	ele	nat_gas
Old investment: Hot water from natural gas boilers	o1	2	1200	1848	0.005	0.9901
Heat exchangers	o2	10	1450	1848	0	0
Reinvestment: Hot water from natural gas boilers	o3	25	1200	1848	0.005	0.9901
Old investment: Hot water from natural gas boilers - Reference	o4	15	1200	1848	0.005	0.9901

A.I.10. – Martini Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Old investment : Hot water from natural gas boilers	198.8909	0.712871	0.000356	0	0.196039	0.000356	0.00025	7.13E-05	3.56E-05	0.00082	0.0071287
Heat exchangers	0	0	0	0	0	0	0	0	0	0	0
Reinvestment: Hot water from natural gas boilers	198.8909	0.712871	0.000356	0	0.196039	0.000356	0.00025	7.13E-05	3.56E-05	0.00082	0.0071287
Old investment : Hot water from natural gas	198.8909	0.712871	0.000356	0	0.196039	0.000356	0.00025	7.13E-05	3.56E-05	0.00082	0.0071287

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boilers - Reference											

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A.I.11. – Petromidia Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Electricity demand	Oil demand
Units			[kW thermal]	[MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	ele	oil
Heat exchangers etc for energy recovery	o1	25	1736	15215	0.0875	-0.8671
dummy	o2	50	0	15215	0.01	0.5

A.I.12. – Petromidia Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Heat exchangers etc for energy recovery	-239.4348	-0.00937	-0.02497	-0.936511	-0.26534	-0.02557	-0.00103	-0.02204	-0.0025	-0.00125	-0.015609
dummy	7981.159	0.31217	0.832455	31.21705	8.844831	0.852225	0.034339	0.734641	0.083245	0.041623	0.5202842

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A.I.13. – RADET Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Work hours demand	Demand water	Demand material	Electricity demand	Natural gas demand	Biofuel demand	Solar thermal demand
Units			[kW thermal]	[MWh thermal]	[h/MWH thermal]	[litre/MWh thermal]	[kg/MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]	[MWh fuel /MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	man_hours	water	mtrl	ele	nat_gas	biofuel	sol_th
Old investment: Natural gas HOB	o1	25	286150	8468.531	0.693	336	3.85	0.0014	0.890472	0	0
Old investment: RADET natural gas HOB	o2	30	31609	199.2457	1.78	200	0	0.0014	0.815661	0	0
Pellet HOB to DHN	o3	45	1000	8500	0	0	0	0.005	0	1.06383	0
Solar thermal to DHN	o4	50	230	167.777	0	0	0	0.003	0	0	2.2222222
Reinvest: Natural gas HOB	o5	35	286150	8468.531	0.693	336	3.85	0.0014	0.890472	0	0
Reinvest: RADET natural gas HOB	o6	40	31609	199.2457	1.78	200	0	0.0014	0.815661	0	0

A.I.14. – RADET Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	voc emissions	waste water emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	voc	ws_wat
Old investment: Natural gas HOB	227.32	0	0	0	0.279	0	560
Old investment: RADET natural gas HOB	255.4	0.006909	0.01104	0.02577	0.2209	0.011508	0
Pellet HOB to DHN	201	0	0	0.013	0.393	0	0
Solar thermal to DHN	0	0	0	0	0	0	0
Reinvest: Natural gas HOB	227.32	0	0	0	0.279	0	560
Reinvest: RADET natural gas HOB	255.4	0.006909	0.01104	0.02577	0.2209	0.011508	0

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A.I.1. – Umicore Technical information per option

	Option	Years of operation	Installation size	Annual waste heat production / heat production	Demand water	Demand material	Electricity demand	Natural gas demand
Units			[kW thermal]	[MWh thermal]	[litre/ MWh thermal]	[kg/MWh thermal]	[MWh ele/MWh thermal]	[MWh fuel /MWh thermal]
abbreviation	O	OT	size	util	water	mtrl	ele	nat_gas
Old investment: Natural gas steam grid (CHP/boilers) - 2020	o1	2	52000	259107	0.517192	0	-0.26182	1.529287
Internal heat grid - 2021	o2	40	8000	41960	0	0	0.007102	0
Heat exchangers - 2021	o3	10	8000	41960	0	0	0	0
Old investment: Natural gas steam grid (CHP/boilers) - less use	o4	9	52000	217147	0.61713	0	0	1.242232
Reinvestment: Natural gas steam grid (CHP/boilers) - reference	o5	20	52000	259107	0.517192	0	-0.26182	1.529287
Reinvestment: Natural gas steam grid (CHP/boilers) - less use	o6	20	52000	217147	0.61713	0	0	1.242232
Old investment: Natural gas steam grid (CHP/boilers) - reference, 10 years left	o7	10	52000	259107	0.517192	0	-0.26182	1.529287

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A.I.2. – Umicore Emission factors per option

	CO2 emissions	CH4 emissions	N2O emissions	SO2 emissions	NOx emissions	PM2.5 emissions	OC emissions	PMres emissions	BC emissions	NH3 emissions	voc emissions
Units	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]	[kg/MWh thermal]
abbreviation	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
Old investment: Natural gas steam grid (CHP/boilers) - 2020	307.203	0.003854	0.000551	0.000551	0.13213	0.000551	0.000385	0.00011	5.51E-05	0.004404	0.0165163
Internal heat grid - 2021	0	0	0	0	0	0	0	0	0	0	0
Heat exchangers - 2021	0	0	0	0	0	0	0	0	0	0	0
Old investment: Natural gas steam grid (CHP/boilers) - less use	249.5394	0.00313	0.000447	0.000447	0.107329	0.000447	0.000313	8.94E-05	4.47E-05	0.003578	0.0134161
Reinvestment: Natural gas steam grid (CHP/boilers) - reference	307.203	0.003854	0.000551	0.000551	0.13213	0.000551	0.000385	0.00011	5.51E-05	0.004404	0.0165163
Reinvestment: Natural gas steam grid (CHP/boilers) - less use	249.5394	0.00313	0.000447	0.000447	0.107329	0.000447	0.000313	8.94E-05	4.47E-05	0.003578	0.0134161
Old investment: Natural gas steam grid (CHP/boilers) - reference, 10 years left	307.203	0.003854	0.000551	0.000551	0.13213	0.000551	0.000385	0.00011	5.51E-05	0.004404	0.0165163

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Appendix II
Input data for variable costs and emissions

A.II.1 – Electricity emission factors for Electricity in Belgium

Year	Emission factors [kg / MWh electricity									
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	104	0.020	0.003	0.042	0.128	0.008	0.0004	0.007	0.0003	0.003	0.023
2025	198	0.024	0.002	0.037	0.171	0.006	0.0007	0.005	0.0003	0.002	0.027
2030	165	0.020	0.003	0.042	0.150	0.006	0.0005	0.005	0.0003	0.003	0.024
2035	171	0.021	0.003	0.029	0.146	0.007	0.0005	0.006	0.0003	0.002	0.025
2040	133	0.021	0.004	0.035	0.129	0.009	0.0005	0.008	0.0003	0.003	0.023
2045	32.6	0.019	0.003	0.033	0.120	0.008	0.0004	0.008	0.0003	0.003	0.016
2050	22.5	0.019	0.003	0.031	0.118	0.008	0.0004	0.007	0.0002	0.003	0.016
2055	22.5	0.019	0.003	0.031	0.118	0.008	0.0004	0.007	0.0002	0.003	0.016
2060	22.5	0.019	0.003	0.031	0.118	0.008	0.0004	0.007	0.0002	0.003	0.016
2065	22.5	0.019	0.003	0.031	0.118	0.008	0.0004	0.007	0.0002	0.003	0.016
2069	22.5	0.019	0.003	0.031	0.118	0.008	0.0004	0.007	0.0002	0.003	0.016

A.II.2 – Electricity emission factors for Electricity in Italy

Year	Emission factors										
	[kg CO2/ MWh Ele]	[kg CH4/ MWh Ele]	[kg N2O/ MWh Ele]	[kg SO2/ MWh Ele]	[kg NOx/ MWh Ele]	[kg PM2.5/ MWh Ele]	[kg OC/ MWh Ele]	[kg PMres/ MWh ele]	[kg BC/ MWh ele]	[kg NH3/ MWh ele]	[kg VOC/ MWh ele]
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	293	0.044	0.010	0.087	0.221	0.004	0.0003	0.003	0.0001	0.003	0.025
2025	222	0.034	0.008	0.067	0.180	0.004	0.0002	0.003	0.0001	0.002	0.022
2030	186	0.030	0.006	0.055	0.150	0.003	0.0003	0.003	0.0001	0.002	0.023
2035	198	0.033	0.006	0.049	0.149	0.004	0.0004	0.004	0.0001	0.002	0.013
2040	74.9	0.035	0.005	0.034	0.124	0.002	0.0003	0.002	0.0001	0.001	0.012
2045	67.6	0.033	0.004	0.033	0.118	0.002	0.0003	0.002	0.0001	0.001	0.016
2050	57.8	0.031	0.004	0.032	0.106	0.002	0.0003	0.002	0.0001	0.001	0.018
2055	57.8	0.031	0.004	0.032	0.106	0.002	0.0003	0.002	0.0001	0.001	0.018
2060	57.8	0.031	0.004	0.032	0.106	0.002	0.0003	0.002	0.0001	0.001	0.018
2065	57.8	0.031	0.004	0.032	0.106	0.002	0.0003	0.002	0.0001	0.001	0.018
2069	57.8	0.031	0.004	0.032	0.106	0.002	0.0003	0.002	0.0001	0.001	0.018

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A.II.3 – Electricity emission factors for Electricity in Portugal

Year	Emission factors										
	[kg CO2/ MWh Ele]	[kg CH4/ MWh Ele]	[kg N2O/ MWh Ele]	[kg SO2/ MWh Ele]	[kg NOx/ MWh Ele]	[kg PM2.5/ MWh Ele]	[kg OC/ MWh Ele]	[kg PMres/ MWh ele]	[kg BC/ MWh ele]	[kg NH3/ MWh ele]	[kg VOC/ MWh ele]
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	151	0.031	0.008	0.063	0.171	0.007	0.0002	0.007	0.0002	0.003	0.015
2025	86.1	0.024	0.006	0.051	0.126	0.007	0.0002	0.007	0.0002	0.003	0.014
2030	30.6	0.014	0.006	0.041	0.090	0.006	0.0002	0.006	0.0002	0.002	0.011
2035	20.3	0.012	0.006	0.034	0.077	0.005	0.0001	0.005	0.0001	0.002	0.010
2040	16.7	0.011	0.005	0.029	0.064	0.003	0.0000	0.003	0.0001	0.002	0.008
2045	15.5	0.011	0.004	0.025	0.056	0.002	0.0000	0.002	0.0001	0.002	0.007
2050	12.4	0.009	0.004	0.021	0.047	0.002	0.0000	0.002	0.0001	0.001	0.006
2055	12.4	0.009	0.004	0.021	0.047	0.002	0.0000	0.002	0.0001	0.001	0.006
2060	12.4	0.009	0.004	0.021	0.047	0.002	0.0000	0.002	0.0001	0.001	0.006
2065	12.4	0.009	0.004	0.021	0.047	0.002	0.0000	0.002	0.0001	0.001	0.006
2069	12.4	0.009	0.004	0.021	0.047	0.002	0.0000	0.002	0.0001	0.001	0.006

A.II.4 – Electricity emission factors for Electricity in Romania

Year	Emission factors										
	[kg CO2/ MWh Ele]	[kg CH4/ MWh Ele]	[kg N2O/ MWh Ele]	[kg SO2/ MWh Ele]	[kg NOx/ MWh Ele]	[kg PM2.5/ MWh Ele]	[kg OC/ MWh Ele]	[kg PMres/ MWh ele]	[kg BC/ MWh ele]	[kg NH3/ MWh ele]	[kg VOC/ MWh ele]
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	302	0.104	0.010	0.333	0.214	0.033	0.0001	0.033	0.0001	0.002	0.023
2025	211	0.061	0.008	0.247	0.160	0.026	0.0001	0.025	0.0001	0.002	0.018
2030	124	0.018	0.007	0.167	0.112	0.018	0.0001	0.017	0.0001	0.002	0.013
2035	89.1	0.083	0.004	0.052	0.087	0.009	0.0001	0.009	0.0001	0.001	0.007
2040	14.1	0.092	0.003	0.029	0.074	0.006	0.0001	0.006	0.0001	0.001	0.006
2045	12.4	0.082	0.003	0.028	0.068	0.006	0.0001	0.006	0.0001	0.001	0.006
2050	12.1	0.101	0.004	0.020	0.069	0.005	0.0001	0.005	0.0001	0.002	0.006
2055	12.1	0.101	0.004	0.020	0.069	0.005	0.0001	0.005	0.0001	0.002	0.006
2060	12.1	0.101	0.004	0.020	0.069	0.005	0.0001	0.005	0.0001	0.002	0.006
2065	12.1	0.101	0.004	0.020	0.069	0.005	0.0001	0.005	0.0001	0.002	0.006
2069	12.1	0.101	0.004	0.020	0.069	0.005	0.0001	0.005	0.0001	0.002	0.006

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A.II.5 – Electricity emission factors for Electricity in Spain

Year	Emission factors										
	[kg CO2/ MWh Ele]	[kg CH4/ MWh Ele]	[kg N2O/ MWh Ele]	[kg SO2/ MWh Ele]	[kg NOx/ MWh Ele]	[kg PM2.5/ MWh Ele]	[kg OC/ MWh Ele]	[kg PMres/ MWh ele]	[kg BC/ MWh ele]	[kg NH3/ MWh ele]	[kg VOC/ MWh ele]
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	272	0.033	0.004	0.222	0.235	0.007	0.0002	0.007	0.0001	0.003	0.016
2025	159	0.016	0.003	0.107	0.149	0.006	0.0001	0.005	0.0001	0.002	0.011
2030	58.7	0.008	0.002	0.062	0.079	0.004	0.0001	0.004	0.0001	0.002	0.008
2035	36.3	0.009	0.001	0.034	0.053	0.003	0.0001	0.002	0.0001	0.001	0.005
2040	23.2	0.011	0.002	0.028	0.058	0.003	0.0001	0.003	0.0001	0.001	0.005
2045	25.8	0.011	0.002	0.021	0.058	0.002	0.0001	0.002	0.0000	0.001	0.005
2050	15.9	0.007	0.001	0.012	0.036	0.002	0.0000	0.002	0.0000	0.001	0.004
2055	15.9	0.007	0.001	0.012	0.036	0.002	0.0000	0.002	0.0000	0.001	0.004
2060	15.9	0.007	0.001	0.012	0.036	0.002	0.0000	0.002	0.0000	0.001	0.004
2065	15.9	0.007	0.001	0.012	0.036	0.002	0.0000	0.002	0.0000	0.001	0.004
2069	15.9	0.007	0.001	0.012	0.036	0.002	0.0000	0.002	0.0000	0.001	0.004

A.II.6 – External costs per kg emissions from Belgium

Year	External cost of emissions (€2020 / kg emission)										
T	**co2**	**ch4**	**n2o**	**so2**	**nox**	**pm2.5**	**oc**	**pmres**	**bc**	**nh3**	**voc**
2020	0.1	2.5	23.3	36.6	3.3	71.2	-4.1	-4.1	35.2	29.8	2.6
2025	0.1	2.9	27.8	38.7	3.3	76.2	-4.9	-4.9	42.0	31.7	2.8
2030	0.1	3.4	32.3	41.1	3.4	81.7	-5.7	-5.7	48.8	33.8	3.1
2035	0.1	3.9	36.8	43.7	3.5	87.8	-6.5	-6.5	55.6	36.2	3.4
2040	0.2	4.4	41.3	46.7	3.7	94.6	-7.3	-7.3	62.3	38.9	3.7
2045	0.2	4.8	45.8	50.0	3.9	101.7	-8.0	-8.0	69.1	41.8	4.0
2050	0.2	5.3	50.3	53.6	4.1	109.6	-8.8	-8.8	75.9	45.0	4.4
2055	0.2	5.3	50.3	53.6	4.1	109.6	-8.8	-8.8	75.9	45.0	4.4
2060	0.2	5.3	50.3	53.6	4.1	109.6	-8.8	-8.8	75.9	45.0	4.4
2065	0.2	5.3	50.3	53.6	4.1	109.6	-8.8	-8.8	75.9	45.0	4.4
2069	0.2	5.3	50.3	53.6	4.1	109.6	-8.8	-8.8	75.9	45.0	4.4

A.II.7 – External costs per kg emissions from Italy

Year	External cost of emissions (€2020 / kg emission)										
T	**co2**	**ch4**	**n2o**	**so2**	**nox**	**pm2.5**	**oc**	**pmres**	**bc**	**nh3**	**voc**
2020	0.1	2.5	23.3	23.0	9.0	60.5	-4.1	-4.1	35.2	16.8	4.6
2025	0.1	2.9	27.8	23.9	9.3	64.1	-4.9	-4.9	42.0	17.6	5.0
2030	0.1	3.4	32.3	25.0	9.8	68.0	-5.7	-5.7	48.8	18.5	5.4
2035	0.1	3.9	36.8	26.2	10.3	72.3	-6.5	-6.5	55.6	19.5	5.8
2040	0.2	4.4	41.3	27.6	10.8	76.9	-7.3	-7.3	62.3	20.7	6.2
2045	0.2	4.8	45.8	29.3	11.5	82.5	-8.0	-8.0	69.1	22.1	6.7
2050	0.2	5.3	50.3	31.3	12.3	88.5	-8.8	-8.8	75.9	23.6	7.3
2055	0.2	5.3	50.3	31.3	12.3	88.5	-8.8	-8.8	75.9	23.6	7.3
2060	0.2	5.3	50.3	31.3	12.3	88.5	-8.8	-8.8	75.9	23.6	7.3
2065	0.2	5.3	50.3	31.3	12.3	88.5	-8.8	-8.8	75.9	23.6	7.3
2069	0.2	5.3	50.3	31.3	12.3	88.5	-8.8	-8.8	75.9	23.6	7.3

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A.II.8 – External costs per kg emissions from Portugal

Year	External cost of emissions (€2020 / kg emission)										
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	0.1	2.5	23.3	3.3	1.0	27.0	-4.1	-4.1	35.2	3.9	1.3
2025	0.1	2.9	27.8	3.1	0.9	29.0	-4.9	-4.9	42.0	4.0	1.4
2030	0.1	3.4	32.3	3.0	0.9	31.3	-5.7	-5.7	48.8	4.2	1.6
2035	0.1	3.9	36.8	3.0	0.8	33.7	-6.5	-6.5	55.6	4.4	1.7
2040	0.2	4.4	41.3	3.0	0.8	36.4	-7.3	-7.3	62.3	4.7	1.9
2045	0.2	4.8	45.8	3.1	0.8	39.4	-8.0	-8.0	69.1	5.0	2.1
2050	0.2	5.3	50.3	3.2	0.9	42.7	-8.8	-8.8	75.9	5.4	2.3
2055	0.2	6.1	57.7	3.1	0.8	46.3	-10.1	-10.1	87.0	5.7	2.5
2060	0.2	6.9	65.0	3.0	0.7	50.3	-11.4	-11.4	98.1	6.1	2.8
2065	0.3	7.6	72.4	3.0	0.7	54.7	-12.7	-12.7	109.2	6.6	3.1
2069	0.3	8.3	78.2	3.1	0.7	58.6	-13.7	-13.7	118.0	7.0	3.3

A.II.9 – External costs per kg emissions from Romania

Year	External cost of emissions (€2020 / kg emission)										
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	0.1	2.5	23.3	16.0	6.6	42.1	-4.1	-4.1	35.2	15.5	1.6
2025	0.1	2.9	27.8	16.0	6.6	43.2	-4.9	-4.9	42.0	15.7	1.7
2030	0.1	3.4	32.3	16.0	6.6	44.4	-5.7	-5.7	48.8	16.0	1.9
2035	0.1	3.9	36.8	16.2	6.8	46.2	-6.5	-6.5	55.6	16.4	2.0
2040	0.2	4.4	41.3	16.5	6.9	48.1	-7.3	-7.3	62.3	16.9	2.2
2045	0.2	4.8	45.8	16.9	7.1	50.1	-8.0	-8.0	69.1	17.5	2.4
2050	0.2	5.3	50.3	17.3	7.3	52.2	-8.8	-8.8	75.9	18.1	2.5
2055	0.2	5.3	50.3	17.3	7.3	52.2	-8.8	-8.8	75.9	18.1	2.5
2060	0.2	5.3	50.3	17.3	7.3	52.2	-8.8	-8.8	75.9	18.1	2.5
2065	0.2	5.3	50.3	17.3	7.3	52.2	-8.8	-8.8	75.9	18.1	2.5
2069	0.2	5.3	50.3	17.3	7.3	52.2	-8.8	-8.8	75.9	18.1	2.5

A.II.10 – External costs per kg emissions from Spain

Year	External cost of emissions (€2020 / kg emission)										
T	co2	ch4	n2o	so2	nox	pm2.5	oc	pmres	bc	nh3	voc
2020	0.1	2.5	23.3	10.2	0.8	33.4	-4.1	-4.1	35.2	4.9	1.6
2025	0.1	2.9	27.8	10.5	0.7	35.9	-4.9	-4.9	42.0	5.1	1.8
2030	0.1	3.4	32.3	10.9	0.6	38.6	-5.7	-5.7	48.8	5.4	2.0
2035	0.1	3.9	36.8	11.4	0.5	41.7	-6.5	-6.5	55.6	5.7	2.2
2040	0.2	4.4	41.3	12.1	0.5	45.2	-7.3	-7.3	62.3	6.1	2.4
2045	0.2	4.8	45.8	12.9	0.5	49.0	-8.0	-8.0	69.1	6.5	2.6
2050	0.2	5.3	50.3	13.9	0.5	53.2	-8.8	-8.8	75.9	7.1	2.8

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2055	0.2	5.3	50.3	13.9	0.5	53.2	-8.8	-8.8	75.9	7.1	2.8
2060	0.2	5.3	50.3	13.9	0.5	53.2	-8.8	-8.8	75.9	7.1	2.8
2065	0.2	5.3	50.3	13.9	0.5	53.2	-8.8	-8.8	75.9	7.1	2.8
2069	0.2	5.3	50.3	13.9	0.5	53.2	-8.8	-8.8	75.9	7.1	2.8

A.II.11 – Variable costs in Belgium

	Variable costs				
	[€/hour]	[€/litre]	[€/ MWh ele]	[€/ MWH fuel]	[€/ MWH fuel]
T	**man_hours**	**water**	**ele**	**nat_gas**	**waste**
2020	40.9	0.0043	155	27.2	-39.1
2025	40.9	0.0043	164	29.8	-39.1
2030	40.9	0.0043	166	32.5	-39.1
2035	40.9	0.0043	170	34.8	-39.1
2040	40.9	0.0043	168	37.1	-39.1
2045	40.9	0.0043	165	39.4	-39.1
2050	40.9	0.0043	164	41.7	-39.1
2055	40.9	0.0043	164	41.7	-39.1
2060	40.9	0.0043	164	41.7	-39.1
2065	40.9	0.0043	164	41.7	-39.1
2069	40.9	0.0043	164	41.7	-39.1

A.II.12 – Variable costs in Italy

	Variable costs	
	[€/ MWh ele]	[€/ MWH fuel]
T	**ele**	**nat_gas**
2020	167	25.4
2025	176	27.9
2030	181	30.3
2035	185	32.4
2040	187	34.5
2045	186	36.6
2050	183	38.7
2055	183	38.7
2060	183	38.7
2065	183	38.7
2069	183	38.7

A.II.13 – Variable costs in Portugal

	Variable costs			
	[€/hour]	[€/litre]	[€/ MWh ele]	[€/ MWH fuel]
T	**man_hours**	**water**	**ele**	**nat_gas**
2020	14.7	0.0019	148	27.3
2025	14.7	0.0019	154	29.9
2030	14.7	0.0019	158	32.6

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2035	14.7	0.0019	160	34.9
2040	14.7	0.0019	155	37.2
2045	14.7	0.0019	153	39.6
2050	14.7	0.0019	151	41.9
2055	14.7	0.0019	151	41.9
2060	14.7	0.0019	151	41.9
2065	14.7	0.0019	151	41.9
2069	14.7	0.0019	151	41.9

A.II.14 – Variable costs in Romania

	Variable costs						
	[€/hour]	[€/litre]	[€/kg]	[€/ MWh ele]	[€/ MWH fuel]	[€/ MWH fuel]	[€/ MWH fuel]
T	**man_hours**	**water**	**mtrl**	**ele**	**oil**	**nat_gas**	**biofuel**
2020	7.78	0.0024	0.2	116	27.8	90.1	29.8
2025	7.78	0.0024	0.2	129	29.3	107	30.4
2030	7.78	0.0024	0.2	137	30.7	124	30.9
2035	7.78	0.0024	0.2	148	31.9	129	32.1
2040	7.78	0.0024	0.2	153	33.1	133	33.2
2045	7.78	0.0024	0.2	151	34.3	138	34.4
2050	7.78	0.0024	0.2	147	35.5	142	35.6
2055	7.78	0.0024	0.2	147	35.5	142	35.6
2060	7.78	0.0024	0.2	147	35.5	142	35.6
2065	7.78	0.0024	0.2	147	35.5	142	35.6
2069	7.78	0.0024	0.2	147	35.5	142	35.6

A.II.15 – Variable costs in Spain

	Variable costs		
	[€/ MWh ele]	[€/ MWH fuel]	[€/ MWH fuel]
T	**ele**	**nat_gas**	**biofuel**
2020	184	26.7	31.0
2025	179	29.3	31.5
2030	178	31.9	32.1
2035	178	34.2	33.3
2040	177	36.4	34.5
2045	175	38.7	35.7
2050	172	40.9	36.9
2055	172	40.9	36.9
2060	172	40.9	36.9
2065	172	40.9	36.9
2069	172	40.9	36.9

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Appendix III
Upscaling of results

In this section the method to scale up the individual results of the nine demo sites of the SO WHAT project to a national result is described more in detail.

Input data

The recoverable excess heat potential per demo site country and industry sector was assessed in D1.2 "First release of SO WHAT industrial sectors WH/C recovery potential" of the SO WHAT project [63] and these potentials are the main input for creating scaling factors. The nine demo sites were categorized in the seven industry sectors used in D1.2, the categorization can be seen in Table 12.

Country	Iron & Steel	Non-ferrous Metals	Chemical & Petro-chemical	Non-metallic Minerals	Food & Beverage & Tobacco	Paper, Pulp and Printing	Other
Belgium	-	Umicore	IMERYS	-	-	-	ISVAG
Italy	-	-	-	-	Pessione Destillery	-	-
Portugal	-	-	-	-	-	-	Lipor Maia
Romania	-	-	Petromida refinery	-	-	-	Constanta DHN
Spain	-	-	-	-	-	ENCE	-
UK	MPI	-	-	-	-	-	-

Table 12 Categorization of demo sites

In D1.2 two methods were used to assess the recoverable excess heat potential, these are described in D1.2 [54]. For this report both results have been used. The potential for each country and industry sector, calculated using both method 1 and method 2, are seen in Table 13 and Table 14.

METHOD 1 Recoverable Excess Heat Potential Country and Industry Totals 2017 (TWh)							
Country	Iron & Steel	Non-ferrous Metals	Chemical & Petro-chemical	Non-metallic Minerals	Food & Beverage & Tobacco	Paper, Pulp and Printing	Other
Belgium	5.629	0.433	4.087	2.390	1.327	0.708	0.293
Italy	4.954	0.476	1.836	3.719	1.229	1.080	0.715
Portugal	0.243	0.025	0.245	1.218	0.239	0.814	0.109
Romania	1.075	0.143	0.484	0.652	0.181	0.058	0.113
Spain	2.823	0.616	1.166	2.375	0.864	0.661	0.345
UK	2.300	0.376	1.458	1.820	0.970	0.743	0.967

Table 13 The recoverable excess heat potential per country and industry, 2017, using method 1

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METHOD 2 Recoverable Excess Heat Potential Country and Industry Totals 2017 (TWh)							
Country	Iron & Steel	Non-ferrous Metals	Chemical & Petro-chemical	Non-metallic Minerals	Food & Beverage & Tobacco	Paper, Pulp and Printing	Other
Belgium	1.899	0.179	2.399	0.991	0.335	0.395	0.713
Italy	3.383	0.398	2.180	3.121	0.627	1.221	3.858
Portugal	0.136	0.017	0.238	0.836	0.100	0.752	0.413
Romania	1.014	0.166	0.793	0.756	0.127	0.091	0.783
Spain	2.430	0.649	1.745	2.513	0.556	0.942	2.273
UK	1.814	0.363	2.001	1.765	0.572	0.970	6.030

Table 14 The recoverable waste heat potential per country and industry, 2017, using method 2

Waste-to-energy facilities in Portugal and Belgium

As waste-to-energy plants, which LIPOR and ISVAG demo sites belong to, were not included in the excess heat potential assessment done in D1.2 in SO WHAT, numbers have been gathered from the STRATEGO project [55]. The analysis was made on data mainly from 2011 when Portugal had 2 facilities and Belgium 16 facilities.. According to CEWEP the numbers of waste-to-energy facilities in 2017 have increased to 4 in Portugal and 17 in Belgium [72], so using the 2011 estimate will give a conservative result for the excess heat potential from waste-to-energy plants. To be classified as an "energy recovery" (R1) activity facility the WTE facility needs to attain a certain level of efficiency [73]. If this level is not achieved the facility is categorized as a "waste disposal" activity (D10). Achieving the R1 efficiency factor is more viable if having cogeneration compared to electricity only. The waste-to-energy plants included in the STRATEGO assessment were R1 plants meaning that heat only plants may have been excluded, hence the potential is even more conservatively estimated.

The conservatively estimated potentials from the STRATEGO project:

- Portugal excess heat potential from waste-to-energy plants 2.78 TWh.
- Belgium excess heat potential from waste-to-energy plants 4.72 TWh.

District heating networks in Romania

District heating networks as the one in Constanta, Romania, were also excluded from the excess heat potential assessment in SO WHAT D1.2. In order to scale up the result of the Romanian demo site, where the focus of the analysis is RES integration in district heating systems, the amount of natural gas fired CHP district heating systems was used. In 2015 Romania the district heating production amounted to roughly 22 TWh/year [56]. In 2014, 94% of the heat in the district heating systems came from heat only boilers [57]. The main share of energy used in the district heating system in 2015 was natural gas with 80%. Given the large share of heat only boilers in the district heating systems, it is assumed that natural gas was 80% of the fuel for heat only boilers. To scale up the result for RES integration, it is assumed that 1% of these natural gas, heat only boiler district energy systems were substituted to RES.

With the assumptions above:

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- The potential energy from RES in Romanian natural gas fueled district heating system is 0,17 TWh.

Formula for upscaling

To calculate the potential welfare effect in each country and industry sector the following input was used:

- The industrial excess/RES heat production of the individual demo site, P_{demo} *[TWh]*
- The welfare effect of the individual demo site for the preferred scenario, W_{demo} *[€]*
- The industrial excess/RES heat potential of the industry sector and country, $P_{sector,country}$ *[TWh]*

To calculate the welfare effect for each sector and country, $W_{sector,country}$, the following formula was used:

$$W_{sector,country} = \frac{W_{demo}}{P_{demo}} P_{sector,country}$$

Finally, the welfare effect for each demo site country, $CB_{sector,country}$, was obtained by summarizing the result for all sectors:

$$W_{country} = \sum W_{sector,country}$$

Calculations for upscaling

Method 1

Demo site	Country	Wdemo [M€]	Pdemo [MWh]	Psector,country [TWh]	Wsector, country [M€]
Umicore	Belgium	-	-	0.433	0
Imerys	Belgium	11.6	16,700	4.087	2842.8
ISVAG	Belgium	89.1	82,703	4.72	5082.6
Martini&Rossi	Italy	2.5	1,848	1.229	1692.1
Lipor	Portugal	21.5	19,200	2.78	3109.0
Petromidia	Romania	1.0	15,215	0.484	31.3
RADET	Romania	222.7	8,668	0.17	4367.7
Ence	Spain	40.6	29,487	0.661	910.3

Method 2

Demo site	Country	Wdemo [M€]	Pdemo [MWh]	Psector,country [TWh]	Wsector, country [M€]
Umicore	Belgium	-	-	0.179	0
Imerys	Belgium	11.6	16,700	2.399	1668.7
ISVAG	Belgium	89.1	82,703	4.72	5082.6
Martini&Rossi	Italy	2.5	1,848	0.627	863.3
Lipor Maia	Portugal	21.5	19,200	2.78	3109.0
Petromidia	Romania	1.0	15,215	0.793	51.2

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Radet	Romania	222.7	8,668	0.17	4367.7
Ence	Spain	40.6	29,487	0.942	1297.3

Country	Wcountry, Method 1 [M€]	Wcountry, Method 2 [M€]
Belgium	7925	6751
Italy	1692	863
Portugal	3109	3109
Romania	4399	4419
Spain	910	1297

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Appendix IV
RES potential and scenarios

The value of coupling renewables and industrial excess heat and cold

In the last years one of the main topics involved in almost all the human activities is environmental pollution, and in particular, the necessity to reduce the GHG emissions. As reported in [74] and [75], the EU goal for 2020 was to achieve a 20% of reduction of GHG emission in relation to the level of the 1990. The future goals are to reach in 2030 a reduction target of 40% from the 1990 levels, and to meet the 95% in 2050, see Figure 39.

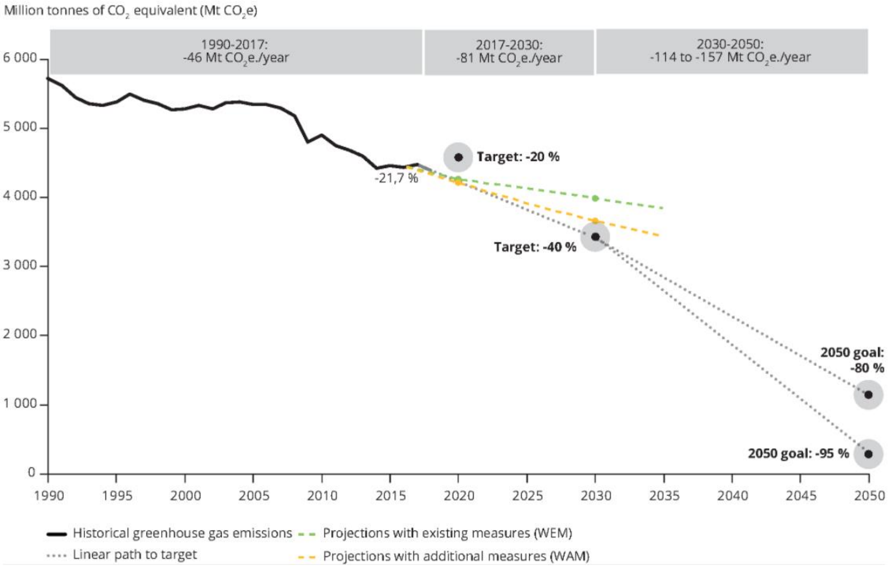

Figure 39 Greenhouses gas emission trend projection and target [75]

One of the strategies that can be adopted to reach this goal is increasing the exploitation of the renewable energy sources [74]. The goal is to reach the 20% share of energy from renewable sources by 2020 [76]; in 2018 this percentage was 18% and the target was not achieved yet principally because of the increasing energy consumption [77]. The future aims are the 27% share of RES consumption by 2030, and a level between 55% and 75% by 2050, see Figure 40.

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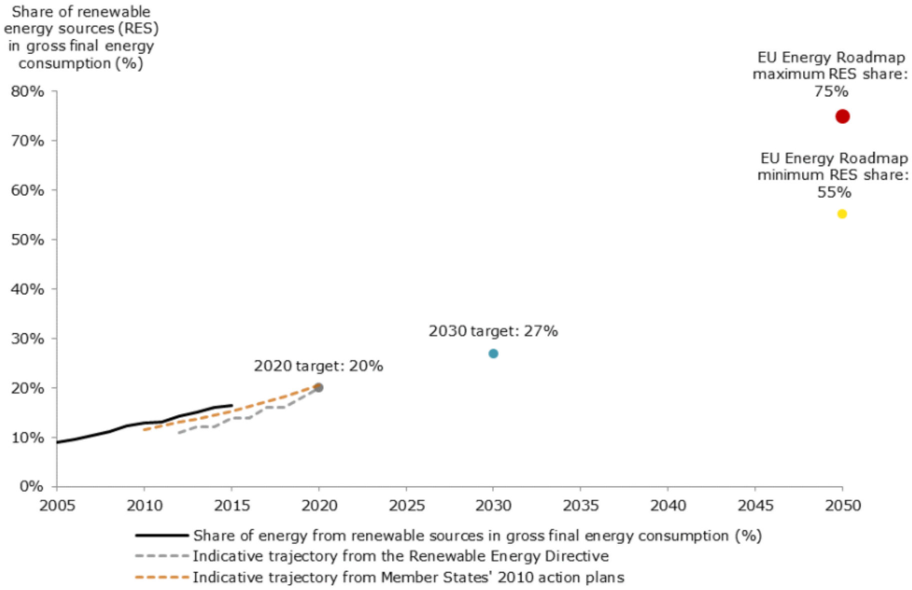

Figure 40 Share of energy from renewable sources in EU's gross final energy consumption, 2005-2050

Even if the share of renewable energy has doubled since 2005 [77], policy effort and investments would be required in the short term to obtain a higher penetration of RES. In an economic point of view, complex and uncertain factors are at play; relatively low-priced RES development options are becoming scarcer as the easiest and least expensive options are gradually being exploited. However, at the same time, the cost for new RES capacity is being reduced through economies of scale, better knowledge integration and increasing experience. Moreover, the increase of the renewable energy technologies installations is strongly affected by policies, incentives and feed-in tariffs in the European countries [78]. The CBA analysis could be one of the methods to reduce the uncertainty about the investments and to estimate the revenues about specific scenarios in which the integration of different technologies is evaluated.

Considering the electricity production, one of the greater challenges is the management of fluctuating production caused by renewable energy technologies [79]. Now more than ever, coordination between local and national grids or between grids of different countries is required in order to guarantee the energy supply and infrastructure investments are required to allow for higher levels of RES penetration. However, to allow the local exploitation of RES the distribution grids need also to become smarter to deal with variable generation from different types of distributed sources (e.g. solar photovoltaic and small wind applications) and variable consumption by different technologies, to increase demand response velocity and to add storage systems that allow mismatch between use and production of renewable energy. In this project, the coupling between excess heat and cold technologies and electrical RES is evaluated. This solution can lead to the increase of local consumption of electrical energy produced by renewable technologies and, simultaneously, the decrease of the electrical consumption from the national grid. These two aspects are both relevant for the European goals about the environmental pollution reduction. Indeed, the local consumption allows to increase the overall distribution efficiency avoiding the losses associated with the energy transport. Moreover, the reduction of the national grid energy consumption is directly linked to a CO_2 reduction considering that the electrical energy deriving from the grid is characterized by an emission

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factor not equal to zero and dependent on the national energy mix that includes also no carbon free technologies.

RES potential estimation

The renewable energy sources can be differentiated between the thermal RES and the electrical RES. The thermal RES are the sources that are employed to produce heat and, in this project, are considered solar thermal, biomass and geothermal energy sources. The biomass and the geothermal energy sources are further distinguished in two types: the first one is divided by the origin of the biomass, from forestry or from agriculture, and the second one by the depth reached by the drilling activities, shallow or deep geothermal. The electrical RES are sources that are employed to be directly converted in electrical energy and, in this project, are considered solar radiation and wind; the technologies considered that allow this direct conversion are the photovoltaic panels and the wind turbines.

For each one of the two categories of RES described above, the physical/geographical potential and the technical potential can be estimated. The physical/geographical potential is the estimation of the energy, or power, available on a geo-referred site (that is a site identified by geographical coordinates) without considering the characteristics of the technologies that use the source (e.g. the solar panel efficiency about the solar radiation). Instead, the technical potential is evaluated considering the physical/geographical potential evaluation and applying technical parameters and technologies operative range that affect the possibility to exploit an energy source completely (for example the boiler efficiency).

Physical/Geographical potential estimation

In this project the estimation of the physical/geographical potential has been carried out employing two tools.

The first one is Planheat, see Figure 41, an open source software developed in an EU funded project. In this case a tool specific functionality (named SMM, Supply Mapping Module) has been used in order to detect the potential of different energy sources in a geo-referenced location of interest. In the following evaluations this tool has allowed to identify biomass and geothermal potentials in a buffer area around the location of interest of 20km radius, see Figure 42.

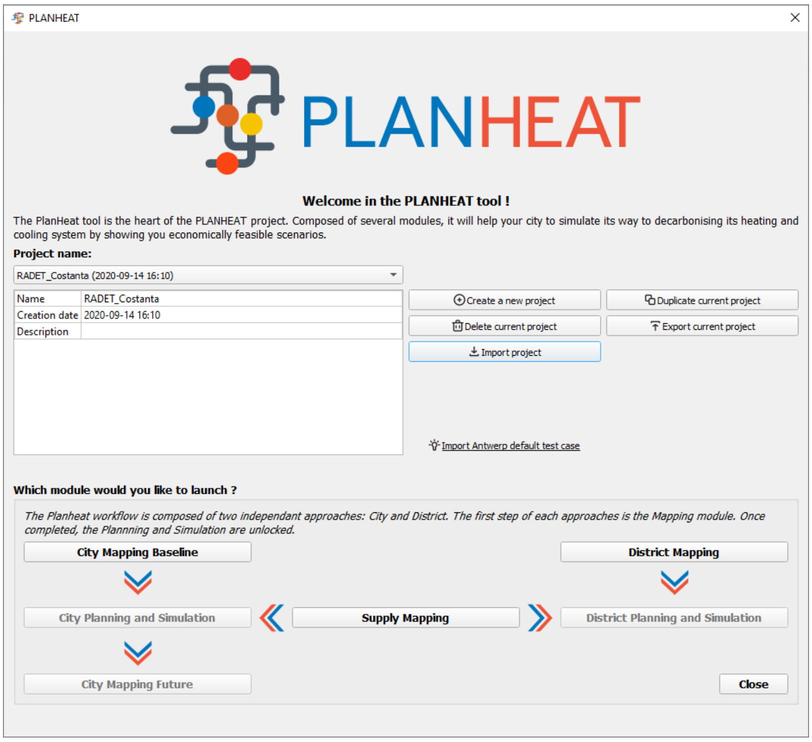

Figure 41 Planheat tool's starting dialog window

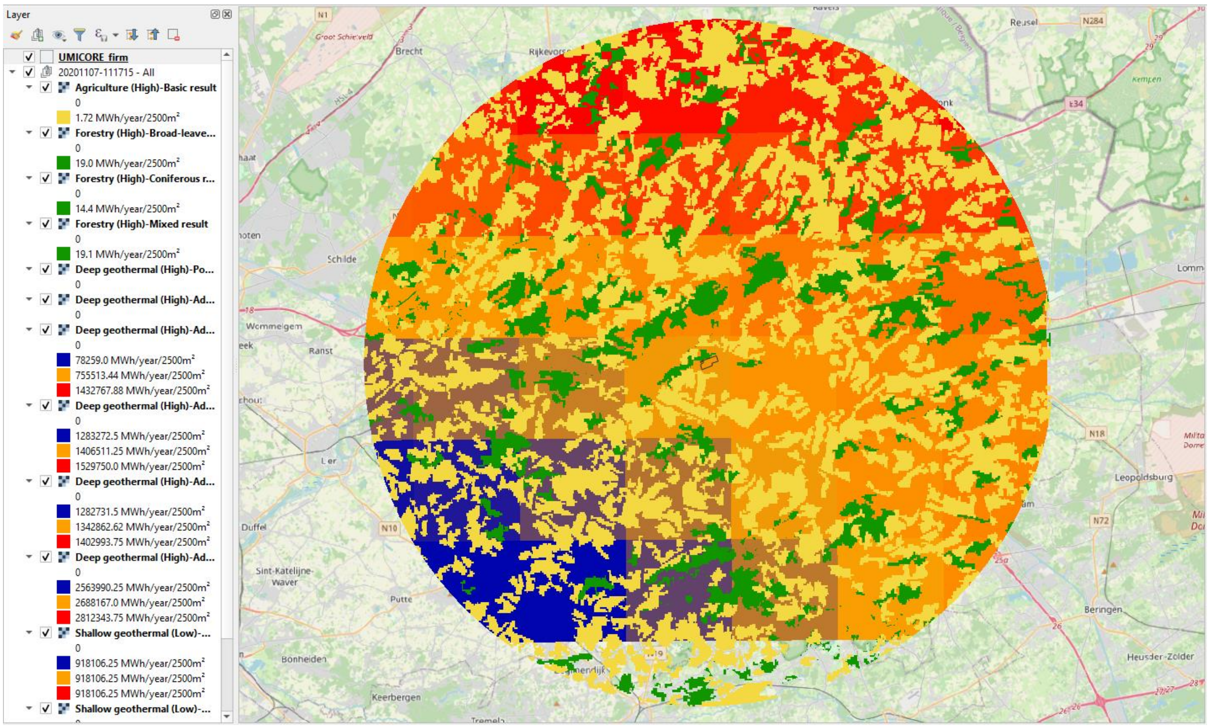

Figure 42 Buffer area (simulation of Umicore demo site)

The second tool is PVGIS, an open source web tool developed by JRC that gives information about meteorological conditions of a specific geo-referenced location. The data about the meteorological

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conditions are available for many territories above the sea level and can be downloaded in formats that allow to visualize, during a single year, a monthly or an hourly variation. Moreover, the value of the solar radiation can be obtained for a horizontal or an optimally inclined plane (considering the slope angle). This tool has been used to determine the solar radiation level and the wind speed for each demo site. To evaluate the physical/geographical potential of solar thermal and photovoltaics panels the monthly distribution data of irradiance has been derived from PVGIS and the following equation has been used:

$$E_{pot,solar} = \sum_{i=1}^{12} Ir_i$$

Where:

- $\mathrm{E_{pot,solar}}$ is the annual physical/geographical potential of solar energy on a single square meter of surface [kWh/(m² yr)];
- Ir is the month long total solar irradiance on optimally incline flat plane [kWh/ M²].

To evaluate the wind physical/geographical potential the hourly wind speed distribution has been derived from PVGIS and the following equation has been used:

$$P_h = \sum_{i=1}^{8760} \frac{1}{2}\,\rho\, {w_i}^3$$

Where:

- P_h is the annual potential power for a single square meter of area sweeping by the aerogenerator [W/(yr m²)];
- ρ is the air density [kg/ M³];
- w_i is the wind speed [m/s].

Technical potential estimation

In order to calculate the technical potential, specific technologies parameters have to be applied to the physical/geographical potential. It is important here to highlight that, for the scope of the CBA, an estimation of the technical potential using averaged parameter has been performed. The SOWHAT tool instead could perform in Manufacturing, Community and Decision Support Modules more detailed calculations in line with the scopes of the evaluation of waste heat potentials.

The technology that in most cases could be used to exploit the biomass potentiality is the boiler. For this device the parameter considered is only the efficiency; the biomass boiler efficiency of conversion from fuel to heat is quite high (rising up to 95% for 5 stars class boilers) and not strongly dependent from the size of the installation.

To exploit the geothermal potential, in particular shallow geothermal (characterized by low temperature of the ground), heat pumps can be employed. The typical parameter of this device, the coefficient of performance (COP), it is strongly dependent on both the source and the sink temperatures as well as to the size of the device. In the following discussion the COP is assumed to not be influenced by temperature variations over the year, and its value derives from tables reported in [68] and assumed to be equal to the seasonal value.

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The solar irradiance can be exploited both by solar and photovoltaic panels. For these technologies the characteristic parameters are the efficiency of converting solar irradiance to heat or electricity, that is strongly affected by the type of technology and the available area. For the solar thermal panels, the efficiency has been imposed to the reference value of 45% (considering evacuated solar tube collectors that allows to reach high fluid vector temperature), while for the photovoltaic panels it has been set to 17% [21].

The typical parameters of a wind turbine are the power coefficient (C_p), the operative wind speed range, and the dimensions. The C_p is the ratio between the maximum power that a wind turbine can produce and the whole available power from the wind; its maximum theorical value is equal to 0,593 [80], however in reality it is lower and strongly dependent on the generator type. The selection of the wind turbine type influences also the other two parameters. The wind speed range is limited by a lower value, the cut-in wind speed (typically assumed equal to 4 m/s [21].), and a higher value, the cut-off wind speed (typically assumed equal to 25 m/s [21]). The physical dimensions of the installation are the height of the hub and the rotor diameter; the first one influences the wind speed perceived by the aerogenerator, while the second one conditions the total amount of energy that is available for the conversion. In order to take into account the hub height dependency, the following equation has been used because PVGIS wind speed data are available only at a reference height (z_0) equal to 10m [81]:

$$w_z = w_0 \frac{log\left(\frac{z}{z_\alpha}\right)}{log\left(\frac{z_0}{z_\alpha}\right)}$$

Where:

- w_z is the wind speed at a set specific height z [m/s];
- w_0 is the wind speed at z_0 [m/s]
- z_α is the roughness length of a specific demo site [-] (available in PVGIS data).

Moreover, the orientation of the generators are assumed variable in order to follow the wind direction.

RES limitations and assumptions

Method: The method used to evaluate the technical potential does not take into account the possibility of the variation of some technical parameter with the operative conditions, e.g. the dependency on the wind speed of the power coefficient of an generator or the difference of the heat pump COP during the year due to the temperature variation of the sources.

PVGIS database [82]**:** The global solar radiation and the wind speed data are estimated using the geostationary meteorological satellites measurements and, to estimate the value of the parameter at the ground level, complicate mathematical algorithms, that could be affected by accuracy losses in some conditions (e.g. the presence of snow).

Technical and economic parameters: In most cases the technical and economic data, e.g. heat pumps COP or the photovoltaic panels fixed operational cost, are not referred to a specific device but

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they have been assumed or derived from tables created analyzing in a statistic way the parameters of many different devices on market (i.e. [21] and [68]).

Available area: In the demo sites in which the installation of the photovoltaic panels has been evaluated the available area was unknown, so its value has been assumed as result imposing the electrical production equal to the auxiliaries consumption of the thermal technologies taken into account in the different plants.

RES geographical potential

The evaluation of the RES potentials has been done, using the methods explained in Chapter 0, for biomass (agriculture and forestry), geothermal (deep and shallow), solar and wind potential. The results have been used to identify the sources that could lead to an economical advantage, in addiction to emission reduction. The choice of the sources has been done to determine the technologies for the different scenarios listed in the sensitivity analysis of this report. The decisions have been based on the comparison of physical/geographical and technical potential values and the already done investments on the different sites, besides the specific information and requests received from the demo site representative. This analysis has been carried out also with the purpose to point out the availability of sources that the demo sites have not yet considered for a future exploitation.

RES geographical potential RADET

The RES potential values obtained from the analysis of this demo site are the following (for each source the physical potential is reported except for the wind potential, where an operative wind speed range between 4 and 25m/s and a reference height value of 30m were imposed):

- Forestry biomasses: 30,915 MWh/yr;
- Agriculture biomasses: 475,014 MWh/yr;
- Deep geothermal:
  - Depth from 2 to 3 km (60-70°C): 2,147 MWh/yr;
  - Depth from 3 to 4 km (70-100°C): 879,392 MWh/yr;
  - Depth from 4 to 5 km (100-150°C): 882,663 MWh/yr;
  - Depth from 5 to 7 km (150-200°C): 1,765,365 MWh/yr;
- Shallow geothermal: 917,201 MWh/yr;
- Solar irradiance: 1,578 kWh/(yr m^2);
- Wind: 2,117 kWh/(yr m^2).

For the RADET demo site forestry biomass potential is not so high compared to the agriculture potential. However, considering the high cost of the land around Constanta (information provided by demo responsible), solutions that include the use of local biomasses were disregarded.

The geothermal sources were disregarded because of high investment cost and possible restrictions for the installation.

The solar irradiance is considered a relevant source by RADET; indeed, installation of solar thermal panels was already considered. In order to satisfy the electrical demand of the auxiliaries of the technology installed, the installation of photovoltaic panels has been evaluated and added to the possible scenarios.

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In this case, also the wind energy potential is remarkable. The number of hours in which the wind speed is in the operative range is 6,771 hours. RADET showed interest in this source, therefore the integration between water source heat pumps and small wind turbines could be investigated.

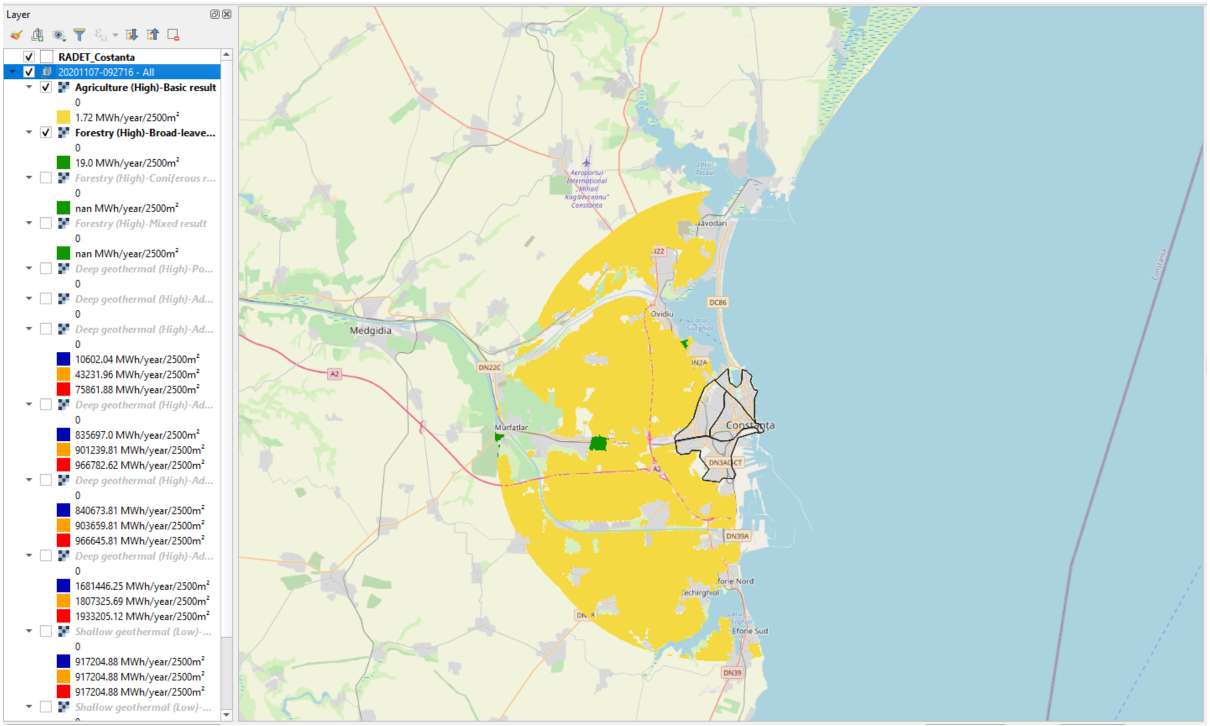

Figure 43 Planheat view about forestry (green areas) and agriculture (yellow areas) biomasses potential for RADET

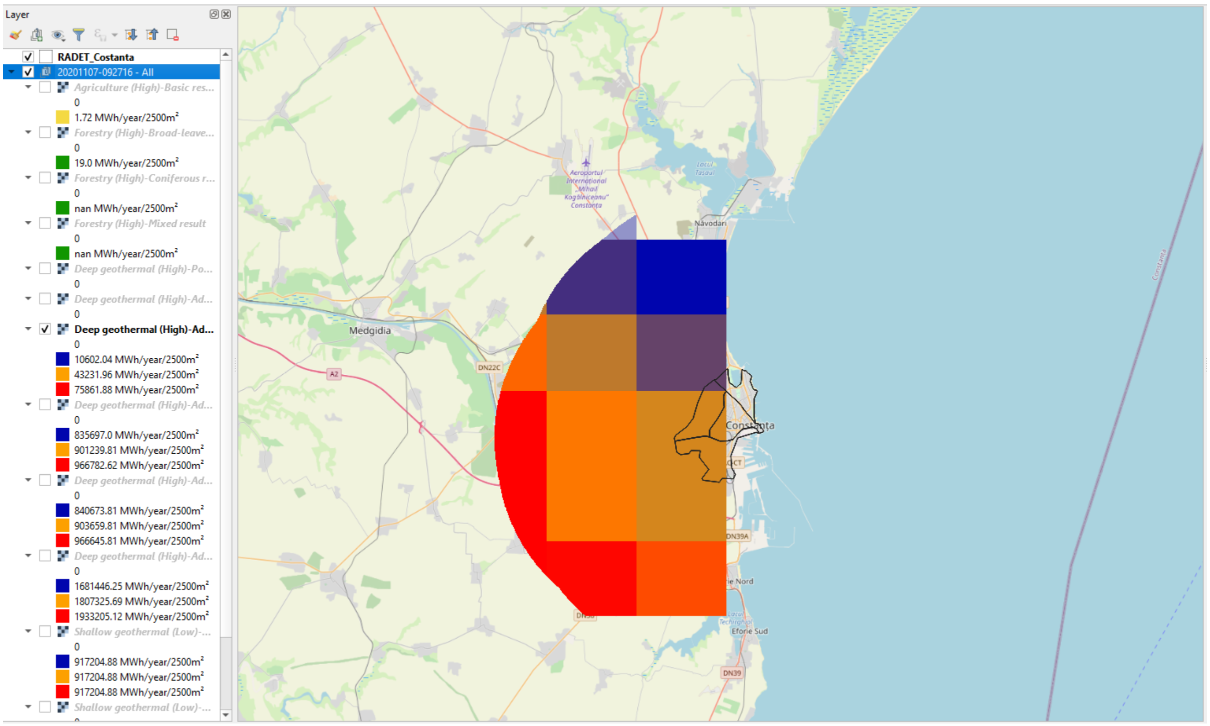

Figure 44 Planheat view about deep geothermal potential (depth from 2 to 3 km) for RADET

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RES geographical potential LIPOR

The RES potential values obtained from the analysis of this demo site are the following (for each source the physical potential is reported except for the wind potential, where an operative wind speed range between 4 and 25m/s and a reference height value of 30m were imposed):

- Forestry biomasses: 1,339,254MWh/yr;
- Agriculture biomasses: 213,951MWh/yr;
- Deep geothermal:
  - Depth from 2 to 3 km (60-90°C): 313,531MWh/yr;
  - Depth from 3 to 4 km (90-150°C): 1,222,220MWh/yr;
  - Depth from 4 to 5 km (150-200°C): 1,221,770MWh/yr;
  - Depth from 5 to 7 km (200-250°C): 2,441,837MWh/yr;
- Shallow geothermal: 1,834,706MWh/yr;
- Solar irradiance: 1,797 kWh/(yr m^2);
- Wind: 1,172 kWh/(yr m^2).

The biomass potential, in particular forestry biomass, is considerable. In this case LIPOR was not aware of this possibility and further analysis will be done in order to identify the real exploitation.

The geothermal potentials, specifically the shallow geothermal and the deep geothermal at depths from 3 to 7km, are remarkable. The firm has already started to do a feasibility analysis, mainly regarding the chance to obtain the authorization for soil exploitation, however precise results have not been achieved yet.

The interest about solar irradiance exploitation is high also in this case, mainly due to some government incentives. The presence of photovoltaic panels is considered in one of the scenarios in the sensitivity analysis where their installation has been considered to satisfy the electrical demands of other technologies and to reduce the electrical consumption of energy from the national grid.

About the wind potential, it is lower than the values obtained on Umicore and RADET demo sites and, even if the wind speed remains in the operative range for many hours during the year (5234h), there is no interest about the exploitation of this source for now.

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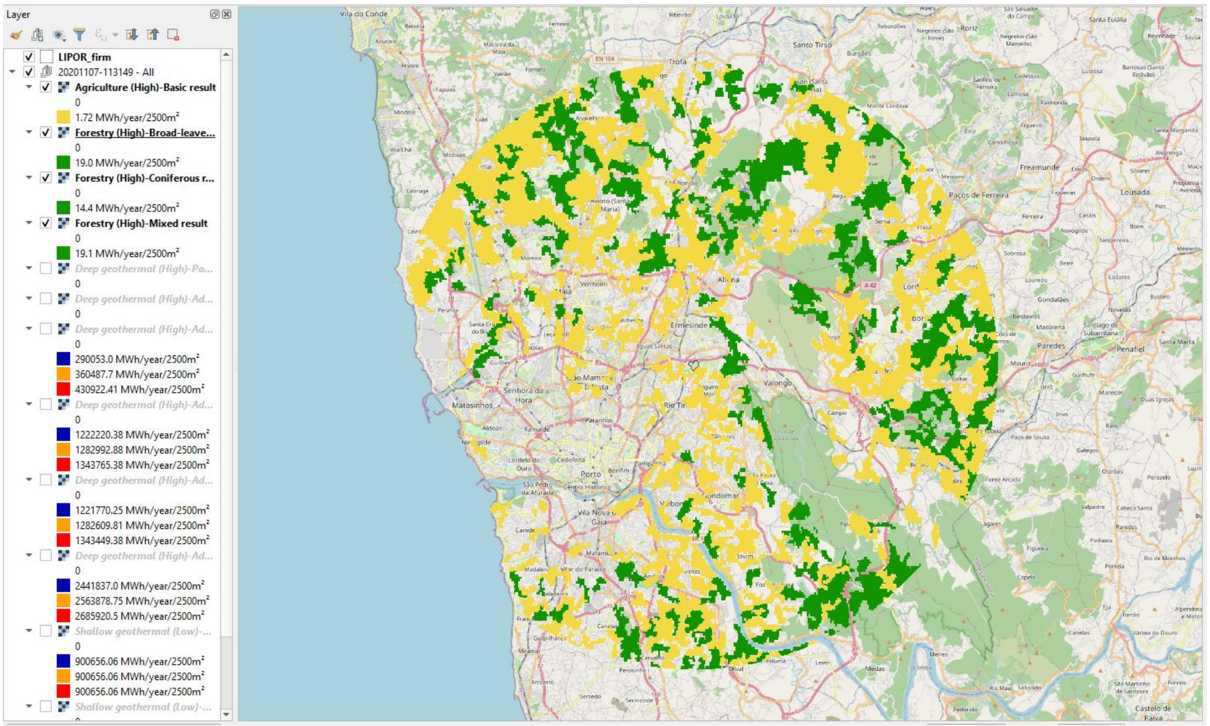

Figure 45 Planheat view about forestry (green areas) and agriculture (yellow areas) biomasses potential for Lipor demo site

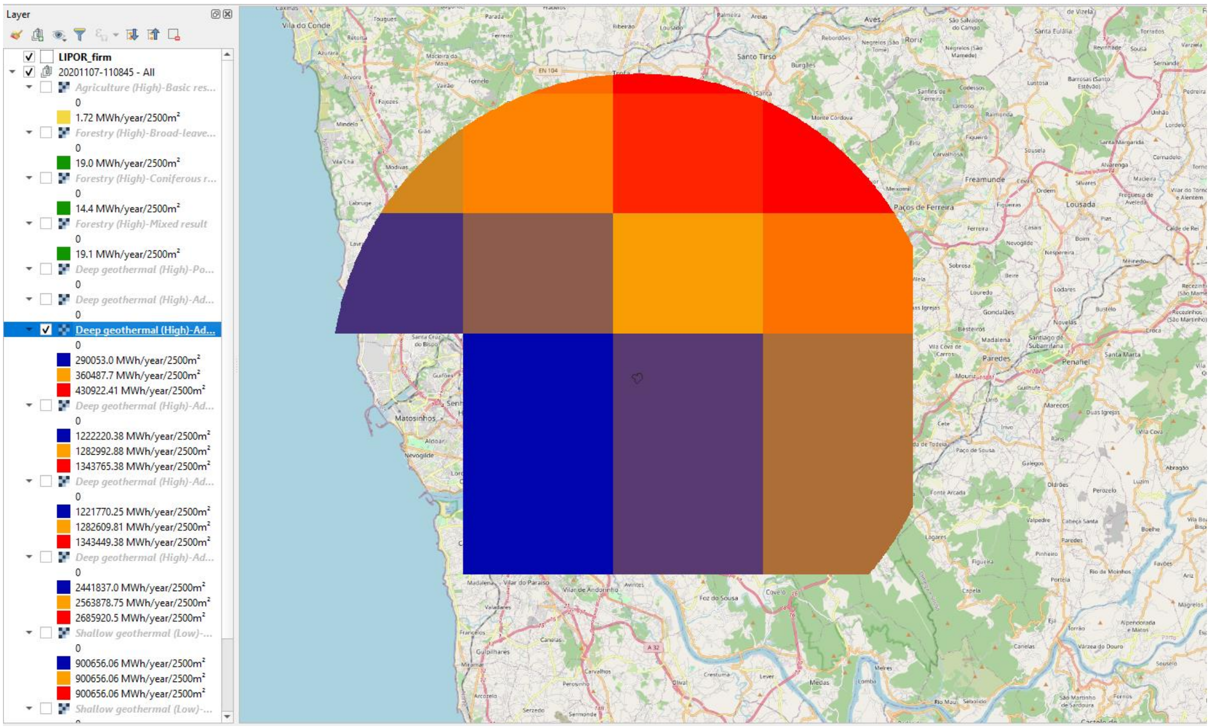

Figure 46 Planheat view about deep geothermal potential (depth from 2 to 3 km) for Lipor demo site

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RES geographical potential UMICORE

The RES potential values obtained from the analysis of this demo site are the following (for each source the physical potential is reported except for the wind potential, where an operative wind speed range between 4 and 25m/s and a reference height value of 30m were imposed):

- Forestry biomasses: 908,800MWh/yr;
- Agriculture biomasses: 317,493MWh/yr;
- Deep geothermal:
  - Depth from 2 to 3 km (40-70°C): 722,307MWh/yr;
  - Depth from 3 to 4 km (70-100°C): 1,428,148MWh/yr;
  - Depth from 4 to 5 km (100-150°C): 1,321,154MWh/yr;
  - Depth from 5 to 7 km (150-200°C): 2,640,155MWh/yr;
- Shallow geothermal: 1,834,649MWh/yr;
- Solar irradiance: 1408 kWh/(yr m^2);
- Wind: 2,277 kWh/(yr m^2).

In this case, even if the potentials are quite high for each source the main interest was to include in a CBA scenario the installation of wind turbines. On this site, three wind generators have already been installed and the project is to add two other wind turbines in the next future. This energetic strategy find support in the considerable wind potential value and in the high number of hours in which the wind speed stays in the operative range (6126h during the year).

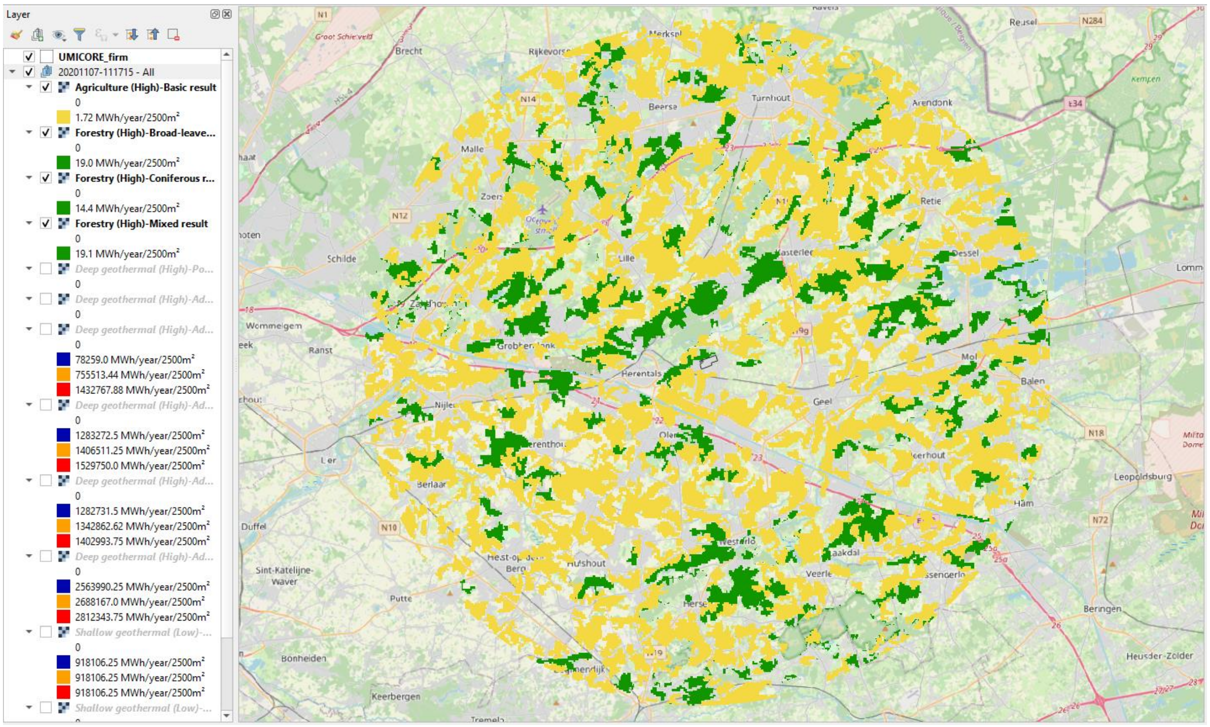

Figure 47 Planheat view about forestry (green areas) and agriculture (yellow areas) biomasses potential for Umicore

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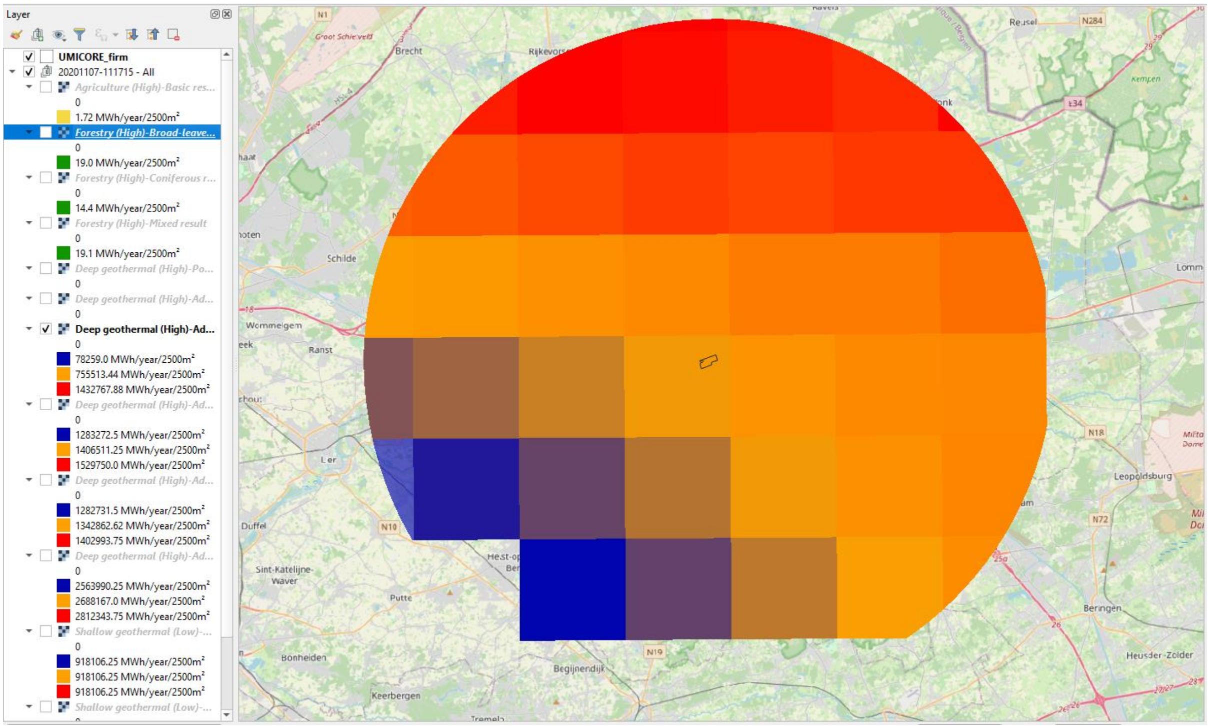

Figure 48 Planheat view about deep geothermal potential (depth from 2 to 3 km) for Umicore

RES scenarios

Based on the assessment of the demo site RES potential a couple of scenarios have been developed. The buildings bricks of these scenarios are similar to the scenarios developed for the industrial excess heat recovery, but also include the production of electricity. Some of these scenarios have been used for making a sensitivity analysis on the impact of RES integrated with industrial waste heat, with some small adjustments, while the others provide valuable information for the demo sites but also for the future development of the SO WHAT tool.

RADET RES Scenario 1

In scenario 2 photovoltaic panels are added in order to satisfy the electrical demand of biomass pellet boilers and solar thermal collectors already considered in scenario 1. For this reason, the investment year is considered the same.

Scenario assumptions:

- The boilers and solar thermal panels annual electrical demand is estimated to be approximately 171 MWh (considering the data about the electricity demand per MWh of heat generated that are reported in scenario 1).
- The investment cost of the photovoltaic panels is assumed to be 800€/kW [21].
- The fixed operation and maintenance cost of the photovoltaic panels is assumed to be 9.5€/kW [21].
- The efficiency is assumed to be equal to 17% [21].
- The area covered by the panels is equal to 635m².

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- The installation size, assuming the peak irradiance equal to 1,000W/ M^2, is approximatively 108kW.

RADET RES Scenario 2

In scenario 3 the heat produced by the natural gas heat only boilers (8,868 MWh annually) is replaced by the heat from heat pumps. In this scenario the heat pumps source is the sea water and the electrical consumption is satisfied adding some small wind turbines. The investment year is considered, for both the technologies, the same for the scenario 1 because the heat pumps are assumed to be an alternative to the installation of boilers and solar thermal panels. This scenario has not been studied in the CBA analysis but only in the sensitivity analysis in Chapter 5.

Scenario assumptions:

- The investment cost of the water source heat pumps is assumed to be 1100€/kW [21].
- The fixed operation and maintenance cost of the water source heat pumps is assumed to be 1% of the investment costs (1100 €/kW of thermal energy) [21].
- The coefficient of prestation (COP) of the water source heat pumps is imposed equal to 3 [21].
- The investment cost of the wind turbines is assumed to be 3000€/kW [21].
- The fixed operation and maintenance cost of the wind turbines is assumed to be 100€/kW [21].
- The power coefficient of a single small wind turbine is assumed to be 0,3 [80].
- It is supposed to install 66 wind turbines in order to have a power peak (evaluate with wind speed equal to 13m/s) approximately around 300kW (more or less 1/3 of the heat pumps' power).

RADET RES Scenario 3

Also in scenario 3 the heat produced by the natural gas heat only boilers (8,868 MWh annually) is replaced by heat from heat pumps, however, in this scenario the heat pumps source is the ground. Also in this case the electrical consumption is satisfied by adding some small wind turbines. The investment year is considered, for both the technologies, the same for the scenario 1 because the heat pumps are assumed to be an alternative to the installation of boilers and solar thermal panels. This scenario has not been studied in the CBA analysis but only in the sensitivity analysis in Chapter 5.

Scenario assumptions:

- The investment cost of the ground source heat pumps is assumed to be 655€/kW) [21].
- The fixed operation and maintenance cost of the ground source heat pumps is assumed to be 2% of the investment costs (655 €/kW of thermal energy) [21].
- The coefficient of prestation (COP) of the ground source heat pumps is imposed equal to 3.8 [21].
- The assumptions for the wind turbines are the same of the scenario 2.

LIPOR RES Scenario 1

The technologies applied in scenario 2 are the same used in scenario 1, however, in this case photovoltaic panels are installed to supply the electrical energy consumed by the airport's absorption chillers. The investment year of the PV panels is considered the same of the technologies used in scenario 1.

Scenario assumptions:

- The investment cost of the photovoltaic panels is assumed to be 800€/kW [21].
- The fixed operation and maintenance cost of the photovoltaic panels is assumed to be 9.5€/kW [21].
- The annual electrical energy that the photovoltaics panels should produce is evaluate considering the electrical consumption for a single absorption chiller equal to 130,32 MWh (datum provided by Lipor).
- The efficiency is assumed to be equal to 17% [21].
- The area covered by the panels is equal to 1280m^2.
- The installation size, assuming the peak irradiance equal to 1,000W/ M^2, is approximatively 218kW.

LIPOR RES Scenario 2

The technologies applied in scenario 3 are the same that are used in scenario 2, however, in this case the photovoltaic panels are used to supply electrical energy both for the absorption chillers installed at the airport and the pumps of the hydraulic heat network. Also for this scenario the investment year of the PV panels is considered the same of the technologies present in scenario 1.

Scenario assumptions:

- The investment cost is assumed to be 800€/kW [21].
- The fixed operation and maintenance cost of the photovoltaic panels is assumed to be 9.5€/kW [21].
- The annual electrical energy that the photovoltaics panels should supply is evaluate adding up the thermal energy produced by the heat pumps divided by the related COP (assumed equal to 3.6 [68]) and the electrical consumption of the absorption chillers.
- The efficiency is assumed to be equal to 17% [21].
- The area covered by the panels is equal to 2,565m^2.
- The installation size, assuming the peak irradiance equal to 1,000W/ M^2, is approximatively 441kW.

UMICORE RES Scenario 1

In scenario 2 the installation of two wind turbines, each one with a 3,450kW rated power, is taken into account in order to increase the amount of electrical energy produced by renewable energy sources (indeed three wind turbines has been already installed on site) and, at the same time, reduce the consumption from the national grid. The investment year is considered the same of the technologies in scenario 1.

Scenario assumptions:

- The investment cost of the wind turbines is assumed to be 1900€/kW, given by the demo site representative.

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- The fixed operation and maintenance cost of the wind turbines is assumed to be 14€/kW and the variable 1.4 €/ MWh [21].
- The hub height is 116,5m and the rotor diameter is 117m [83].
- The rated power of the wind turbines type considered for this site is 3,450kW and wind speed used to evaluate it is 11,5m/s [83].

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