Final Report
External Costs

Energy costs, taxes and the impact of government interventions on investments

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Energy costs, taxes and the impact of government interventions on investments

In association with:

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PRESENTED BY

Consortium led by:

Trinomics B.V.

Westersingel 34

3014 GS Rotterdam

The Netherlands

CONTACT

Matthew Smith

Matthew.smith@trinomics.eu

Tel: +31 6 1292-9246

DATE

Rotterdam, 12th October 2020

AUTHORS

Matthew Smith, Joris Moerenhout (Trinomics)

Mihaela Thuring, Sofie de Regel (VITO)

Matthias Altmann (LBST)

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Glossary

Life Cycle Assessment (LCA) (also known as life-cycle analysis, ecobalance, and cradle-to-grave analysis - source 1) is a technique for assessing potential environmental impacts associated with a product (or service). It can include all or only some of the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. According to the ISO 14040 and 14044 standards, a Life Cycle Assessment is carried out in four distinct phases: 1. Goal and scope definition; 2. Inventory analysis (or lifecycle inventory – LCI) - by compiling an inventory of relevant inputs and outputs; 3. Impact assessment (LCIA) - by evaluating the potential environmental impacts associated with those inputs and outputs 4. Interpretation of the results of the inventory and impact phases in relation to the objectives of the study.

Sources:

1. ISO 14040 (2006): Environmental management – Life cycle assessment – Principles and framework, International Organisation for Standardisation (ISO), Geneve;
2. ISO 14044 (2006): Environmental management – Life cycle assessment – Requirements and guidelines, International Organisation for Standardisation (ISO), Geneve;
3. "Defining Life Cycle Assessment (LCA)." US Environmental Protection Agency. 17 October 2010. Web.

LCI – Lifecycle Inventory is the second phase of a lifecycle analysis (LCA) study, consisting of the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product (system) throughout its life cycle. It involves creating an inventory of flows from and to nature for a product system. Inventory flows include inputs of water, energy, raw materials, and emissions to air, water and soil. The input and output data needed for the construction of the model are collected for all activities within the system boundary, including from the supply chain (referred to as inputs from the technosphere).

LCIA – Lifecycle Impact Assessment 3rd phase of a Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (ISO 14040:2006). The evaluation is done using methods (such as CML[1], ReCiPe[2], PEF[3]), each including a set of environmental indicators (or impact categories) that assess the impact on a specific environmental dimension (climate change / global warming, ozone layer depletion, toxicity, ….etc.). At their turn, each environmental indicator includes a list of flows (such as materials, ingredients/substances) to which a characterisation factor (CF) is assigned. This characterisation factor represents the impact on the environment per unit of flow on the respective indicator. It can be that a specific flow generates impacts on more than one environmental indicator.

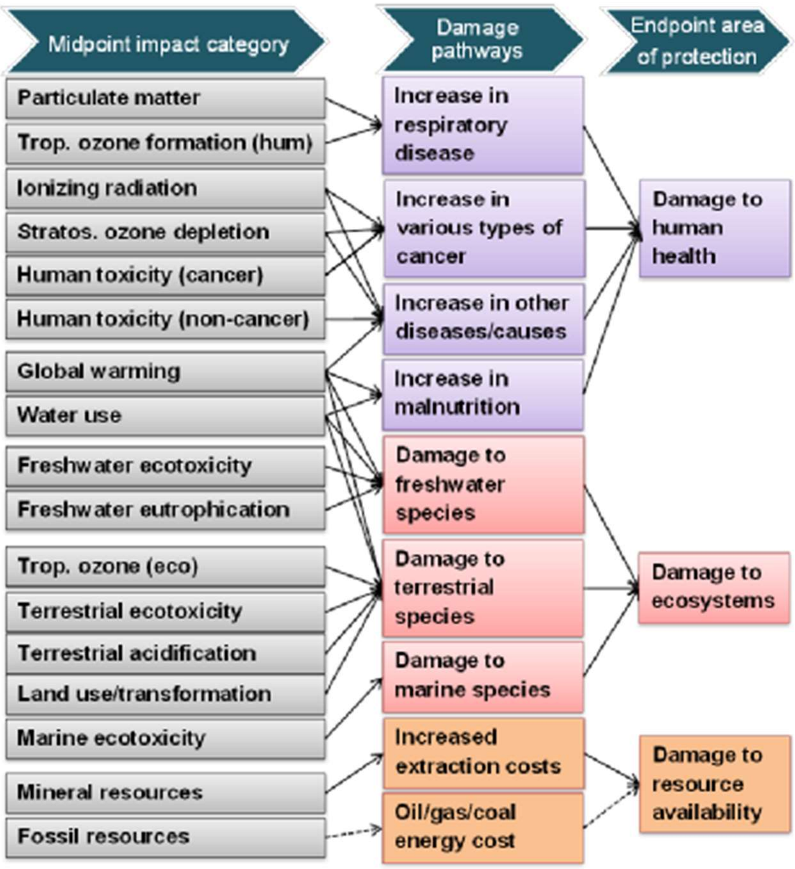
[1] A problem-oriented Life Cycle Assessment (LCA) method developed by the Institute of Environmental Sciences of the University of Leiden (CML).

[2] ReCiPe is a method for the life cycle impact assessment (LCIA). It was first developed in 2008 through cooperation between RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability. ReCiPe 2016 is an improvement on ReCiPe 2008, and its predecessors CML 2000 and Eco-indicator 99. ReCiPe2016 was developed in collaboration between the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé.

[3] Product Environmental Footprint (PEF) is a methodology by the European Commission’s Joint Research Center (JRC) which is based on Life Cycle Assessment.

Endpoint / Midpoint indicators are the two mainstream ways to derive characterisation factors, i.e. at midpoint level and at endpoint level. **Midpoint indicators** focus on single environmental problems, for example climate change or acidification. **Endpoint indicators** show the environmental impact on three higher aggregation levels, being 1) the effect on human health, 2) biodiversity and 3) resource scarcity. Converting midpoints to endpoints simplifies the interpretation of the LCIA results. However, with each aggregation step, uncertainty in the results increases. The relationship between midpoint environmental impact indicators (left), damage pathways (middle) and endpoint indicator (right) in ReCiPe 2016 can be seen in the image below. Endpoint / Midpoint indicators are useful especially for communication purposes, where the midpoint indicators are aggregated based on a weighting factor in endpoint indicators, encompassing a wider impact aspect. For example, ReCiPe calculates 18 midpoint indicators and 3 endpoint indicators (see figure below).

Figure 0-1 Overview of structure ReCiPe from https://www.rivm.nl/en/life-cycle-assessment-lca/recipe



Abbreviations

CCGT	Combined Cycle Gas Turbine
CF	Characterisation Factor
CFC	Chlorofluorocarbons
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
CTUh	Comparative Toxic Units - ecosystem
CTUh	Comparative Toxic Units - human
DALY	Disability Adjusted (lost) Life Year
EF	Environmental Footprint
EIA	Energy Information Administration (US)
EU-ETS	EU Emissions Trading System
EUR	Euros
GDP	Gross Domestic Product
HH	Human Health
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardisation
JRC	Joint Research Centre (European Commission)
LCA	Life Cycle Assessment (see glossary)
LCI	Life Cycle Inventory (see glossary)
LCIA	Life Cycle Impact Assessment (see glossary)
MJ	Megajoule
MMG	Environmental Performance of Building Elements (from Flemish)
MS	Member State (EU)
MW	Megawatt
MWh	Megawatt hour
NMVOC	Non-Methane Volatile Organic Compound
OCGT	Open Cycle Gas Turbine
PEF	Product Environmental Footprint
PPP	Purchasing Power Parity
PV	Photovoltaic (solar)
Sb	Antimony
SCC	Social Cost of Carbon
tCO_2e	Tonnes CO_2 equivalent
UNEP	United Nations Environment Programme
USD	United States Dollar
VOLY	Value of (lost) Life Year
VSL	Value of Statistical Life
WTA	Willingness to Accept
WTP	Willingness to Pay

1 Introduction

This report chapter identifies the external costs in the energy sector in power and heating[4] and also make a first estimate of the externalities of energy consumption. The external costs are disaggregated by the environmental impact and are presented at technology and country level. Within the results the sensitivities of the external cost estimates are examined and the extent to which externality costs are internalised is also explored. This provides the most comprehensive analysis of the external costs of energy to date, building upon the previous version of this work published in 2014[5].

1.1 Objectives and scope

The objective of this work was to provide a full range of disaggregated external costs data for the different energy technologies and countries.

The scope of the work in this task covered the 13 electricity and 9 heat technologies[6] listed below in Table 1-1. These cover a very high share of electricity and heat production in the EU27 and non-EU G20 countries. A handful of technologies, e.g. energy from waste (electricity and heat), ocean energy (electricity) and domestic coal boilers/stoves, were excluded from the analysis as the LCA data was unavailable or unreliable, and therefore an assessment was not possible. The technology selection therefore does not cover 100% of a nations electricity and heat production – see also notes on the production data in Annex B.

Table 1-1 Electricity and Heat technologies covered

Electricity	Heating[7]
Hard Coal (including CHP)	Domestic gas boiler (condensing)
Lignite (including CHP)	Domestic oil boiler
Natural Gas (CCGT, OCGT, CHP)	Domestic wood (logs, pellets, chips) boiler
Oil	Domestic heat pump
Nuclear	Domestic solar thermal
Biomass	CHP Hard Coal
Solar PV - rooftop & utility	CHP Lignite
Solar - CSP	CHP Gas
Wind – onshore*	CHP Biomass
Wind – offshore*	
Hydropower – large (>10 MW)#	
Hydropower – small (up to 10MW)#	
Geothermal	

** and # for these technologies no differentiated LCIA data was available. Therefore, the estimated external costs per MWh are very similar for each. The external costs per technology do show some minor variance due to differences in the scaling factors applied to countries with proxies.*

[4] Heating includes heat for space heating, hot water and cooking – therefore countries with low space heating needs such as Saudi Arabia or Indonesia, still register significant heat consumption from biomass used as fuel for residential uses.
[5] Ecofys (2014) Subsidies and costs of EU energy
[6] Transport technologies have been the subject of a major study commissioned by DG MOVE the key findings of which were presented in a box text (3.1) later in this report.
[7] Please note that external costs for heating from electrical heaters is accounted in the external costs of electricity production.

In addition to the main analysis at technology level, an indicative analysis of the external costs of energy consumption was also made, this is a new step compared to previous work. This analysis addressed energy consumption in the following sectors.

- Industry;
- Agriculture (including forestry and fisheries);
- Residential;
- Commercial and Public sector.

These correspond to the categories in IEA energy consumption statistics from where the consumption data was sourced. The transport sector was not included as this has been addressed separately and comprehensively in a recent study for DG MOVE, see footnote 6 above and Box 3.1 later in this report.

1.2 Methodology

1.2.1 *Definition – what is an external cost?*

An **externality** is a cost (or benefit) of an activity to those that are not directly participating in the activity itself. In the case of energy and this work, we use the definition that the **total cost of energy** includes both the **'private costs'** of energy, e.g. those directly related to the activity such as the price paid for a power plant, any fuel costs, plus any taxes or other charges; and the **'external costs'** to society such as the impacts of emissions from the power plant on health, ecosystems, agriculture, buildings and the climate.

A full glossary of terms is provided at the start of this report.

1.2.2 *Our approach*

Our approach to this work mirrors that employed in the 2014 study noted in the introduction above. Therefore, we focus only on the environmental externalities of energy and use **Life Cycle Assessment (LCA)** to define the specific impacts and emissions we quantify and monetise. The use of a life cycle approach means that we assess costs from all steps of the energy supply process, from (1) the initial extraction of fuels and materials; to (2) their transport, processing and distribution; to (3) the combustion or power/heat generation step; and, to (4) decommissioning and waste management.

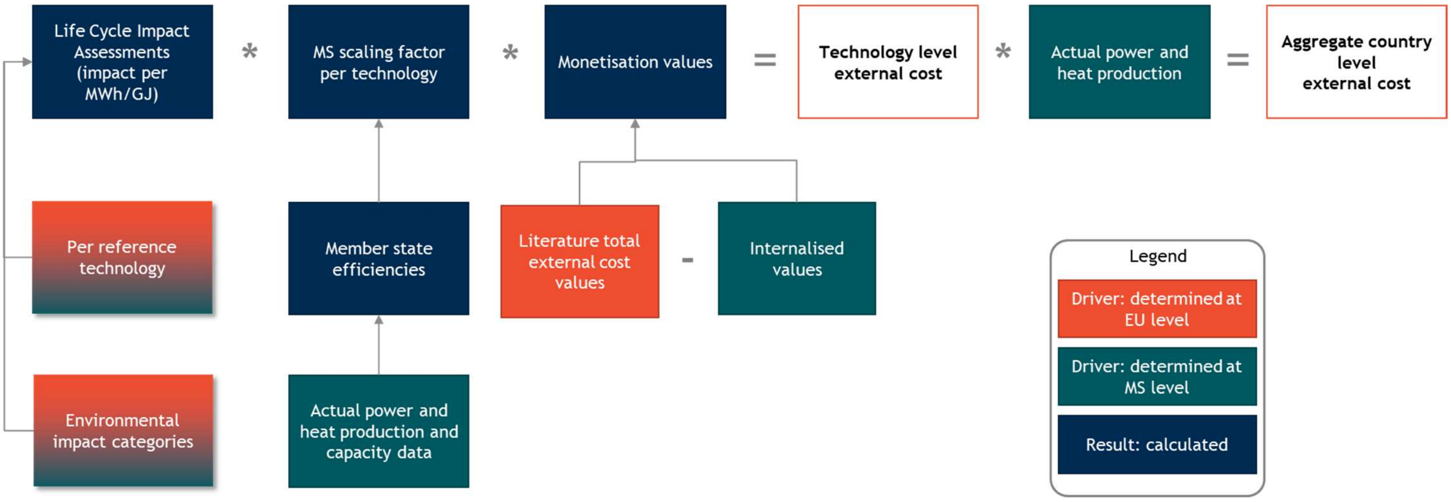
Furthermore, the impact assessment was calculated from cradle-to-grave for the energy production for each technology considered. The functional unit (reference basis) for the life cycle assessments is defined as "*one MWh of electrical energy or heat from cradle to grave: from the production of the primary raw material extraction up to the final waste treatment at end of life*". As shown below in Figure 1-1, life cycle impacts are then multiplied by monetisation factors (identical for all countries), and in some cases scaling factors, to estimate technology level external costs, and further again by power and heat generation data at country level to assess aggregate country level costs. Internalisation of external costs, i.e. when a tax or levy directly targets an environmental externality, to fully or partially 'internalise' the externality in the prices is also carried out, primarily focused on climate measures, but also analysed at a higher level based on the tax data gathered as part of this study – see the report on energy taxes and levies for further information. Further detail on the data sources and calculation of each value is provided in the Annexes to this report.

The LCA underpinning our approach is based on two key methodological choices:

1. The use of the **Product Environmental Footprint (PEF)** Life Cycle Impact Analysis (LCIA) framework with its Environmental Footprint (EF) method 2.0, as developed by the Joint Research Centre (JRC) of the European Commission, whose indicators and factors are also used for the monetisation of costs; and,
2. The use of **Environmental Footprint (EF-compliant)** datasets for the LCIA analysis, and only whenever such datasets were not available for a specific technology Ecoinvent 3.5[8] datasets were used.

This methodological approach was discussed with DG ENER and the JRC and specific comments and recommendations were integrated in the study. Further details on the choices can be found in Annex B.

Figure 1-1 Summary of calculation approach to external costs



Our approach applied the following monetisation values to quantify the environmental impacts in 2018 Euros[9]. The impact categories are those of the EF framework[10]. The values were derived from a handful of key sources, including the Handbook on the External Cost of Transport and its annexes[11], the Environmental Prices Handbook – EU28[12], a report on Monetisation of the MMG (Environmental Performance of Building Elements) method[13], and through advice from the JRC. Detailed information on the selection of the external cost values is provided in Annex B of this report. Unless otherwise stated, i.e. in the sensitivity analyses, the central values are used in all following sections.

[8] https://www.ecoinvent.org/database/database.html
[9] Values are presented in 2018 euros for consistency with the rest of the work. This was implemented through the use of the ECB Eurozone currency deflators [MNA.A.N.I8.W2.S1.S1.B.B1GQ._Z._Z._Z.IX.D.N] to convert values, for example converting from 2012 euros to 2018 euros involves a multiplier of 1.071.
[10] The EF framework also includes an indicator on Eutrophication Terrestrial, but no satisfactory monetization approach is yet available and therefore this indicator was not included.
[11] For EC DG MOVE: CE Delft (2019): Handbook on the external costs of transport
[12] CE Delft (2018) Environmental Prices Handbook: EU 28 version
[13] VITO for OVAM (2017) Annex: Monetisation of the MMG method [update 2017]

Table 1-2 Monetisation values for the impact categories[14]

Environmental category	Unit	Monetisation value (EUR_{2018}/impact unit)		
		Low	Central	High
Climate Change	kg CO_2 eq	0.0615	**0.1025**	0.1936
Ozone depletion	kg CFC-11 eq	22.8	**31.4**	127.2
Ionising radiation, Human health	kBq U235 eq	0.0008	**0.0012**	0.0461
Photochemical ozone formation, human health	kg NMVOC eq	0.87	**1.19**	1.90
Particulate matter	Disease incidence	661 974	**784 126**	1 204 600
Human toxicity, non-cancer	CTUh	30 211	**163 447**	755 270
Human toxicity, cancer	CTUh	174 324	**902 616**	2 789 181
Acidification	mol H+ eq	0.176	**0.344**	1.617
Eutrophication, freshwater	kg P eq	0.26	**1.92**	2.18
Eutrophication, marine	kg N eq	3.21	**3.21**	3.21
Ecotoxicity, freshwater	CTUe	2.39E-24	**3.82E-05**	1.88E-04
Land use (Soil quality index)	dimensionless (pt)	0.000087	**0.000175**	0.000349
Water use	m3 water eq	0.00419	**0.00499**	0.2359
Resource use, fossils	MJ	0	**0.0013**	0.0068
Resource use, minerals and metals	kg Sb eq	0	**1.64**	6.53

Actual power and heat production data, and energy consumption by fuel data, was collected for the latest available year, typically 2016-2018, for each country and technology. This data was mainly sourced from Eurostat (mainly for EU27 and UK), IEA and IRENA statistical publications. Data, particularly for heat production, was not always complete, and therefore the total costs presented in chapter 3 are not fully representative and comparative across countries.

For the external costs of energy consumption analysis a number of simplifying assumptions were required to enable such an analysis, particularly the assumption of single processes to represent energy consumption by a sector. Whilst necessary given the time and resources available, this has an important impact on the robustness of the results, particularly for industry as for example, the many thousands of different industrial energy consuming processes are represented only by a single LCIA dataset per fuel.

Full and detailed explanations of all steps in the methodological approach are provided in the methodological annex to this report.

1.2.3 *Interpreting the external cost results*

By their very nature external costs are something for which there is no market or price established. Attempting to place a value on these costs requires new methodologies and assumptions, which have varying degrees of robustness and uncertainty. The calculations of external costs need to deal with the high complexity of each energy technology, its value chain and national energy systems. When combined with the methodological simplifications and assumptions necessary to carry out this work, this means that the results should be regarded as an approximation based on a set of general assumptions rather than a precise estimate of actual external costs. This can be summarised:

[14] Full explanations of the impact categories and which damages are included can be found in Annex B

"It is important to acknowledge both the inherent limitations of the concept of externalities, and the partial character of the information conveyed in the highly aggregated external cost estimates in order to use external costs in environmental policy decisions in an appropriate way."[15]

It should also be noted that although externalities for energy production are calculated at national level in this report, due to the life cycle approach of the work, and also global supply chains, it is not the case that the externalities attributed to a country are experienced by it. For example, many of the external costs of fuel extraction may be primarily experienced by the fuel producer country, but are attributed in this work to the country that uses the fuel. This applies similarly for manufacturing, whilst many of the impacts are experienced where the manufacturing takes place, the costs are attributed to the country which eventually uses the technology and its manufactured components, rather than the manufacturing country itself. Similarly the analysis of energy production does not attribute the external costs of electricity imports to the importing country, but rather to the producer[16]. As a general rule for consideration, the external costs for renewable energies will be experienced for a large part by the manufacturing countries. Whilst for fossil fuels they will be experienced by the user countries themselves as a large part of the impacts is tied to fuel combustion e.g. through air pollution leading to respiratory impacts. This does not apply equally to all impacts, e.g. climate change is a global impact regardless of the location of the emissions; and impacts vary per country, but it is important to be aware of this approach. The indicative analysis of the external costs of energy consumption goes some way to give insights into these issues.

It is also the case that many of the valuation methodologies are based on studies focused on Europe, and sometimes more specifically to North West Europe or individual countries. It has not been possible within this work, nor in the main source studies for valuation, to differentiate specific values for individual countries based on factors such as population density, location of sources, etc; unless this was already implicit in the LCIA datasets. 'Average' monetisation values are used as the starting point for all countries, but may not fully reflect the impacts in a particularly country, e.g. human health impacts from emissions to air may vary with population density, and therefore countries with high population densities could value damages higher than the average.

We do make an adjustment at country level, known as a unit value transfer, to account for differences in income across locations. This is used to adjust monetisation factors on the basis of per capita GDP (PPP) to account for differences in valuation of life years and willingness to pay for damage avoidance. This is consistent with the approach taken in the 2019 DG MOVE Handbook on the External Costs of Transport. The adjustment is applied to all impacts affecting human health and ecosystems, but not to climate change, land use, water use or resource use.

Finally, the technology definitions do not always closely fit the recorded consumption, for example for heating technologies, residential consumption of fuels for heating are attributed to the residential boiler/stove technologies considered in the LCIA. This may not match the actual usage of the fuel recorded in the energy statistics, i.e. use of biomass as fuel for cooking or heating in Indonesia may not

[15] Krewitt (2002) External Costs of Energy –do the Answers Match the Questions? Looking back at ten years of ExternE, Energy Policy 30:839–848

[16] This is particularly relevant to a number of countries, often smaller countries which are highly integrated in regional networks, with high (>10% total consumption) electricity imports such as AT, BE, BG, CZ, DK, EE, FI, EL, HU, IT, LT, LV, LU, NL, SK, SI.

be carried out in equivalents of the boiler technology modelled in this work. This may under or overestimate the actual costs, and applies primarily to the residential heating technologies.

The estimations of external costs for energy production technologies, the main focus of this work, and for energy consumption, for which an indicative analysis is provided, do overlap significantly, as the electricity and heat use by consuming sectors is also counted in the energy production sectors. The overlap is not 100%, particularly as consumption includes energy consumption not included in the scope of the production technologies. Given the limitations of the energy consumption analysis, we do not recommend the comparison of production and consumption external costs.

Nevertheless, despite these limitations, we believe that there is value in calculating external costs. In doing so we can identify their order of magnitude, relate them to monetary units that are better understood, including existing energy costs and prices, and provide insights into which impacts are greatest. This latter point is of particular interest to policy makers and the prioritisation of policy measures to internalise external costs.

2 External costs per technology

2.1 Electricity technologies

Figure 2-1 presents a production weighted (by electricity generation) average[17] of the external costs of electricity generation technologies in the EU27.

As expected, it shows the highest total external cost per MWh impacts for the fossil fuel power technologies, hard coal, lignite, natural gas and oil, ranging from €68/MWh - €177/MWh in the EU27, and from €81/MWh - €305/MWh in the non-EU G20 (hereafter 'G20' or 'Non-EU'). The average G20 costs are typically higher than for the EU27. For the G20 the largest external costs impact is attributed to electricity production from hard coal (in contrast to the situation in EU27, where lignite has the largest external cost). This is caused mainly by the high external costs of hard coal generation in non-EU G20 countries, such as China, India or Indonesia due to weaker pollutant emissions controls resulting in higher respiratory organics impacts. Lignite use is lower in these countries, giving more weight within the lignite category to the other G20 countries where emissions controls are more similar to the EU27. G20 climate change impacts are a little (5-15%) higher than the EU27 per MWh for the fossil technologies, a result of lower average thermal efficiencies.

External costs for non-fossil technologies are very similar between the EU27 and G20 averages. The costs for Biomass (around €52-€54/MWh) are less than those for natural gas, but higher than for nuclear (€15-€16/MWh) and the other renewable energy technologies. Solar PV, solar CSP, and geothermal generation have external costs ranging from €7/MWh - €17/MWh. The technologies with external costs significantly lower than all the others are wind and hydropower, each with costs of around €2-€3/MWh.

Amongst the impacts, the largest impact on average is from climate change impacts, which is largest for coal, lignite, oil and natural gas. This represents more than 65% of the external costs for all of the fossil technologies in the EU, but less for the G20, where the particulate matter impact plays a much more important role.

The second largest share of external costs is associated with particulate matter – this represents disease damages to human health from emissions to air - and is highest for the combustion-based power sources (fossil fuels and biomass, with the exception of natural gas) and almost zero for the renewable and nuclear power technologies. Solar PV is an exception, with a small, but relatively high value for a renewable energy technology. This is caused by the electricity use in the manufacture of the panels which most often occurs in countries such as China which have an energy system with very high proportions of coal in their energy mix, and therefore indirectly solar PV generates these external cost impacts. Slightly lower external costs for Solar PV can be observed for the G20 largely due to the higher solar irradiation compared to the EU27.

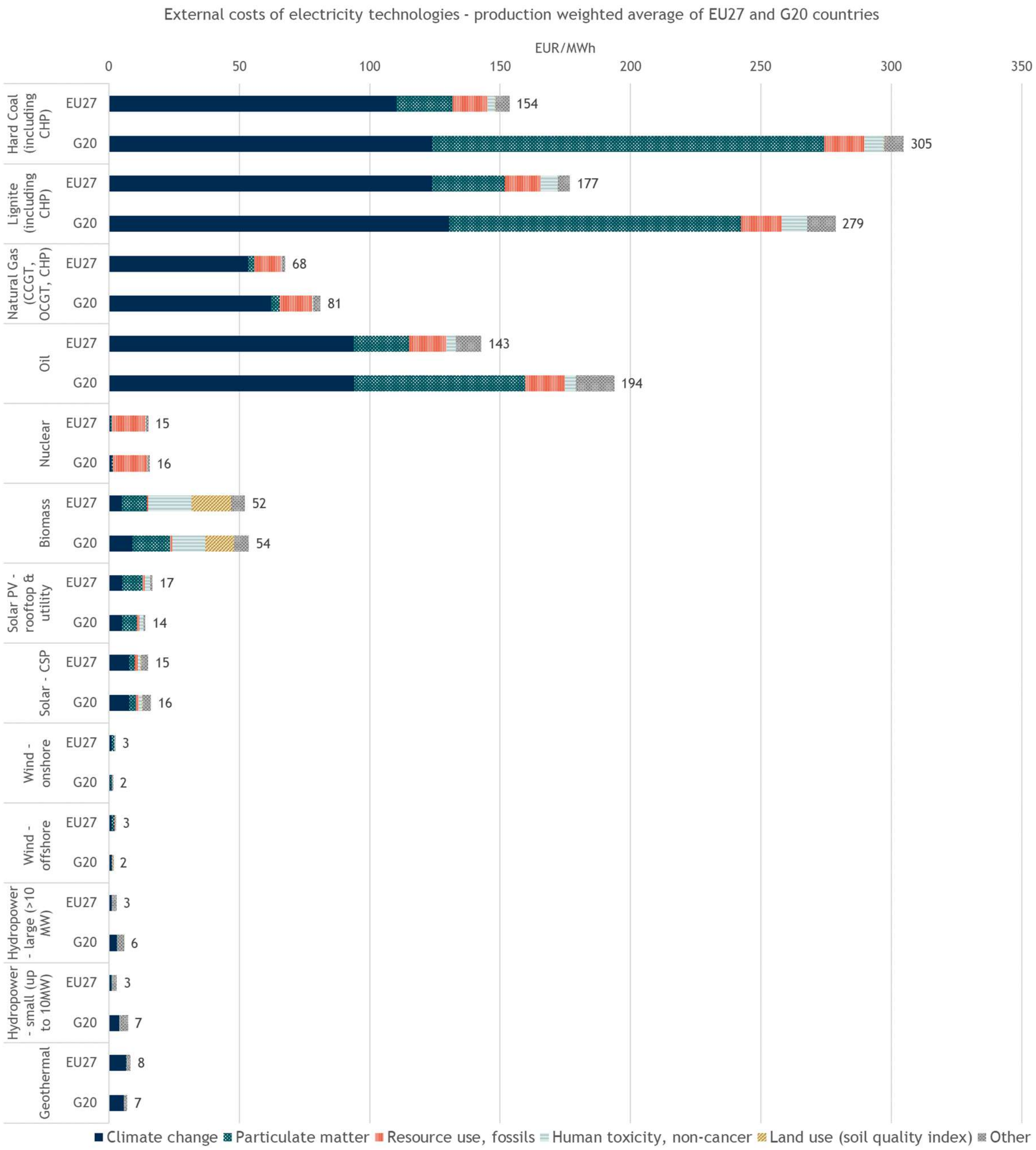
The third largest share of external costs is associated with resource use of energy carriers and is significant for all of the fossil fuels, and also nuclear energy[18]. It should be noted that whilst the

[17] Use of production weighted average gives a more realistic picture of average external costs compared to a simple average by reducing the influence of impact data from countries which may only have very low production.
[18] The monetization of this externality is one that sparks debate, there is an argument that there should be no externality cost for depletion as this is already included in the market price of the resource. These arguments are explained and explored further in Annex B.

valuation of this indicator is based on the energy content of the fuel, the monetisation value used is based on calculations of oil reserves. It has not been possible to adjust these values for other fuels for which reserves and costs are different, this likely results in an overestimate of this cost for coal, lignite and nuclear, which should be kept in mind.

These three cost categories are followed by the impacts of human toxicity, non-cancer impacts (significant especially for power generation from biomass, and also coal, lignite and oil). Land use is the 5th largest impact, and unsurprisingly is highest for biomass. Finally, within the 'other' category, the next most important impacts are human toxicity cancer impacts and photochemical ozone formation, both of which are mainly important for fossil fuel technologies. A few other impacts are valued as only very minor impacts overall, but are important for a few technologies e.g. water use (hydropower and geothermal), ionising radiation (nuclear) and resource use, metals and minerals (solar PV).

Figure 2-1 EU27 and G20 average (production weighted) external cost of electricity per technology in €$_{2018}$/MWh



2.1.1 Sensitivity analysis

The monetisation work determined Low, Central and High monetisation values for most impacts – see Table 1-2 and Annex B for further details on the values and sources. These represent the, sometimes large, ranges in uncertainty present in the monetisation methodologies. The main results of this work (as presented in the previous section) are based on the central monetisation values, in Figure 2-2 we show how the results vary when the low and high monetisation values are used.

When considering the low monetization values, total external costs fall by between 24% (hydropower – small) -90% (nuclear), and an average of 45%, across the technologies. The relative distribution of costs across the technologies remains broadly the same as in the central scenario, although nuclear power, with the reduction in the resource use, fossils impact to zero, sees its external cost reduced to around €1/MWh, similar to wind and hydro power, the other technologies with the lowest external costs.

The climate change and particulate matter impacts still form the majority of external costs with the low monetisation values. Compared to the central values, the importance of energy carrier resources use diminishes in the low monetization scenario, as these are assumed to have no monetary impact with the low monetisation values. The external costs of marine eutrophication and land use become more important in this case, the former mostly associated with coal, lignite, oil and biomass, the latter almost entirely with biomass.

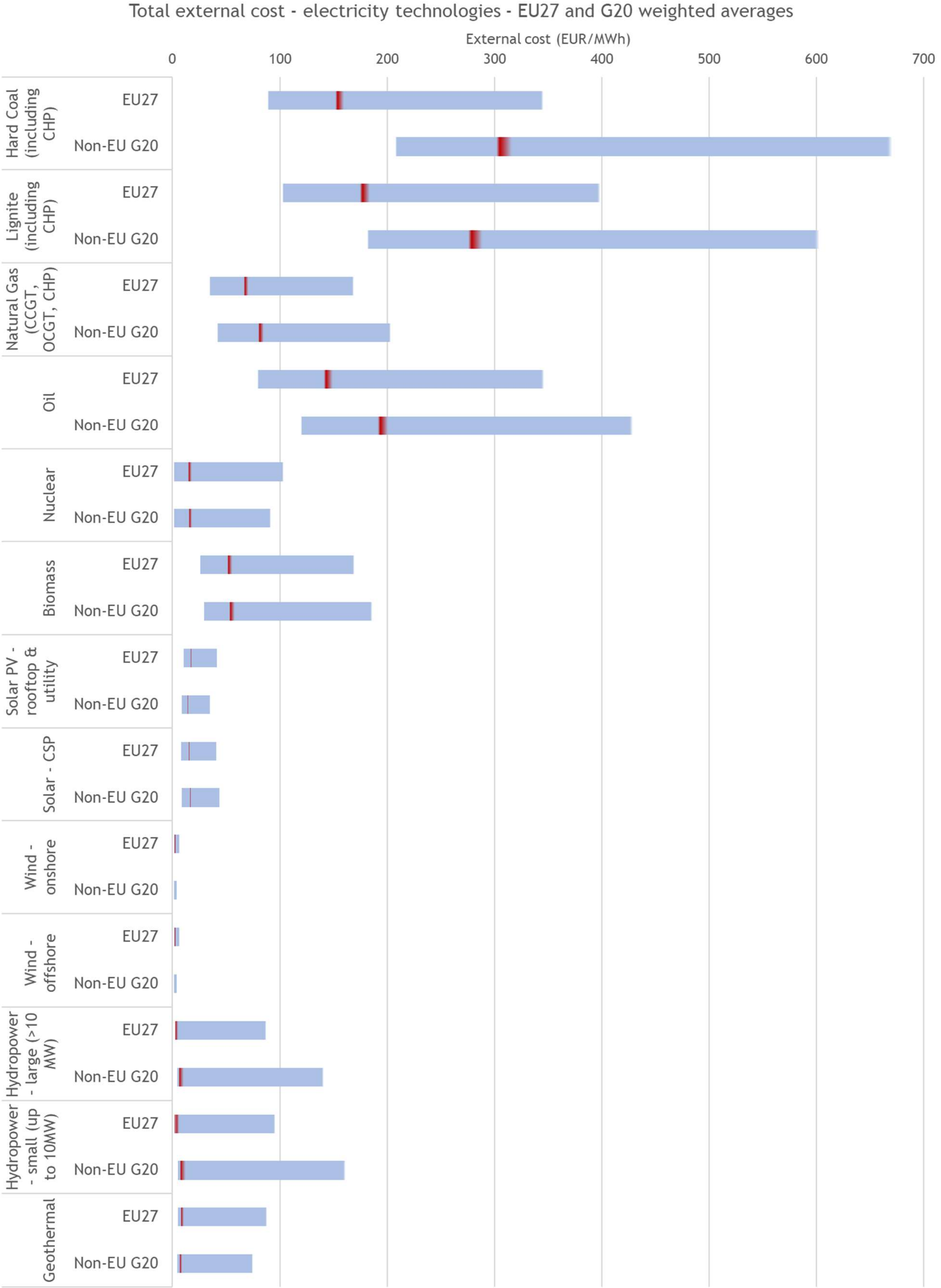
Using the high monetization values, total external costs increase by around 120% (lignite) to around 3 000% (small hydro), across the technologies. The hydro (+2 800% large hydro & +3 000% small hydro) and geothermal (+950%) technologies, which have very low costs using the central values, see very high percentage increases, as water scarcity is valued much higher in this scenario, i.e. the monetisation value increases from 0.005 central to 0.24 (+4 364%) high value. The other technologies see increases averaging 153% overall.

Overall, the cost increases for hydropower and geothermal see them become more costly than solar PV and nuclear, although still less than biomass and the fossil technologies. The gap between biomass and natural gas narrows to only a few euros. In contrast to these increases, the external costs associated with power generation from wind remain very low (€4-€6/MWh) in this scenario as well.

The highest external cost impact remains climate change in a high monetisation scenario, but the external costs of particular matter become more marginal compared to both the central and low monetization scenarios, surpassed by energy carriers resource use and costs of water scarcity.

The changes in results are highly consistent across the EU27 and G20.

Figure 2-2 EU27 and G20 average (production weighted) external cost of electricity per technology in €2018/MWh, range of total costs using Low and High monetisation values, excluding internalisations



2.1.2 *Internalisation of external costs*

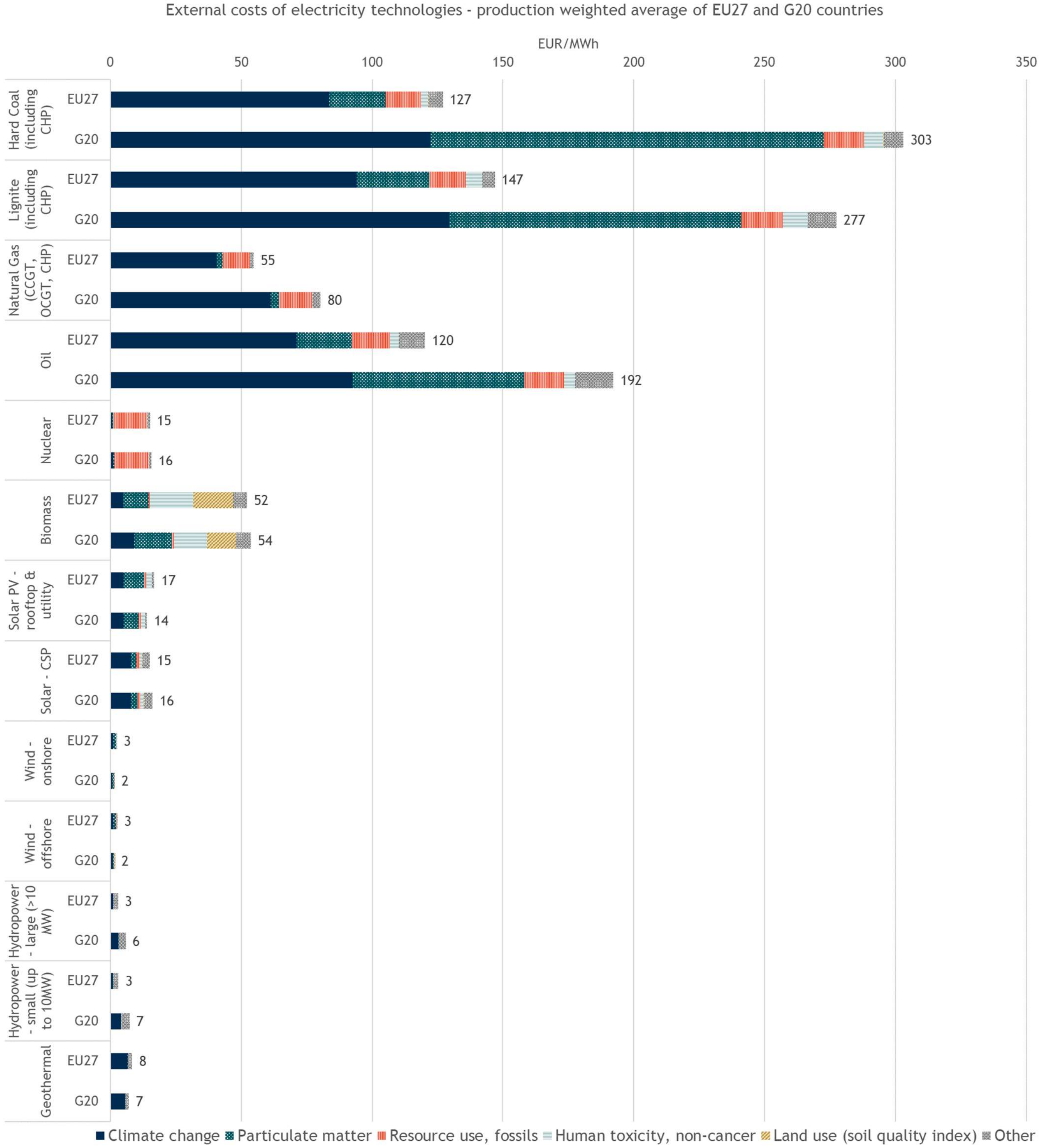
This section provides an insight into how policies have internalised parts of the external costs identified in the previous section. Internalisation, through policy such as a tax, helps to bring the real costs of an externality into economic consideration by the relevant actors. As such the cost is no longer external. A variety of tax policies are possible to achieve such internalisations. Regulatory measures can also be effective means to internalise costs, internalisation through regulation is already captured within the LCIA step in our approach.

Examination of the tax data gathered in this work shows that there are very few instruments outside the area of climate change that can be considered as internalisations of the external cost impacts we assess. The main reason is that by far the largest share of energy taxes and measures are taxes on consumption, these are therefore evaluated in chapter 4 of this report. This section therefore presents results following the application of a range of identified carbon measures and taxes which apply to energy producers. The largest measure by far is the EU-ETS (EU Emissions Trading System), whereby the climate change impact for the electricity technologies in the EU27 is reduced by €24.72 per tCO_2e (see Figure 2-3), this value representing the average price of 1 tCO_2 in the EU-ETS in 2019. As almost all major (fossil) power plants in the EU27 are subject to the EU-ETS they would face this cost[19], and therefore this can be considered a partial internalisation of the climate change externality, reducing the external cost from €102 tCO_2e to €77 tCO2e, a change of -24%. This is applied to all fossil power technologies. In some EU27 countries further carbon taxes apply (see Annex B for details), and carbon measures globally are also applied. In the US an SO_2 trading mechanism is active which internalises part of the acidification impact, which is also included in our calculations.

When the identified internalisations are applied to the results previously presented in Figure 2-1, as shown in Figure 2-3 below, this results in significant declines of 16%-19% for the EU27 average total external costs for the fossil energy technologies, although their costs remain highest of all technologies overall. The effect is much less pronounced (-0.4 – 1.2%) in the G20 due to the lack of carbon policies, or the low effective rate of any policies that are in place.

[19] We have applied the EU-ETS internalization to all EU-ETS MS, although it should be noted that transitional arrangements were used by 8 countries (BG, CY, CZ, EE, HU, LT, PL, RO) to provide (a decreasing number of) free allowances to existing power plants up until 2019, in return they committed to spend an equivalent amount on investments in cleaner energy. From 2020 only 3 countries (BG, HU, RO) are taking advantage of this derogation. More information is available here: https://ec.europa.eu/clima/policies/ets/allowances/electricity_en

Figure 2-3 EU27 and G20 average (production weighted) external cost of electricity <u>with internalisations,</u> per technology in €2018/MWh



2.2 Heat technologies

Note: the LCIA datasets underpinning the analysis, particularly for domestic heating technologies, whilst valid are not considered as robust as those used for the electricity technologies.

The results for the external costs of heat technologies for the EU27 and G20 are presented in Figure 2-4. The highest total external cost per MWh is estimated for domestic wood boilers, reaching more than €170/MWh. The main share (almost 70%) of this cost is caused by external costs associated with particulate matter, pointing to the incomplete /dirty combustion of the fuel in installations lacking filters or other emissions controls, in contrast to the larger CHP biomass technology also evaluated. Part of this result may also stem from a somewhat outdated LCIA dataset for such boilers within Europe. Although it is also the case that EU Ecodesign requirements for domestic solid fuel (biomass) boilers, including emissions controls, do not enter force until 2020 or 2022[20] and therefore weaker, or non-existent national controls apply. The corresponding average value for the G20 countries is much lower (€80/MWh) but this stems largely from the income adjustment of the dominant human health impacts, as the countries that dominate the G20 weighting for this technology are India, China and Indonesia, all with considerably lower incomes than the EU average.

For the other domestic heating technologies assessed, oil boilers (€51/MWh) have the next highest costs. Domestic gas boilers and heat pumps are assessed to have approximately the same external costs (around €36/MWh)[21]. Our view is that the LCIA dataset for heat pumps may be outdated and that it does not fully reflect the current situation of efficiency and electricity mix that heat pumps face. Therefore we would note that we expect the impact for heat pumps to be lower in reality and also to be declining over time as the efficiency of the technology is increasing and the indirect external costs from electricity consumption, which form around 85% of the climate change impact for heat pumps, is declining each year as the electricity mix becomes cleaner and less GHG intensive in most countries. The lowest recorded external costs are associated with domestic solar thermal heat generation.

The total external costs of heat from larger installations for hard coal CHP (€57-€103/MWh) and lignite CHP (€58-€78/MWh) are also relatively higher than for CHP gas and biomass technologies.

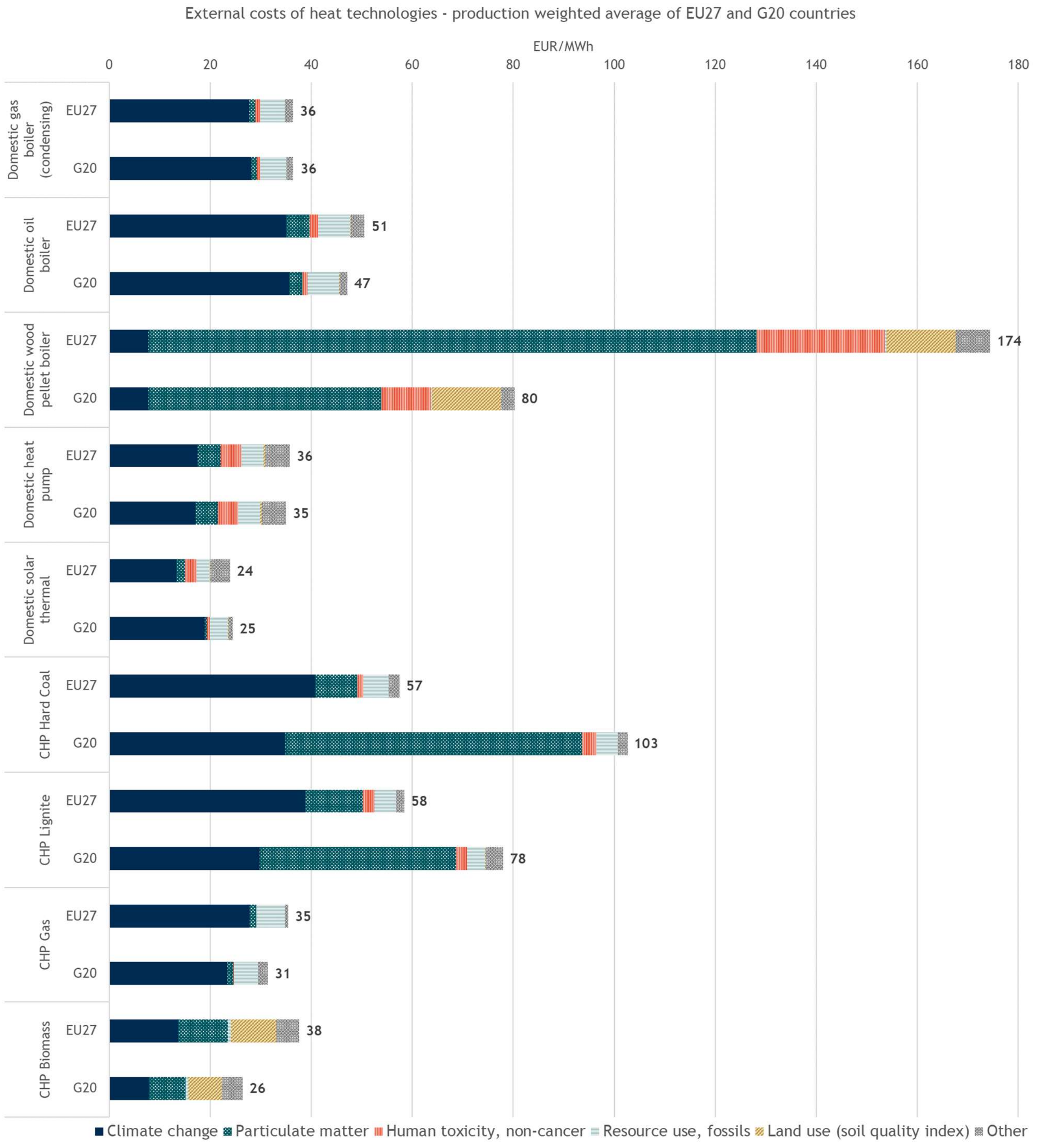
Climate change is the largest impact across all technologies, whilst particulate matter is the second most important, and is particularly relevant for domestic wood boilers and hard coal, lignite and biomass CHP. The human toxicity, non-cancer, resource use, energy carriers and land use make up the rest of the top five drivers of external costs. For the latter impact, the biomass-based technologies have relatively high costs.

The results do not vary substantially for G20 countries for most technologies, with the exception of the domestic wood boiler mentioned above, and also heat from lignite and hard coal CHP plants where the particulate matter impact is significantly higher, despite the income effect. This leads to costs almost doubling for hard coal CHP and significantly increasing for lignite CHP compared to the all country EU27 average.

[20] See Regulations Ecodesign (Lot 15) 2015/1187 and 2015/1189: Solid fuel boilers; and, Ecodesign (Lot 20) Local space heating products: 2015/1188, 2015/1185 and 2015/1186

[21] It should be noted that in the following chapter when total external costs are calculated at country level that the indirect electricity use for heat pumps is removed from the calculation to avoid double counting. This results in a climate impact for the technology significantly lower than shown here in the technology-level comparison.

Figure 2-4 EU27 and G20 averages (production weighted) external cost of heat per technology in €$_{2018}$/MWh



2.2.1 *Sensitivity analysis*

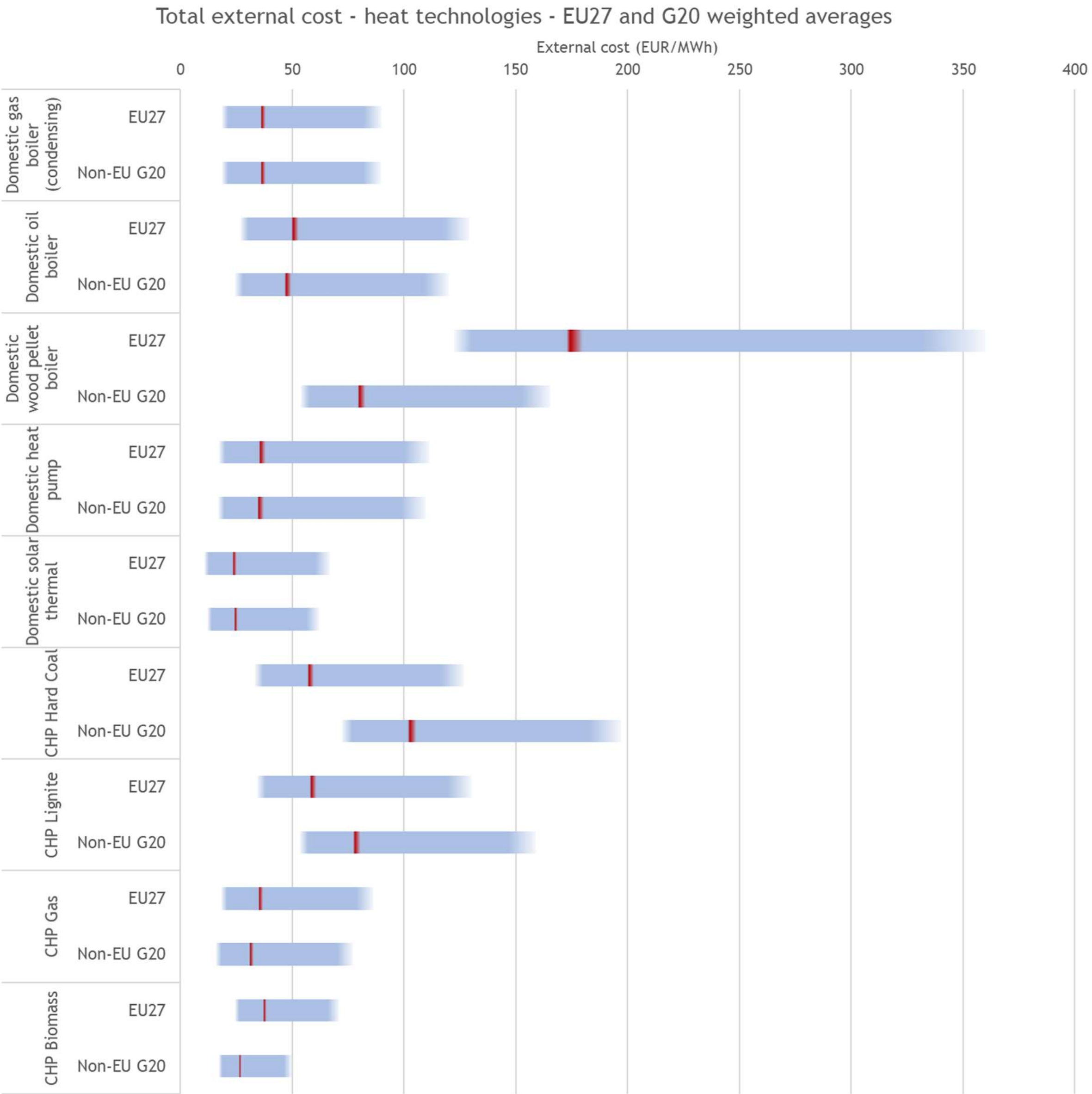
The monetisation work determined Low, Central and High monetisation values for most impacts. These represent the, sometimes large, ranges in uncertainty present in the monetisation values. The main results presented in the previous section are based on the Central values, Figure 2-5 below shows how these change when the low and high values are used.

In the Low monetisation scenario, total external costs are between -30% (domestic wood boiler and CHP Coal) and -54% (domestic solar thermal), and an average of -43%, lower across the technologies.

Notwithstanding the fact that the external costs are generally lower in the low monetization scenario, the relative distribution of the costs among the technologies remains the same for both the EU27 and G20. In terms of impacts the relative share of external costs associated with photochemical ozone formation and land use gain in importance. The external costs of energy carrier resource use are reduced to zero in this scenario.

Using the High monetization values, total external costs are between 88% (CHP Biomass) and 213% (Domestic heat pump), and an average of 138%, higher across the technologies. The relative distribution of the costs among the technologies remains the same for both the EU27 and G20 with the exception of domestic heat pumps, which in a high value scenario would become more costly than domestic gas boilers. Across the impacts, the five main groups of external costs with highest shares remain the same for both the EU27 and G20 weighted average, the only change being that the external costs of energy carriers resource use, surpass non-cancer human health effects as the third largest group of costs (and their share is one of the main drivers of higher costs in this scenario in general).

Figure 2-5 EU27 average (production weighted) external cost of heat per technology in €2018/MWh, using Low monetisation values, excluding internalisation

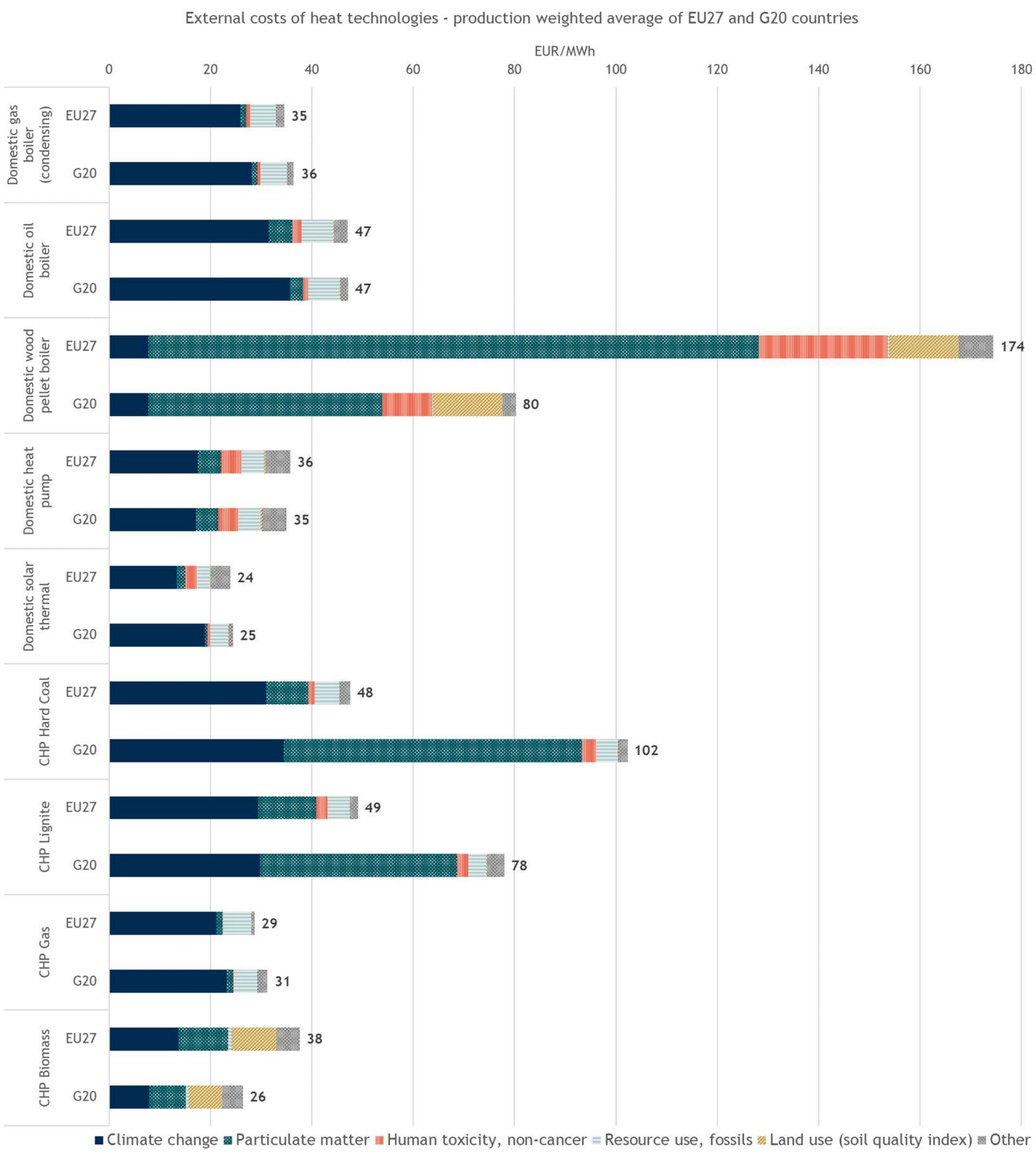


2.2.2 Internalisation of external costs

As explained in section 2.1.2 this section applies adjustments to the external costs based on the existence of policies which introduce equivalent costs for producers. As for electricity, the only policies that can be directly identified as internalisations are climate change policies such as carbon taxes, which in the case of heating applies to the fuels used. The policies that are internalised are listed in the Annexes to this report, but include the EU-ETS which affects the large-scale CHP heat technologies, and a number of country specific carbon taxes which affect residential heating use of natural gas and oil.

When the identified internalisations are applied to the results previously presented in Figure 2-4, as shown in Figure 2-6 below, this results in significant declines of 16%-19% for the EU27 average total external costs for the large scale fossil heat CHP technologies. It also results in declines of 5-7% in the external costs of domestic natural gas and oil boilers as part of their climate change impact is internalised. The effect is much less pronounced (-0.3 – 0.5%) in the G20 due to the lack of carbon policies, or low effective rates of any policies that are in place.

Figure 2-6 EU27 and G20 average (production weighted) external cost (with internalisations) of heat per technology in €2018/MWh



3 External costs per country

3.1 Normalised (per MWh) system level external costs

3.1.1 Electricity

By summing the multiplications of external cost impacts per technology by actual generation per technology and then dividing by the total electricity generation, a per MWh external cost of electricity can be estimated per country[22].

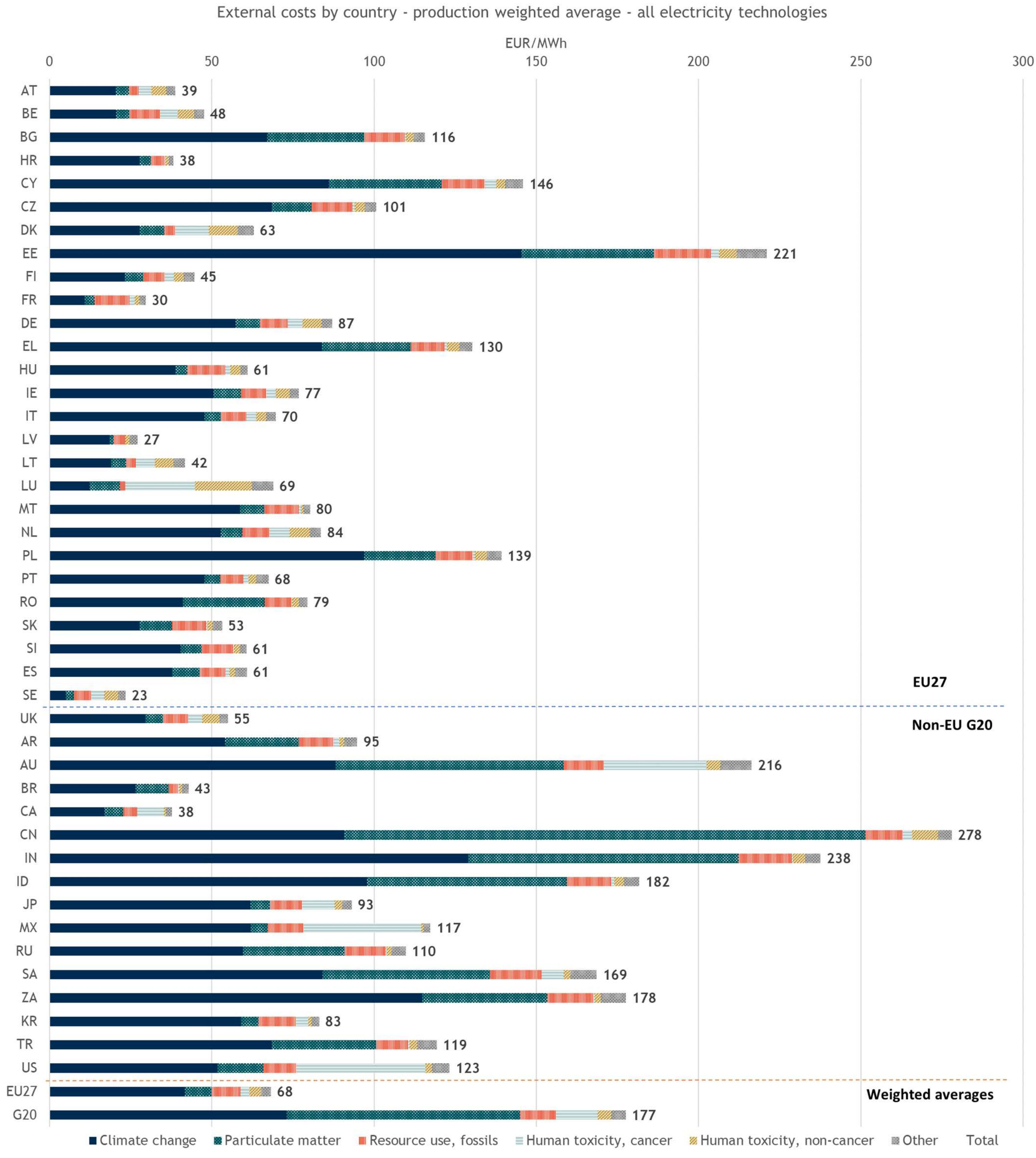
The results are presented in Figure 3-1 and show the influence of the actual energy mix in a country on the average external costs of generation. The average external costs in the EU27 is €68/MWh. The lowest values are found in Sweden (€24/MWh), Latvia (€27/MWh) and France (€30/MWh), Sweden with a high share (60%) of hydropower paired with natural gas, Latvia with high shares (40% each) of nuclear and hydropower, and France with a high share (70%) of nuclear. The countries with highest average external costs in the EU27 of €120-220/MWh are unsurprisingly those still heavily dependent on power production from fossil fuels, mainly from lignite and/or hard coal (Bulgaria, Poland, Greece) or from oil (Estonia [power from shale oil], Cyprus).

The EU27 average is significantly lower than the G20 weighted average of €178/MWh. As can be seen on the figure there is significant variation in the G20 values. Whilst the other most developed countries in the G20 (for example the UK, Canada, South Korea, or Japan) record values not too different or below the EU average, the resulting G20 weighted average value is heavily influenced by the high values of China (€278/MWh) and India (€238/MWh) that have very large weightings in the average. Australia is notable as a highly developed country but with a relatively high external cost of €216/MWh, due to high shares of coal in its electricity production. Indonesia (€182/MWh) and South Africa (€178/MWh) also stand out for their high external costs, also driven by high shares of coal in their electricity mix. The main drivers of the very high external costs in China, India and to a lesser extent Australia, Indonesia and South Africa, were already described in the previous chapter, e.g. high shares of inefficient coal power with weak emissions controls, leading to very high climate and particulate impacts. For Australia, their power plants may be somewhat cleaner than China and India, but relatively high income levels mean that the human health impacts are attributed higher external costs. The US has relatively high external costs of €123/MWh compared to the EU average, similarly to Australia, relatively high income levels (+34% compared to the EU average) drive higher costs of human health impacts.

[22] Can be written as:

$$\frac{external\ cost_{el}}{MWh_{el}} = \frac{\sum_{tech=1}^{13} external\ cost_{el,tech} * MWh_{el}\ actual\ production_{tech}}{\sum_{tech=1}^{13} MWh_{el}\ actual\ production_{tech}}$$

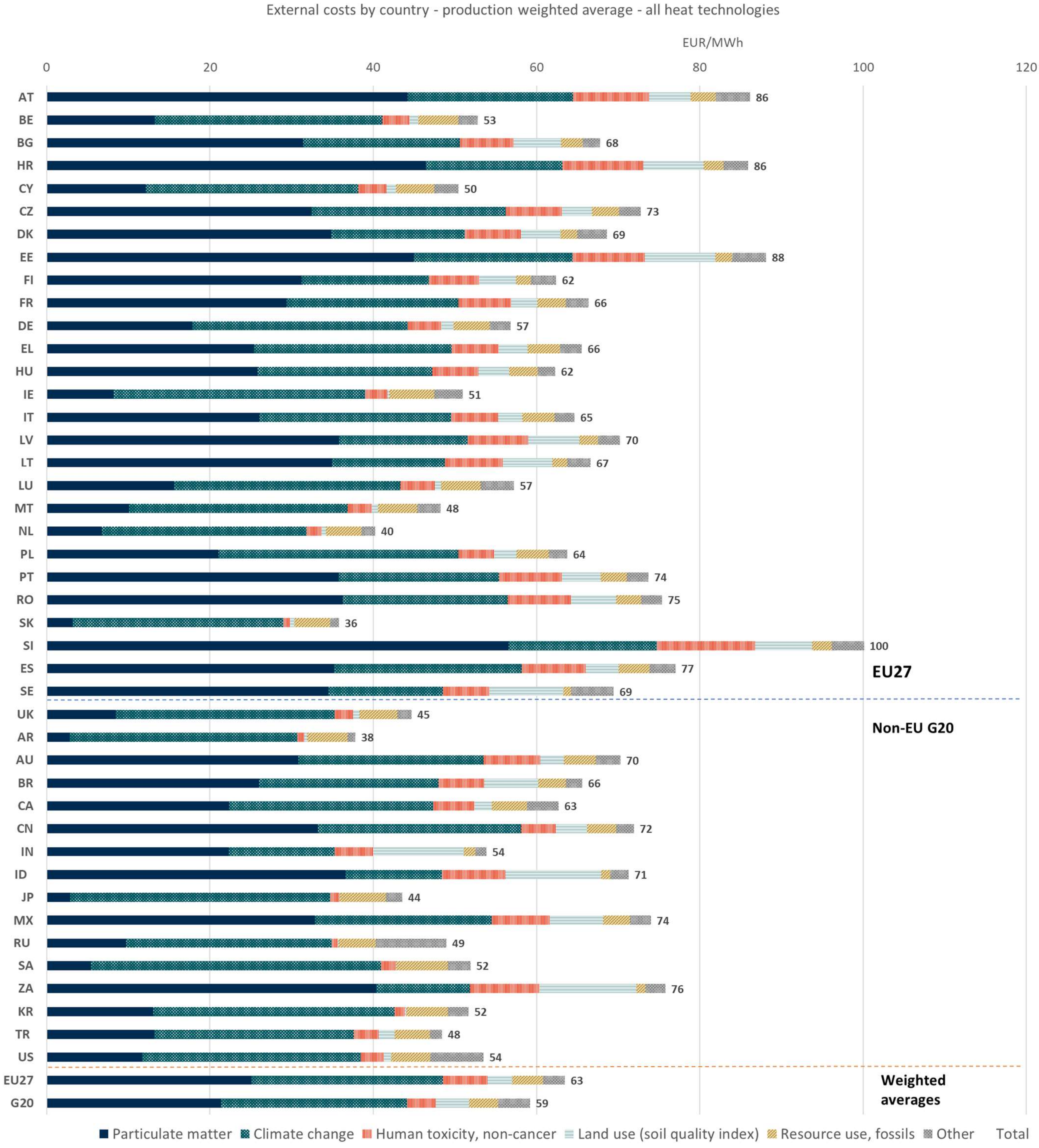
Figure 3-1 Average (production weighted) external cost of electricity per country in €2018/MWh



3.1.2 *Heat*

The analysis of external costs of heating per country (see Figure 3-2) shows a more varied picture than in the case of electricity between the EU and G20. There is no clear trend across the countries although the average external costs for the G20 are a little lower than those of the EU. The countries with lowest total external costs in the EU are Slovakia (€36/MWh) and the Netherlands (€40/MWh), driven by high shares of gas (domestic and CHP). Amongst the G20 Argentina (€38/MWh), Japan (€44/MWh) and the UK (€45/MWh) have the lowest costs. The EU27 countries with largest external impacts are Slovenia (€100/MWh) and Estonia (€88/MWh), driven by high shares of domestic wood boilers. Amongst the G20 countries, those with largest costs are South Africa (€76/MWh) and Mexico (€74/MWh), the former driven by very high shares of domestic wood boilers, the latter by high use of both wood and oil boilers.

Figure 3-2 Average (production weighted) external cost of heat per country in €$_{2018}$/MWh



3.2 Total external costs

The total external costs across all 43 countries are almost €4 100 billion per year (see Table 3-1). This is clearly a huge number, representing about 6.6% of the total annual GDP of the 43 countries considered. The comparison of total annual external costs shows that, of all the analysed countries, the most significant impact by far is recorded by China, reaching almost €1 900 billion; the United States has the next highest total cost of almost €600 billion. The only other countries surpassing the €100 billion threshold are India, Russia and Japan – notably amongst the most populous countries of the G20. Brazil and Indonesia, which have populations of 210 and 270 million, respectively, are exceptions, Brazil with relatively low costs – mostly due to the large role of hydropower (60% of electricity) in its energy mix; Indonesia more closely linked to low income levels and therefore lower valuation of human health impacts. From the EU27 countries, the largest sums of external costs are also linked closely to population and economy size, and therefore Germany, France, Italy, Poland and Spain have the highest costs.

Focusing on just the EU27 and electricity, for which the numbers are most robust, the external costs of €179 billion represent around 1.3% of annual GDP. For countries with relatively high costs per MWh and relatively low GDP this value increases, e.g. to 5% for Poland and then 10% for Bulgaria and 12% for Estonia. These types of values are also achieved in many G20 countries, with ratios of 14% external costs of electricity to GDP in China, India and South Africa.

When comparing the external costs of heating to electricity production, it is notable that the relative importance of heating externalities is higher in the EU27 countries than in the rest of G20 economies, as for example 14 EU countries have higher total external costs for heating than for electricity, whereas the same is the case for only one G20 country - the UK.

The country with highest external costs for heating is China (€234 billion), whilst Russia with its relatively cold climate and high heating needs is second at €101 billion. The three largest EU27 countries (Germany, France and Italy) also register significant external costs for heating. The robustness and coverage of the heating production data is lower than that for electricity, this should be kept in mind when considering and comparing the results. Further discussion on this point is provided in Annex B.

Table 3-1 Total external costs per country, latest year (2016-2018), EUR_{2018} billion

EU27 Country	External Cost Total (EUR bn)			G20 Country	External Cost Total (EUR bn)		
	Electricity	Heat	Total		Electricity	Heat	Total
Austria	2.0	6.6	8.5	United Kingdom	14.3	16.1	30.4
Belgium	2.8	4.6	7.4	Argentina	13.0	4.2	17.3
Bulgaria	5.3	1.4	6.7	Australia	57.5	4.4	61.9
Croatia	0.5	2.0	2.5	Brazil	23.2	10.3	33.5
Cyprus	0.7	0.1	0.8	Canada	24.2	14.1	38.4
Czech Republic	8.6	6.1	14.7	China	1 642.6	234.3	1 876.9
Denmark	1.0	4.1	5.1	India	329.5	91.8	421.3
Estonia	3.0	1.0	4.0	Indonesia	46.6	46.6	93.2
Finland	2.6	4.6	7.2	Japan	90.3	11.5	101.8
France	14.2	23.6	37.8	Mexico	36.5	10.8	47.4

EU27 Country	External Cost Total (EUR bn)			G20 Country	External Cost Total (EUR bn)		
	Electricity	Heat	Total		Electricity	Heat	Total
Germany	47.5	35.0	82.5	Russia	117.6	100.9	218.5
Greece	7.2	2.1	9.2	Saudi Arabia	58.1	1.1	59.2
Hungary	1.8	4.4	6.3	South Africa	43.8	4.1	47.9
Ireland	2.3	1.0	3.3	South Korea	45.9	10.4	56.3
Italy	17.5	24.4	42.0	Turkey	35.3	9.2	44.5
Latvia	0.2	1.1	1.3	United States	508.8	85.9	594.6
Lithuania	0.1	1.2	1.2	**Non-EU G20 Total**	**3 087.3**	**655.8**	**3 743.1**
Luxembourg	0.0	0.4	0.4				
Malta	0.1	0.0	0.1	**Global Total**	**3266.4**	**817.3**	**4083.7**
Netherlands	8.0	5.0	13.0				
Poland	23.7	10.5	34.3				
Portugal	3.7	1.9	5.6				
Romania	5.3	6.7	12.1				
Slovakia	1.5	0.9	2.3				
Slovenia	1.0	1.1	2.1				
Spain	16.4	7.7	24.1				
Sweden	1.9	4.1	6.0				
EU27 Total	**179.0**	**161.5**	**340.6**				

In terms of impact categories, at the global level climate change is the no.1 impact, with costs of €1 700 billion, or around 42% of the total. Impacts of 13.6 $GtCO_2e$ are accounted for in the analysis, equivalent to around 1/3 of global annual GHG emissions. Particulate matter, with costs of €1 575 billion (39%) is a close second; indeed in 9 countries, including China, particulate matter is the larger impact. This similarity in cost between the climate and particulate impacts is broadly consistent with other estimates of the cost of air pollution, with some studies noting that these could be higher than climate impacts[23]. These two key impacts are followed by resource use, fossils (€270 billion), and then human toxicity, cancer (€253 billion) and non-cancer (€127 billion) human health effects. The other 10 impact categories total €154 billion together.

Box 3-1 External costs of transport

A key source study on the external costs of transport was published in 2019, the Handbook on the External Costs of Transport (Version 2019). Transport is an important energy using sector and was also considered highly relevant for this work. Given the publication of the 2019 study it was agreed not to repeat a similar exercise within this work, as this would be 're-inventing the wheel'. Nevertheless it is useful to reflect upon and summarise some of the key findings from that work and place them in the context of the results for the electricity and heat sectors.

Key results

The study summarises total external costs of transport (road, rail, inland waterways, aviation and maritime) within the EU28 of €987 billion in 2016, or 6.6% of GDP. Road transport accounted for 83% of these total costs, of which the split was 76:24 between passenger transport and road freight. Maritime (10%) and aviation (5%) were the other major contributors. The largest external cost impact category was accidents, accounting for 29% or €286 billion, whilst congestion costs accounted for 27% or €271 billion. However, part of these delay costs are internalised and hence they are only partly external. Climate change and air pollution, both contributed

[23] Such as those highlighted in OECD/NEA (2018) The costs of electricity provision

approximately 14% or €140 billion, whilst well-to-tank emissions accounted for around 5% or €53 billion of the total costs.

Comparing results

The total external costs of transport in the EU of €987 billion cannot be compared to total EU external costs in this work of €341 billion, as transport external costs include significant costs such as congestion and accidents that are not relevant for this study. On measures that are consistent across the studies, such as climate change, the total cost of €140 billion per year for transport compares to a cost of €143 billion per year in this study (for electricity+heat) for the climate change impact, very similar totals. For air pollution the €138 billion in the transport study, can be taken as corresponding to the aggregate of the photochemical oxidant formation and particulate matter categories in this work, and the total impact of €91 billion. However, it is important to note that these comparisons are not highly robust, given the methodological differences highlighted below. Similarly, comparisons could be made with the sector values derived in chapter 4 of this work, but we would caution against giving much weight to these given the associated uncertainties.

Comparing methodologies

The DG MOVE study methodology and especially the underlying work in the Environmental Prices Handbook EU28 has been a key source for the monetisation of impacts in this work and therefore there is a relatively high level of consistency in the valuation approaches across the two studies. However, there are important differences in a few areas:

1. The Transport study considers different external costs than this work: Whilst climate change costs are handled broadly the same by both studies, the transport study considers some impacts also considered in this work in an aggregated way (air pollution, habitat damage); for other impacts it mentions these in aggregate, but does not include them (soil and water pollution); and, it includes some impacts not considered in this work (accidents, noise, congestion);
2. The Transport study does not focus on the entire life cycle of transport emissions, it focuses most heavily on the use phase of impacts, as is most appropriate for transport. Through the addition of Well-to-Tank impacts it does include a broader set of life-cycle impacts than just the use phase, adding the air pollution and climate impacts of the fuel extraction (well) and the steps through to its transport to fuelling stations (tank). Beyond this, the impacts of the other life-cycle stages, such as the manufacture or disposal/decommissioning of the vehicles or infrastructure, whilst mentioned (upstream and downstream emissions of vehicles and infrastructure) are not included;
3. The Well-to-Tank costs represent a potentially large share of costs that can be considered a double counting with the total climate and air pollution costs in this study, given that a large part derive from energy use (electricity or heat).

3.3 Sensitivity analysis

The monetisation work determined Low, Central and High monetisation values for most impacts. These represent the, sometimes large, ranges in uncertainty present in the estimates. The main results are based on the Central values presented in previous sections, Table 3-2 below shows how these change when the Low and High values are used.

The variation in costs can be quite significant, in the EU a range of external costs between €196 - €854 billion is estimated (or -42% and +151% compared to the total using the central values), whilst for the G20 between €2 300 billion and €9 000 billion costs are estimated (or -38% and +140% compared to the total using the central values). In the high value scenario all impacts increase, but especially water use, resource use fossils and the human toxicity impacts all increase significantly their proportions in the total.

Table 3-2 Total external costs per country, comparison of low-central-high monetisation scenarios, latest year (2016-2018), EUR$_{2018}$ billion

EU27 Country	External Cost Total (EUR bn)			G20 Country	External Cost Total (EUR bn)		
	Low	Central	High		Low	Central	High
Austria	5.4	8.5	19.1	United Kingdom	16.1	30.4	77.3
Belgium	3.8	7.4	19.8	Argentina	9.8	17.3	42.9
Bulgaria	4.1	6.7	16.0	Australia	36.4	61.9	148.5
Croatia	1.6	2.5	5.5	Brazil	20.5	33.5	81.0
Cyprus	0.5	0.8	1.9	Canada	20.1	38.4	105.8
Czech Republic	8.6	14.7	34.0	China	1 307.1	1 876.9	4 004.8
Denmark	3.3	5.1	11.0	India	268.9	421.3	912.0
Estonia	2.5	4.0	8.7	Indonesia	60.0	93.2	200.2
Finland	4.4	7.2	16.9	Japan	52.0	101.8	248.5
France	20.1	37.8	118.9	Mexico	22.5	47.4	125.7
Germany	46.4	82.5	194.3	Russia	123.6	218.5	515.7
Greece	5.5	9.2	24.2	Saudi Arabia	35.7	59.2	133.3
Hungary	3.7	6.3	14.9	South Africa	29.3	47.9	120.3
Ireland	1.8	3.3	7.8	South Korea	29.7	56.3	140.5
Italy	24.6	42.0	104.5	Turkey	27.1	44.5	136.9
Latvia	0.8	1.3	2.8	United States	274.9	594.6	1 960.9
Lithuania	0.8	1.2	2.7	**Non-EU G20 Total**	**2 333.8**	**3 743.1**	**8 954.2**
Luxembourg	0.2	0.4	0.9				
Malta	0.1	0.1	0.3	**Global Total**	**2529.9**	**4083.7**	**9808.2**
Netherlands	7.0	13.0	31.1				
Poland	20.3	34.3	75.6				
Portugal	3.3	5.6	15.7				
Romania	7.6	12.1	27.5				
Slovakia	1.2	2.3	6.1				
Slovenia	1.2	2.1	4.8				
Spain	14.0	24.1	71.1				
Sweden	3.4	6.0	17.7				
EU27 Total	**196.1**	**340.6**	**853.9**				

3.4 Internalisation of external costs

As noted earlier in sections 2.1.2 and 2.2.2 we also identified policies that directly intend to internalise the costs of an environmental externality for energy production. Although these are primarily limited to measures that address climate change, namely the EU-ETS and other emissions trading and carbon tax policies (see Annex B for further details). Table 3-3 below presents the estimated total internalisations of the external costs of energy identified in this work.

The table shows how approximately €34.5 billion of the external costs are internalised in the EU, but only €18.1 billion in the G20, which is much lower proportionally when considering the comparative size of the external costs (G20 has more than x10 the base external costs than the EU).

For the EU the reduction of €34.5 billion from total external costs of €340 billion, represents a 10% internalisation of the external costs. For electricity the €28.1 billion represents a 16% internalisation of the €179 billion costs. For heat the €6.4 billion internalisation represents 4% of the €162 billion external costs. The EU-ETS is responsible for by far the largest share of this internalisation.

For the G20 the reduction of €18.1 billion from total external costs of €3 750 billion, represents a 0.5% internalisation of the external costs. The internalisations occurring mostly through measures in the UK (including the EU ETS), China (Pilot ETS), Canada, India and the US. These apply almost entirely to electricity, with minimal internalisation of heat externalities.

We note that this direct internalisation of external costs to electricity and heat producers only tells part of the story. Consumers of electricity and heat, in sectors such as industry, agriculture, residential and commercial and public services, tend to face significant energy taxes. These measures on energy consumption form by far the largest share of energy taxes and potential internalisations of the external costs of energy. These sectors and the relevant taxes are addressed in the following chapter.

Table 3-3 Total internalisation of external costs per country, latest year (2016-2018), EUR_{2018} billion

EU27 Country	Internalised External Cost Total (EUR bn)			G20 Country	Internalised External Cost Total (EUR bn)		
	Electricity	Heat	Total		Electricity	Heat	Total
Austria	0.3	0.1	0.4	United Kingdom	2.1	0.1	2.3
Belgium	0.4	0.0	0.4	Argentina	0.2	0.0	0.2
Bulgaria	0.7	0.1	0.8	Australia	0.0	0.0	0.0
Croatia	0.1	0.0	0.1	Brazil	0.0	0.0	0.0
Cyprus	0.1	0.0	0.1	Canada	1.2	0.0	1.2
Czech Republic	1.4	0.3	1.7	China	5.2	0.4	5.6
Denmark	0.2	0.2	0.3	India	4.8	0.0	4.8
Estonia	0.5	0.0	0.5	Indonesia	0.0	0.0	0.0
Finland	0.4	0.3	0.6	Japan	0.5	0.0	0.5
France	1.2	2.8	4.0	Mexico	0.6	0.0	0.6
Germany	8.3	0.8	9.1	Russia	0.0	0.0	0.0
Greece	1.1	0.0	1.1	Saudi Arabia	0.0	0.0	0.0
Hungary	0.3	0.1	0.4	South Africa	0.8	0.0	0.8
Ireland	0.4	0.1	0.5	South Korea	0.3	0.0	0.3
Italy	3.1	0.3	3.4	Turkey	0.0	0.0	0.0
Latvia	0.0	0.0	0.1	United States	1.7	0.0	1.7
Lithuania	0.0	0.0	0.0	**Non-EU G20 Total**	**17.5**	**0.6**	**18.1**
Luxembourg	0.0	0.0	0.0				
Malta	0.0	0.0	0.0	**Global Total**	**45.6**	**7.0**	**52.6**
Netherlands	1.4	0.2	1.6				
Poland	4.0	0.7	4.7				
Portugal	0.7	0.1	0.8				
Romania	0.7	0.1	0.8				
Slovakia	0.2	0.0	0.2				
Slovenia	0.2	0.0	0.2				
Spain	2.5	0.0	2.5				
Sweden	0.1	0.1	0.1				
EU27 Total	**28.1**	**6.4**	**34.5**				

4 Indicative analysis of external costs of energy consumption

In this chapter we present an indicative analysis of external costs from an **energy consumption** perspective for the industry, agricultural, residential and commercial and public sectors. This is in contrast to the **energy production** perspective presented in the previous chapters.

The analysis again takes a life-cycle approach, so all attributable costs across the full life-cycle are accounted. In doing so there can be considerable overlap in the costs being attributed, both with the energy sector analysis of previous chapters (e.g. electricity and heat use by sectors) and also between the consuming sectors (e.g. use of biomass as fuel by a sector can overlap with the consumption of the agricultural sector, energy use in manufacture by industry will also be included in products used for consumption in the other sectors). Therefore, significant care is needed when comparing sectors or aggregating the results, as substantial double counting may occur. We recommend therefore to only consider the results at the sector level, and not to aggregate them.

The approach used mirrors the main approach taken for the energy sector, with the main variations being:

- The use of different datasets for the Life Cycle Impact Assessment, based on 1 MWh of use of a particular fuel in a general process, the specific datasets are detailed in the Annexes. It should be noted that these datasets, as they are very general, do not robustly represent all different types of consumption and their impacts – this is why we present the results here only as indicative;
- Consumption data per fuel type is based on the IEA World Energy Balances – fuels included are: Coal; Oil Products; Natural Gas; Geothermal, Solar, etc; Biofuels, Waste; Electricity; and, Heat.
  - Note: the inclusion of oil products provides for a potential overlap with transport energy use as covered in the work referenced in box 3-1 in the previous chapter. This is particularly relevant for agricultural energy consumption.
- For Electricity and Heat consumption the weighted average external cost impacts of the previous chapters were used for the calculations.

4.1 Indicative external costs of energy consumption per sector

4.1.1 External costs per fuel per sector

In Figure 4-1 we present the average results across all countries for the external costs of energy consumption per fuel and per sector.

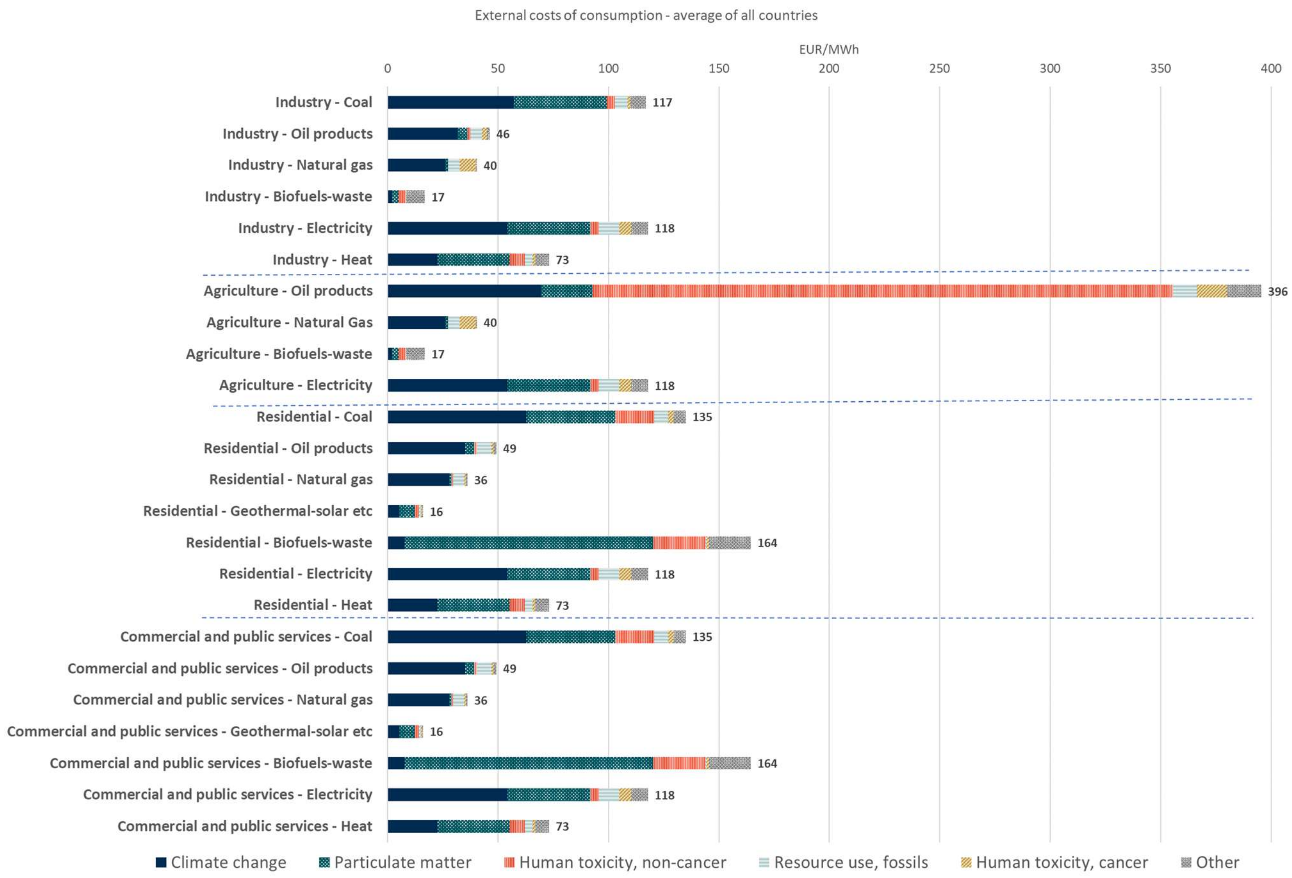
For industrial energy consumption these show that per MWh the external cost of energy use ranges from €17-€118/MWh. The highest costs are calculated for electricity and coal use. The value for electricity is taken from the results presented in previous chapters. The external cost value for coal is lower than the cost for power from coal but higher than the value for heat from Coal CHP, the value therefore appears consistent with the use of coal in industrial processes for heat, not always with CHP. The value for oil products (€46/MWh) is comparable to natural gas (€40/MWh); this is due to limitations in the life cycle impact datasets available for this fuel, for which only a dataset for LPG was available. Whilst LPG fits the oil product classification, it has qualities and impacts very similar to natural gas, i.e. it is relatively ‘cleaner’ than other ‘heavier’ oil products. In reality the actual usage of these heavier oil products, in addition to LPG, means the average impact would likely be higher, closer to coal, and similar to the impacts for power from oil in chapter 2. Low impacts (€17/MWh) for use of biofuels / waste are estimated, compared to residential use; this takes into account that non-residential boilers tend to be more efficient and have significantly improved emissions controls.

For agricultural energy consumption the results show very high external cost impacts per MWh for Agricultural use of oil products (€396/MWh), in this case ‘diesel burned in agricultural machinery’. The life cycle dataset shows very large impacts on human toxicity, non-cancer impacts from the way these fuels are consumed, most often in farm vehicles. These costs do not compare closely with the oil product consumption in other sectors, notably as the consumption is a different type, e.g. thermal energy at a heat plant from LPG (industry) or from oil boilers (residential and commercial), where fuel efficiencies and emissions controls are higher than for agricultural machinery.

For residential energy consumption the results show high external cost impacts for residential coal (€135/MWh) and biofuels/waste (€164/MWh) consumption. Consumption from renewable energy sources (€16/MWh) has the lowest external cost.

For commercial and public sector energy consumption the results are identical to residential energy consumption, as the source life cycle datasets are also identical.

Figure 4-1 External cost of energy consumption, per fuel, per sector, all countries average in €$_{2018}$/MWh



In Figure 4-2 we present the results at sector level when consumption is weighted per fuel, and provide comparison between the EU27 and G20.

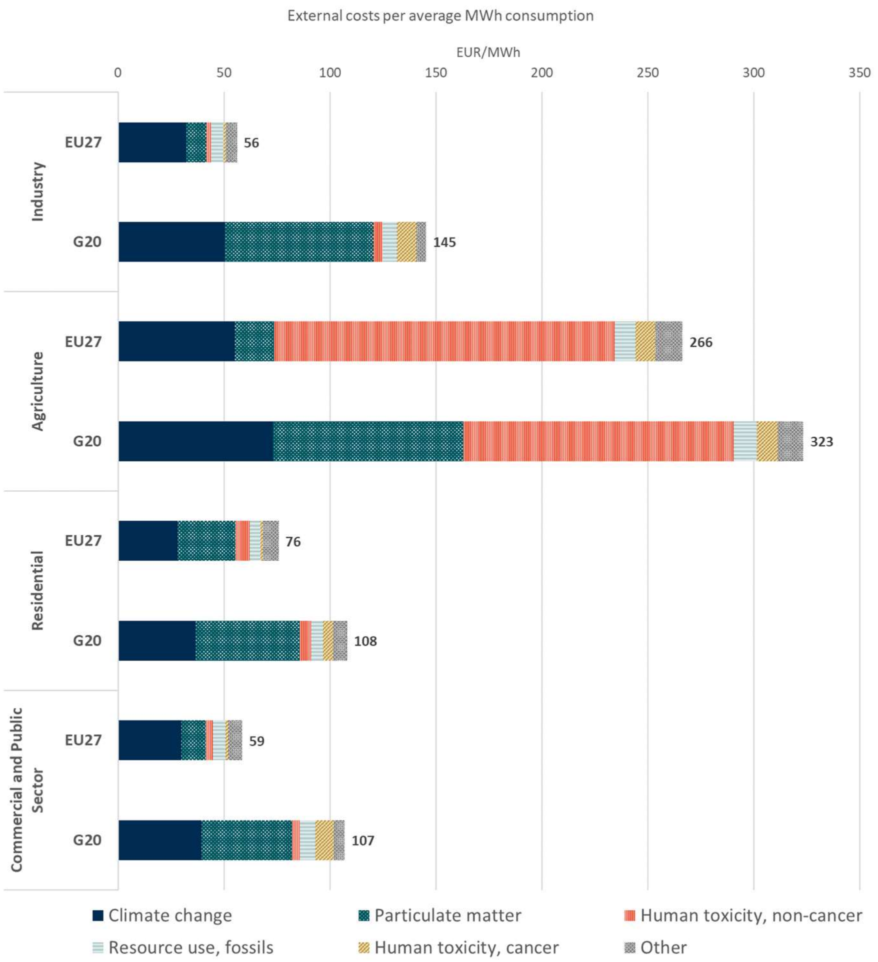
Industry energy consumption in the EU averages external costs of €56/MWh, significantly lower than the €145/MWh average cost calculated for the G20. This is consistent with high natural gas use by EU industry and also high electricity consumption with a much lower average external cost than the central value of €118/MWh presented above. For the G20 the latter factor, significantly higher coal use and electricity with significantly higher external costs are the major factors in the relatively high costs.

Agricultural energy consumption sees a less marked difference between the EU27 and G20, although the EU has the lower costs. The relatively high values for both highlight the importance of oil products consumption in the total sector energy use, primarily for farm vehicles.

Residential energy consumption shows average external costs of €76/MWh in the EU and €108/MWh in the G20.

Commercial and public sector energy consumption shows a lower external cost than residential energy consumption of €59/MWh in the EU, but a very similar cost value for the G20 of €107/MWh. For the EU the difference derives from a relatively much higher share of electricity which has lower average costs, and a lower share of biomass/waste which has high external costs.

Figure 4-2 Average external costs of energy consumption, consumption weighted per sector, EU27 and G20 in €$_{2018}$/MWh



4.1.2 Total

By using the country specific datasets where available and applying country specific monetisation factors, income-adjusted for human health, we were able to calculate country specific costs per fuel and sector. Multiplying these by actual energy consumption of each fuel has allowed for calculation of external costs of consumption.

The results are presented below in Table 4-1. As noted previously, these figures are indicative given both the uncertainties and lack of specificity in the datasets used, and should not be aggregated as there are likely significant overlaps in costs across consumption sectors and the calculated externalities of energy production presented in chapters 2 and 3.

Industry energy consumption is calculated to have an external cost of €157 billion in the EU and €3 560 billion in the G20. Within the EU Germany has more than double the costs of the 2nd country with total costs of €41.5 billion, or around 26% of the total. In the G20 China is even more dominant than Germany is within the EU, with external costs of €2 365 billion almost 10 times higher than the next highest country, the US at €290 billion, and representing 66% of the total. The percentage is not much lower as part of the global share highlighting China's role as the industrial powerhouse of the world, and the environmental costs that come with the profits being made from this.

Agricultural energy consumption is calculated to have external costs of €71 billion in the EU and €485 billion in the G20. Within the EU France has the highest costs of €16 billion. Within the G20 India has the highest external costs for energy consumption of €130 billion, China (€107 billion) and United States (€95 billion) also have high costs.

Residential energy consumption is calculated to result in annual external costs of €217 billion in the EU and €1 500 billion in the G20. The external costs are highly linked to population and climate. In the EU Germany, France and Italy have the highest total costs. Whilst in the G20 China, India and the United States have the highest costs.

Commercial and Public sector energy consumption is calculated to result in annual external costs of €90 billion in the EU and €660 billion in the G20. As before this is closely linked to population and climate, and also to a greater extent in this case, income. In the EU Germany and France have the highest associated external costs. Whilst in the G20 China and United States have the highest costs.

Table 4-1 Total external costs per country, latest year (2016-2018), EUR$_{2018}$ billion

EU27 Country	External Cost Total (EUR bn)				G20 country	External Cost Total (EUR bn)			
	Industry	Agriculture	Residential	Commercial and public services		Industry	Agriculture	Residential	Commercial and public services
Austria	3.6	1.0	6.4	1.3	United Kingdom	13.2	2.7	21.5	8.6
Belgium	6.2	2.1	5.2	2.1	Argentina	12.2	13.1	9.3	4.3
Bulgaria	2.3	0.4	3.2	1.5	Australia	26.9	13.6	16.2	14.2
Croatia	0.6	0.7	2.3	0.4	Brazil	34.4	15.0	18.2	8.1
Cyprus	0.2	0.1	0.3	0.3	Canada	31.6	29.1	19.9	28.0
Czech Republic	5.6	1.7	8.2	2.7	China	2 364.8	106.5	655.7	195.4

EU27 Country	External Cost Total (EUR bn)				G20 country	External Cost Total (EUR bn)			
	Industry	Agriculture	Residential	Commercial and public services		Industry	Agriculture	Residential	Commercial and public services
Denmark	1.3	2.7	4.7	1.4	India	354.3	130.0	249.9	66.0
Estonia	0.7	0.5	1.5	0.8	Indonesia	43.0	6.0	74.6	17.4
Finland	5.2	2.1	5.3	1.8	Japan	79.8	22.6	37.1	37.4
France	17.2	16.0	32.7	13.4	Mexico	39.5	11.8	19.8	3.7
Germany	41.5	*	44.6	24.3	Russia	124.7	16.3	79.7	35.3
Greece	2.8	0.5	4.8	2.8	Saudi Arabia	33.2	*	24.0	15.8
Hungary	2.7	1.6	5.3	1.2	South Africa	39.8	4.4	19.7	8.1
Ireland	1.6	1.4	2.2	0.8	South Korea	44.0	6.7	14.3	18.5
Italy	15.7	11.0	27.1	9.6	Turkey	31.2	12.1	18.4	12.9
Latvia	0.3	0.5	1.3	0.4	United States	288.2	95.1	224.6	186.4
Lithuania	0.6	0.2	1.5	0.4	**Non-EU G20 Total**	**3 560.9**	**485.1**	**1 502.9**	**660.1**
Luxembourg	0.3	0.2	0.4	0.2					
Malta	0.0	0.0	0.1	0.1	**EU27 + G20 total**	**3718.1**	**555.8**	**1720.3**	**749.8**
Netherlands	8.9	5.0	5.9	4.7					
Poland	15.3	9.1	23.2	9.3					
Portugal	2.3	1.6	2.5	1.3					
Romania	4.3	1.2	7.9	*					
Slovakia	2.3	0.3	1.1	0.8					
Slovenia	0.8	0.3	1.3	0.3					
Spain	10.5	9.7	12.6	5.9					
Sweden	4.4	0.5	5.5	1.9					
EU27 Total	**157.2**	**70.8**	**217.4**	**89.7**					

** = no energy consumption for this sector is recorded in IEA data, therefore no total cost is estimated*

4.2 Internalisation of energy consumption externalities

4.2.1 Comparing energy consumption externalities and energy consumption taxes

Using the tax database prepared for the energy taxes work in this study we are able for the EU27 and UK to make a comparison between the external costs of energy consumption and taxes. It should be noted that the energy taxes considered here are not usually, apart from some climate measures, targeted at reducing a specific externality. Rather they are general energy taxes with a variety of purposes including both environmental protection and revenue raising amongst others. In this section we use a simple rule, that any increase in the cost of energy through taxes equates to a general internalisation of the environmental external costs we calculate.

It is also important to note that the share of taxes on energy production were identified in the parallel report on energy taxes as very low, only 2% of total energy taxes, and concentrated in the handful of primary energy producers in the EU. Secondly, of the taxes on energy consumption, more than 60% of the total energy tax revenues come from taxes on transport fuels. These are excluded from our analysis.

The approach to this analysis includes all energy consumption taxes applied to the energy products of Electricity, LPG, Natural Gas, Manufactured Gases, Peat, Coke, Solid fuels and Refinery gas, as defined in the parallel work on taxes. These are categorised by consumption sector and the 2018 values are used.

The results are presented in Table 4-2 below, this shows in 4 sections the comparison of the (1) external costs calculated per country and sector as shown in section 4.1 and the (2) sum of energy consumption taxes derived from the energy tax data prepared in the parallel taxes work. The latter of which identifies approximately €104 billion of energy consumption taxes relevant to these sectors, or around 40% of the €263 billion taxes identified in the tax work.

Comparing the two, to estimate the amount of internalisation of environmental externalities we find:

For industry the calculated external costs of €157 billion can be compared against around €26 billion energy consumption taxes on industry, representing around 16% of the external cost. Amongst EU member states the highest ratios between taxes and external costs can be found in Denmark (43%), Italy (40%) and Germany (29%). Rates are below 5% in many countries, including BE, BG, HR, CZ, EE, IE, LV, LT, LU, MT, PL, PT and RO.

For agriculture the calculated external costs of €71 billion can be compared against around €4.4 billion energy consumption taxes, representing only around 6% of the external cost. This is the lowest ratio of any of the consumption sectors, and could point to a relatively privileged position for the agricultural sector and its energy use. Amongst EU member states the highest ratios between taxes and external costs can be found in Sweden (47%), Slovakia (13%) and Austria (12%). Rates are below 5% in many countries, including BE, BG, HR, CY, DK, EE, IE, IT, LV, LT, LU, MT, PL, RO and ES.

For residential energy consumption the calculated external costs of €217 billion can be compared against around €40 billion energy consumption taxes, representing around 18% of the external cost. Amongst EU member states the highest ratios between taxes and external costs can be found in the Netherlands (86%), Germany (37%) and Denmark (35%). Rates are below 5% in many countries, including BE, BG, HR, CY, CZ, EE, HU, LV, LT, LU, MT, PL, PT, RO and SI.

For commercial and public sector energy consumption the calculated external costs of €90 billion can be compared against around €33.7 billion energy consumption taxes, representing around 38% of the external cost. This is the highest ratio for any of the sectors. Amongst EU member states the highest ratios between taxes and external costs can be found in Italy (79%), Germany (62%) and Sweden (56%). Rates are below 5% in many countries, including BE, BG, HR, CY, CZ, EE, LV, LT, LU, MT, PL and PT.

Table 4-2 Indicative internalisation of energy consumption externalities in the EU27 and UK.

	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	EU27 Total	UK
(1) External Cost Total (EUR bn)																													
Industry	3.6	6.2	2.3	0.6	0.2	5.6	1.3	0.7	5.2	17.2	41.5	2.8	2.7	1.6	15.7	0.3	0.6	0.3	0.0	8.9	15.3	2.3	4.3	2.3	0.8	10.5	4.4	**157.2**	13.2
Agriculture	1.0	2.1	0.4	0.7	0.1	1.7	2.7	0.5	2.1	16.0	*	0.5	1.6	1.4	11.0	0.5	0.2	0.2	0.0	5.0	9.1	1.6	1.2	0.3	0.3	9.7	0.5	**70.8**	2.7
Residential	6.4	5.2	3.2	2.3	0.3	8.2	4.7	1.5	5.3	32.7	44.6	4.8	5.3	2.2	27.1	1.3	1.5	0.4	0.1	5.9	23.2	2.5	7.9	1.1	1.3	12.6	5.5	**217.4**	21.5
Commercial and Public Sector	1.3	2.1	1.5	0.4	0.3	2.7	1.4	0.8	1.8	13.4	24.3	2.8	1.2	0.8	9.6	0.4	0.4	0.2	0.1	4.7	9.3	1.3	*	0.8	0.3	5.9	1.9	**89.7**	8.6
(2) Results from taxes (EUR bn)																													
Industry	0.73	0.10	0.04	0.02	0.01	0.05	0.56	0.02	0.89	2.03	11.99	0.21	0.19	0.04	6.30	0.01	0.00	0.00	0.00	0.51	0.09	0.08	0.04	0.40	0.09	0.81	0.74	**25.92**	0.71
Agriculture	0.12	0.01	0.00	0.03	0.00	0.16	0.07	0.02	0.13	0.92	1.02	0.04	0.16	0.02	0.48	0.01	0.00	0.00	0.00	0.55	0.00	0.08	0.01	0.04	0.04	0.21	0.24	**4.37**	0.13
Residential	0.46	0.13	0.00	0.02	0.02	0.03	1.65	0.01	0.64	6.42	16.70	0.94	0.11	0.12	4.78	0.00	0.00	0.01	0.00	5.12	0.04	0.05	0.05	0.16	0.03	1.10	1.60	**40.19**	0.40
Commercial and Public Sector	0.23	0.09	0.02	0.01	0.01	0.04	0.23	0.02	0.50	5.17	15.14	0.59	0.06	0.06	7.56	0.00	0.00	0.00	0.00	1.84	0.09	0.05	0.02	0.24	0.02	0.65	1.07	**33.71**	1.18
Total	1.54	0.34	0.06	0.07	0.04	0.28	2.50	0.07	2.16	14.55	44.85	1.77	0.52	0.24	19.11	0.02	0.00	0.01	0.00	8.02	0.22	0.26	0.12	0.83	0.18	2.77	3.65	**104.18**	2.42
(3) External Cost Total after internalisation (1) – (2) (EUR bn)																													
Industry	2.89	6.11	2.29	0.61	0.15	5.54	0.73	0.66	4.30	15.15	29.47	2.57	2.53	1.53	9.43	0.28	0.63	0.34	0.05	8.36	15.22	2.21	4.26	1.86	0.69	9.69	3.71	**131.27**	12.49
Agriculture	0.89	2.04	0.43	0.72	0.15	1.55	2.59	0.48	2.02	15.08	N/A	0.50	1.41	1.40	10.55	0.52	0.24	0.19	0.03	4.43	9.13	1.52	1.24	0.24	0.28	9.52	0.28	**66.40**	2.57
Residential	5.95	5.12	3.20	2.32	0.33	8.20	3.06	1.53	4.68	26.29	27.90	3.91	5.17	2.09	22.33	1.32	1.55	0.38	0.07	0.81	23.13	2.48	7.87	0.90	1.29	11.49	3.87	**177.22**	21.05
Commercial and Public Sector	1.08	1.96	1.49	0.36	0.31	2.67	1.15	0.79	1.28	8.24	9.19	2.19	1.18	0.73	2.00	0.39	0.44	0.16	0.08	2.83	9.24	1.28	N/A	0.60	0.29	5.25	0.83	**56.01**	7.46
(4) Internalisation % (2) / (1)																													
Industry	-20%	-2%	-2%	-2%	-8%	-1%	-43%	-3%	-17%	-12%	-29%	-7%	-7%	-2%	-40%	-3%	0%	0%	0%	-6%	-1%	-3%	-1%	-18%	-11%	-8%	-17%	**-16%**	-5%
Agriculture	-12%	-1%	0%	-4%	-1%	-10%	-3%	-3%	-6%	-6%	N/A	-8%	-10%	-2%	-4%	-2%	0%	0%	0%	-11%	0%	-5%	-1%	-13%	-11%	-2%	-47%	**-6%**	-5%
Residential	-7%	-2%	0%	-1%	-5%	0%	-35%	-1%	-12%	-20%	-37%	-19%	-2%	-6%	-18%	0%	0%	-1%	-1%	-86%	0%	-2%	-1%	-15%	-2%	-9%	-29%	**-18%**	-2%
Commercial and Public Sector	-17%	-5%	-1%	-2%	-4%	-1%	-16%	-2%	-28%	-39%	-62%	-21%	-5%	-7%	-79%	-1%	0%	-3%	-4%	-39%	-1%	-4%	N/A	-28%	-7%	-11%	-56%	**-38%**	-14%

4.2.2 *Comparing energy production externalities and energy consumption taxes*

For energy production, if the consumption taxes total of €104 billion were to be compared with the total EU27 external costs of €340.6 billion for electricity and heat production presented in Table 3-1, then we might estimate that around 30% of the external costs of energy production are internalised in energy consumption. If the previously identified internalisation of €34.5 billion of the energy production external costs (see Table 3-3) were also added to this total then around 40% of external costs could be argued to be internalised.

One level further, if the analysis focused only on consumption taxes on **electricity consumption** then total taxes of €77 billion can be identified (74% of total consumption taxes). These taxes can be compared to the external cost of electricity of €151 billion, or €123 billion after existing internalisation of EU-ETS and other climate measures. The taxes on energy consumption would then represent around 63% of the energy production externalities (after internalisation). The comparison is apt as is noted in the report on energy taxes, '*energy inputs to the electricity sector are not taxed to avoid double taxation – only the final consumer is taxed on electricity consumption, not the power producer on the consumption of input fuels*'.

At the MWh level the work in section 3.1 identifies average electricity system external costs of €68/MWh before internalisation, and €59/MWh with internalisation. Whilst the tax work identifies energy consumption taxes on electricity of €32.1/MWh in 2018 (see Figure 11 in the tax report). Comparing these, we see that the electricity consumption taxes per MWh represent around 54% of the total external costs of production. Putting the two together would see external costs of around €27/MWh.

In conclusion, whilst there are a number of uncertainties and differences in the calculation of consumption taxes and production externalities, we believe that the analysis presented above provides useful indications that EU electricity consumption taxes total around 50%-60% of the EU electricity production externalities, and could be read as an internalisation of the same.

Annex A - Definitions

Table A-1: Country abbreviations list (ISO 2-digit codes)

EU28	Code	Non-EU G20	Code
Austria	AT	United Kingdom	UK[24]
Belgium	BE	Argentina	AR
Bulgaria	BG	Australia	AU
Croatia	HR	Brazil	BR
Cyprus	CY	Canada	CA
Czech Republic	CZ	China	CN
Denmark	DK	India	IN
Estonia	EE	Indonesia	ID
Finland	FI	Japan	JP
France	FR	Mexico	MX
Germany	DE	Russia	RU
Greece	EL	Saudi Arabia	SA
Hungary	HU	South Africa	ZA
Ireland	IE	South Korea	KR
Italy	IT	Turkey	TR
Latvia	LV	United States	US
Lithuania	LT		
Luxembourg	LU		
Malta	MT		
Netherlands	NL		
Poland	PL		
Portugal	PT		
Romania	RO		
Slovakia	SK		
Slovenia	SI		
Spain	ES		
Sweden	SE		

[24] UK is used in this work (as this is the EC convention) noting that the ISO code is GB

Annex B - Detailed Methodology

External costs – approach and methodology

Methodological choices

Building on the summary of our approach presented in section 1.2 of this report we further elaborate the methodological choices made.

Firstly, to restate, the LCA underpinning our approach is based on two key methodological choices:

1. The use of the **Product Environmental Footprint (PEF)** Life Cycle Impact Analysis (LCIA) framework with its Environmental Footprint (EF) method 2.0, as developed by the Joint Research Centre (JRC) of the European Commission, whose indicators and factors are also used for the monetisation of costs; and,
2. The use of **Environmental Footprint (EF-compliant)** datasets for the LCIA analysis, and only whenever such datasets were not available for a specific technology Ecoinvent 3.5 datasets were used.

These methodological choices were discussed with DG ENER and the JRC and specific recommendations were integrated in the study.

For the **LCIA framework** the decision on the use of the EF method was made in consultation with the JRC. Two options were considered: 1) Using the ReCiPe 2016 method, which is the update of the ReCiPe 2008 method used in the 2014 study; and, 2) Using the EF method, recommended by JRC and supported by the Commission. JRC recommended use of the EF method instead of ReCiPe, as a substantial amount of work has been done to develop updated and robust models. Moreover, the use of ReCiPe 2016 would not ensure superior consistency when comparing with 2014 results as the basis of these has changed too much. This is a drawback of all approaches, and a consequence of the LCA field itself in which methodologies, approaches and data are being rapidly updated, refined and improved. The EF method is also intended to be consistently used for communicating on environmental impacts of products and organisations in the European Union. Therefore, the choice of the EF LCIA framework and EF-compliant datasets was made to ensure an approach consistent with EC (JRC) standards and which has a robust basis and datasets. More specific details on the PEF approach are provided below.

For the **datasets** of the life cycle inventory of the reference technologies, two different options were assessed: 1) using the (updated) Ecoinvent database, similar to that used in 2014; and, 2) using Environmental Footprint (EF)-compliant datasets, tendered by the Commission[25] under its PEF/OEF project, as recommended by JRC. The Ecoinvent database v3.5[26] is an update of a previous version (v2.2) which was used in the study on subsidies and costs of EU Energy of 2014. It should be noted that Ecoinvent 3 is not just an update of Ecoinvent 2, but that there are some significant differences between how the data behind it is aggregated[27]. These differences make it difficult to explain in a systematic and coherent manner the changes of results/impacts from one version to another. However,

[25] The European Commission tendered the EF compliant datasets, data providers developed them and the EC has acquired the user rights.
[26] https://www.ecoinvent.org/database/database.html
[27] Full description of these differences can be consulted on the Ecoinvent website (https://www.ecoinvent.org/support/faqs/differences-between-ecoinvent-2-and-3/differences-between-ecoinvent-2-and-3.html).

during communication with the JRC the recommendation was to use the EF-compliant datasets. These are high quality secondary datasets (from aggregated primary datasets or other statistical, average, literature or proxy sources) that have been developed to fit with the EF requirements. Furthermore, by using the EF method 2.0, the use of the EF-compliant datasets for the life cycle inventory phase, together with the EF method for the life cycle impact assessment phase, ensures the highest level of robustness. It was therefore decided to use the EF-compliant datasets for the LCA assessment, with the latest version of Ecoinvent 3.5 to fill any gaps whenever EF-compliant datasets were not available for a specific technology.

Furthermore, in order to better understand the results, the disaggregated EF-compliant database was consulted, as it was made available to us specifically for this study. However, the information that could be extracted from it was extremely limited for the following reasons:

- the limited availability of EF-compliant disaggregated datasets – only some of the aggregated datasets have a corresponding disaggregated dataset;
- the way the disaggregated datasets are built:
    - these datasets are in fact partially aggregated, where a very limited number of processes are provided at level 1 disaggregation, such as the fuel used for the respective technology, and sometimes the concrete and steel used. All other specific inputs cannot be identified. In our case for the analysis at aggregated level per countries it was relevant to exclude the electricity used for producing further electricity with a specific technology. However, this is not possible with the EF-compliant disaggregated datasets;
    - The partially disaggregated processes are not actually included in the disaggregated datasets, but they have to be linked, one by one, manually, for each process. Due to time limitations this was not feasible within this study. Our recommendation is to ensure that the future versions of the EF-compliant datasets have the appropriate level of information, appropriate for each type of dataset, and to ensure that the disaggregated datasets have by default all the processes linked, ensuring thus that each disaggregated dataset has the same results as the corresponding aggregated dataset.

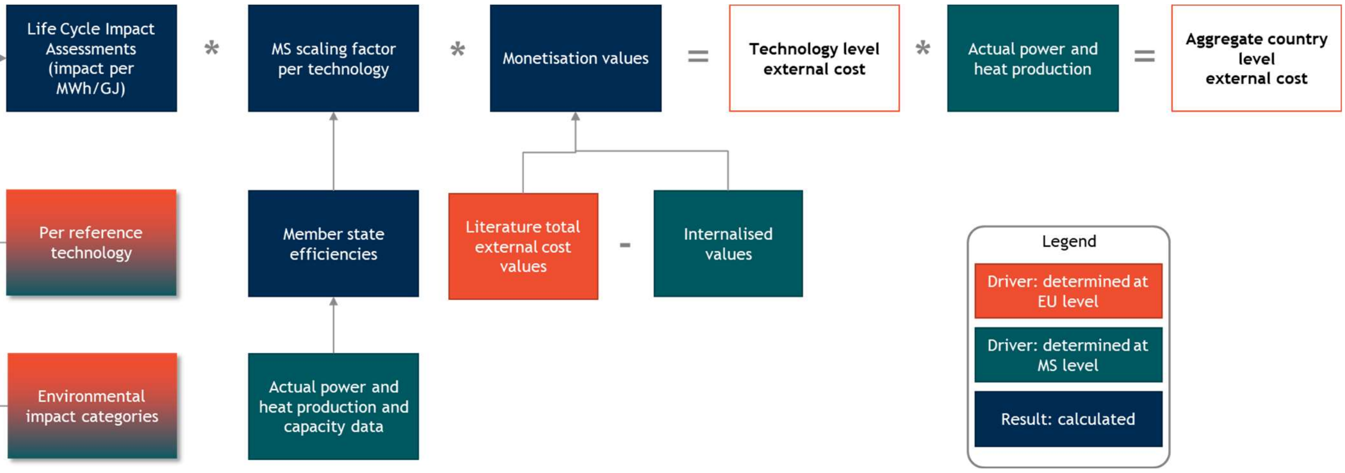
Calculation approach

To restate the calculation approach, as shown below in Figure B-1, life cycle impacts are multiplied by monetisation factors, and in some cases scaling factors, to estimate technology level external costs, and further again by power generation data at country level to assess aggregate country level costs. Internalisation of external costs, i.e. when a tax or levy directly targets an environmental externality, to fully or partially 'internalise' the externality in the prices is also applied. An example of this calculation is provided in the last section of this annex.

One step not elaborated in the diagram, but also applied, is a difference in calculation approach for the technology level external cost and the aggregate country level external cost. This step removes the use of electricity in the generation of electricity or heat for the country level aggregate calculation to avoid double counting. At technology level inclusion of all inputs is valid, but at country level including all electricity used as an input at an earlier life cycle step risks significant double counting of electricity generated in the country being used as an input at one of the life cycle steps of the energy generating technology. Therefore 2 LCA results scenarios were produced, Scenario A including these electricity inputs, and Scenario B excluding these electricity inputs. Scenario B results were used to calculate the country level costs. JRC was consulted to finalise the approach for determining the necessary data adjustments for Scenario B.

For the results for energy consumption presented in chapter 4 no scaling factors are applied but the overall approach remains the same for the consumption LCIA datasets, combined with the use of actual consumption data for aggregate costs.

Figure B-1 External costs calculation methodology adapted from (2014) Costs and subsidies study



Life cycle assessment and impact assessments

As noted earlier, this work has built upon the methodology developed in the 2014 study. Life cycle assessments (LCA) have been performed for each of the energy generation technologies. The LCA was carried out according to the International Standards for LCAs (ISO 14040[28] and ISO 14044[29]). The assessment was performed by using the LCA software SimaPro 9.0.0 in combination with the Excel-based tool for the aggregation of the LCA and monetization results. The way the Excel tool was developed and how the results are aggregated is explained in the sections below.

A life cycle assessment according to the respective ISO standards consists typically of four steps: 1) goal and scope definition, 2) life cycle inventory, 3) impact assessment and 4) interpretation. The approach for the four steps is described below.

Goal and scope definition

The goal and scope of this part of the study and the LCAs is defined at the start of this chapter. The impact assessment was calculated for the energy generation technologies – specifically electricity and heat - from cradle-to-grave (from the raw material extraction to the final waste treatment). The functional unit (FU; reference basis) for the life cycle assessment is defined as "*one MWh of electrical energy or heat from cradle to grave: from the production of the primary raw material extraction up to the final waste treatment at end of life*".

Life cycle inventory

In a second step, a life cycle inventory (LCI) was compiled for all energy generating technologies considered. The LCI phase involved data collection and calculation procedures to quantify the environmental inputs and outputs that are associated with the considered energy generation technologies identified in task 1. As the FU is set to one MWh, no additional data collection for the LCA part was necessary.

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[28] ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework
[29] ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines

Impact assessment

The impact assessment phase of the LCAs of the different energy generating technologies is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. The PEF impact categories included in the assessment are presented in Table B-1 below. The EF 2.0 method was used for the calculation of the results.

Table B-1 List of recommended models at midpoint, together with their indicator, unit and source[30]

Recommendation at midpoint					
Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**	**Source of Characterisation Factors (CFs)**	**Robustnes (I=highest, III=lowest)**
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)	EC-JRC, 2017	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$	Steady-state ODPs as in (WMO 1999)	EC-JRC, 2017	I
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)	EC-JRC, 2017	III/interim
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)	EC-JRC, 2017	III/interim
Respiratory inorganics	Impact on human health	disease incidence	PM method recomended by UNEP (UNEP 2016)	EC-JRC, 2017	I
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq $U^{235}{}_{eq}$	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	EC-JRC, 2017	II
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC $_{eq}$	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008	EC-JRC, 2017	II
Acidification	Accumulated Exceedance (AE)	mol H+ $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EC-JRC, 2017	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EC-JRC, 2017	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P $_{eq}$	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EC-JRC, 2017	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N $_{eq}$	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EC-JRC, 2017	II
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox model, (Rosenbaum et al, 2008)	EC-JRC, 2017	III/interim
Land use - soil quality index	Soil quality index (composed from indicators on biotic production, erosion resistance, mechanical filtration and groundwater replenishment)	Dimensionless (pt)	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	EC-JRC, 2017	III
Water depletion	User deprivation potential (deprivation-weighted water consumption)	m^3 world $_{eq}$	Available WAter REmaining (AWARE) as recommended by UNEP, 2016	EC-JRC, 2017	III
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb $_{eq}$	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.		III
Resource use, fossils	Abiotic resource depletion - fossil fuels (ADP-fossil)[31]	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002	EC-JRC, 2017	III

[30] Table reproduced from JRC (2018) Developing of a weighting approach for the environmental footprint

Each technology was modelled by identifying an appropriate dataset in the EF database, and whenever necessary in the Ecoinvent database. For some of the technologies the datasets were also country specific. However, whenever no country specific datasets could be identified, a proxy country was identified from the available datasets. The datasets used to model each technology are presented in Annex C, indicating also the database that was used. Furthermore, tables in Annex D present the countries for which datasets for the respective technologies were available, and where not, and which proxies were used in the latter case. For the countries in which there is no production of electricity or heat with a specific technology this was indicated as not applicable (#N/A).

Production and consumption data and scaling factors

Production data for the latest available year (typically 2016-2017) for each country and technology was sourced from 4 key sources, EUROSTAT, IEA, US EIA and IRENA. The following table gives a brief overview of the data sources per technology and per country grouping.

Table B-2 Electricity and Heat technologies covered

<table>
<tr><th rowspan="2">Electricity</th><th colspan="3">Production data sourced from</th></tr>
<tr><th>EU27 + UK & TR</th><th>Non-EU, IEA members</th><th>Non-EU G20, non-IEA members</th></tr>
<tr><td>Hard Coal (including CHP)</td><td rowspan="6">Eurostat [nrg_bal_peh]</td><td rowspan="6">IEA Monthly Electricity Generation 2019</td><td rowspan="6">IEA Electricity Information (2018)</td></tr>
<tr><td>Lignite (including CHP)</td></tr>
<tr><td>Natural Gas (CCGT, OCGT, CHP)</td></tr>
<tr><td>Oil</td></tr>
<tr><td>Nuclear</td></tr>
<tr><td>Biomass</td></tr>
<tr><td>Solar PV - rooftop & utility</td><td colspan="2">IEA Monthly Electricity Generation 2019</td><td>US EIA data (2019)</td></tr>
<tr><td>Solar - CSP</td><td colspan="3" rowspan="3">IRENA (2019) Renewable Energy Statistics</td></tr>
<tr><td>Wind – onshore</td></tr>
<tr><td>Wind – offshore</td></tr>
<tr><td>Hydropower – large (>10 MW)</td><td colspan="2" rowspan="2">IEA Monthly Electricity Generation 2019</td><td rowspan="3">US EIA data (2019)</td></tr>
<tr><td>Hydropower – small (up to 10MW)</td></tr>
<tr><td>Geothermal</td><td>Eurostat [nrg_bal_peh]</td><td>IEA Electricity Information (2018)</td></tr>
<tr><th>Heating</th><th></th><th></th><th></th></tr>
<tr><td>Domestic gas boiler (condensing)</td><td>Eurostat [nrg_cb_gas]</td><td colspan="2">IEA World Energy Balances (2019)</td></tr>
<tr><td>Domestic oil boiler</td><td colspan="3">IEA World Energy Balances (2019)</td></tr>
<tr><td>Domestic wood boiler</td><td>Eurostat [nrg_cb_rw]</td><td colspan="2">IEA World Energy Balances (2019)</td></tr>
<tr><td>Domestic heat pump</td><td>Eurostat [nrg_cb_rw]</td><td>IEA Electricity (2018)</td><td>No data</td></tr>
<tr><td>Domestic solar thermal</td><td>Eurostat [nrg_cb_rw]</td><td colspan="2">IEA World Energy Balances (2019)</td></tr>
<tr><td>CHP Hard Coal</td><td colspan="3" rowspan="4">IEA Electricity Information (2018)</td></tr>
<tr><td>CHP Lignite</td></tr>
<tr><td>CHP Gas</td></tr>
<tr><td>CHP Biomass</td></tr>
</table>

It should be noted that production data was not always complete, especially for heating technologies, and particularly for non-EU and non-IEA countries (AG, BR, CN, ID, IN, SA, ZA). Also as noted in the introduction in section 1.1, certain technologies were not included in the analysis, such as energy from waste (electricity and heat) and domestic coal boilers, therefore the country totals do not represent full coverage of the electricity and heating consumption. Also as noted in section 1.1 country production totals do not include energy imports or exports, all is accounted in the location of generation.

For the consumption sectors and fuels presented in chapter 4 the energy consumption data was sourced from the 2019 IEA world energy balances.

For countries for which a proxy country was allocated we also, if appropriate data was available, applied a **scaling factor** to attempt to better approximate the actual country value based on additional available data. As an example, this was applied to the Hard Coal dataset for Sweden. As no LCIA dataset specific for Sweden was available the dataset for Finland was used as a proxy. Yet there was sufficient data (from IEA) to calculate a relative thermal efficiency value for both Sweden and Finland each, based on actual fuel inputs and electricity and heat outputs. The % difference between the efficiency value for Finland and Sweden was then used to adjust the Finnish LCIA impacts for the Swedish situation. For renewable energy technologies a relative load factor was calculated based on IRENA capacity and production data, the average value for 2015-2017 was used. Adjustments were then made in a similar way to that for fossil technologies. The use of proxy datasets is presented in Annex C of this report.

Monetisation

This section summarises the methodological approach, the choices that were made for the monetisation and our review of specific monetisation values used in the external costs Excel tool. Per impact category, the recent developments are discussed.

Key sources and developments in the literature

Since the publication of the 2014 study the literature on external costs and monetisation of environmental impacts has advanced significantly. The most relevant new publications in the light of this study are:

- Handbook on the external costs of transport, for EC DG MOVE, published by CE Delft in 2019;
- Environmental Prices Handbook EU28 version, published by CE Delft in 2018;
- *Handboek milieuprijzen 2017*, published by CE Delft in 2017 (this is the Dutch version of the EU28 Handbook and contains slightly more methodological details);
- Environmental profile building elements. Annex: Monetisation of the MMG method, published by OVAM in 2017;
- Developing of a weighting approach for the environmental footprint. Published by the European Commission (JRC) in 2018.

General methodological changes compared to previous study

As noted previously the methodological choice to use the PEF approach in this work rather than the ReCiPe approach used in the 2014 study, has resulted in changes in around half of the impact categories and their units. This had several implications for the monetisation of the impact categories through building upon earlier work. Table B-3 below summarises the 2014 impact categories and methods with the current impact categories used in the PEF approach. This shows that 6 of the 16 PEF impact categories were identical to ReCiPe, whilst a further 5 impact categories were the same but used different units, which potentially allows for conversion. The remaining impacts generally had some similarities to the 2014 ReCiPe categories but units and approaches were more significantly different. Only for land use was a significantly different approach taken.

Table B-3 Comparison between ReCiPe 2008 and PEF 2017

ReCiPe 2008 (in report 2014*)		PEF Guidance 2017**		Comparison
Life cycle categories	**Units**	**Life cycle categories**	**Units**	**Assessment**
Climate change	kg CO2 eq	Climate change	kg CO2 eq	Identical categories/units
Ozone depletion	kg CFC-11 eq	Ozone depletion	kg CFC-11 eq	Identical categories/units
Fossil depletion	kg oil eq	Resource use, fossils	MJ	Identical categories, different units
Human toxicity	kg 1.4-DB eq	Human toxicity, cancer	CTUh	Identical categories, different units
Photochemical oxidant formation	kg NMVOC	Photochemical ozone formation	kg NMVOC eq	Identical categories/units[1]
Particulate matter formation	kg PM10 eq	Particulate matter	disease incidence	Identical categories, different units
Ionising radiation	kg U235 eq	Ionising radiation, human health	kBq U235 eq	Identical categories/units
Terrestrial acidification	kg SO2 eq	Acidification	mol H+ eq	Identical categories, different units
Freshwater eutrophication	kg P eq	Eutrophication, freshwater	kg P eq	Identical categories/units
Marine eutrophication	kg N eq	Eutrophication, marine	kg N eq	Identical categories/units
		Eutrophication, terrestrial	mol N eq	Some similarities with ReCiPe categories
Terrestrial ecotoxicity	kg 1.4-DB eq			
Freshwater ecotoxicity	kg 1.4-DB eq	Ecotoxicity, freshwater	CTUe	Identical categories, different units
Marine ecotoxicity	kg 1.4-DB eq			Some similarities with ReCiPe categories
		Human toxicity, non-cancer	CTUh	
Agricultural land occupation	m2*a	Land use - soil quality index		
Urban land occupation	m2*a		Dimensionless (pt)	No direct match
Natural land transformation	m2			
Water depletion	m3	Water use	m3 world eq	Identical categories, different units
Metal depletion	kg Fe eq	Resource use, minerals and metals	kg Sb eq	Similar categories, different units

[1] *Identical categories and units, but methodology was changed in ReCiPe 2016 (compared to ReCiPe 2008)*

The second most significant change compared to the previous study is the change in assumption that all lives are valued equally, this assumption has become inconsistent with the latest work carried out in the *2019 Handbook on the external costs of transport* and the *2018 Environmental Prices Handbook EU28 version*. Additionally the larger range in income differences across countries from the introduction of lower income G20 countries make it less tenable to assume that willingness to pay and/or income would remain broadly similar across the studied countries. This adjustment is more consistent with cross-country comparison of the external costs on a fairer basis.

The third most significant change compared to the previous study is the assumption that **positive income elasticity** is no longer deemed relevant for environmental quality which results in constant prices of health impacts over time, following the *2018 Environmental Prices Handbook EU28 version*. The rationale in the handbook is that the positive income elasticity of health (i.e. the relative demand for health services increases as income increases) is balanced out by the increased supply of health services due to technological change.

Valuation methods

There are various methods to estimate the external costs of environmental impacts. The main ones are:

- **The damage cost approach** which values all damage caused by an externality. The costs are typically monetised using the willingness to pay (WTP) or willingness to accept (WTA) principles – i.e. the extent to which individuals are eager to pay to avoid damage or to which individuals are willing to accept the damage. Damage cost approaches include the concept of the Social Cost of Carbon (SCC) which attempts to value all climate damages to society. A further important aspect is that major costs may be incurred in the longer-term future, discounting them to the present year includes major uncertainties related to the discount rate to be used, which effectively determines how highly future damages are valued;
- **The avoidance cost approach** values the costs of externalities based on the total costs required to reach a certain (policy) target. This approach assumes that a certain policy target reflects collective preferences with respect to the externality and, as such, it is a proxy for the collective WTP to avoid damage caused by an externality. This is helpful in cases when damages are uncertain or difficult to measure, which is particularly the case for climate change with a number of impacts not fully understood, significant uncertainties in values and risks of feedbacks or extreme events[32];
- **The replacement cost approach** values the costs of externalities based on the total costs required to repair or replace the adverse impacts as a result of the externalities.

Even though there is no perfect approach, each approach has its own (dis)advantages and the 'best' approach is dependent on case specific conditions. More specifically, the best fitting valuation method differs per environmental impact category. To illustrate this, taking the impact of climate change, the damage costs approach could underestimate the costs of climate change as it only aggregates the costs of individual phenomena and, as such, cannot take potentially catastrophic system effects into account (e.g. melting of polar ice caps). On the other hand, the avoidance costs approach is generally not regarded as a 'first best' solution as it does not directly measure and value the impacts, but rather values policy targets.

Table B-4 shows the approach used per environmental indicator in this study.

For the external costs that result in damages to human health the valuation methodologies are typically based upon WTP studies which are used to calculate either the value of a statistical life (VSL) or the

[32] A more detailed discussion of these and other approaches can be found in the study for DG MOVE by CE Delft (2019) Handbook on the external costs of transport, Version 2019

Value of a Life Year (VOLY). One of the central source studies for this work, the 2018 Environmental Prices Handbook EU28 version, applies a VOLY value of $€_{2015}$70 000 for the EU as a whole, and provides a significant literature review of the range of values used elsewhere, summarising that these range from around €50 000 - €110 000 per VOLY. We adopt the same approach and use a central $€_{2018}$72 363 VOLY value in this work.

VSL and VOLY values can and typically are varied across countries to account for the differences between countries, e.g. different income levels reflecting in the VSL and VOLY values. Relatively high differences in income exist within the EU, for example from per capita GDP (PPP) of around USD107k in Luxembourg (the 3rd highest in the world) to USD23k in Bulgaria (ranked 60). The inclusion of the G20 countries makes this range still wider, with low-end values of around USD8k per capita found in India. In the 2014 study despite the large range in income values within the EU, a single assumption for the value of VSL / VOLY was used. Income adjustments to VSL/VOLY are applied in other key studies on external costs, for example in the DG MOVE Transport externalities study, to account for this range in income. We have adopted the same approach in this work and therefore the monetisation values derived for the EU27 as a whole are adjusted to each country (EU and G20) on the basis of the relative 2018 GDP (PPS) per capita with an income elasticity assumption of 0.8. The same income adjustments have also been made for the ecosystem impacts. As a result all impacts except for climate change, land use, water use, resource use fossils and resource use metal and minerals, have been valued using country-level income adjusted monetisation values[33]. Further details on this approach can be found in the 2019 Handbook on the external costs of transport.

Midpoint valuation categories

Based on a desk-review of external costs literature and discussion and validation with experts we arrived at the following monetisation values per impact category, see Table B-4. This presents the 16 impact categories and the approaches used to monetise them. The approach to arrive at each value and the supporting evidence for each is discussed in the following sub-sections. As noted above, the values are not varied by country.

Table B-4 EU27 Monetisation values for external environmental impacts

Environmental impact category	Unit	Approach used	Costs approach	Monetisation factor [EUR_{2018}/unit impact]		
				Low	Central	High
Climate Change	kg CO_2 eq	DG Move	Avoidance costs	0.0615	**0.1025**	0.1936
Ozone depletion	kg CFC-11 eq	Env. Prices Handbook EU28	Damage costs	22.8	**31.4**	127.2
Ionising radiation, Human health	kBq U235 eq	Env. Prices Handbook EU28	Damage costs	0.0008	**0.0012**	0.0461
Photochemical ozone formation, human health	kg NMVOC eq	Env. Prices Handbook EU28	Damage costs	0.87	**1.19**	1.90
Particulate matter	Disease incidence	Env. Prices Handbook EU28 & UNEP 2016	Damage costs	661 974	784 126	1 204 600
Human toxicity, non-cancer	CTUh	JRC – based on DG Move and other studies	Damage costs	30 211	**163 447**	755 270
Human toxicity, cancer	CTUh	JRC – based on DG Move and other studies	Damage costs	174 324	**902 616**	2 789 181

[33] From a central income value of around €37 000 per person in the EU27 a range of income multipliers were calculated and applied, from 0.22 for India to 2.20 for Luxembourg.

Environmental impact category	Unit	Approach used	Costs approach	Monetisation factor [EUR2018/unit impact]		
				Low	Central	High
Acidification	mol H+ eq	OVAM	Damage & avoidance costs	0.176	**0.344**	1.617
Eutrophication, freshwater	kg P eq	Env. Prices Handbook EU28	Damage costs	0.26	**1.92**	2.18
Eutrophication, marine	kg N eq	Env. Prices Handbook EU28	Damage costs	3.21	**3.21**	3.21
Eutrophication, terrestrial*	molc N eq	None	-	-	-	-
Ecotoxicity, freshwater	CTUe	OVAM	Damage costs	2.39E-24	**3.82E-05**	1.88E-04
Land use (Soil quality index)	dimensionless (pt)	JRC		0.000087	**0.000175**	0.000349
Water use	m3 water eq	JRC	Resource depletion costs	0.00419	**0.00499**	0.2359
Resource use, fossils	MJ	ReCiPe	Resource depletion costs	0	**0.0013**	0.0068
Resource use, minerals and metals	kg Sb eq	OVAM	Resource depletion costs	0	**1.64**	6.53

** It was advised by JRC that no suitable method is available to value this impact at present and that values from the other eutrophication impacts may not be adapted.*

Internalisation

Internalisation of externalities has been applied directly for the electricity and heat technologies in cases where a tax or measure that directly internalises a relevant externality has been identified. In practice this almost exclusively means measures that price or tax carbon for the climate change impact. Internalisation of the costs of the other impacts, if addressed at all are primarily addressed through either consumption taxes or through regulation, e.g. requirements for end-of-pipe solutions to mitigate air pollution and related impacts; regulation of radioactive materials. In a handful of cases taxes are applied to energy production but do not explicitly target the internalisation of a single external cost impact. The internalisation of these other impacts is discussed in section 4.2 of the report.

The specific internalisations of impacts are presented below in the sections on monetisation of climate change and acidification.

Climate change

A first screening of key literature, including the recently released DG MOVE study noted above, shows that some significant methodological developments have been made since 2014. For example, in respect of climate change impacts the 2014 study was monetised on the basis of climate damage, whereas subsequent work on behalf of the European Commission has used avoidance costs. The development of an avoidance cost estimate in the study for DG MOVE resulted in significantly higher values for CO_2 externalities than the base value of €$_{2012}$50/tCO_2e used in 2014, for example with central values of either €$_{2016}$100/tCO_2e for short-and-medium-run costs or €$_{2016}$269/tCO_2e for the long run costs[34]. . The increase reflecting the change in method, higher values which price in greater uncertainty and also higher marginal costs of emissions reduction.

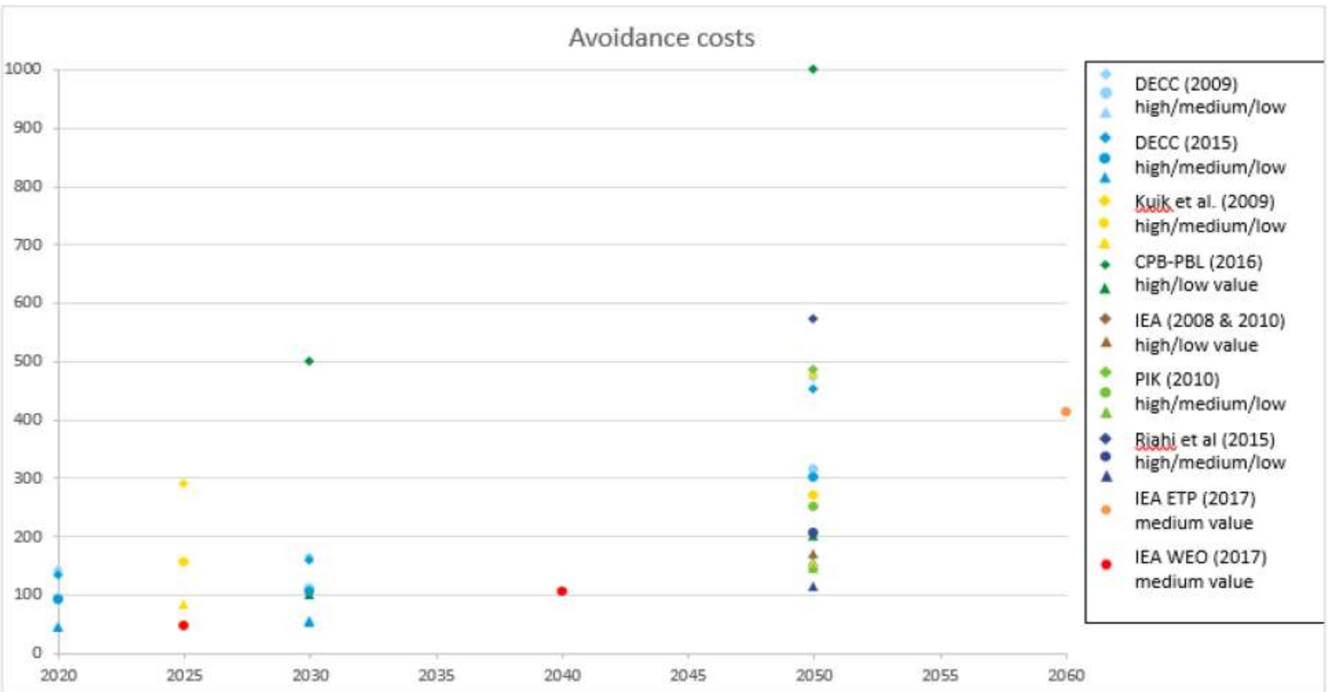
[34] https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1

As noted previously, even though the methodologies to incorporate system effects in the damage cost approach are improving, it is still not regarded as the most accurate methodology to estimate the costs of climate change. Instead, the avoidance costs approach is regarded as the best fitting approach in the literature[35] as a clear global policy target has been set by means of the Paris Agreement to keep global warming below 2°C, or ideally 1.5°C. Therefore, avoidance costs are preferred over damage costs as damage costs have serious limitations in the types of damage included, i.e. much is missing; and also in accounting for potentially catastrophic systemic effects, such as the melting of the polar ice caps in Greenland or West Antarctica or changes in climate subsystems such as the El Niño Southern Oscillation. Avoidance costs can be used in this case as there is a socially accepted goal being worked towards, as embodied by the Paris Agreement. The DG MOVE Handbook on the external costs of transport provides a detailed assessment of climate change costs. We refer the interested reader to Annex D of that report for further detail.

The DG MOVE study carried out an analysis of latest work on avoidance costs estimates, summarised below, which shows the main estimates (excluding outliers) from the range of studies carried out. These demonstrate increasing cost values over time, reflecting the principle that the marginal cost of emissions increases as the carbon budget to remain within targeted emissions is used up. These show a range of costs between €50-300tCO_2e in the short-term (to 2025), increasing to €100-1,000tCO_2e in the long term (2050). These led to the selection of a central value of €$_{2016}$100/tCO2e for the short-medium (up to 2030) term.

Figure B-2 Summary of avoidance cost estimates from various studies

Figure 18 - Review of avoidance cost values found in the literature (€$_{2016}$/t CO_2 equivalent)



Source: DG MOVE – CE Delft (2019) Handbook on the external costs of transport

[35] For instance in: (1) Handbook on the external costs of transport (2019). European Commission, (2) Environmental Prices Handbook EU28 version (2018). CE Delft and (3) Annex: Monetisation of the MMG method (2017). OVAM.

For comparison one of the major pieces of work on damage costs is carried out in the US, which, prior to values being slashed for politically motivated reasons in recent years[36], estimated the Social Cost of Carbon (SCC) for use in policymaking. This estimated rates of USD_{2007}14-138/tCO_2 in 2025, increasing to USD_{2007}26-212/tCO_2 by 2050[37] (based on exchange rates and deflators these numbers can be translated roughly 1:1 to EUR_{2018}). Therefore, the avoidance cost estimates of the DG MOVE study are within, although towards the upper end of, the 2025 SCC range.

This study has identified other pieces of work published concurrently or subsequently to the DG MOVE handbook, including two important reports by OECD/NEA, the first from (2018) on The Full Costs of Electricity Provision and the second from (2019) on the costs of decarbonisation. These offer additional perspectives on carbon pricing for the energy sector and externalities, the former restating the case for abatement costs as the better approach for valuing the climate externalities and noting a social cost of carbon of 'USD 100 per tCO_2 would be included inside the range of possible values of the great majority of estimates'.

Based on the various literature it was decided to use the 2030 climate change values from the DG MOVE Handbook on the external costs of transport (2019), updated from 2016 EUR values to 2018 EUR values. Resulting in a **central climate change external cost value of €102/tCO_2e.** This is based on emissions in 2030. The low value €61/tCO_2e and a high value of €194/tCO_2e were also estimated based on the DG MOVE handbook.

These compare to a value of €50/tCO_2e used in the 2014 study, which represented an estimate based on literature review of diverse sources on abatement costs and damage costs. The approximate doubling of the CO_2 value has a consequent impact on the total value of the climate externalities in the work.

Internalisations

A variety of carbon tax and price initiatives have been introduced globally in the last 10 years or more[38], many of which apply to the energy sector. The following Table B-5 summarises the main measures applied in the internalisation of external costs of the climate change impact. As expected the EU-ETS is by far the most important policy overall, although significant carbon taxes are also in place in a handful of countries such as Sweden, Finland and France, these mostly apply to residential heating production technologies.

[36] https://www.nytimes.com/2018/08/23/climate/social-cost-carbon.html
[37] https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html
[38] For the interested reader the World Bank 'State and Trends of Carbon Pricing' reports provide a comprehensive overview.

Table B-5 Internalisations of the climate change impact external cost

	Measure 1	Value of internalisation (EUR/tCO2e)	Applies to technologies[39]	Notes	Measure 2	Value of internalisation (EUR/tCO2e)	Applies to technologies	Notes
Austria	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Belgium	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Bulgaria	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Croatia	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Cyprus	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Czech Republic	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Denmark	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	23.75	H (1), H (2)	**Carbon tax (DKK177/tCO2) does not apply to fuels used to generate electricity. But does to fuels for heating.**
Estonia	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	2.00	El (1), (2), (3), (4), H (6), (7), (8)	**Carbon tax EUR 2 / tCO2 on all fossils**
Finland	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	58.00	H (1), H (2)	**Carbon tax (€58/tCO2) does not apply to fuels used to generate electricity. But does to fuels for heating.**
France	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	44.60	H (1), H (2)	**Carbon tax does not apply to ETS sectors, but does apply to heating fuels**
Germany	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Greece	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Hungary	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Ireland	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	26.00	H (1), H (2)	Carbon tax does not apply to ETS sectors, but does apply to heating fuels
Italy	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Latvia	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	9.00	H (1), H (2)	Carbon tax does not apply to ETS sectors, but does apply to heating fuels
Lithuania	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					

[39] These technologies can be matched to the lists in Annex D

	Measure 1	Value of internalisation (EUR/tCO2e)	Applies to technologies[39]	Notes	Measure 2	Value of internalisation (EUR/tCO2e)	Applies to technologies	Notes
Luxembourg	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Malta	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Netherlands	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Poland	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Portugal	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon tax	23.62	El (1), (2), (3), (4); H (1), H (2) H (6), (7), (8)	**Carbon tax on non EU-ETS sectors (23.62/tCO2), also as a top-up for ETS sectors. Rate of 0.69 for ETS sectors in latest year.**
Romania	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Slovakia	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)					
Slovenia	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		CO2 tax	17.30	H (1), H (2)	Carbon tax does not apply to ETS sectors, but does apply to heating fuels
Spain	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)			0.00		
Sweden	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	110.00	H (1), H (2)	Carbon tax does not apply to ETS sectors, but does apply to heating fuels
United Kingdom	EU-ETS	24.72	El (1), (2), (3), (4), H (6), (7), (8)		Carbon Tax	0		Carbon Price Floor introduced to top up ETS prices, set at GBP18 currently (below ETS price) - no additional reduction included
Argentina	Carbon Tax	8.47	El (1), (2), (4), H (6), (7), (8)	Since 2018 this tax applies to fossil fuels except Natural Gas, at a rate of US$10/tCO2				
Australia	No Policies	0						
Brazil	No Policies	0						
Canada	Pan-Canadian Approach to Pricing Carbon Pollution	11.85	El (1), (2), (3), (4), H (6), (7), (8)	This is a federal backstop policy that applies nationally at USD14/tCO2. State level policies may go further than this amount.				
China	Pilot ETS	1.00	El (1), (2), (3), (4), H (6), (7), (8)	ETS pilots, not fully implemented auctioning, only low CO_2 cost if regional pilots were summed and applied nationally, nominal value of 1 EUR/tCO2 applied				

	Measure 1	Value of internalisation (EUR/tCO2e)	Applies to technologies[39]	Notes	Measure 2	Value of internalisation (EUR/tCO2e)	Applies to technologies	Notes
India	Clean Environment cess	2.79	El (1), El (2), H(6), H(7)	The Clean Environment cess applies tax to coal for climate and environmental purposes				
Indonesia	No Policies	0						
Japan	National carbon tax	0.84	El (1), (2), (3), (4), H (6), (7), (8)	Tax for climate mitigation is top-up of Petroleum and coal tax. Applies to all fossils., rate of JPY11/kWh				
Mexico	Carbon Tax	3.13	El (1), (2), (4), H (6), (7), (8)	Aprx US$3.7tCO2. Does not apply to natural gas.				
Russia	No Policies	0						
Saudi Arabia	No Policies	0						
South Africa	Carbon Tax	3.07	El (1), (2), (3), (4), H (6), (7), (8)	R120 per tonne, but with minimum 60% free allowances in current phase				
South Korea	National ETS	0.84	El (1), (2), (3), (4), H (6), (7), (8)	ETS covering power sector, but only 3% auctioning in current system, rest is free allowances				
Turkey	No Policies	0						
United States	RGGI, California Cap and Trade	0.79	El (1), (2), (3), (4), H (6), (7), (8)	No national measures. State and regional measures in place. RGGI includes full auction, average price USD6/tCO2. California average price USD16.84, full auction. Applied nationally in proportion to energy emissions covered by schemes.				

Ozone depletion

The Ozone Depletion category values impacts on human health and ecosystems, the former based on the ReCiPe methodology to value the impact of UV-B radiation and the latter the damages to agricultural crop production. Damage is expressed per unit of kg CFC_{11} equivalent. We adopt the values proposed in the Environmental Prices Handbook EU28 (2018), which is an updated version of the handbook used as a basis for valuation in the 2014 study. The values are based on the individualist perspective[40] for the low and central values, and the hierarchist for the high values, the latter differing by not discounting future damages and including additional (less certain / robustly estimated) impacts. When inflated to 2018 euros these result in the following monetisation factors:

- Low: €21.85/kg CFC_{11} eq;
- **Central: €31.43/kg CFC_{11} eq;**
- High: €127.15/kg CFC_{11} eq.

These compare to a value of €107/kg CFC_{11} eq. used in the 2014 study, which represented a direct valuation of endpoints, and importantly no discounting of future impacts. Updates in the handbook, recommend the use of discounting for future impacts, these result in equivalent impacts having around 1/5 of the external cost attributed in the previous work. As a relatively minor impact in the total, ranking 14 of 16, and with total costs across all countries and technologies of around €8 million, this is not a major influence on the results.

Ionising radiation, human health

This category values the damage to human health caused by emissions to air and water of radionuclide substances. This is most relevant to nuclear power, but is also to a much lesser extent relevant for other technologies, e.g. coal, where radionuclide substances may be released in combustion. For this category we apply an update of the approach used in 2014 which uses direct valuation of the human health endpoints for different radionuclides. The impact of the radionuclides is characterised based on the NEEDS approach and uses emission/dose factors for different illnesses. Impacts at this level are converted to their kBq U-235 eq. values, and the endpoint damages characterised and measured in DALYs. An average of these values is taken, as the actual emission distribution of the individual radionuclides is unknown, to provide a DALY/ kBq U-235 eq. value of 1.64E-08. This is consistent with other approaches to valuing this indicator, such as those used in the Monetisation of the MMG method study published by OVAM in 2017.

Using the assumption that 1 DALY = 1 VOLY an impact valuation can be derived. Valuation is based upon a VOLY of $€_{2018}$ 72 363, consistent with the EU28 handbook and based on NEEDS. As a result we calculate the following monetisation factors:

- Low: €0.0008 kBq U235eq;
- **Central: €0.0012 kBq U235eq;**
- High: €0.0461 kBq U235eq.

This approach updates the valuation methods applied in the 2014 study, with the changes largely reflecting an update of the VOLY value underpinning the calculation and application of deflators to 2018. The change in the monetisation value is therefore quite small, from seis has a significant impact

[40] The perspectives have been used within the ReCiPe work amongst other things, to reflect different views on risks and valuation of future damages - particularly as would be embodied in discount rates. The individual perspective reflecting a higher discount rate than the hierarchist perspective.

on the monetary values applied, these increasing from around €$_{2018}$0.001 kBq U235eq. used in 2014 to €$_{2018}$0.0012 kBq U235eq. used in this work. The impact on the results shows that from EU impacts of €$_{2012}$1.1 billion noted in 2014, a decline to €$_{2018}$0.6 billion in this work, ranking it as the 11th largest impact overall.

The high value for ionising radiation reflects the central monetisation value recommended in the Environmental Prices Handbook EU28 (2018). This was tested as a central value and discussed during the work, but it was not consistent with the previous work and in-depth studies carried out in the sector, such as NEEDS[41], returning results significantly higher than expected or realistic. Therefore the alternative central value described above was adopted.

Photochemical ozone formation, human health

This category measures the damages to human health from photochemical oxidant formation, otherwise known as (summer) smog. It is caused by pollution of the lower atmosphere with Ozone (O_3), Nitrogen Dioxide (NO_2) and other chemicals, with Ozone the most important component. Ozone is not emitted directly but is formed from the interaction of other chemicals with sunlight, the main catalysts being nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO). Fuel combustion in power plants can be a major source of NOx, NMVOC and CO.

For this category we apply values proposed by the Environmental Prices Handbook EU28 (2018) which are derived from NEEDS and supplemented by latest understanding on the (higher) impact of NOx on human health as published by the WHO[42]. These result in the following values being used.

- Low: €0.87 kg NMVOCeq;
- **Central: €1.19 kg NMVOCeq;**
- High: €1.90 kg NMVOCeq.

In addition to damages to human health photochemical oxidant formation can also cause damage to crops, ecosystems and buildings (rubber, plastics and paint are susceptible to damage). These are understood to be a rather small part of the total damages and also with more uncertainties in their valuation, and are therefore only included within the high value estimate.

The proposed central value of €1.19 kg NMVOCeq. compares to a value of €0.0023 used in the 2014 study, in this case a significant difference (x500 higher). This is due to two reasons (1) the much better understanding of the health impacts of emissions of NOx and presence of ozone; and (2) the move from direct endpoint valuation to a damage cost valuation approach in the EU28 handbook. The change in values has a consequent impact on the importance of this impact category within external costs, from being one of the 5 lowest impacts in 2014, with a total impact of less than €0.1 billion across the EU28, it now ranks 7 of the 15 impacts in this work and accounts for external costs of around €4.9 billion across the EU.

[41] See NEEDS D6.1 RS1a External costs from emerging electricity generation technologies

[42] It is noted that the Environmental Prices Handbook provides a value based on NEEDS damage costs, adjusted Concentration Response Functions based on WHO (2013) and ReCiPe (2013) characterisation factors. It is not entirely clear if these values would change if a different set of characterisation factors would be used, but changes would most likely be relatively small.

Particulate matter

This category values the impacts of airborne particulate matter on human health and buildings. The main, but not only, source of these particulates being fuel combustion. It is increasingly well understood that exposure to particulate matter is amongst the greatest risks to human health. As various pollutants, many of them toxic, can attach to the particles, and once breathed in to the mouth, nose, throat or lungs can cause serious short and/or longer-term damage, contributing to or causing disease.

Befitting its status as a major threat to human health the area of particulate matter has received significant attention and research, particularly in the last 10 years. This has led to various advances in understanding of damage pathways and impacts when compared to the 2014 study. This category is valued in the EF framework through the 'disease incidence' unit, this represents one of the five main steps on the general LCA framework for characterising the impacts of emissions of air pollutants. These are described in detail in a 2016 study for UNEP by Fantke et al. on Global Guidance for Life Cycle Impact Assessment Indicators vol 1, starting from (1) mass emissions to air; (2) time-integrated mass (concentration) in air; (3) mass inhaled; (4) disease incidences; and then lastly, (5) human health impacts.

The valuation approach is based on values prepared for the DG MOVE Handbook on the external costs of transport (2019) prepared units of €/kg PM10 eq. and converted to the required unit of disease incidence on the basis of the 2016 UNEP study and the relationships between the impact pathway steps. The DG MOVE handbook is based heavily on the Environmental Prices Handbook EU28 (2018) which is based on the NEEDS approach but includes various modifications based on subsequent work for WHO and from other studies. Furthermore, the Environmental Prices Handbook notes that emissions from high smokestacks (>100m) as is the case for most power plants, leads to an almost 50% reduction in damage costs. As this is the case for the main technologies and life cycle steps in this work, we have applied a 50% reduction to the original monetisation values.

These result in the following values being used.

- Low: €661 974 per unit disease incidence;
- **Central: €784 126 per unit disease incidence;**
- High: €1 204 600 per unit disease incidence.

This impact category compares to the particulate matter formation category assessed in the 2014 report, although the valuation of the impact units is not directly comparable, the underlying values from the 2014 study (€15/kg PM_{10}-eq.) and the Environmental Prices Handbook (€39.2/kg PM_{10}-eq.) have more than doubled, although if the 50% adjustment would also be applied to the Environmental prices handbook the values are much closer to each other. We note that the equivalent impact category was assessed as the 3rd largest impact category in 2014, and that it has now become the 2nd largest category globally. This increased cost is consistent with the noted changes in valuation and increased understanding of the high costs to human health.

Human toxicity

This category values the adverse human health effects caused by '(1 – cancer) the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer; and (2 – non-cancer) the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.'[43] It mostly encompasses heavy metals and chemicals, small concentrations of which are released in fossil fuel combustion. It is measured in units of Comparative Toxic Units for humans (CTUh), this unit describes the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).

The valuation approach is based upon the values prepared for the DG MOVE Handbook on the external costs of transport (2019) and its derivation of €/DALY values[44]. The DG MOVE handbook is based heavily on the Environmental Prices Handbook EU28 (2018). The €/DALY values can be converted to €/CTUh values based on assumptions on the ratio DALY/CTUh. On the advice of the JRC we have taken as the central value for both human toxicity impacts the value derived from the average of the DALY/CTUh values derived by 3 key studies in this area[45]. This results in the following values being used, which are comparable to values derived in other studies such as the OVAM (2017) work:

Non-cancer

- Low: €30 211 /CTUh;
- **Central: €163 447 /CTUh;**
- High: €755 270 /CTUh.

Cancer

- Low: €174 324 /CTUh;
- **Central: €902 616 /CTUh;**
- High: €2 789 181 /CTUh.

Low and high values for both indicators are based on OVAM (2017).

These two impacts are the 4th (cancer) and 5th (non-cancer) highest of all of the impacts across all countries and technologies, with impacts of around €380 billion per year estimated. For the EU27 the respective rank of impacts is 8th (cancer) and 4th (non-cancer), and a total of €22 billion. Although the impact category is different to that used in 2014, many of the underlying methodologies and values are similar, a €17 billion total human toxicity impact was estimated in 2014, highlighting an underlying consistency in results. Nevertheless, it should be noted that these impact categories and their monetisation have perhaps the highest uncertainties of any of the impact categories, due to uncertainties in the impact of the many hundreds of substances covered and their respective impact pathways.

[43] EC/2013/179/EU Annex 2 Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

[44] DALYs or Disability Adjusted (Lost) Life Years are a measure used to attach a value to Years of Life Lost (YOLL) and Years Lost to Disability (YLD). This is done through Valuation of a Life Year lost (VOLY) with much of the underlying work relying on Willingness to Pay methods and the methodology established by the NEEDS project. These also underly the valuation of human health damages in the DG MOVE study and the Environmental Prices Handbook EU28.

[45] Namely: (1) Ponsioen, T. C., & Goedkoop, M. J. (2016). Midpoint weighting based on endpoint information. Personal Communication on a paper in preparation for the IJLCA; (2) Humbert, S. 2015. OEF retail screening report in the context of the EU Organization Environmental Footprint Sector Rules (OEFSR) Pilots - section 3.7 Normalisation and weighting, and damage assessment.;(3) Vargas-Gonzalez, M., Witte, F., Martz, P., Gilbert, L., Humbert, S., Jolliet, O., ... & L'Haridon, J. (2019). Operational Life Cycle Impact Assessment weighting factors based on Planetary Boundaries: Applied to cosmetic products. Ecological Indicators, 107, 105498.

Acidification

This impact includes the damages to ecosystems, crops and buildings from acids caused by air pollution, carried either through rain or air. Whilst there are natural sources, e.g. volcanoes, for the air pollutants that cause acidification, the main sources are human, and especially include fossil fuel combustion and livestock farming.

The approach used to value acidification is based on a 2017 study by VITO for OVAM on Monetisation of the MMG method. This is based on damage cost and avoidance (restoration) cost approaches and includes impacts of building materials and ecosystems, but not crops. The values are based on results from the Ecosense model developed by ExternE and NEEDS, and other literature. The values are broadly consistent with those proposed in the Environmental Prices Handbook EU28, but the central and higher values are lower than the Environmental Prices Handbook values.

Values from the OVAM study were converted from kg SO_2 eq. to Mol H+ eq. using the characterisation factors from the EF2.0, with an approximate conversion of 1.31 Mol H+ eq. per 1 kg SO_2 eq. This resulted in the following values being used:

- Low: €0.176 / Mol H+ eq;
- **Central:** €0.344 / Mol H+ eq;
- High: €1.617 / Mol H+ eq.

These values compare to an equivalent value of €0.164 / Mol H+ eq. used in the 2014 study, and therefore an approximate doubling in the value of the impact. This being driven by improved understanding and modelling of the damage pathways. The total acidification impact is around €16 billion across all countries, ranking 10th amongst the 15 impacts. The impact in the EU27 only accounts for €1.4 billion of the total, with the largest share of the impact attributable to countries with weak SO_2 and NOx emission controls on their fossil fuel plants. The €1.4 billion value is around double the value estimated in the 2014 study, and is explained almost entirely by the doubling of the monetisation value.

Internalisations

In addition to the climate change internalisations applied a single measure for acidification is also applied. The Acid Rain Program in the United States is a cap and trade system for SO2 emissions designed to reduce emissions and acidification. The program has been highly successful in the past at reducing SO2 and NOx emissions in the US although it now seems to be somewhat obsolete with market prices now very low, averaging less than USD1/tSO2 in 2019[46]. An internalisation of the external cost based on a USD1tSO2 , converted to Mol H+, of €0.013 / Mol H+ eq., or representing an internalisation of around 4% of the impact, has been applied to the acidification impact in the US.

Eutrophication

Eutrophication is a term used when excessive nutrients present in ecosystems disturb the natural processes and cycles. This can move ecosystems out of balance, and, for example lead to particular plants or species becoming dominant, with a negative impact assumed relative to the original ‘balanced’ state. Nutrient overload in water bodies, leading to algal blooms which then deplete the oxygen in the water, and the death of fish and other animals, being one of the classic examples. Soil,

[46] https://www3.epa.gov/airmarkets/progress/reports/market_activity_figures.html#figure2

air and water can all be affected, with nitrogen, phosphorus and potassium the main pollutants. Agricultural activity is typically the main source of these emissions, but NOx emissions from combustion are also an important source.

We apply values for eutrophication derived from the Environmental Prices Handbook EU28 (2018) which are based on a mix of damage and abatement cost approaches for the different pollutants. These draw upon the work carried out in NEEDS and by Kuik (2008) in valuing ecosystem damages. The valuation is made for eutrophication of freshwater and marine ecosystems on the basis of this approach. In discussion with JRC it was decided that there was not yet a robust enough value to use for terrestrial eutrophication, therefore this category is not valued in this work. The following values are used:

Freshwater eutrophication

- Low: €0.26/kg P eq.
- **Central: €1.92/kg P eq.**
- High: €2.18/kg P eq.

This impact is the 13th largest of the 15 valued, accounting for around €110 million external costs per year across all countries. This compares to the 2014 study which found higher costs (€0.3 billion total for the EU28) despite using much lower monetisation values (€0.26/kg P eq in 2014). The major differences manifesting in how the pollutants are valued compared to 2014 and improvements in the characterisation of these impacts in LCA.

Marine eutrophication

For this case no low or high values were suggested by the source valuation literature.

- Low: €3.21/kg N eq.
- **Central: €3.21/kg N eq.**
- High: €3.21/kg N eq.

This impact is the 8th largest of the 15 valued, accounting for around €23.9 billion in external costs per year across all countries. Looking at just the EU28 the damages are €2.9 billion, this compares to the 2014 study which found lower costs (€0.7 billion total for the EU28). An increase in the monetisation value from €1.97/kg N eq in 2014, accounts for some of the difference, but the largest part of the differences result from how the pollutants are valued compared to 2014 and improvements in the characterisation of these impacts in LCA.

Terrestrial eutrophication

Not valued as approaches are not yet robust enough.

Ecotoxicity, fresh water

This category values the 'toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.'[47] The EF impact category only covers the impact of emissions to freshwater. It mostly encompasses heavy metals and chemicals, small concentrations of which are released in fossil fuel

[47] EC/2013/179/EU Annex 2 Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

combustion. Other significant sources include agricultural chemicals such as pesticides and biocides. It is measured in units of Comparative Toxic Units for ecosystems (CTUe), this unit provides an estimate of the Potentially Affected Fraction (PAF) of species, integrated over time and volume per unit mass of a chemical emitted ($PAFm^3/day/kg$).

The valuation approach for this indicator is based on OVAM (2017), this is a variation on the approach applied for the human toxicity categories. The OVAM work uses valuation of the Potentially Disappeared Fraction (PDF) of terrestrial species, and conversions to both the freshwater environment and PAF to estimate a value per CTUe. This results in the following values being used:

- Low: **€2.23E-24** /CTUe;
- **Central: €3.82E-05 /CTUe;**
- High: €1.88E-04 /CTUh

The low value is based on advice of the JRC, with the value derived from the average of the species.yr/CTUe values derived from 2 key sources[48] and a conversion being applied based on €/species.yr values from the Environmental Prices Handbook EU28 (2018). The high value is based on OVAM (2017).

This impact ranks 12th of all impact categories considered with a total impact across all countries and technologies of around €0.17 billion per year estimated. Although the impact category is different to those used in 2014 (3 impact categories addressed ecotoxicity), many of the underlying methodologies and values are similar. Negligible impacts of any kind were estimated in 2014. Whilst values have increased from around zero in 2014, the total of around €8 million for the EU27 demonstrates this is not a significant externality for the energy sector. Nevertheless, it should be noted that, similar to human toxicity, this impact category and its monetisation have perhaps the highest uncertainty of any of the impact categories, due to uncertainties in the impact of the many hundreds of substances covered and their respective impact pathways.

Land use

This impact category considers the 'use (occupation) and conversion (transformation) of land area by activities such as agriculture, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area).' [49] The land use impact category is measured in terms of a soil quality index by a dimensionless unit called "pt". The pt unit is a composite indicator of 4 indicators produced by the associated LCIA approach based on the LANCA model, these include: biotic production (kg); erosion resistance (kg soil); mechanical filtration (m^3 water) and groundwater replenishment (m^3 groundwater).

[48] Namely: (1) Ponsioen, T. C., & Goedkoop, M. J. (2016). Midpoint weighting based on endpoint information. Personal Communication on a paper in preparation for the IJLCA; (2) Humbert, S. 2015. OEF retail screening report in the context of the EU Organization Environmental Footprint Sector Rules (OEFSR) Pilots - section 3.7 Normalisation and weighting, and damage assessment.
[49] EC/2013/179/EU Annex 2 Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

In discussion with JRC a value for the pt unit was recommended. JRC noted that the value was derived according to the method suggested in the 2015 study from Cao et al. 2015[50]. The method was adapted to be used in combination with the land use impact assessment model from the EF presented in De Laurentiis et al. 2019[51]. It is noted that the value only characterises the impacts caused by land occupation, not transformation. This results in the following values being used:

- Low: **€0.000087** /pt;
- **Central: €0.000175 /pt;**
- High: €0.000349 /pt.

The low and high values test 50% and 200% versions of the central value for sensitivity check purposes.

This impact ranks 6th of all impacts, with a total estimated impact across all countries and technologies of around €57 billion per year. The impact category and unit are different to those used in 2014 (in which 2 impact categories addressed land occupation). The underlying basis of the methodologies is also quite different. It is not possible to give detailed explanation of the differences but it can be noted that equivalent costs in 2014 totalled around €2.7 billion for the EU28, and have increased to €8.9 billion for the EU27 demonstrating a tripling of the valuation of this impact. It should be noted, that this impact category and its monetisation has a high associated uncertainty.

Resource depletion

This impact category 'addresses use of natural resources, either renewable or non-renewable, biotic or abiotic.'[52] with the aim to place a value on the additional scarcity caused by resource use. In this work it covers 3 specific impact categories, water, fossil (energy) resources, and minerals and metals. External costs associated with resource depletion can be controversial as there is a case to be made that markets for the resources will already price in the scarcity and therefore that there is no externality cost. This is particularly relevant for fossil, mineral and metal resources for which there are relatively open global markets and prices. For water this is much less the case, as markets are rare and prices very often do not price the consumption, at best they tend to aim for cost recovery of the investments necessary in water treatment and distribution systems. Despite these concerns we include monetisation of these impact categories, following the approach used in 2014, and with the same rationale, rooted on the basis that the private markets for resources do not adequately price in the additional marginal cost of present consumption on prices of and scarcity to future generations, i.e. implicitly the needs of future generations are more heavily discounted by private markets than may be optimal from a societal perspective.

Dissenting views on this approach are available in the literature, for example a good summary is provided in OECD/NEA (2018)[53]. The overall rationale being that as there are effectively no other non-commercial uses for the resources, that it is then most appropriate to use the commercial market values as having effectively internalised the relevant scarcity costs. An important note relates to the uncertainties for valuing resources, in that their economic availability varies considerably over time with changes in supply and demand, new discoveries, depletion of quality of existing reserves and

[50] Cao et al. 2015 - Aggregated indicator to assess land use impacts in life cycle assessment (LCA) based on the economic value of ecosystem services
[51] De Laurentiis et al. (2019) - Soil quality index Exploring options for a comprehensive assessment of land use impacts in LCA
[52] EC/2013/179/EU Annex 2 Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.
[53] OECD/NEA (2018) The full costs of electricity provision.

improvements in technology (which can reduce extraction costs) all being reflected in prices. We take this overall argument into account through our sensitivity analysis and 'low' monetisation values, where the monetisation is set to zero for fossil as well as metal and mineral resources.

Water use

This impact category addresses water use with an indicator on 'user deprivation potential (deprivation-weighted water consumption)', which is measured in m3 water (world) equivalents. It is based on an LCIA method called Available Water Remaining (AWARE) by Boulay et al., 2015[54].

The valuation approach was based on discussions with JRC from which a recommended monetisation value consistent with the EF approach was suggested. It was noted that this value does not need to be varied by country/region as this type of characterisation already happens within the LCIA. Alternative approaches based on an update of the value used in 2014 and shadow prices as examined by Lighart et al (2019)[55] were also suggested. The following values were used:

- Low: €0.00419 /m3 water eq;
- **Central: €0.00499 /m3 water eq;**
- High: €0.23624 /m3 water eq.

The low and high values are based on OVAM (2017). As can be noted the high value tests a significantly different value to the central value but is consistent with an update of the 2014 value.

This impact ranks 11th of all impacts, with a total estimated impact across all countries and technologies of around €22 billion per year. Despite variations in method, LCIA approach and valuation, the impact of water use is quite similar to the 2014 study, in 2014 totalling around €1.0 billion for the EU28, and for this work €0.86 billion for the EU27. It should be noted, that this impact category and its monetisation has a high associated uncertainty, for example in the high value scenario it becomes the 5th largest impact overall.

Resource use, fossils

This impact category addresses fossil resource use with an indicator on 'abiotic resource depletion – fossil fuels (ADP-fossil)', which is measured in MJ. It is based on two LCIA methods from 2002, notably CML 2002 (Guinee et al., 2002) and van Oers et al. 2002.[56]

The valuation approach represents an update of the value used in the 2014 study, with a conversion to MJ. The following values were used:

- Low: €0 /MJ;
- **Central: €0.0013 /MJ;**
- High: €0.0068 /MJ.

---

[54] A.-M. Boulay, J. Bare, C.D. Camillis, P. Döll, F. Gassert, D. Gerten, S. Humbert, A. Inaba, N. Itsubo, Y. Lemoine, M. Margni, M. Motoshita, M. Núñez, A.V. Pastor, B. Ridoutt, U. Schencker, N. Shirakawa, S. Vionnet, S. Worbe, S. Yoshikawa, S. Pfister; Consensus building on the development of a stress-based indicator for LCA-based impact assessment of water consumption: outcome of the expert workshops; Int. J. Life Cycle Assess., 20 (2015), pp. 577-583

[55] Ligthart, T. N., & van Harmelen, T. (2019). Estimation of shadow prices of soil organic carbon depletion and freshwater depletion for use in LCA. The International Journal of Life Cycle Assessment, 1-18.

[56] Van Oers, L., de Koning, A., Guinee, J.B. and Huppes, G. (2002). Abiotic Resource Depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam

One of the limitations of the approach for the central value is that the valuation of scarcity is based on the scarcity of oil, with values then adjusted relative to energy content for the other fuels. This therefore does not account for differing reserves for different fuels, which in reality would see lower scarcity values for coal and uranium as these fuels are much more abundant than oil. The central value therefore likely overestimates the external costs of this impact for the coal, lignite and nuclear technologies.

The high value is based on OVAM (2017). As noted in the introduction to this sub-section the low value is set to zero to reflect a case where all relevant scarcity costs are internalised in the market price.

This impact ranks 3rd of all impacts, with a total estimated impact across all countries and technologies of around €269 billion per year. Given that the monetisation value is an update of the 2014 study it is unsurprising that the total values for 2014 for the EU28 of €43 billion and for the EU27 in this work of €35 billion are relatively close. The difference explained by two factors, firstly the change in the energy mix of the EU energy system and a continued move away from fossil energy, and secondly, variations in the LCIA outputs. It should be noted, that this impact category and its monetisation has a high associated uncertainty and there are arguments that the cost should be zero.

Resource use, minerals and metals

This impact category addresses use of mineral and metal resources with an indicator on 'abiotic resource depletion (ADP ultimate reserves)', which is measured in kg Sb (antimony) eq. It is based on two LCIA methods from 2002, notably CML 2002 (Guinee et al., 2002) and van Oers et al. 2002.[57]

The valuation approach is based on OVAM (2017) as it was not possible to update the 2014 indicator from units of kg Fe eq. to units of kg Sb eq. The OVAM approach notes limitations in applying the ReCiPe method, used in 2014, to units of Sb, as conversion of the value on the basis of characterisation factors results in an external cost value many times higher than the market price of Sb. The OVAM approach uses the ReCiPe Resource Depletion Costs and the market prices to calculate an average ratio between the two (of 83%). This was used to calculate a high resource depletion value for kg Sb which was comparable to the ReCiPe values. A central value was derived on the basis of an assumed bandwidth in values. The following values were used:

- Low: €0 /kg Sb eq;
- **Central: €1.64** /kg Sb eq;
- High: €6.53 /kg Sb eq.

This impact ranks 15th of all impacts, with a total estimated impact across all countries and technologies of around €6 million. This is significantly lower than the €1.3 billion for the EU28 in 2014. The difference in valuation is not understood to be the major driver of this difference given the reconciliation of the original ReCiPe source and the new value in OVAM (2017). The change in LCIA approach is likely the major driver of these differences.

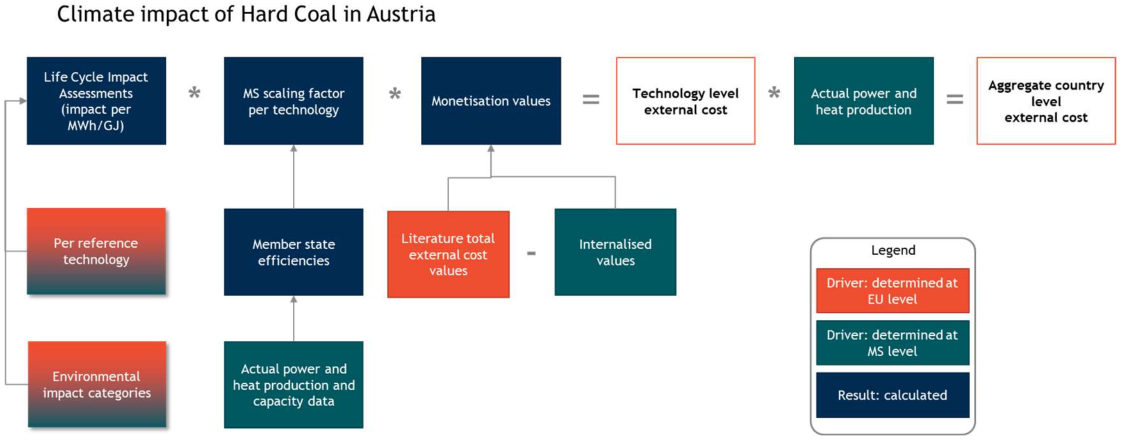
Example calculation

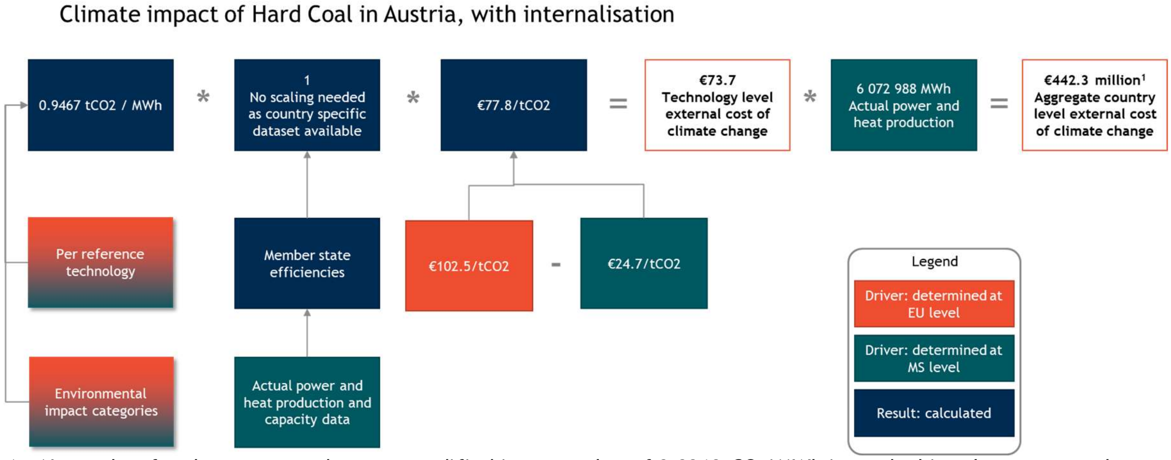
The following figures provide a worked example of the calculation, structured by the framework set out earlier in this Annex. This shows the calculation of one impact (climate change) at technology level

[57] Van Oers, L., de Koning, A., Guinee, J.B. and Huppes, G. (2002). Abiotic Resource Depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam

(hard coal plant) for Austria. Reading left to right, in the first step the LCIA exercise provides a climate impact for this technology, of 946.7 $kgCO_2$/MWh generated. In this case, the second step (scaling) is not needed as a country specific LCIA dataset was available. If this was not the case then a reference country would be chosen, e.g. for Solar power only the dataset for France was available, all countries impacts are scaled from the French dataset based on ratios of capacity/production relative to France. For others only a handful of country datasets were missing and therefore if for example a Romania dataset was unavailable then Bulgaria may be used as a proxy, and then the results scaled by the relative thermal efficiency of production in the two countries as calculated from actual production data. As a third step the impact is monetised by multiplication with the monetisation value. This is derived from the monetisation review, for example the cost of 102.5 EUR/tCO2e is used, from which the EU-ETS price of 24.72 EUR/tCO_2e is subtracted as this represents an internalisation of the external cost, so that a final monetisation value of 77.8 EUR/tCO_2e is used and multiplied by the 0.9467 tCO2/MWh to reach a climate externality cost of EUR 73.7/MWh. For the total numbers a modified technology level cost, removing indirect electricity use, is used and multiplied by actual production of 6 072 988 MWh to calculate a total external cost of €442.3 million for the climate change impact of hard coal in Austria.

Figure B-3 An example of the external cost framework in action, the framework (top) and the example calculation (bottom)





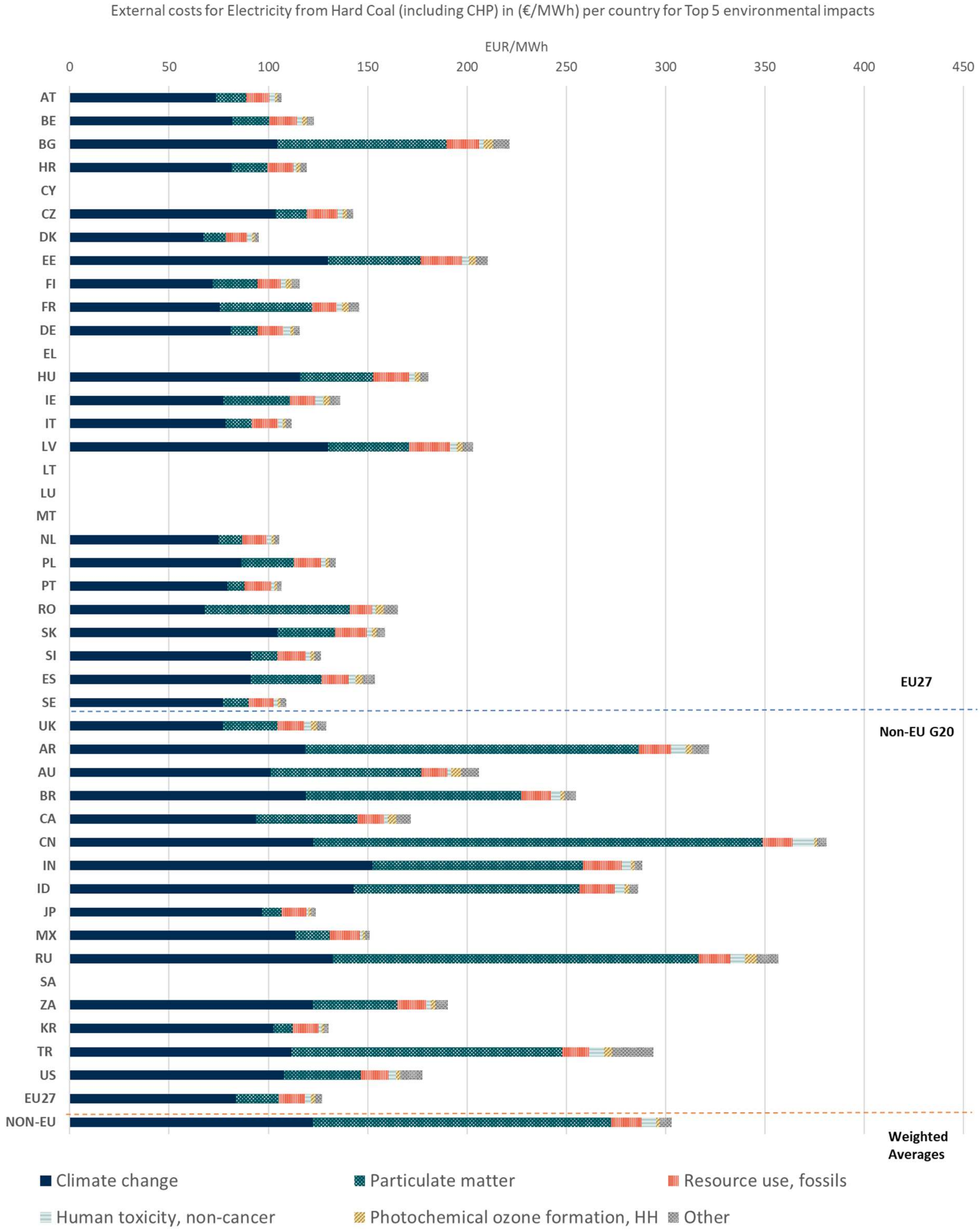
1 = Note, that for the aggregated costs a modified impact value of 0.9369tCO_2/MWh is used, this value removes the use of electricity in generating electricity to avoid double counting the impacts at the country aggregate level

Annex C - Detailed technology results

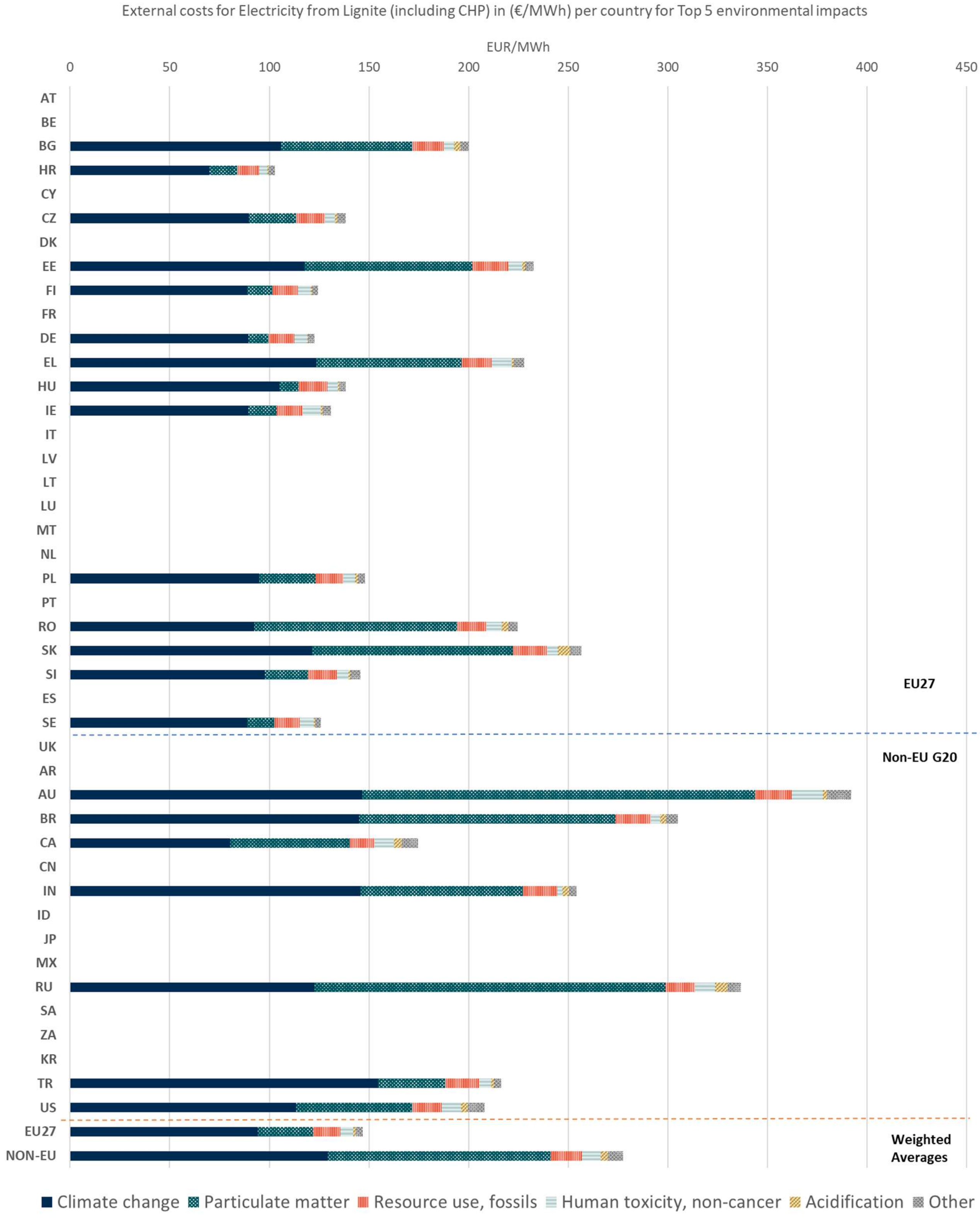
The following results are all presented with internalisations of external costs included.

Electricity

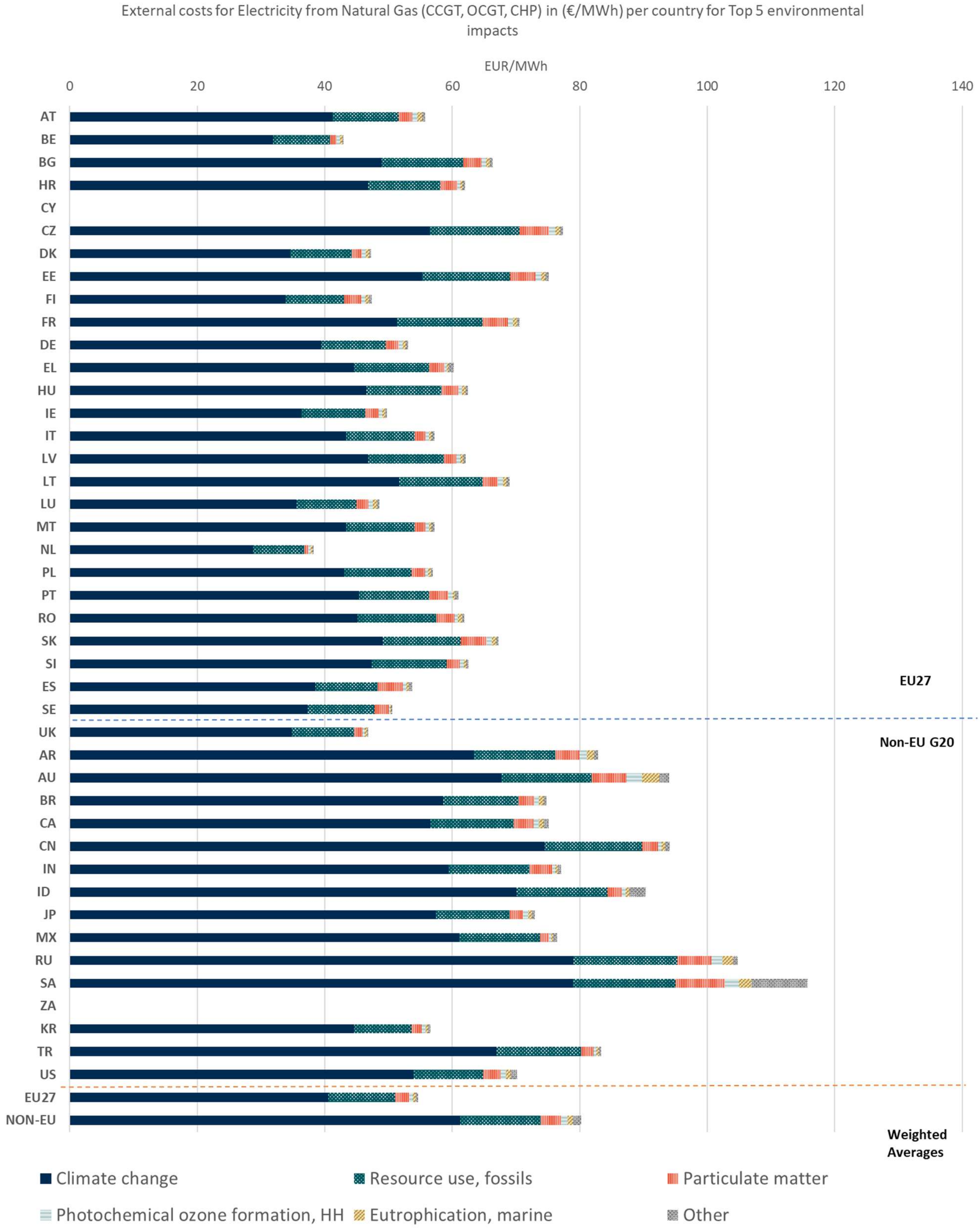
Hard Coal (including CHP)



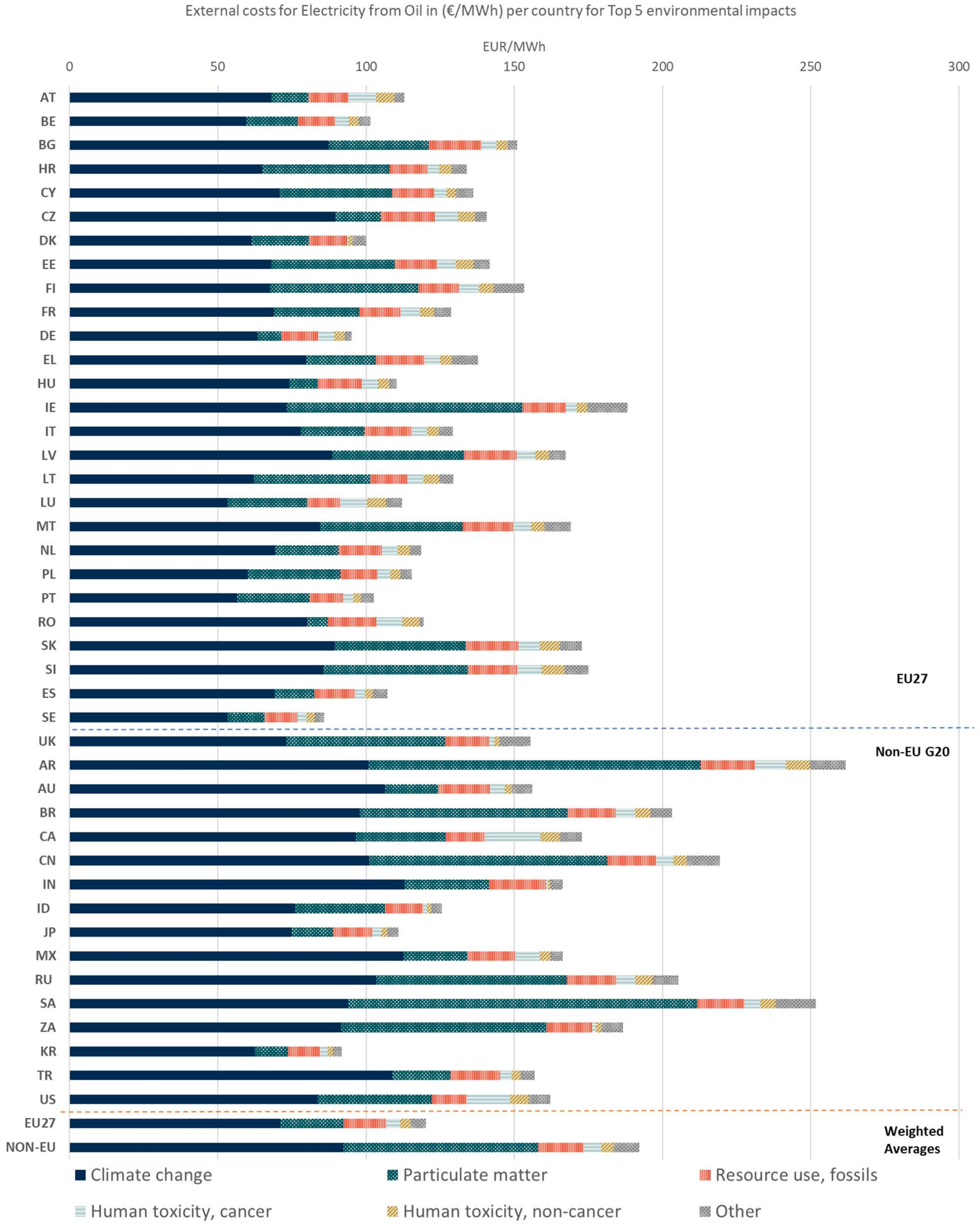
Lignite (including CHP)



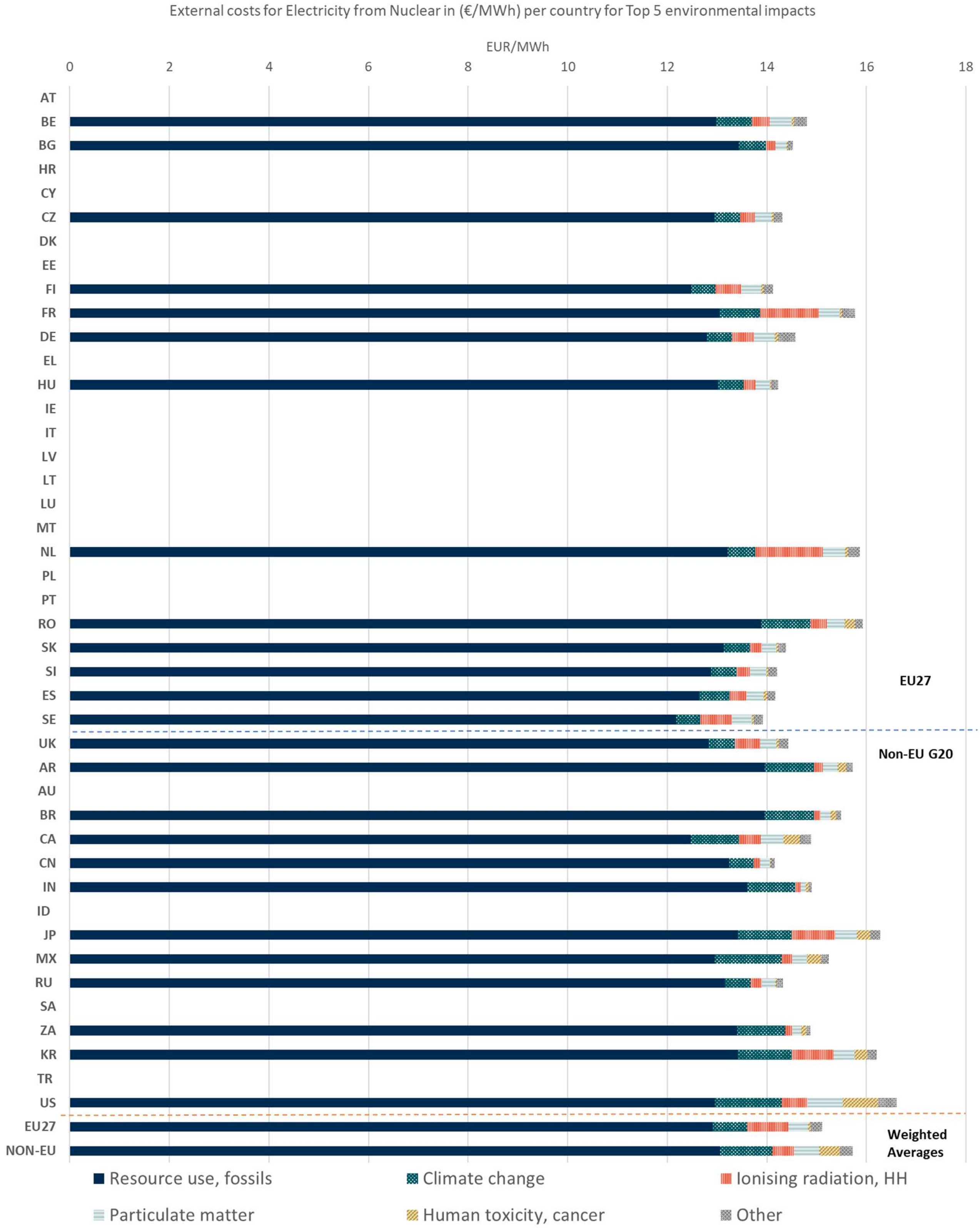
Natural Gas (CCGT, OCGT, CHP)



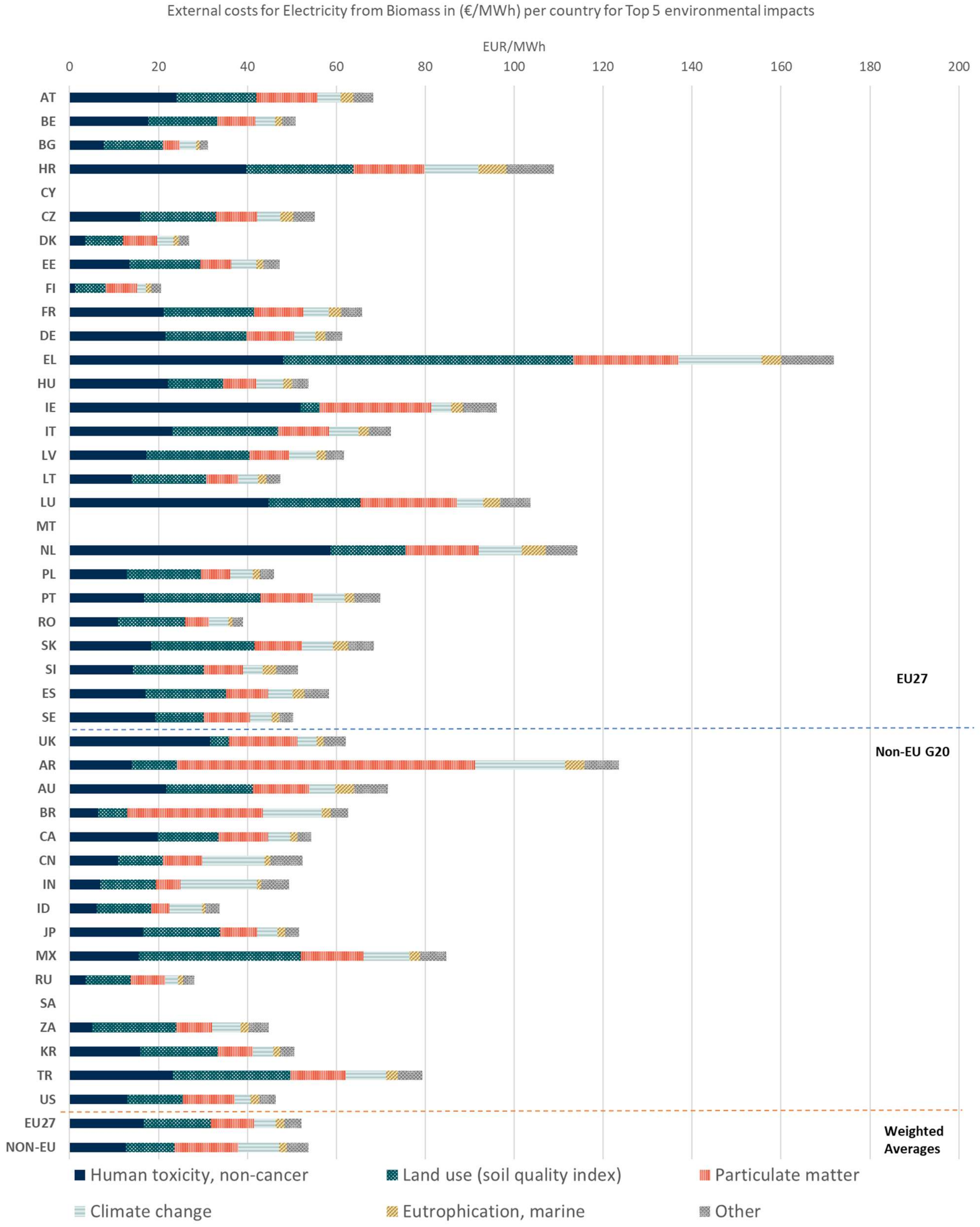
Oil


External costs for Electricity from Oil in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
50
100
150
200
250
300
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
PT
RO
SK
SI
ES
SE
UK
AR
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
EU27
NON-EU
EU27
Non-EU G20
Weighted Averages
Climate change
Particulate matter
Resource use, fossils
Human toxicity, cancer
Human toxicity, non-cancer
Other

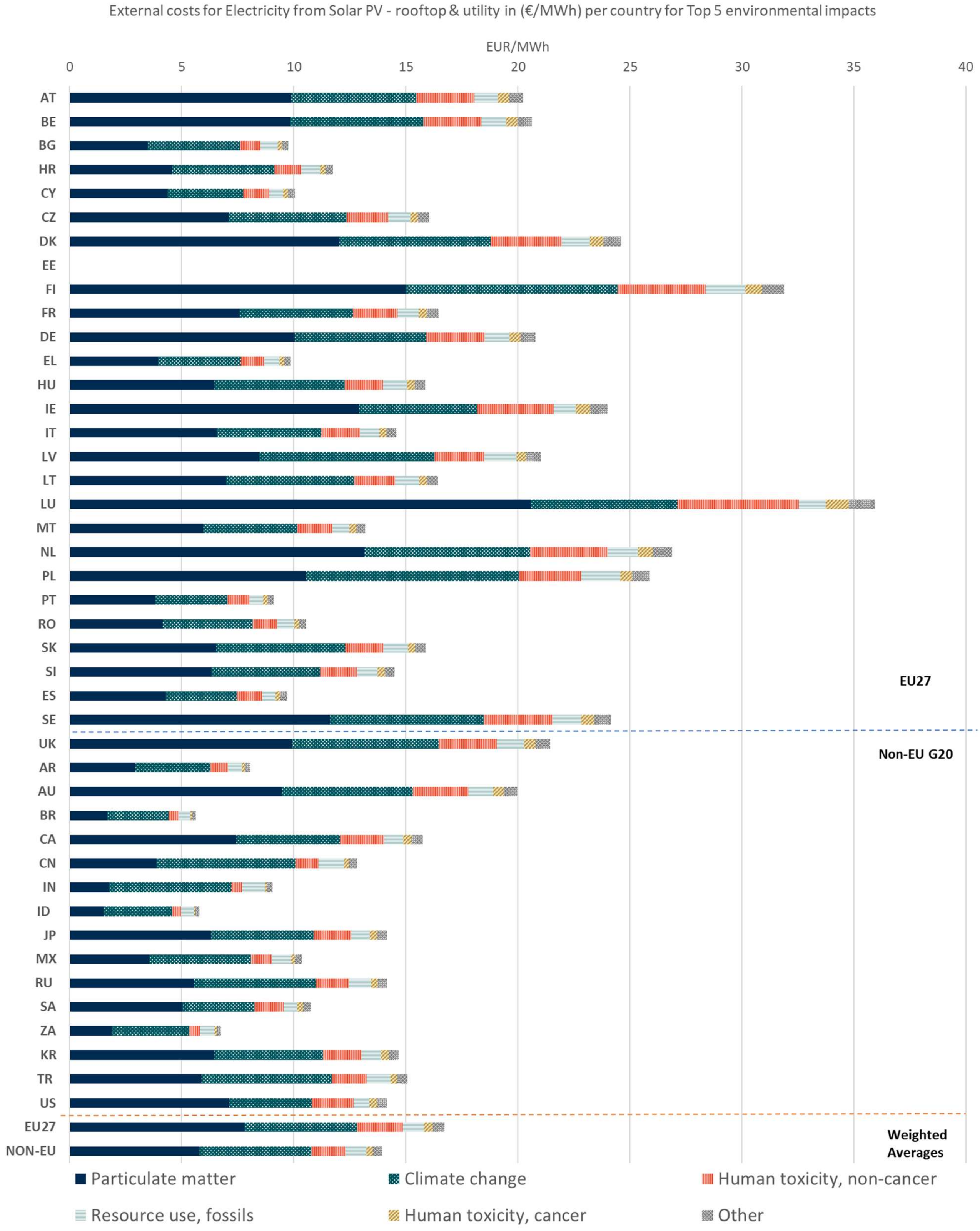
Nuclear


External costs for Electricity from Nuclear in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
2
4
6
8
10
12
14
16
18
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
PT
RO
SK
SI
ES
SE
EU27
UK
AR
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
Non-EU G20
EU27
NON-EU
Weighted Averages
Resource use, fossils
Climate change
Ionising radiation, HH
Particulate matter
Human toxicity, cancer
Other

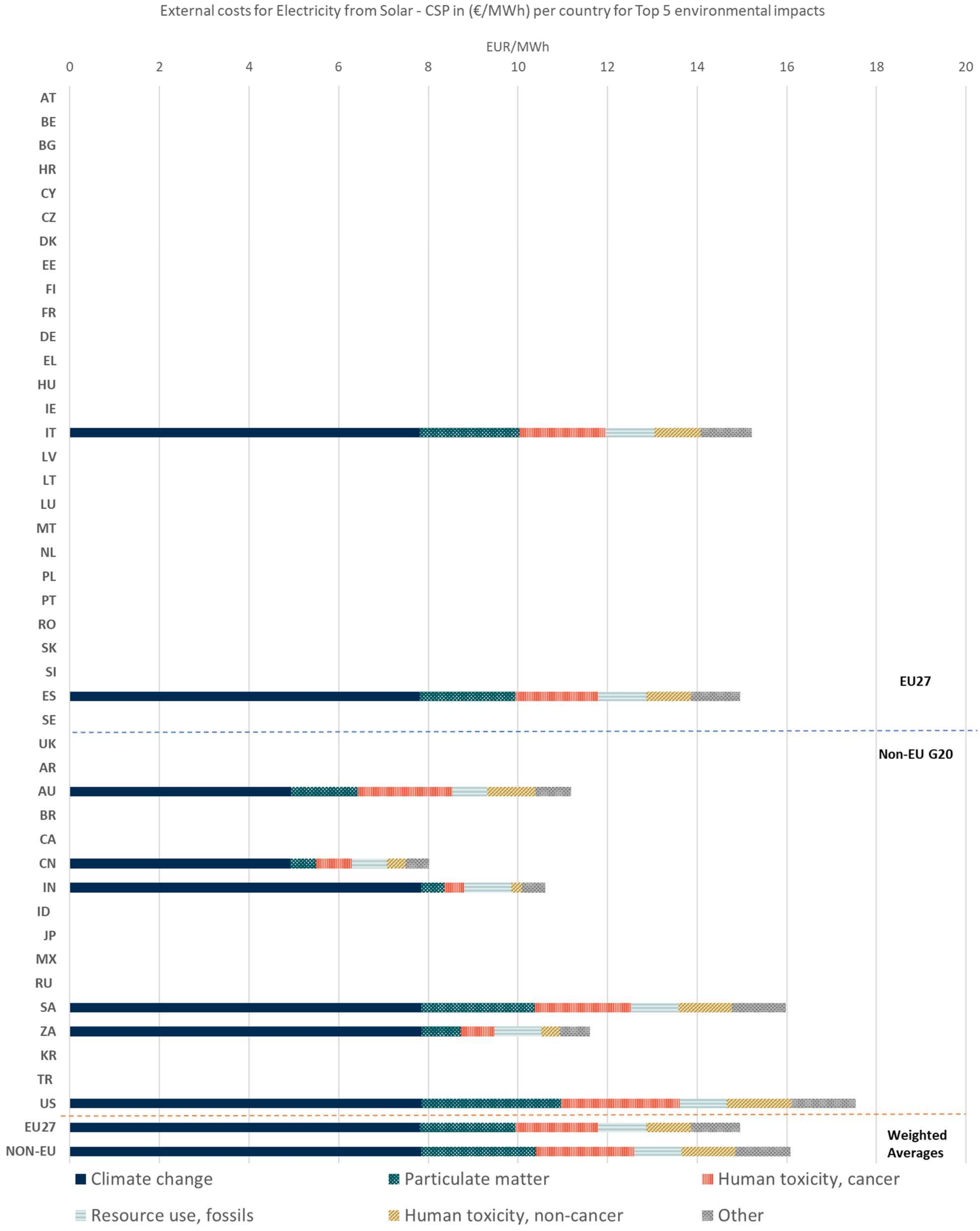
Biomass


External costs for Electricity from Biomass in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
20
40
60
80
100
120
140
160
180
200
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
PT
RO
SK
SI
ES
SE
UK
AR
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
EU27
NON-EU
EU27
Non-EU G20
Weighted Averages
Human toxicity, non-cancer
Land use (soil quality index)
Particulate matter
Climate change
Eutrophication, marine
Other

Solar PV - rooftop & utility



Solar - CSP


External costs for Electricity from Solar - CSP in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
2
4
6
8
10
12
14
16
18
20
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
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LU
MT
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PL
PT
RO
SK
SI
ES
SE
UK
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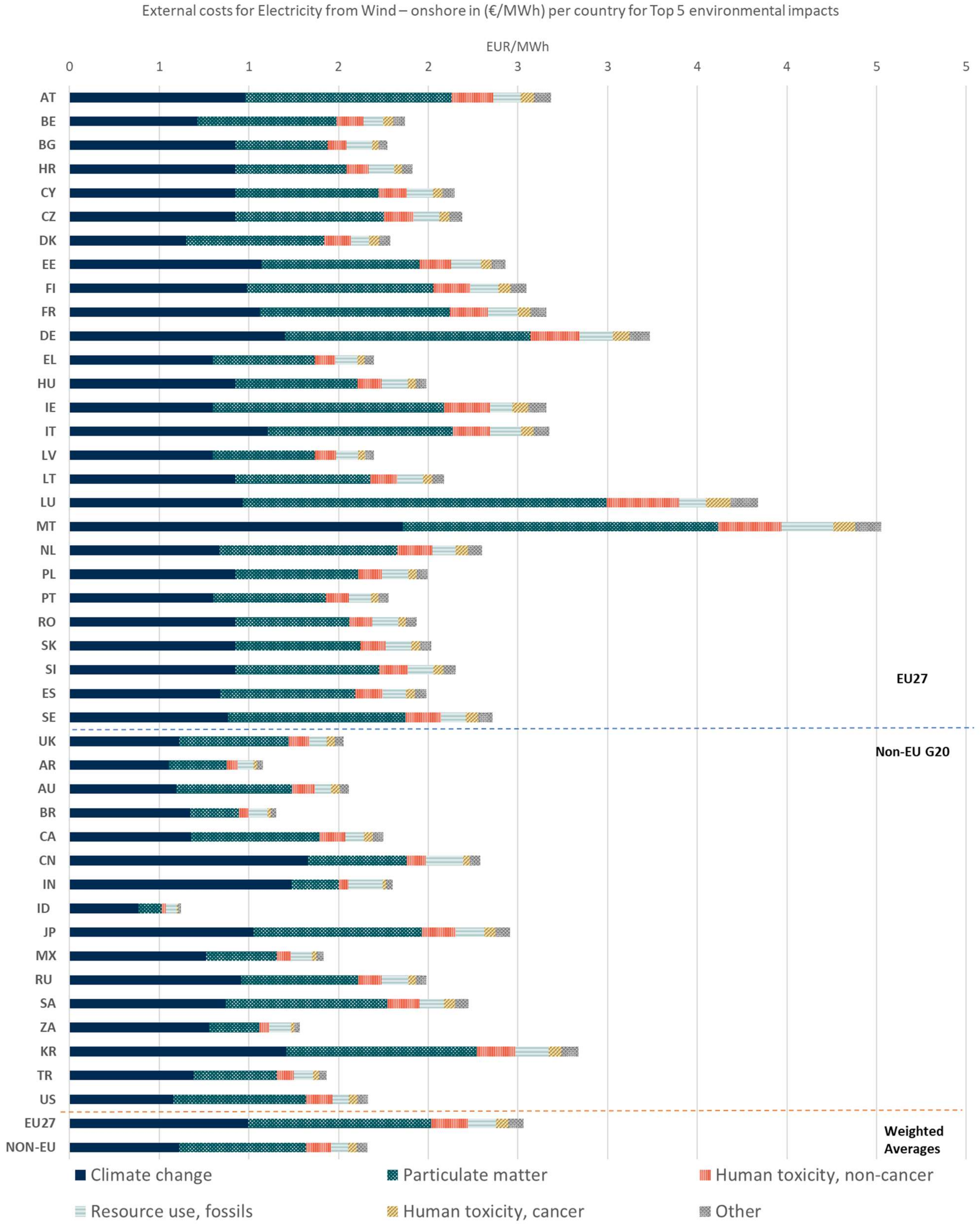
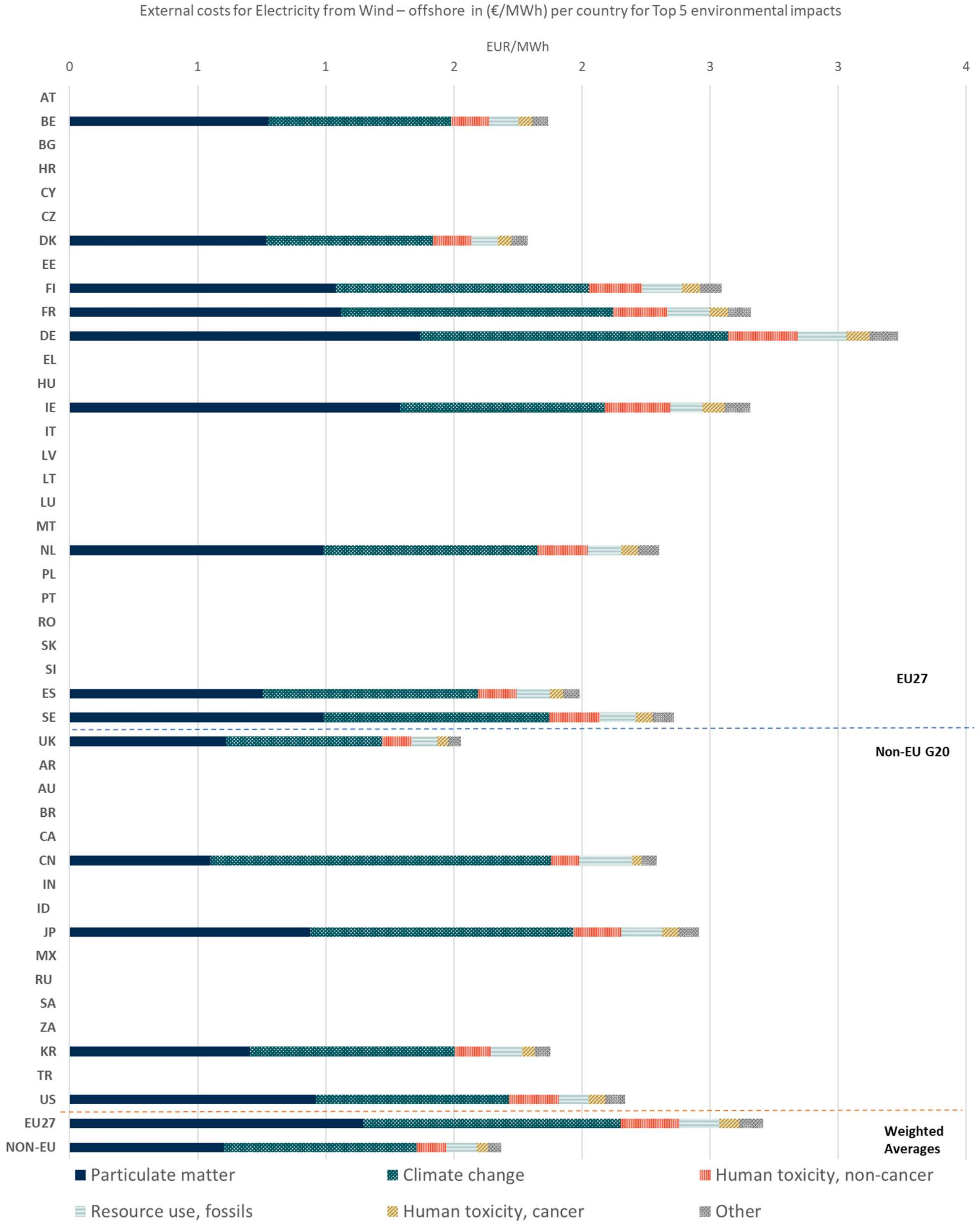
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
EU27
NON-EU
EU27
Non-EU G20
Weighted Averages
Climate change
Particulate matter
Human toxicity, cancer
Resource use, fossils
Human toxicity, non-cancer
Other

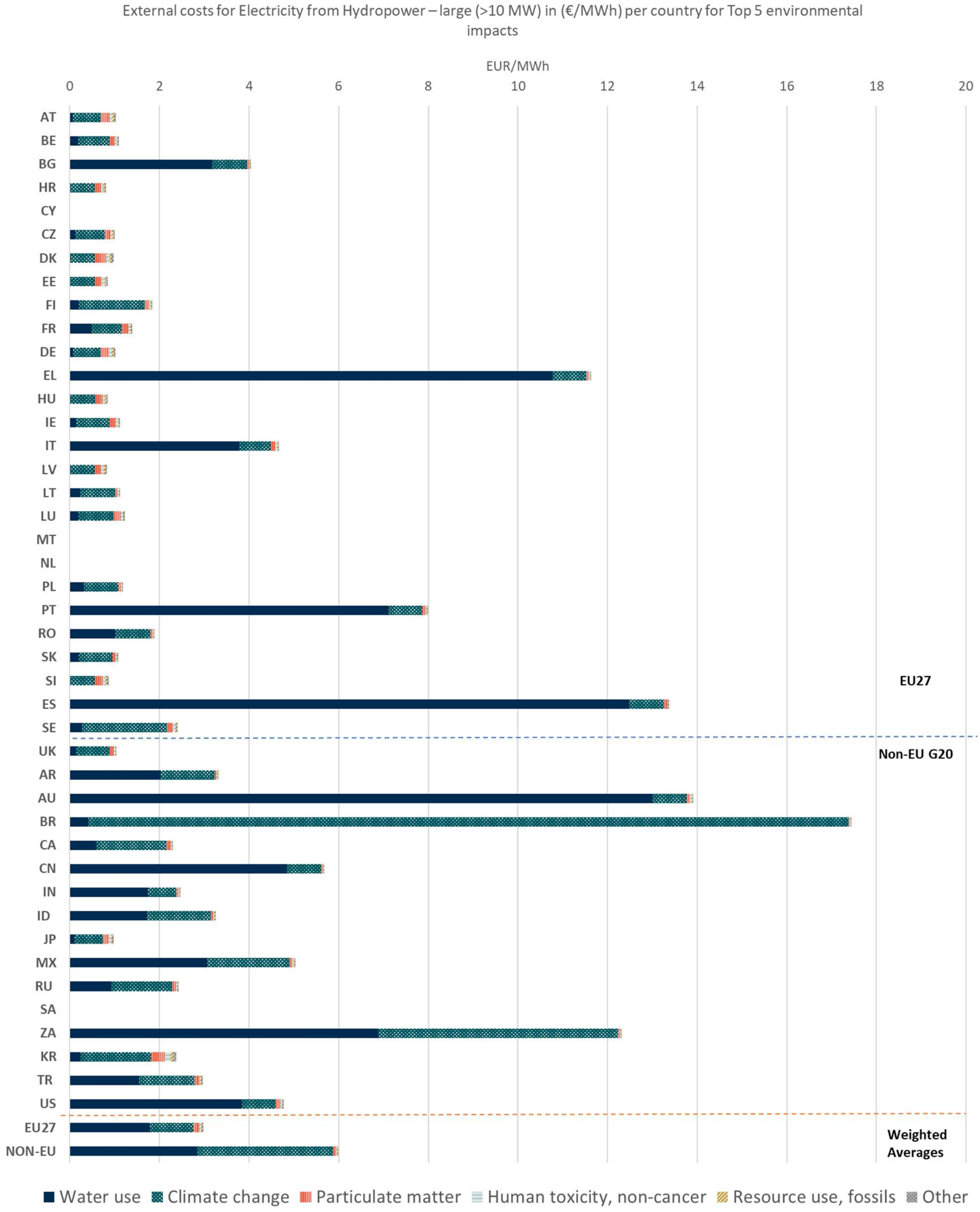
Wind - onshore



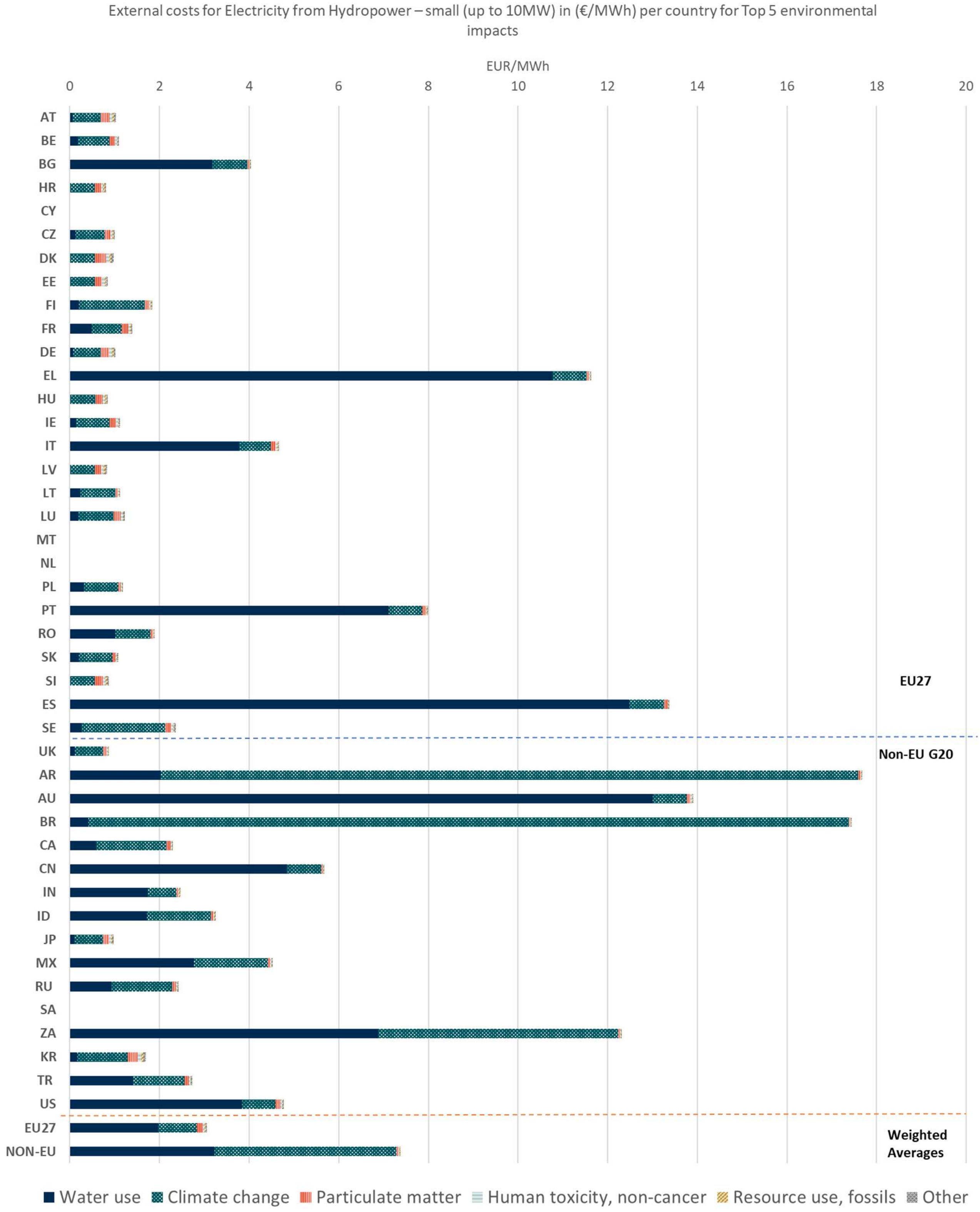
Wind - offshore



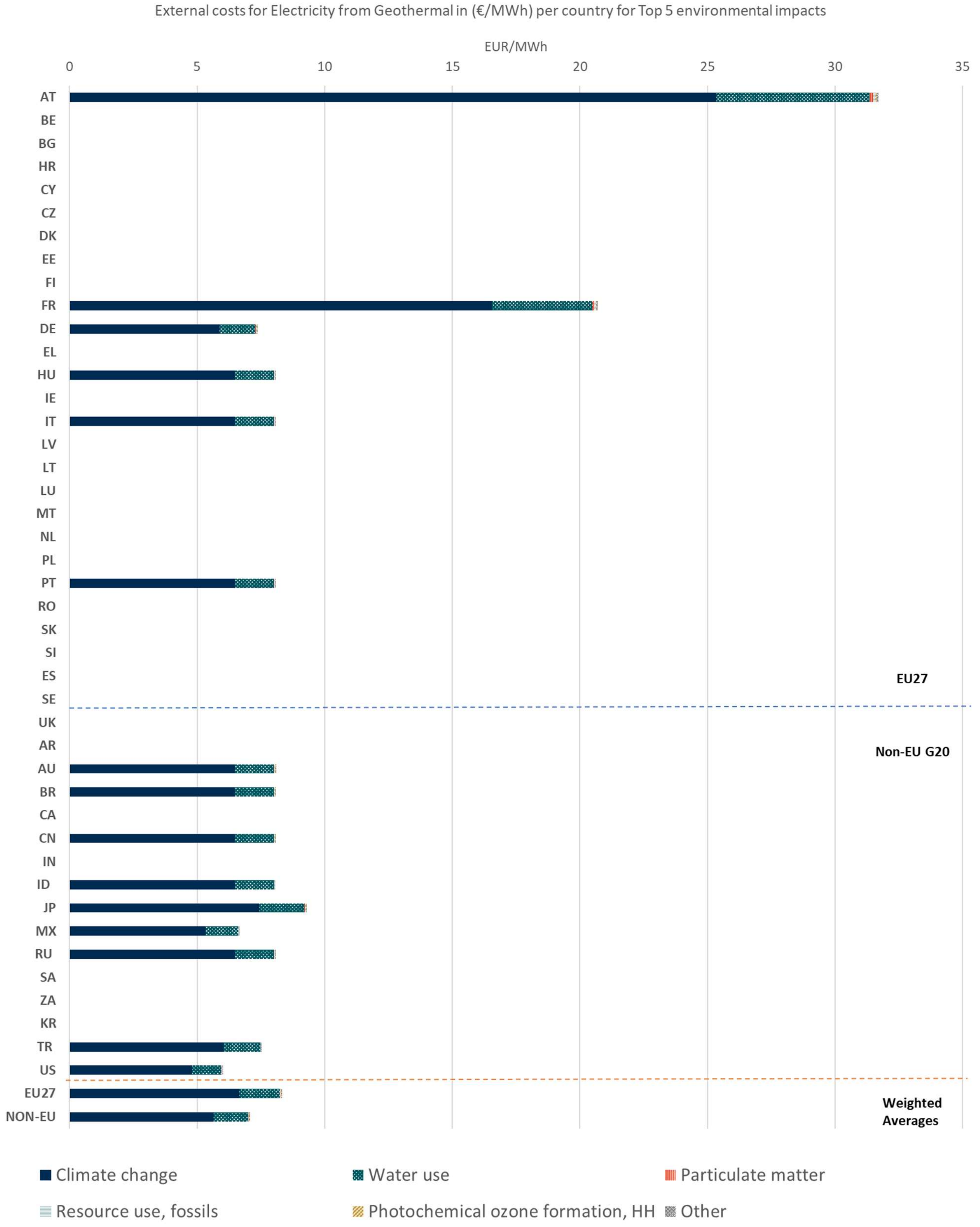
Hydropower - large (>10 MW)



Hydropower - small (up to 10MW)



Geothermal


External costs for Electricity from Geothermal in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
5
10
15
20
25
30
35
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
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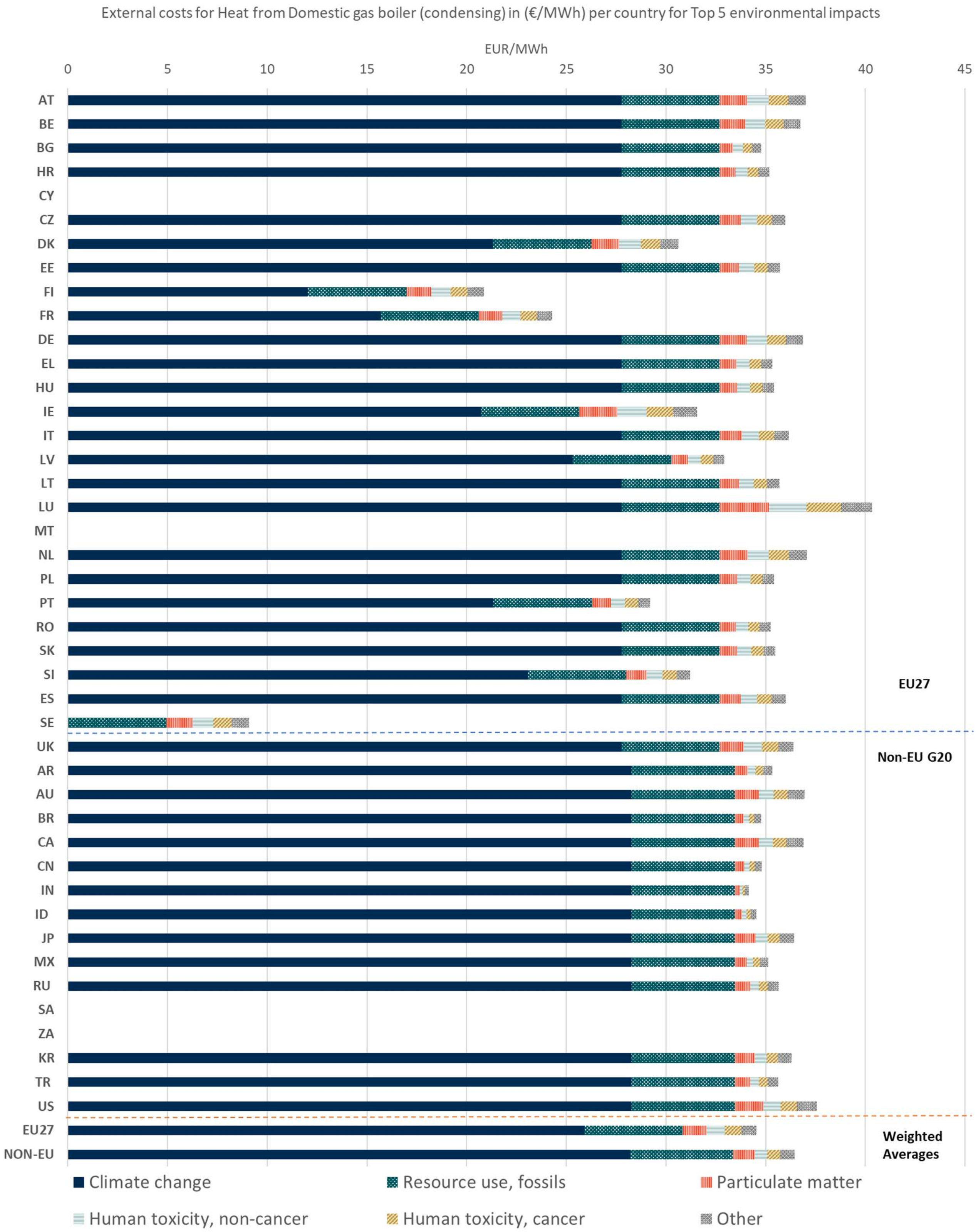
SE
EU27
UK
AR
Non-EU G20
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
EU27
NON-EU
Weighted Averages
Climate change
Water use
Particulate matter
Resource use, fossils
Photochemical ozone formation, HH
Other

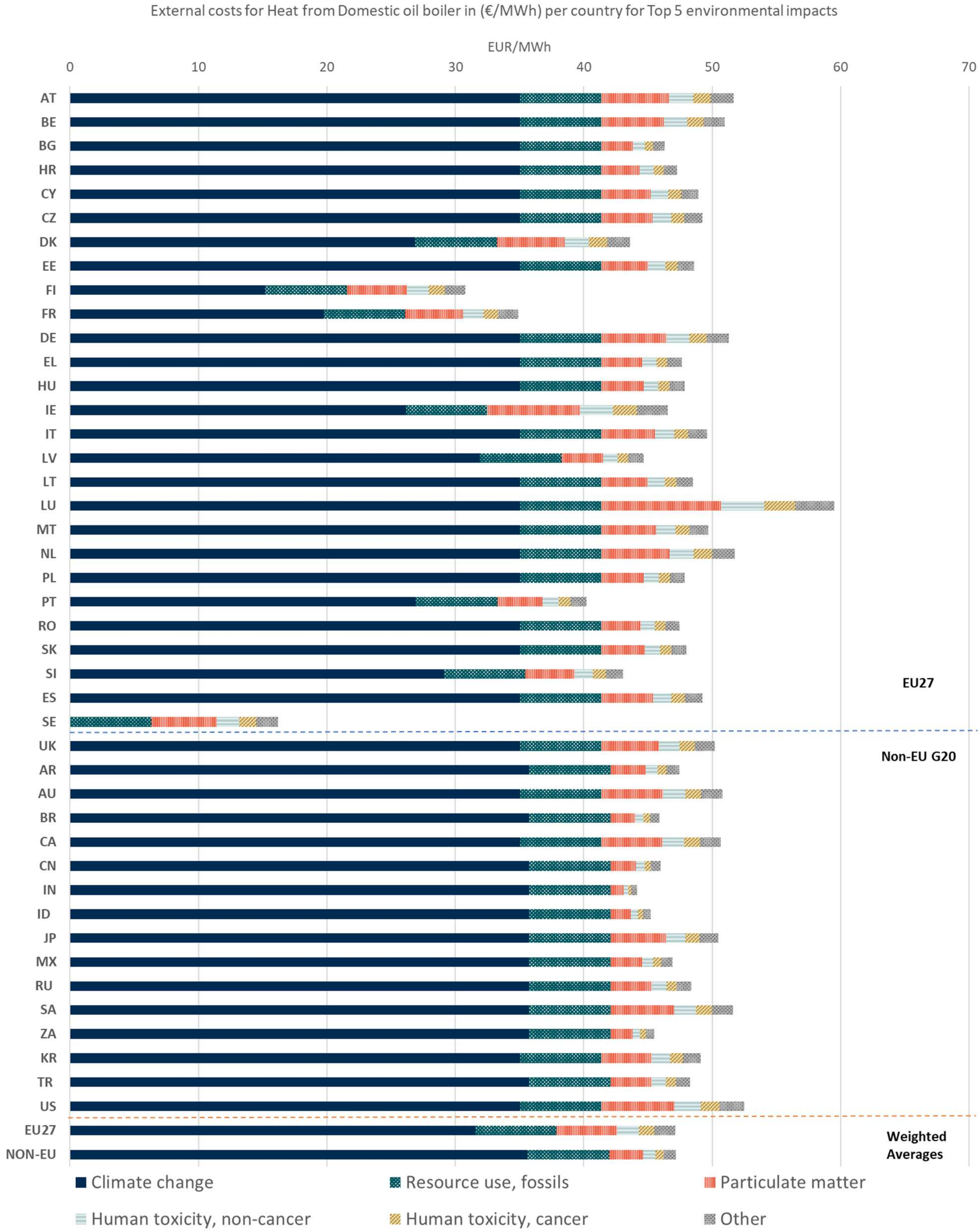
Heating

Domestic gas boiler (condensing)

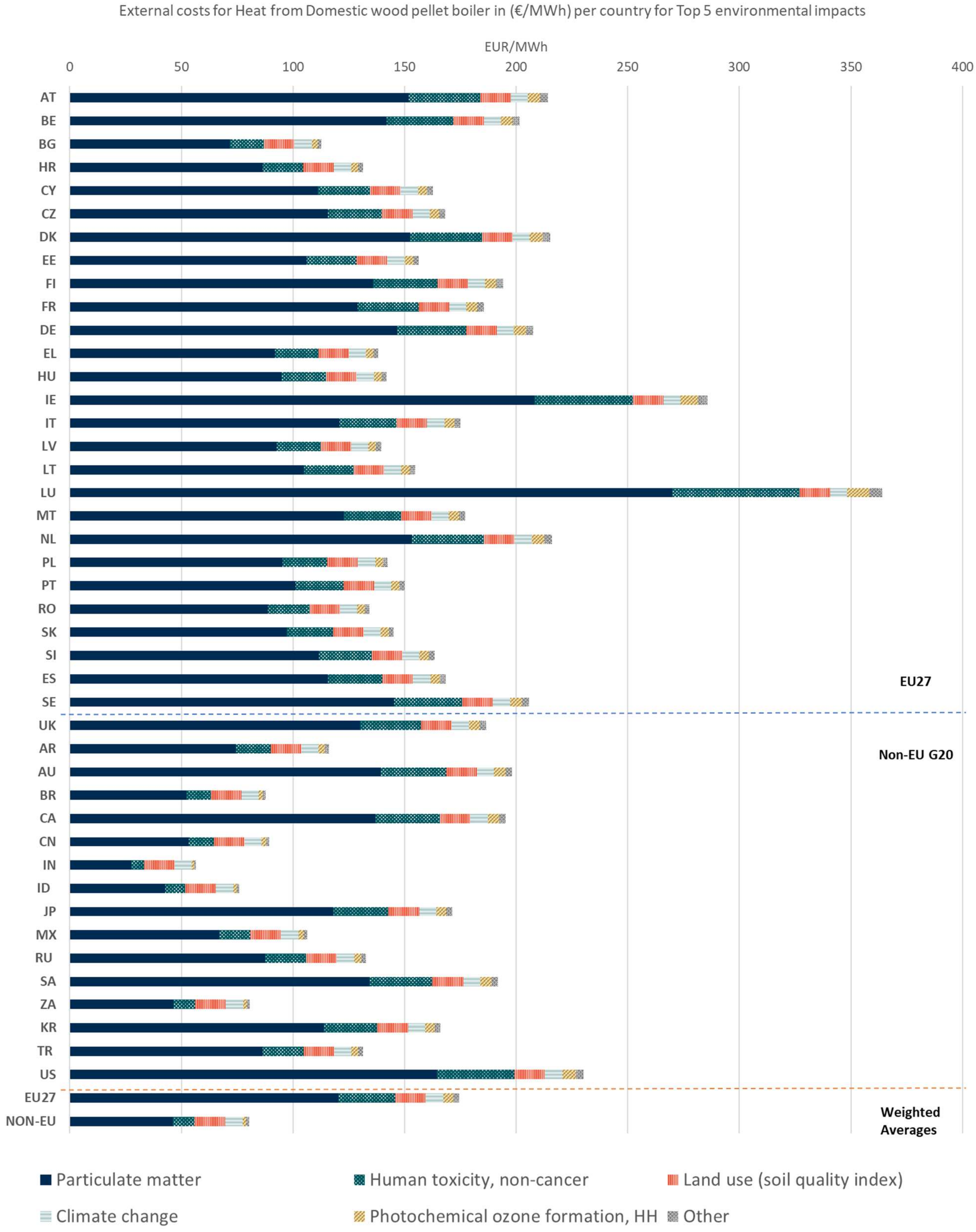
Note: In Sweden the Carbon tax has entirely removed the climate externality.



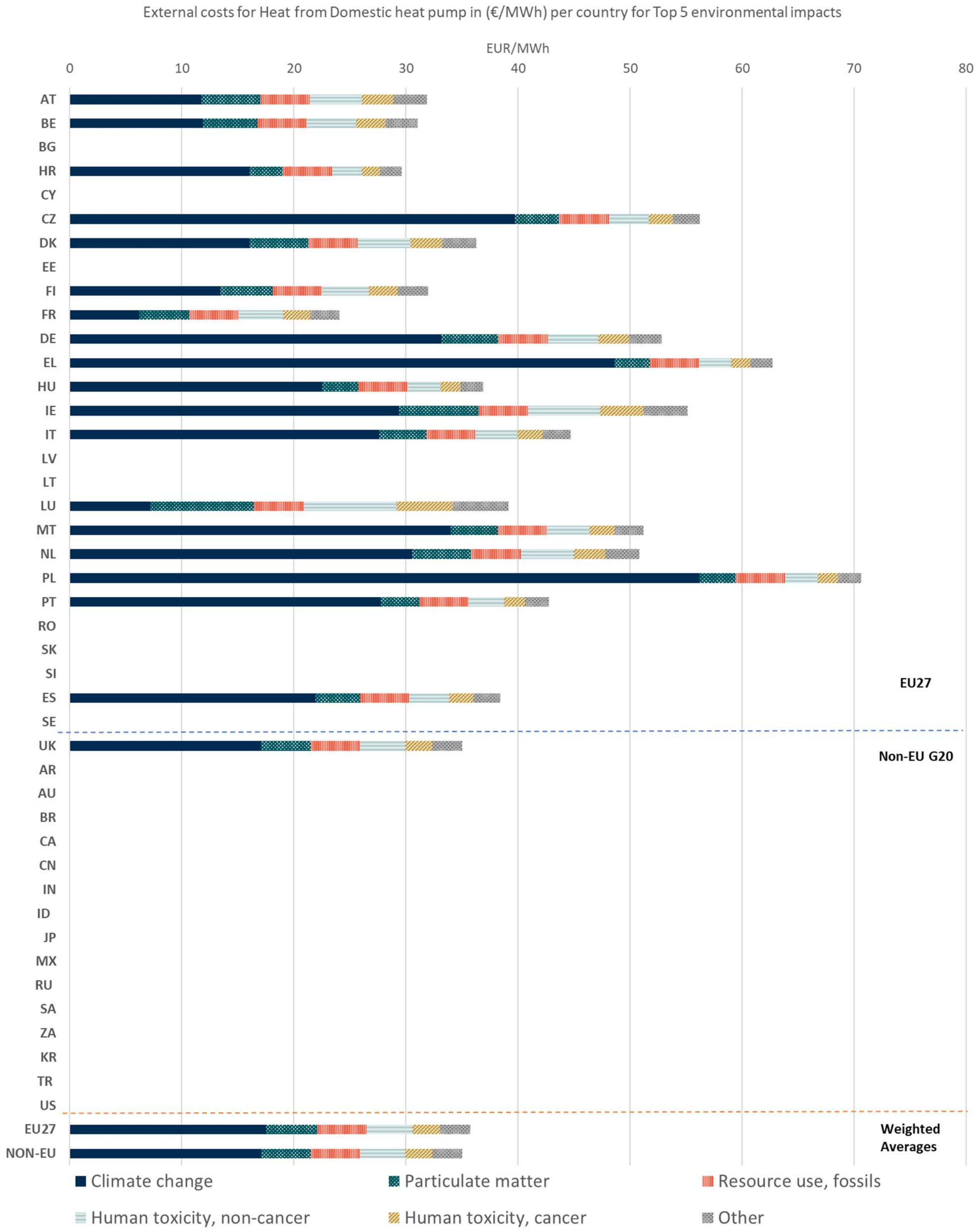
Domestic oil boiler



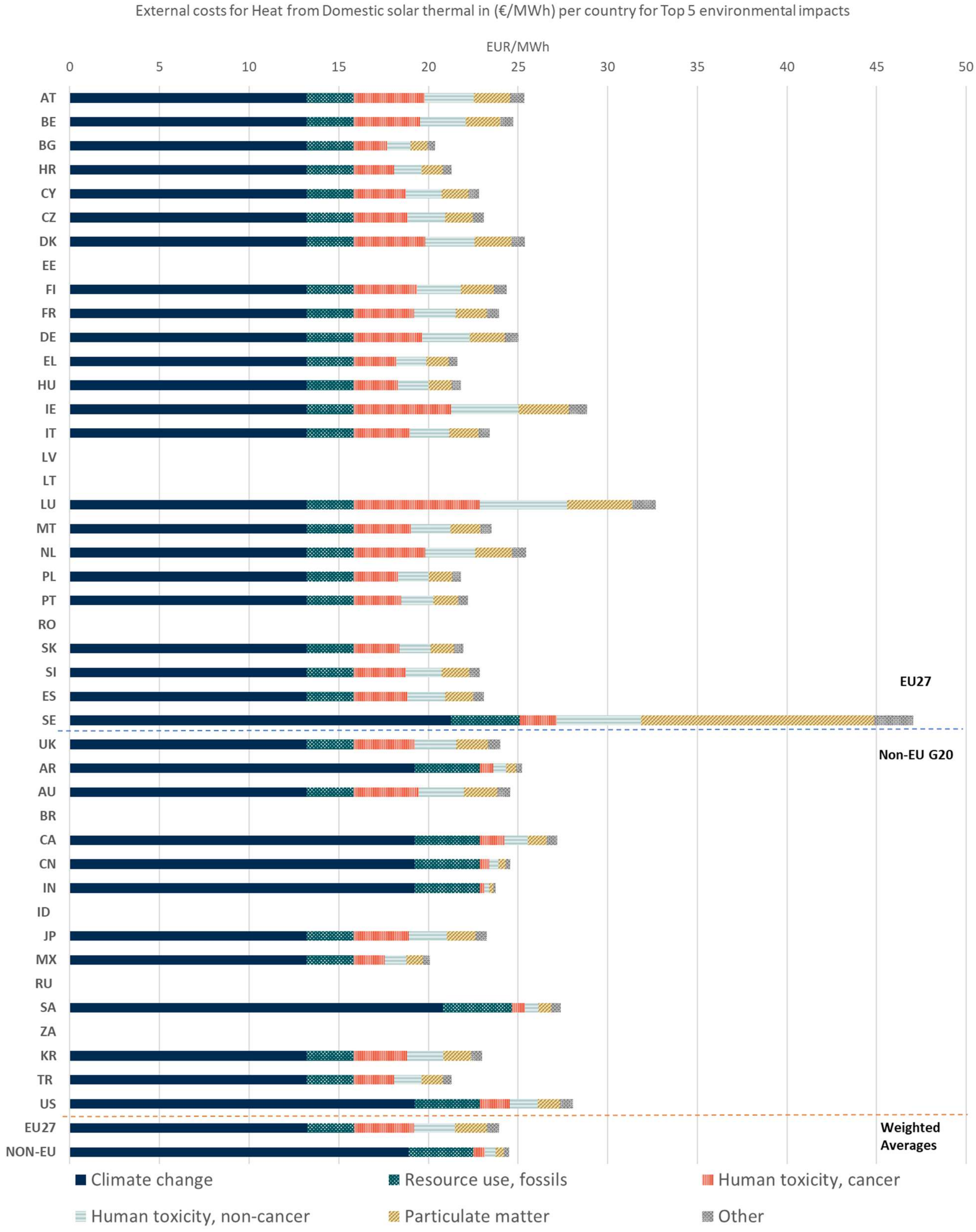
Domestic wood (logs, pellets, chips) boiler



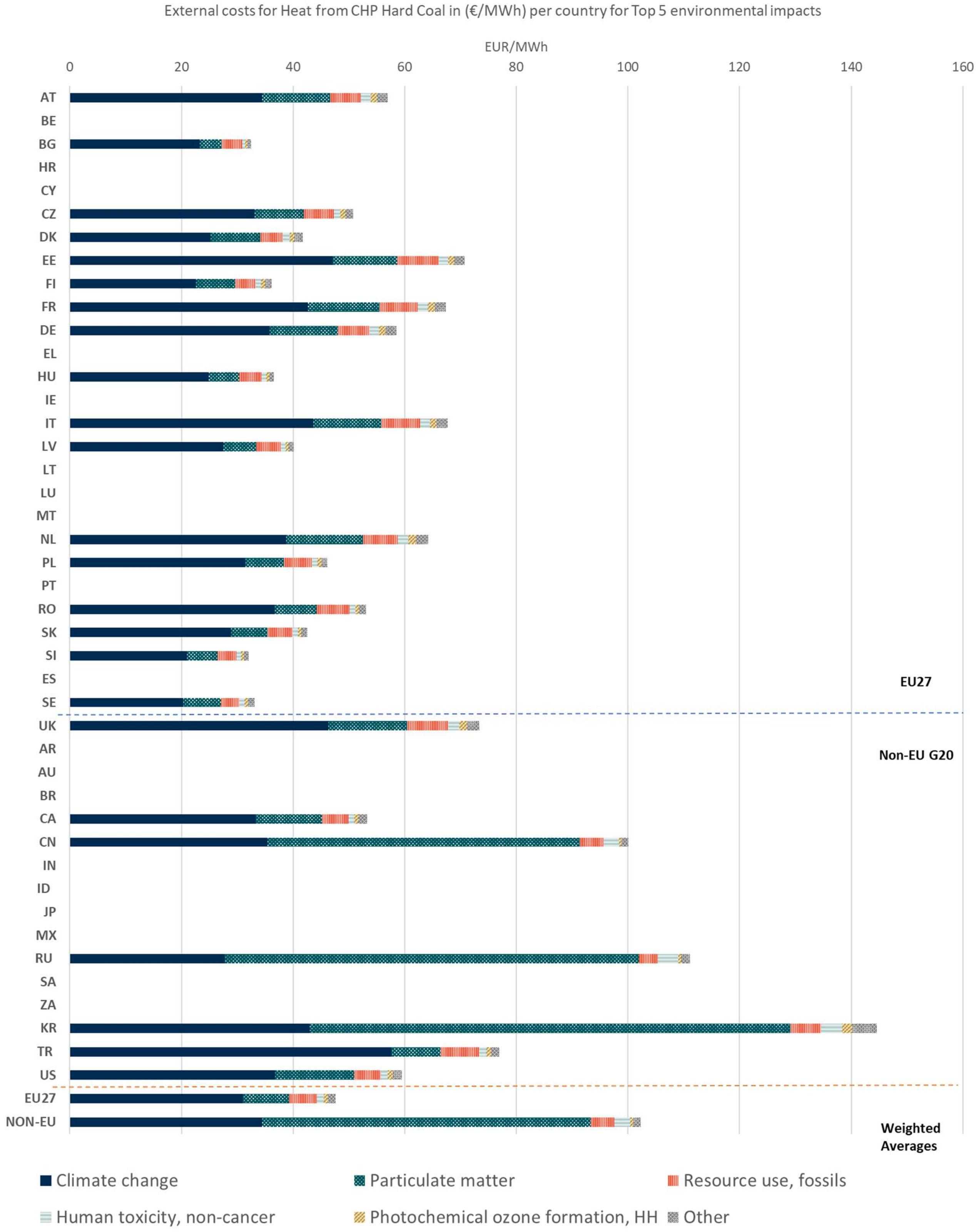
Domestic heat pump



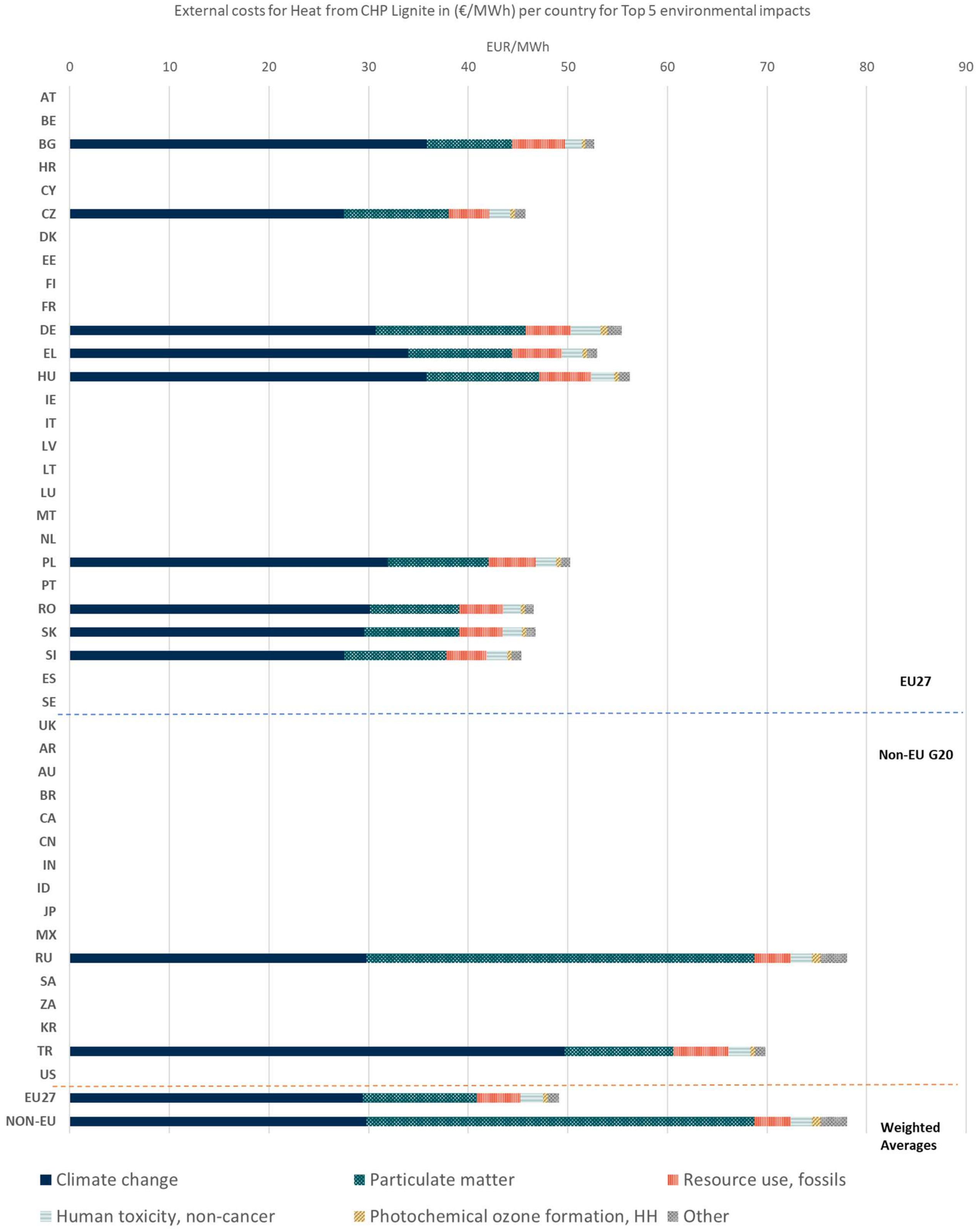
Domestic solar thermal



CHP Hard Coal



CHP Lignite


External costs for Heat from CHP Lignite in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
10
20
30
40
50
60
70
80
90
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
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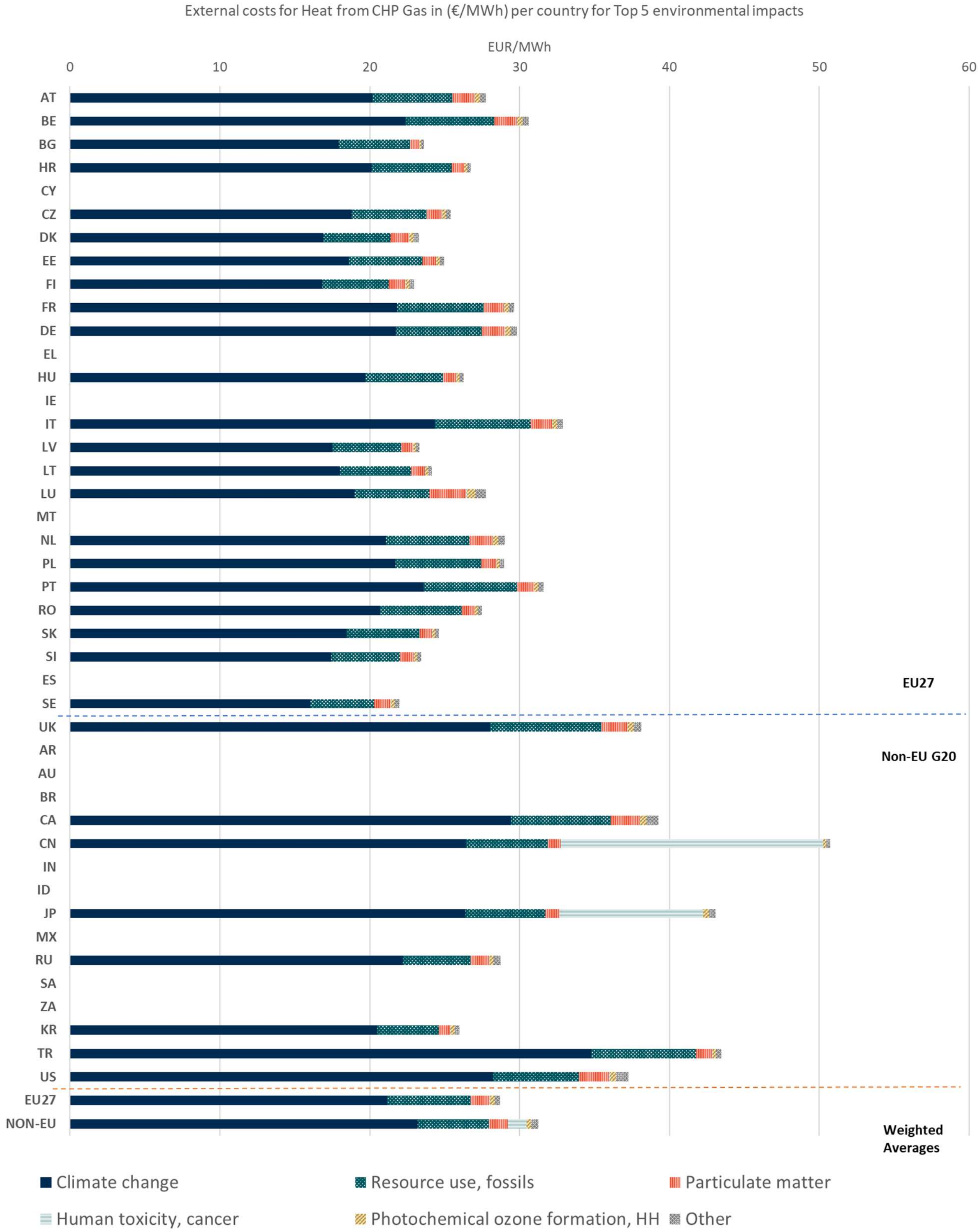
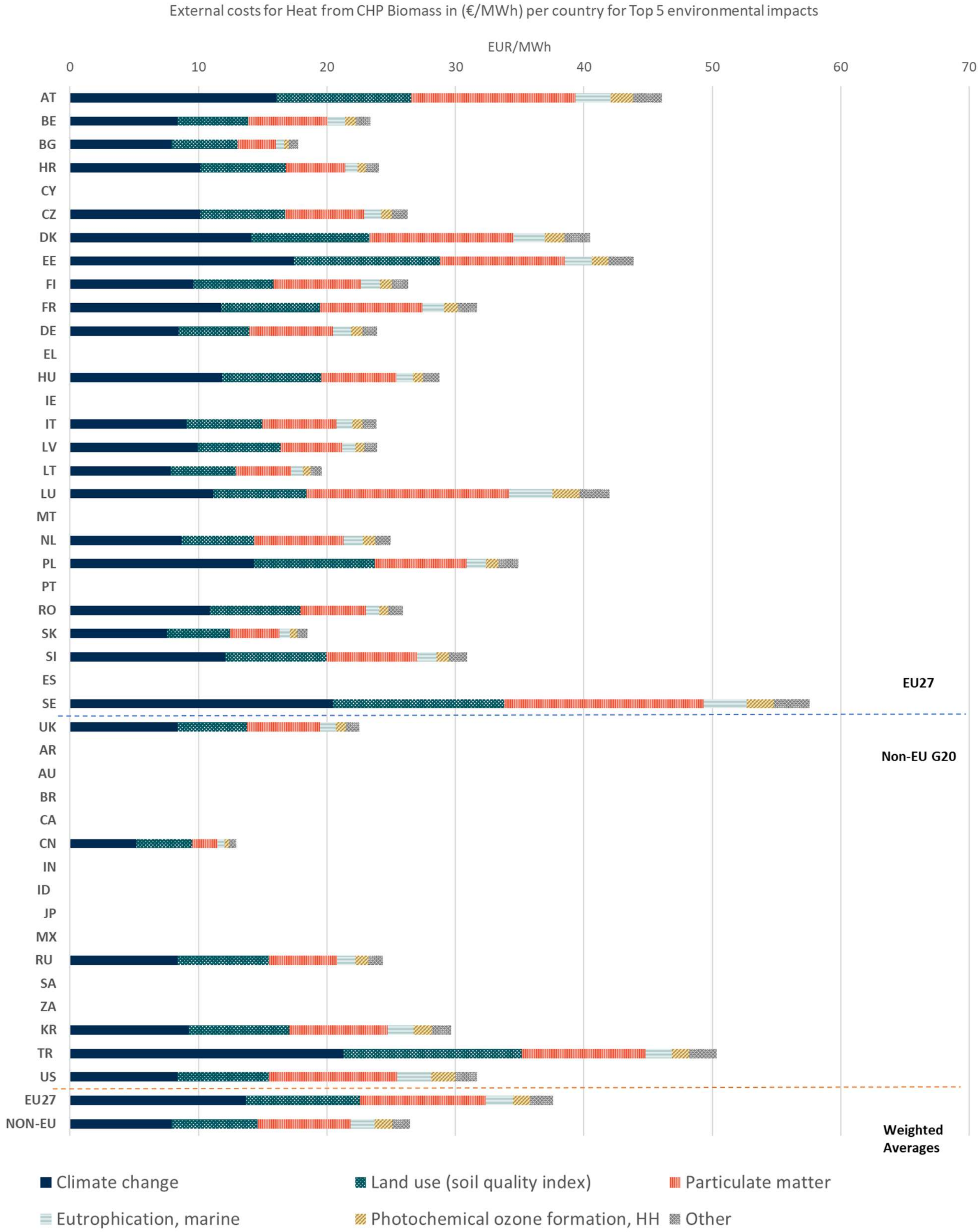
ZA
KR
TR
US
EU27
NON-EU
EU27
Non-EU G20
Weighted Averages
Climate change
Particulate matter
Resource use, fossils
Human toxicity, non-cancer
Photochemical ozone formation, HH
Other

CHP Gas


External costs for Heat from CHP Gas in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
10
20
30
40
50
60
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
PT
RO
SK
SI
ES
SE
EU27
UK
AR
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
Non-EU G20
EU27
NON-EU
Weighted Averages
Climate change
Resource use, fossils
Particulate matter
Human toxicity, cancer
Photochemical ozone formation, HH
Other

CHP Biomass


External costs for Heat from CHP Biomass in (€/MWh) per country for Top 5 environmental impacts
EUR/MWh
0
10
20
30
40
50
60
70
AT
BE
BG
HR
CY
CZ
DK
EE
FI
FR
DE
EL
HU
IE
IT
LV
LT
LU
MT
NL
PL
PT
RO
SK
SI
ES
SE
UK
AR
AU
BR
CA
CN
IN
ID
JP
MX
RU
SA
ZA
KR
TR
US
EU27
NON-EU
EU27
Non-EU G20
Weighted Averages
Climate change
Land use (soil quality index)
Particulate matter
Eutrophication, marine
Photochemical ozone formation, HH
Other

Annex D - External costs - datasets and country matching

Table D-1 Technology list with datasets used for calculating the environmental impacts for energy production technologies

		Name of the technology	Dataset used	Database*	Ecoinvent dataset used to extract electricity for scenario B	Comments
Electricity production technologies	1	Hard coal (including CHP)	Electricity from hard coal {Country} | AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| heat and power co-generation, hard coal | Cut-off, U	
	2	Lignite (including CHP)	Electricity from lignite {country} | AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, lignite | Cut-off, U	
	3	Natural Gas (CCGT, OCGT, CHP)	Electricity from natural gas {country} | AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	
	4	Oil	Electricity from heavy fuel oil (HFO) {country} | AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	1 kWh of Electricity, high voltage {average country}| electricity production, oil | Cut-off, U.	
	5	Nuclear	Electricity from nuclear {country} | AC, technology mix of BWR and PWR | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, nuclear, pressure water reactor | Cut-off, U	
	6	Biomass	Electricity from biomass (solid) {country} | AC, mix of direct and CHP, technology mix regarding firing and flue gas cleaning | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	
	7	Solar PV - rooftop & utility	Electricity from photovoltaic {FR} | AC, technology mix of CIS, CdTE, mono crystalline and multi crystalline | production mix, at plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, low voltage {average country}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off, U	
	8	Solar - CSP	Electricity, high voltage {country/region}| electricity production, solar tower power plant, 20 MW | Cut-off, U Electricity, high voltage {country/region}| electricity production, solar thermal parabolic trough, 50 MW | Cut-off, U	Ecoinvent dataset	Electricity, high voltage {average country}| electricity production, solar tower power plant, 20 MW | Cut-off, U	Two datasets can be used for this technology, each with a different capacity. In the tables with the proxies used it is indicated which of them was used for each producing country
	9	Wind - onshore	Electricity from wind power {country} | AC, technology mix of onshore and offshore | production mix, at plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, wind, 1-3MW turbine, onshore | Cut-off, U	

		Name of the technology	Dataset used	Database*	Ecoinvent dataset used to extract electricity for scenario B	Comments
	10	**Wind - offshore**	Electricity from wind power {country} | AC, technology mix of onshore and offshore | production mix, at plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, wind, 1-3MW turbine, offshore | Cut-off, U	In some instances the proxy was calculated as an average (AV) of the available datasets for this technology
	11	**Hydropower - large (>10 MW)**	Electricity from hydro power {Country} | AC, technology mix of run-off-river, storage and pump storage | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, hydro, reservoir, alpine region | Cut-off, U	In some instances the proxy was calculated as an average (AV) of the available datasets for this technology
	12	**Hydropower - small (up to 10MW)**	Electricity from hydro power {Country} | AC, technology mix of run-off-river, storage and pump storage | production mix, at power plant | 1kV - 60kV | LCI result	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, hydro, run-of-river | Cut-off, U	In some instances the proxy was calculated as an average (AV) of the available datasets for this technology
	13	**Geothermal**	Electricity from geothermal| AC, CHP, technology mix| production mix, at power plant| 1kV - 60kV {average of available countries} [LCI result]	EF 2.0 dataset	Electricity, high voltage {average country}| electricity production, deep geothermal | Cut-off, U	In some instances the proxy was calculated as an average (AV) of the available datasets for this technology
Heat production technologies	1	**Domestic gas boiler (condensing)**	Heat, central or small-scale, natural gas {Europe without Switzerland/RoW}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Cut-off, U	Ecoinvent	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Cut-off, U	Based on Ecoinvent. Only two datasets were identified as suitable to model this technology. The dataset for Europe without Switzerland was used for the European countries, and the dataset for the Rest of the World (RoW) was used for the other G20 countries.
	2	**Domestic oil boiler (non-condensing)**	Heat, central or small-scale, natural gas {Europe without Switzerland/RoW}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Cut-off, U	Ecoinvent	Heat, central or small-scale, natural gas {Europe without Switzerland/RoW}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Cut-off, U	Based on Ecoinvent. Only two datasets were identified as suitable to model this technology. The dataset for Europe without Switzerland was used for the European countries, and the dataset for the Rest of the World (RoW) was used for the other G20 countries.
	3	**Domestic wood boiler**	Heat, central or small-scale, other than natural gas {RoW/RER}| heat production, mixed logs, at wood heater 6kW | Cut-off, U	Ecoinvent	Heat, central or small-scale, other than natural gas {RoW/RER}| heat production, mixed logs, at wood heater 6kW | Cut-off, U	Based on Ecoinvent. Region of Europe (RER) dataset is based on CH and customized for RER; only 2 datasets available
	4	**Domestic heat pump**	Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | Cut-off, U	Ecoinvent	1 MJ Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	Based on Ecoinvent. Only one alternative was found suitable to model this technology, hence Europe without Switzerland dataset was used as a proxy for all countries.
	5	**Domestic solar thermal**	Heat, solar+gas, one-family house, for hot water {OP1 (CH)}| heat production, at hot water tank, solar+gas, flat plate, one-family house | Cut-off, U Heat, solar+wood, one-family house, for combined system {OP2 (CH)}| heat production, at solar+wood heating, flat plate, one-family house, combined system | Cut-off, U Heat, solar+gas, one-family house, for combined system {OP3 (CH)}| heat production, at solar+gas heating, tube collector, one-family house, combined system | Cut-off, U	Ecoinvent	Heat, solar+gas, one-family house, for combined system {CH}| heat production, at solar+gas heating, flat plate, one-family house, combined system | Cut-off, U	Based on Ecoinvent. Datasets only for CH are available, with a few combinations that inlcuded solar+glass, solar+electric or solar+wood, one-family house or multiple-dwelling, with flat plate or tube collector. The selected dataset was considered the most representative.

		Name of the technology	Dataset used	Database*	Ecoinvent dataset used to extract electricity for scenario B	Comments
			Heat, solar+gas, multiple-dwelling, for hot water {OP4 (CH)}| heat production, at hot water tank, solar+gas, flat plate, multiple dwelling | Cut-off, U			
	6	CHP Coal (CHP)	Thermal energy from hard coal {country or region} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result	EF 2.0 dataset	Heat, district or industrial, other than natural gas {average country}| heat and power co-generation, hard coal | Cut-off, U	For the European countries EU-28+3 was used as proxy, as the best available option. Country specific datasets were used for some G20 countries.
	7	CHP Lignite (CHP)	Thermal energy from lignite {country or region} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result	EF 2.0 dataset	Heat, district or industrial, other than natural gas {average country}| heat and power co-generation, hard coal | Cut-off, U	For the European countries EU-28+3 was used as proxy, as the best available option. Country specific datasets were used for some G20 countries.
	8	CHP Gas	Thermal energy from natural gas {country or region} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result	EF 2.0 dataset	Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U	For the European countries EU-28+3 was used as proxy, as the best available option. In some instances the RoW dataset was used, and also country specific datasets for some G20 countries.
	9	CHP Biomass	Thermal energy from biogas {country} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result	EF 2.0 dataset	Heat, district or industrial, other than natural gas {average country}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	

Table D-2 Technology list with datasets used for calculating the environmental impacts of consumption sectors

		Name of the technology	Dataset used	Database*	Comments
Industrial energy use	1	Industry - Coal	1 MWh Heat, district or industrial, other than natural gas {RoW}| heat production, at coal coke industrial furnace 1-10MW | Cut-off, S (of project Ecoinvent 3 - allocation, cut-off by classification - system)	Ecoinvent dataset	Only a single dataset was available, applied to all countries
	2	Industry - Oil products	Thermal energy from LPG {country} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency | LCI result	EF 2.0 dataset	Whilst LPG is an oil product fuel by definition it is amongst the 'cleaner' oil products. This dataset likely underestimates the impact of the average oil product fuel use.
	3	Industry - Natural Gas	Thermal energy from natural gas {country} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | LCI result	EF 2.0 dataset	
	4	Industry - Biomass / waste	Process steam from biomass (solid) 90% {EU-27} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MWh, 90% efficiency | LCI result	EF 2.0 dataset	Only a single dataset was available, applied to all countries. Dataset does not include waste.
	5	Industry - Electricity	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
	6	Industry - Heat	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
Agricultural energy	1	Agriculture - Oil Products	Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	Ecoinvent	Only a single dataset was available, applied to all countries
	2	Agriculture - Natural Gas	Thermal energy from natural gas {CN} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | LCI result	EF 2.0 dataset	Same dataset as used for industry.

		Name of the technology	Dataset used	Database*	Comments
	3	Agriculture - Biomass / waste	Process steam from biomass (solid) 90% {EU-27} | technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MWh, 90% efficiency | LCI result	EF 2.0 dataset	Same dataset as used for industry. Only a single dataset was available, applied to all countries. Dataset does not include waste.
	4	Agriculture - Electricity	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
Residential energy use	1	Residential - Coal	Heat, central or small-scale, other than natural gas {country}| heat production, hard coal briquette, stove 5-15kW | Cut-off, U	Ecoinvent dataset	
	2	Residential - Oil Products	Used H(2) dataset from production analysis		
	3	Residential - Natural Gas	Used H(1) dataset from production analysis		
	4	Residential - Biofuels/Waste	Used H(3) from production analysis		
	5	Residential - Geothermal, solar, etc;	Used El (7) from production analysis		
	6	Residential - Electricity	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
	7	Residential - Heat	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
Commercial and public sector energy use	1	Commercial and public sector - Coal	Heat, central or small-scale, other than natural gas {country}| heat production, hard coal briquette, stove 5-15kW | Cut-off, U	Ecoinvent dataset	Used same dataset as residential
	2	Commercial and public sector - Oil Products	Used H(2) dataset from production analysis		
	3	Commercial and public sector - Natural Gas	Used H(1) dataset from production analysis		
	4	Commercial and public sector - Biofuels/Waste	Used H(3) from production analysis		
	5	Commercial and public sector - Geothermal, solar, etc;	Used El (7) from production analysis		
	6	Commercial and public sector - Electricity	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	
	7	Commercial and public sector - Heat	Country level system results from the main energy production analysis were used to calculate these impacts.	N/A	

Table D-3 List with available datasets for the electricity production technologies (specific, proxies or not applicable)

Specific datasets available for the specified country for the respective technology
The dataset for the indicated country was selected as proxy for the respective technology
#N/A = Not applicable - no production data are available for the respective country, therefore no datasets were selected

TOW/STP - RoW - 20/50 MW = solar tower/solar parabolic power plant - Country/Region - voltage
EwS = Europe without Switzerland (this is how datasets are available in Ecoinvent) AV = Average of all other existing datasets specified for other countries EU w/o CH = Europe without Switzerland
RoW = Rest of the World; RER = Region of Europe; RSA = Region of Asia; RAF = Region of Africa

Country	Country code	Hard Coal (including CHP)	Lignite (including CHP)	Natural Gas (CCGT, OCGT, CHP)	Oil	Nuclear	Biomass	Solar PV - rooftop & utility	Solar - CSP	Wind - onshore	Wind - offshore	Hydropower - large (>10 MW)	Hydropower - small (up to 10MW)	Geothermal
Austria	AT	AT	#N/A	AT	AT	#N/A	AT	FR	#N/A	AT	#N/A	AT	AT	AV
Belgium	BE	BE	#N/A	BE	BE	BE	BE	FR	#N/A	BE	BE	BE	BE	#N/A
Bulgaria	BG	BG	BG	BG	BG	BG	BG	FR	#N/A	BG	#N/A	BG	BG	#N/A
Croatia	HR	HR	HR	HR	HR	#N/A	HR	FR	#N/A	HR	#N/A	HR	HR	#N/A
Cyprus	CY	#N/A	#N/A	#N/A	CY	#N/A	#N/A	FR	#N/A	CY	#N/A	#N/A	#N/A	#N/A
Czech Republic	CZ	CZ	CZ	CZ	CZ	CZ	CZ	FR	#N/A	CZ	#N/A	CZ	CZ	#N/A
Denmark	DK	DK	#N/A	DK	DK	#N/A	DK	FR	#N/A	DK	DK	#N/A	DK	#N/A
Estonia	EE	LV	EE	EE	EE	#N/A	EE	NA	#N/A	EE	#N/A	#N/A	EE	#N/A
Finland	FI	FI	FI	FI	FI	FI	FI	FR	#N/A	FI	FI	FI	FI	#N/A
France	FR	FR	#N/A	FR	FR	FR	FR	FR	#N/A	FR	FR	FR	FR	AV
Germany	DE	DE	DE	DE	DE	DE	DE	FR	#N/A	DE	DE	DE	DE	AV
Greece	GR	#N/A	GR	GR	GR	#N/A	IT	FR	#N/A	GR	#N/A	GR	GR	#N/A
Hungary	HU	HU	HU	HU	HU	HU	HU	FR	#N/A	HU	#N/A	HU	HU	AV
Ireland	IE	IE	DE	IE	IE	#N/A	IE	FR	#N/A	IE	IE	IE	IE	#N/A
Italy	IT	IT	#N/A	IT	IT	#N/A	IT	FR	STP - ES - 50 MW	IT	#N/A	IT	IT	IT
Latvia	LV	LV	#N/A	LV	LV	#N/A	LV	FR	#N/A	LV	#N/A	LV	LV	#N/A
Lithuania	LT	#N/A	#N/A	LT	LT	#N/A	LT	FR	#N/A	LT	#N/A	LT	LT	#N/A
Luxembourg	LU	#N/A	#N/A	LU	LU	#N/A	BE	FR	#N/A	LU	#N/A	LU	LU	#N/A
Malta	MT	#N/A	#N/A	IT	MT	#N/A	#N/A	FR	#N/A	EU-28+3	#N/A	#N/A	#N/A	#N/A
Netherlands	NL	NL	#N/A	NL	NL	NL	NL	FR	#N/A	NL	NL	NL	#N/A	#N/A
Poland	PL	PL	PL	PL	PL	#N/A	PL	FR	#N/A	PL	#N/A	PL	PL	#N/A
Portugal	PT	PT	#N/A	PT	PT	#N/A	PT	FR	#N/A	PT	#N/A	PT	PT	PT
Romania	RO	RO	RO	RO	RO	RO	RO	FR	#N/A	RO	#N/A	RO	RO	#N/A
Slovakia	SK	SK	SK	SK	SK	SK	SK	FR	#N/A	SK	#N/A	SK	SK	#N/A
Slovenia	SI	SI	SI	SI	SI	SI	SI	FR	#N/A	SI	#N/A	SI	SI	#N/A

Country	Country code	Hard Coal (including CHP)	Lignite (including CHP)	Natural Gas (CCGT, OCGT, CHP)	Oil	Nuclear	Biomass	Solar PV - rooftop & utility	Solar - CSP	Wind - onshore	Wind - offshore	Hydropower - large (>10 MW)	Hydropower - small (up to 10MW)	Geothermal
Spain	ES	ES	#N/A	ES	ES	ES	ES	FR	STP - ES - 50 MW	ES	ES	ES	ES	#N/A
Sweden	SE	SE	FI	SE	SE	SE	SE	FR	#N/A	SE	SE	SE	FI	#N/A
United Kingdom	UK	GB	#N/A	GB	GB	GB	GB	FR	#N/A	GB	GB	GB	IE	#N/A
Argentina	AR	BR	#N/A	BR	BR	BR	BR	FR	#N/A	BR	#N/A	RNA	RNA	#N/A
Australia	AU	AU	AU	AU	AU	#N/A	AU	FR	TOW - AU - 20 MW	AU	#N/A	AU	AU	AV
Brazil	BR	BR	BR	BR	BR	BR	BR	FR	#N/A	BR	#N/A	BR	BR	AV
Canada	CA	CA	CA	CA	CA	CA	CA	FR	#N/A	CA	#N/A	CA	CA	#N/A
China	CN	CN	#N/A	CN	CN	CN	CN	FR	TOW - RoW - 20 MW	CN	CN	CN	CN	AV
India	IN	IN	IN	IN	IN	IN	IN	FR	STP - RoW - 20 MW	IN	#N/A	IN	IN	#N/A
Indonesia	ID	RAS w/o CN	#N/A	RAS w/o CN	RAS w/o CN	#N/A	RAS w/o CN	FR	#N/A	IN	#N/A	RAS w/o CN	RAS w/o CN	AV
Japan	JP	JP	#N/A	JP	JP	JP	JP	FR	#N/A	JP	JP	JP	JP	AV
Mexico	MX	RNA	#N/A	RNA	RNA	RNA	RNA	FR	#N/A	RNA	#N/A	RNA	RNA	AV
Russia	RU	RU	RU	RU	RU	RU	RU	FR	#N/A	RU	#N/A	RU	RU	AV
Saudi Arabia	SA	#N/A	#N/A	RAS w/o CN	RAS w/o CN	#N/A	SA	FR	STP - RoW - 20 MW	IN	#N/A	#N/A	#N/A	#N/A
South Africa	ZA	ZA	#N/A	ZA	RAF	RAF	RAF	FR	PTR - ZA - 50 MW	EU-28+3	#N/A	RAF	RAF	#N/A
South Korea	KR	JP	#N/A	JP	JP	JP	JP	FR	#N/A	JP	JP	JP	JP	#N/A
Turkey	TR	TR	EU-28+3	EU-28+3	EU-28+3	#N/A	EU-28+3	FR	#N/A	EU-28+3	#N/A	EU-28+3	EU-28+3	AV
United States	US	US	RNA	RNA	RNA	RNA	RNA	FR	STP - US - 50 MW	CA	RNA	US	US	AV

Table D-4: List with available datasets for the heat production technologies (specific, proxies or not applicable)

Legend

Specific datasets available for the specified country for the respective technology	EU-28+3 – European Region + Norway, Switzerland, Iceland EU w/o CH = Europe without Switzerland EwS = Europe without Switzerland (this is how datasets are available in Ecoinvent)
The dataset for the indicated country was selected as proxy for the respective technology	AV = Average of all other existing datasets specified for other countries
#N/A = Not applicable – no production data are available for the respective country, therefore no datasets were selected	OP1: Heat, solar+gas, one-family house, flat plate collector OP2: Heat, solar+wood, one-family house, flat plate collector OP3: Heat, solar+gas, one-family house, tube collector OP4: Heat, solar+gas, multiple-dwelling, flat plate collector

Country	Country code	Domestic gas boiler (condensing)	Domestic gas boiler (non-condensing)	Domestic wood boiler	Domestic heat pump	Domestic solar thermal	CHP Hard Coal	CHP Lignite	CHP Gas	CHP Biomass
Austria	AT	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Belgium	BE	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	EU-28+3	EU-28+3
Bulgaria	BG	EwS	EwS	_RER	#N/A	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Croatia	HR	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	EU-28+3	EU-28+3
Cyprus	CY	#N/A	EwS	_RER	#N/A	OP1	#N/A	#N/A	#N/A	#N/A
Czech Republic	CZ	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Denmark	DK	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Estonia	EE	EwS	EwS	_RER	#N/A	#N/A	EU-28+3	#N/A	EU-28+3	EU-28+3
Finland	FI	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
France	FR	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Germany	DE	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Greece	GR	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	EU-28+3	#N/A	#N/A
Hungary	HU	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Ireland	IE	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	#N/A	#N/A
Italy	IT	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Latvia	LV	EwS	EwS	_RER	#N/A	#N/A	EU-28+3	#N/A	EU-28+3	EU-28+3
Lithuania	LT	EwS	EwS	_RER	#N/A	#N/A	#N/A	#N/A	EU-28+3	EU-28+3
Luxembourg	LU	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	EU-28+3	EU-28+3
Malta	MT	#N/A	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	#N/A	#N/A
Netherlands	NL	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Poland	PL	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Portugal	PT	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	EU-28+3	#N/A
Romania	RO	EwS	EwS	_RER	#N/A	#N/A	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Slovakia	SK	EwS	EwS	_RER	#N/A	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Slovenia	SI	EwS	EwS	_RER	#N/A	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
Spain	ES	EwS	EwS	_RER	EU w/o CH	OP1	#N/A	#N/A	#N/A	#N/A
Sweden	SE	EwS	EwS	_RER	#N/A	OP2	EU-28+3	#N/A	EU-28+3	EU-28+3
United Kingdom	UK	EwS	EwS	_RER	EU w/o CH	OP1	EU-28+3	#N/A	EU-28+3	EU-28+3
Argentina	AR	RoW	RoW	_RER	#N/A	OP3	#N/A	#N/A	#N/A	#N/A
Australia	AU	RoW	EwS	_RER	#N/A	OP1	#N/A	#N/A	#N/A	#N/A
Brazil	BR	RoW	RoW	_RER	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Canada	CA	RoW	EwS	_RER	#N/A	OP3	RNA	#N/A	RNA	#N/A
China	CN	RoW	RoW	_RER	#N/A	OP3	RAS	#N/A	CN	RoW
India	IN	RoW	RoW	_RER	#N/A	OP3	#N/A	#N/A	#N/A	#N/A
Indonesia	ID	RoW	RoW	_RER	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Japan	JP	RoW	RoW	_RER	#N/A	OP1	#N/A	#N/A	JP	#N/A
Mexico	MX	RoW	RoW	_RER	#N/A	OP1	#N/A	#N/A	#N/A	#N/A
Russia	RU	RoW	RoW	_RER	#N/A	#N/A	RoW	RoW	RoW	RoW
Saudi Arabia	SA	#N/A	RoW	_RER	#N/A	OP4	#N/A	#N/A	#N/A	#N/A
South Africa	ZA	#N/A	RoW	_RER	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
South Korea	KR	RoW	EwS	_RER	#N/A	OP1	RSA	#N/A	JP	RoW
Turkey	TR	RoW	RoW	_RER	#N/A	OP1	EU-28+3	EU-28+3	EU-28+3	EU-28+3
United States	US	RoW	EwS	_RER	#N/A	OP3	RNA	#N/A	US	RNA

Method to produce scenarios to avoid double counting of electricity

The aggregation of the results was done per country and per technology. When the aggregation was done at country level it was necessary to exclude the electricity used for power production, otherwise it would be double counted. This step was problematic to apply though, as the currently available EF-compliant datasets are fully aggregated. At our specific request DG Environment did give us access to the package of disaggregated EF datasets. However this package was provided in the ILCD format that was not possible to import in SimaPro, the software used to do the modelling. Additional efforts to convert the database in a usable format was intended, however after in-depth discussions with the data providers (thinkstep), it became apparent that in fact the way the datasets were disaggregated was based on other considerations than what was of relevance for our project. Thus, for the energy technologies, the datasets were disaggregated to allow the adjustment of the amount of fuel used for the power production, but did not indicate the electricity used, which made it impossible for us to perform the extraction of this electricity, as we needed.

The alternative was to identify instead the amount of electricity used in the Ecoinvent 3.5 datasets that described the same technology, and determine the percentage it represented of the overall impact, for each impact category of the EF method. Only the European electricity flows were deducted to avoid double counting when looking at the European energy market. The percentage of electricity used was determined by calculating the network of the Ecoinvent dataset. This approach cannot cover all possible flows, as the level of disaggregation can go to thousands of connected flows, and it is extremely difficult to determine the precise amount of electricity. For this reason the identification of the European electricity used was done at a cut-off level between 0.1 – 1 %, depending on the complexity of the dataset.

This percentage was used to calculate the impacts per country when the electricity used was excluded (total impact - % representing the contribution of the electricity used for power generation). This approach was also discussed with JRC and determined as the best option available. This specific calculation will however generate some uncertainties in the final results. The Ecoinvent dataset used to extract the electricity was listed previously in this Annex.

Annex E - Impact results per technology

The following tables provide summaries of the EU27 impact results produced by the external costs calculation tool.

Table E-1 Summary EU average impact results per technology - electricity

Technology	Unit	Hard Coal (including CHP)	Lignite (including CHP)	Natural Gas (CCGT, OCGT, CHP)	Oil	Nuclear	Biomass	Solar PV - rooftop & utility	Solar - CSP	Wind - onshore	Wind - offshore	Hydropower - large (>10 MW)	Hydropower - small (up to 10MW)	Geothermal
Climate change	kg CO2 eq	1076.48	1210.65	521.82	915.01	6.74	47.36	49.13	76.18	9.71	9.80	9.47	8.43	64.98
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionising radiation, HH	kBq U235 eq	0.82	1.65	1.32	2.71	690.46	1.65	8.03	2.06	0.33	0.37	0.06	0.06	0.13
Photochemical ozone formation, HH	kg NMVOC eq	1.71	1.27	0.48	1.60	0.03	1.38	0.15	0.22	0.02	0.03	0.01	0.01	0.01
Particulate matter	Disease incidence	2.74E-05	3.54E-05	2.85E-06	2.71E-05	5.11E-07	1.23E-05	9.94E-06	2.73E-06	1.30E-06	1.46E-06	1.66E-07	1.63E-07	3.35E-08
Human toxicity, non-cancer	CTUh	1.76E-05	3.93E-05	4.01E-07	2.19E-05	7.57E-07	1.02E-04	1.25E-05	6.05E-06	1.25E-06	1.39E-06	2.75E-07	2.69E-07	3.37E-08
Human toxicity, cancer	CTUh	5.26E-07	6.05E-07	8.61E-08	5.39E-06	5.82E-08	5.36E-07	4.29E-07	2.04E-06	7.60E-08	8.59E-08	7.14E-09	6.99E-09	1.22E-09
Acidification	mol H+ eq	2.84	3.27	0.41	3.45	0.05	1.64	0.21	0.32	0.04	0.04	0.01	0.01	0.01
Eutrophication, freshwater	kg P eq	1.31E-04	5.72E-05	1.97E-05	1.75E-04	4.02E-05	1.19E-02	1.51E-04	1.65E-02	2.40E-05	2.71E-05	5.23E-06	5.10E-06	3.31E-07
Eutrophication, marine	kg N eq	0.60	0.43	0.13	0.49	0.02	0.63	0.04	0.10	0.01	0.01	0.00	0.00	0.00
Eutrophication, terrestrial	molc N eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity, freshwater	CTUe	18.35	28.07	3.98	167.02	19.72	62.01	31.67	68.20	2.47	2.78	0.22	0.22	0.05
Land use (soil quality index)	dimensionless (pt)	227.31	156.87	45.27	51.02	15.88	86742.52	466.04	1531.49	23.93	24.34	4.61	4.58	0.00
Water use	m3 water eq	32.28	31.41	23.72	74.42	0.00	112.08	11.83	20.96	2.25	2.29	358.50	394.95	316.91
Resource use, fossils	MJ	10487.22	10764.94	8181.03	11242.72	10098.02	425.20	736.78	847.65	121.67	123.10	18.71	18.66	17.84
Resource use, mineral and metals	kg Sb eq	2.94E-06	4.51E-06	2.00E-05	2.16E-05	3.90E-06	5.20E-05	3.98E-03	2.17E-04	4.62E-04	4.67E-04	1.51E-04	1.49E-04	3.45E-06

Table E-2 Summary EU average impact results per technology - heat

Technology	Unit	Domestic gas boiler (condensing)	Domestic oil boiler	Domestic wood pellet boiler	Domestic heat pump	Domestic solar thermal	CHP Hard Coal	CHP Lignite	CHP Gas	CHP Biomass
Climate change	kg CO2 eq	270.90	341.72	75.28	171.18	129.27	398.20	378.39	271.94	133.41
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionising radiation, HH	kBq U235 eq	6.18	29.01	1.17	97.18	15.58	0.31	0.56	2.90	0.86
Photochemical ozone formation, HH	kg NMVOC eq	0.30	0.49	3.76	0.46	0.18	0.67	0.43	0.25	1.11
Particulate matter	Disease incidence	1.52E-06	6.00E-06	1.54E-04	5.80E-06	2.27E-06	1.07E-05	1.46E-05	1.63E-06	1.25E-05
Human toxicity, non-cancer	CTUh	5.61E-06	1.03E-05	1.56E-04	2.50E-05	1.41E-05	7.22E-06	1.40E-05	3.37E-07	0.00E+00
Human toxicity, cancer	CTUh	9.22E-07	1.36E-06	1.52E-06	2.73E-06	3.67E-06	1.84E-07	2.00E-07	4.64E-08	4.73E-07
Acidification	mol H+ eq	0.36	1.08	0.56	1.44	0.34	1.15	1.21	0.21	1.80
Eutrophication, freshwater	kg P eq	1.50E-02	2.08E-02	3.66E-03	1.96E-01	3.40E-02	3.99E-05	1.88E-05	1.92E-05	2.78E-02
Eutrophication, marine	kg N eq	0.07	0.13	0.25	0.20	0.05	0.24	0.15	0.07	0.66
Eutrophication, terrestrial	molc N eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity, freshwater	CTUe	76.17	55.82	127.67	79.50	60.47	6.81	10.68	2.36	0.00
Land use (soil quality index)	dimensionless (pt)	140.65	267.44	78558.98	1578.20	287.82	76.97	48.53	54.17	51094.50
Water use	m3 water eq	3.72	24.77	3.51	50.60	9.04	2.89	7.63	1.43	0.00
Resource use, fossils	MJ	3860.81	4963.64	217.67	3443.98	2055.04	3874.79	3395.53	4361.43	549.35
Resource use, mineral and metals	kg Sb eq	9.42E-05	1.86E-04	3.24E-05	4.45E-04	6.65E-04	1.12E-06	1.55E-06	1.10E-05	2.99E-04

Annex F - Comparing results with the 2014 study

The results presented in this work are not directly comparable with the external cost results of the 2014 study[58], for a number of reasons, the primary being that the field of LCIA and the supporting datasets have been rapidly improving and evolving. In the last 5 years there have been significant improvements in both methodologies and data such that current methodologies give sometimes significantly different, but more robust, results than the methods used 6 years previously. These issues are discussed further in Annex B of this report. But among the specific reasons for reduced comparability and differences:

1. This study uses the EF LCIA framework (PEFCR Guidance 6.3), rather than the ReCiPe framework used in the 2014 study. This choice was agreed with the European Commission to ensure consistency across other recent EC funded work. Two further points should be noted, (1) the ReCiPe approach was also substantially updated in the interim and therefore if the new, improved characterisation factors of the ReCiPe approach were used this would also have resulted in results not directly comparable;; and (2) the 2014 study also reviewed and recommended to use the EF approach as presented in PEFCR Guidance 6.3 in the future after its full release.
2. This study uses EF-compliant datasets rather than Ecoinvent datasets used in 2014. As above, the datasets are constructed in different ways, with the EF-compliant datasets agreed for use here based on the high level of validation and checks undertaken. Furthermore, the Ecoinvent datasets have also undergone a major revision since the last study.

Nevertheless, some comparison and comment can be made to help explain the evolution in external cost results as the two studies do have some important overlaps in impacts studied, units valued and underlying methodologies for values. A comparison for EU28 results is presented below in Table F-1. This shows that total external costs have increased by 57% compared to the previous work, and with significant variations noted per impact. The most notable changes include climate change, which has increased by more than 50%; and particulate matter which has increased by more than 180% as a result of improved methodologies and increased monetisation values. Impacts for which the valuation approach and underlying methods stayed broadly the same, such as ionising radiation and resource use, fossils have seen their overall impacts decline, whilst improved life cycle datasets and characterisation play a role, it is also the case that these measures, particularly on fossil resources, show the result of changes in the energy mix. The differences are all discussed and explained in Annex B of this report.

[58] Ecofys et al (2014) for DG ENER: Subsidies and Costs of EU energy

Table F-1 Comparison of total external costs for the EU28 between this work and the 2014 study

PEFCR Guidance 6.3		ReCiPe 2008 (in report 2014)[59]			Difference as % of 2020 study value	
Life cycle categories	**External Cost (EUR_{2018} bn)**	**Life cycle categories**	**Assessment - indicator alignment**	**External Cost (EUR_{2018} bn)**	**EUR**	**% change**
Climate Change	159.8	Climate change	Identical categories/units	105.7	54.1	51%
Ozone depletion	0.0	Ozone depletion	Identical categories/units	0.0	0.0	negligible
Ionising radiation, Human health	0.7	Ionising radiation	Identical categories/units	1.2	-0.5	-43%
Photochemical ozone formation, human health	5.3	Photochemical oxidant formation	Identical categories/units[1]	0.0	5.3	
Particulate matter	90.1	Particulate matter formation	Identical categories, different units	31.8	58.3	183%
Human toxicity, non-cancer	20.6	Human toxicity	Identical categories, different units	18.2	5.6	31%
Human toxicity, cancer	3.2					
Acidification	1.6	Terrestrial acidification	Identical categories, different units	1.5	0.1	4%
Eutrophication, freshwater	0.0	Freshwater eutrophication	Identical categories/units	0.3	-0.3	-88%
Eutrophication, marine	3.1	Marine eutrophication	Identical categories/units	0.7	2.4	318%
Eutrophication, terrestrial	0.0		Not monetised, no corresponding indicator in ReCiPe			
Ecotoxicity, freshwater	0.0	Freshwater ecotoxicity	Identical categories, different units	0.0	0.0	
Land use (Soil quality index)	9.3	Agricultural land occupation	No direct match	2.0	4.9	111%
		Urban land occupation		0.9		
		Natural land transformation		1.5		
Water use	0.9	Water depletion	Identical categories, different units	1.1	-0.2	-18%
Resource use, fossils	39.6	Fossil depletion	Identical categories, different units	46.6	-7.0	-15%
Resource use, minerals and metals	0.0	Metal depletion	Similar categories, different units	1.4	-1.4	-100%
		Terrestrial ecotoxicity	Not valued in PEF	0.0	0.0	
		Marine ecotoxicity	Not valued in PEF	0.0	0.0	
Total	**334.2**			**212.9**	**121.3**	**57%**

[59] Goedkoop, M, Heijungs, R., Huijbregts, M., De Schrijver, A., Struijs, J., Van Zelm, R. 2009. ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level First edition Report I: Characterisation.

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