Environmental impact indicators for the electricity mix and network development planning towards 2050 – a POLES and EUTGRID model

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Abstract

Most prospective studies of the European power system rely on least-cost evaluations. This study assessed the influence of environmental impact indicators on prioritisation of 'dispatchable' technologies in the European energy mix up to 2050, compared with a purely cost-optimal system based on carbon tax incentives, without suppressing economic growth considerations. A model that combined the *Prospective Outlook for Long-term Energy Systems* model (POLES) and the *European and Transmission Grid Investment and Dispatch* model (EUTGRID)was used in the analysis. Combined current and prospective life cycle assessment (LCA) methodologies were added to the EUTGRID model to include environmental considerations in the decision-making process. Shifting from an economic to an environmental merit order in prioritisation increased the share of renewables by 2.65% (with variations between countries) and decreased overall emissions by 9.00%. This involved a change in grid infrastructure. Investments were found to be more important when optimisation was based on an environmental criterion on new high-voltage AC power lines, which resulted in a 1.50% increase in the overall cost of the power system. Finally, considering an environmental, instead of an economic, merit order allowed decarbonisation to be achieved slightly faster, resulting in lower cumulative greenhouse gas emissions to the atmosphere.

Keywords:
Environmental emissions, Electricity modelling, POLES, EUTGRID, Environmental merit order, economic merit order

1. Long term energy systems planning

1.1. Context

The Kyoto protocol requires countries to meet at conferences of parties (COP) to discuss and set individual objectives for each country wishing to contribute to decreasing anthropogenic impacts and better protect the global environment. In 2015, the COP was held in Paris and resulted in what is known as the Paris agreement [44], under which every ratifying country agrees to preventing the global temperature rising above the critical level of 2°C by 2100 compared with the 'pre-industrial' era [22].

The energy sector must also change, in order to handle population growth, and the related increase in energy demand, while still maintaining the same level of services and reliability. Meanwhile, emissions from energy production must decrease drastically if agreements reached in COPs are to be kept. For instance, in 2009, the European Council encouraged its member states to cut their emissions by 80% from the 1990s level [18]. This target was later integrated into the European Commission's 2050 energy roadmap, in its decarbonisation scenario [16].

1.2. Existing models

To quantify the distance between reality and those environmental goals, scenarios simulated using multiple long-term modelling of the energy system are used [4]. A set of top-down and bottom-up models are now available for this purpose. In addition to POLES, the model used in this article, two main alternatives are available in the literature.

The European Commission mainly uses the partial equilibrium Price-Induced Market Equilibrium System (PRIMES) energy model to evaluate the impact of climate policy on the European energy system [13]. The PRIMES model projects scenarios considering a five-year time step for the energy sector in all European countries. To better illustrate each sector, PRIMES is linked to other models describing e.g. non-CO_2 emissions, exogenous factors (e.g. gross domestic product, fossil energy prices), transportation or biomass usage. It covers a wide range of the technologies used for energy production, including various investment schemes for the electric grid and Renewable Energy Sources (RES) integration. The power sector has a resolution at the level of the country and interconnections are represented to show the dynamics of the power system. The latest

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Glossary

COP	Conferences of parties
EDGAR	Emission Database for Global Atmospheric Research
ETS	Emission trading scheme
ETSAP	Energy Technology Systems Analysis Program
EUCAD	European Unit Commitment And Dispatch model
EUTGRID	European – Transmission Grid Investment and Dispatch
HVAC	high voltage AC
HVDC	high voltage DC
LCA	Life Cycle Assessment
LCI	Life cycle inventory
NEEDS	New Energy Externalities Development for Sustainability
POLES	Prospective Outlook for Long-term Energy Systems
PRIMES	Price-Induced Market Equilibrium System model
RES	Renewable Energy Sources
TIMES	The Integrated MARKAL-EFOM System
VRES	Variable renewable energy sources

development concerning the power system sector includes an equivalent of the transmission network considering electricity curtailment, interconnections and line congestion. This add-on is called PLEXOS, an additional module to PRIMES [5]. It results in a meshed network of a balanced system using a single point per country focusing on the year 2030.

Another widely used model for representation of the energy sector is the Integrated MARKAL-EFOM System (TIMES) model [32] developed by the Energy Technology Systems Analysis Program (ETSAP), which has branches in over 20 countries. The TIMES model is a least-cost equilibrium model for technology and economic energy supply and demand over a defined time horizon and a yearly minimum granularity. The model can be extended to integrate regional endogenous factors, and thus multiple TIMES models co-exist for specific usages.

1.3. Environmental impact indicators

All these models aim at better addressing climate change challenges through prospective scenarios, thereby contributing to limiting the increase in mean global temperature. Environmental emissions are estimated in technical and economic analysis, including the six greenhouse gases emitted directly from combustion processes as listed in the Kyoto protocol [43]. For this reason, Pang et al. [35] emphasise the need for other indicators that consider various environmental impacts. In particular, to implement the European climate legislation, new modelling tools for assessing environmental impact that can use Life Cycle Assessment (LCA) for integrated evaluations are needed [36].

The use of LCA indicators in integrated assessment models in order to take a snapshot of environmental impacts of future possible energy mixes is increasing [2]. A recent study examined the influence of using LCA results, including indirect emissions, in decision making on future technology deployment [34]. It concluded that integrating indirect emissions resulted in lower penetration of variable renewable energy source (VRES) installed capacity. The use of LCA indicators in optimising the electricity sector has been studied in the case of Norway by García-Gusano et al. [19] and further tested in the Spanish context [20]. These optimisations reveal the impact of using LCA indicators during the electricity production phase. Including the impacts in the entire life cycle could increase total emissions by 50% [37]. Challenges arise in defining a unified methodology for including LCA results in the decision-making process [40]. Moreover, the impact on infrastructure of integrating more VRES and the infrastructure investments needed to support such developments have not been well studied.

The current incentive to increase the share of renewable energy sources (RES) is the Emissions Trading Scheme (ETS), which sets carbon prices and drives the technology development market. In this system, biomass-based power production receives specific treatment, as it is excluded from the ETS under the biomass zero-treatment scheme [17]. As this may compromise evaluation of emissions and decision making on choice of technologies, there has been a call for emissions from biomass to be integrated in the next ETS framework [45].

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1.4. Objectives of the present study

The main objective of this study was to assess the influence of environmental impact indicators on prioritisation of 'dispatchable' technologies in the energy mix, and thus the environmental impact on climate change, and the infrastructure costs involved in that change of paradigm. The environmental impact of current technologies changes over time and therefore needs to be compared against the environmental impact of prospective technologies. This secondary objective was necessary to achieve the main one and represents an additional methodological contribution of the study. In the analysis, economic growth remained the basis of prospective computations run by POLES, while environmental criteria were taken into account in the optimisation process.

Section 2 of this paper describes the models used to implement direct and indirect emissions into the decision-making process on 'dispatchable' technologies and the adapted regional environmental impact database for the production technologies present in the energy models. The objective function to minimise emissions from 'dispatchable' technologies is presented in Section 3. The results are presented and discussed in Section 4, in relation to other ongoing research. Section 5 presents the main conclusions.

2. Modelling energy systems and environmental impacts

This study was conducted using two interconnected models: the Prospective Outlook for Long-term Energy Systems (POLES) [8, 27] and the European Transmission Grid Investment and Dispatch (EUTGRID) [1], an extension of the European Unit Commitment And Dispatch (EUCAD) model developed by Després et al. [10].

2.1. The POLES model

POLES is a bottom-up model of the world-wide energy sector. It was developed in the 1990s and was fully deployed in 1997. POLES has since been upgraded several times and is currently in its 6th version. It is being refined concurrently by the Joint Research Center (JRC) [26], the Sustainable Development and Energy Economics laboratory at the University of Grenoble (GAEL-EDDEN) [14], and the energy consulting company ENERDATA [15]. The POLES model allows the energy sector to be simulated up to the year 2100. Simulations in POLES are based on partial equilibrium, which requires exogenous data. The input data to the model, such as population and gross domestic product (GDP), are set using the work of the JRC to define reference scenarios [26, 28, 25].

Among the different energy sectors covered, the electricity production is modelled by including 41 current and prospective technologies (refer to Table A.3 in appendix). In order to characterise electricity production as an output, POLES considers exogenous parameters such as GDP alongside population changes and carbon constraints, which are included by setting a carbon price within the system. Furthermore, market data are included using resources constraints and the interdependencies between fuel prices and fuel demand. Other outputs are also available, such as greenhouse gas emissions, system prices and energy consumption for each year and country within the model's scope. However, POLES lacks a representation of developments in the electricity grid and its components, such as storage. As storage technologies will be crucial for large-scale deployment of VRES, an optimisation tool that considers all these aspects is needed [9].

2.2. The EUCAD/EUTGRID

In order to integrate new aspects of the European electricity grid, an external module that optimises the EUCAD model has been developed [11, 9]. Recently, transmission line investments were incorporated within a finer geographical resolution of the European electricity grid, in an updated module (EUTGRID) [1]. Transmission planning is critical for best incorporating production of VRES that considers the optimal balance between economic and technical constraints [47]. The model considers the development of both high-voltage alternating current (HVAC) and high-voltage direct current (HVDC). The EUCAD/EUTGRID module is based on an optimisation problem, interfaced with POLES, developed in GAMS and uses the CPLEX solver. This module considers the 41 technologies present in POLES for energy production (Table A.3). It implements storage elements, characterised by their temporal variations, by simulating hourly electricity production, demand, international exchange and load curtailment. EUTGRID is limited to 24 countries within the European Union (EU24) that are present in POLES[2]. Each country is divided into a variable number of clusters representing the transmission network connections within the country. In total, the model considers 87 clusters. For each simulated year, two typical load days (one for summer and one for winter) and 12 representative VRES production days are modelled: 6 days for the summer period and 6 days for the winter period. Each represents 12 distinct VRES constraints that could statistically occur on the European electricity grid. Ultimately, the EUTGRID module aims at minimising operation costs at the European level. To achieve a balance of electricity demand and production at the European level, it maximises the use of VRES in the network and adjusts the production of other technologies to meet its initial objective.

2.3. Environmental impact of production technologies

To minimise the emissions of the entire power system, the environmental impact of each technology must be known. One of the limitations in existing studies is that the environmental impact of technologies for power production is limited to evaluation of: i) only equivalent carbon dioxide emissions (CO_{2eq}), meaning that all other environmental impacts are intentionally disregarded; ii) combustion technologies, for their direct contribution to global warming; and iii) the six Greenhouse Gases (GHG) listed in the Kyoto protocol. Furthermore, technologies

[2] EU24: Austria, Belgium, Bulgaria, Switzerland, Czech Republic, Germany, Denmark, Spain, Finland, France, Great-Britain, Greece, Hungary, Ireland, Italy, Luxembourg, The Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovakia, Slovenia

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based on similar fuels are considered identical, as primary energy consumption is used to consider CO_{2eq} emissions. This results in a misleading representation of the overall environmental impact in which there are geographical specificities, including environmental culture and long-term policy planning [12]. For example, a coal power plant will have different emissions in different countries. The decision-making process must reflect this particularity.

To this end, use of LCA methodology, based on the EcoInvent 3.01 database, can be advantageous [46]. The EcoInvent database provides the life cycle inventory (LCI) for multiple energy production technologies and multiple regions. Each LCI is further characterised using the ReCiPe2008 methodology [21]. In order to compute the environmental impact for each technology, these technologies are divided into current technologies and prospective technologies (Table A.3 in appendix). Furthermore, biomass-based technologies are taken into account until the electricity production phase without reallocating the CO_2 produced during the production phase. This avoids allocation issues, as well as accounting only for the CO_2 actually emitted. The methods for building the database are presented in Figure 1 while characterised data are available as supplemental information (SI) [31].

2.3.1. *Current technologies*

The first step towards including the environmental impacts of power production technologies is to obtain a preliminary overview of these impacts. Of the 41 technologies used in the POLES model, LCA for 28 of these are available in the EcoInvent database. These LCA do not represent the full life cycle but rather cradle-to-product, including the waste management stream but disregarding the end-of-life phase of infrastructure. Therefore, we decided to consider the emissions within these life cycle boundaries.

The output is the generation of a three-dimensional[3] matrix $F_{i,j,k,l-Today}$ where k is the characterised emission factor for each technology j (expressed per GWh), for different clusters i, and all European countries l. The characterised environmental impacts are not available for all countries (e.g. no marine technologies for countries without coastlines, technology not currently present in the country etc.). Therefore, each country lacking a technology was consolidated using data available in other countries. Impossible solutions such as tidal power production in central Europe were resolved in a higher level in POLES that does not allow such combinations. Thus, although environmental impacts are associated with all countries, this did not affect the decision making of the optimisation tool. Note that all data are available in SI [31].

2.3.2. *Future and prospective technologies*

Amongst the pool of technologies included in the EUTGRID model, some are considered prospective. Prospective technologies are not only future non-existent technologies, but also technologies that are in the pilot phase. Therefore, the environmental impact of these technologies is not known and must be estimated. For this, we used data assessing the full costs and benefits of the future energy system taken from the New Energy Externalities Development for Sustainability (NEEDS) database [38] database. The NEEDS model comprises five scenarios: Pessimistic Business as Usual (*P-BAU*), Pessimistic 440 ppm (*P-440ppm*), Realistic-Optimistic 440 ppm (*RO-440ppm*), very optimistic 440 ppm (*VO-440ppm*), very optimistic based on a renewable energy electricity (*VO-Renew*). Each of the five scenarios is detailed for the period until 2025 and 2050. The NEEDS database is based on the EcoInvent v1.3 database, which is an obsolete version considering the different aggregation of products. However, we left technologies that are still considered prospective as described in the NEEDS database, while we removed incorrect products that are misplaced as outputs in the technologies (e.g. tidal and wave energy, concentrated solar power plants etc.).

To overcome the changes between the different versions of the EcoInvent database, we downgraded the EcoInvent database for the current technologies to similar products that appear in the NEEDS database ($F_{i,j,k,l-Today} \rightarrow F_{NEEDS-Today}$). Therefore, products appearing in the latest version of the EcoInvent database were not integrated into the system. This did not affect the output for any of the indicators characterised except water depletion, human toxicity and land occupation. The main reason why this was done was to avoid discrepancies between the database of prospective technologies and that of current technologies, while computing the prospective emissions of power production technologies for every country. Thus for each technology present in the NEEDS database, the ratio between the current scenario and prospective scenarios was calculated as:

$$f_{i,j,k,l-ratio} = \left(\frac{F_{\mathrm{NEEDS}-scenario}}{F_{\mathrm{NEEDS}-Today}}\right) - 1 \quad (1)$$

where $f_{i,j,k,l-ratio}$ is the ratio of a specific product's emissions between the current scenario and a given prospective scenario [%], $F_{\mathrm{NEEDS}-Today}$ is the emissions for a specific product in the LCI of a technology for the current scenario, and $F_{\mathrm{NEEDS}-scenario}$ is the emissions for the same specific product in the LCI of a technology for the prospective scenario.

Once the ratio for each product is calculated, it is possible to obtain, for each technology, country and prospective scenario, a database that reproduces the emissions behaviour of the existing technology in $F_{i,j,k,l-Today}$.

$$F_{i,j,k,l-Scenario} = F_{i,j,k,l-Today} \times f_{i,j,k,l-ratio} \quad (2)$$

where $F_{i,j,k,l-Scenario}$ is the LCI of all technologies for the prospective scenario. It is further characterised using the ReCiPe2008 method to evaluate the emissions for specific indicators.

Finally, when a technology was not available in either the EcoInvent database or the NEEDS database, information from the literature was considered. This was the case for solar concentrated technology, for which a study carried out in Spain was used [6]. In that study, the authors claimed [39] that *'the indicators published in that paper are the most pertinent to the*

[3] 41-by-24-by-18 – 41 technologies, 24 countries and 18 characterised indicators as in ReCiPe.

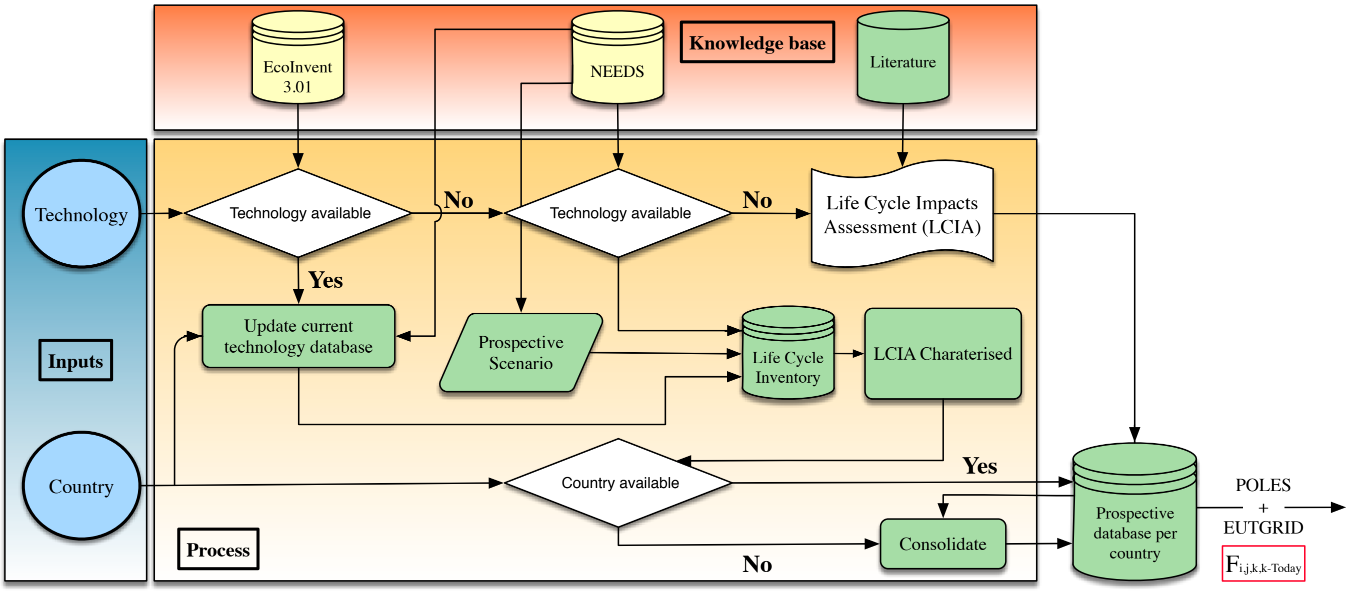

Figure 1: Prospective environmental impact database used with the EUTGRID model.

technology. We believe that results from all other indicators are not relevant to this investigation, due to high uncertainty.', and therefore disregarded them in their environmental impact assessment study. All data are available as SI [31].

3. Environmental optimisation method

The main objective of the environmental optimisation method is to minimise the environmental emissions k. The impact indicators given in the ReCiPe 2008 method for environmental impact assessment are used (see Table A.2 in appendix). These 18 indicators reflect the impact of a process or technology on e.g. climate change, water depletion, ionising radiation or ozone depletion. In order to achieve the environmental optimisation goal, yearly emissions for a selected indicator k are calculated for the energy mix optimised in the upstream process of the EUTGRID model. The objective function to minimise is:

$$\min\left(E_{m,Europe-k}\right) = \sum_{i,j,k,l,t} \left(F_{i,j,k,l} \times P_{i,j,t}\right) \qquad (3)$$

where $E_{m,Europe-k}$ is the total yearly emissions for a given indicator k. In the overall emissions F, k is the characterised emissions factor for each technology j [/GWh], for different clusters i, and all European countries l. P is the power production for each cluster i [GW], for each technology j and each yearly scenario t [h]. The characterised emissions of $F_{i,j,k,l-Scenario}$ and $P_{i,j,t}$ are the energy produced $F_{i,j,k,l}$ [GWh/h].

The minimisation is used for two purposes: to recalculate the electricity produced by the 'dispatchable' production units and to set the investments to be made on the transmission network. The EUTGRID model computes different energy mixes for 12 representative days considering physical and economic constraints. Constraints are described in the EUTGRID description model [10, 1] and comprise the minimum OFF and ON times and the ramping time per technology, the storage, demand response, electric vehicle constraints and the 'dispatchable' loads. Moreover, the investments on transmission line reinforcements are recalculated every three years using prospective environmental emissions. In order to achieve this, the EUTGRID model uses a three-year rolling window: at the beginning of the period, investments are based on the expected electricity mix on a 10-year time horizon from the current year provided by POLES to alleviate future bottlenecks; and at the end of the period, investments are determined using the actual electricity mix to solve possible existing congestions. We also used this mechanism to plan investments (line reinforcment) based on the expected emissions for the given electricity mix.

We divided the model into three periods, spanning 2000-2050. The period 2000-2012 was used for calibrating the model and was based on historical information from POLES. The second period, 2013-2025, included the environmental impact objectives only using the current database. In 2025, the environmental impacts were updated with the prospective database using the five scenarios mentioned in section 2.3.2. These environmental impacts were used until 2050.

4. Results and discussion

The model was run over the period 2000-2050 with an investment period of three years and a yearly energy mix optimisation that satisfied 12 hourly-scenarios (6 for the summer period, 6 for the winter period). The results are analysed below considering the energy mix per country, environmental emissions and the economic aspect of reinforcing or creating new lines (both HVAC and HVDC technologies).

The combined model makes it possible to assess how each European country needs to invest in its transmission network in order to maximise the use of RES using an environmental merit

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order under technical constraints, instead of the more conventional economic merit order of technologies. In other words, the model uses the 2°C climate policy of each country and adjusts the electricity mix accordingly.

4.1. The share of RES

We analysed the share of RES in the electricity mix of each country from the perspective of their production, thus excluding the import and export share of the electricity mix.

$$P_{RES} = \frac{P_{Bio} + P_{Sol} + P_{Wind} + P_{Hydro} + P_{Earth} - P_{Curt}}{P_{Tot}} \quad (4)$$

where P_{res} is the ratio of RES production within a country [%], P_{Bio} is the power production for Biomass, P_{Sol} the solar power, P_{Wind} the onshore and offshore wind power, P_{Hydro} the hydro-power, P_{Earth} the geothermal energy, and P_{Curt} in case curtailment is necessary. The total power produced within a country is P_{Tot}.

The share of RES in the electricity mix on the consumption side, including the electricity trading of RES, is reported in SI. The share of RES in the national production mix is presented in Figure 2 for the years 2000 and 2050.

The general trend was naturally an increase in RES in the electricity mix of all European countries throughout the period 2000–2050. Countries that devoted the most effort to RES deployment were those with the lowest RES share in 2000, e.g. Hungary, Poland, Czech Republic, Belgium. In contrast, countries with a high share of RES in 2000 showed the weakest increase in terms of RES share over time, e.g. Norway, Sweden, Austria, Finland. By 2050, the 24 countries had integrated 51.4% of RES into the European electricity network. Countries in eastern Europe continued to have the lowest share of RES in their electricity mix. The countries that progressed most between 2000 and 2050 were Slovenia (3.40% → 54.7%), Greece (10.2% → 70.2%) and Germany (4.70% → 59.3%). Countries that showed the lowest increase were Slovakia (13.1% → 23.6%), the Netherlands (11.9% → 34.0%) and Finland (43.0% → 53.0%). In the case of Finland, the main reason was an increase in the nuclear share in the energy mix, which counter-balanced the effect of VRES penetration, while biomass-based technology was already prominent [24]. Moreover, the prospect for new hydropower plants is limited due to the geographical specificities of Finland. In the case of Slovakia, the low increase was a political outcome, as the Slovakian government seems to prioritise biomass-based electricity production and nuclear production for decarbonising electricity production, while VRES are avoided because of their higher costs of installation, production and management [23, 29].

Optimising the electricity system based on environmental criteria increased the use of RES by 2.65% ($\sigma = 5.48$) at the EU24 level by 2050 compared with a system based on economic criteria only. The main difference was a decreased use of coal and gas in the environmental optimisation (-21.7% and -9.00%, respectively). This was partly compensated for by use of oil power in the electricity mix and increased use of offshore wind turbines. The share of RES increased most for Austria (+22.0%). This was attributable to a change of strategy between the emissions objective and the costs objective. In optimisation of costs for Austria, there was an increase in power production and therefore an increase in export of electricity to trading partners. In optimisation of emissions, the production level decreased overall and Austria became a significant country regarding its share of RES in power production.

Thus, considering the RES share as the ratio of production of electricity from RES to total production by the country benefited most countries by increasing their exchanges and decreasing their national production.

Finally, the RES share decreased in optimisation of emissions for three countries, namely Denmark, Hungary and Norway. This seems contradictory to the goal of this form of optimisation. In the case of Hungary, nuclear production increased significantly and resulted in higher exports, which in turn decreased the RES ratio. In the case of Denmark, imports decreased by 77.0% and were replaced by increased oil and gas production. Finally, in the case of Norway, the change derived from a shift from excess production and a high export mechanism to lower production from biomass and coal, which decreased the overall RES ratio of Norway (-3.60%).

4.2. Changes in emissions

The POLES model uses historical data from 2000 to 2012. Optimisation started from the year 2013, considering the environmental impacts of the electricity mix. This explains the sudden drop in climate change emissions (CO_{2eq}) shown in Figure 3. Note that, even if the optimisation criterion is based on an environmental assessment, economic growth considerations are automatically taken into consideration by POLES and thus are not omitted even when considering environmental criteria. Thus, the optimisation loop contains POLES without interfering directly with its economic prospective computations.

As time passed and climate policy was enforced in every country, the emissions due to electricity generation decreased for both the economic and environmental optimisation methods (Figure 3). By 2050, optimisation using economic criteria decreased emissions by 72.0% compared with 2000, while optimisation using environmental criteria decreased emissions by 81.0% on average for the five environmental scenarios. The gap between the two optimisations decreased in absolute terms and tended to converge eventually (Figure 3). This tendency suggests that, in general, economic optimisation would be sufficient to operate the electricity system considering the climate change emissions target. However, climate change emissions under environmental optimisation were always lower, by on average 22.0%, and even 27.0% in the case of the very optimistic 440 ppm scenario.

To test the robustness of the combined model, three datasets were used: the outcome of PRIMES for future emissions up to 2050; the historical emission values from EuroStat; and the Emissions Database for Global Atmospheric Research (EDGAR) [7], which also records emissions per country and industrial sectors such as the power sector. PRIMES, unlike the other sources, reports the CO_{2eq} emissions for electricity and district

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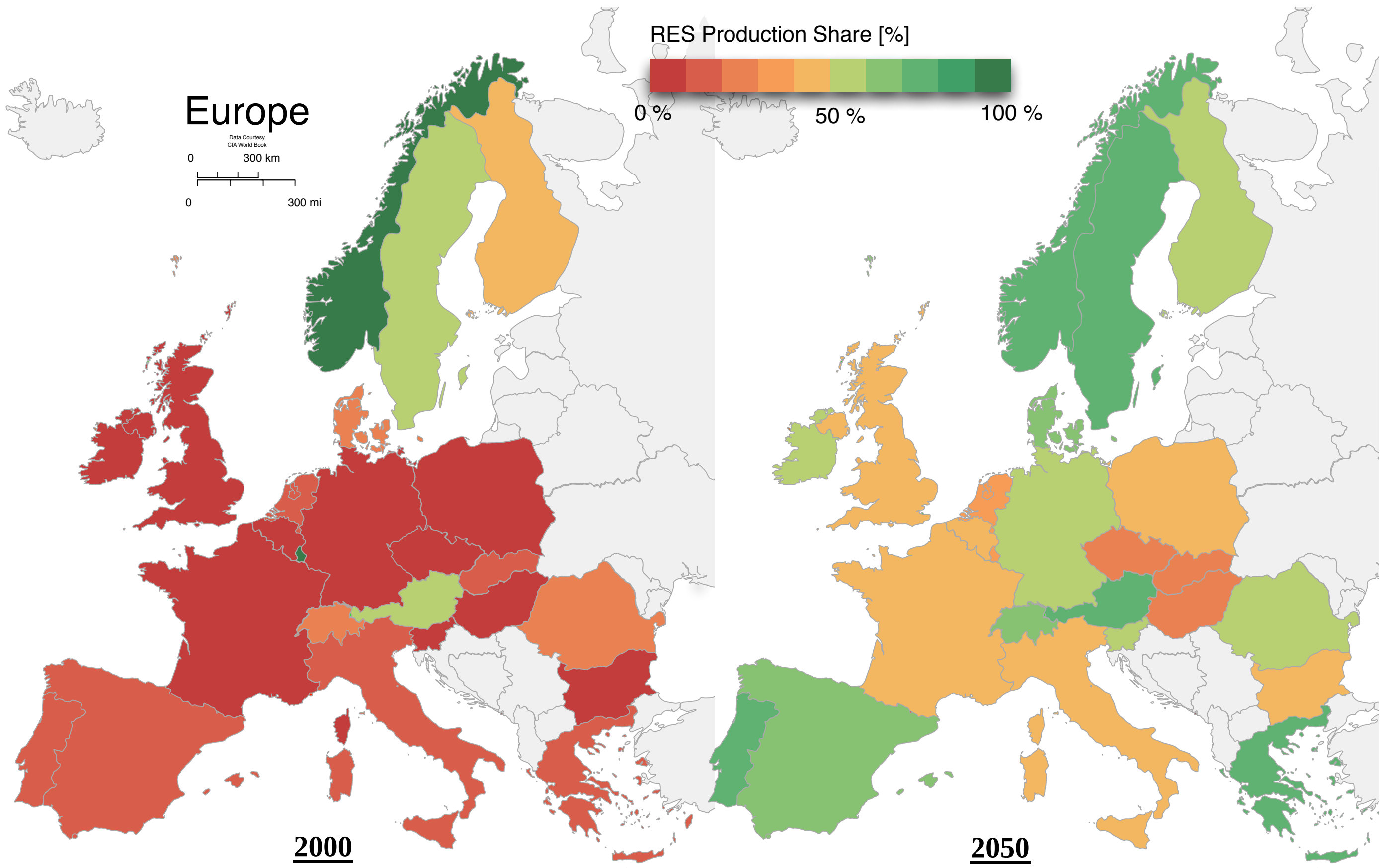

Figure 2: Share of renewable energy sources (RES) production within the domestic electricity production mix for Europe (24 countries) in 2000 and 2050 under the 2°C climate policy framework and the VO-440 ppm prospective environmental impact of technologies by minimising the environmental impact of electricity production.

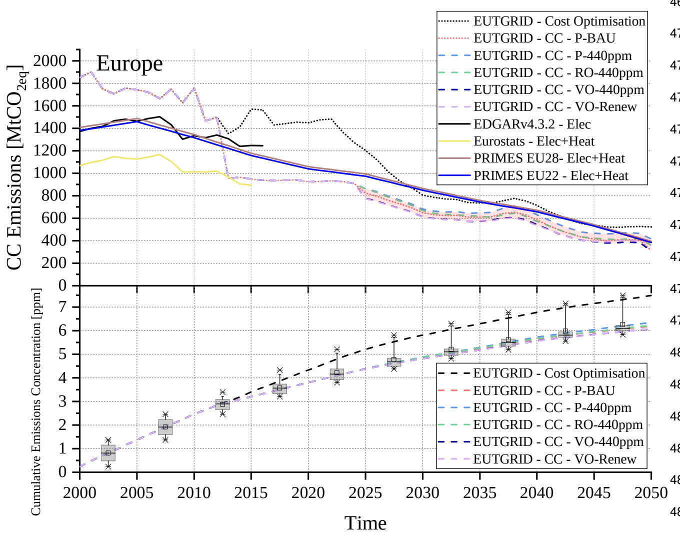

Figure 3: Climate change (CC) impact for the different optimisations from 2000 to 2050 under the 2°C climate policy framework including both direct and indirect emissions for all technologies (see section 2.3.2 for abbreviations). Carbon dioxide equivalent (CO_{2eq}) emissions from Eurostat and the PRIMES model include both heat and electricity and only consider direct CO_{2eq} emissions from the six GHG listed in the Kyoto protocol, plus nitrogen trifluoride.

heating combined. In addition, Switzerland and Norway are not included in the PRIMES model and therefore we split the emissions between the reported EU28 and the 24 countries considered in the EUTGRID model, deducting Norway and Switzerland.

An F-test applied to the ANOVA results showed no significant differences ($p > 0.05$) in mean values between the EUTGRID and the EDGAR emissions reports for the period 2000–2016 The statistical spread of the climate change indicators is presented in Figure 4.

One of the main reasons why the EUTGRID model gives higher emissions levels than the other reference points is that it includes both direct and indirect emissions for all technologies.

For the period from 2000 to 2050, the PRIMES and EUTGRID models with environmental optimisation did not give statistically significant variations in means. However, the differences in means between all environmental objectives and the costs objective were significant ($p < 0.05$). This could indicate that in a large-scale, long-term perspective, using an LCA future path scenario may not be pertinent in this case (although giving a difference of 19.0% between the lowest and highest scenario by 2050). When the emissions level is drastically reduced, it does not make much difference whether emissions are characterised using a pessimistic or an optimistic scenario

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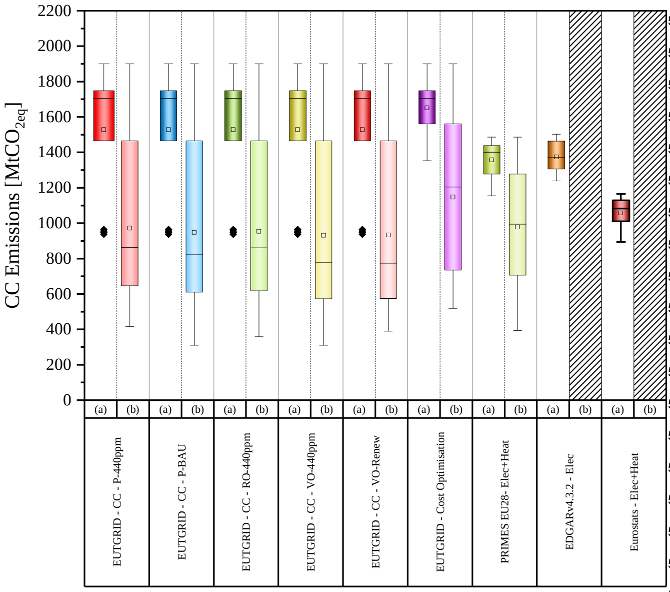

Figure 4: Climate change (CC) impact statistics for the different optimisations for the period (a) 2000-2016 and (b) 2000-2050 under the 2°C climate policy framework including both direct and indirect emissions for all technologies.

when studying European emissions. However, the differences in means between costs optimisation and environmental optimisation were significant ($p < 0.05$) in all the NEEDS scenario cases. This supports the claim that environmental optimisation can achieve a lower emissions rate than costs optimisation in the long run, despite the use of the ETS framework. The emissions optimisations gave on average (for all NEEDS scenarios) 30.0% lower emissions levels than costs optimisation under the 2°C climate policy framework.

Raw emissions can also be converted into accumulated CO_2 in the atmosphere, expressed in ppm. The accumulated emissions are presented in Figure 3. At the European level, electricity production for the 24 countries contributed to raising the CO_2 concentration by 6.27 ppm from 2000 to 2050, or 0.13 ppm/year. In contrast, the average increase in GHG occurs at a pace of 2.10 ppm/year world-wide and the concentration reached 405 ppm in November 2017 [41]. Note that, as mentioned earlier, biomass reabsorption was disregarded in the life cycle impact assessment and could thus be deducted from the resulting emissions. Furthermore, a gap arises when power production is managed under economic merit order driven by the carbon tax compared with an environmental merit order. This gap could suggest that the economic incentive to decrease carbon-intensive production systems reaches a limit and that greater reductions could be achieved by considering the environmental impact of these power production systems.

4.3. *Impacts on infrastructure*

Inclusion of an environmental objective in handling electricity production to satisfy demand obviously affects the infrastructure of the power system. Therefore, in the EUTGRID model, the grid development infrastructure is re-evaluated on a five-year basis. The infrastructure should be able to integrate as much VRES as possible and thus avoid curtailments. The EUTGRID model looks at the development of both HVAC and HVDC lines for satisfying the demand. The development of these networks has different costs. The difference between a costs optimisation system and an environmental optimisation system is depicted in Figure 5.

From this perspective, it is possible to compare the optimisation objectives by looking at the total required capacity of HVAC and HVDC lines, the deployed length of those lines, the total installed capacity and the corresponding investments for grid reinforcement between 2010 and 2050.

The main difference in technology developments for transmission grids between the costs and environmental optimisations is that HVAC is preferred in environmental optimisation, while HVDC is preferred in costs optimisation. Thus in the present case environmental optimisation required the installation of 275 GW ($\sigma = 11$) of capacity, representing 57 100 km ($\sigma = 3200$) of HVAC lines, while costs optimisation required 270 GW of capacity for 54 600 km of HVDC lines. On the other hand, the added HVDC lines resulted in 115 GW of new installed capacity (42 600 km) in the cost optimisation approach, while the environmental optimisation had lower capacity at 111 GW ($\sigma = 7.50$) and 42 600 km ($\sigma = 1\,670$).

Installation of these new lines involved different level of investments. Overall, the cost optimisation resulted in an investment plan of 315 billion US$ for the period 2010–2050. The environmental optimisation had a mean investment plan of 321 billion US$ ($\sigma = 8.30$) for the same period. These costs reflect only the investments required by the transmission network to reinforce its capacity for transporting electricity. Nevertheless, the carbon intensity of the investments from the environmental optimisation were found to be much lower than in the case of costs optimisation, as summarised in Table 1.

As the investments increased, the climate change-related environmental impact decreased overall. Therefore, the costs optimisation approach had the highest carbon intensity on the investments needed to reach the 2°C climate scenario (130 $kgCO_{2eq}/\$_{inv}$), although it followed the least costly trajectory and therefore incontestably the lowest electricity system cost. In contrast, the greenest pathway was the scenario VO-Renew, with a carbon intensity of 91 $kgCO_{2eq}/\$_{inv}$ although all the environmental emissions optimisation scenarios had on average a carbon intensity of 96 $kgCO_{2eq}/\$_{inv}$ ($\sigma = 3.6$). To compare the different alternatives and define which one is to be preferred, the stochastic multiobjective acceptability analysis (SMAA) [30, 42] was applied. The SMAA approach allows comparing and ranking the alternatives between each other's, giving to decision-makers information about the most interesting alternative. The three criteria - investments, emissions, system cost - were used to rank the alternatives. First, we analysed each alternative individually. Then, emission optimisations were averaged and the related standard deviation calculated to be used in a Gaussian distribution. Results indicate that the EUTGRID - CC - VO-440ppm was the favoured alternative (rank acceptability $a = 0.64$) before the cost optimisation ($a = 0.36$). In case the emission optimisations were put together, there was no clear winning alternative, meaning that any of them would be appro-

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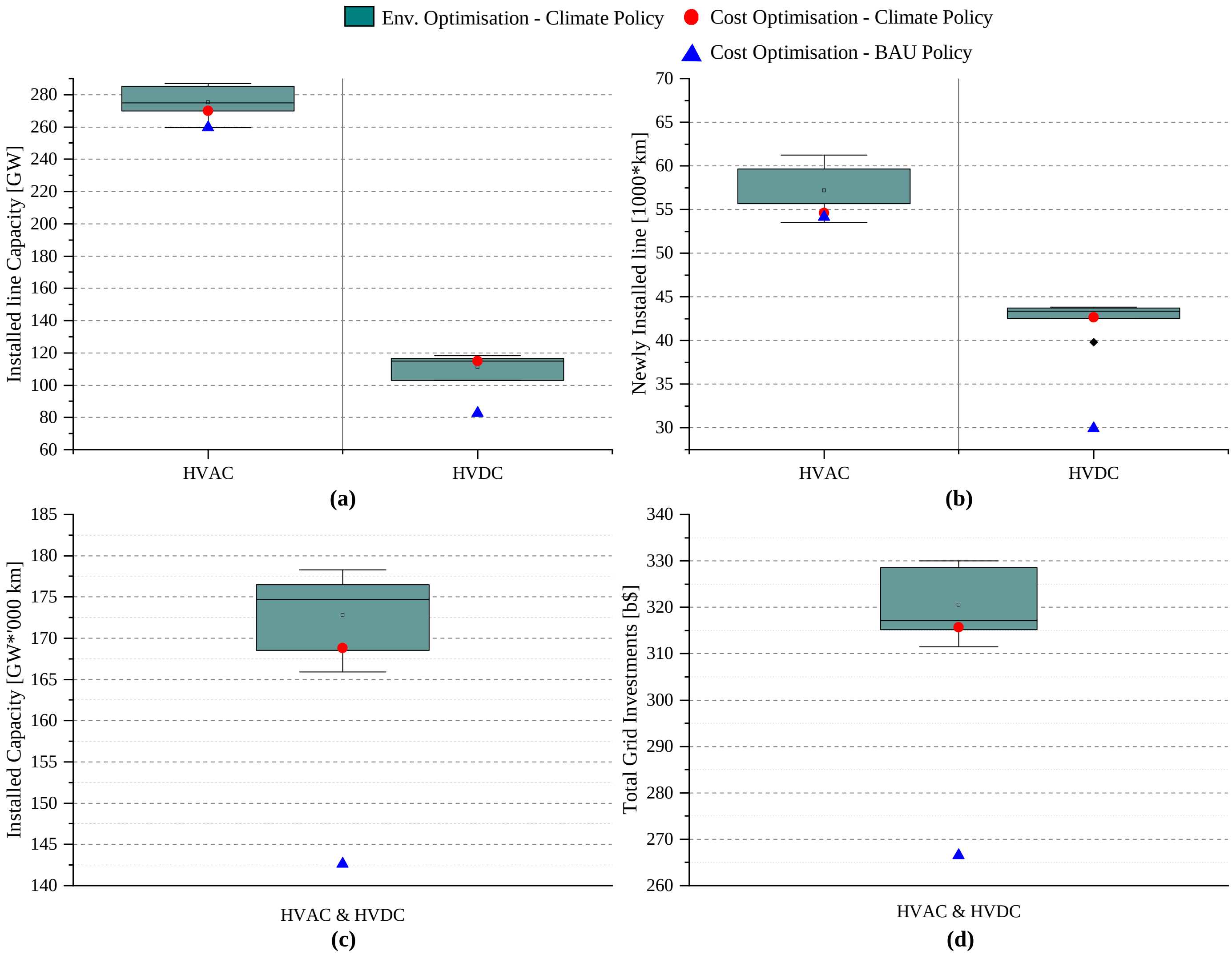

Figure 5: Improvements required in transmission line infrastructure in environmental optimisation and costs optimisation of the electricity system at the European level (EU24) for the period 2010-2050. The infrastructure changes comprised (a) new line capacity and (b) relationship to the length of line installed, (c) summarised for the entire power system and (d) the total investments needed for the power system to support the use of more variable renewable energy sources (VRES).

Table 1: Carbon intensity of investments made in the pan-European electricity transmission network for the period 2010–2050 under costs and environmental (emissions) optimisation.

Optimisation	Scenario	Grid infrastructure investments [b$$_{inv}$]	System cost [b$$_{inv}$]	Emissions [$MtCO_{2eq}$]	Carbon intensity [$kgCO_{2eq}$/$$_{inv}$]
Cost	-	316	7 483	41 032	130
Emissions	EUTGRID - CC - P-BAU	329	9 821	30 899	94
	EUTGRID - CC - P-440ppm	315	9 460	32 094	102
	EUTGRID - CC - RO-440ppm	317	9 377	31 150	98
	EUTGRID - CC - VO-440ppm	312	9 408	30 012	96
	EUTGRID - CC - VO-Renew	330	9 420	30 102	91

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priate. Nevertheless, giving preferences to the environmental weight criteria over the cost criteria put the emission optimisation alternative a rank acceptability of 0.93, meaning that it is clearly the best alternative to enforce. However, giving preferences to any cost related criteria placed the cost optimisation as the best alternative with a rank acceptability of 0.97. The SMAA analysis data are available in SI [31].

4.4. Criteria based on other emissions

The model was primarily designed to optimise climate change-related emissions. However, any other kind of environmental criterion can be set as an objective function. As mentioned earlier, under high penetration of VRES it is foreseeable that nuclear will, to some extent and including technical constraints, contribute to balancing power [33, 3].

For this reason, we examined the possibility of using nuclear power plant flexibility to reduce ionising radiation at the network level, as nuclear is the main contributor to this environmental indicator. Extreme scenarios such as nuclear disasters were not considered when including the nuclear power plant flexibility, as they represent another set of scenarios. Although a small decrease in nuclear usage was identified compared with the climate change indicator optimisation, it was not statistically significant ($p>0.05$). This implies that including ionising radiation in the optimisation equation does not influence the overall emissions as such and that using nuclear power flexibility for environmental purposes does not make any significant difference.

Other indicators were not investigated, as they did not fall within the scope of decarbonisation.

5. Conclusions

This study investigated the impact of using purely environmental criteria as the merit order system under carbon tax incentives. A combined POLES and EUTGRID model was used for this purpose. To include environmental considerations in the decision-making process, a combined module using current and prospective LCA methodologies was added to the EUTGRID model.

The share of RES in the European electricity mix increased by 2.65% under environmental optimisation compared with costs optimisation, which is more conservative. There was also a difference in strategies for power production management. Climate change criteria favoured the use of offshore wind production and decreased the use of coal-based generation at the European level, under the same climate policy constraints. The energy mix varied only slightly at the European level, but with integration of VRES it varied significantly from country to country, even to the extent of changing market strategies. In some cases, some countries (e.g. Austria) changed from importing to exporting power and some (e.g. Norway) did the opposite.

Shifting from an economic to an environmental merit order, but still keeping economic growth consideration from POLES, decreased overall emissions by 9.00%. As time passed and the system became increasingly decarbonised, the CO_{2eq} emissions decreased and tended to converge. However, emissions based on environmental criteria decreased faster and therefore the cumulative emissions concentration in the atmosphere was lower than in the optimisation based on economic objectives. In a way, managing power production based only on an economic merit order will inevitably result in more cumulative CO_{2eq} emissions in the long run than a system based on an environmental merit order. In that case, however, the use of various environmental impacts from LCA studies did not show a significant difference. Moreover, the change of power management is accompanied by a change in infrastructure planning.

The power infrastructure has to evolve to integrate more VRES in the network. With environmental optimisation, the investments in HVAC reinforcements and new lines were slightly higher in power but much higher in distance, implying more low-power HVAC lines. The changes in infrastructure also involved higher costs in the environmental optimisation case, by 6.00 billion US$ or +1.50% compared with costs optimisation.

Climate policy drives the change in power production through economic incentives. Current policy can reach the decarbonisation target set by the EU using a least-cost trajectory. Our research suggests that considering a purely environmental, instead of an economic, merit order would allow decarbonisation to be achieved slightly faster, resulting in lower cumulative GHG emissions to the atmosphere. The gain on the environmental side comes with higher investments in the power system but is counterbalanced by the greater amount of non-emitted GHG. This suggests that including an environmental indicator in the decision-making process on the power system would result in higher investments but would bring more cumulative environmental gains.

The integration of characterised LCA emissions factors involved uncertainty at all levels, and the results should be regarded as a 'best guess'. Work is underway world-wide to produce the best environmental impact estimates for future technologies. As the EUTGRID model is dependent on POLES to set the energy mix per country, in this study it was not possible to influence the investments in the energy production system, which shaped the energy mix for each country up to 2050.

However, environmental impact could be integrated in the upper layer of the EUTGRID model, directly in POLES. It would act as complementary information to the carbon tax already in place and influence the decision-making process. Furthermore, to balance the system, other environmental indicators should be investigated, such as particulate matter formation, which has direct impacts on human health. Our next goal is to find the sweet spot between infrastructure investments costs, environmental emissions and actual system costs. We have already started work on this, in the form of a multi-objective optimisation.

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Appendix A. Indicators

Table A.2: Abbreviations and related units in the ReCiPe environmental impact characterisation method.

Indicator	Abb.	Unit [/kWh$_{pro}$]
Climate change	CC	$kgCO_{2eq}$
Ozone depletion	OD	kgCFC-11$_{eq}$
Terrestrial acidification	TA	$kgSO_{2eq}$
Freshwater eutrophication	FE	kgP_{eq}
Marine eutrophication	ME	kgN_{eq}
Human toxicity	HT	kg1,4-DB$_{eq}$
Photochemical oxidant formation	POF	kgNMVOC
Particulate matter formation	PMF	kgPM10$_{eq}$
Terrestrial ecotoxicity	TEco	kg1,4-DB$_{eq}$
Freshwater ecotoxicity	FEco	kg1,4-DB$_{eq}$
Marine ecotoxicity	MEco	kg1,4-DB$_{eq}$
Ionising radiation	IR	kBqU235$_{eq}$
Agricultural land occupation	ALO	m^2a
Urban land occupation	ULO	m^2a
Natural land transformation	NLT	m^2
Water depletion	WD	m^3
Metal depletion	MD	kgkgFe$_{eq}$
Fossil depletion	FD	kgOil$_{eq}$

Table A.3: The 41 current and prospective technologies considered in the EUT-GRID and POLES model of the electricity production system.

Abbreviation	Name
NUC	Conventional nuclear design
NND	New nuclear design (4th generation)
PFC	pressurised coal supercritical
PSS	pressurised coal supercritical with CCS
ICG	Integrated coal gasification with combined cycle (CC)
ICS	Integrated coal gasification with Combined Cycle and CCS
LCT	Lignite
CCT	Coal Conventional Thermal
GCT	Gas Conventional Thermal
GGT	Gas turbine
GGC	Gas Combined Cycle
GGS	Gas Combined Cycle with CCS
OCT	Oil Conventional thermal
OGC	Oil Combined Cycle
HRR	Hydraulic run-of-river
HLK	Hydraulic with reservoir (lake)
HPS	Pumped hydro
SHY	Small hydro (<10 MW)
OCE	Tidal and wave
GEO	Geothermal
BTE	Biomass Conventional Thermal
BGTE	Biomass and Gasification
BGAE	Biogas
BCS	Biomass Conventional Thermal with CCS
BTC	Biomass with combined heat and power (CHP)
BGTC	Biomass and Gasification with CHP
BGAC	Biogas with CHP
BWC	Biodegradable waste with CHP
WN1	Wind onshore with different wind quality resource (1)
WN2	Wind onshore with different wind quality resource (2)
WN3	Wind onshore with different wind quality resource (3)
WO1	Wind offshore with different wind quality resource (1)
WO2	Wind offshore with different wind quality resource (2)
WO3	Wind offshore with different wind quality resource (3)
CPV	PV power plant (centralised)
DPV	Decentralised PV
SPP	Solar thermal power plant
SPPS	Solar thermal power plant with thermal storage
CHP	Coal Conventional Thermal
HFC	Hydrogen fuel cell
GFC	Gas fuel cells

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