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Sun coupled innovative Heat pumps

D7.2 – SunHorizon Technologies benefit impact in terms of emissions

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Table of Contents

Abbreviations

ARP	Alpha RiskPoll (model)
BH	BoostHeat, Industrial partner of the project
CH_4	Methane
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO_2	Carbon dioxide
DHW	Domestic Heat Water
DS	Dual Sun, Industrial partner of the project
EF	Emission factor
EMEP	European Monitoring and Evaluation Programme
FAHR	Fahrenheit, Industrial partner of the project
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies (model)
GDP	Gross Domestic Product
GHG	Greenhouse gas
GRE	Industrial partner of the project
H&C	Heating and Cooling
HP	Heat Pumps
ISO	International Standard Organisation
LCA	Life-cycle Assessment
MSC-W	Meteorological Synthesizing Centre West
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
OECD	Organisation for Economic Cooperation and Development
$PM_{2.5}$	Fine particulate matter (particles with diameter <5 μm)
PV	Photovoltaic (panel)
PV-T	Combined panel that operates simultaneously as a Photovoltaic panel and a solar thermal panel
RAINS	Regional Air Pollution Information and Simulation (model)
RTU	Ratiotherm, Industrial partner of the project
SLCP	Short-lived climate pollutants
SO_2	Sulphur dioxide
TP	Technology package
TVP	Industrial partner of the project
UNECE	United Nations Economic Commission for Europe
VOLY	Value Of Life Year lost
VSL	Value of Statistical Life

Executive summary

Deliverable *D7.2 SunHorizon technologies benefit impact in terms of emissions* is part of the EU-financed project *Sun coupled innovative Heat pumps.* The overall aim of the project is to demonstrate up to TRL 7 innovative and reliable Heat Pump solutions (thermal compression, adsorption, reversible) that acting properly coupled and managed with advanced solar panels (PV, hybrid, thermal) can provide heating and cooling (H&C) to residential and tertiary buildings with lower emissions, energy bills and fossil fuel dependency. The aims of task 7.1, presented in the deliverable, are:

- To investigate environmental performance of SunHorizon technologies and technology packages (TP) in the life-cycle perspective,
- To estimate monetized health and climate benefits from implementation of SunHorizon technologies.

Life-cycle assessment LCA is focused on the environmental impacts of SunHorizon technologies installed at the demonstration sites (SunHorizon scenarios, developed separately for each site), compared to the corresponding impacts in the baseline scenario for each demonstration site (baseline means business as usual, i.e. existing H&C technologies are used in the buildings, no new, SunHorizon technologies are installed). The analysis considers environmental impacts such as global warming, ozone depletion, fossil abiotic depletion, photochemical ozone creation, acidification and eutrophication.

The preliminary results of the LCA show as a general trend that the deployment of SunHorizon technologies has an environmental investment cost for the production and installation of equipment (solar panels, heat pumps, accumulation tanks), but this environmental cost is a trade-off, compensated by environmental benefits in the operational stage in most impact categories. For all technology packages, the scenario where SunHorizon technologies are deployed, results in higher impacts for abiotic depletion of resources and lower impacts for global warming, ozone depletion, fossil abiotic depletion and photochemical ozone creation. Meanwhile, acidification and eutrophication result in lower impacts for all technology packages except TP1.

General conclusions from the LCA should not be drawn yet, since key data for operation, maintenance and end-of-life is missing at the time of writing (M26). Still, key aspects have been identified for SH technologies to achieve optimal environmental results: a high share of renewables in the electricity mix, an end-of-life scenario with a high recycling rate, and an extended service life.

Interim results of the LCA are life-cycle emission factors for main air pollutants (NO_x, SO_2, NH_3, NMVOC and $PM_{2.5}$) and greenhouse gases (CO_2, CH_4) emitted by technologies aggregated in SunHorizon technology packages – TP1, TP2 and TP3[1]. These emission factors serve as input data to the analysis of monetized health and climate benefits from implementation of SunHorizon technologies.

Health and climate benefits from implementation of SunHorizon technologies are estimated for target years 2030 and 2050 for three SunHorizon scenarios[2]:

1. SunHorizon technology package 1 (*SH_TP1*);
2. SunHorizon technology package 2 (*SH_TP2*);
3. SunHorizon combo (*SH_c*), including TP1 and TP2.

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[1] For TP4 and TP5 no empirical data was available at the time of writing (M26), so these two technology packages were considered neither in the benefits assessment nor in LCA presented in the current version of D7.2. D7.2 will be updated with the final results no later than in M48.

[2] Both LCA and benefit assessment investigate SunHorizon and baseline scenarios: however, these two scenario sets are not directly linked to each other, they are developed separately at different levels and for different types of analysis. Baseline scenarios in both cases imply business as usual with no changes or new technologies deployed – but in the LCA, this situation is analyzed at the level of buildings for specific demo sites, while assessment of benefits considers the country level. The same applies to SunHorizon scenarios – in the LCA, demo-site specific technologies only are included in the analysis, while in the benefit assessment one can develop different country-level scenarios making assumptions about the deployment rates of different SunHorizon technology packages in each country in the chosen target years.

Baseline energy demands and SunHorizon technologies deployment rates are estimated based on the analysis presented in *D2.2. – Mapping of solar resource and building demand for SunHorizon implementation* (1). In each of the SunHorizon scenarios, it is assumed that a part of the conventional heating technologies in the residential and tertiary sector in the EU-28 is replaced by SunHorizon technologies combined in technology packages. In scenarios *SH_TP1* and *SH_TP2*, conventional technologies are replaced by TP1 and TP2, respectively, while in *SH_c* there is a combination consisting of 50% TP1 and 50% TP2.

Benefit assessment is conducted using impact pathway approach, following the steps *Source (Emissions) – Dispersion – Dose-Response function – Monetary valuation.* Emission calculations in each of the SunHorizon scenarios are done based on the emission factors (EFs) obtained from a life-cycle assessment (LCA) carried out for the technologies and technology packages deployed. Besides obtaining these emission factors, the goal of the LCA is to assess the environmental potential of SH and identify environmental hot spots. Primary data for the production of the equipment was collected from the partners, while real-life data for operation and installation was provided by demonstration sites. The CML method[3] was selected for impact assessment.

For most of the emitted substances included in the analysis, emission factors for SunHorizon technology packages are lower than for conventional H&C technologies, which results in emission decrease in SunHorizon scenarios, compared to the baseline development in 2030 and 2050. Lower emissions of main pollutants from SH technologies, compared to conventional technologies, result in lower concentrations of primary and secondary $PM_{2.5}$ and ground-level ozone, and, subsequently, in reduced negative health effects.

The total monetized health and climate benefits in EU-28 from implementation of SunHorizon technologies are presented in Table below. If monetized health effects in the entire Europe, including non-EU countries, are considered in the analysis, the total human health-related benefits become 6 – 7% higher than the numbers presented in Table below.

Table Summary. Total health and climate benefits in EU-28 from implementation of SunHorizon technologies in the residential and tertiary sector.

Impacts	Benefits in 2030, million €$_{2015}$			Benefits in 2050, million €$_{2015}$		
	SH_TP1	**SH_TP2**	**SH_c**	**SH_TP1**	**SH_TP2**	**SH_c**
Human Health, low	7 100	8 400	7 800	14 500	17 800	16 200
Human Health, mid	17 700	21 000	19 300	43 300	53 100	48 200
Human Health, high	41 600	49 300	45 500	103 000	126 100	114 500
Climate impact, low	2 400	2 500	2 450	6 000	6 200	6 100
Climate impact, mid	11 600	12 000	11 800	28 900	30 100	29 500
Climate impact, high	21 800	22 800	22 300	54 600	56 900	55 700
Total, low	**9 500**	**10 900**	**10 250**	**20 500**	**24 000**	**22 300**
Total, central	**29 300**	**33 000**	**31 100**	**72 200**	**83 200**	**77 700**
Total, high	**63 400**	**72 100**	**67 800**	**157 600**	**183 000**	**170 200**

Estimating country-specific benefits from implementation of SunHorizon technologies in the EU Members States, and expressing them in monetary terms, are aimed at providing investors and strategic decision-makers with additional analysis for futher justification of SunHorizon technologies' wider deployment in the coming years.

[3] https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

1. Introduction

Heating and cooling in the residential and tertiary sector[4] accounts for just over 50% of the total EU[5] energy consumption and today the demand is mostly met by fossil fuels. To reach the climate targets set by the European Commission for 2050, a shift away from fossil fuels is imperative, and the necessary technologies in the heating and cooling sector are available. Implementation of technologies based on renewable energy sources – heat pumps, solar energy – is increasing.

The SunHorizon project combines innovative heat pump technologies with solar appliances into technology packages targeted towards providing heating and cooling in refurbished and new single/multi-family/tertiary buildings. The technology packages are tested at eight demonstration sites in four different EU countries (Germany, Spain, Belgium and Latvia). Different aspects of practical implementation of new technologies needs careful consideration from engineers, scientists and policy-makers – these are aspects such as market availability, replicability and possibilities for mass-production, investment and maintenance costs, user friendliness, level of social acceptance, environmental performance and potential benefits to society from technology implementation. In this deliverable, we investigate environmental performance of SunHorizon technologies and technology packages (TP) in the life-cycle perspective and put monetary values on health and climate benefits from implementation of SunHorizon technologies.

The report is structured into five main sections. Section 1 is introductory; it is followed by Sections 2 and 3 explaining methodology used in the LCA and for the country-level benefit assessment, respectively. Section 4 presents the results. In Section 5, we discuss the methods used and the obtained results. Section 6 concludes the deliverable.

1.1 Background

One of the main environmental impacts of heating and cooling technologies in the residential and tertiary sector is air pollution and climate impact caused by air emissions. Carbon dioxide (CO_2) and methane (CH_4) affect climate, while nitrogen oxides (NO_x), sulphur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), non-methane volatile organic compounds (NMVOC), and ammonia (NH_3) have negative effects on ecosystems and people's health – both directly and being precursors to secondary air pollutants such as ozone and secondary particles. Air pollutants mix physically and undergo complex chemical reactions with each other while they are being transported to the long-range distances where they reach recipients. Long-range transport of air pollution is regulated via the UNECE Convention on Long-range Transboundary Air Pollution (UNECE CLRTAP) signed in 1979. Within the 40 years of Convention's work, methods to measure, map, report and model emissions have been constantly evolving. New models have been developed to study chemical reactions, transport and dispersion of air pollutants, and to estimate damage costs from impacts on people health, dominated by premature mortality from exposure to fine particles and ozone. Setting monetary values on climate impact from emissions of greenhouse gases (GHG) is also part of the common practice when trying to monetize the full range of effects from air emissions.

Testing SunHorizon technologies at demonstration sites enables coupling of health benefit assessment with real-life emissions of air pollutants and greenhouse gases measured. Also, a lot of other aspects of the technologies' environmental performance can be observed based on the actual data rather than on modelling – including impacts such as acidification, eutrophication, use of energy and mineral resources, ozone depletion, etc. Studying these aspects in the life-cycle perspective is the subject of life-cycle assessment (LCA).

Several research studies have previously investigated the environmental impact of solar PVs (2); however, most studies lack a life-cycle perspective. In addition, there is a clear need for an updated life-cycle assessment that explores the environmental impact of solar cells as the technology changes rapidly. The life-cycle assessments performed on PV panels commonly focus on the manufacturing phase, where the country's electricity mix has been identified as a major

[4] Residential sector includes dwelling stock or other living areas; tertiary sector includes economic activities related to trade, hotel and restaurant, traffic and data transmission, finance, health, education, public administration and other services such as waste, sport, social services and real estate (1).

[5] The project started in 2018 when there was 28 Member States in the EU. All the assessments on the EU level in this study are done for EU-28.

influencing factor as it is an energy-intensive process, although the recycling phase is an energy-intensive process as well (3). Still, it is during the use phase that the solar PV's positive environmental impact occurs. Important factors are solar radiation, the efficiency of the solar cell (2), and the service life of the system (4). These factors have effect on how quickly the energy and climate debt from production and recycling is repaid and how much solar cell systems contribute to climate and energy-related benefits. The influencing factors in the use phase can also vary depending on the business or collaboration model. For example, in one study the average specific yield for less decentralized roof-mounted systems was estimate at 798 – 890 kWh/kWp for 2017 and for 2018 (5), respectively, while expected and validated production in photovoltaic parks was around 900 – 1100 kWh/kWp.

Several authors (6) (7) conclude that the use of heat pumps is an effective strategy to help to reduce the carbon footprint of the building sector. These systems have been studied in deep from a life cycle perspective, although some of these studies often focus on just one impact category, such as global warming and energy consumption (8). In particular, the study by Greening et al. (2012) (6) concluded that the use of Heat Pumps instead of gas boilers would mean a reduction in the consumption of fossil fuels and the emission of greenhouse gases, although some trade-offs arise as a consequence of the consumption of electricity and the use of critical raw materials (6). Therefore, an effective use of these technologies combined with other alternatives such as solar collectors and PV panels is required to ensure the sustainability of the technology.

Health and climate benefits of solar PV and heat pumps have been estimated in monetary terms. Yang et al. (2018) (9) investigate health benefits from wider implementation of solar PV in China, concluding that around 10 000 premature deaths could be avoided in 2030. Wiser et al. (2016) (10) analyse environmental and public health benefits of achieving high penetrations of solar energy in the US – they estimate $250 billion climate benefits from GHG reductions, and $167 billion benefits to people's health from reduced air pollution due to solar panel deployment between 2015 and 2050. Potential benefits from air source heat pump technologies in Ireland as alternative to solid and liquid fuels are studied in Kelly et al. (2016) (11) – the estimate is €100 million per annum. A range of socio-economic benefits beside reduced premature mortality and climate impact has been analysed in IRENA (2019) (12), investigating sector employment and local value chains created by wider implementation of solar PV.

1.2 Aim and purpose

The aim of the task presented in this deliverable is to assess health and environmental effects and related health and climate benefits due to wider implementation of SunHorizon technologies in EU-28 in the future years (2030, 2050). Estimating country-specific benefits from implementation of SunHorizon technologies in the EU Members States, and expressing them in monetary terms, are aimed at providing investors and strategic decision-makers with additional analysis for further justification of SunHorizon technologies' wider deployment in the coming years.

For more accurate assessment of health and climate benefits on the country level, analysis of environmental performance of SunHorizon technologies and technology packages on the building/technology levels are highly beneficial. The purpose of the LCA analysis conducted within the same task, is to quantify different aspects of SunHorizon technologies' environmental performance, and to make a comparative analysis of technology packages, based on the real-life operational data provided by demonstration sites. A secondary purpose is to identify hot spots of the SunHorizon technologies life cycle environmental impacts, as a way to identify the processes and life cycle stages with the highest potential for future mitigation measures.

1.3 Technology packages

In the SunHorizon project innovative technology packages combining heat pumps with solar energy systems are demonstrated at 9 different sites in four geographically dispersed EU countries (Germany, Latvia, Spain and Belgium). The SunHorizon project is developing five different technology packages. All technology packages combine a solar system with innovative heat pump technology integrated with a thermal energy storage. The five technology packages are summarised in Table 1. For a more detailed description about the technology packages see D2.3 (13), D2.5 (14).

Table 1. Summary of the technology packages being developed in SunHorizon (15).

Technology package	Notation	Solar system	Heat pump technology	End user energy
TP1	Parallel solar-heat pump integration	Solar thermal panels (TVP)	Thermal compression HP (BH)	Space heating + district heating water (DHW)
TP2	Mixed solar-assisted/parallel solar-heat pump integration	Solar thermal + Solar PV (DS)	Thermal compression HP (BH)	Appliance electricity+ space heating + DHW
TP3	Solar driven heat pump for cooling	Solar thermal (TVP)	Hybrid sorption/ compression chiller (FAHR)	Space heating + DHW + Space cooling
TP4*	Parallel solar-heat pump integration	Solar thermal + Solar PV (DS)	Reversible HP (BDR)	Appliance electricity + space heating + DHW + space cooling
TP5*	Mixed solar-assisted/parallel solar-heat pump integration	Solar thermal panels (TVP)	Hybrid sorption/ compression chiller (FAHR) + Thermal compression HP (BH)	Space heating + DHW + Space cooling

*For TP4 and TP5, no empirical data was available at the time of writing (M26). These two technology packages are not considered in the LCA presented in D7.2 and therefore not mentioned in Sections 2 and 4 below. The LCA results for TP4 and TP5 will be included in the updated version of the D7.2 (to be delivered in M48).

1.4 Demonstration sites

Demonstration sites[6] and the details on pre-SunHorizon heating and cooling technologies and SunHorizon technology packages are summarized in Table 2.

Table 2. Summary of the demonstration sites in SunHorizon (15).

City	Facility type	H&C technologies before SunHorizon	TP installed	TP details
Berlin	Small privately-owned residential building with two apartments	Two natural gas fuelled boilers and a solar thermal panel coupled together with a thermal energy storage tank	TP1	The solar thermal panel is used to cover as much of the space heating and DHW demand as possible and the natural gas fuelled heat pump covers the additional demand
Nürnberg	Residential, multi-family building with four apartments	Connection to the natural gas grid; the flats have additional individual heating solutions, two gas boilers, one wood stove and one oil boiler	TP2	The electricity generated by the hybrid solar panels is used to cover appliance electricity demand within the building, and the heat generated is used to cover space heating demand as large extent as possible. The remaining heat demand is covered by the natural gas-fuelled heat pump
Sant Cugat del Vallés	Tertiary civic centre owned by the municipality	Electricity through a reversible heat pump and several variable refrigerant flow air condition units	TP3	Thee solar thermal panels supply as much of space heating and DHW demand as possible and the hybrid chiller provide space cooling

[6] One of the partners has left the project, and at the time of writing (M26) no information on the replacing partner (facility in Piera) was available. This facility is not mentioned in Table 2 and is excluded from the benefit analysis and LCA presented in D7.2. Empirical data for the demo site in Madrid was not available either in M26; this facility is currently excluded from the LCA and will be included in the final LCA results in the updated version of D7.2 (to be delivered in M48).

City	Facility type	H&C technologies before SunHorizon	TP installed	TP details
Madrid	Multi-family residential building with nine apartments owned by the municipality	Gas boiler per apartment supplying DHW and space heating and air/air split for cooling	TP4	The thermal output from the hybrid solar panels installed covers some of the heating demand in the building, the electricity produced powers the reversible heat pump or else supplies electricity to appliances in the building. The reversible heat pump supplies additional demand of DHW, space heating and cooling
Verviers, 1	Tertiary sport centre owned by the municipality	Natural gas boilers	TP1	Solar thermal panels installed supply as much of the hot water demand as possible and the additional demand is met by the heat pump
Verviers, 2	Tertiary swimming pool owned by the municipality	Natural gas boilers	TP2	The thermal output of the hybrid solar panels installed supplies as much of the heating demand as possible and assist with evaporation of the heat pump, that supplies the additional heating demand. The electricity generated by the hybrid solar panel covers part of appliance electricity.
Riga Sunisi	Privately-owned single house	Natural gas boilers	TP2	The thermal output from the solar hybrid panel covers the heat demand and assists with evaporation of the heat pump. The electricity production from the hybrid solar panel is used in the building appliances.
Riga Imanta	Privately-owned single house	Natural gas boilers	TP2	The thermal output from the solar hybrid panel covers the heat demand and assists with evaporation of the heat pump. The electricity production from the hybrid solar panel is used in the building appliances.

1.5 Relationship with other work packages

Inputs to the Task 7.1 (WP7), presented in the current deliverable, is based on the outputs from earlier or parallelly performed project tasks. Long-term scenarios are based on the estimates of SunHorizon technologies' potential deployment rates in the future, performed within task 2.2 (WP2) and presented in D2.2 (1). In these scenarios, it is assumed that part of the conventional H&C technologies is replaced with SunHorizon technology packages, designed as defined in D2.3 (13), D2.5 (14) (tasks 2.2, 2.4, WP2). Assessment of SunHorizon technologies' performance within LCA uses as reference key performance indicator (KPI) definition elaborated in task 2.3 (WP2), especially those related to energy consumption of the different energy carriers.

The results presented in the current deliverable are supposed to be an input to task 7.3 (WP7), due to this is a key aspect for some of the business models, like such related to municipalities with clear objectives for improving the air quality in the city, which has a deep impact on its building refurbishment strategy.

1.6 Contribution from partners

IVL has had the lead in structuring and developing the deliverable. IVL has been responsible for conducting the assessment of health and climate benefits from implementation of SunHorizon technologies. IVL also has conducted a part of the LCA with focus on solar panel technologies.

CARTIF has been responsible for a larger part of the LCA with focus on heat pump technologies.

The industrial partners (BoostHeat, TVP, DS, Ratiotherm, Fahrenheit) have been responsible for providing the operational data for the LCA.

RINA-C has had main responsibility for developing country-specific long-term scenarios (including baseline and SunHorizon scenarios) based on the estimates of potential deployment rates of SunHorizon technologies. RINA-C has been the reviewer of the deliverable.

2 Life-cycle Assessment – Method

This section describes the methodology applied in the LCA. LCA comprises a wider range of aspects of SunHorizon technologies' environmental performance than those needed for the monetary assessment of health and climate benefits. The methodology described in Section 2 applies to the entire LCA, while the results summarized below in Section 4.1 include only the outputs needed for the benefit assessment. At the time of writing (month 26), real-life operational data from demonstration sites, used as inputs in LCA, are preliminary. More data will be collected during months 27-48 of the project – based on these data, LCA results will be updated, and more methodological details and results will be included in the final version of this deliverable (to be submitted no later than month 48).

2.1 Goal and scope

The goal of this study was to evaluate the environmental impacts linked to the life cycle of different systems for the production of DHW and space heating and cooling for buildings using new technologies that combine solar photovoltaic, solar thermal and a range of heat pump configurations. This assessment has been done following the guidelines in ISO 14040 and ISO 14044 standards. This study performed the evaluation from a **building-level perspective**, addressing the impact linked to the life cycle of the building service life was considered considering the different technology packages involved in the project (Table 3) and also considering the different utility needs and the particular features of each demo site (Table 4). This LCA is intended to provide the environmental assessment of the different technologies developed under this project across the different demo sites. The intended audience of this study is mainly the stakeholders involved in the project (project partners, the EC, and other stakeholders involved in the value chain of the project, such as equipment manufacturers, research centres, universities, municipalities, construction and energy specialists, etc.), as well as the general audience interested in the environmental results of SunHorizon.

Table 3. Summary of the technologies addressed in the benefit assessment and LCA within the scope of SunHorizon.

Technology package	Individual Technologies	Description
TP1	TVP + BH	TVP for space heating + DHW; BH to cover non-solar periods.
TP2	DS + BH	BH for space heating + DHW support; DS PV-T thermal output to cover as much heat demand as possible + excess electricity production for appliances.
TP3	TVP + FAHR	TVP for space heating + DHW in winter + activation of the thermal compressor of the adsorption chiller (FAHR).

Table 4. Summary of demonstration sites and related technologies, included in the benefit assessment and LCA.

Demonstration site	TP	Description
Berlin (Germany)	TP 1	Small residential. House with 2 apartments.
Nürnberg (Germany)	TP 2	Multifamily residential. Apartment block with 4 floors
Saint Cugat del Vallés (Spain)	TP 3	Tertiary Civic centre.
Verviers (Belgium)	TP 1	Tertiary building. Sports Centre.
Verviers (Belgium)	TP 2	Tertiary building. Swimming pool.
Riga (Latvia)	TP 2	Small residential. 2 single houses two-storey.

To evaluate the environmental benefits/burdens of these new technologies, the assessment identified **environmental hotspots** and compared the scenario implying new technology packages installed with their respective baseline scenarios (business-as-usual), e.g. considering that no change in the heating/cooling system is done and the building continues its operation with the conventional equipment.

2.2 Functional unit

The selected functional unit was the energy required for heating and cooling 1 m^2 of building for 1 year for each of the demonstration sites presented in Table 4. The only exception is the demonstration site in Verviers (Swimming pool). In this case, the SunHorizon system is used to heat up a swimming pool, so the selected functional unit was "the energy required to keep the desired temperature of 1 m^3 of water in a swimming pool for recreational use for 1 year"

2.3 System boundaries

This study considered all the **stages** from the extraction of the raw materials, transportation to the different sites where the intermediate processing takes place, component manufacturing, transport to assembly facilities, assembly and finishing, transportation to demo site, installation and operation. Maintenance, disposal and end-of-life activities has been excluded from the system due to the lack of information – see Figure 1.

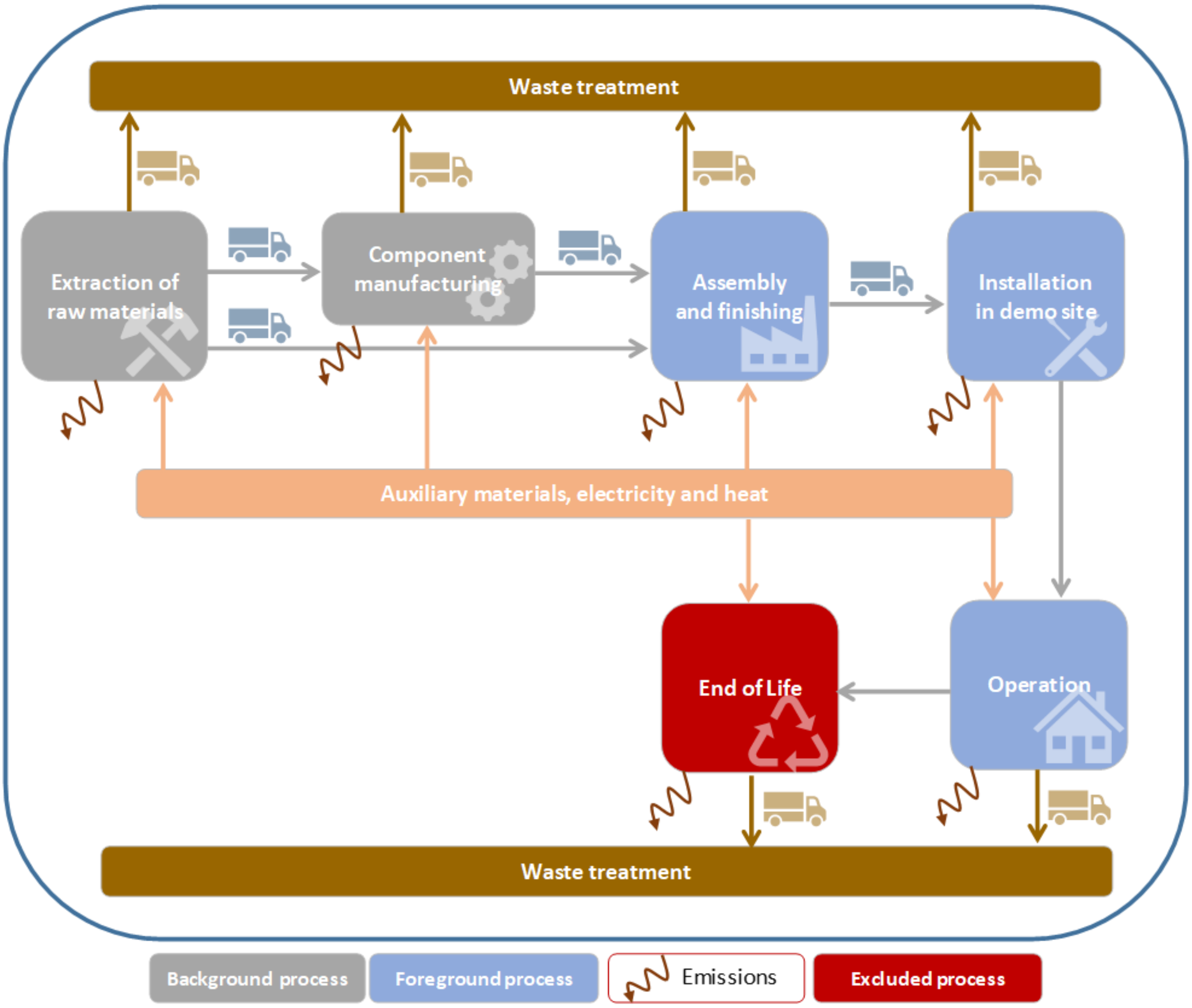

Figure 1. LCA system boundaries.

The **geographical scope** of the project considered was limited to Europe (Figure 2). Accordingly, representative data for the countries where each stage of the project takes place was selected when possible. Where no geographical information was available, recognised European databases were used. Regarding the time coverage, primary data for the time when the project was developed has been used, using the most up-to-date datasets for the designing of the models. For all the background processes, representative technologies from European industry databases were used.

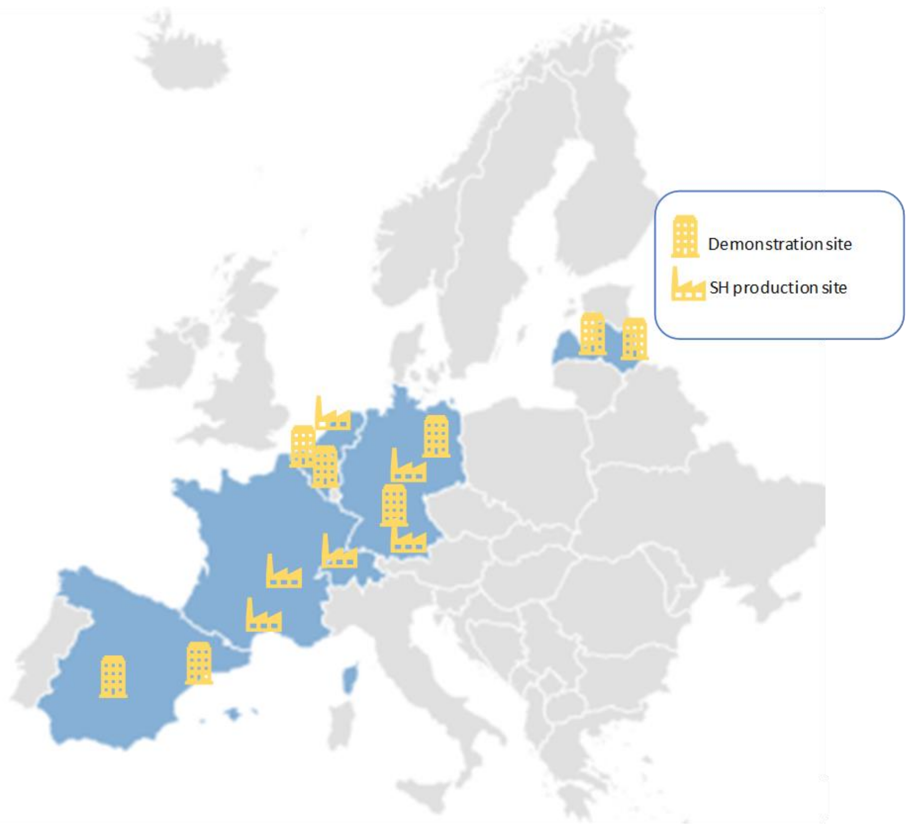

Figure 2. Geographical scope of the LCA – Location of factories and demo sites (including Madrid whose data was not yet available in M26).

2.4 Data and assumptions

The activities of the projects focus mainly in the production of the equipment and its operation. For these stages, high-quality primary data is used where possible – the data sets are provided by the industrial partners of the project (equipment manufacturers) involved in TP1, TP2 and TP3:

- **BoostHeat** (Vénissieux, France) – producer of thermal compression HP, technology us included in TP1 and TP2;
- **Fahrenheit** (Halle, Germany) – producer of hybrid sorption/compression chiller, technology is included in TP3;
- **TVP** (Geneva, Switzerland) – producer of solar thermal panels; technology is included in TP1 and TP3;
- **Dual Sun** (Marseille, France) -- producer of solar thermal and solar PV panels; technology is included in TP2;
- **Ratiotherm** (Dollnstein, Germany) – producer of stratified accumulation tanks included in all technology packages.

Data gaps were filled using appropriate estimations and information for relevant sources. Upstream processes were modelled using data from relevant databases such as Ecoinvent v3.5. Initially, all material and energy flows involved in the process were identified, although for further quantification and analysis certain cut-off criteria were selected to optimize the use of time and resources.

The most relevant inventory data from equipment producers, and assumptions for each SunHorizon technology, are presented in Annex 1 (classified). Where the empirical data have not been collected yet, modelling results are used for the analysis.

2.4.1 Production stage

The production stage comprises the manufacture of the raw materials, the transport of the raw materials to each partner's facilities and the production and assembly of all the individual components into the final product. Although the information for this stage has been largely provided by demonstration sites, when needed, some assumptions needed to be made to cover significant data gaps.

2.4.2 Installation stage

The installation step includes the transport of the product to each demo site, as well as the assembly with all the required auxiliary materials, energy consumption for tooling and any other inputs/outputs resulting from these operations. As this project comprises several manufacturers and a variety of demo sites, the main transportation distances have been summarised in Table 5.

Table 5. Transport distances between production sites and demonstration sites [km].

Distance production facilities – demo site [km]	Berlin	Nürnberg	San Cugat	Verviers	Riga
BoostHeat (Vénissieux, France)	1 231	806	-	693	2 393
Ratiotherm (Dollnstein, Germany)	510	94.7	1 494	604	1 670
TVP (Geneva, Switzerland)	1 115	-	779	739	-
Dual Sun (Marseille, France)	-	1 121	-	-	2 758
Fahrenheit (Halle, Germany)	-	-	1 686	-	-

2.4.3 Use stage

The use stage includes the operation of the different technologies for energy production (thermal, electrical) along its useful life. Maintenance operation, replacement parts and other relevant activities have been included when information was available. The main aspect in this stage is the energy consumption and production. To assess the impact of the different SunHorizon technologies at the **building level**, first a baseline scenario for all the demos operating with conventional technologies was defined. The values for the energy consumption for this scenario (summarized in Table 6) have been calculated with a combination of modelling and monitoring of the different demo sites. Energy consumption in case SunHorizon technologies are used is presented in Table 7. This data is based on the information provided by the demonstration sites[7].

Table 6. Energy consumption for each demo site in the baseline scenario.

	Baseline scenario						
Energy source	**Berlin**	**Nürnberg**	**Sant Cugat**	**Verviers sport centre**	**Verviers swimming pool**	**Riga Imanta**	**Riga Sunisi**
Oil [kWh/year]	-	3 891	-	-	-	-	-
Wood [kWh/year]	-	5 104	-	-	-	-	-
Gas [kWh/year]	35 548	30 701	-	287 564	314 000	37 400	13 300

[7] Not all the data is available at the time of writing; in the final version of the deliverable with updated LCA methodology and results (to be delivered in month 48), Table 7 will be complemented with the results obtained from monitoring campaigns.

Baseline scenario							
Energy source	**Berlin**	**Nürnberg**	**Sant Cugat**	**Verviers sport centre**	**Verviers swimming pool**	**Riga Imanta**	**Riga Sunisi**
Coal [kWh/year]	-	22 360	-	-	-	-	-
Grid Electricity [kWh/year	-	43 420	155 269	-	333 756	4 400	7 700
Oil [kWh/m²]	-	11.8	-	-	Swimming pool, the unit kWh/m² is not relevant	-	-
Wood [kWh/m²]	-	15.5	-	-		-	-
Gas [kWh/m²]	114.7	93.0	-	104.4		159.1	138.5
Coal [kWh/m²]	-	67.8	-	-		-	-
Grid Electricity [kWh/m²]	2.1	131.6	192.6			18.72	80.21

Table 7. Energy consumption for each demo site using SunHorizon technologies.

SunHorizon scenario							
Energy source	**Berlin**	**Nürnberg**	**Sant Cugat**	**Verviers sport centre**	**Verviers swimming pool**	**Riga Imanta**	**Riga Sunisi**
Oil [kWh/year]	-	-	-	-	-	-	-
Wood [kWh/year]	-	-	-	-	-	-	-
Gas [kWh/year]	18 928	68 900	-	207 752	185 609	27 731	10 407
Coal [kWh/year]	-	-	-	-	-	-	-
Grid Electricity [kWh/year]	1 054	15 517	43 801	1 339	279 167	-993	1 310
Oil [kWh/m²]	-	-	-	-	Swimming pool, the unit kWh/m² is not relevant	-	-
Wood [kWh/m²]	-	-	-	-		-	-
Gas [kWh/m²]	68.95	208.79	-	75.42		118.00	108.41
Coal [kWh/m²]	-	-	-	-		-	-
Grid Electricity [kWh/m²]	3.7	47.0	54.3	0.5		-4.2	13.6

Energy balances for specific SunHorizon technologies across the demonstration sites are illustrated in Annex 2 (classified).

2.5 Environmental impact categories

The outcomes of the LCA feed the model for the assessment of health and climate benefits at the country level. The necessary input data for the benefit assessment is an inventory of the air emissions (NO_x, NMVOC, NH_3, SO_2, $PM_{2.5}$, CH_4 and CO_2) from SunHorizon technologies. Environmental impact categories in the LCA were chosen with respect to this – a range of environmental indicators included in the analysis (Table 8) are directly linked to emissions of GHG (global warming potential) and air pollutants (acidification, eutrophication). Abiotic depletion, ozone layer depletion and photochemical oxidation were considered to widen the scope of the assessment and provide a complete environmental evaluation of each system. The CML-IA[8] baseline method was selected for the evaluation.

[8] https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

Table 8. Set of environmental indicators assessed.

Environmental indicator	Unit	Description
Global warming potential	kg CO_2-eq.	Global Warming Potential (GWP) is an indicator to measure climate change, the global warming effect of greenhouse gases (GHG) caused by human activity. When emitted to the atmosphere, GHG increase the temperature at the earth's surface by absorbing energy and slowing the release of energy back to space, causing a greenhouse effect. Different greenhouse gases have different effects on earth's warming, and the effect caused by carbon dioxide is used as a reference unit referred to as CO_2 equivalents.
Abiotic depletion	kg Sb eq.	This indicator measures the depletion of abiotic resources, in this case more specifically fossil fuels, minerals and metals. The abiotic depletion potential (ADP) indicators measure this in terms of the scarcity of the resources, meaning the amount of resources left and the extraction rate. These indicators are affected by the intake of specific resources from nature. This ADP indicator accounts for a set of scarce metals and minerals including antimony, copper, lithium and clays, among others; and is measured in antimony equivalents.
Abiotic depletion (Fossil Fuels)	MJ	The ADP fossil indicator accounts for all extractions of fossil fuels (natural gas, coal, oil), and is measured in MJ.
Ozone layer depletion	kg CFC-11 eq.	Ozone depletion occurs when halogenated compounds that are emitted to the atmosphere are transported to the stratosphere and encounter the ozone there, destroying these molecules more quickly than it is naturally created. Stratospheric ozone is key for earth's ecosystems, since it provides protection from the most damaging types of radiation emitted by the sun. Ozone depletion is mostly caused by ozone depleting substances such as halocarbon refrigerants, solvents, propellants and blowing agents. For this impact category, trichlorofluoromethane (CFC-11) is used as a reference.
Photochemical oxidation	kg C_2H_4 eq.	This impact category measures the environmental impact of emissions to air that cause the formation of ozone at the ground level of the troposphere. Such emissions are typically generated from fuel combustion processes in transport vehicles and machinery; and are mostly volatile organic compounds (VOCs), carbon monoxide and nitrogen oxides. Ozone at the ground level can impact vegetation, cause human respiratory problems and infrastructure damage.
Acidification	kg SO_2 eq.	Acidification of water bodies occurs when substances of acidic nature are discharged to the environment and reach water bodies or soil. Acidification occurs naturally but when human-caused acidic emissions to air and discharges to water becomes too much for ecosystem's buffering capacity, it has negative effects in aquatic ecosystems and biodiversity. The substances that contribute the most to the acidification of ecosystems are emissions or sulphates and nitrogen oxides; mostly generated from incineration of fossil fuels (sulphates), cleaning agents and fertilizers (nitrogen oxides).
Eutrophication	kg PO_4^{-3} eq.	Eutrophication occurs when water bodies become excessively enriched by an excess of nutrients that are transported to them via wastewater or fertilizer discharges into the water cycle. This excess causes an excessive grow of algae, which causes oxygen depletion and blockage of sunlight, affecting the capacity of the water bodies to host life any forms. The nutrients that cause Eutrophication typically come from detergents, fertilizers applied on the soil and transported via runoff or sewage discharges.

3 Assessment of environmental and health benefits – Method

Assessment of environmental and health benefits of SunHorizon technologies is performed at the country level. Part of the LCA results for SunHorizon technologies – emission factors per technology package – are further aggregated into emission factors per technology package (TP). TP-based emission factors are used to calculate country-specific emissions, which are the starting point in the benefit assessment.

The environmental performance of H&C technologies comprises several emission-related impacts, such as acidification, eutrophication, changes in biodiversity, etc. In general, the methodology for estimating health damage costs from air pollution is very well developed and actively used, while the methodology for setting monetary values on damage from other impacts (e.g. ozone depletion, acidification) is not as well-developed, and available literature data on damage costs is very scarce. In the current benefit assessment, we only include aspects associated with health damage from emissions of air pollutions and greenhouse gases (climate impact).

Health benefits from reduced air pollution due to wider application of SunHorizon technologies are estimated with impact pathway approach. Furthermore, the economic valuation of health impacts is complemented with economic valuation of climate impact from greenhouse gas emission changes. Benefits are calculated as differences in external costs[9] between scenarios with and without use of SunHorizon technologies.

3.1 Impact Pathway approach

To calculate the **external costs of the air pollutions** from alternative heating and cooling technologies, we have used the Impact Pathway Approach, presented in detail in Bickel and Friedrich (2005) (16) and summarized in Figure 3.

In this study, the **source** of emissions of air pollutants is residential and tertiary sector in EU countries, where a range of SunHorizon technologies are used as replacement for conventional heating and cooling technologies. Emissions included in the assessment of health effects are NO_x, SO_2, NH_3, NMVOC, and $PM_{2.5}$. To calculate annual country-specific emission levels, long-term scenarios were developed, based on assumed levels of implementation of technologies in 2030 and 2050, chosen as target years in the analysis. The developed long-term scenarios, including one baseline (business as usual) scenario and three SunHorizon scenarios, and the underlying assumptions are presented in detail in Section 3.2.

Emissions are introduced into the GAINS model[10], used to calculate **emission dispersion** and resulting population-weighted concentrations of $PM_{2.5}$ and ozone exposure at receptor countries. The $PM_{2.5}$ concentration in ambient air is caused by primary $PM_{2.5}$ emissions, but also by emissions of NO_x and SO_2 since these form secondary $PM_{2.5}$ during their residence time in the air. Ground-level ozone formation is directly affected by NO_x concentrations.

Dose-response functions for each of the endpoints (such as e.g. premature mortality at adults and infants, asthma cases, etc.) are included in the Alpha RiskPoll (ARP) model[11], which uses the results from the GAINS model to calculate the impact on human health and the monetary values of these impacts.

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[9] The concept of *external costs, or externalities*, is used by environmental economists to capture negative or positive impacts of consumption and production that are not included in the price of the goods or services produced.

[10] GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies) is an integrated assessment model, an extension of the RAINS (Regional Air Pollution Information and Simulation) model, originally developed within the UNECE CLRTAP to identify and explore cost-effective emission control strategies for air pollutants (17). Later, the possibility to analyse greenhouse gas emissions and measures was included. The model is widely used as a unified tool for scientific analysis of economic and environmental consequences of air pollution abatement strategies and climate mitigation measures. With its broad database on abatement measures and in-built emission dispersion parameters, GAINS enables analysis of emissions, costs and health and environmental effects for relevant policy scenarios.

[11] The ALPHA RiskPoll (ARP) model (18) enables analysis of a wide range of chronic and acute health effects from exposure to $PM_{2.5}$, ozone and NO_x. Health effects per country are calculated by combining data on age distribution of population, population-weighted concentrations of secondary $PM_{2.5}$ and effect-specific dose-response relationships (18) (19) (20). The model's main outputs are quantified impacts of air pollution (e.g. asthma cases, premature deaths) and their monetary valuation. ARP and the

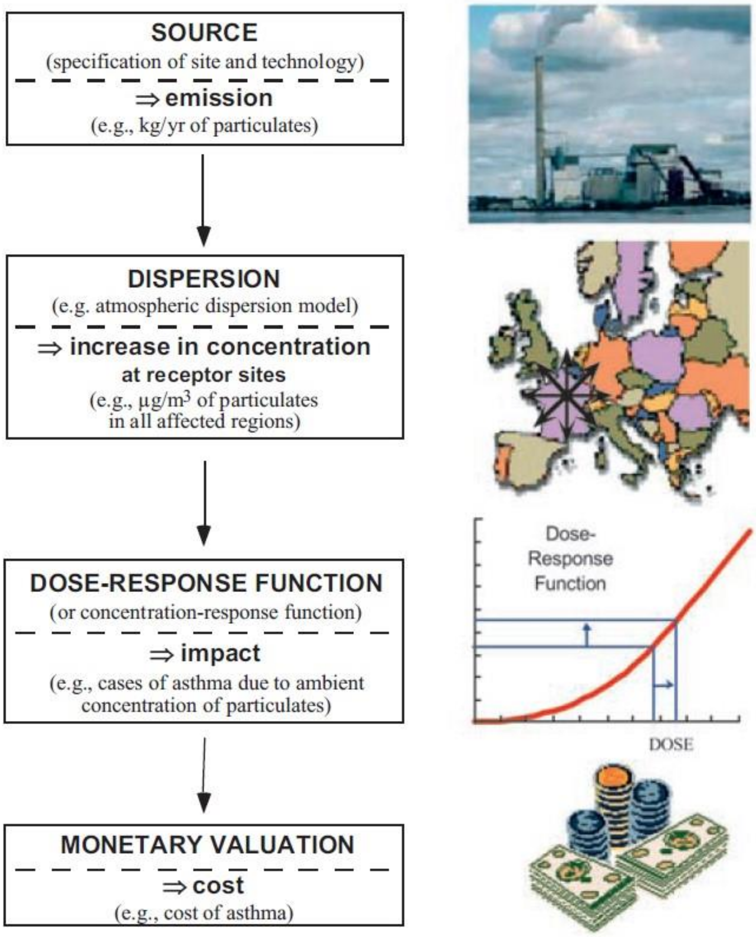

Figure 3. The main steps of an impact pathway analysis (16).

The sequence of the steps in the assessment and corresponding inputs and outputs are summarized in Table 9. These steps are applied for each of the scenarios. Monetized damage (external costs) for each of the SunHorizon scenarios are than compared to monetized damage in the baseline scenario, to estimate health benefits resulting from application of SunHorizon technologies.

It is assumed that SunHorizon technologies are applied in the EU-28 countries only.

Table 9. Assessment of benefits: steps, inputs and outputs.

Step of the assessment	Inputs	Outputs
1. Long-term scenarios	LCA results: technology-specific emission factors Assumptions on country-specific deployment rates of considered SunHorizon Technologies	Country-specific emissions of main pollutants
2. GAINS modelling	Country-specific emissions of main pollutants	Country-specific population-weighted concentrations of $PM_{2.5}$ and ozone exposure
3. Effect valuation and benefit assessment (ARP modelling)	Country-specific population-weighted concentrations of $PM_{2.5}$ and ozone exposure	Country-specific effects on health Country-specific monetized damage

version preceding ARP have been extensively used for assessing benefits from air pollution abatement measures and instruments in Europe — in particular during the work leading up to the European Commission.

3.2 Long-term scenarios

This Section describes the definition of the long-term scenarios for the assessment of environmental and health benefits at the country level. The scenarios are based on the assumptions on future heating and cooling (H&C) energy demand in EU countries and on the assumptions on rates of replacement of conventional H&C technologies with SunHorizon technologies.

3.2.1 Scenario definition

The time frame in the analysis is as follows: 2020 is chosen as base year, and 2030, 2050 – as target years for long-term scenarios. 2030 corresponds to short-to-medium-term development stage, while 2050 – to a long-term stage.

To analyse the effects of the installation of SunHorizon technologies replacing conventional H&C technologies, three so called SunHorizon scenarios are developed, beside the **baseline scenario** that reflects the "business as usual" development without implementation of SunHorizon technologies. Baseline scenario assumes development of future heating and cooling demand under the assumption that already agreed policies are continued to be implemented, but no decisions on new, stricter policies are taken.

In each of the SunHorizon scenarios, it is assumed that a certain part of conventional H&C technologies is replaced with SunHorizon technologies combined in technology packages. In each SunHorizon scenario, the total percentage of the replaced technologies is the same (see Section 3.2.3); what differs SunHorizon scenarios between each other is the combination of SunHorizon technology packages replacing the conventional technologies.

Long-term scenarios included in the analysis are summarized in Table 10.

In **SunHorizon TP1**, conventional heating technologies are partly replaced by TP1 (TVP for space heating + DHW; BH to cover non-solar periods).

In **SunHorizon TP2**, conventional heating technologies are partly replaced by TP2 (BH for space heating + DHW support; DS PV-T thermal output to cover as much heat demand as possible + excess electricity production for appliances).

In **SunHorizon TP1+TP2 (combo)**, it is implied that conventional heating technologies are replaced partly by TP1 (50%) and partly by TP2 (50%).

In all three SunHorizon scenarios, conventional cooling technologies are replaced by TP3.

Since for TP4 and TP5 no empirical data was available at the time of writing (M26), these two technology packages were not considered in the scenario set in the benefit analysis.

Table 10. Scenarios in the benefit assessment.

Scenario	Scenario – short name	Conventional heating technologies are partly replaced by	Conventional cooling technologies are partly replaced by
Baseline	BL	-	-
SunHorizon TP1	SH_TP1	Technology package 1 (TP1)	Technology package 3 (TP3)
SunHorizon TP2	SH_TP2	Technology package 2 (TP2)	Technology package 3 (TP3)
SunHorizon TP1+TP2 (combo)	SH_c	Combination of TP1 (50%) and TP2 (50%)	Technology package 3 (TP3)

3.2.2 H&C demand in the baseline scenario

Country-specific H&C demand in the residential and tertiary sector used in the baseline scenario is adopted from the sector-specific current policy (baseline) scenario described in Fleiter et al. 2017 (21). This scenario considers targets and measures for residential H&C and energy efficiency, which have been agreed or already implemented by the end of 2016. Within this scenario, all implemented instruments are assumed to be in place by 2030, including current financial support programs, without significant changes in those programs throughout the years, and adherence to the measures implied in the Clean Energy for all Europeans Package (per March 2018) (22).

The same assumptions and the same demand trend are applied in the baseline scenario in the benefit assessment of SunHorizon technologies. Although Fleiter et al. 2017 (21) includes 14 Member States in the analysis, they account for over 90% of the total EU H&C demand. The average numbers for these 14 Member States are thus considered to be representative for the remaining 14 EU Member States and are applied in our analysis. The distribution of the H&C demand by technology/energy source is considered to be constant from the present time (2020) onwards. The total heating demand in EU-28 in the baseline scenario, and the share of the demand by technology and/or energy source is shown in Figure 4 (the entire demand is satisfied via electricity). Annex 3 (Tables 3.1, 3.2, 3.4) provides data on heating and cooling demand in the baseline scenario, distributed by technology, by Member State.

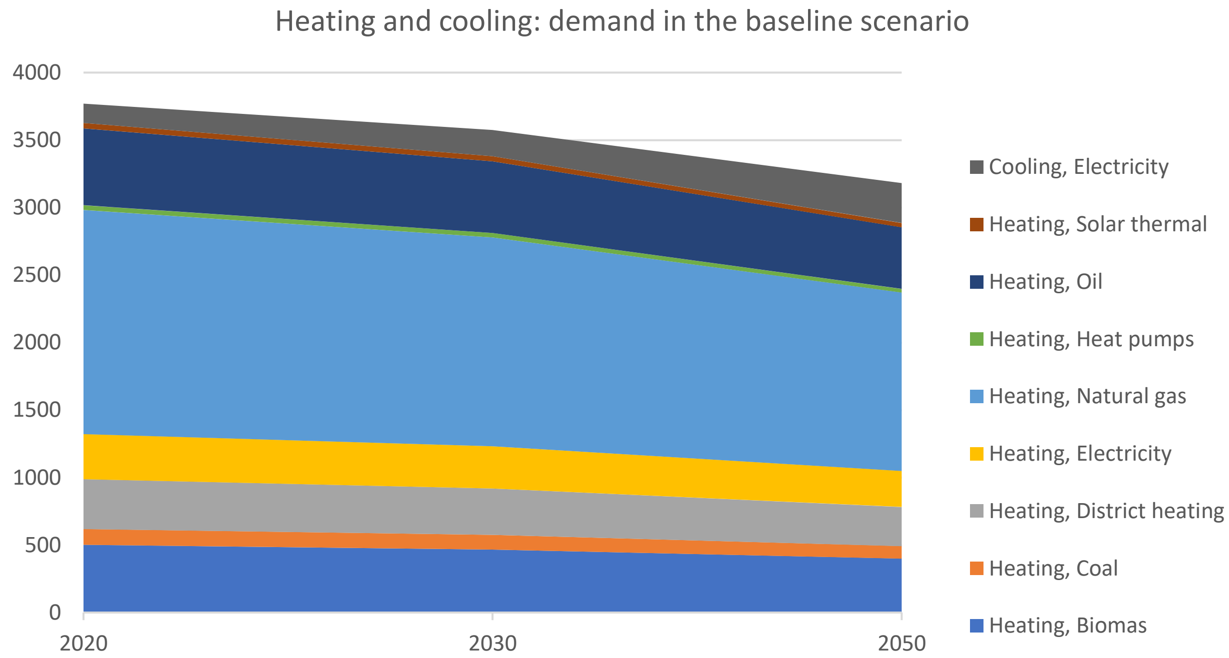

Figure 4. Heating and cooling demand in EU-28, baseline scenario, TWh per year. Source: Fleiter et al. 2017 (21).

3.2.3 H&C demand: Technology replacement

In the three analysed SH scenarios (Table 11), it is assumed that whereas the total heating and cooling demand remains the same as in the baseline scenario, part of the conventional heating and cooling technologies is replaced by relevant SunHorizon technologies combined in technology packages. Deployment rates of SunHorizon technologies are estimated based on the replicability assessment of SunHorizon technologies in members states, reported in D2.2 (1). The starting point in the assessment of technology replacement rates is the assumptions for the year 2050, based on the estimated replicability rates and summarized in Table 11.

Table 11. Maximum deployment rate in 2050 based on the replicability assessment (1).

Replicability level	Deployment rate in 2050
Low replicability	10%
Medium / Low replicability	20%
Medium replicability	40%
Medium / High replicability	60%
High replicability	80%

Based on the current values of emissions, it is reasonable to assume that SunHorizon technologies can replace – in the order of priority - the use of coal, oil, natural gas and electricity for H&C purposes. It is furthermore assumed that biomass, solar thermal systems, heat pumps and district heating will not be replaced by any SunHorizon technology. Thus, the deployment rates of SunHorizon technologies are adjusted for certain countries where a large part of the heating and cooling demand is covered by biomass, solar thermal systems, heat pumps and district heating, implying a lower need for SunHorizon technologies.

In the assessment of the SunHorizon technologies' deployment rates before 2050, it is assumed that deployment rates are linearly increasing between 2020 (present time) and 2050, following the gradual replacement of conventional technologies with relevant SunHorizon technologies.

The total heating and cooling demands in EU28 in the baseline scenario, and the share of the demand by technology and/or energy source, considering gradual technology replacement, is shown in Figure 5. Annex 3 (Tables 3.3, 3.5, 3.6) provides data on heating and cooling demand distributed by technology (including SunHorizon technologies) by Member State.

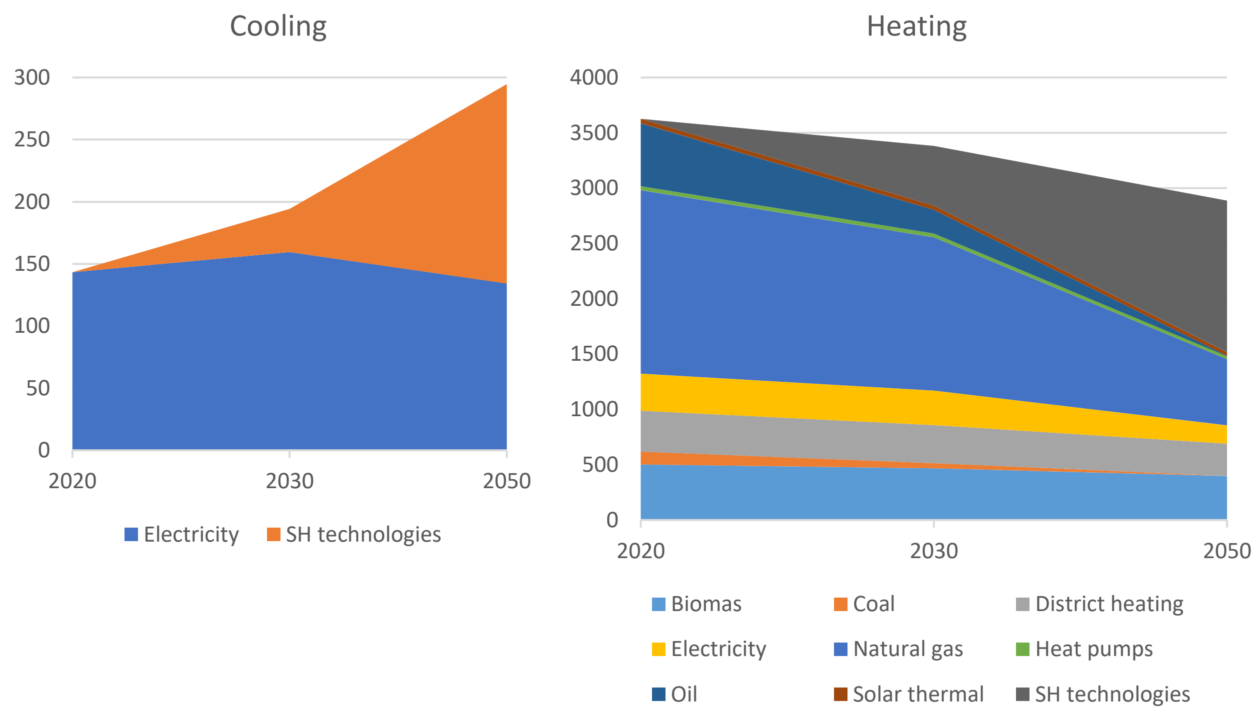

Figure 5. Cooling and heating demand in EU28, scenarios with SunHorizon technologies, TWh per year.

In Annex 3 and Figures 4 and 5, SunHorizon technologies are not distinguished by type but considered as one aggregated category. At the further stage of more detailed definition of SunHorizon scenarios (Section 3.2.1), it is specified which SunHorizon technology package replace conventional technologies in each of the scenarios.

3.2.4 Emissions Factors

In order to estimate country-specific emissions in each of the considered scenarios, TP-specific emission factors for main air pollutants are used in combination with estimated heating and cooling demands in 2030 and 2050. Emission factors are calculated within LCA (Section 2); they differ between SunHorizon technologies, but it is assumed that they do not differ between the EU countries.

Calculated emission factors are as much as possible based on the empirical results of SunHorizon technologies' deployment at the demonstration sites. Where empirical data for SunHorizon technologies is not yet available, as well as for calculation of emission factors for conventional technologies, generic data from LCA databases[12] are used for modelling. The main LCA stages (production, transport and installation, use) are included in the emission factors, excluding maintenance and end-of-life (see Section 2 for details on the LCA methodology).

The set of emission factors used in the analysis is presented in Table 12, while the data sources and underlying assumptions for conventional technologies used are presented in Table 13.

Table 12. Emission factors used in the benefit assessment, kg/TWh.

Technology /TP	Air pollutants					Greenhouse gases*	
	NO_x	NMVOC	NH_3	SO_2	$PM_{2.5}$	CO_2	CH_4
HEATING TECHNOLOGIES							
Biomass boiler	609 500	173 000	15 100	92 200	390 000	28 800 000	434 800
Coal boiler	613 000	1 140 000	9 400	2 890 000	462 000	590 000 000	2 120 000
District heating	301 700	42 000	7 500	166 200	7 400	222 252 500	423 300
Electricity heating	454 000	51 200	8 900	399 000	14 000	375 000 000	641 000
Gas boiler	144 000	80 100	1 000	663 000	21 400	258 000 000	1 150 000
Heat pump	306 000	26 000	6 300	665 000	63 700	169 000 000	446 000
Oil boiler	268 000	96 600	1 000	555 000	26 900	331 000 000	190 000
Solar energy	82 000	16 500	6 700	225 000	34 500	22 768 000	59 800
SunHorizon TP1	159 600	69 600	3 100	187 800	42 600	148 091 000	641 700
SunHorizon TP2	122 400	45 900	1 400	121 300	15 800	140 057 500	601 100
COOLING TECHNOLOGIES							
Electricity cooling	454 000	51 200	8 900	399 000	14 000	375 000 000	641 000
SunHorizon TP3	103 300	38 100	2 300	178 700	44 800	38 265 500	134 000

*For greenhouse gases, only the fossil part of the emissions is included

Table 13. Data sources and underlying assumptions in the emission factors for conventional technologies.

Technology	Specification, assumptions	Source
Biomass boiler	Weighted emission factor: 50%: Heat, district or industrial, other than natural gas {CH}| heat production, hardwood chips from forest, at furnace 300kW | Alloc Def, U 50%: Heat, central or small-scale, other than natural gas {Europe without Switzerland} | heat production, wood pellet, at furnace 9kW | APOS, U	Ecoinvent v3.5
Coal boiler	Heat, central or small-scale, other than natural gas {Europe without Switzerland} | heat production, hard coal coke, stove 5-15kW | Alloc Def, U	Ecoinvent v3.5
District heating	District heating mix EU-28. This dataset represents the average region-specific district heat supply at consumer.	GaBi Professional, Thinkstep database
Electricity heating	EU-28 electricity mix, as consumption mix to consumer. The data set represents the average country or region-specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses of electricity supply and electricity imports from neighbouring countries.	GaBi Professional

[12] GaBi professional, Ecoinvent v. v3.5

Technology	Specification, assumptions	Source
Gas boiler	Heat, central or small-scale, natural gas {Europe without Switzerland} | heat production, natural gas, at boiler fan burner low-NOx non-modulating <100kW | Alloc Def, U	Ecoinvent v3.5
Heat pump (conventional)	Heat, air-water heat pump 10kW {Europe without Switzerland} | production | Alloc Def, U	Ecoinvent v3.5
Oil boiler	Heat, central or small-scale, other than natural gas {Europe without Switzerland} | heat production, light fuel oil, at boiler 100kW, non-modulating | Alloc Def, U	Ecoinvent v3.5
Solar energy (conventional)	Weighted emission factor: 91%: Heat, central or small-scale, other than natural gas {CH}| operation, solar collector system, Cu flat plate collector, one-family house, for combined system | APOS, U 9%: Heat, central or small-scale, other than natural gas {CH}| operation, solar collector system, evacuated tube collector, one-family house, for combined system | APOS, U	Ecoinvent v3.5
Electricity cooling	EU-28 electricity mix, as consumption mix to consumer. The data set represents the average country or region-specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses of electricity supply and electricity imports from neighbouring countries.	GaBi Professional

3.3 Emissions and dispersion modelling in GAINS

After country-specific emissions for each target year are estimated, they are introduced as input data into the GAINS model. In the GAINS model, a set of country-to-cell **source-receptor matrices**, calculated in the EMEP[13] model, are used for the air pollutants dispersion simulations (24). The results of the simulations are the following effects, further introduced into ARP model:

- Population-weighted $PM_{2.5}$ concentrations;
- Ozone exposure (SOMO35[14] metric).

Linear form emission dispersion pattern is illustrated in Equation 1 showing an example for calculation of $PM_{2.5}$ concentrations in the receptor country:

$$PM_i = \sum_i pm_i * P_{i,r} + \sum_i s_i * S_{i,r} + \sum_i a_i * A_{i,r} + \sum_i n_i * N_{i,r} + \sum_i v_i * V_{i,r} + k_{0,r} \quad (1)$$

where r = receptor region; PM_r = concentration of $PM_{2.5}$ in receptor region r [µg/m³]; pm_i = emissions of primary $PM_{2.5}$ in country i [ktonne]; s_i = emissions of SO_2 in country i [ktonne]; n_i = emissions of NO_x in country i [ktonne]; v_i = emissions of NMVOC in country i [ktonne]; $k_{0,r}$ = background concentration constant in region r [µg/m³]; P, S, A, N, V = transfer coefficients between source region i and receptor region r [µg/m³/ktonne], for the different pollutants PM, SO_2, NH_3, NO_x, and NMVOC (24).

More often, GAINS scenario analysis starts with introducing into the model other types of input data than emissions – amounts of combusted fuels and produced goods in different economic sectors. Emissions are then calculated in the model for each economic sector/activity with Equation 2:

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13 The EMEP MSC-W model (23) is a 3-dimensional Eulerian model that calculates emissions, transport, chemistry and loss processes of pollutants. The model's main purpose is to support governments in their efforts to design effective emission control strategies. The model simulates air concentrations of gaseous (including SO_2, NO_2 and ozone) and particulate pollutants, as well as acidifying and eutrophying depositions on ecosystems.

14 The SOMO35 metric quantifies the yearly sum of the daily maximum 8-hour ozone concentrations exceeding a 35 ppb (70 µg/m³) threshold

$$E_i = \sum_{j,k,m} E_{i,j,k,m} = \sum_{j,k,m} A_{i,j,k} * ef_{i,j,k} * (1 - eff_m) * x_{i,j,k,m} \quad (2)$$

where i, j, k, m = country or sea region, sector, activity type, control measure; E_i = emissions in country i [ktonne]; A = activity in a given sector [PJ fuel or other units corresponding to the activity driving emissions]; ef = emission factor when not using any control measure [ktonne/unit of emission- driving activity]; eff = emission reduction efficiency of measure m [%]; x = implementation rate of the considered control measure m, and of the residual no-control option [%] (24).

In GAINS, heating and cooling in the residential and tertiary sector is allocated in *residential-commercial sector*. Figure 6 illustrates current (2020) distribution of energy demand in the residential and tertiary sector by energy type for EU-28: as assumed in one of the most recent publicly available GAINS baseline scenarios – *ECLIPSE_V5a_CLE_base*[15], as in the long-term scenarios used in the current analysis (developed by RINA, see Section 3.2.2), and as in the Eurostat statistics[16,17]. The three data sets show quite good compliance for fossil fuels, biomass consumption and district heating. Consumption of solar energy and electricity is assumed to be significantly higher in the GAINS baseline than in the other two data sets – most probably, because the GAINS model includes other energy needs in the *residential-commercial sector* than heating and cooling – for instance, lightning and home appliances running on electricity, which, according to the Eurostat, account for ~75% of electricity use in households. However, found discrepancies between energy consumption numbers do not represent an obstacle for benefit assessment, since in the analysis we consider relative changes only.

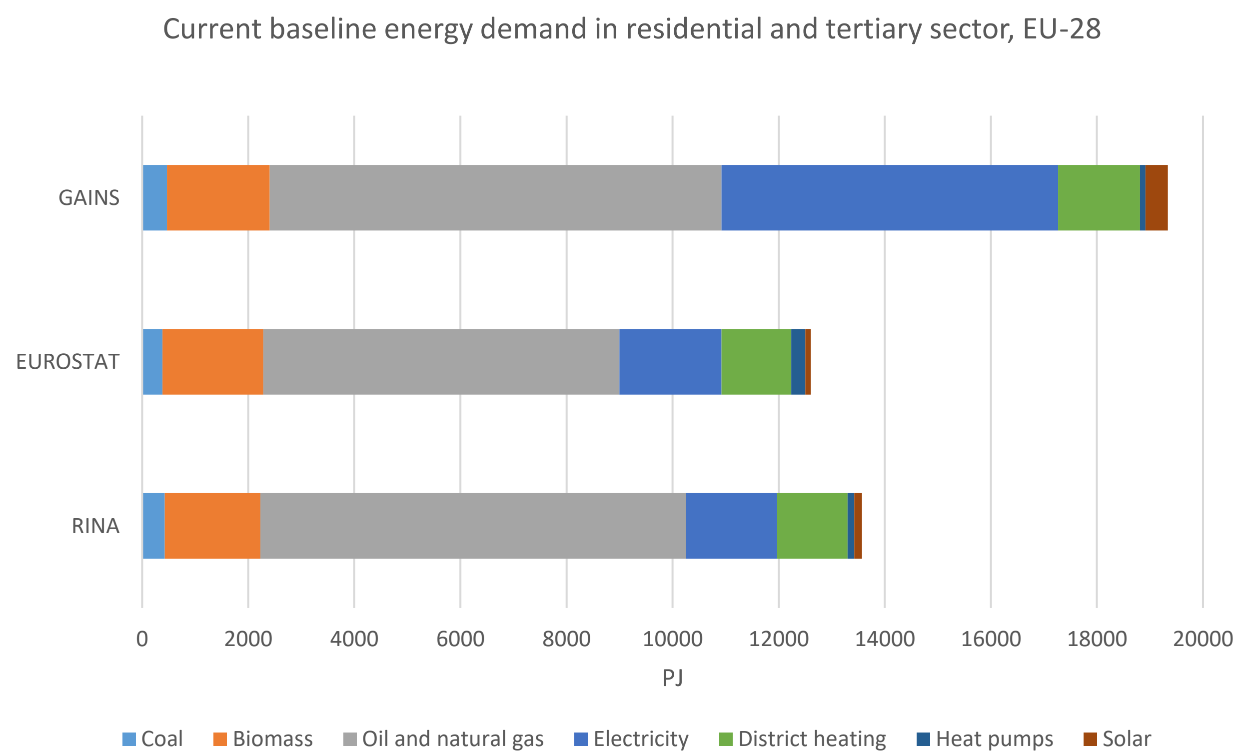

Figure 6. Baseline energy demand in the residential and tertiary sector in EU-28, long-term scenarios for 2020 (RINA) vs GAINS model scenario *ECLIPSE_V5a_CLE_base* for 2020 (GAINS) vs Eurostat statistics for 2018 (EUROSTAT).

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[15] Described in detailed in Stohl et al. 2015 (25)

[16] Energy statistics from Eurostat is for 2018, not 2020, but it is assumed to be representative enough for data validation purposes

[17] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_products_used_in_the_residential_sector; Eurostat database, selections "Total energy consumption in households", "Total energy consumption in services". For services, it is assumed that 100% of each energy source is used for H&C, except for electricity where 50% is used for H&C.

Gradual introduction of SunHorizon technologies results in changes in the country-specific emissions in the residential and tertiary sector, compared to the baseline scenario emissions. The models we use – GAINS and ARP – imply a linear dependency between emissions, health and environmental effects, and corresponding damage costs. Benefits from SunHorizon technologies are thus in direct proportion to country-specific emission changes. Furthermore, the GAINS model does not distinguish between sectors or geographic locations where the emissions occur: Equation 1 considers country-to-cell source-receptor coefficients, so dispersion modelling is based on this level of aggregation with no consideration of spatial distribution of emissions within each country. Taking all this into account, we for simplicity introduce into the GAINS model not the total calculated emissions from residential and tertiary sector for each of the long-term scenarios, but the emission differences that would affect benefits in a linear way. For the baseline GAINS scenario (BL in Table 10), no emission differences are assumed. For scenarios *SH_TP1, SH_TP2* and *SH_c*, we adjust total emissions that GAINS model calculates for each country so that the emission differences are the same as calculated for our long-term scenarios for residential and tertiary sector.

3.4 Effect valuation and benefit assessment

Assessment of health and climate benefits in each of the SunHorizon scenarios are estimated by comparing the damage costs in the SunHorizon scenarios to the damage costs in the baseline scenario. All monetary values are expressed in €$_{2015}$. For recalculation between valuations from different years, we use GDP deflators by OECD.

3.4.1 Health damage

The health impact with highest monetary value is the "avoided mortality (fatality)", which is valued by either estimating the Value of Statistical Life (VSL) or the Value Of Life Yea lost (VOLY)[18]. The estimated economic value of these varies in the literature and between methods. The values can also differ between VOLY and VSL due to differences in how many life years that are assumed to be lost when a fatality occurs. We therefore include low, mid and high values in the results below. Low values imply that the valuation of avoided mortality is based on the median VOLY estimate from Desaigues (2011) (26); mid values imply that we've used the median VSL estimate from Friedrich (2004) (27) and Hurley (2005) (28); high values imply that the mean VSL value from OECD (2012) (29) has been used. Table 14 presents the values for VSL and VOLY used in the monetization of main health impacts. The health impacts from air pollution are specified by the use of exposure-response functions, and in our analysis, we have used values from the WHO/EU Health Risks of air pollution in Europe (HRAPIE) project (19) (20) (30).

We use the same monetary values for human health (and for crop damage impacts) as used by the European Commission. To avoid risk of double-counting health effects from $PM_{2.5}$ and ground-level ozone, chronic mortality from ozone exposure is not included in the valuation. This approach was used in the Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package (31).

The model does not quantify all possible health effects. In particular, health effects attributable to the black carbon fraction, chronic morbidity (in addition to chronic bronchitis), infant morbidity from $PM_{2.5}$, and effects attributable to NO_2 are not included (18) (31). They may however be associated with significant healthcare costs.

[18] The VOLY and VSL approaches differ in terms of how many life years that are assumed to be lost when a fatality occurs. The VOLY method is based on life tables; it takes into account at what age people die from air pollution and gives results in terms of life expectancy. The VSL method does not use life tables and instead operates with mortality rates. As the VSL method does not take into account age or death reasons, it is sometimes considered to be overestimating health benefits from air pollution reduction (26) while VOLY approach is considered as more conservative.

Table 14. Economic value of VOLY and VSL used in this analysis.

End point	Impact	Valuation, €2015	Data source
Mortality from long term exposure (All ages) median VOLY	Life years lost	48 400	Desaigues, 2011 (26)
Mortality from long term exposure (All ages) median VOLY	Life years lost	69 800	Friedrich, 2004 (27), Hurley, 2005 (28)
Mortality from long term exposure (All ages) mean VOLY	Life years lost	167 700	Friedrich, 2004 (27), Hurley, 2005 (28)
Mortality from long term exposure (30yr +) deaths median VSL	Premature deaths	1 317 700	Friedrich, 2004 (27), Hurley, 2005 (28)
Mortality from long term exposure (30yr +) deaths mean VSL	Premature deaths	2 683 800	Friedrich, 2004 (27), Hurley, 2005 (28)
Mortality from long term exposure (30yr +) deaths mean VSL	Premature deaths	3 384 900	OECD 2012 (29)
Infant Mortality (0-1yr) median VSL	Premature deaths	1 976 500	Friedrich, 2004 (27), Hurley, 2005 (28)
Infant Mortality (0-1yr) mean VSL	Premature deaths	4 025 600	Friedrich, 2004 (27), Hurley, 2005 (28)
Infant Mortality (0-1yr) mean VSL	Premature deaths	5 077 400	Friedrich, 2004 (27), Hurley, 2005 (28), OECD 2012 (29)

3.4.2 Climate impact

The use of SunHorizon technologies is associated with changed emissions of greenhouse gases (CO_2, CH_4[19])[20], which also have a monetary value. Using economic values from the EU ETS market and the Handbook on the External Costs of Transport (32), a range of external costs of CO_2-equivalents can be estimated. The economic values used for greenhouse gas emissions are listed in Table 15.

Table 15. Economic values per tonne of CO_2-equivalent used in this analysis.

Economic value of greenhouse gases		Unit	Source
Low	20.6	€2015/tonne CO_2-eq.	Current (June 2020) EU ETS market price[21]
Mid	99.8	€2015/ tonne CO_2-eq.	EC Handbook on External Costs for Transport (2019) (32), central value
High	188.7	€2015/ tonne CO_2-eq.	EC Handbook on External Costs for Transport (2019) (32), high-end value

[19] GWP_{100}=25 is applied for CH_4, according to decision 4/CMP.7 https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

[20] Beside CO_2 and CH_4, climate is affected by air pollutants being short-lived climate pollutants (SLCPs) such as black carbon and tropospheric ozone (O_3). These impacts are not included in the analysis of climate benefits from implementation of SunHorizon technologies.

[21] http://www.nasdaqomx.com/transactions/markets/commodities, as of 2020-06-02

4 Results: LCA and Benefit assessment

The results presented below separately for LCA (Section 4.1) and for the sub-sequent analysis of environmental and health benefits (Section 4.2).

4.1 LCA results

The analysis carried out for this version of the deliverable focus mainly in the production and installation life cycle stages. Therefore, the results are presented at two levels; one set of results for each technology and another set for each technology package. Presented LCA results are preliminary. Final LCA results, based as much as possible on operational data from demonstration sites, will be presented in the final version of this deliverable (to be submitted no later than month 48).

4.1.1 LCA results per technology and technology package

The first result obtained from the LCA are the emission factors for air pollutants and greenhouse gases for SunHorizon technologies. The emission factors for average SunHorizon heat pump, solar panel, and cooling technology, are shown in Tables 16, 17 and 18, respectively. These average emission factors comprise data obtained from several producers of heat pumps and solar panel. For each SunHorizon technology, emissions from construction stage include emissions from the manufacture and the installation of Ratiotherm stratification tank.

Table 16. Average SunHorizon Heat Pump (BDR, BoostHeat, Ratiotherm).

SH Heat Pump (BDR[22], BoostHeat, Ratiotherm).					
Substance	**Unit**	**Production**	**Operation**	**Construction (Ratiotherm)**	**Total**
NO_x	g/MWh	5.68E+01	2.46E+02	3.13E+01	3.34E+02
NMVOC	g/MWh	1.24E+01	3.43E+01	1.38E+01	6.04E+01
NH_3	g/MWh	2.51E+00	2.20E+00	8.33E-01	5.54E+00
SO_2	g/MWh	9.60E+01	3.82E+02	4.59E+01	5.24E+02
$PM_{2.5}$	g/MWh	3.53E+01	4.21E+01	1.58E+01	9.32E+01
CO_2 fossil	kg/MWh	2.00E+01	1.43E+02	6.78E-01	1.63E+02
CH_4 fossil	g/MWh	6.91E+01	5.44E+02	5.20E+01	6.65E+02

[22] BDR is not involved in TP1, TP2, TP3 but included in the calculation of average emission factors for SunHorizon technologies as a one of the heat pump producers

Table 17. Average SunHorizon heating solar (TVP, DS, Ratiotherm).

SH heating solar (TVP, DS, Ratiotherm)					
Substance	Unit	Production	Operation	Construction (Ratiotherm)	Total
NO_x	g/MWh	5.57E+04	0	8.08E+03	6.37E+01
NMVOC	g/MWh	8.40E+03	0	3.55E+00	1.19E+01
NH_3	g/MWh	4.20E+02	0	2.15E-01	6.35E-01
SO_2	g/MWh	9.44E+04	0	1.18E+01	1.06E+02
$PM_{2.5}$	g/MWh	1.44E+04	0	4.06E+00	1.84E+02
CO_2 fossil	kg/MWh	2.53E+07	0	1.75E-01	2.53E+04
CH_4 fossil	g/MWh	7.51E+04	0	8.08E+03	8.85E+02

Table 18. Average SunHorizon Cooling (FAHR, Ratiotherm).

SH Cooling (FAHR, Ratiotherm)					
Substance	Unit	Production	Operation	Construction (Ratiotherm)	Total
NO_x	g/MWh	5.83E+00	1.78E+02	2.06E+00	1.86E+02
NMVOC	g/MWh	1.83E+00	1.02E+01	9.03E-01	1.29E+01
NH_3	g/MWh	5.75E-01	1.83E+00	5.47E+01	5.71E+01
SO_2	g/MWh	2.47E+01	3.23E+02	3.01E-03	3.48E+02
$PM_{2.5}$	g/MWh	2.55E+00	3.79E+01	1.03E+00	4.15E+01
CO_2 fossil	kg/MWh	1.48E+00	6.18E+01	4.45E-02	6.33E+01
CH_4 fossil	kg/MWh	5.30E+00	1.92E+02	3.41E+00	2.01E+02

The emission factors in Tables 16-18 correspond to raw life cycle inventory results from the LCA, meaning that they represent raw emissions to air and not indicators of actual environmental impact. Presented further below impact assessment (figures in Section 4.1.2) correspond to midpoint life cycle impact indicators (such as GWP, ozone layer depletion, etc.) that do measure environmental impact. Both result sets are extracted from the same LCA models, but at different levels of aggregation.

Emission factors produced within the LCA are used as inputs in the long-term scenarios (see Sections 3.2.4, 4.2.1) – the first stage of the benefit analysis presented in Section 4.2. However, to be applied in the long-term scenarios, emission factors for specific SunHorizon technologies (as exemplified in Tables 16 – 18) need to be recalculated into emission factors per technology package. In other words, for each SunHorizon technology package included in the analysis (TP1, TP2 and TP3), the aggregated emission factor at each life cycle stage needs to account for contributions from technologies included in this particular technology package.

Aggregated, or weighted average, emission factors for technology packages are presented in Table 19. These weighted emission factors are calculated based on the percentage that each technology provides for covering the total energy consumption at each demonstration site corresponding to relevant TP[23]. For example, for TP1, demonstration site in

[23] In cases when several demo sites correspond to one technology package, an average value is calculated after the emission factors for each of the demo sites are estimated.

Berlin, the total energy production is 30.2 MWh/year. Of this energy, 82.6% is supplied by the BoostHeat HP (25.0 MWh/year) and the remaining 17.4% (5.2 MWh/year) by TVP. Therefore, to calculate the production stage impact of TP1, the production impacts of BH HP is multiplied by 0,826 while the production impact of TVP is multiplied by 0,174 and then the impacts are summed up.

Table 19. Aggregated emission factors for SunHorizon technology packages.

Substance	Unit	TP1	TP2	TP3
NO_x	g/MWh	1.60E+05	1.22E+05	1.03E+05
NMVOC	g/MWh	6.96E+04	4.59E+04	3.81E+04
NH_3	g/MWh	3.09E+03	1.45E+03	2.35E+03
SO_2	g/MWh	1.88E+05	1.21E+05	1.79E+05
$PM_{2.5}$	g/MWh	4.26E+04	1.58E+04	4.48E+04
CO_2 fossil	kg/MWh	1.48E+08	1.40E+08	3.83E+07
CH_4 fossil	g/MWh	6.42E+05	6.01E+05	1.34E+05

4.1.2 LCA results for demonstration sites

The results of the comparative assessment for the different demo sites is presented in this section. The results for the demo site in Madrid were not available at the date this deliverable was prepared as no data was available. These results will be included in the final version of the deliverable in month 48. Additionally, the results for the rest of the demo sites will also be updated in the final version of the deliverable with the information from the monitoring stage.

Demo site Berlin

Figure 7 shows the results for the comparative assessment between the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario). The figures show that the impact of the SH scenario is higher in the category: "Abiotic depletion, (resources)" as a result of the consumption of raw materials for the construction and installation of the heat pump, the solar panels and the accumulation tank (TP1). On the contrary, the baseline scenario assumes that the operation of the building goes on without any modifications of the current system, therefore no additional equipment needs to be installed.

This "environmental investment" in new equipment in the SH scenario is a necessary trade-off that yields environmental benefits in other impact categories. Benefits such as a 27% reduction in CO_2 emissions, 29% reduction in the consumption of fossil fuels, 23 % reduction in the impact on the ozone layer, and 19% reduction in the impact in the "Photochemical Oxidation" category. In contrast, the switch to SunHorizon technologies results in a slight increase in the impact for Acidification and Eutrophication that stems mainly from the production of the solar panels and the increase in the consumption of electricity.

These results demonstrate that deploying SH technologies in this particular demo site results in significant benefits in terms of climate change, fossil fuel consumption, ozone layer depletion and photochemical oxidation. However, the need for new equipment increases the consumption of raw materials with the subsequent impact on water eutrophication and acidification.

These results highlight two key aspects that are required for SH technologies to achieve optimal environmental results:

- The electricity mix, which should have a high share of renewable energies (ideally 100%) to reduce the trade-off impacts derived from the switch from natural gas to electricity.
- The fate of the different pieces of equipment at the end of their service life is key to reduce the consumption of resources, the acidification and the eutrophication impacts. Extending the service life and increasing recycling rates and the use of secondary materials in the different technologies would reduce the need for virgin raw materials, balancing the consumption of resources and further lowering the overall impact of the system.

Demo site Nurnberg

Figure 8 shows the results for the comparative assessment between the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario). In this case, the figures also show that the impact of the SH scenario is higher in the category: "Abiotic depletion, (resources)" as a result of the consumption of different raw materials for the construction and installation of the heat pump, the solar panels and the accumulation tank (TP2).

The baseline scenario assumes that the building is operated with its currently installed technologies. This means that in the baseline scenario no improvements over the energy efficiency of the system are achieved, a fact that is reflected on the results, as the impact for the baseline scenario is significantly higher for the rest of impact categories. This reduction in the impact is explained by the replacement of oil and coal by natural gas, while significantly lowering the electricity consumption.

This comparative assessment is a good example of the potential benefits of a wider deployment of SunHorizon technology, although some measures should be considered to deal with the increased resource consumption. Measures such as increased share of secondary raw materials, extended service life, and appropriate end-of-life strategies.

Figure 7. LCA results for demo site Berlin, Germany.

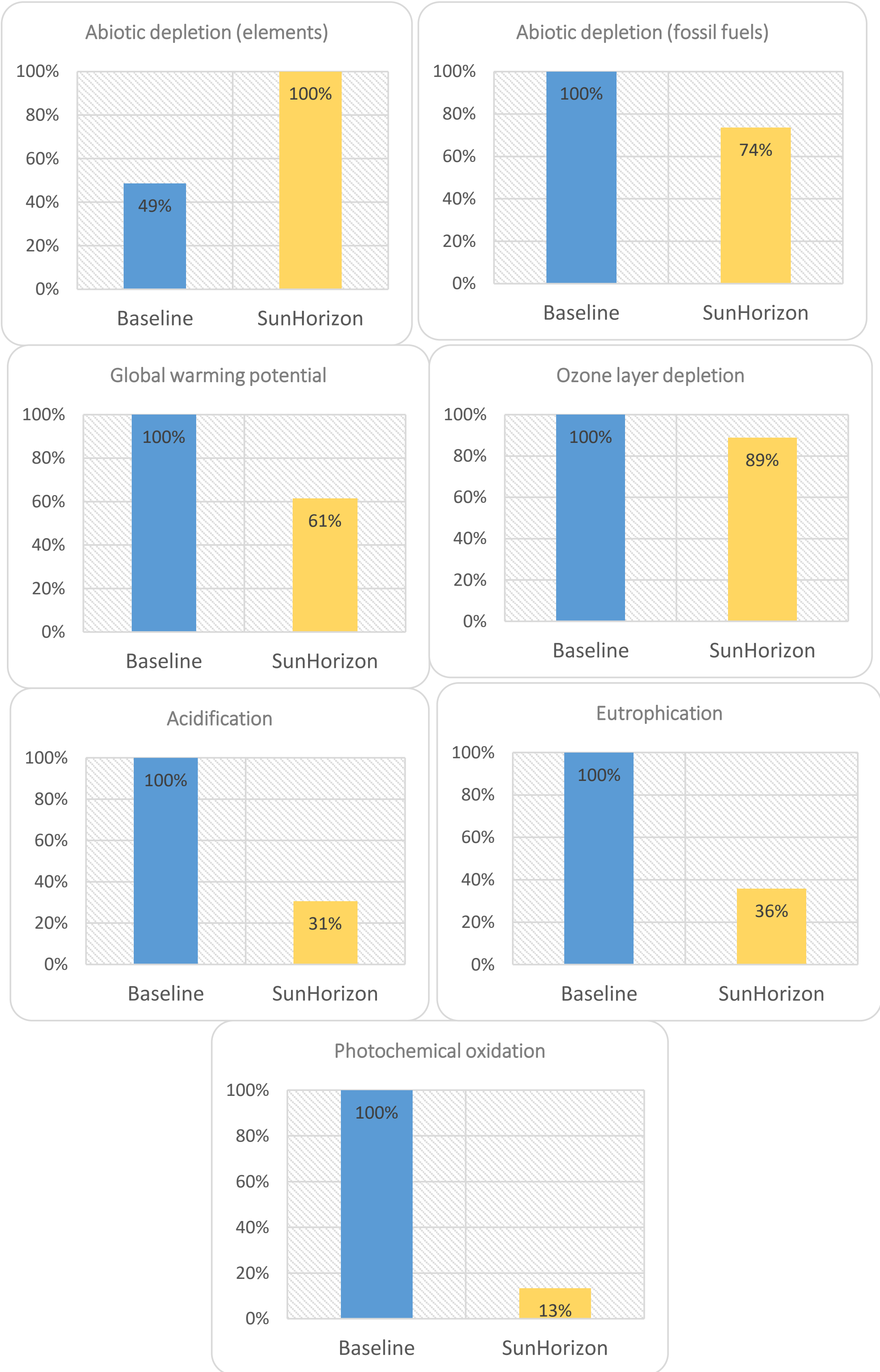


Figure 8. LCA results for demo site Nurnberg, Germany.

Demo site Sant Cugat del Vallés

Figure 9 shows the results of the comparative assessment between the baseline scenario (Business-as-usual), and the SH scenario in the demonstrator at Sant Cugat del Vallés. In this case, the impact of the SH scenario is again higher in the category: "Abiotic depletion, (resources)" as a result of the consumption of raw materials for the construction of the cooling system, the solar panels and the accumulation tank.

In this demo site, the meaningful reduction in the energy consumption outweighs the consumption of resources, as the results show that significant reductions for the rest of the categories are achieved as a consequence of the use of TP3 technology. This yields around a 60 % reduction for all the categories except for abiotic depletion. In this situation, an end-of-life scenario with a significant recycling rate for all the components is a must to reduce the need for virgin raw materials, and minimising the impact linked to the implementation of this technology.

Demo site Madrid

At this point of the project, there is no information available for this demonstrator. Over the course of the project, new information will be collected, and the results will be presented in the final version of the deliverable in month 48.

Demo site Verviers (sports centre)

Figure 10 shows the results of the comparative assessment between the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario) for the Verviers demo site (sports centre). This demo site, as the one in Berlin, employs the TP1, so the results follow the same trend with higher resource abiotic depletion, eutrophication and acidification but lower impacts for all the remaining categories.

Demo site Verviers (swimming pool)

The results of the comparative assessment for the swimming pool in Verviers are shown in Figure 11, evaluating the impact of the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario). The results follow the same trend as for Nurnberg, as both scenarios use the same technologies. The results follow the same trend as for Nurnberg, as both scenarios use the same technology. The impact for the category: "Abiotic depletion elements" is higher for the SH scenario because of the construction and installation of the new equipment. However, the use of the highly-efficient SH technologies results in a reduction in the consumption of electricity and natural gas, which is translated into environmental benefits for the rest of the impact categories, especially for the consumption of fossil fuels (28% reduction) and the emission of greenhouse gases (28% reduction).

Demo site Riga (Imanta)

The results of the comparative assessment for the first demo site in Riga, in this case in Imanta, are shown in Figure 12, evaluating the impact of the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario). Again, the results replicate the previous results for the other demos using TP2. The construction and installation stage of the equipment required for the SH scenario is responsible for the higher impact in abiotic depletion of elements. Nonetheless, the benefits for the rest of the categories are significant, with reductions ranging from 12% to 68 %.

Demo site Riga (Sunisi)

Finally, the results of the comparative assessment between the baseline scenario (Business-as-usual), and the scenario resulting from the application of SunHorizon technologies (SH scenario) in Riga (Sunisi) are shown in Figure 13. The charts show that the higher impact in the category Abiotic Depletion of elements resulting from the construction of the different pieces of equipment is overcome by the reduction in the impact for the rest of the categories under study. This reduction is consequence of the lower energy consumption of the highly efficient SunHorizon technologies.

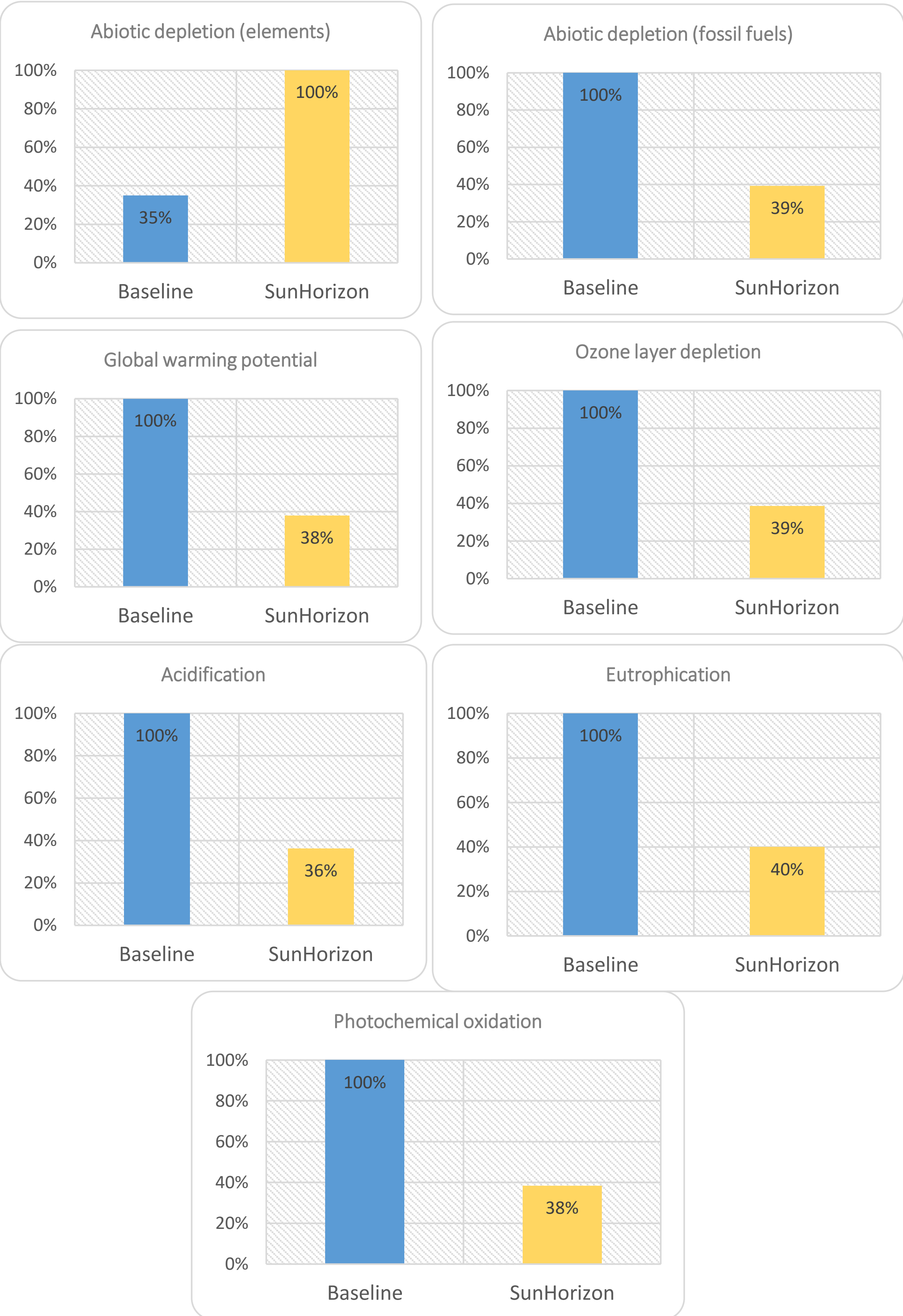


Figure 9. LCA results for demo site Sant Cugat del Vallés, Spain.

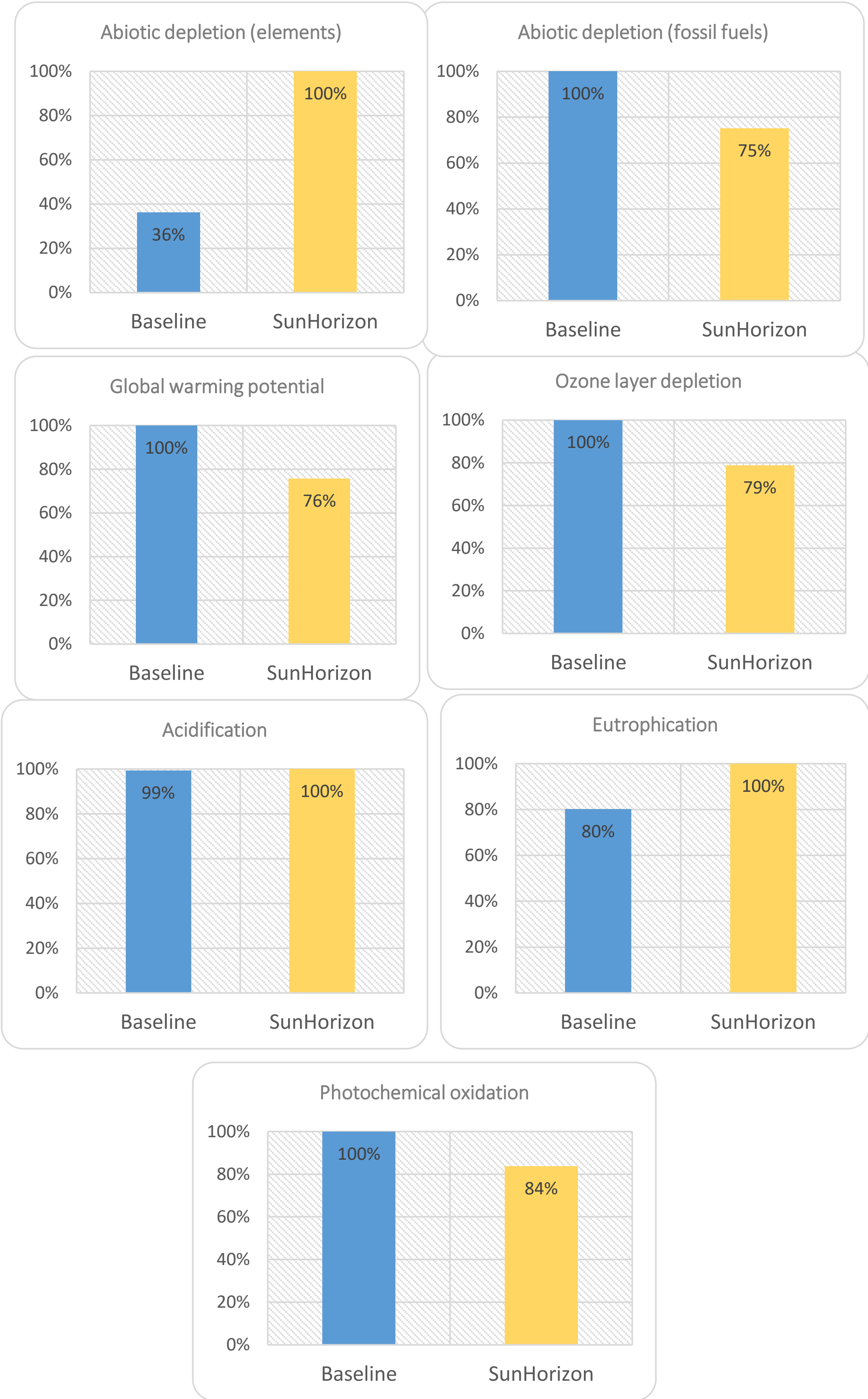


Figure 10. LCA results for demo site Verviers (sports centre), Belgium.

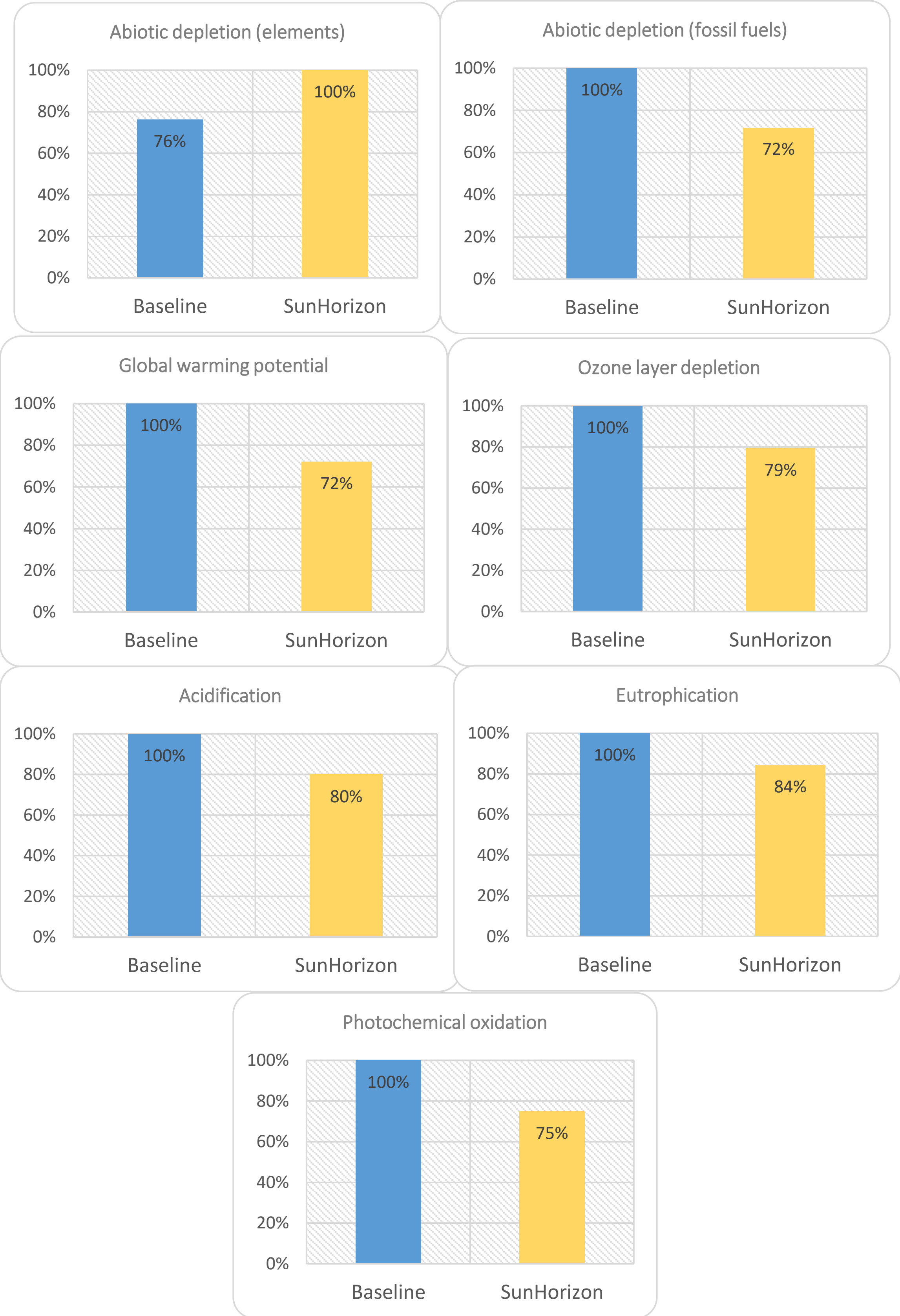


Figure 11. LCA results for demo site Verviers (swimming pool), Belgium.

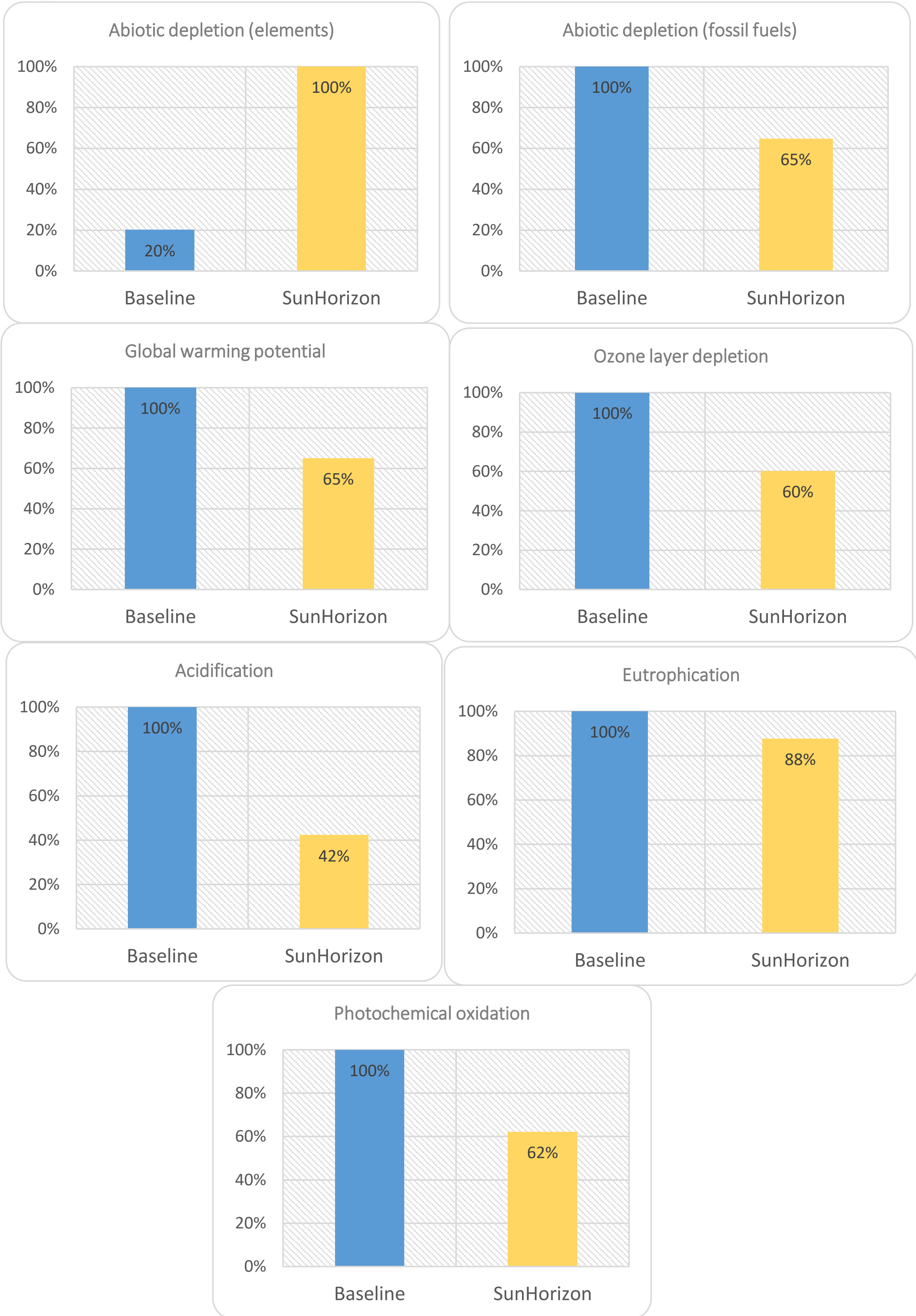


Figure 12. LCA results for demo site Riga (Imanta), Latvia.

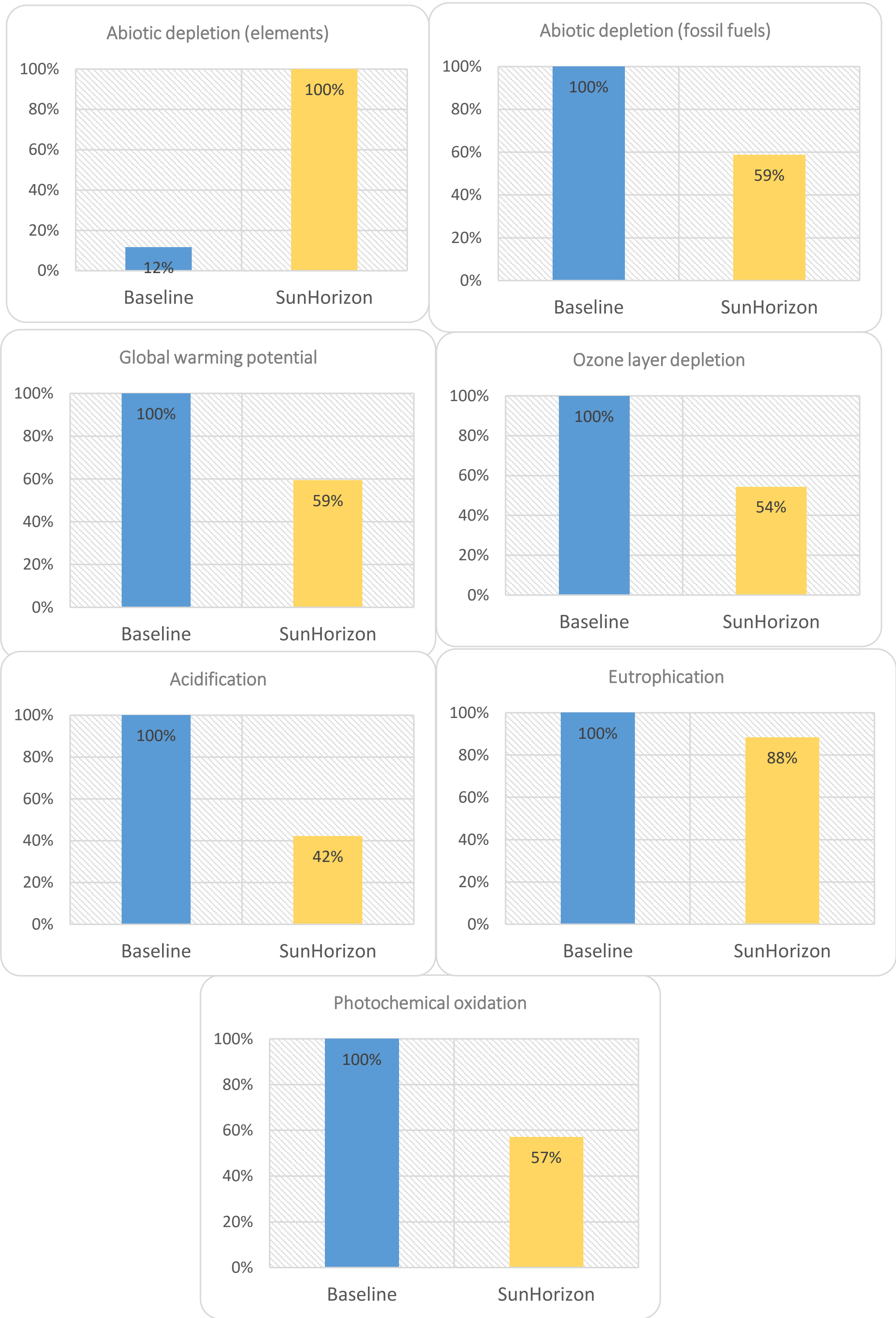


Figure 13. LCA results for demo site Riga (Sunisi), Lavtia.

4.2 Environmental and health benefits

Benefits to health and environment are calculated for each of SunHorizon scenarios, for target years 2030 and 2050.

4.2.1 Long-term scenarios: Emissions on country level

Country-specific annual emissions are estimated as explained in Section 3. Emission calculations are based on the estimated demand values for heating and cooling purposes in the residential and tertiary sector for each scenario (as summarized in Figures 4 and 5, and Annex 3) and on the emissions factors retrieved from the LCA-analysis (see Table 12 in Section 3.2.4).The total emissions of air pollutants and greenhouse gases in EU-28, as calculated for the baseline scenario and SunHorizon scenarios, are illustrated in Figure 14. Certain emission reductions (12-20% in 2050, in relation to the 2020-level) due to energy efficiency-increasing measures, fuel/technology shifts and pollution abatement measures are implied in the baseline scenario. With implementation of SunHorizon technologies, emissions of most substances decrease further – by 17-22% for NO_x, 47-52% – for SO_2, 3-18% – for $PM_{2.5}$, and 32-41% – for NMVOC. Emissions of NH_3 are estimated to be decreasing in the scenario SH_TP2 (by 12%, compared to the baseline level in 2050), while for SH_TP1 emissions increase by 2%.

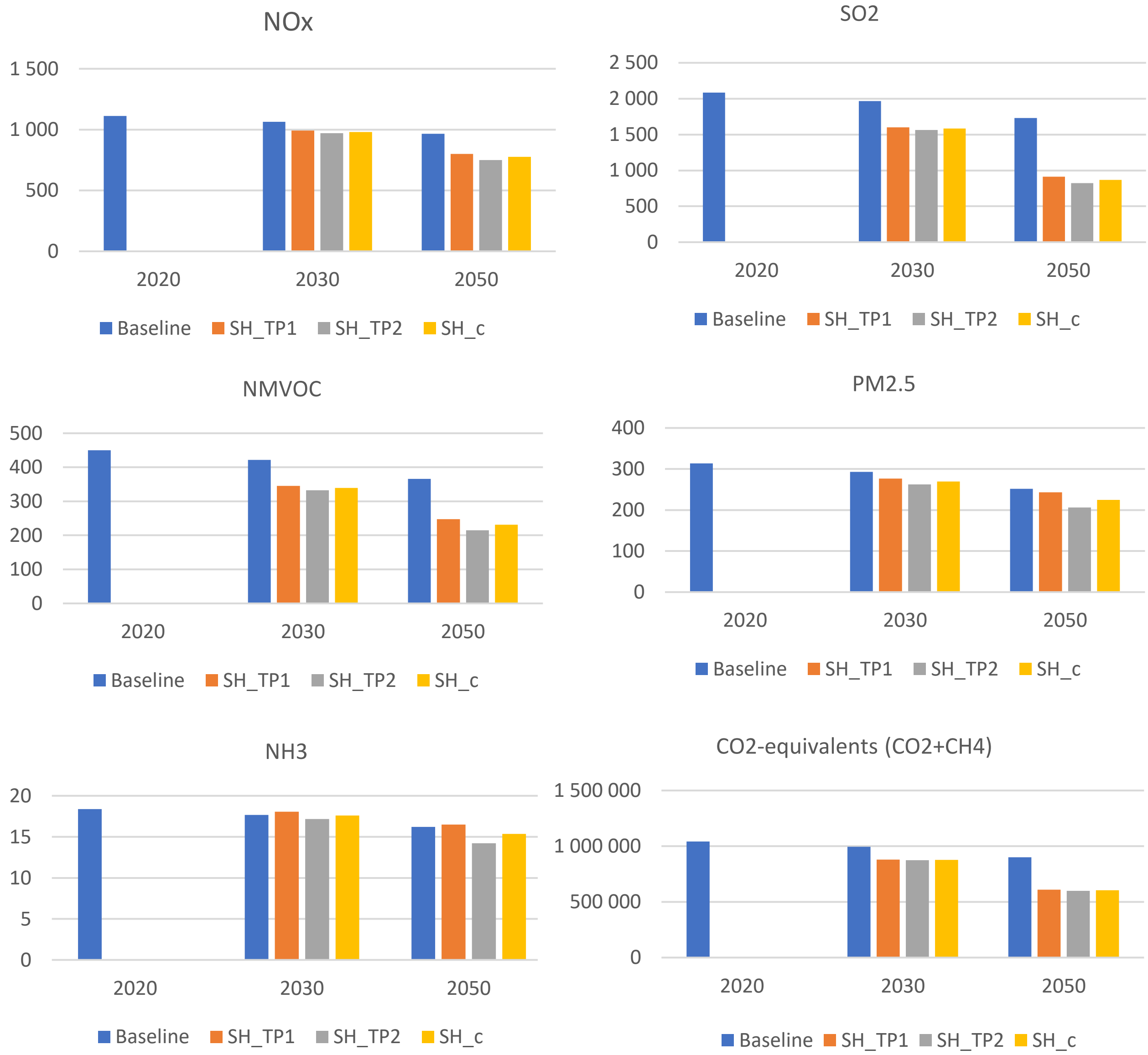


Figure 14. Emissions of main air pollutants and greenhouse gases in the residential and tertiary sector in EU-28, ktonnes.

Emissions of main air pollutants and greenhouse gases from each country in each of the considered scenarios are summarized in Annex 4. In most countries, implementation of SunHorizon technologies result in emission reductions. Percentual emission reductions differ between countries – see Figures 15-20 illustrating emission changes in 2050 in relation to the baseline level. Figures 15-20 indicate that country-specific emission changes correlate with the assumed level of conventional technology replacement by SunHorizon technologies.

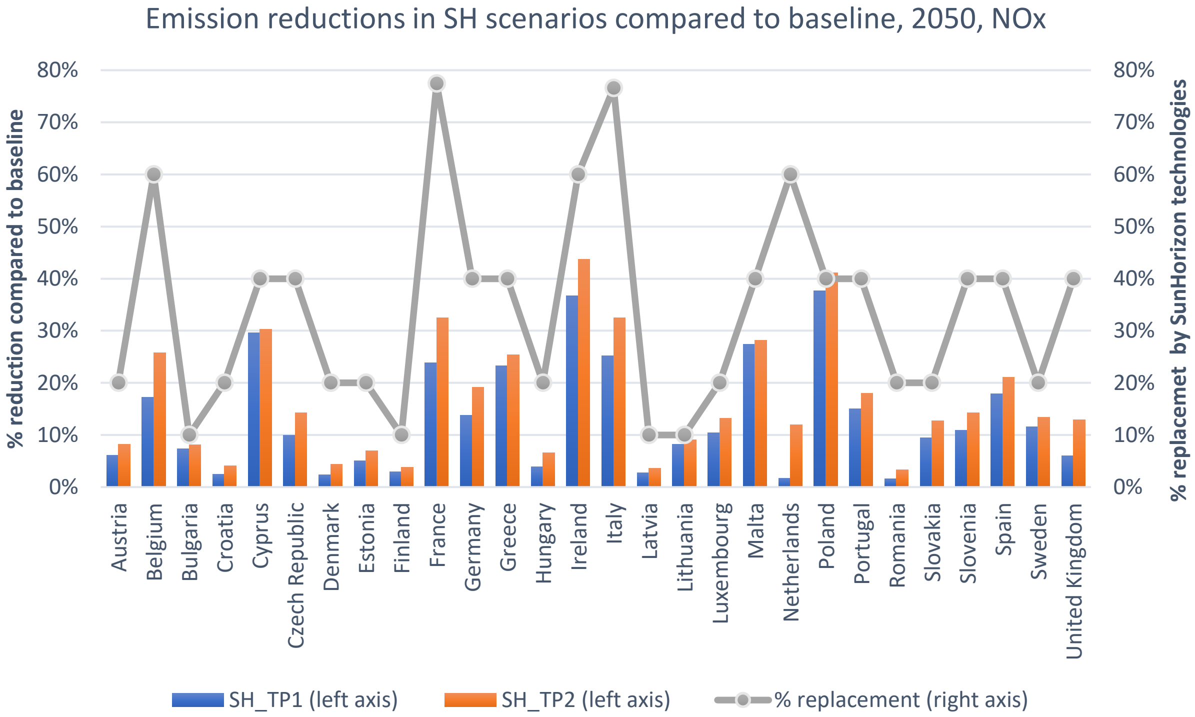


Figure 15. Country-specific emission changes in 2050 in relation to the baseline level, NO_x.

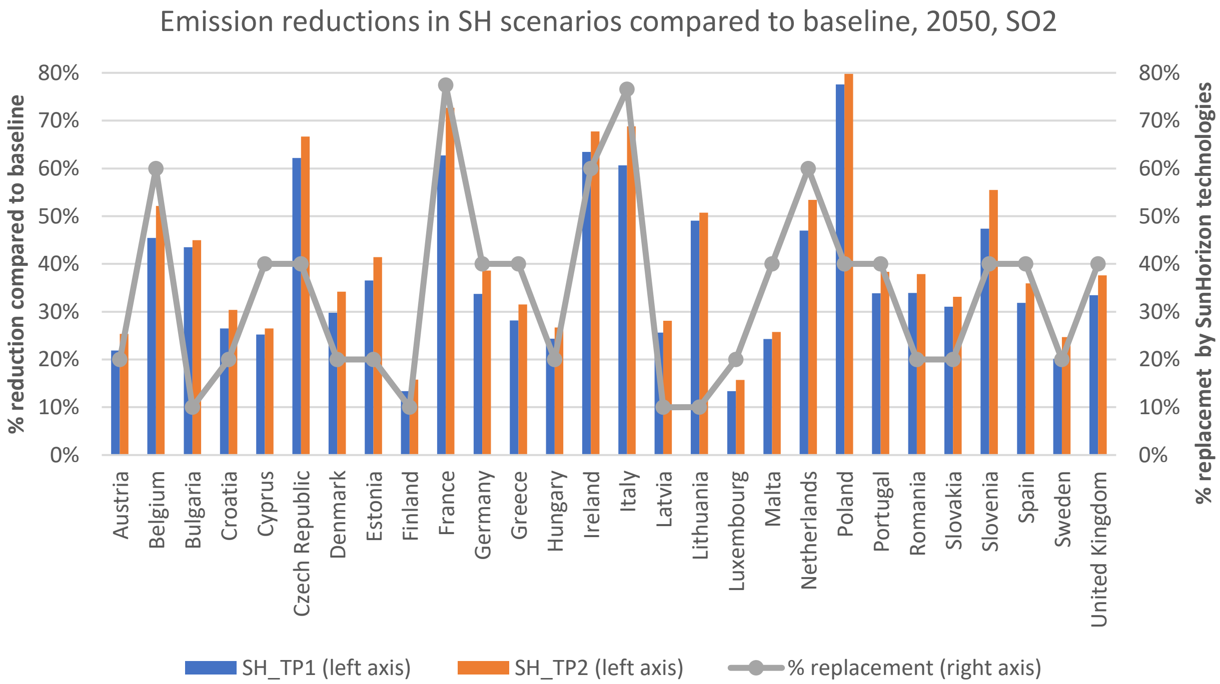


Figure 16. Country-specific emission changes in 2050 in relation to the baseline level, SO_2.

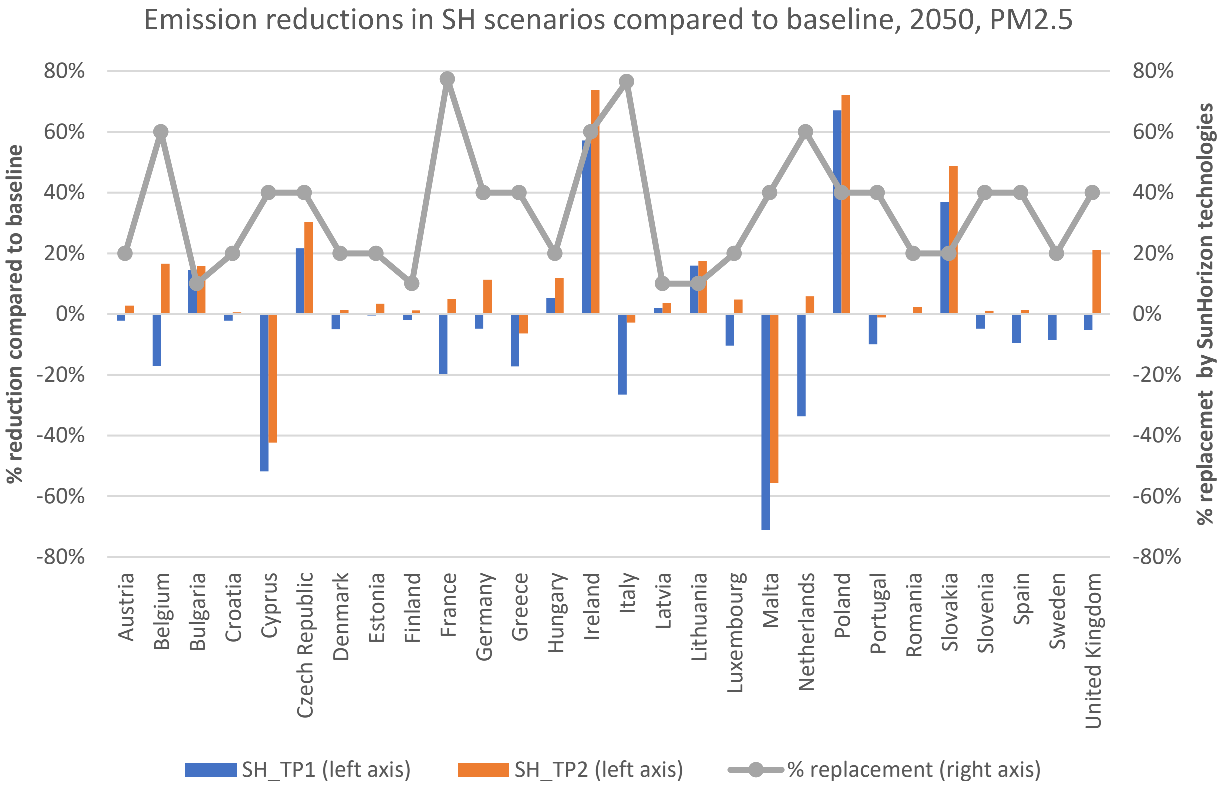


Figure 17. Country-specific emission changes in 2050 in relation to the baseline level, $PM_{2.5}$.

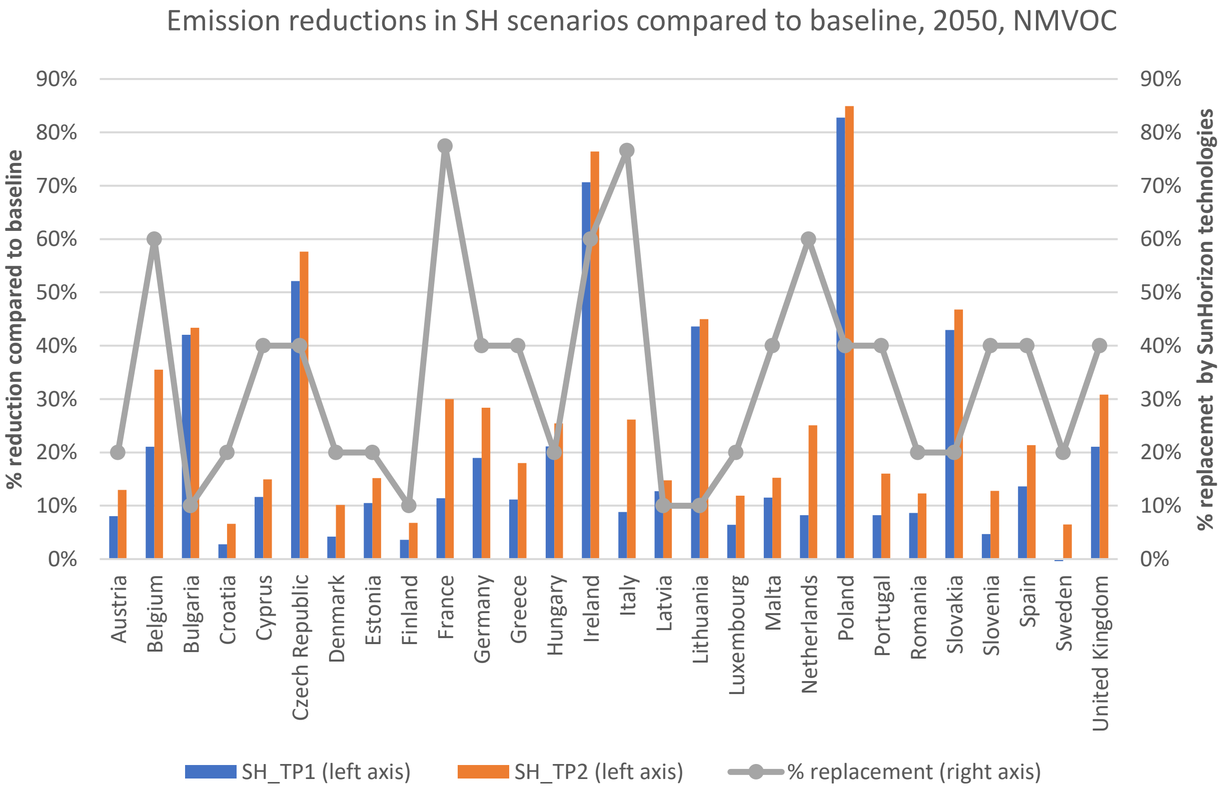


Figure 18. Country-specific emission changes in 2050 in relation to the baseline level, NMVOC.

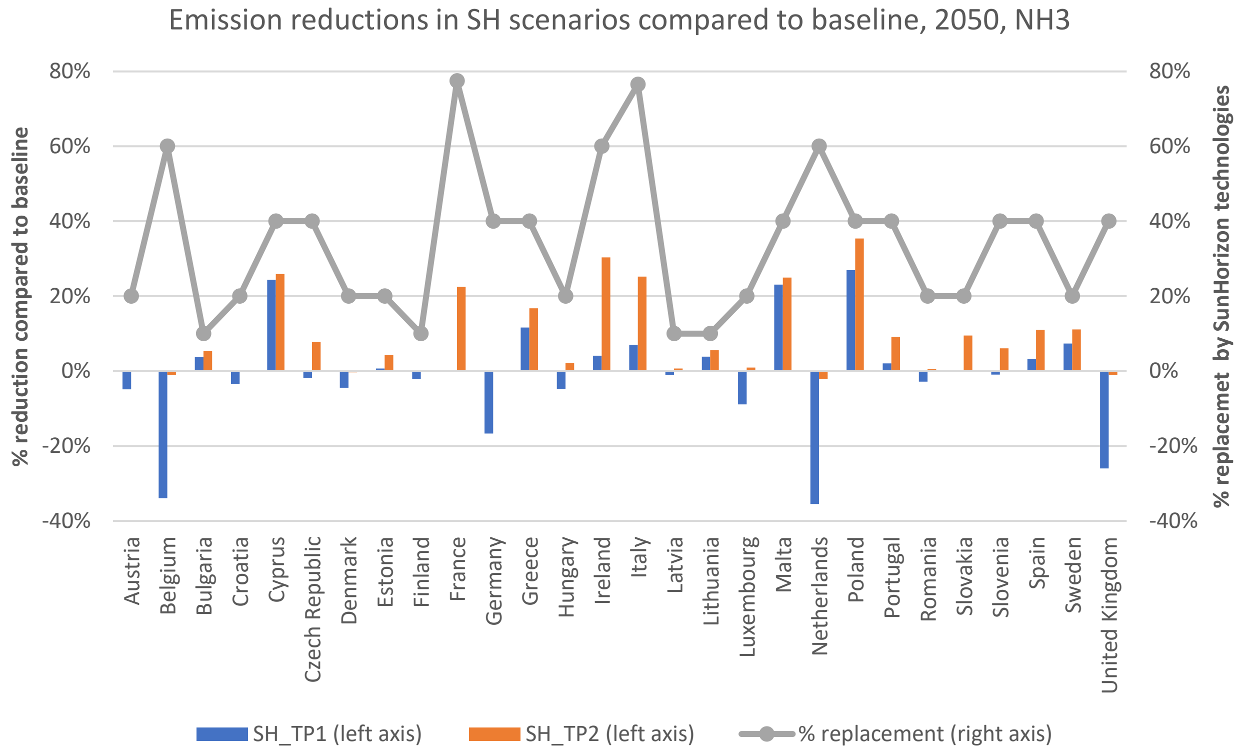


Figure 19. Country-specific emission changes in 2050 in relation to the baseline level, NH_3[24].

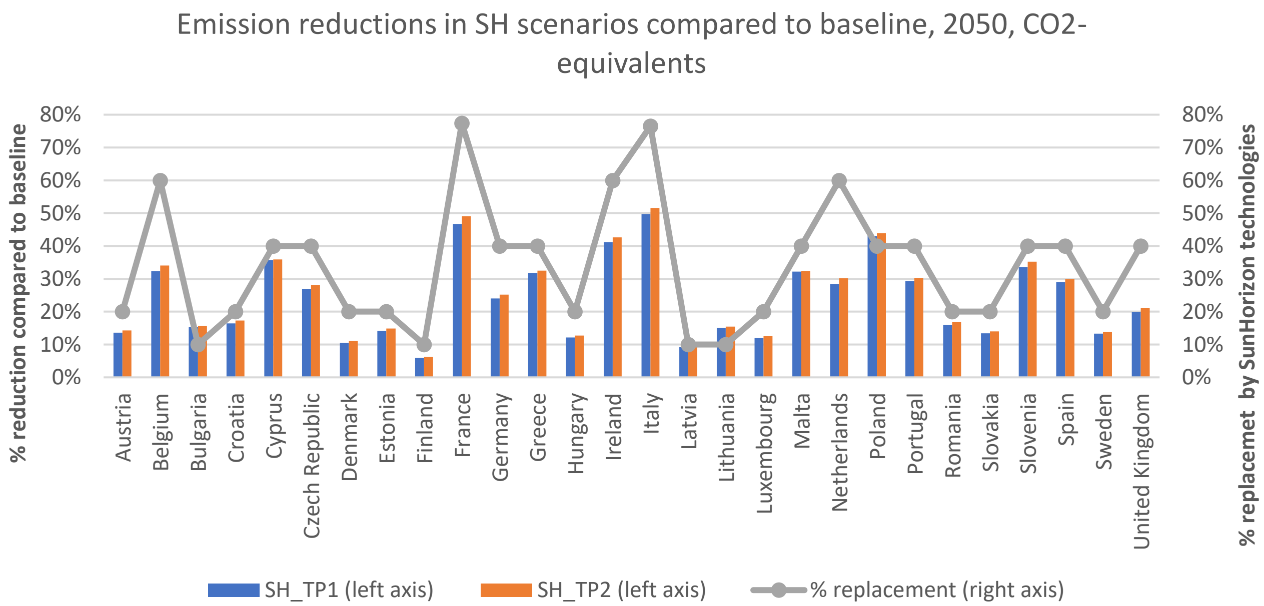


Figure 20. Country-specific emission changes in 2050 in relation to the baseline level, CO_2-equivalents.

[24] The main reason for increasing emissions of NH_3 in the scenario *SH_TP1* is significant difference between LCA emission factors for *SH_TP1* and for conventional gas boilers. According to the Ecoinvent v3.5 database, NH_3 emissions for TP1 mainly come from the production of silicon wafers for the solar panels, silver mining operations related to silver extraction to produce solar panels, and metal extraction for the production of Printed Wired Boards and other electronic components for BH heat pump. Conventional gas boilers have lower NH_3 emissions since the main contribution here is the extraction of copper for its use in different components of the boiler. The higher emissions linked to TP1 construction stage are not offset by the reduction in energy consumption.

4.2.2 GAINS modelling: End-point exposure

Main results from GAINS modelling are end-point exposure – population-weighted $PM_{2.5}$ concentrations and ozone exposure (SOMO35). As explained in Section 3.3 above, health benefits are in direct proportion to the relative, not absolute, exposures. Annex 5 presents differences between country-specific population-weighted $PM_{2.5}$ concentrations and ozone exposure in the baseline scenario and the same exposure metrics in scenarios *SH_TP1, SH_TP2* and *SH_c*. The differences on the European level are presented in Figure 21. As a result of the emission reductions in SunHorizon scenarios, exposure to harmful concentrations of $PM_{2.5}$ and ozone decreases over time.

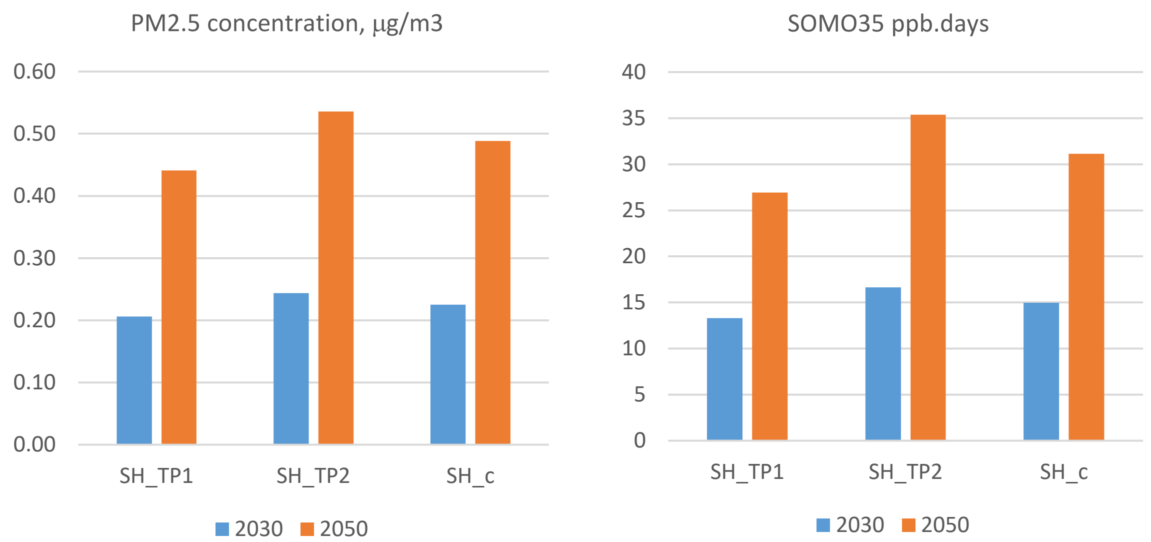


Figure 21. Scenario-specific differences in average end-point exposure to harmful pollutants in Europe (all countries in the ARP model, including non-EU countries).

4.2.3 ARP modelling: Health effects, valuation of benefits

Table 20 summarizes reductions in negative health effects from air pollution in EU-28 due to implementation of SunHorizon technologies.

Table 20. Reductions of health effects from air pollution in EU-28 due to implementation of SunHorizon technologies.

Health effect	Unit	SH_TP1		SH_TP2		SH_c	
		2030	2050	2030	2050	2030	2050
Chronic mortality from $PM_{2.5}$, all ages	10^3 life years lost	103	203	121	246	112	225
Acute mortality from ozone, all ages	Deaths	196	457	245	602	221	530
Chronic Bronchitis, >27 years	10^3 cases	9	21	11	25	10	23
Bronchitis in children, 6-12 years	10^3 added cases	30	64	36	78	33	71
Respiratory hospital admissions, >18 years	10^3 cases	4.1	8.7	4.8	10.5	4.4	9.6
Cardiac Hospital Admissions, >18 years	10^3 cases	3.2	6.9	3.8	8.4	3.5	7.7
Restricted Activity Days, all ages	10^6 days	13	29	15	35	14	32
Asthma symptom days, children 5-19 years	10^3 days	318	681	378	838	348	760
Lost working days, 15-64 years	10^6 days	3.2	6.1	3.7	7.3	3.4	6.7

Figures 22 and 23 present monetary values of reduced negative health effects – these values, estimated with methodology described in Section 3.4.1, correspond to avoided health damage, or health benefits. Figure 22 illustrates health benefits in EU-28 – the same countries where emissions are reduced. Figure 23 illustrates the total health benefits over all European countries from the same emission reductions. The figures indicate that about 5 – 7 % of health benefits from emission reductions in EU-28 occur in non-EU countries – this is due to long-range trans-boundary effects of air pollution.

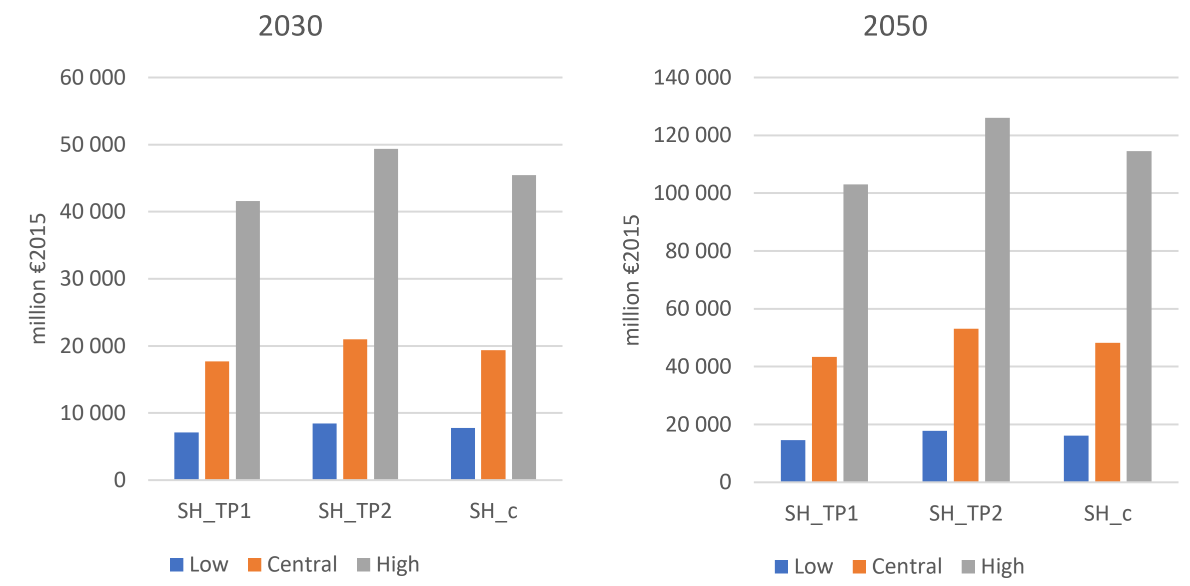


Figure 22. SunHorizon scenarios – health benefits in EU-28.

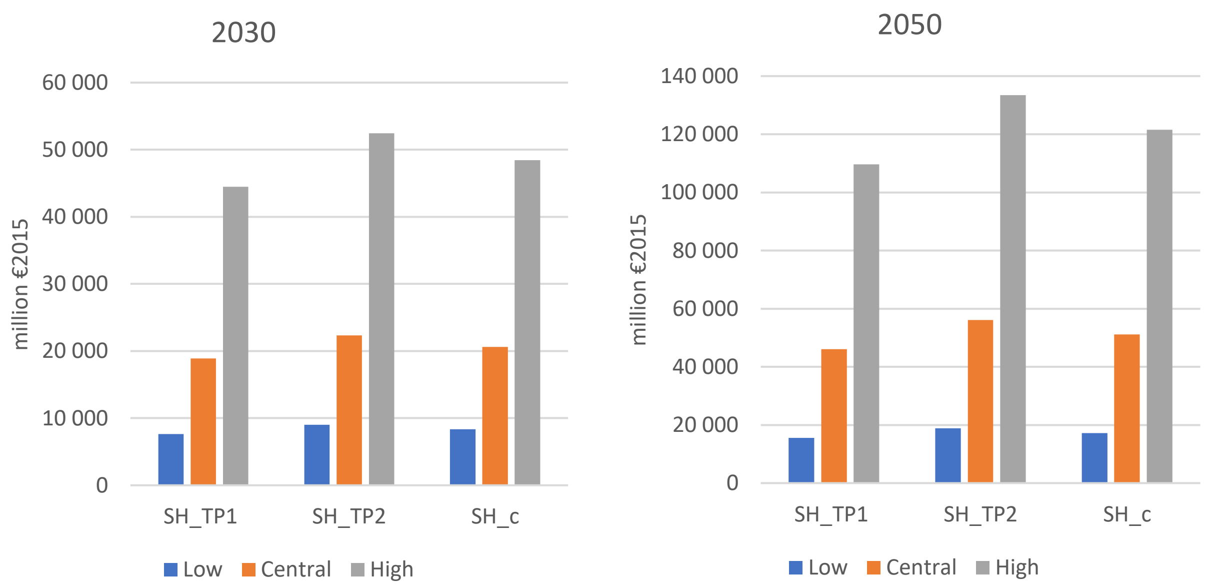
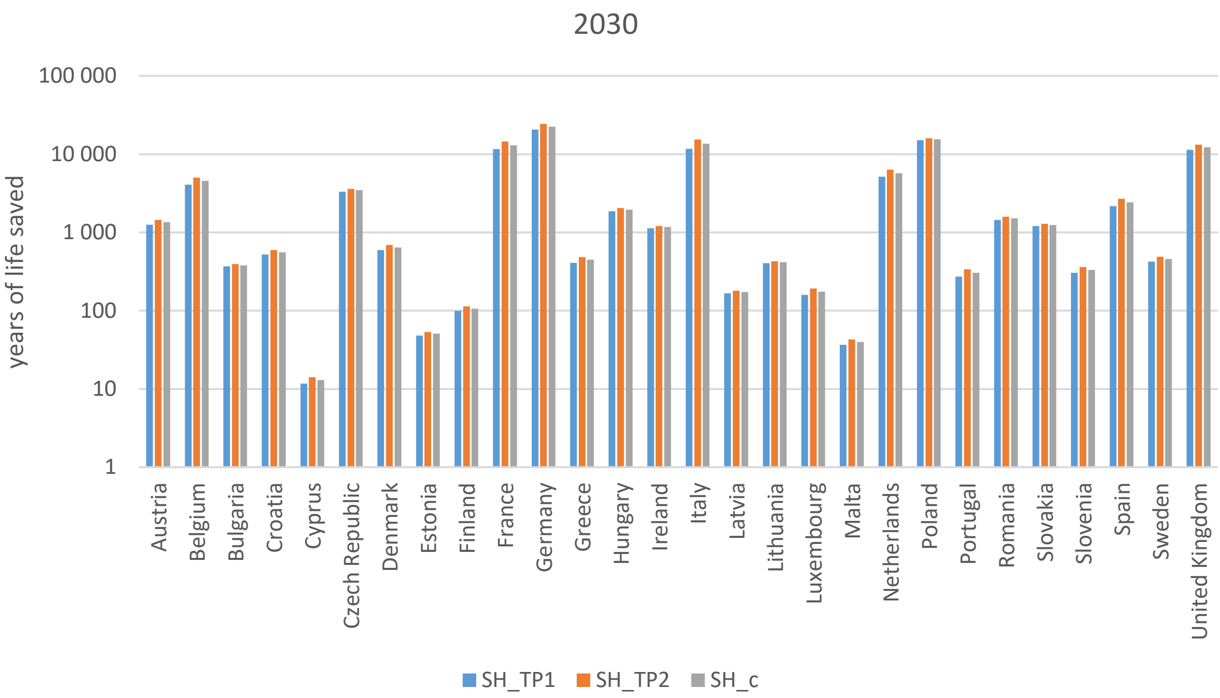


Figure 23. SunHorizon scenarios – health benefits in all European countries (as in ARP).

The most significant health effect – reduced premature mortality as life years saved – is illustrated in Figure 24 where the numbers are presented per country. Differences between countries arise not only from different levels of emissions, but also from different population density and structure (age distribution), and country's geographical location. In some cases, small countries without quite low levels of own emissions can be affected by neighbouring countries where emission levels are much higher.



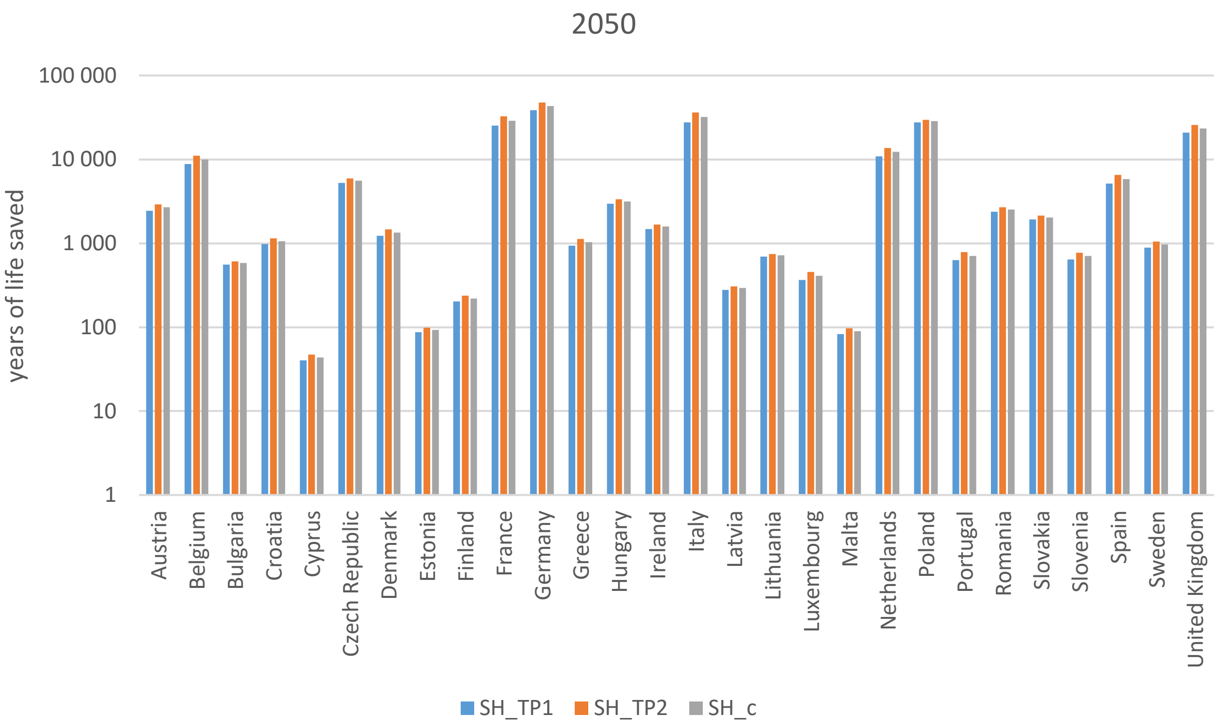


Figure 24. Reduced premature mortality in SunHorizon scenarios, life years saved.

The total number of life years saved in EU-28 due to implementation of SunHorizon technologies amounts to 96 – 113 thousand in 2030 and 189 – 231 thousand – in 2050. If life years saved in all European countries are taken into account, these numbers increase by 7 – 8%: to 103 – 121 thousand life years saved in 2030, and 203 – 246 thousand – in 2050.

Low, central and high estimates of health benefits per country in monetary terms are presented in Annex 6.

4.2.4 Valuation of climate impact

Climate impact from greenhouse gas emissions is of global character and thus is not estimated or valued per country. Instead, the low, central and high values (Table 15) are applied to the differences in estimated greenhouse gas emissions (CH_4 and CO_2) between the baseline and the SunHorizon scenarios. The results are illustrated in Figure 25.

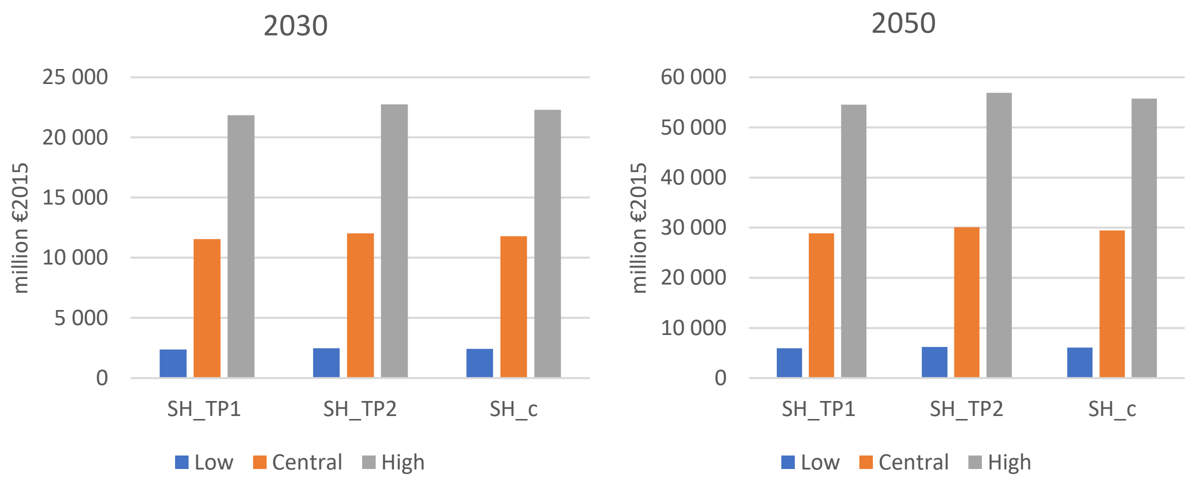


Figure 25. SunHorizon scenarios – valuation of climate impacts.

Relative input of CH_4 in the resulting climate impact is rather low – 3-4%. Major part of climate-related benefits from implementation of SunHorizon technologies is achieved by reductions of CO_2 emissions.

4.2.5 Total benefits from implementation of SunHorizon technologies

Total estimated benefits from implementation of SunHorizon technologies comprise health effects (dominated by reduced premature mortality) and climate impact. In Table 21, total benefits in EU-28 are summarized per scenario. As noted in Section 4.2.4, health benefits are even larger if all European countries are taken into consideration.

Table 21. Total health and climate benefits in EU-28 from implementation of SunHorizon technologies.

Impacts	Benefits in 2030, million $€_{2015}$			Benefits in 2050, million $€_{2015}$		
	SH_TP1	SH_TP2	SH_c	SH_TP1	SH_TP2	SH_c
Human Health, low	7 100	8 400	7 800	14 500	17 800	16 200
Human Health, mid	17 700	21 000	19 300	43 300	53 100	48 200
Human Health, high	41 600	49 300	45 500	103 000	126 100	114 500
Climate impact, low	2 400	2 500	2 450	6 000	6 200	6 100
Climate impact, mid	11 600	12 000	11 800	28 900	30 100	29 500
Climate impact, high	21 800	22 800	22 300	54 600	56 900	55 700
Total, low	**9 500**	**10 900**	**10 250**	**20 500**	**24 000**	**22 300**
Total, central	**29 300**	**33 000**	**31 100**	**72 200**	**83 200**	**77 700**
Total, high	**63 400**	**72 100**	**67 800**	**157 600**	**183 000**	**170 200**

The total health and climate benefits in EU-28 from SunHorizon technologies application in scenario with the largest benefits (*SH_TP2*) are estimated at 11 – 72 billion $€_{2015}$ in 2030 and 24 – 183 billion $€_{2015}$ in 2050. The benefits increase by 120 – 154% (13 – 111 billion $€_{2015}$) from 2030 to 2050, along with higher implementation rates of SunHorizon technologies. In *SH_TP1*, total health and climate benefits are estimated at 9.5 – 63 billion $€_{2015}$ in 2030 and 21 – 158 billion $€_{2015}$ in 2050. The benefits increase by 116 – 148% (11 – 95 billion $€_{2015}$) from 2030 to 2050.

5 Discussion and Conclusions

5.1 LCA

The results of the LCA show that the implementation of the different SunHorizon technologies across the different demonstration sites result in significant environmental benefits, especially in terms of climate change, ozone layer depletion, consumption of fossil fuels and photochemical oxidation. In particular, TP2 and TP3 show significant environmental benefits for every impact category apart from Abiotic Depletion of resources. TP1 performs slightly worse in Acidification and Eutrophication, a trade-off resulting from the increase in electricity consumption, although it achieves meaningful reductions for climate change, consumption of fossil fuels, impact on the ozone layer and photochemical oxidation. For example, on average, reductions of 25.5% were achieved for TP1, 35.75% for TP2 and 62% for TP3 for the Global Warming category.

This means that the large-scale deployment of SunHorizon technologies replacing conventional heating and cooling technologies would largely reduce the environmental footprint of the building stock, contributing to the objectives of carbon neutrality that the European Union has set for the next decades. However, these benefits are coupled to an increased consumption of resources, as a consequence of the construction and installation of the different components that are part of SunHorizon technologies. This is an important aspect that needs to be addressed to minimize the impact of the project, and suitable strategies to reduce the consumption of raw materials should be adopted, such as the use of secondary raw materials and service-life extension.

It is important to say that this is a partial cradle-to-gate assessment with preliminary data for the operation of the demo sites. A more comprehensive analysis will be performed in the coming stages of the project as the monitoring stage progresses, providing more detailed information that will be presented in the updated version of this deliverable in M48.

5.2 Health and climate benefits

When estimating health and environmental effects due to use of SunHorizon technologies in comparison to the use of conventional heating and cooling technologies, significant benefits are found. The benefits partly occur from reduced climate impact of emitted greenhouse gases, but mostly – from reduced negative health effects caused by air pollution. Assessment of the health and climate benefits from implementation of SH technologies are presented as ranges. Considered uncertainties arise in the different approaches to valuation discussed in Section 3.4. Uncertainties in the applied emission factors for H&C technologies are not accounted for in the present analysis, neither are uncertainties in the projected deployment rates of SH technologies and total H&C demand in the residential and tertiary sector.

In the developed long-term SunHorizon scenarios, we assume that part of the conventional technologies for heating and cooling in the residential and tertiary sector will be replaced by SunHorizon technologies. The EU-28-average share of the replaced technologies is estimated at 11% in 2030 (with country variations from 3% to 26%) and 34% in 2050 (with country variations from 10% to 77%). Corresponding differences in emissions of main air pollutants between SunHorizon scenarios and the baseline scenario in EU-28 are calculated to 366-402 ktonnes of SO_2, 15 – 30 ktonnes of $PM_{2.5}$, 77 – 89 ktonnes of NMVOC, -0.4 – 0.5 ktonnes of NH_3, and 72 – 92 ktonnes of NO_x in 2030. In 2050, the corresponding numbers are 816 – 907 ktonnes of SO_2, 8 – 45 ktonnes of $PM_{2.5}$, 119 – 151 ktonnes of NMVOC, -0.3 – 2.0 ktonnes of NH_3, and 165 – 216 ktonnes of NO_x. There are certain variations in emission changes between countries, caused by different replacement rates assumed in SunHorizon scenarios, and by different baseline energy demands for heating and cooling. Emission reductions are larger in *SH_TP2* scenario than in *SH_TP1*, which is explained by lower life-cycle emission factors for air pollutants of TP2 technologies.

Lower emissions main pollutants from SH technologies, compared to conventional technologies, result in lower concentrations of primary and secondary $PM_{2.5}$ and ground-level ozone, and subsequently reduced premature mortality and other negative health effects. The European average population-weighted concentration of $PM_{2.5}$ in SunHorizon scenarios decreases by 0.21 – 0.24 ug/m3 in 2030, and 0.44 – 0.54 ug/m3 in 2050, compared to baseline levels the same years. For ozone exposure the differences are 13 – 17 ppb. days in 2030 and 27 – 35 ppb. days in 2050. Reduced exposure levels in 2030 result in 96 – 113 thousand life years saved in EU-28 and 103 – 121 thousand life years saved

– in all European countries. In 2050, number if the life years saved is 189 – 231 thousand for EU-28 and 203-246 thousand – for all European countries.

In monetary terms, health benefits estimated for EU-28 from implementation of SunHorizon technologies in EU-28 in 2030 are estimated at 18 (7.1 – 42) billion $€_{2015}$ for *SH_TP1*, 21 (8.4 – 49) billion $€_{2015}$ for *SH_TP2*, and 19 (7.8 – 46) billion $€_{2015}$ for *SH_c*. In 2050, the benefits become higher: 43 (15 – 103) billion $€_{2015}$ for *SH_TP1*, 53 (18 – 126) billion $€_{2015}$ for *SH_TP2*, and 48 (16 – 115) billion $€_{2015}$ for *SH_c.* If health effects in the entire Europe, including non-EU countries, are taken into account, the benefits are 6 – 7% higher. This is due to trans-boundary pollution effects meaning that emitting countries affect not only own population but population in other countries as well. Trans-boundary effects also partly explain variations in the health and climate benefits between the EU Member States – for instance, in 2030, the range is from ~2 million $€_{2015}$ in Cyprus to 4 – 5 billion $€_{2015}$ in Germany (central values). Differences between countries arise also from different levels of emissions as well as from different population density and structure (age distribution).

When we add values for external costs of GHG emissions (CO_2 and CH_4), the monetized effect is further increased. The total health and climate benefits for *SH_TP1* are estimated at 29 (9.5 – 63) billion $€_{2015}$ in 2030 and 72 (21 – 158) billion $€_{2015}$ in 2050. For *SH_TP2*, the corresponding numbers are 33 (11 – 72) billion $€_{2015}$ in 2030 and 83 (24 – 183) in 2050. The combined scenario *SH_c* results in 31 (10 – 68) billion $€_{2015}$ health and climate benefits in 2030 and 78 (22 – 170) – in 2050. About 60 – 80% of these benefits are due to reduced negative health effects, dominated by premature mortality. The total health and climate benefits in EU-28 are expected to increase by 116 – 154% (43 – 50 billion $€_{2015}$ with central values) from 2030 to 2050, due to wider implementation of SunHorizon technologies. It is worth to notice that positive effect on climate of SunHorizon technologies is most probably underestimated, since climate impacts of SLCPs are not included in the analysis.

From the analysed SunHorizon scenarios, *SH_TP2* seems to bring the highest benefits in a form of reduced harmful health effects and climate impact – 33 billion $€_{2015}$ in 2030, compared to 29 billion $€_{2015}$ in *SH_TP1* the same year (central values). In 2050, the difference between two scenarios becomes larger: 83 billion $€_{2015}$ in *SH_TP1*, compared to 72 billion $€_{2015}$ in *SH_TP2* (central values). The combined scenario, implying equal implementation rates of the two alternative SunHorizon heating technologies, results, as expected, in the benefit values lying in-between the results of the *SH_TP1* and *SH_TP2*.

Quantification of environmental and health effects and setting monetary values on the related benefits provides investors and strategic decision-makers with scientific background analysis for justification of SunHorizon technologies' wider deployment in the coming years.

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Annex 3. Long-term scenarios: Heating and cooling demand in the baseline scenario

Table 3.1. Heating demand in 2020.

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
Austria	78.6	23%	0%	23%	9%	24%	1%	17%	3%
Belgium	112.4	6%	1%	1%	8%	49%	0%	34%	1%
Bulgaria	23.7	37%	7%	21%	17%	7%	2%	2%	7%
Croatia	26.8	49%	0%	7%	6%	28%	0%	7%	3%
Cyprus	2.8	8%	0%	0%	8%	0%	0%	47%	37%
Czech Republic	80.1	19%	8%	23%	10%	40%	0%	0%	0%
Denmark	54.7	19%	0%	49%	7%	17%	1%	7%	0%
Estonia	11.3	32%	1%	38%	12%	12%	1%	3%	1%
Finland	71.9	18%	0%	41%	27%	1%	2%	10%	1%
France	490.2	16%	0%	4%	15%	44%	1%	20%	0%
Germany	828.8	11%	1%	9%	5%	43%	1%	29%	1%
Greece	41.4	17%	0%	1%	11%	14%	2%	47%	8%
Hungary	71.8	14%	2%	10%	7%	65%	0%	2%	0%
Ireland	36.8	2%	15%	1%	10%	32%	1%	37%	2%
Italy	433.6	17%	0%	3%	9%	61%	2%	7%	1%
Latvia	16.1	41%	1%	33%	4%	14%	0%	6%	1%
Lithuania	16.1	35%	7%	41%	2%	11%	0%	3%	1%

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
Luxembourg	8.5	4%	0%	12%	4%	50%	0%	30%	0%
Malta	1	0%	0%	0%	50%	0%	0%	50%	0%
Netherlands	141.6	5%	0%	4%	5%	84%	1%	1%	0%
Poland	237	12%	33%	24%	6%	21%	0%	3%	1%
Portugal	21.2	26%	0%	1%	12%	36%	0%	22%	3%
Romania	72.8	49%	1%	16%	2%	29%	0%	2%	1%
Slovakia	31.4	2%	5%	20%	5%	67%	0%	1%	0%
Slovenia	14.4	43%	0%	10%	11%	14%	0%	19%	3%
Spain	161.3	19%	1%	0%	11%	39%	0%	27%	3%
Sweden	86.1	12%	0%	52%	24%	2%	5%	5%	0%
United Kingdom	456.5	4%	1%	1%	10%	75%	0%	9%	0%

Table 3.2. Heating demand in 2030 – Baseline scenario.

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
Austria	73.0	23%	0%	23%	9%	24%	1%	17%	3%
Belgium	104.1	6%	1%	1%	8%	49%	0%	34%	1%
Bulgaria	22.2	37%	7%	21%	17%	7%	2%	2%	7%
Croatia	24.8	49%	0%	7%	6%	28%	0%	7%	3%
Cyprus	2.8	8%	0%	0%	8%	0%	0%	47%	37%
Czech Republic	74.6	19%	8%	23%	10%	40%	0%	0%	0%
Denmark	51.1	19%	0%	49%	7%	17%	1%	7%	0%

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
Estonia	10.4	32%	1%	38%	12%	12%	1%	3%	1%
Finland	66.1	18%	0%	41%	27%	1%	2%	10%	1%
France	452.8	16%	0%	4%	15%	44%	1%	20%	0%
Germany	774.1	11%	1%	9%	5%	43%	1%	29%	1%
Greece	38.9	17%	0%	1%	11%	14%	2%	47%	8%
Hungary	66.3	14%	2%	10%	7%	65%	0%	2%	0%
Ireland	34.2	2%	15%	1%	10%	32%	1%	37%	2%
Italy	402.9	17%	0%	3%	9%	61%	2%	7%	1%
Latvia	14.9	41%	1%	33%	4%	14%	0%	6%	1%
Lithuania	15.2	35%	7%	41%	2%	11%	0%	3%	1%
Luxembourg	7.8	4%	0%	12%	4%	50%	0%	30%	0%
Malta	1.0	0%	0%	0%	50%	0%	0%	50%	0%
Netherlands	131.4	5%	0%	4%	5%	84%	1%	1%	0%
Poland	218.7	12%	33%	24%	6%	21%	0%	3%	1%
Portugal	20.9	26%	0%	1%	12%	36%	0%	22%	3%
Romania	67.5	49%	1%	16%	2%	29%	0%	2%	1%
Slovakia	29.2	2%	5%	20%	5%	67%	0%	1%	0%
Slovenia	13.4	43%	0%	10%	11%	14%	0%	19%	3%
Spain	156.5	19%	1%	0%	11%	39%	0%	27%	3%
Sweden	80.2	12%	0%	52%	24%	2%	5%	5%	0%
United Kingdom	428.2	4%	1%	1%	10%	75%	0%	9%	0%

Table 3.3. Heating demand in 2030 – SunHorizon technologies

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]	SH technologies [%]
Austria	73.0	23%	0%	23%	9%	23%	1%	11%	3%	7%
Belgium	104.1	6%	0%	1%	8%	49%	0%	15%	1%	20%
Bulgaria	22.2	37%	3%	21%	17%	7%	2%	2%	7%	4%
Croatia	24.8	49%	0%	7%	6%	28%	0%	0%	3%	7%
Cyprus	2.8	8%	0%	0%	7%	0%	0%	33%	37%	15%
Czech Republic	74.6	19%	0%	23%	10%	34%	0%	0%	0%	14%
Denmark	51.1	19%	0%	49%	7%	17%	1%	0%	0%	7%
Estonia	10.4	32%	0%	38%	12%	8%	1%	0%	1%	8%
Finland	66.1	18%	0%	41%	27%	1%	2%	7%	1%	3%
France	452.8	16%	0%	4%	15%	35%	1%	0%	0%	29%
Germany	774.1	11%	0%	9%	5%	43%	1%	16%	1%	14%
Greece	38.9	17%	0%	1%	11%	14%	2%	34%	8%	13%
Hungary	66.3	14%	0%	10%	7%	61%	0%	0%	0%	8%
Ireland	34.2	2%	0%	1%	10%	31%	1%	33%	2%	20%
Italy	402.9	17%	0%	3%	9%	41%	2%	0%	1%	27%
Latvia	14.9	41%	0%	33%	4%	14%	0%	4%	1%	3%
Lithuania	15.2	35%	4%	41%	2%	11%	0%	3%	1%	3%
Luxembourg	7.8	4%	0%	12%	4%	50%	0%	23%	0%	7%
Malta	1.0	0%	0%	0%	50%	0%	0%	37%	0%	13%
Netherlands	131.4	5%	0%	4%	5%	65%	1%	0%	0%	20%

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]	SH technologies [%]
Poland	218.7	12%	21%	24%	6%	20%	0%	3%	1%	13%
Portugal	20.9	26%	0%	1%	12%	35%	0%	9%	3%	14%
Romania	67.5	49%	0%	16%	2%	25%	0%	0%	1%	7%
Slovakia	29.2	2%	0%	20%	5%	66%	0%	0%	0%	7%
Slovenia	13.4	43%	0%	10%	11%	14%	0%	6%	3%	13%
Spain	156.5	19%	0%	0%	11%	38%	0%	15%	3%	14%
Sweden	80.2	12%	0%	52%	23%	1%	5%	0%	0%	7%
United Kingdom	428.2	4%	0%	1%	10%	72%	0%	0%	0%	13%

Table 3.4. Heating demand in 2050 – Baseline scenario.

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
Austria	62.0	23%	0%	23%	9%	24%	1%	17%	3%
Belgium	87.9	6%	1%	1%	8%	49%	0%	34%	1%
Bulgaria	19.1	37%	7%	21%	17%	7%	2%	2%	7%
Croatia	21.2	49%	0%	7%	6%	28%	0%	7%	3%
Cyprus	2.5	8%	0%	0%	8%	0%	0%	47%	37%
Czech Republic	63.7	19%	8%	23%	10%	40%	0%	0%	0%
Denmark	43.8	19%	0%	49%	7%	17%	1%	7%	0%
Estonia	8.7	32%	1%	38%	12%	12%	1%	3%	1%
Finland	55.2	18%	0%	41%	27%	1%	2%	10%	1%

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]
France	380.9	16%	0%	4%	15%	44%	1%	20%	0%
Germany	660.0	11%	1%	9%	5%	43%	1%	29%	1%
Greece	34.0	17%	0%	1%	11%	14%	2%	47%	8%
Hungary	55.7	14%	2%	10%	7%	65%	0%	2%	0%
Ireland	29.2	2%	15%	1%	10%	32%	1%	37%	2%
Italy	343.7	17%	0%	3%	9%	61%	2%	7%	1%
Latvia	12.6	41%	1%	33%	4%	14%	0%	6%	1%
Lithuania	12.9	35%	7%	41%	2%	11%	0%	3%	1%
Luxembourg	6.5	4%	0%	12%	4%	50%	0%	30%	0%
Malta	0.8	0%	0%	0%	50%	0%	0%	50%	0%
Netherlands	111.0	5%	0%	4%	5%	84%	1%	1%	0%
Poland	185.0	12%	33%	24%	6%	21%	0%	3%	1%
Portugal	19.0	26%	0%	1%	12%	36%	0%	22%	3%
Romania	57.6	49%	1%	16%	2%	29%	0%	2%	1%
Slovakia	24.7	2%	5%	20%	5%	67%	0%	1%	0%
Slovenia	11.5	43%	0%	10%	11%	14%	0%	19%	3%
Spain	141.2	19%	1%	0%	11%	39%	0%	27%	3%
Sweden	67.8	12%	0%	52%	24%	2%	5%	5%	0%
United Kingdom	369.7	4%	1%	1%	10%	75%	0%	9%	0%

Table 3.5. Heating demand in 2050 – SunHorizon technologies.

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]	SH technologies [%]
Austria	62.0	23%	0%	23%	9%	21%	1%	0%	3%	20%
Belgium	87.9	6%	0%	1%	8%	24%	0%	0%	1%	60%
Bulgaria	19.1	37%	0%	21%	17%	6%	2%	0%	7%	10%
Croatia	21.2	49%	0%	7%	6%	15%	0%	0%	3%	20%
Cyprus	2.5	8%	0%	0%	7%	0%	0%	6%	37%	42%
Czech Republic	63.7	19%	0%	23%	10%	7%	0%	0%	0%	41%
Denmark	43.8	19%	0%	49%	7%	3%	1%	0%	0%	21%
Estonia	8.7	32%	0%	38%	7%	0%	1%	0%	1%	21%
Finland	55.2	18%	0%	41%	27%	1%	2%	0%	1%	10%
France	380.9	16%	0%	4%	0%	0%	1%	0%	0%	79%
Germany	660.0	11%	0%	9%	5%	33%	1%	0%	1%	40%
Greece	34.0	17%	0%	1%	11%	14%	2%	7%	8%	40%
Hungary	55.7	14%	0%	10%	7%	48%	0%	0%	0%	21%
Ireland	29.2	2%	0%	1%	10%	24%	1%	0%	2%	60%
Italy	343.7	17%	0%	3%	0%	0%	2%	0%	1%	77%
Latvia	12.6	41%	0%	33%	4%	10%	0%	0%	1%	11%
Lithuania	12.9	35%	0%	41%	2%	10%	0%	0%	1%	11%
Luxembourg	6.5	4%	0%	12%	4%	50%	0%	10%	0%	20%
Malta	0.8	0%	0%	0%	50%	0%	0%	10%	0%	40%
Netherlands	111.0	5%	0%	4%	5%	25%	1%	0%	0%	60%

Country	Heating demand [TWh/y]	Biomass [%]	Coal [%]	District Heating [%]	Electricity [%]	Natural gas [%]	Heat pumps [%]	Oil [%]	Solar thermal [%]	SH technologies [%]
Poland	185.0	12%	0%	24%	6%	17%	0%	0%	1%	40%
Portugal	19.0	26%	0%	1%	12%	17%	0%	0%	3%	41%
Romania	57.6	49%	0%	16%	2%	12%	0%	0%	1%	20%
Slovakia	24.7	2%	0%	20%	5%	52%	0%	0%	0%	21%
Slovenia	11.5	43%	0%	10%	4%	0%	0%	0%	3%	40%
Spain	141.2	19%	0%	0%	11%	26%	0%	0%	3%	41%
Sweden	67.8	12%	0%	52%	11%	0%	5%	0%	0%	20%
United Kingdom	369.7	4%	0%	1%	10%	45%	0%	0%	0%	40%

Table 3.6. Cooling demand – SunHorizon technologies replacing electricity.

	2020	2030			2050		
Country	Cooling demand [TWh/y]	Cooling demand [TWh/y]	Electricity [%]	SH technologies [%]	Cooling demand [TWh/y]	Electricity [%]	SH technologies [%]
Austria	1.8	2.1	93%	7%	2.3	80%	20%
Belgium	3	3.5	80%	20%	3.8	40%	60%
Bulgaria	0.8	1.1	97%	3%	1.7	90%	10%
Croatia	0.8	1.1	93%	7%	1.5	80%	20%
Cyprus	2.7	4.8	87%	13%	10.8	60%	40%
Czech Republic	1	1.2	87%	13%	1.3	60%	40%
Denmark	1.9	2.2	93%	7%	2.3	80%	20%
Estonia	0.1	0.1	93%	7%	0.1	80%	20%
Finland	1.4	1.6	97%	3%	1.7	90%	10%

	2020	2030			2050		
Country	Cooling demand [TWh/y]	Cooling demand [TWh/y]	Electricity [%]	SH technologies [%]	Cooling demand [TWh/y]	Electricity [%]	SH technologies [%]
France	17.6	21.6	74%	26%	27.4	23%	77%
Germany	18.9	21.7	87%	13%	23.6	60%	40%
Greece	9.3	15.1	87%	13%	29.7	60%	40%
Hungary	0.8	1.1	93%	7%	1.5	80%	20%
Ireland	0.8	0.9	80%	20%	0.9	40%	60%
Italy	36.5	54.0	74%	26%	93.6	23%	77%
Latvia	0.1	0.1	97%	3%	0.1	90%	10%
Lithuania	0.1	0.1	97%	3%	0.1	90%	10%
Luxembourg	0.5	0.6	93%	7%	0.6	80%	20%
Malta	0.8	1.4	87%	13%	2.9	60%	40%
Netherlands	5.2	5.9	80%	20%	6.4	40%	60%
Poland	2.7	3.2	87%	13%	3.5	60%	40%
Portugal	3	4.4	87%	13%	7.5	60%	40%
Romania	1.6	2.2	93%	7%	3.5	80%	20%
Slovakia	0.3	0.3	93%	7%	0.4	80%	20%
Slovenia	0.5	0.6	87%	13%	0.7	60%	40%
Spain	23.5	34.4	87%	13%	56.8	60%	40%
Sweden	3.3	3.8	93%	7%	4.0	80%	20%
United Kingdom	4.2	5.1	87%	13%	6.0	60%	40%

Annex 4. Emissions from residential and tertiary sector

Table 4.1. NO_x emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	27.53	25.77	22.11	25.14	20.75	24.96	20.29	25.05	20.52
Belgium	28.50	26.71	22.94	23.95	18.99	23.18	17.02	23.57	18.00
Bulgaria	10.77	10.25	9.15	9.90	8.48	9.87	8.41	9.89	8.44
Croatia	11.29	10.57	9.31	10.37	9.08	10.31	8.93	10.34	9.00
Cyprus	1.87	2.82	5.47	2.55	3.85	2.54	3.81	2.55	3.83
Czech Republic	27.39	25.61	22.00	22.90	19.82	22.54	18.87	22.72	19.35
Denmark	19.49	18.37	15.97	17.95	15.59	17.83	15.26	17.89	15.42
Estonia	4.54	4.19	3.53	4.12	3.35	4.10	3.28	4.11	3.32
Finland	28.89	26.69	22.45	26.44	21.79	26.36	21.58	26.40	21.68
France	155.67	146.23	127.19	134.78	96.83	130.32	85.84	132.55	91.33
Germany	226.57	213.45	184.29	198.86	158.81	195.05	148.98	196.96	153.90
Greece	17.25	19.09	24.19	17.84	18.54	17.65	18.04	17.74	18.29
Hungary	19.21	17.88	15.31	17.13	14.71	16.97	14.30	17.05	14.50
Ireland	11.49	10.76	9.25	8.17	5.86	7.91	5.20	8.04	5.53
Italy	132.08	131.84	134.03	125.13	100.31	121.16	90.50	123.14	95.41
Latvia	6.69	6.21	5.26	6.09	5.11	6.07	5.07	6.08	5.09
Lithuania	6.75	6.36	5.43	6.14	4.98	6.12	4.93	6.13	4.96
Luxembourg	2.16	2.04	1.76	1.97	1.57	1.95	1.53	1.96	1.55
Malta	0.72	0.98	1.64	0.90	1.19	0.89	1.18	0.90	1.19
Netherlands	29.65	28.02	24.28	27.87	23.86	26.90	21.37	27.38	22.61
Poland	100.23	92.78	78.87	79.55	49.19	78.48	46.43	79.01	47.81
Portugal	8.31	8.85	9.62	8.35	8.17	8.24	7.89	8.29	8.03
Romania	30.55	28.68	25.19	28.30	24.79	28.13	24.36	28.22	24.57
Slovakia	7.07	6.60	5.61	5.93	5.08	5.86	4.90	5.89	4.99
Slovenia	6.21	5.85	5.11	5.63	4.55	5.56	4.38	5.60	4.46
Spain	59.24	62.77	68.31	58.64	56.04	57.87	53.94	58.25	54.99
Sweden	33.31	31.32	26.87	30.79	23.77	30.60	23.27	30.70	23.52
United Kingdom	98.01	92.45	80.56	85.74	75.68	83.64	70.17	84.69	72.92
EU-28	1 111	1 063	966	991	801	971	750	981	775

Table 4.2. SO_2 emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	29.61	27.68	23.71	25.45	18.51	25.13	17.69	25.29	18.10
Belgium	66.59	61.97	52.67	52.30	28.72	50.93	25.21	51.62	26.96
Bulgaria	10.25	9.74	8.67	7.75	4.90	7.70	4.77	7.73	4.83
Croatia	8.72	8.18	7.23	7.57	5.32	7.46	5.04	7.51	5.18
Cyprus	2.12	2.95	5.24	2.67	3.92	2.65	3.85	2.66	3.88
Czech Republic	47.38	44.20	37.86	26.23	14.32	25.57	12.63	25.90	13.48
Denmark	16.19	15.27	13.28	14.00	9.33	13.77	8.74	13.89	9.04
Estonia	3.05	2.82	2.37	2.31	1.51	2.27	1.39	2.29	1.45
Finland	19.72	18.25	15.38	17.44	13.32	17.29	12.95	17.37	13.13
France	247.73	230.96	197.97	178.38	73.76	170.43	54.13	174.41	63.95
Germany	446.39	418.54	358.87	363.38	237.88	356.58	220.31	359.98	229.10
Greece	22.16	23.35	27.00	21.03	19.39	20.69	18.49	20.86	18.94
Hungary	40.00	37.05	31.38	32.23	23.74	31.94	23.00	32.09	23.37
Ireland	33.89	31.59	26.98	16.90	9.86	16.45	8.70	16.67	9.28
Italy	237.97	229.12	214.41	178.38	84.47	171.31	66.95	174.85	75.71
Latvia	4.34	4.03	3.41	3.41	2.54	3.38	2.45	3.39	2.50
Lithuania	6.43	6.06	5.16	4.70	2.63	4.67	2.54	4.69	2.59
Luxembourg	4.81	4.48	3.78	4.28	3.28	4.24	3.19	4.26	3.23
Malta	0.80	1.01	1.58	0.93	1.19	0.92	1.17	0.92	1.18
Netherlands	86.71	80.93	68.88	68.43	36.51	66.70	32.07	67.57	34.29
Poland	289.63	267.50	226.64	189.41	50.76	187.49	45.84	188.45	48.30
Portugal	10.45	10.89	11.28	9.74	7.47	9.56	6.96	9.65	7.21
Romania	23.39	21.99	19.40	18.72	12.81	18.43	12.05	18.58	12.43
Slovakia	20.26	18.85	15.97	14.85	11.01	14.73	10.68	14.79	10.84
Slovenia	4.58	4.32	3.79	3.66	1.99	3.54	1.69	3.60	1.84
Spain	88.94	90.95	92.31	80.32	62.90	78.94	59.14	79.63	61.02
Sweden	24.68	23.25	20.00	21.13	15.97	20.78	15.07	20.95	15.52
United Kingdom	289.46	271.96	235.45	235.78	156.74	232.02	146.90	233.90	151.82
EU-28	2 086	1 968	1 731	1 601	915	1 566	824	1 583	869

Table 4.3. $PM_{2.5}$ emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	8.48	7.89	6.70	7.89	6.85	7.76	6.52	7.82	6.69
Belgium	5.35	4.97	4.21	4.95	4.92	4.40	3.51	4.67	4.22
Bulgaria	4.49	4.20	3.63	3.90	3.10	3.88	3.05	3.89	3.08
Croatia	5.36	4.96	4.24	4.98	4.33	4.94	4.22	4.96	4.28
Cyprus	0.19	0.22	0.29	0.24	0.43	0.23	0.41	0.24	0.42
Czech Republic	9.80	9.13	7.80	6.71	6.11	6.45	5.43	6.58	5.77
Denmark	4.59	4.29	3.69	4.35	3.87	4.26	3.64	4.30	3.76
Estonia	1.55	1.43	1.20	1.40	1.20	1.38	1.16	1.39	1.18
Finland	5.96	5.48	4.58	5.52	4.67	5.46	4.52	5.49	4.60
France	41.03	37.97	32.08	39.49	38.43	36.28	30.51	37.88	34.47
Germany	54.78	51.22	43.74	49.74	45.86	47.00	38.77	48.37	42.32
Greece	3.71	3.57	3.35	3.71	3.93	3.58	3.57	3.64	3.75
Hungary	5.84	5.40	4.55	4.92	4.31	4.80	4.01	4.86	4.16
Ireland	3.59	3.34	2.85	1.18	1.22	1.00	0.75	1.09	0.98
Italy	36.47	34.16	29.81	36.71	37.71	33.85	30.64	35.28	34.18
Latvia	2.83	2.62	2.22	2.55	2.17	2.54	2.14	2.54	2.15
Lithuania	2.84	2.67	2.28	2.46	1.91	2.45	1.88	2.46	1.90
Luxembourg	0.30	0.28	0.23	0.29	0.26	0.27	0.22	0.28	0.24
Malta	0.03	0.04	0.06	0.05	0.10	0.04	0.09	0.05	0.10
Netherlands	5.73	5.33	4.52	5.91	6.05	5.21	4.26	5.56	5.15
Poland	50.26	46.38	39.25	34.29	12.94	33.51	10.95	33.90	11.95
Portugal	2.50	2.48	2.31	2.54	2.54	2.47	2.33	2.50	2.43
Romania	14.78	13.72	11.73	13.56	11.78	13.44	11.47	13.50	11.63
Slovakia	1.42	1.32	1.12	0.75	0.71	0.70	0.58	0.73	0.64
Slovenia	2.59	2.41	2.08	2.45	2.18	2.40	2.05	2.42	2.11
Spain	15.47	15.17	14.05	15.25	15.38	14.70	13.87	14.98	14.63
Sweden	5.21	4.86	4.13	4.96	4.48	4.82	4.12	4.89	4.30
United Kingdom	18.58	17.44	15.08	15.85	15.87	14.34	11.90	15.09	13.88
EU-28	314	293	252	277	243	262	207	269	225

Table 4.4. NH_3 emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	0.55	0.51	0.44	0.52	0.46	0.51	0.44	0.51	0.45
Belgium	0.32	0.30	0.26	0.33	0.35	0.30	0.27	0.32	0.31
Bulgaria	0.25	0.23	0.21	0.23	0.20	0.23	0.20	0.23	0.20
Croatia	0.25	0.23	0.20	0.23	0.21	0.23	0.20	0.23	0.21
Cyprus	0.04	0.06	0.11	0.05	0.08	0.05	0.08	0.05	0.08
Czech Republic	0.54	0.51	0.43	0.48	0.44	0.46	0.40	0.47	0.42
Denmark	0.43	0.40	0.35	0.41	0.36	0.40	0.35	0.40	0.36
Estonia	0.10	0.10	0.08	0.10	0.08	0.10	0.08	0.10	0.08
Finland	0.63	0.58	0.49	0.58	0.50	0.58	0.49	0.58	0.49
France	2.58	2.43	2.12	2.62	2.13	2.43	1.65	2.53	1.89
Germany	3.20	3.02	2.62	3.15	3.06	2.98	2.62	3.07	2.84
Greece	0.29	0.33	0.43	0.32	0.38	0.31	0.36	0.32	0.37
Hungary	0.33	0.30	0.26	0.30	0.27	0.30	0.26	0.30	0.26
Ireland	0.13	0.13	0.11	0.10	0.11	0.08	0.08	0.09	0.09
Italy	2.26	2.28	2.37	2.41	2.20	2.24	1.77	2.32	1.99
Latvia	0.15	0.14	0.12	0.14	0.12	0.14	0.12	0.14	0.12
Lithuania	0.15	0.14	0.12	0.14	0.12	0.14	0.12	0.14	0.12
Luxembourg	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02
Malta	0.01	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Netherlands	0.39	0.37	0.33	0.42	0.44	0.38	0.33	0.40	0.39
Poland	1.82	1.68	1.43	1.50	1.04	1.45	0.92	1.47	0.98
Portugal	0.15	0.16	0.18	0.16	0.17	0.16	0.16	0.16	0.17
Romania	0.69	0.64	0.56	0.65	0.58	0.64	0.56	0.64	0.57
Slovakia	0.11	0.10	0.08	0.09	0.08	0.09	0.08	0.09	0.08
Slovenia	0.13	0.12	0.11	0.13	0.11	0.12	0.10	0.13	0.10
Spain	0.98	1.06	1.18	1.06	1.15	1.03	1.05	1.05	1.10
Sweden	0.73	0.69	0.59	0.70	0.55	0.69	0.53	0.70	0.54
United Kingdom	1.17	1.11	0.97	1.18	1.23	1.08	0.99	1.13	1.11
EU-28	18	18	16	18	16	17	14	18	15

Table 4.5. NMVOC emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	7.50	6.99	5.96	6.66	5.48	6.55	5.19	6.61	5.33
Belgium	10.95	10.18	8.64	8.74	6.82	8.25	5.57	8.50	6.19
Bulgaria	4.05	3.81	3.31	3.02	1.92	3.00	1.88	3.01	1.90
Croatia	3.25	3.02	2.61	2.98	2.54	2.94	2.44	2.96	2.49
Cyprus	0.33	0.43	0.72	0.41	0.64	0.40	0.61	0.41	0.62
Czech Republic	13.65	12.72	10.88	6.30	5.21	6.07	4.61	6.18	4.91
Denmark	4.29	4.03	3.48	3.94	3.34	3.86	3.13	3.90	3.23
Estonia	1.13	1.04	0.88	0.93	0.78	0.92	0.74	0.93	0.76
Finland	5.39	4.97	4.17	4.91	4.02	4.86	3.88	4.88	3.95
France	47.48	44.13	37.59	39.63	33.31	36.80	26.32	38.21	29.81
Germany	82.96	77.70	66.50	67.29	53.90	64.87	47.65	66.08	50.78
Greece	4.34	4.40	4.69	4.23	4.17	4.11	3.85	4.17	4.01
Hungary	7.82	7.24	6.11	5.80	4.82	5.69	4.56	5.74	4.69
Ireland	9.05	8.43	7.19	2.81	2.11	2.65	1.70	2.73	1.90
Italy	41.18	39.29	35.95	37.53	32.77	35.01	26.53	36.27	29.65
Latvia	1.91	1.77	1.50	1.56	1.31	1.55	1.28	1.56	1.29
Lithuania	2.73	2.57	2.19	2.03	1.23	2.02	1.20	2.03	1.22
Luxembourg	0.73	0.68	0.57	0.66	0.54	0.65	0.50	0.66	0.52
Malta	0.11	0.14	0.21	0.14	0.19	0.13	0.18	0.14	0.18
Netherlands	11.79	11.00	9.36	10.69	8.59	10.08	7.02	10.39	7.80
Poland	105.10	97.01	82.11	66.10	14.13	65.42	12.38	65.76	13.25
Portugal	2.29	2.33	2.30	2.25	2.11	2.19	1.93	2.22	2.02
Romania	9.33	8.69	7.50	8.04	6.85	7.93	6.58	7.98	6.71
Slovakia	3.86	3.59	3.04	2.09	1.73	2.04	1.62	2.07	1.68
Slovenia	1.67	1.56	1.35	1.51	1.29	1.47	1.18	1.49	1.23
Spain	17.69	17.76	17.34	16.23	14.97	15.74	13.64	15.99	14.30
Sweden	5.60	5.24	4.48	5.12	4.51	4.99	4.19	5.05	4.35
United Kingdom	43.96	41.29	35.73	33.81	28.21	32.48	24.71	33.14	26.46
EU-28	450	422	366	345	247	333	215	339	231

Table 4.6. CO_2 emissions, Mtonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	17.4	16.3	14.0	15.3	11.7	15.3	11.6	15.3	11.6
Belgium	32.4	30.3	25.9	26.1	16.9	25.9	16.5	26.0	16.7
Bulgaria	4.8	4.6	4.3	4.3	3.5	4.3	3.5	4.3	3.5
Croatia	4.3	4.1	3.7	3.8	3.1	3.8	3.0	3.8	3.0
Cyprus	1.5	2.3	4.5	2.0	2.9	2.0	2.9	2.0	2.9
Czech Republic	19.8	18.5	15.9	15.4	11.2	15.3	11.0	15.3	11.1
Denmark	12.1	11.5	10.0	10.8	8.7	10.8	8.6	10.8	8.7
Estonia	2.1	2.0	1.7	1.8	1.4	1.8	1.4	1.8	1.4
Finland	17.5	16.2	13.7	15.8	12.6	15.8	12.6	15.8	12.6
France	128.6	120.8	105.1	99.0	53.2	98.0	50.9	98.5	52.0
Germany	219.3	206.4	177.8	184.8	129.8	184.0	127.7	184.4	128.8
Greece	13.7	15.2	19.5	13.6	13.0	13.6	12.9	13.6	12.9
Hungary	17.4	16.2	13.8	15.1	12.1	15.1	12.0	15.1	12.0
Ireland	12.8	11.9	10.2	9.3	5.8	9.2	5.7	9.2	5.7
Italy	113.2	112.7	114.0	94.3	55.5	93.4	53.4	93.8	54.5
Latvia	2.6	2.4	2.1	2.3	1.8	2.3	1.8	2.3	1.8
Lithuania	3.1	2.9	2.5	2.7	2.0	2.7	2.0	2.7	2.0
Luxembourg	2.5	2.3	2.0	2.2	1.7	2.2	1.7	2.2	1.7
Malta	0.7	0.9	1.4	0.8	0.9	0.8	0.9	0.8	0.9
Netherlands	37.3	35.1	30.1	31.7	21.5	31.5	20.9	31.6	21.2
Poland	82.3	76.2	64.8	63.3	34.8	63.1	34.2	63.2	34.5
Portugal	5.8	6.3	7.0	5.6	4.8	5.5	4.8	5.6	4.8
Romania	11.2	10.7	9.7	9.9	8.0	9.8	7.9	9.8	7.9
Slovakia	8.5	7.9	6.7	7.2	5.7	7.2	5.7	7.2	5.7
Slovenia	2.7	2.6	2.3	2.2	1.4	2.2	1.4	2.2	1.4
Spain	47.8	50.8	55.5	45.2	38.5	45.1	38.1	45.2	38.3
Sweden	21.8	20.5	17.7	19.5	14.7	19.5	14.6	19.5	14.6
United Kingdom	125.1	117.7	102.3	106.6	81.2	106.2	80.0	106.4	80.6
EU-28	968	925	838	811	558	806	547	809	553

Table 4.7. CH_4 emissions, ktonne.

Country	Baseline			SH_TP1		SH_TP2		SH_c	
	2020	2030	2050	2030	2050	2030	2050	2030	2050
Austria	46.21	43.21	37.01	44.96	40.55	44.77	40.04	44.86	40.29
Belgium	84.59	78.81	67.09	86.17	66.76	85.33	64.61	85.75	65.68
Bulgaria	14.81	14.10	12.61	13.00	10.61	12.97	10.53	12.99	10.57
Croatia	17.09	16.00	14.06	16.70	13.19	16.64	13.02	16.67	13.11
Cyprus	2.25	3.60	7.37	3.44	5.64	3.42	5.60	3.43	5.62
Czech Republic	69.55	64.89	55.60	54.12	37.54	53.72	36.50	53.92	37.02
Denmark	31.03	29.22	25.36	30.66	23.45	30.52	23.09	30.59	23.27
Estonia	6.16	5.69	4.79	5.51	4.26	5.48	4.19	5.50	4.22
Finland	34.05	31.49	26.52	32.45	28.93	32.36	28.70	32.41	28.81
France	368.66	343.96	295.26	360.27	232.61	355.42	220.63	357.85	226.62
Germany	593.02	556.48	477.70	587.12	513.73	582.97	503.01	585.05	508.37
Greece	22.87	25.56	32.93	26.87	33.04	26.66	32.48	26.76	32.76
Hungary	67.43	62.44	52.88	60.34	47.20	60.16	46.75	60.25	46.97
Ireland	31.34	29.26	25.04	22.18	22.28	21.90	21.57	22.04	21.93
Italy	398.85	383.47	357.58	348.32	225.93	344.00	215.24	346.16	220.58
Latvia	8.74	8.11	6.87	7.97	6.75	7.95	6.70	7.96	6.72
Lithuania	9.98	9.40	8.02	8.66	6.89	8.64	6.83	8.65	6.86
Luxembourg	6.51	6.07	5.14	6.28	5.67	6.26	5.62	6.27	5.65
Malta	0.93	1.29	2.24	1.25	1.79	1.25	1.78	1.25	1.79
Netherlands	150.57	140.47	119.50	127.81	84.69	126.75	81.99	127.28	83.34
Poland	276.41	255.46	216.65	212.58	122.02	211.41	119.02	211.99	120.52
Portugal	15.51	16.22	16.98	17.17	15.64	17.06	15.33	17.12	15.49
Romania	48.76	45.70	40.01	43.89	34.25	43.71	33.79	43.80	34.02
Slovakia	31.36	29.18	24.72	27.10	21.26	27.03	21.06	27.07	21.16
Slovenia	7.48	7.06	6.18	7.82	6.20	7.75	6.01	7.78	6.11
Spain	121.54	125.39	129.61	130.74	125.85	129.90	123.56	130.32	124.70
Sweden	43.63	41.06	35.27	42.26	35.63	42.05	35.08	42.16	35.35
United Kingdom	454.68	427.21	369.89	427.89	319.19	425.59	313.18	426.74	316.18
EU-28	2 964	2 801	2 473	2 754	2 092	2 732	2 036	2 743	2 064

Annex 5. End-point exposure to air pollution

Table 5.1. Differences in population weighted $PM_{2.5}$ concentrations, mg/m^3.

Country	SH_TP1		SH_TP2		SH_c	
	2030	2050	2030	2050	2030	2050
Austria	0.26	0.53	0.30	0.63	0.28	0.58
Belgium	0.61	1.36	0.75	1.71	0.68	1.53
Bulgaria	0.08	0.15	0.08	0.16	0.08	0.16
Croatia	0.19	0.41	0.22	0.48	0.20	0.45
Cyprus	0.02	0.05	0.02	0.06	0.02	0.06
Czech Republic	0.48	0.84	0.52	0.95	0.50	0.89
Denmark	0.16	0.36	0.19	0.43	0.18	0.40
Estonia	0.05	0.11	0.06	0.12	0.06	0.12
Finland	0.03	0.07	0.03	0.08	0.03	0.07
France	0.30	0.67	0.38	0.86	0.34	0.76
Germany	0.44	0.93	0.53	1.14	0.49	1.03
Greece	0.06	0.14	0.07	0.17	0.06	0.15
Hungary	0.27	0.50	0.30	0.57	0.29	0.53
Ireland	0.37	0.46	0.40	0.52	0.39	0.49
Italy	0.34	0.87	0.45	1.14	0.40	1.00
Latvia	0.11	0.22	0.12	0.24	0.11	0.23
Lithuania	0.17	0.36	0.18	0.39	0.18	0.37
Luxembourg	0.44	0.96	0.53	1.19	0.48	1.07
Malta	0.14	0.36	0.17	0.42	0.16	0.39
Netherlands	0.51	1.16	0.63	1.46	0.57	1.31
Poland	0.60	1.27	0.63	1.36	0.61	1.32
Portugal	0.04	0.12	0.05	0.14	0.05	0.13
Romania	0.10	0.20	0.11	0.22	0.10	0.21
Slovakia	0.32	0.59	0.34	0.65	0.33	0.62
Slovenia	0.24	0.56	0.29	0.68	0.27	0.62
Spain	0.08	0.19	0.10	0.24	0.09	0.21
Sweden	0.07	0.16	0.08	0.18	0.08	0.17
United Kingdom	0.28	0.52	0.33	0.64	0.30	0.58

Table 5.2. Differences in ozone exposure, SOMO35, ppb.days.

Country	SH_TP1		SH_TP2		SH_c	
	2030	2050	2030	2050	2030	2050
Austria	24.09	46.87	29.84	61.44	26.96	54.16
Belgium	13.36	22.70	17.12	32.22	15.24	27.46
Bulgaria	14.60	29.31	17.23	36.00	15.91	32.66
Croatia	23.61	49.23	29.66	64.53	26.63	56.88
Cyprus	14.73	61.42	16.93	67.08	15.83	64.25
Czech Republic	27.98	47.99	32.39	59.23	30.18	53.61
Denmark	10.43	17.17	12.46	22.38	11.45	19.77
Estonia	6.73	12.48	7.91	15.51	7.32	14.00
Finland	5.11	9.60	6.06	12.04	5.59	10.82
France	15.68	32.64	20.73	45.31	18.21	38.98
Germany	17.81	31.59	22.15	42.59	19.98	37.09
Greece	12.43	28.20	15.53	36.07	13.98	32.14
Hungary	26.00	46.25	30.53	57.78	28.26	52.01
Ireland	6.06	7.76	7.07	10.35	6.56	9.06
Italy	23.17	63.62	33.66	89.77	28.42	76.69
Latvia	9.19	17.23	10.65	20.97	9.92	19.10
Lithuania	11.60	22.02	13.27	26.29	12.44	24.15
Luxembourg	17.52	33.66	22.46	46.12	19.99	39.89
Malta	18.77	53.21	25.95	71.16	22.36	62.19
Netherlands	11.91	18.96	15.04	26.96	13.47	22.96
Poland	26.13	50.30	29.37	58.59	27.75	54.44
Portugal	7.34	17.03	9.21	21.91	8.27	19.47
Romania	15.09	28.09	17.90	35.26	16.49	31.67
Slovakia	28.95	51.39	33.23	62.30	31.09	56.84
Slovenia	24.45	52.75	31.35	70.17	27.90	61.46
Spain	9.85	22.69	12.81	30.25	11.33	26.47
Sweden	7.59	13.57	9.07	17.36	8.33	15.46
United Kingdom	7.74	11.56	9.25	15.42	8.50	13.49

Annex 6. Health benefits, monetary valuation

Table 6.1. Health benefits, million €$_{2015}$/year, low-end valuation.

Country	SH_TP1		SH_TP2		SH_c	
	2030	2050	2030	2050	2030	2050
Austria	95	193	110	230	103	211
Belgium	301	669	368	840	335	755
Bulgaria	26	41	28	44	27	42
Croatia	38	73	43	86	41	79
Cyprus	1	3	1	4	1	4
Czech Republic	242	395	264	448	253	421
Denmark	44	93	51	111	47	102
Estonia	3	6	4	7	4	7
Finland	8	16	9	19	8	17
France	876	1 979	1 102	2 559	989	2 269
Germany	1 561	3 029	1 858	3 739	1 710	3 384
Greece	31	72	37	88	34	80
Hungary	132	216	144	245	138	231
Ireland	84	114	89	129	87	121
Italy	897	2 183	1 181	2 859	1 039	2 521
Latvia	12	20	12	22	12	21
Lithuania	28	49	29	53	28	51
Luxembourg	12	28	14	35	13	31
Malta	3	6	3	8	3	7
Netherlands	384	838	473	1 057	428	947
Poland	1 082	2 040	1 146	2 184	1 114	2 112
Portugal	20	49	25	60	23	55
Romania	102	174	112	196	107	185
Slovakia	85	142	92	157	89	149
Slovenia	23	50	27	60	25	55
Spain	167	409	208	519	187	464
Sweden	32	70	37	83	35	76
United Kingdom	835	1 585	976	1 958	906	1 771
EU-28	7 123	14 540	8 444	17 799	7 784	16 170
Europe, all countries	7 655	15 546	9 024	18 911	8 339	17 229

Table 6.2. Health benefits, million €2015/year, central valuation.

Country	SH_TP1		SH_TP2		SH_c	
	2030	2050	2030	2050	2030	2050
Austria	232	596	268	711	250	653
Belgium	725	1 852	888	2 328	806	2 090
Bulgaria	70	128	75	140	73	134
Croatia	99	222	114	260	106	241
Cyprus	2	8	2	9	2	9
Czech Republic	586	1 107	639	1 254	612	1 180
Denmark	104	251	121	298	113	275
Estonia	8	18	9	20	9	19
Finland	19	44	21	52	20	48
France	1 987	5 241	2 497	6 774	2 242	6 008
Germany	4 340	10 193	5 164	12 579	4 752	11 386
Greece	76	213	91	257	83	235
Hungary	332	601	364	683	348	642
Ireland	221	363	235	410	228	387
Italy	2 405	7 066	3 165	9 251	2 785	8 159
Latvia	29	58	32	64	31	61
Lithuania	67	141	71	152	69	147
Luxembourg	22	67	27	83	25	75
Malta	7	19	8	22	7	21
Netherlands	922	2 469	1 134	3 113	1 028	2 791
Poland	2 573	5 986	2 724	6 409	2 649	6 197
Portugal	53	163	66	203	59	183
Romania	244	516	268	582	256	549
Slovakia	192	408	206	451	199	430
Slovenia	58	154	68	185	63	169
Spain	380	1 211	473	1 538	426	1 375
Sweden	75	180	87	213	81	197
United Kingdom	1 864	4 064	2 179	5 020	2 021	4 542
EU-28	17 693	43 340	20 997	53 061	19 345	48 200
Europe, all countries	18 904	46 120	22 314	56 143	20 609	51 132

Table 6.3. Health benefits, million €$_{2015}$/year, high-end valuation.

Country	SH_TP1		SH_TP2		SH_c	
	2030	2050	2030	2050	2030	2050
Austria	541	1 416	625	1 688	583	1 552
Belgium	1 701	4 380	2 085	5 505	1 893	4 943
Bulgaria	169	309	181	338	175	323
Croatia	235	531	269	621	252	576
Cyprus	4	19	5	22	4	20
Czech Republic	1 378	2 622	1 502	2 970	1 440	2 796
Denmark	245	593	285	704	265	649
Estonia	20	42	22	47	21	45
Finland	44	105	50	122	47	114
France	4 612	12 292	5 797	15 889	5 204	14 091
Germany	10 265	24 386	12 214	30 093	11 240	27 240
Greece	178	505	213	611	196	558
Hungary	790	1 433	867	1 627	828	1 530
Ireland	524	868	556	980	540	924
Italy	5 668	16 851	7 459	22 059	6 564	19 455
Latvia	70	139	76	153	73	146
Lithuania	160	338	170	365	165	351
Luxembourg	51	156	61	193	56	174
Malta	16	45	18	53	17	49
Netherlands	2 159	5 858	2 655	7 387	2 407	6 623
Poland	6 068	14 287	6 423	15 295	6 246	14 791
Portugal	125	392	155	486	140	439
Romania	579	1 236	636	1 396	608	1 316
Slovakia	450	973	484	1 077	467	1 025
Slovenia	136	366	161	440	148	403
Spain	879	2 866	1 095	3 640	987	3 253
Sweden	176	421	203	499	189	460
United Kingdom	4 343	9 548	5 078	11 792	4 711	10 670
EU-28	41 587	102 979	49 344	126 053	45 466	114 516
Europe, all countries	44 458	109 627	52 464	133 415	48 461	121 521