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New approach for assessing and optimising the environmental performance of multinational electricity sectors: A European case study

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ABSTRACT

The aim of energy planning is to achieve a reliable supply of energy resources at competitive costs and with the least negative impacts on society and the environment. However, most of the existing studies tend to ignore environmental impacts, although the electricity sector contributes greatly to environmental degradation. Therefore, the aim of this study is threefold: i) to assess the environmental performance of the most common types of renewable and non-renewable power plants in Europe, ii) to estimate an environmental index for each one of the electricity sectors in the European countries, and iii) to evaluate and optimise the environmental behaviour of the European electricity sector as a whole; in all cases taking into account fifteen environmental midpoint indicators with a cradle-to-grave approach. A combined procedure including a multi-criteria decision making model and an optimisation approach under three different scenarios was used for such a purpose. According to the results, hydro as well onshore and offshore wind resulted to be the best alternatives with environmental indices above 0.95 (being 1 the maximum possible value), while biogas and oil-fired power plants usually occupied the last positions of the ranking, with indices below 0.5. Some countries achieved outstanding environmental results such as Austria, Croatia, Ireland, Lithuania, Luxembourg, Latvia or Sweden, with indices always above 0.85, while Bulgaria, Cyprus, Estonia or Poland obtained discouraging results, since their production is largely based on oil, lignite or hard coal. Europe should boost hydro, onshore and offshore wind and natural gas power plants in order to improve its current index of 0.7363.

1. Introduction

Electricity is essential to the development of modern economies [1]. In fact, it is indispensable for almost any type of social and economic activity [2], and, as such, it facilitates both the technological progress and economic growth of a country [1]. In meeting human needs, such as transport, lighting or cooking, among others, electricity plays a key role; it is also crucial for the majority of industrial processes [3]. Therefore, it can be stated that electricity is a determinant factor for the economic [2], social [4] and technical development of a nation. In this sense, providing universal access to electricity is a priority [4], although reaching this goal is an ongoing process. Furthermore, as world population figures rise and nations, particularly developing ones, are increasingly technified, the demand for electricity steadily grows [5], a trend that is likely to continue in the near future.

On the other hand, all power generation alternatives cause some type of negative impact [6]. It is a well-known fact that the electric sector contributes greatly to climate change [7] through the emission of greenhouse gases (GHG) [8]. Consequently, the European Union [9] and a growing number of countries around the world such as Spain or Peru [10], among others, are adopting measures in the power sector to fight against global warming. Nevertheless, power plants, including those

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Table 1
Existing studies addressing different energy planning problems.

Source	Year	Type of problem	Method/model	Application	Description
[31]	2000	GEP	New genetic algorithm (GA)	Two generic systems	Total discounted cost minimisation.
[32]	2000	Future scenario assessment	Optimisation model combined with the Analytic Hierarchy Process (AHP)	Spain	The MCDM model includes total costs, radioactive waste, and the following emission rates: CO_2, NO_x and SO_2.
[33]	2002	Assessment of technologies and future energy scenarios	Optimisation technique combined with AHP	Spain	The MCDM model includes the same indicators defined in Ref. [32]. Definition of four scenarios based on the Spanish Ministry of Industry.
[34]	2003	Technology selection	ELimination Et Choice Translating Reality (ELECTRE) method	Sardinia (Italy)	Assessment of different power plants by taking into account economic, social and environmental indicators. Application of a MCDM method. Environmental issues are measured in a qualitative way.
[35]	2004	GEP	New interactive algorithm	Example close to Portugal	Multi-objective problem including: total expansion costs, environmental impacts and environmental costs. Environmental issues limited to CO_2, SO_2 and NO_x.
[36]	2005	Distributed generation (DG)	GA	Example of distributed network	Sizing and siting distributed generation. Multi-objective problem including costs such as the ones derived from service interruptions or energy losses.
[37]	2006	GEP	GA and adaptive simulated annealing genetic algorithm (ASAGA)	Turkey	Total cost minimisation.
[38]	2006	GEP	GA	Thailand	Total cost minimisation including the ones derived from SO_2 and PM emissions.
[39]	2006	Portfolio generation and optimisation	Portfolio-based approach	European Union, United States and Mexico	Generation of portfolios to illustrate how renewables can contribute to both reduce costs and improve energy security.
[40]	2007	GEP	Multi-criteria programming method together with AHP	Mexico	Four objective functions: i) investment, operation and transmission costs, ii) amount of imported fuel, iii) CO_2 emissions, and iv) the fuel price risk.
[41]	2007	GEP and technology assessment	Value function multi-criteria approach	South Africa	Identification of the preferred portfolio of alternatives. The study includes the total discounted costs and environmental indicators: emissions of CO_2 and SO_2 as well as water consumption.
[42]	2007	Scenario development and assessment	Long range energy alternatives planning system (LEAP) model	China	Special focus on CO_2 emissions.
[43]	2008	GEP	Linear programming optimisation tool: MARKet and Allocation (MARKAL) model	Vietnam	Total discounted cost minimisation including the internalisation of the following pollutants: CO_2, NO_x, SO_2 and PM.
[44]	2008	Mix diversification	Mean-variance portfolio technique combined with Monte Carlo simulation	Liberalised electricity markets	The authors explored the correlation between CO_2 emissions and electricity prices.
[45]	2008	Optimal allocation of electricity forward contracts	Mean-variance approach	Two generic cases	Consideration of volumetric and price risks.
[46]	2008	Scenario generation and optimisation, GEP	Simulation model combined with simultaneous optimisation	Spain	The study is limited to economic issues, CO_2 emissions and energy production.
[47]	2009	GEP	Evolutionary algorithm, K-means algorithm and AHP	Mexico	Same objective functions defined in Ref. [40]. The transmission network was modelled in a more realistic way.
[48]	2010	GEP	New mixed integer linear programming model	Malaysia	Total cost minimisation. Integration of renewable energy systems.
[49]	2010	Energy system management	Multi-objective optimisation model together with business-as-usual (BAU) scenario generation	Portugal	Multi-objective optimisation problem including costs as well as the optimal management of intermittencies. Massive penetration of renewables.
[50]	2010	Scenario generation and assessment	LEAP model	Bangladesh	Estimation of future electricity demand.
[51]	2010	Scenario development and assessment	MARKAL model	Philippines, Indonesia and Vietnam	The authors analysed both costs and CO_2 emissions.
[52]	2010	Portfolio allocation	Mean-variance-skewness model combined with an adapted particle swarm optimisation (PSO) algorithm	Pennsylvania, New Jersey, and Maryland (PJM) electricity market, (United States)	Return maximisation and risk minimisation.
[53]	2011	GEP in pool markets	PSO	–	Profit maximisation. Case study including three generation companies and several types of power plants
[54]	2011	GEP	GA	–	Profit maximisation. Case study including three generation companies and 8 technologies.

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Table 1 (*continued*)

Source	Year	Type of problem	Method/model	Application	Description
[55]	2011	Environmental impact assessment	LCA approach	world	Large-scale introduction of 120-MW onshore and 250-MW offshore wind farms. The following environmental impacts were taken into account: climate change, marine eutrophication, terrestrial acidification and photochemical oxidant formation.
[56]	2011	Electricity mix generation and assessment	Mean-variance portfolio theory (MVPT)	Scotland	Risk and cost assessment of technologies. Incorporation of wave and tidal alternatives.
[57]	2012	DG expansion	Modified honey bee mating algorithm together with chaotic local search	Generic distribution network	Multi-objective problem including the following objective functions: cost, emissions and voltage profile.
[58]	2012	Optimal portfolio generation	Mean-variance optimisation	Turkey	Portfolio optimisation for natural gas combined cycle power plants, lignite-fired thermal plants and hydro power plants.
[59]	2012	Scenario generation and environmental assessment	LCA technique, in particular the environmental design of industrial products (EDIP) 2003 method.	Denmark	The following environmental impacts were studied: global warming, acidification, aquatic eutrophication and land occupation.
[60]	2012	Electricity portfolio management	MPT together with stochastic optimisation	Scandinavian retailer	Total discounted cost minimisation.
[61]	2013	GEP	Lexicographic optimisation technique combined with a boundary intersection method	Generic system	Multi-objective problem: reliability maximisation and minimisation of both costs and CO_2 emissions.
[16]	2013	Energy mix generation and optimisation	LCA approach together with an optimisation model	Belgium	The environmental dimension of the model is limited to global warming, land use and human toxicity.
[62]	2013	GEP	MVPT	Brazil	Costs, risks and CO_2 emissions are taken into account.
[63]	2013	GEP	Stochastic optimisation model based on Monte Carlo simulation and Benders decomposition	Generic model	Investment and operation costs minimisation.
[64]	2014	GEP	Branch and bound algorithm	United Kingdom	Two objective functions: minimisation of both costs and global warming potential
[65]	2014	GEP	Stochastic dynamic programming	Hokkaido (Japan)	Total cost minimisation. Constraints associated with CO_2 emissions and supply reliability. Mass penetration of renewables.
[66]	2014	GEP	GA	Turkey	Total cost minimisation under the consideration of increasing the penetration of renewables.
[67]	2014	Technology assessment	Multi-criteria method based on a simple additive weighting approach	Brazilian Amazon	Rural electrification. The model includes economic, technical, environmental, social and institutional indicators.Most of the indicators are assessed through a scale that varies between 0 and 100.In terms of emissions, this study only includes GHG.
[68]	2014	Microgrid sizing	GA	Dongfushan (China)	Optimal microgrid sizing including minimisation of both costs and emissions (SO_2, CO, CO_2, NO_x and dust), as well as renewable penetration maximisation.
[69]	2014	Environmental assessment of power plants	LCA approach	Portugal	The focus is on fossil power plants. The study is limited to 6 environmental impacts.
[6]	2014	Scenario generation and optimisation	Combination of LCA and a linear programming model	Greece	Cost minimisation including externalities. The external costs are estimated for pollutants instead of being calculated for environmental impact categories.
[70]	2014	Scenario development and environmental assessment	Mixed integer linear programming and LCA approach	Ireland	Cost minimisation. Only the following pollutants were included: CO_2, NO_x and SO_2. High penetration of wind.
[13]	2014	Scenario generation and environmental assessment	The LCA model environmental assessment system for environmental technologies (EASETECH) Energy	Denmark	The model includes twelve environmental impact indicators.
[71]	2014	Optimal electricity allocation	Mean-variance-skewness model together with different multi-objective genetic algorithms	Two generic case studies	Return and skewness maximisation. Portfolio variance minimisation.
[72]	2014	Portfolio selection	MPT and learning curves	Taiwan	Costs and risk minimisation.It includes a constraint for limiting CO_2 emissions.
[73]	2015	Technology assessment	MCDM method based on the principal component analysis	Illustration example in India	Rural electrification. The model includes economic, social, environmental, technical and institutional criteria. From an environmental point of view, only GHG emissions and land used are assessed.

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Table 1 (*continued*)

Source	Year	Type of problem	Method/model	Application	Description
[10]	2015	Environmental assessment of electrical mixes	LCA method, in particular ReCiPe	Spain and Peru	Testing the extent to which policies aimed at combating climate change affect other environmental impacts. Special focus on GHG emissions.
[74]	2015	Scenario generation and assessment	Scenario generation through a linear programming tool	England, Scotland and Wales	Different generation levels for renewables, nuclear and fossil fuels. The following aspects were analysed: energy security, levelised costs, and equivalent CO_2 emissions.
[75]	2015	Scenario development and assessment	LCA approach and multi-criteria geographic information system (GIS)	California (United States)	Special focus on land use and decarbonisation.
[76]	2016	GEP	Mixed integer linear programming model: eMix	Poland	Total cost minimisation including CO_2 emission allowances.
[77]	2016	GEP	PSO	Generic system	Total cost minimisation including those derived from the emission of CO_2, SO_2 and NO_x. Inclusion of large-scale energy storage systems.
[78]	2016	GEP	Mixed-integer linear programming problem solved with the CPLEX (initially abbreviation of C programming and simplex) solver	Portugal	Single and multi-objective optimisation problems, establishing CO_2 emissions and costs as objective functions.
[79]	2016	GEP	Linear programming model	United States	Cost minimisation. Mass penetration of renewables.
[80]	2016	Energy system management	Mixed integer linear programming algorithm	Helsinki (Finland)	Marginal costs minimisation and marginal revenues maximisation. Optimal managing of the entire power system with a considerable presence of variable renewables.
[81]	2016	Technology assessment and finding the renewable optimal mix	MARKAL model and the aggregated preferenceindices system (APIS) method	United Kingdom	Ranking of different types of power plants according to economic, social and environmental indicators.In terms of environmental impacts, the model is limited to CO_2 emissions and the use of land and water.
[82]	2016	Scenario generation and assessment	Optimisation model combined with a LCA approach	Norway	Climate change, ecosystem quality and impact on human health are the environmental indicators included in this study.
[83]	2016	Scenario generation and assessment	Optimisation model combined with a LCA approach	Europe	The authors analysed the following environmental indicators: climate change, freshwater ecotoxicity and eutrophication impacts as well as particulate matter formation, land occupation and mineral resource depletion. Year 2050.
[84]	2016	Scenario development and assessment	LEAP model	Thailand and Indonesia	Identification of the scenario with the lowest costs. Calculation of CO_2 emissions.
[1]	2016	Risk and uncertainty consideration in GEP	Scenario generation combined with Monte Carlo simulation and a optimisation model	Case close to Portugal	The scenarios are compared according to the costs, CO_2 emissions, share of renewables and electricity production excess.
[23]	2016	Scenario generation and environmental assessment	LCA method, in particular ReCiPe	United Arab Emirates	The environmental results are limited to climate change, human toxicity, terrestrial acidification, ecotoxicity, metal depletion and particulate matter.
[85]	2017	GEP	Mixed-integer nonlinear programming model solved with the Discrete Continuous Optimisation Package (DICOPT) solver	Portugal	Minimisation of fixed and variable costs. Integration of renewables in hydro-thermal-wind electrical systems.
[86]	2017	GEP	Mixed integer linear programming model combined with the ReCiPe LCA method.	Germany	Multi-objective problem including both cost and environmental impacts minimisation.It includes 17 environmental midpoint indicators.
[87]	2017	Microgrid sizing	GA	Five generic cases	Minimisation of the microgrid operation costs
[88]	2017	Technology assessment	AHP	Jordan	Assessment of the most relevant types of power plants. The model includes costs, CO_2 emissions, employment generation, or accidents, among other indicators.
[89]	2017	Power system expansion and assessment	LEAP model	Java-Bali (Indonesia)	Analysis of the trade-offs between power system expansion and CO_2 mitigation.
[3]	2018	GEP	Multi-objective linear problem solved with the Interactive Multi-Objective Linear Programming explorer (iMOLPE)	Brazil	Multi-objective problem including cost minimisation and the maximisation of both peak load generation and non-hydro renewables contribution. Mass penetration of renewables.
[90]	2018	Scenario generation and environmental optimisation	LCA approach together with a linear programming model	Switzerland	Global warming, land use, particulate matter, cumulative energy demand and water scarcity were the impacts studied. Special focus on bioenergy.
[91]	2018	Scenarios generation and management	GIS combined with optimisation procedures	Catania (Italy)	Reduction of CO_2 emissions. Energy exchanges minimisation. Urban approach.

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Table 1 (*continued*)

Source	Year	Type of problem	Method/model	Application	Description
[92]	2019	Technology assessment, scenario generation and microgrid optimisation	AHP together with the optimisation tool hybrid optimisation of multiple energy resources (HOMER PRO)	Remote region (India)	The MCDM model includes social, economic, environmental and technical indicators. A limited number of pollutants are included in the environmental dimension: CO, CO_2, NOx or SO_2, among others. Size and costs are optimised.
[93]	2019	Scenario development and assessment	LEAP model	Pakistan	Assessment of costs, job creation and CO_2 emissions.
[8]	2019	Scenario generation and optimisation	New approach for developing future scenarios together with a multi-period linear programming model	Chile	Cost optimisation. Massive penetration of renewables. Analysis of storage options.
[9]	2020	Scenario generation and assessment	Specific methodology for scenario generation	Italy	Special focus on power sector decarbonisation.
[21]	2020	Renewable energy expansion	Scenario generation, IO analysis and linear programming.	Indonesia	Cost minimisation. Environmental impacts are modelled as constraints. The environmental dimension is limited to GHG emissions and resource consumption.
[94]	2021	Analysis of the electricity demand pattern	Linear optimisation tool	Europe	Total cost minimisation. A CO_2 emissions constraint was established.
[95]	2021	Scenario generation and optimisation	New optimisation model: flexibility from interconnections and electricity storage (FLEXIES)	Central Europe	Total cost minimisation. CO_2 emissions assessment and comparison among scenarios.
[96]	2021	GEP	PSO	Iran	Total cost minimisation. The costs derived from the emission of CO_2 are included.
[97]	2021	GEP	Mixed integer linear programming problem solved using the CPLEX solver.	Pakistan	Cost minimisation. Technical and environmental constraints were defined. The latter one only considers CO_2 emissions.
[98]	2021	Scenario generation and assessment	The advanced analysis of smart energy systems (EnergyPLAN) model	Montenegro	Technical, economic and environmental aspects are assessed and compared. Analysis of CO_2 emissions.
[99]	2021	Scenario generation and assessment	EnergyPLAN model	Kosovo	High penetration of renewables. Assessment of both total costs and CO_2 emissions.
[100]	2022	Energy system modelling and expansion	Linear optimisation tool	Europe	Environmental assessment is limited to particulate matter and CO_2 emissions.
[101]	2022	Scenario development, assessment and optimisation	Combination of analytical network process (ANP), a linear programming model and a MCDM method, in particular the VIekriterijumsko KOmpromisno Rangiranje (VIKOR) one	Iran	The MCDM model includes economic, social technical and environmental indicators. The following environmental impact categories were included: global warming, acidification, human toxicity, land use, and water consumption.
[102]	2022	Scenario generation and optimisation	Next energy modelling system for optimisation (NEMO)	Indonesia	Cost minimisation including the ones derived from CO_2 emissions.
[103]	2022	Generation and storage expansion planning (GSEP)	Mixed integer linear programming model	São Vicente (Cape Verde)	Cumulative cost minimisation. Only the costs derived from CO_2 emissions are considered.
[104]	2022	GEP	Investment decision model (MDI)	Brazil	Total cost minimisation. GHG emissions were studied.
[105]	2022	GEP	Mixed integer linear programming model	Turkey	Total cost minimisation. Employment generation maximisation. GHG emissions minimisation. Gross domestic product maximisation.

reliant on renewable sources, can contribute to environmental impacts including acidification, eutrophication, human toxicity [11] or water depletion [12], in addition to climate change. These negative impacts usually receive less attention in the specialised literature. Authors such as Vázquez-Rowe et al. [10] or Turconi et al. [13] point out that, by focusing solely on climate change goals, stakeholders are overlooking other factors that can have pernicious consequences.

Therefore, politicians, academia and, in general, decision-makers in the energy sector face increasingly complex energy policy concerns [14]. In other words, a range of energy planning problems can arise; these vary in terms of objectives, as well as in geographical reach and temporal scope. However, the first and foremost objective of energy planning is to meet the growing demand for energy, guaranteeing an interrupted and quality supply. Some of the most common energy planning problems are briefly described below.

One such a problem is related to generation expansion planning (GEP). As its name suggests, GEP entails finding the best alternatives and determining their optimal size to complement the electricity system currently in place and cover the demand expected over a given time horizon [15]. GEP was initially understood as an economic problem subject to economic and technical constraints [14]. That is, the objective would involve finding the least-costly option for expansion. Integrating renewables into existing energy systems is another recurrent challenge for energy planning. Although there are exceptions [11], renewable power plants usually generate fewer environmental impacts when compared with conventional energy sources. However, electricity production from renewables is often conditioned by both intermittency and uncertainty, making energy system management more complicated. Other energy planning problems are not necessarily the result of expanding an existing energy system or integrating renewables. For example, the best options must be sought to replace power plants approaching the end of their useful lives. In this case, the energy planning problem involves using different criteria to assess existing technologies and help stakeholders choose the ones that should be promoted in the future. Although this alone would not guarantee the coverage of the energy demand, it is the first step towards solving this problem efficiently. Other issues related to energy planning include the generation and assessment of potential future scenarios, the optimal sizing and siting of energy systems, the diversification of the energy system, sizing a microgrid in an optimal way, or the optimal energy system management under specific conditions, among many others.

A decision-making process lies behind every energy planning problem, irrespective of the specific type. These decisions are made according to a wide range of criteria, the most common of which is total cost minimisation, as previously indicated for GEP problems. In recent years, however, it has become accepted that environmental [16], social [17], and newly emergent technical [18] or geo-political issues should be taken into account when energy planning problems are being addressed. An extensive analysis of the existing literature has revealed that the environmental dimension has not yet been fully considered. In their attempt to formulate and tackle energy planning problems, many authors continue to overlook environmental aspects. Furthermore, those who do take into account environmental criteria often need to go further. Their analysis may have only focused on the emission of certain pollutants or, at best, on a small number of environmental impact categories, such as global warming. The present study aims to bridge this gap by demonstrating how to carry out a thorough analysis of environmental aspects when defining and solving energy planning problems. For this task, three types of techniques, widely used in energy research, come into play. The intention is for a sound foundation to be built so that authors can carry out studies knowing that no relevant environmental impact has been overlooked.

Before further information is provided on the specific objectives and novel aspects of this work, an overview of existing studies is necessary. A great number of authors have addressed energy planning problems with different objectives in mind and by adopting diverse methodological approaches. The most common approach is to formulate and solve single or multi-objective optimisation problems [19]. Among other options are multi-criteria decision making (MCDM) methods [20], life cycle assessment (LCA) [10], deterministic models, probabilistic simulation [1], input–output (IO) models [21], cost-benefit analysis, modern portfolio theory (MPT) [22] (also known as portfolio optimisation) and, in particular, mean–variance analysis, scenario generation and assessment [23], general [24] and partial [19] equilibrium models, among others. Hybrid approaches combine two or more of the previous options. Table 1 lists some of the most representative studies to date.

The reader should bear in mind that providing a detailed literature review falls outside the scope of this work. For further information on literature reviews, the reader is referred to Connolly et al. [25] (tools for integrating renewables), Deng and Lv [18] (review of optimisation models), Gamarra and Guerrero [26] (microgrid-oriented optimisation techniques), Hansen et al. [27] (review of fully renewable energy systems), Huang et al. [28] (urban energy planning studies), Løken [29] (multi-criteria decision analysis for energy planning), Oree et al. [14] (review of GEP studies with special focus on renewable integration), Pérez Odeh et al. [17] (portfolio optimisation) and Ringkjøb et al. [30] (energy modelling tools review), to name a few.

From the existing literature, it is clear that a great number of authors have considered energy planning problems. Although there are models for dealing with almost every single potential problem to be solved, mostly on an individual basis [30], no study is capable of addressing all the challenges that energy systems face today.

Nevertheless, certain gaps in current knowledge have yet to be addressed. As previously indicated, there is much to be done from an environmental point of view. Environmental impacts are overlooked in many of the existing models. In other cases, environmental issues are only addressed as constraints in optimisation models, in the form of emission rate limits [14]. Even when authors define explicit environmental objectives, two main limitations remain:

- The authors analyse emissions from certain pollutants (for example: CO_2, SO_2 or NO_x, among others) instead of working with environmental impact categories such as acidification, eutrophication or global warming. This limitation is of paramount importance because the same pollutant can contribute to more than one environmental impact. By way of example, nitrogen dioxide can be harmful in terms of human toxicity, acidification or eutrophication. However, a substance that contributes to several environmental indicators may not do so in a uniform way or to the same degree (characterisation factors). For this reason, quantifying, limiting or controlling the emission of certain substances does not necessary lead to solid results (and conclusions) from an environmental point of view. From Table 1, it is clear that most of the existing studies only analyse a limited number of pollutants, CO_2 being the most common one.
- A limited number of environmental impacts are analysed; in most cases, only global warming is studied. Climate change is one of the greatest challenges that current and future generations have to face. It has already been mentioned that electricity production is among human activities that contribute most to climate change. This production, however, also causes other types of environmental degradation. If only global warming is addressed when energy planning issues are tackled, the temperature increase that the planet is experiencing might be stalled. Yet there the risk remains that the current situation will also worsen due to other environmental impacts. In other words, climate change should not be tackled by significantly increasing acidification, resource consumption, ecotoxicity or other environmental impacts. All the relevant environmental impact categories should be analysed, yet Table 1 shows that most of the existing studies only consider one environmental indicator.

Few authors addressed the environmental dimension of energy planning in depth, including a significant number of the possible environmental impact categories. These include studies by Vázquez-Rowe et al. [10] for Spain and Peru, Treyer and Bauer [23] for the United Arab Emirates, Garcia et al. [69] for Portugal, or Rauner and Budzinski [86] for Germany, among others (Table 1). As can be seen, such studies are limited to only one or two countries. In fact, energy planning studies with a local, regional or national scope are more abundant than those that go farther afield (Table 1): another gap to be filled in the existing literature. Studies with a broader geographical scope (for example, Europe) usually present one of the above-mentioned shortcomings (limited number of pollutants or only one environmental impact). The study by Berril et al. [83] is one of the few exceptions. The authors analysed Europe with particular focus on the penetration of renewables. Six environmental indicators were included for this purpose. One way to improve the study by Berril et al. [83] would be to increase the number of environmental impact categories, since there are more than six potential ways of degrading the environment. An alternative way of improving this study (also applicable to others that consider more than one environmental impact) is to integrate the environmental results into a single index. Doing so would facilitate decision making processes and help establish environmental objective functions (optimisation problems).

This study aims to bridge some of the gaps in the current knowledge, with Europe considered a case study (year 2017). The main objectives, as well as novel aspects, of this work are:

- A MCDM model based on the Integrated Value Model for Sustainability Assessment (MIVES[1]) method is used to assess the environmental performance of the electricity sector in each country belonging to the EU-27 (European Union) and also the electricity sector in the United Kingdom (UK) for 2017. The input values to this model are the results obtained for the 15 environmental midpoint indicators recommended by the International Reference Life Cycle Data System Handbook (ILCD) [106]. Such input values were estimated through several LCA studies carried out with GaBi software and its corresponding databases. Based on the input data, the MIVES model generates a dimensionless number for each type of power plant and also for each country, herein called Environmental Index (*EI*) and Country Environmental Index (*CEI*), respectively, the latter of which measures the environmental performance of a country's electricity sector. The following types of power plants are considered: biogas (PP1), biomass (PP2), coal gas (PP3), hard coal (PP4), oil (PP5), hydro (PP6), lignite (PP7), natural gas (PP8), nuclear (PP9), peat (PP10), photovoltaic (PP11), waste (PP12) and onshore and offshore wind (PP13) alternatives. To determine the share of electricity production for each these 13 technologies in every country, the 2017 Eurostat database was consulted [107]. The reader should bear in mind that solar thermal, geothermal or wave and tidal power, among other options, were not addressed in this study; these alternatives represent a very small percentage of the electricity produced in the EU-27 and UK [107]. To the best of the authors' knowledge, this is the first time that a MCDM model- based on thorough information from LCA studies- has been used to quantify the environmental performance of each type of power plant and of each electricity sector belonging to EU-27 and UK countries. This is valuable information that could be used in different energy planning applications.
- The MIVES model together with the LCA input data and the participation of each type of power plant in each country for the year 2017 was used to estimate a European Environmental Index (*EEI*). This index provides an insight into the environmental performance of the European electricity sector as a whole. No similar application has been found in the existing literature. It is important to note that with the model presented here, along with the corresponding input data, the reader could perform similar assessments for other groups of countries (*CEIs* and *EEIs*) for other years.
- The third main objective is to demonstrate how useful it can be to integrate the MIVES model into other existing energy planning tools as an aid for the decision-making process for the electricity sector. Thus, these energy planning decisions will be based on an exhaustive environmental analysis. The MIVES model must be integrated into tools that consider constraints arising from: physical processes [14], resource availability [14], energy storage [18], generation capacity [12], plant size [12], reliability [15], legal and political issues [78], the transmission grid [18] and stakeholders, among other factors. To demonstrate the usefulness of the proposed approach, an optimisation problem is formulated and solved for three different scenarios. The objective was to maximise the *EEI* under different constraints; the electricity production of each type of power plant in each country (in relation to the total) served as the optimisation variable to be calculated. The results would help determine which types of power plants should be promoted in each country according to the technology each has installed. Similarly, the results would also make it easier to identify which technologies should not be boosted. Further research is needed on these undesirable technologies in an effort to counter their negative environmental impacts. Moreover, the *EEI* can be one of the multiple objective functions used in an energy planning tool that incorporates the model described here. In other words, the ultimate target of energy planning must be to achieve an optimal energy system in terms of integral sustainability, a goal that is outside this study's remit. Nevertheless, this study can be seen as an intermediate step towards achieving this ambitious goal. On the other hand, the results presented here will serve to clarify where the EU electricity policies should be directed from an environmental perspective in years to come.
- From a methodological point of view, this is the first time that MIVES (MCDM method) is combined with the results derived from LCA studies (input values) for defining and solving an optimisation problem in the energy planning field.

To the best of the authors' knowledge, no similar study exists in the current literature. The remainder of this paper is structured as follows. The calculation procedure implemented in this study is described in Section 2 (Materials and methods). It includes a brief overview of the MIVES method, as well as the description of the model based on this method. The way in which *CEIs* and *EEI* are calculated is also explained in Section 2. All the information related to the proposed optimisation problem can also be found in Section 2. The results are presented in Section 3 and discussed in Section 4. Finally, the main conclusions, as along with potential future developments, are contained in Section 5.

2. Materials and methods

Fig. 1 includes a flowchart with the two main steps followed in this study. It is clearly divided into two main stages: assessment and optimisation.

In the assessment phase, the starting point is to estimate the input data feeding the MIVES model. These input values are the result of performing several LCA studies following the ILCD recommendations [106]. Together with the Professional [108] and Energy [109] Thinkstep databases, GaBi software was used to this end. With the software and databases, it was possible to determine the average impact for every midpoint indicator included in Fig. 2 for each one of the 28 countries. In this way, for example, the average amount in kg of equivalent CO_2 (climate change indicator) emitted at the time of producing 1 kWh of electricity in hard coal-fired power plants in Spain was calculated. Similarly, with the software and databases, the equivalent average results were determined for all the indicators, for all types of power plants in the 28 countries studied. Exceptions arise; these will be explained later. It is important to clarify that a detailed explanation about LCA techniques falls out of the scope of this study. Nor was it an objective of this article to provide all the values obtained to feed the MIVES model for each technology and country. However, the reader can find, in Table A.1 (Appendix A), the minimum and maximum values that each type of power plant adopts for each midpoint indicator, as well as the associated country.

In the next step, the MIVES model comes into play and, therefore, a brief explanation of this method is needed. MCDM methods are valuable tools for assessing energy planning problems. They allow the user to compare and rank different alternatives according to multiple criteria. Consequently, these techniques are suitable for deciding on the best power plant (or set of power plants). Their relative simplicity makes them easy to integrate into more complex energy planning models.

MIVES is a deterministic MCDM method based on the use of requirement trees and value functions [110]. A requirement tree is a hierarchical outline that usually consists of three disaggregation levels: requirements, criteria and indicators. In the third level, the specific characteristics of the alternative under assessment are analysed. The other two levels facilitate the calculation process and make it easier to understand the problem. By means of a value function, the performance of each indicator of the model is assessed. Value functions are

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[1] The acronym corresponds to the Spanish name of the method: Modelo Integrado de Valor para una Evaluación Sostenible.

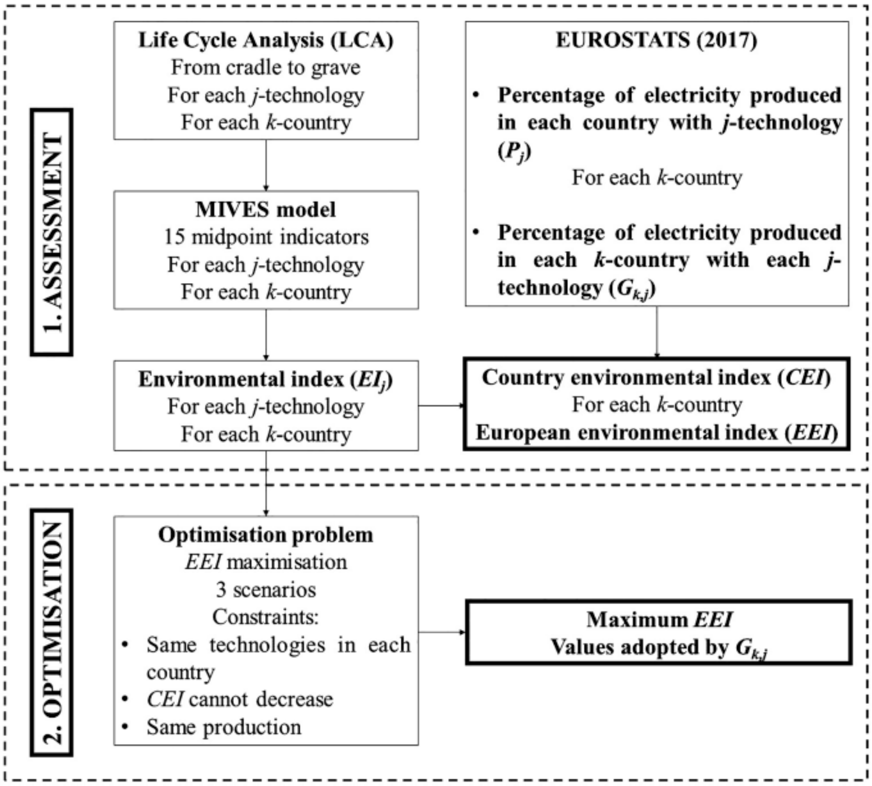

Fig. 1. Flowchart for the procedure followed in this study.

ENVIRONMENTAL MIDPOINT INDICATORS
Climate change (kg $CO_{2\text{-eq.}}$), 11.2%
Acidification (Mole $H^{+}_{eq.}$), 7.4%
Ecotoxicity, freshwater (CTUe), 8.2%
Eutrophication, freshwater (kg $P_{eq.}$), 5.5%
Eutrophication, marine (kg $N_{eq.}$), 1.2%
Eutrophication, terrestrial (Mole $N_{eq.}$), 1.2%
Human toxicity, cancer (CTUh), 0.5%
Human toxicity, non-cancer (CTUh), 8.0%
Ionising radiation (kBq $U235_{eq.}$), 6.9%
Ozone depletion (kg CFC-$11_{eq.}$), 7.5%
Particulate matter (kg PM $2.5_{eq.}$), 8.1%
Photochemical ozone formation (kg NMVOC), 7.8%
Resource depletion, water ($m^{3}_{eq.}$), 9.7%
Resource depletion, minerals, fossils and renewables (kg $Sb_{eq.}$), 8.1%
Land Use Indicator Value Calculation in Life Cycle Assessment (points), 8.7%

Fig. 2. Environmental midpoint indicators, their units of measurement and their weights. CTUe: Comparative toxic unit ecotoxicity, CTUh: Comparative toxic unit for human, NMVOC: Non-methane volatile organic compounds.

mathematical tools that serve to transform the different units of the indicators into a common and dimensionless parameter called value or level of satisfaction (V_i), Eq. (1) [111].

$$V_i = \frac{1 - \exp\left(- m_i \cdot \left(\frac{|P_i - P_{i,\min}|}{n_i} \right)^{A_i} \right)}{1 - \exp\left(- m_i \cdot \left(\frac{|P_{i,\max} - P_{i,\min}|}{n_i} \right)^{A_i} \right)} \tag{1}$$

In Eq. (1), P_i is the input value of the alternative under assessment for a specific indicator. In this case, P_i will be the value that each power plant (in each country) adopts for a specific environmental indicator (Fig. 2). For instance, this might be the amount in kg of equivalent CO_2 (climate change indicator) emitted in hard coal-fired power plants in Spain. $P_{i,\min}$ and $P_{i,\max}$ are the input values associated with the minimum (0) and maximum (1) levels of satisfaction for that indicator, respectively. The parameters m_i, n_i and A_i serve to define different geometries for the value functions, allowing the user to consider potential non-linearities in the assessment by employing concave, convex or s-shaped geometries. On the other hand, once an alternative is evaluated for a specific indicator by using the corresponding value function (Eq. (1)), the dimensionless parameter V_i is obtained. It varies between 0 and 1, once again, the minimum and maximum levels of satisfaction, respectively. That is, V_i measures how an alternative performs in terms of a specific indicator. Since V_i is a dimensionless parameter, it allows the user to compare, for example, the performance of an alternative according to different indicators, measured with different units.

Once a specific alternative is assessed in terms of all the indicators included in the requirement tree, the corresponding V_i values are calculated. Consequently, they can be aggregated by a weighted sum with the objective of obtaining a single index (I) (Eq. (2)) [110].

$$I = \sum_{i=1}^{n} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i \tag{2}$$

This index (I) serves to measure the global performance of the alternative under assessment. It also varies between 0 and 1, the worst and best possible scores, respectively. In Eq. (2), n is the number of indicators on the requirement tree and, α_i, β_i and γ_i are the weights for the requirements, criteria and indicators, respectively. The definition of the weights can be done by direct allocation, although MIVES also integrates AHP [112] as alternative. The weights can also be based on the existing literature, as is the case in this study.

In this study, A MIVES model previously defined and employed in Cartelle Barros et al. [11] (although with a different purpose from the one pursued here) is used. It includes the 15 (n = 15) environmental indicators shown in Fig. 2. The model serves to assess the environmental performance of a specific power plant by providing an environmental index (*EI*), the result of applying the general MIVES equation (Eq. (1)). The weights for the criteria are included in Fig. 2 and they are based on the relative importance factors proposed by Kupfer et al. [113]. The weights for the other two levels of the requirement tree always adopt a value of 100 % [11].

The units of measurement are also included in Fig. 2. It is important to note that these units are associated with the production of 1 kWh of electricity. In other words, if the specific terminology of LCA studies is adopted, 1 kWh would be the functional unit [11] for each indicator. The scope of the indicators is from cradle to grave, but certain exceptions are explained in Ref. [11]. The reader can also find more information about environmental indicators in Kupfer et al. [113]. Further details about the 13 types of energy systems considered in this study are provided in the Professional [108] and Energy [109] Thinkstep databases. Consequently, by using the MIVES model and the data from the LCA studies, it is possible to estimate the environmental index (*EI*) of each type of power plant in each country (Eq. (2)). The parameters used for estimating the corresponding V_i values can be found in Cartelle Barros et al. [11]. Since the Professional and Energy Thinkstep databases provide average results, it is possible to say that the *EI* for each type of power plant in each country will be an average result (Section 3.1).

With the Environmental Indices (*EIs*) provided by the MIVES model and electricity production percentage for each type of power plant in each country, it is possible to estimate the corresponding *CEI* for each country (Eq. (3)).

$$CEI = \sum_{j=1}^{13} P_j \cdot EI_j \tag{3}$$

where *j* represents each one of the thirteen technologies considered in this study, P_j is the percentage of electricity produced with each *j*-technology in the country and EI_j is the environmental index for each *j*-technology, also, in the corresponding country. Table 2 includes the percentage of electricity produced by each technology in each country for 2017 [107]. Therefore, the sum of the percentages for each row in the table is equal to 100 %. As previously indicated, solar thermal, geothermal or wave and tidal power, among other options, were not taken into account at the time of constructing Table 2. The reader should bear in mind that *CEI* also varies between 0 and 1, the worst and best possible results, respectively.

Estimating the European Environmental Index (*EEI*) (Eq. (4)) is the last step in the assessment process (Fig. 1).

$$EEI = \sum_{k=1}^{28} \sum_{j=1}^{13} G_{k,j} \cdot EI_j \tag{4}$$

In Eq. (4), $G_{k,j}$ is the percentage of electricity produced in each *k*-country with each *j*-technology in relation to the total production of EU-27 and UK. $G_{k,j}$ values are included in Table 3. Once again, they are based on data from Eurostat for 2017 [107]. The sum of all the values included in Table 3, excluding the last column, is equal to 100 %. Similarly, the sum of the values shown in the last column is also equal to 100 %.

The European Environmental Index (*EEI*) varies between 0 and 1, the worst and best possible solutions, respectively. Consequently, the *EEI* condenses the environmental performance of almost the entire EU-27 and UK electricity sector into a single and dimensionless number. In this way, it provides information on how the current (in fact, for 2017) EU electricity sector is performing from an environmental point of view, by taking into account all the indicators included in Fig. 2.

Once the assessment step is completed, it is possible to formulate and solve the optimisation problem (second main step in the general

Table 2
Electricity production percentage with each technology in relation to the country's total for year 2017 (P_j). Based on Ref. [107].

Country[1]	Type of power plant[2]												
	PP1	PP2	PP3	PP4	PP5	PP6	PP7	PP8	PP9	PP10	PP11	PP12	PP13
AT	0.888	5.206	3.041	2.480	1.147	59.574	0.000	15.482	0.000	0.000	1.789	1.121	9.270
BE	1.096	4.458	2.726	0.106	0.193	1.632	0.000	26.758	49.325	0.000	3.840	2.260	7.605
BG	0.473	0.395	0.000	0.868	0.879	7.664	45.017	4.218	34.107	0.000	3.078	0.000	3.300
CY	1.034	0.000	0.000	0.000	91.303	0.000	0.000	0.000	0.000	0.000	3.437	0.000	4.225
CZ	3.036	2.546	2.855	5.135	0.137	3.497	42.534	4.233	32.603	0.000	2.523	0.219	0.680
DE	5.211	1.639	1.676	14.392	0.857	4.023	22.822	13.488	11.740	0.000	6.061	1.832	16.258
DK	2.210	15.454	0.000	20.002	0.902	0.058	0.000	6.160	0.000	0.000	2.421	5.176	47.617
EE	0.324	7.719	5.841	0.136	0.930	0.202	76.822	0.488	0.000	0.842	0.000	1.093	5.603
ES	0.349	1.618	0.453	15.779	5.845	7.811	0.951	23.739	21.516	0.000	3.156	0.572	18.212
FI	0.613	16.244	0.874	8.736	0.274	22.033	0.000	4.922	33.527	4.133	0.065	1.425	7.152
FR	0.373	0.596	0.432	2.254	1.318	9.830	0.000	7.214	71.060	0.000	1.708	0.807	4.408
GB	2.287	6.151	0.223	6.674	0.478	2.607	0.000	40.509	20.836	0.000	3.414	2.006	14.813
GR	0.543	0.018	0.000	0.000	9.969	7.310	33.954	30.965	0.000	0.000	7.222	0.000	10.019
HR	2.584	1.802	0.000	11.255	1.755	45.961	0.154	25.786	0.000	0.000	0.657	0.000	10.047
HU	1.022	5.034	0.508	0.609	0.260	0.673	14.476	23.973	49.237	0.000	1.067	0.823	2.318
IE	0.640	1.236	0.000	11.806	0.460	2.899	0.000	50.793	0.000	7.011	0.035	1.004	24.116
IT	2.918	1.488	0.868	11.466	4.053	13.369	0.006	49.347	0.000	0.000	8.571	1.676	6.238
LT	3.241	7.723	0.000	0.000	3.542	30.089	0.000	15.220	0.000	0.000	1.733	3.716	34.736
LU	3.241	2.327	0.000	0.000	0.013	63.621	0.000	9.884	0.000	0.000	4.853	5.555	10.506
LV	5.382	6.975	0.000	0.003	0.006	58.166	0.000	27.470	0.000	0.000	0.006	0.000	1.992
MT	0.592	0.000	0.000	0.000	11.719	0.000	0.000	78.245	0.000	0.000	9.440	0.000	0.004
NL	0.788	1.513	2.353	26.700	1.011	0.052	0.000	50.708	2.905	0.000	1.882	3.066	9.023
PL	0.644	3.116	1.338	46.368	1.186	1.781	30.621	5.890	0.000	0.000	0.097	0.206	8.752
PT	0.484	4.347	0.000	24.772	2.162	12.890	0.000	31.915	0.000	0.000	1.675	1.068	20.688
RO	0.104	0.713	0.120	0.000	0.984	23.101	26.098	16.574	17.900	0.000	2.886	0.000	11.520
SE	0.007	6.243	0.431	0.196	0.177	39.694	0.000	0.165	40.016	0.121	0.140	2.083	10.726
SI	0.798	0.949	0.000	0.001	0.088	25.385	29.572	2.900	38.531	0.000	1.740	0.000	0.035
SK	2.154	3.916	1.991	4.689	1.592	16.764	6.157	6.045	54.687	0.000	1.835	0.149	0.022

[1] Country codes according to ISO 3166-1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

[2] PP1: biogas, PP2: biomass, PP3: coal gas, PP4: hard coal, PP5: oil, PP6: hydro, PP7: lignite, PP8: Natural gas, PP9: Nuclear, PP10: Peat, PP11: Photovoltaic, PP12: waste, PP13: onshore and offshore wind.

Table 3

Electricity production percentage with each technology in each country in relation to the total of EU-27 and UK for year 2017 ($G_{k,j}$). Based on Ref. [107].

Country[1]	Type of power plant[2]													
	PP1 bgas	PP2 bmass	PP3 clgas	PP4 hrdcl	PP5 oil	PP6 hydro	PP7 lgnte	PP8 natgas	PP9 nucl	PP10 peat	PP11 phtvlt	PP12 waste	PP13 wind	Sum
AT	0.0193	0.1128	0.0659	0.0537	0.0249	1.2910	0.0000	0.3355	0.0000	0.0000	0.0388	0.0243	0.2009	2.17
BE	0.0287	0.1166	0.0713	0.0028	0.0050	0.0427	0.0000	0.7000	1.2903	0.0000	0.1005	0.0591	0.1989	2.62
BG	0.0066	0.0055	0.0000	0.0121	0.0122	0.1067	0.6270	0.0587	0.4750	0.0000	0.0429	0.0000	0.0460	1.39
CY	0.0016	0.0000	0.0000	0.0000	0.1396	0.0000	0.0000	0.0000	0.0000	0.0000	0.0053	0.0000	0.0065	0.15
CZ	0.0806	0.0676	0.0758	0.1364	0.0036	0.0929	1.1297	0.1124	0.8659	0.0000	0.0670	0.0058	0.0181	2.66
DE	1.0352	0.3256	0.3329	2.8590	0.1702	0.7992	4.5335	2.6793	2.3322	0.0000	1.2039	0.3640	3.2296	19.86
DK	0.0210	0.1466	0.0000	0.1897	0.0086	0.0005	0.0000	0.0584	0.0000	0.0000	0.0230	0.0491	0.4516	0.95
EE	0.0013	0.0304	0.0230	0.0005	0.0037	0.0008	0.3029	0.0019	0.0000	0.0033	0.0000	0.0043	0.0221	0.39
ES	0.0288	0.1334	0.0373	1.3006	0.4817	0.6438	0.0783	1.9567	1.7734	0.0000	0.2602	0.0472	1.5011	8.24
FI	0.0126	0.3328	0.0179	0.1790	0.0056	0.4514	0.0000	0.1008	0.6868	0.0847	0.0013	0.0292	0.1465	2.05
FR	0.0639	0.1021	0.0740	0.3862	0.2258	1.6839	0.0000	1.2357	12.1723	0.0000	0.2925	0.1382	0.7551	17.13
GB	0.2359	0.6344	0.0230	0.6884	0.0493	0.2689	0.0000	4.1784	2.1492	0.0000	0.3522	0.2069	1.5279	10.31
GR	0.0092	0.0003	0.0000	0.0000	0.1684	0.1234	0.5734	0.5229	0.0000	0.0000	0.1220	0.0000	0.1692	1.69
HR	0.0095	0.0066	0.0000	0.0412	0.0064	0.1683	0.0006	0.0944	0.0000	0.0000	0.0024	0.0000	0.0368	0.37
HU	0.0102	0.0503	0.0051	0.0061	0.0026	0.0067	0.1446	0.2395	0.4919	0.0000	0.0107	0.0082	0.0232	1.00
IE	0.0060	0.0117	0.0000	0.1114	0.0043	0.0273	0.0000	0.4791	0.0000	0.0661	0.0003	0.0095	0.2275	0.94
IT	0.2536	0.1293	0.0754	0.9965	0.3522	1.1619	0.0005	4.2885	0.0000	0.0000	0.7449	0.1457	0.5421	8.69
LT	0.0039	0.0093	0.0000	0.0000	0.0042	0.0361	0.0000	0.0183	0.0000	0.0000	0.0021	0.0045	0.0417	0.12
LU	0.0022	0.0016	0.0000	0.0000	0.0000	0.0434	0.0000	0.0068	0.0000	0.0000	0.0033	0.0038	0.0072	0.07
LV	0.0124	0.0161	0.0000	0.0000	0.0000	0.1339	0.0000	0.0632	0.0000	0.0000	0.0000	0.0000	0.0046	0.23
MT	0.0003	0.0000	0.0000	0.0000	0.0059	0.0000	0.0000	0.0393	0.0000	0.0000	0.0047	0.0000	0.0000	0.05
NL	0.0282	0.0542	0.0842	0.9557	0.0362	0.0019	0.0000	1.8150	0.1040	0.0000	0.0674	0.1098	0.3229	3.58
PL	0.0335	0.1622	0.0697	2.4137	0.0617	0.0927	1.5940	0.3066	0.0000	0.0000	0.0051	0.0107	0.4556	5.21
PT	0.0088	0.0786	0.0000	0.4481	0.0391	0.2332	0.0000	0.5773	0.0000	0.0000	0.0303	0.0193	0.3742	1.81
RO	0.0020	0.0140	0.0024	0.0000	0.0193	0.4539	0.5127	0.3256	0.3517	0.0000	0.0567	0.0000	0.2263	1.96
SE	0.0003	0.3132	0.0216	0.0098	0.0089	1.9913	0.0000	0.0083	2.0074	0.0061	0.0070	0.1045	0.5381	5.02
SI	0.0040	0.0047	0.0000	0.0000	0.0004	0.1265	0.1474	0.0145	0.1921	0.0000	0.0087	0.0000	0.0002	0.50
SK	0.0182	0.0330	0.0168	0.0395	0.0134	0.1413	0.0519	0.0509	0.4608	0.0000	0.0155	0.0013	0.0002	0.84

[1] Country codes according to ISO 3166-1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

[2] PP1: biogas, PP2: biomass, PP3: coal gas, PP4: hard coal, PP5: oil, PP6: hydro, PP7: lignite, PP8: Natural gas, PP9: Nuclear, PP10: Peat, PP11: Photovoltaic, PP12: waste, PP13: onshore and offshore wind.

procedure, Fig. 1). The aim is to maximise the European Environmental Index (*EEI*). Eq. (4) and, in particular *EEI*, can be established as the objective function. Along the same lines, $G_{k,j}$ values can be the decision variables to be determined.

It is important to highlight the need to establish constraints so that, to some extent, reasonable results can be obtained. Therefore, three different scenarios will be considered. All of them present the following common constraints:

- Each country produces the same percentage of electricity in relation to the total generation for 2017. In other words, the total percentage of electricity production for each of the countries will be equal to the corresponding figures included in the last column of Table 3.
- Only the types of power plants that produced electricity in 2017 for each country are considered in the optimisation problem. That is, if a specific energy system did not produce electricity in a specific country in 2017, this null level of production will be maintained during the optimisation problem.
- Country Environmental Indices (*CEIs*) cannot be lower than the ones obtained for 2017. Stated another way, an improvement in the *EEI* cannot take place at the expense of certain countries worsening their current environmental performances.

Therefore, the scenarios differ in only one constraint:

- Scenario 1. Each type of power plant, in each country, can experience an increase or decrease in its current level of production equal to 50 %.
- Scenario 2 is similar to Scenario 1 but, in this case, with a potential increase or decrease equal to 25 %.
- Scenario 3 is equivalent to the previous two scenarios, but with a percentage of potential variation equal to 5 %.

Consequently, this is a linear programming problem with mixed constraints. On the other hand, it is important to point out that real scenarios can differ from the ones presented in this work. The first reason for this is that the percentage of electricity produced by each country could present reasonable variations. In other words, if a country, in 2017, produced 10 % of the European total electricity, with its installed capacity, it would be able to slightly increase its production (if necessary). The opposite can also happen. Nevertheless, what is not reasonable is for a country to experience a huge variation in its generation rate, at least in the short or medium term. To make large variations possible, it would be necessary to make a major investment in building new power plants [7]. This is the main reason why the first constraint was defined. The results are not expected to change considerably, if small variations were allowed. Moreover, with the idea of avoiding large-scale investment, new types of power plants are not an option in each country (second constraint). In reality, it is also clear that, those power plants could be built in a specific country. On the other hand, with this second constraint, the authors also intend to demonstrate that each country can improve its environmental performance by changing only the participation percentage for the technologies it has been using over decades.

Regarding the particular constraints of these scenarios, the reader should be aware that they may lead to certain electricity mixes that may not be fully applicable in reality. For instance, after the optimisation problem has been solved, one possible solution is that a certain country must increase electricity production by a certain percentage with a specific power plant. Nevertheless, it could be impossible to achieve such a percentage in the short or medium term due to insufficient installed capacity. It might even be impossible in the long term, in particular, if the country is currently exploiting all the potential it has for this technology. This is why three different scenarios, with different degrees of freedom in the constraints, were considered. Scenarios 1 and 2 are likely to generate some unrealistic results. At the same time, they are likely to generate better *EEIs*. Moreover, it is important to clarify that, in certain countries, tied by strategic, economic or political constraints, power plants types with a poor environmental performance can be allowed to survive into the future.

On the other hand, despite these limitations, the results of solving the optimisation problem under three different scenarios can be of great help for future decision-making processes. They will serve to identify the different generation technologies that should be promoted in the future from an environmental point of view even if they cannot be built in all countries. In a similar vein, the results will also help identify those technologies that should be discarded in the future, when dismantled at the end of their working lives. Furthermore, the type of optimisation problem presented in this study can be adapted to real and specific cases with more precise constraints. For example, the model can be integrated into other energy planning tools with the objective of optimising the global environmental index (a particular case of the *EEI*) of neighbouring countries by considering all the potential constraints as well as the specific electricity market designs.

3. Results

This section is divided into two sub-sections. In the first, (Section 3.1) the results for the assessment step (Fig. 1) are presented. These include the calculation of the Environmental Indices (*EIs*), the Country Environmental Indices (*CEIs*) for the base case (2017) and the European Environmental Index (*EEI*) for the base scenario (2017). The second part (Section 3.2) contains the results for the optimisation problem (second main step in Fig. 1) for the scenarios defined in Section 2.

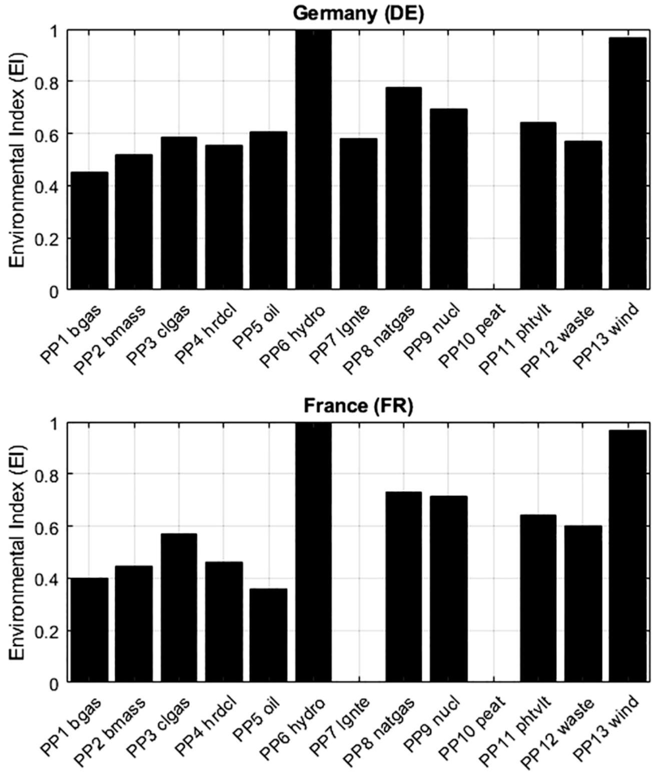

Fig. 3. Environmental Indices (EIs) for the power plants in Germany and France.

3.1. Assessment results

In Table A.2 of Appendix A, the reader can find the Environmental Indices (*EIs*) of the different power plants for each country. For example, Fig. 3 shows the Environmental Indices (*EIs*) for the two countries with the highest electricity production in 2017: Germany (19.86 %) and France (17.13 %). In Fig. 3, an index equal to zero suggests that there was no electricity production in 2017 with the corresponding technology.

The Country Environmental Indices (*CEIs*) for 2017 are included in Fig. 4. They are the result of applying Eq. (3), together with the values included in Tables 2 and A.2. The results of Table A.2 can be used along with the values of Table 3 in Eq. (4), obtaining an European Environmental Index (*EEI*) of 0.7363 for 2017.

3.2. Optimisation results

As indicated in Section 2, the objective of the optimisation step is to maximise the European Environmental Index (*EEI*) under different scenarios. In other words, the resolution of the optimisation problem involves determining the values that the optimisation variables ($G_{k,j}$) must take in order to maximise *EEI*. Those values are included in Tables 4–6. They represent the electricity production percentage of each type of power plant in each country, in relation to the total generation (EU-27 and UK) for Scenarios 1, 2 and 3, respectively.

From Tables 4–6, it is possible to estimate the production share for each type of power plant in relation to the total generation of the corresponding country. That is, from these data, the user can generate tables equivalent to Table 2 for the three scenarios. These tables are necessary for estimating the Country Environmental indices (*CEIs*).

Fig. 5 includes the Country Environmental Indices (*CEIs*) for 2017 and for the three scenarios defined in Section 2. In Table A.3 of Appendix A, the reader can find the same results in tabular format, including the percentage increase for each *CEI* in each scenario with respect to the base one (2017).

The European Environmental Indices (*EEIs*) for the base case (2017) and for the three scenarios defined in Section 2 are included in Fig. 6. The increase that each European Environmental Index experiences with respect to the base case (2017) is also shown in the same figure.

4. Discussion

Due to length constraints, only the discussions on those findings that are more relevant according to the initial purposes are included in this section.

First, it is interesting to comment on the values included in Table A.2 of Appendix A. This table shows the Environmental Indices (*EIs*), that is, the environmental performance of each type of power plant in each country. If an environmental ranking is made for each country, each alternative does not necessarily occupy the same position in all classifications. Using Spain as an example, nuclear (PP9) obtained better results than natural gas (PP8), while the opposite was true for the other countries. Something similar happens with hard coal (PP4) and lignite-fired (PP7) power plants. In most countries, hard coal (PP4) outranks lignite (PP7). However, there are some exceptions, such as Germany, Finland or Greece. Nevertheless, in all cases the differences between hard coal and lignite are reduced, as their *EIs* are far from being the best possible values. Another case in point is shown in Fig. 3 between hard coal (PP4) and oil (PP5) power plants in Germany and France. A detailed analysis of Table A.2 provides the reader with more examples similar to the ones already discussed here. Even so, it is possible to make an approximate ranking with the position (or positions) that each type of power plant usually occupies. Whenever it is present in a country’s electricity mix, hydro (PP6) is clearly the best option from an environmental point of view, closely followed by onshore and offshore wind (PP13). At the other end of the ranking are usually biogas (PP1) or oil

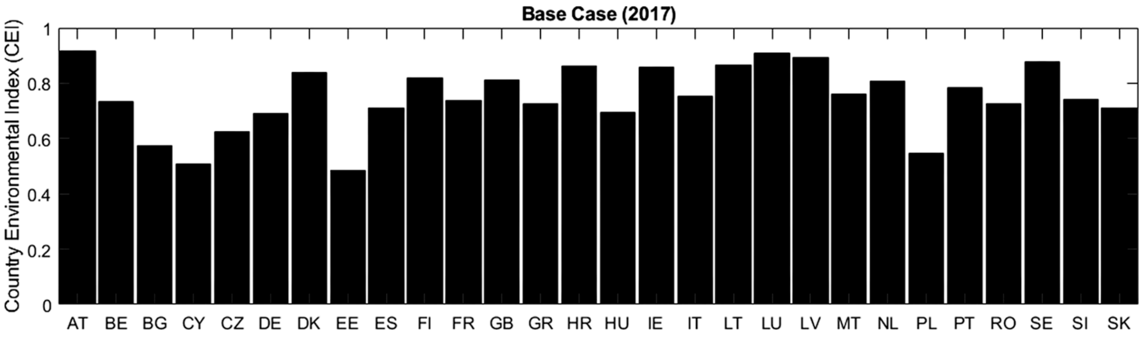

Fig. 4. Country Environmental Indices (CEIs) for 2017.

Table 4
Electricity production percentage with each technology in each country in relation to the total of EU-27 and UK ($G_{k,j}$), Scenario 1.

Country[1]	Type of power plant[2]													
	PP1 bgas	PP2 bmass	PP3 clgas	PP4 hrdcl	PP5 oil	PP6 hydro	PP7 lgnte	PP8 natgas	PP9 nucl	PP10 peat	PP11 phtvlt	PP12 waste	PP13 wind	Sum
AT	0.0096	0.0564	0.0330	0.0269	0.0124	1.7320	0.0000	0.1678	0.0000	0.0000	0.0194	0.0122	0.1004	2.17
BE	0.0143	0.0583	0.0357	0.0014	0.0025	0.0641	0.0000	1.0500	1.0156	0.0000	0.0502	0.0296	0.2984	2.62
BG	0.0033	0.0028	0.0000	0.0060	0.0061	0.1601	0.3135	0.0881	0.7125	0.0000	0.0286	0.0000	0.0689	1.39
CY	0.0024	0.0000	0.0000	0.0000	0.1301	0.0000	0.0000	0.0000	0.0000	0.0000	0.0079	0.0000	0.0097	0.15
CZ	0.0403	0.0338	0.1137	0.1622	0.0018	0.1393	0.5649	0.1686	1.2989	0.0000	0.1005	0.0087	0.0271	2.66
DE	0.5176	0.1628	0.1665	1.4295	0.0851	1.1988	2.2667	4.0190	3.4983	0.0000	1.4894	0.1820	4.8444	19.86
DK	0.0105	0.0733	0.0000	0.0949	0.0043	0.0008	0.0000	0.0528	0.0000	0.0000	0.0115	0.0245	0.6774	0.95
EE	0.0019	0.0457	0.0346	0.0008	0.0018	0.0012	0.2566	0.0029	0.0000	0.0050	0.0000	0.0065	0.0331	0.39
ES	0.0144	0.0667	0.0187	0.6503	0.2409	0.9657	0.0392	0.9784	2.6003	0.0000	0.3902	0.0236	2.2517	8.24
FI	0.0063	0.1664	0.0090	0.0895	0.0028	0.6770	0.0000	0.1513	0.6704	0.0423	0.0007	0.0146	0.2198	2.05
FR	0.0320	0.0510	0.0370	0.1931	0.1129	2.5258	0.0000	1.8535	10.9768	0.0000	0.1463	0.0691	1.1326	17.13
GB	0.1180	0.3172	0.0115	0.3442	0.0247	0.4034	0.0000	5.4450	1.0746	0.0000	0.1761	0.1035	2.2919	10.31
GR	0.0046	0.0002	0.0000	0.0000	0.0842	0.1852	0.2867	0.7844	0.0000	0.0000	0.0911	0.0000	0.2538	1.69
HR	0.0047	0.0033	0.0000	0.0206	0.0032	0.2524	0.0003	0.0472	0.0000	0.0000	0.0012	0.0000	0.0370	0.37
HU	0.0051	0.0251	0.0025	0.0030	0.0013	0.0101	0.0723	0.3593	0.4771	0.0000	0.0053	0.0041	0.0347	1.00
IE	0.0030	0.0058	0.0000	0.0557	0.0022	0.0410	0.0000	0.4531	0.0000	0.0331	0.0002	0.0047	0.3412	0.94
IT	0.1268	0.0647	0.0377	0.4982	0.1761	1.7428	0.0002	4.7849	0.0000	0.0000	0.3724	0.0728	0.8132	8.69
LT	0.0019	0.0046	0.0000	0.0000	0.0021	0.0542	0.0000	0.0091	0.0000	0.0000	0.0010	0.0022	0.0448	0.12
LU	0.0011	0.0008	0.0000	0.0000	0.0000	0.0576	0.0000	0.0034	0.0000	0.0000	0.0017	0.0019	0.0036	0.07
LV	0.0062	0.0080	0.0000	0.0000	0.0000	0.1819	0.0000	0.0316	0.0000	0.0000	0.0000	0.0000	0.0023	0.23
MT	0.0001	0.0000	0.0000	0.0000	0.0029	0.0000	0.0000	0.0445	0.0000	0.0000	0.0024	0.0000	0.0000	0.05
NL	0.0141	0.0271	0.0421	0.4778	0.0181	0.0028	0.0000	2.3731	0.0520	0.0000	0.0337	0.0549	0.4844	3.58
PL	0.0168	0.2433	0.1045	2.7116	0.0309	0.1391	0.7970	0.4599	0.0000	0.0000	0.0076	0.0161	0.6833	5.21
PT	0.0044	0.0393	0.0000	0.2241	0.0196	0.3498	0.0000	0.5867	0.0000	0.0000	0.0151	0.0097	0.5614	1.81
RO	0.0010	0.0070	0.0012	0.0000	0.0097	0.6808	0.2564	0.4603	0.1758	0.0000	0.0284	0.0000	0.3395	1.96
SE	0.0002	0.1566	0.0108	0.0049	0.0044	2.9869	0.0000	0.0041	1.0037	0.0030	0.0035	0.0523	0.7895	5.02
SI	0.0020	0.0024	0.0000	0.0000	0.0002	0.1898	0.0737	0.0217	0.2056	0.0000	0.0043	0.0000	0.0003	0.50
SK	0.0091	0.0165	0.0084	0.0198	0.0067	0.2119	0.0259	0.0764	0.4567	0.0000	0.0077	0.0006	0.0003	0.84

[1] Country codes according to ISO 3166-1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

[2] PP1: biogas, PP2: biomass, PP3: coal gas, PP4: hard coal, PP5: oil, PP6: hydro, PP7: lignite, PP8: Natural gas, PP9: Nuclear, PP10: Peat, PP11: Photovoltaic, PP12: waste, PP13: onshore and offshore wind.

(PP5), both of whose indices are often below 0.5 (with some exceptions). These two alternatives tend to present a poorer environmental performance than lignite (PP7), hard coal (PP4), biomass (PP2), waste (PP12), coal gases (PP13) or peat (PP10), all of which have *EIs* at the opposite end of the spectrum from the best options. It may be surprising that alternatives, such as biogas (PP1) or biomass (PP2) have performed so poorly. Nevertheless, the reader should bear in mind that a complete set of environmental indicators (Fig. 2) are being analysed, not only the global warming potential. If this impact is taken as the sole indicator, biogas and biomass are assumed to be carbon neutral. However, this assumption is increasingly being questioned by the scientific community and all types of energy sources present a range of environmental impacts throughout their life cycle stages. With indices often between 0.7 and 0.85, non-renewable power plants such as those using natural gas (PP8) or nuclear power (PP9) are usually better positioned than biogas (PP1) and biomass (PP2). Along these lines, solar photovoltaic (PP11), despite being a renewable alternative, is usually bellow natural gas (PP8) and nuclear (PP9), although it tends to outperform all other non-renewables, as well as biogas (PP1) and biomass (PP2).

In an effort to clarify the general ranking discussed above, the environmental performance of three types of power plants is compared in detail in Fig. 7. In particular, hydro (PP6) in Greece (GR), lignite (PP7) in Bulgaria (BG) and natural gas (PP8) in Spain (ES) were selected. The first two alternatives were chosen as they have the highest and lowest environmental indices (*EIs*) of this study (Table A.2), while natural gas in Spain obtained an intermediate score, far from the best and worst options. In Fig. 7, a value of 100 was assigned to the worst of the three alternatives for each one of the environmental midpoint indicators. The remaining scores were defined on a proportional basis, by comparing the real values measured in the corresponding units (Fig. 2). As can be observed, hydro (PP6) stood out as the best alternative in all the environmental indicators, with only one exception: resource depletion

Table 5
Electricity production percentage with each technology in each country in relation to the total of EU-27 and UK ($G_{k,j}$), Scenario 2.

Country[1]	Type of power plant[2]													
	PP1 bgas	PP2 bmass	PP3 clgas	PP4 hrdcl	PP5 oil	PP6 hydro	PP7 lgnte	PP8 natgas	PP9 nucl	PP10 peat	PP11 phtvlt	PP12 waste	PP13 wind	Sum
AT	0.0144	0.0846	0.0494	0.0403	0.0186	1.5129	0.0000	0.2516	0.0000	0.0000	0.0291	0.0182	0.1507	2.17
BE	0.0215	0.0875	0.0535	0.0021	0.0038	0.0534	0.0000	0.8750	1.1550	0.0000	0.0753	0.0443	0.2487	2.62
BG	0.0049	0.0041	0.0000	0.0091	0.0092	0.1334	0.4702	0.0734	0.5938	0.0000	0.0344	0.0000	0.0574	1.39
CY	0.0020	0.0000	0.0000	0.0000	0.1334	0.0000	0.0000	0.0000	0.0000	0.0000	0.0066	0.0000	0.0081	0.15
CZ	0.0605	0.0507	0.0948	0.1513	0.0027	0.1161	0.8473	0.1405	1.0824	0.0000	0.0838	0.0073	0.0226	2.66
DE	0.7764	0.2442	0.2497	2.1442	0.1277	0.9990	3.4001	3.3491	2.9152	0.0000	1.3444	0.2730	4.0370	19.86
DK	0.0157	0.1099	0.0000	0.1423	0.0064	0.0007	0.0000	0.0564	0.0000	0.0000	0.0172	0.0368	0.5645	0.95
EE	0.0016	0.0380	0.0288	0.0007	0.0028	0.0010	0.2776	0.0024	0.0000	0.0042	0.0000	0.0054	0.0276	0.39
ES	0.0216	0.1000	0.0280	0.9754	0.3613	0.8048	0.0588	1.4675	2.1856	0.0000	0.3252	0.0354	1.8764	8.24
FI	0.0094	0.2496	0.0134	0.1342	0.0042	0.5642	0.0000	0.1260	0.6793	0.0635	0.0010	0.0219	0.1832	2.05
FR	0.0479	0.0766	0.0555	0.2896	0.1694	2.1049	0.0000	1.5446	11.5748	0.0000	0.2194	0.1037	0.9438	17.13
GB	0.1770	0.4758	0.0173	0.5163	0.0370	0.3361	0.0000	4.8094	1.6119	0.0000	0.2641	0.1552	1.9099	10.31
GR	0.0069	0.0002	0.0000	0.0000	0.1263	0.1543	0.4300	0.6536	0.0000	0.0000	0.1072	0.0000	0.2115	1.69
HR	0.0071	0.0049	0.0000	0.0309	0.0048	0.2104	0.0004	0.0708	0.0000	0.0000	0.0018	0.0000	0.0388	0.37
HU	0.0077	0.0377	0.0038	0.0046	0.0019	0.0084	0.1085	0.2994	0.4850	0.0000	0.0080	0.0062	0.0290	1.00
IE	0.0045	0.0087	0.0000	0.0835	0.0033	0.0342	0.0000	0.4645	0.0000	0.0496	0.0002	0.0071	0.2844	0.94
IT	0.1902	0.0970	0.0566	0.7474	0.2642	1.4524	0.0004	4.5364	0.0000	0.0000	0.5587	0.1093	0.6777	8.69
LT	0.0029	0.0069	0.0000	0.0000	0.0032	0.0451	0.0000	0.0137	0.0000	0.0000	0.0016	0.0033	0.0432	0.12
LU	0.0017	0.0012	0.0000	0.0000	0.0000	0.0514	0.0000	0.0051	0.0000	0.0000	0.0025	0.0028	0.0054	0.07
LV	0.0093	0.0120	0.0000	0.0000	0.0000	0.1578	0.0000	0.0474	0.0000	0.0000	0.0000	0.0000	0.0034	0.23
MT	0.0002	0.0000	0.0000	0.0000	0.0044	0.0000	0.0000	0.0418	0.0000	0.0000	0.0036	0.0000	0.0000	0.05
NL	0.0212	0.0406	0.0632	0.7167	0.0271	0.0023	0.0000	2.0944	0.0780	0.0000	0.0505	0.0823	0.4037	3.58
PL	0.0251	0.2028	0.0871	2.5649	0.0463	0.1159	1.1955	0.3833	0.0000	0.0000	0.0063	0.0134	0.5695	5.21
PT	0.0066	0.0590	0.0000	0.3361	0.0293	0.2915	0.0000	0.5825	0.0000	0.0000	0.0227	0.0145	0.4678	1.81
RO	0.0015	0.0105	0.0018	0.0000	0.0145	0.5673	0.3846	0.3906	0.2638	0.0000	0.0425	0.0000	0.2829	1.96
SE	0.0003	0.2349	0.0162	0.0074	0.0066	2.4891	0.0000	0.0062	1.5056	0.0046	0.0053	0.0784	0.6655	5.02
SI	0.0030	0.0035	0.0000	0.0000	0.0003	0.1582	0.1106	0.0181	0.1996	0.0000	0.0065	0.0000	0.0002	0.50
SK	0.0136	0.0248	0.0126	0.0296	0.0101	0.1766	0.0389	0.0637	0.4574	0.0000	0.0116	0.0009	0.0002	0.84

[1] Country codes according to ISO 3166-1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

[2] PP1: biogas, PP2: biomass, PP3: coal gas, PP4: hard coal, PP5: oil, PP6: hydro, PP7: lignite, PP8: Natural gas, PP9: Nuclear, PP10: Peat, PP11: Photovoltaic, PP12: waste, PP13: onshore and offshore wind.

(minerals, fossils and renewables). In fact, its performance is so outstanding by comparison that it is difficult to distinguish its bar on most impacts. On the other hand, lignite (PP7) was the worst performer in 12 of the 15 environmental indicators. The exceptions were ozone depletion, water consumption and resource depletion. Fig. 7 provides the reader with an idea of the differences between the best and worst types of power plants for each one of the environmental impacts. Additional comparisons can be made by using the data included in Table A.1 of Appendix A.

Results included in Table A.2 of Appendix A are of paramount importance. They provide the decision-makers with an idea of what is likely to happen when variations are allowed in the electricity production percentage for each type of power plant. If the objective is to optimise the environmental performance of the European (EU-27 and UK) electricity sector, as is the case in this study, the logical thing to do is to favour the types of power plants with the highest *EIs* (Table A.2). This increase must be accompanied by an equal decrease in the production of electricity from the worst alternatives in each country. This is what should happen at the time of solving the optimisation problem here proposed, always conditioned by the constraints explained in Section 2 and the situation for the base case (2017). Stated in another way, the production of the best alternative (hydro) should be first increased, followed by an increase in the generation of the second best option (onshore and offshore wind), and so on. This is repeated until the constraints or the objective function no longer allow the next best alternative to raise its electricity production. At a given point, increasing the generation of an alternative necessarily means that a constraint is not met or that the European Environmental Index (*EEI*) decreases. In the end, the increase in hydro (PP6), onshore and offshore wind (PP13) and others comes at the cost of reducing the production of alternatives, such as biogas (PP1), oil (PP5) or lignite (PP4).

In fact, it is possible to know which types of power plants have increased their production and which ones had the opposite effect on a net basis (28 countries as a whole), once the optimisation has been carried out for the three different scenarios (Tables 4-6). This is shown in Fig. 8. The reader can find the same results in tabular format in Table A.4 of Appendix A. As seen, all types of power plants decrease their generation in the European total except hydro (PP6), natural gas (PP8) and onshore and offshore wind energy (PP13). These tend to be the best options according to Table A.2. Moreover, as hydro (PP6) and onshore and offshore wind (PP13) are always better than natural gas (PP8) from an environmental point of view, their percentage increases are also higher than those of natural gas (PP8). Constraints also condition the results. According to Fig. 8 and Table A.4, nuclear energy (PP9), despite being an acceptable option, does not experience a net increase. This is the case in the three scenarios, although to different degrees, depending how limiting the constraints are. Therefore, the largest variations are found in Scenario 1, while the opposite occurs in Scenario 3.

At this point, it is interesting to compare what happens among the three scenarios in terms of the variation that each one experiences with respect to the base case (2017). To this end, the values in Table 3 must be compared with the ones presented in Tables 4-6. On the one hand, the variations that each type of power plant experiences in each scenario for each country are, with certain exceptions, close to the limit established by the corresponding constraint (50, 25 and 5 %, respectively for Scenarios 1, 2 and 3). In other words, in Scenario 1, the electricity production of each type of power plant in each country increases or decreases by 50 % compared to the base case. Similarly, the variations experienced in Scenario 2 are close to 25 %, while, in the third scenario, they are around 5 %. Therefore, the optimisation problem proposed here tries to improve the European Environmental Index (*EEI*) up to the point in which the constraints make this impossible. Exceptions can be

Table 6
Electricity production percentage with each technology in each country in relation to the total of EU-27 and UK ($G_{k,j}$), Scenario 3.

Country[1]	Type of power plant[2]													
	PP1 bgas	PP2 bmass	PP3 clgas	PP4 hrdcl	PP5 oil	PP6 hydro	PP7 lgnte	PP8 natgas	PP9 nucl	PP10 peat	PP11 phtvlt	PP12 waste	PP13 wind	Sum
AT	0.0183	0.1072	0.0626	0.0511	0.0236	1.3377	0.0000	0.3187	0.0000	0.0000	0.0368	0.0231	0.1908	2.17
BE	0.0272	0.1108	0.0678	0.0026	0.0048	0.0448	0.0000	0.7350	1.2665	0.0000	0.0954	0.0562	0.2089	2.62
BG	0.0063	0.0052	0.0000	0.0115	0.0116	0.1121	0.5956	0.0617	0.4970	0.0000	0.0407	0.0000	0.0483	1.39
CY	0.0017	0.0000	0.0000	0.0000	0.1360	0.0000	0.0000	0.0000	0.0000	0.0000	0.0055	0.0000	0.0068	0.15
CZ	0.0766	0.0643	0.0796	0.1425	0.0035	0.0975	1.0732	0.1181	0.9092	0.0000	0.0704	0.0061	0.0190	2.66
DE	0.9835	0.3094	0.3163	2.7160	0.1617	0.8392	4.3068	2.8133	2.4488	0.0000	1.2284	0.3458	3.3911	19.86
DK	0.0199	0.1392	0.0000	0.1802	0.0081	0.0006	0.0000	0.0593	0.0000	0.0000	0.0218	0.0466	0.4742	0.95
EE	0.0013	0.0320	0.0242	0.0006	0.0035	0.0008	0.2944	0.0020	0.0000	0.0035	0.0000	0.0045	0.0232	0.39
ES	0.0273	0.1267	0.0355	1.2355	0.4577	0.6760	0.0744	1.8589	1.8538	0.0000	0.2732	0.0448	1.5762	8.24
FI	0.0119	0.3161	0.0170	0.1700	0.0053	0.4739	0.0000	0.1059	0.6865	0.0804	0.0013	0.0277	0.1538	2.05
FR	0.0607	0.0970	0.0703	0.3668	0.2145	1.7681	0.0000	1.2974	12.0532	0.0000	0.2779	0.1313	0.7928	17.13
GB	0.2242	0.6027	0.0219	0.6540	0.0469	0.2823	0.0000	4.3008	2.0418	0.0000	0.3345	0.1966	1.6043	10.31
GR	0.0087	0.0003	0.0000	0.0000	0.1599	0.1296	0.5447	0.5491	0.0000	0.0000	0.1200	0.0000	0.1776	1.69
HR	0.0090	0.0063	0.0000	0.0392	0.0061	0.1767	0.0005	0.0913	0.0000	0.0000	0.0023	0.0000	0.0386	0.37
HU	0.0097	0.0478	0.0048	0.0058	0.0025	0.0071	0.1374	0.2515	0.4913	0.0000	0.0101	0.0078	0.0243	1.00
IE	0.0057	0.0111	0.0000	0.1058	0.0041	0.0287	0.0000	0.4736	0.0000	0.0628	0.0003	0.0090	0.2389	0.94
IT	0.2409	0.1228	0.0717	0.9466	0.3346	1.2200	0.0005	4.3376	0.0000	0.0000	0.7076	0.1384	0.5692	8.69
LT	0.0037	0.0088	0.0000	0.0000	0.0040	0.0379	0.0000	0.0173	0.0000	0.0000	0.0020	0.0042	0.0420	0.12
LU	0.0021	0.0015	0.0000	0.0000	0.0000	0.0456	0.0000	0.0065	0.0000	0.0000	0.0031	0.0036	0.0075	0.07
LV	0.0118	0.0152	0.0000	0.0000	0.0000	0.1386	0.0000	0.0601	0.0000	0.0000	0.0000	0.0000	0.0044	0.23
MT	0.0003	0.0000	0.0000	0.0000	0.0056	0.0000	0.0000	0.0396	0.0000	0.0000	0.0045	0.0000	0.0000	0.05
NL	0.0268	0.0515	0.0800	0.9079	0.0344	0.0019	0.0000	1.8714	0.0988	0.0000	0.0640	0.1043	0.3391	3.58
PL	0.0318	0.1703	0.0732	2.4475	0.0587	0.0973	1.5143	0.3220	0.0000	0.0000	0.0053	0.0113	0.4783	5.21
PT	0.0083	0.0747	0.0000	0.4257	0.0372	0.2449	0.0000	0.5792	0.0000	0.0000	0.0288	0.0183	0.3930	1.81
RO	0.0019	0.0133	0.0022	0.0000	0.0184	0.4766	0.4871	0.3349	0.3341	0.0000	0.0539	0.0000	0.2376	1.96
SE	0.0003	0.2975	0.0206	0.0093	0.0084	2.0908	0.0000	0.0087	1.9076	0.0058	0.0067	0.0993	0.5650	5.02
SI	0.0038	0.0045	0.0000	0.0000	0.0004	0.1329	0.1400	0.0152	0.1948	0.0000	0.0082	0.0000	0.0002	0.50
SK	0.0172	0.0314	0.0159	0.0375	0.0127	0.1483	0.0493	0.0535	0.4580	0.0000	0.0147	0.0012	0.0002	0.84

[1] Country codes according to ISO 3166-1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

[2] PP1: biogas, PP2: biomass, PP3: coal gas, PP4: hard coal, PP5: oil, PP6: hydro, PP7: lignite, PP8: Natural gas, PP9: Nuclear, PP10: Peat, PP11: Photovoltaic, PP12: waste, PP13: onshore and offshore wind.

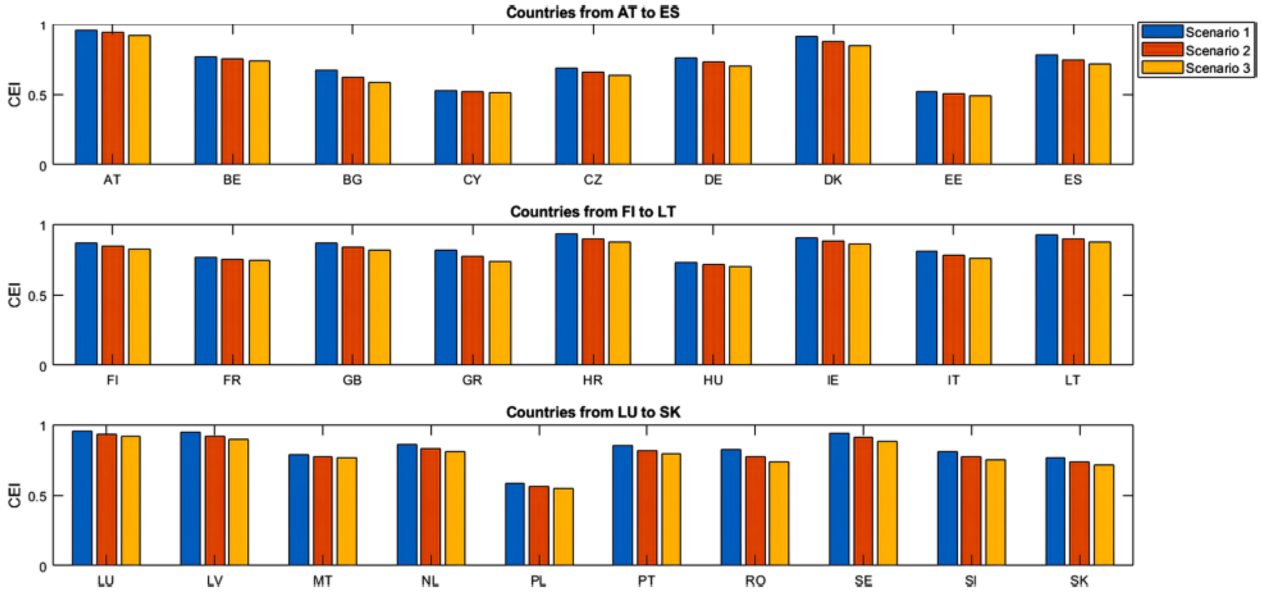

Fig. 5. Country Environmental Indices (CEIs) for Scenarios 1, 2 and 3. Country codes according to ISO 3166–1 [114]. AT: Austria, BE: Belgium, BG: Bulgaria, CY: Cyprus, CZ: Czech Republic, DE: Germany, DK: Denmark, EE: Estonia, ES: Spain, FI: Finland, FR: France, GB: United Kingdom, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LU: Luxembourg, LV: Latvia, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SE Sweden, SI: Slovenia, SK: Slovakia.

classified into two groups. Some are simply the result of rounding off decimals, making possible, apparently, variations over the limits established for each scenario. Nevertheless, as mentioned, this is merely a consequence of the number of decimals employed in Tables 3-6. If a larger number of decimals had been used, it would be possible to verify that limits have not been exceeded. By way of example, a 50 % decrease in an already very small percentage of generation can result in a value very close to zero. Furthermore, if the first non-nil number is positioned

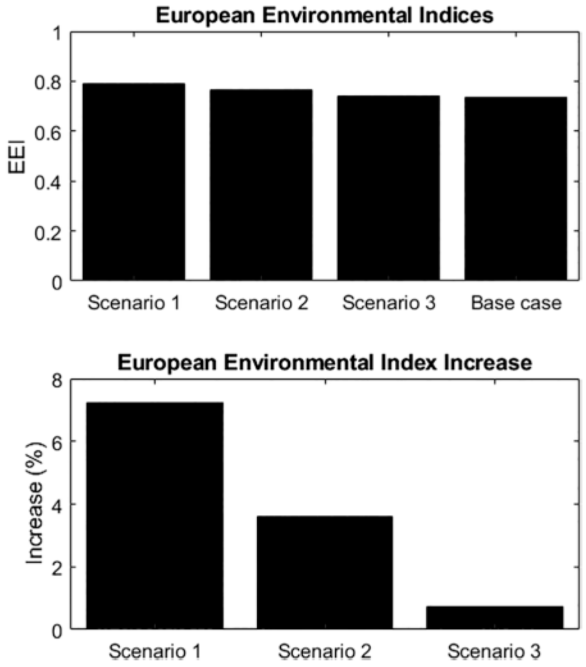

Fig. 6. European Environmental Indices (EEIs) for the base case and for the three scenarios. Increase that each EEI experiences with respect to the base case.

at the right of the fourth decimal and it is lower than 5, a zero value was adopted in Tables 4, 5 and 6.

It is also interesting to analyse why, in certain cases, the variation limits set by the constraints for the three scenarios (Section 2) are not being reached. For instance, hard coal (PP4) does not reduce its generation in a value equal or close to the limit in the Czech Republic and in Poland, under the three scenarios. In fact, for the particular case of Poland, the decreases respect to the base case are around 12.4, 6.3 and 1.4 % in Scenarios 1, 2 and 3, respectively. A certain proportionality can be observed in these three figures, close to that maintained among the limits (50, 25 and 5 % for Scenarios 1, 2 and 3). There are other cases in which the variations are far from the limit. For example, oil (PP5) in Cyprus; hydro (PP5) in Austria, Luxembourg and Latvia; lignite (PP7) in Estonia; natural gas (PP8) in Denmark, UK, Ireland, Italy, Malta, Netherlands, Portugal or Romania, among others, depending on the scenario and nuclear (PP9) in Belgium, Spain, Finland, France, Hungary, Slovenia and Slovakia. Cases affecting solar photovoltaic (PP11) and onshore and offshore wind (PP13) also exist in certain countries. There are several reasons for that. For example, in Austria, hydro (PP6) increased its production by values close to 34, 17.2 and 3.6 % in Scenarios 1, 2 and 3, respectively. On examining Table 2, one realises that this country generated about 60 % of its electricity from hydro power plants in 2017. All other alternatives are far behind this percentage. In fact, the second largest electricity producer was natural gas (PP8), with a value of about 15 %. If hydropower production were to be increased by 50 % (Scenario 1) compared to the base case, it would produce approximately 90 % of Austria's electricity, with an increase of 30 % in Austria's total generation. On the other hand, if the production of the remaining energy sources is reduced by 50 % (Scenario 1) compared to the percentages for the base year, the decrease in Austria's total generation would be close to 20 %, a value below 30 %. Therefore, with the constraints defined for Scenario 1, it is not possible to increase hydro's production by 50 %, as this would require some of the other alternatives to reduce their generation beyond the limit. Consequently, in this case, the maximum value for the increase in hydro's generation, the best alternative from an environmental point of view, is set by the total decrease in production derived from reducing the participation of the remaining alternatives by 50 %, all of which have lower *EIs*. This is also true for Scenarios 2 and 3; it is a logical consequence of the way in which the optimisation problem was modelled. Due to Austria's particular situation, with a high production based on hydroelectric power plants, it is not possible to reach the limit of its production increase and, therefore, no other alternative experiences an increase. This is the reason why, in Austria, wind (PP13), decreased its share even though it is an excellent alternative from an environmental point of view.

Another case in point is nuclear (PP9) in Spain. For example, under Scenario 1, it increased its electricity production a percentage slightly below the limit (50 %), about 46.6 %. In this case, nuclear (PP9) is the fourth best alternative in this country, according to Table A.2 (Appendix A), just behind hydro (PP6), wind (PP13) and solar photovoltaic (PP11). Therefore, during the optimisation process, the production of hydro (PP6) should increase by 50 %. After that, wind should increase its generation by 50 % and so on, until it is no longer possible to continue this process without worsening the *EEI* or not complying with the constraints. From the results it is clear that this happens when it comes to nuclear power (PP9), after the production of hydro (PP6), wind (PP13) and photovoltaic (PP11) has been increased. If these three alternatives raise their production by 50 % (Scenario 1) compared to the base case, they would then produce around 11.7, 27.3 and 4.7 % of the country's

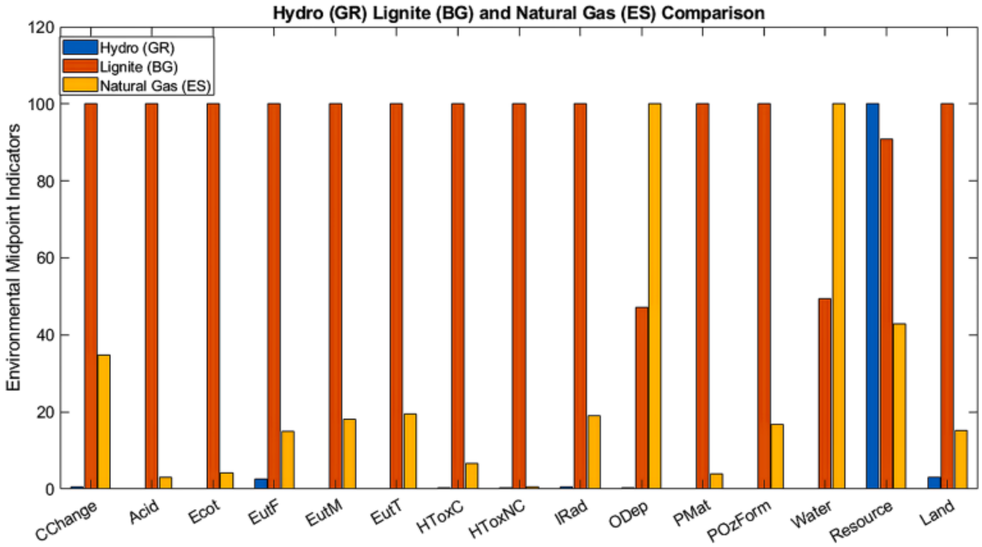

Fig. 7. Environmental comparison of hydro, lignite and natural gas power plants for Greece (GR), Bulgaria (BG) and Spain (ES), respectively. CChange: climate change, Acid: acidification, Ecot: Ecotoxicity freshwater, EutF: Eutrophication freshwater, EutM: Eutrophication marine, EutT: Eutrophication terrestrial, HToxC: Human toxicity cancer, HToxNC: Human toxicity non-cancer, IRad: Ionising radiation, ODep: Ozone depletion, PMat: Particulate matter, POzForm: Photochemical ozone formation, Water: Resource depletion water, Resource: Resource depletion, Land: Land use.

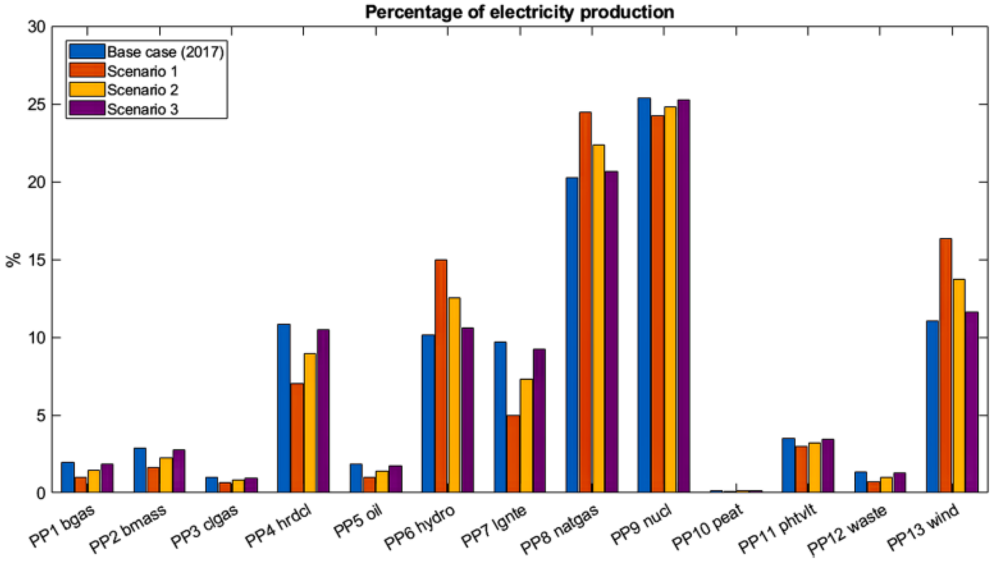

Fig. 8. Electricity production percentage for each technology in EU-27 and UK under different scenarios.

total electricity, respectively. That is, after the optimisation process, these power plants together would produce about 44 % of the total Spanish electricity, compared to 29 % in the baseline year (2017). In short, there was an increase in their combined share close to 15 % (14.6 % to be more precise). Leaving nuclear (PP9) aside, this had to come at the cost of a 50 % reduction in the production of the worst alternatives. If the generation of all the alternatives, except hydro (PP6), nuclear (PP9), solar (PP11) and wind (PP13), is diminished by 50 % compared to their base values, they would go on to produce approximately 24.6 % of Spain's total electricity, half of the base case. A 24.6 % reduction together with the 14.6 % increase leaves a margin of 10 % of the county's total electricity generation. That figure, 10 % of Spain's total production, is the margin with which nuclear energy (PP9) has to boost its production. If nuclear (PP9) increases its base output by 50 %, it would go from producing 21.5 % of the country's total to producing about 32.2 %. The exact difference between the two real values is slightly over the margin. As a result, nuclear power (PP9) cannot be increased by 50 %; it is only possible to reach a value of 46.6 %. Reaching the theoretical limit for Scenario 1 (50 %), would require: i) decreasing the output of some of the worst alternatives by more than 50 % compared to baseline figures or, ii) increasing the generation of hydro (PP6), solar (PP11) or wind (PP13) by less than 50 %, which would go against the optimisation objective. Similar reflections can be made for all other cases in which the model does not allow an alternative to increase or decrease its output by a value close to the limit.

It is also interesting to analyse how the resolution of the optimisation problem, in the three scenarios, affects the *CEI* of each country (Fig. 5 and Table A.3 of Appendix A). Logically, no country has worsened its environmental performance, since this is one of the constraints included in Section 2. If the results of the baseline case (2017) are studied, it can be seen that certain countries have performed remarkably in environmental terms. That is, their *CEIs* are above 0.85 as is the case with Austria (0.9148), Croatia (0.8635), Ireland (0.8571), Lithuania (0.8661), Luxembourg (0.9097), Latvia (0.8927) or Sweden (0.8777). Unsurprisingly, renewables have a considerable presence in these countries. By way of example, hydro (PP6) production accounts for over 30 % of the countries' corresponding total electricity, 63 % being the maximum in the particular case of Luxembourg. Similarly, wind (PP13) generated about 35 % of the total electricity for Lithuania. As for non-renewables in these countries, production from natural gas (PP8) and nuclear (PP9) is generally higher than that derived from other more polluting alternatives. By contrast, other countries, such as Bulgaria, Cyprus, Estonia or Poland, present discouraging results, with *CEIs* below 0.6. All of them based their production on energy sources that greatly contribute to the deterioration of the environment. For example, Bulgaria and Estonia base their electricity generation mainly on lignite-fired power plants (PP7). This alternative is also very present in Poland, second only to hard coal (PP4). In fact, their combined production exceeds 75 % of the total country's electricity. Cyprus consumed mainly oil (PP5). Over 90 % of its electricity was generated from this source in 2017. The remaining countries fall somewhere in between the best and worst alternative groups. The greater the presence of hydro (PP6), wind (PP13), natural gas (PP8) and nuclear (PP9) and the lower the share of other sources, the closer they are to the best group.

The improvement in the *CEI* that each country experiences (Fig. 5 and Table A.3 (Appendix A)) depends on several factors. On the one hand, the baseline situation comes into play. It might be thought that, with a worse initial result, the margin for improvement would be greater. This is true, at least from a theoretical point of view. Such is the case of Bulgaria, which experienced the highest percentage increase in all scenarios. Nevertheless, constraints may work against the previous idea. Cyprus is an example of this. In 2017, it was one of the worst countries from an environmental point of view, yet it experienced very low percentage improvements in all scenarios. This is due to the fact that, in Cyprus, only four different types of power plants generate electricity and one of them (oil) practically monopolises the total production (over 90 %). Therefore, another aspect that plays a key role in the potential improvement of the *CEI* is the number of different energy sources in the baseline case. In addition to the number of alternatives, the share that each one presents is also relevant. The greater the number of different energy sources in the electrical mix, the higher would the margin be for improving the environmental performance under the corresponding constraints. Furthermore, the larger the number of different alternatives with non-negligible outputs, the greater is the scope for improving the *CEI*. A clear example of this is Romania, which boasts ten different energy sources in its electrical network, five of which generated more than 10 % of the country's total electricity in 2017. All this made it possible for its increase in the *CEI* (Fig. 5 and Table A.3 (Appendix A)) to be among the highest values in all scenarios. Many other similar analyses are possible from Table A.3 in Appendix A. On the other hand, it is obvious that, when the percentage of variation allowed (50 %, 25 % and 5 % for Scenarios 1, 2 and 3, respectively) is higher, the increase *CEI* experienced by each country is greater. It is important to clarify that the improvement in each *CEI* may seem small. Nevertheless, even the slightest improvement really does translate into non-negligible reductions in all kinds of pollutants and, in general, negative impacts on the environment. In other words, even if the *CEI* of a country is only marginally improved and its hard coal (PP4) or lignite (PP7) production is somewhat reduced, thousands of tonnes of $CO_{2\text{-eq.}}$ will no longer be emitted into the atmosphere each year. If the largest electricity producer of Europe, Germany, is taken as an example, the base case (2017) leads to the emission of approximately $3.43 \cdot 10^8$ tonnes of equivalent CO_2. However, under Scenario 1, this quantity is reduced to $2.19 \cdot 10^8$. In other words, about 124 million tonnes of equivalent CO_2 would no longer be emitted. Scenario 1 also leads to a reduction of acidification (41 %) or land use (50 %), along with many other decreases under different environmental impact categories in the same country. This type of analysis demonstrates that the study presented here can be of widespread practical interest. On the other hand, the constraint of not allowing the generation with energy systems other than those of the base case considerably limits the possibilities of improvement. With this constraint removed, more significant improvements can be achieved in many countries, although not without potential problems. This comment is also valid for the *EEI* (Fig. 6) that will be discussed here below.

The *EEI* for year 2017 was 0.7363. Without being exceptional, this result is far from the theoretical worst-case scenario due to several factors. On the one hand, this study takes into account fifteen environmental impact indicators (Fig. 2) and not only global warming, which is often the main cause of environmental concern. On the other hand, this figure can be explained by the fact that certain countries that highly contributes to the total electricity production, have a high share of renewables and, in general, of environmentally acceptable sources. This is the case of Sweden with a production of approximately 5 % of the total electricity, mainly from hydro (PP6), nuclear (PP9) and wind (PP13). Moreover, some of the worst countries, such as Bulgaria, Cyprus or Estonia play a small role in the total production; their negative results are diminished by their low net share. However, Fig. 6 shows that, even with highly-demanding constraints, it would be possible to improve the environmental performance of the European electricity sector. These achievements, however small they may seem, would translate into considerably less pressure on the environment. To achieve better results, some countries would have to adopt new technologies and abandon certain sources they currently use.

By way of summary, Fig. 9 provides a final overview of what the optimisation results would mean for the European electricity sector. The 13 types of power plants were grouped into three blocks: i) biogas (PP1), biomass (PP2) and waste (PP12); ii) all other renewable energies (hydro (PP6), photovoltaic (PP11), offshore and onshore wind (PP13)), and iii) non-renewable power plants (coal gas (PP3), hard coal (PP4), oil (PP5), lignite (PP7), natural gas (PP8), nuclear (PP9) and peat (PP10)). Biogas, biomass and waste-to-electricity technologies were included in its own group separate from the second one, for two main reasons. First, the way in which electricity is produced is, to a certain extent, similar to non-renewable thermal power plants. Furthermore, they cannot always be considered as renewable energy sources. For instance, it cannot be said that certain types of biomass are renewable unless the consumption rate is lower than the replacement one. Similarly, not all types of waste used to produce electricity can be classified as renewable [115,116].

It should be noted that the results presented and discussed here are strictly environmental. Nevertheless, energy planning in any country must consider other economic (profitability for investors, costs or payback period, among many others), social (including employment generation, accidents, social acceptability, etc.), technical (for example, stability or uncertainty in generation), and even political or institutional issues (green governments, partner countries, among others). Consequently, before making a final decision on which types of power plants should be promoted, it is necessary to carry out analyses in addition to the one presented here. This may lead policy makers to select an alternative that, while being good from an environmental point of view, is not the best one. Natural gas (PP8), for instance, resulted to be a promising non-renewable option but, current fuel prices in the market would discourage its promotion in Europe.

Finally, comparing the results presented here with those from existing studies is not a trivial task, as this paper is novel in several respects (Section 1). In particular, this study makes new contributions from a methodological point of view: this is the first time that the results of several LCA studies are used to feed a MIVES model with the objective of solving an optimisation problem associated with energy planning. This is also the first time that all the most relevant environmental impact indicators have been taken into account in an analysis of the European electricity sector.

Nevertheless, some specific and limited comparisons are possible. By way of example, according to Vázquez-Rowe et al. [10], an increase in wind power will serve to reduce the environmental impacts derived from the Spanish electricity sector. The authors pointed out that environmental impacts in terms of climate change, water consumption or particulate matter would be reduced. This is in line with the results presented here, since, in the three scenarios, onshore and offshore wind (PP13) increases its generation in Spain. In fact, according to Table A.1 of Appendix A, wind not only serves to reduce the impact on those categories; it also presents better results than most of non-renewables for other environmental indicators such as acidification, ecotoxicity or eutrophication, among others. It is important to note that Vázquez-Rowe et al. [10] adopted an LCA approach to assess the results of policies implemented in Spain, with special focus on GHG emissions. However, the authors did not integrate the results from different environmental indicators into a single index. Furthermore, they did not propose an

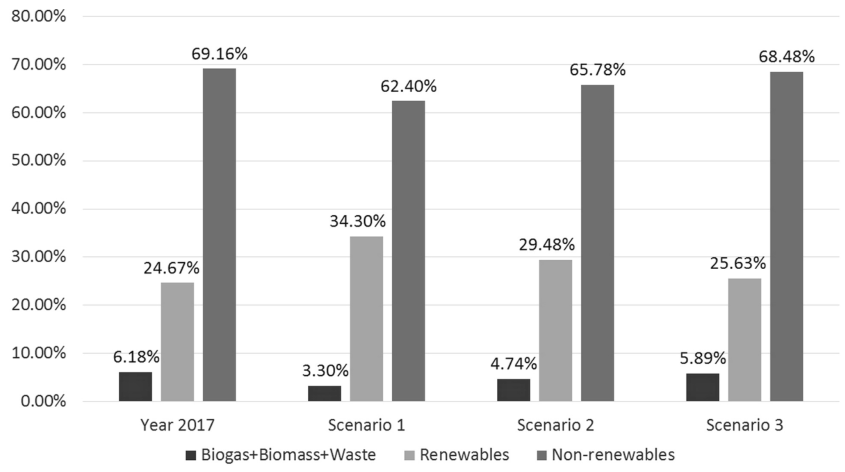

Fig. 9. Electricity production percentage in EU-27 and UK for each scenario.

optimisation problem with the aim of estimating the environmental performance of potential future scenarios. These same authors also analysed the Peruvian electricity sector, indicating that it presents a low normalised environmental impact. Although Peru is not considered in this paper, it can be compared to other European countries in which the participation of hydro (PP6) is very significant. Among these are Austria, Latvia and Luxembourg, all of whose *CEIs* are close to or over 0.9. From Fig. 7, it is also clear that hydro obtains outstanding results when placed alongside other alternatives. Consequently, Ref. [10] serves to validate some of the results presented in this paper.

In a similar way, Garcia et al. [69] adopted an LCA approach. However, the authors only analysed six environmental impact categories. The study also presents some of the limitations attributed to Ref. [10]. They found that hydro (PP6) is the best alternative for Portugal, also from an environmental point of view. The same result was obtained in this study, as can be seen from Table A.2 (Appendix A) in which hydro presents an environmental index (*EI*) of 0.997. In this case, this is the result of analysing 15 environmental impact indicators, instead of using six, as Garcia et al. [69] did. In other words, hydro (PP6) in Portugal also obtained remarkable results in environmental impact categories different from the ones analysed in Ref. [69]. These were related to ecotoxicity, human toxicity or ionising radiation. Furthermore, this type of power plant increases its production under the three scenarios analysed here. On the other hand, the authors stated that oil (PP5) is one of the worst options for the same country, as this source was highly penalised in terms of acidification or ozone layer depletion. In this study, oil (PP5) in Portugal also obtained poor results in those categories. It also resulted in being the worst alternative in terms of ecotoxicity, human toxicity cancer effects and particulate matter, indicators not considered in Ref. [69]. Another point in common is that the authors stated that coal was the worst alternative in Portugal in terms of global warming potential. This finding is line with the LCA results employed in this study. Hard coal power plants in Portugal emitted an average of 1.01 kg of equivalent CO_2 per kWh, oil being the second worst alternative, with an emission factor of 0.728. Finally, the authors suggested that a combination of hydro, natural gas and wind would serve to reduce the environmental deterioration of Portugal. In fact, these options were the only ones that experienced an increase in the three scenarios in Portugal. Consequently, the results presented by Garcia et al. [69] also serve to reinforce the validity of the ones included here. Similar conclusions were obtained by Pereira et al. [78], also for Portugal. According to their results, the participation of wind and hydro increases when demanding constraints for CO_2 emissions are established, a trend that is also highlighted in this work. However, Pereira et al. [78] did not adopt an LCA approach; they only studied CO_2 emissions.

Turconi et al. [13] pointed out that Denmark must replace coal power plants by wind and biomass generation in order to reduce the Danish electricity sector's contribution to climate change. An increase in wind (PP13) participation is in line with the results of this study. In fact, in Denmark, wind (PP13) obtained an environmental index (*EI*) of 0.983 (Table A.2 of Appendix A) only surpassed by hydro. However, the results for biomass (PP2) are not completely in line with the ones in this work. From the LCA results, it is possible to say that biomass is the best alternative in terms of climate change if renewables are not considered. It presented an emission factor of 0.034 kg of $CO_{2\text{-eq.}}$/kWh, while coal and oil took on values of 0.838 and 0.906, respectively. Nevertheless, biomass in Denmark obtained poor results in other environmental impact categories, such as freshwater eutrophication. On the other hand, the results included in Table A.2 of Appendix A indicates that biomass (PP2) obtained its second best *EI* in Denmark, only behind Finland. In the particular case of Denmark, biomass (PP2) is a better option than it may be in other European countries. According to Ref. [70], coal-fired power plants should gradually be dismantled in Ireland in an effort to reduce emissions. The same conclusion is reached in this paper, although the results of this study also suggest it is necessary to decommission other types of technologies (oil, peat or waste). However, the results presented in Ref. [70], only take into account the emission of three pollutants (CO_2, SO_2 and NO_x). If the authors had studied environmental impacts, they could have drawn additional conclusions. For instance, in Ireland, peat contributes to global warming more than coal (1.27 and 0.926 kg of $CO_{2\text{-eq.}}$/kWh, respectively). Oil resulted in being the worst alternative in six environmental indicators (acidification, ecotoxicity, marine and terrestrial eutrophication, particulate matter and photochemical ozone formation). Additional conclusions can be extracted from the LCA results used to feed the MIVES model.

Rentizelas and Georgakellos [6] claimed that if environmental externalities are included, wind and hydro must lead power generation in Greece, being natural gas the only non-renewable with share in the system. This is in accordance with the increase that wind (PP13), hydro (PP6) and natural gas (PP8) experienced in Greece in the three scenarios considered in this study. Furthermore, hydro in Greece stood out for the best environmental performance among all the technologies analysed in this study (Fig. 7). Although, some of the conclusions presented in Ref. [6] are similar to the ones of this study, it is important to note that Rentizelas and Georgakellos [6] quantified pollutants instead of working with environmental impacts. The limitation of this approach was previously explained in Section 1.

For the particular case of UK, Barteczko-Hibbert et al. [64] found that wind, natural gas, and nuclear power plants are relevant in almost all future scenarios. It is important to note that the authors only considered global warming and costs. Nonetheless, their results are similar to the ones presented here. For instance, wind (PP13) and natural gas (PP8) also increased their share in the mix for UK in the three scenarios. The only exception is nuclear (PP9), which in this study limits its generation. However, this difference can be explained. On the one hand, Ref. [64] only focuses on global warming, while in this study, other environmental impacts that penalise nuclear (PP9) are considered. On the other, nuclear obtained a promising *EI* in UK (Table A.2 of Appendix A), only surpassed by hydro (PP6), wind (PP13) and natural gas (PP8). Consequently, if a different optimisation problem, with other constraints, is modelled, nuclear could also boost its generation.

Gerbaulet et al. [117] provided some valuable results for the decarbonisation of Europe. If an emission constraint is considered, wind and, to a lesser extent, photovoltaic must dominate the electricity sector. More specifically, onshore and offshore wind (PP13) should come to the forefront in France, Germany and Spain. The importance of onshore and offshore wind in these three countries and, in general, in Europe has also been highlighted in this study. The same cannot be said for photovoltaic (PP11). This, again, is due to the fact that Gerbaulet et al. [117] focused on CO_2 emissions, instead of analysing a range of environmental impacts, as has been done here. In fact, according to Table A.1 of Appendix A, an increase in photovoltaic share, as suggested by Gerbaulet et al. [117], would also lead to an increased contribution to human toxicity, ozone depletion or resource consumption.

Also within Europe, Berril et al. [83] found that wind power is better than solar energy from an environmental perspective. This finding is particularly relevant, since the authors did not limit the study to global warming. According to Table A.2 of Appendix A, photovoltaic (PP11) always presents a lower *EI* than that for wind (PP13). The main limitations of the study developed by Berril et al. [83] were discussed in Section 1.

The authors of other studies addressed energy planning problems in non-European countries, drawing conclusions close to those of this work. By way of example, Gupta et al. [12] noted that hydro and wind are essential for the decarbonisation of the Canadian electricity sector. Treyer and Bauer [23] analysed the particular case of the United Arab Emirates. The authors stressed that future scenarios should be based on natural gas, nuclear and renewables in order to reduce negative impacts on the environment. With a small number of exceptions, previously discussed in this paper, it is possible to say that their results are in line with this study. The Indonesian energy scene was studied by Al Irsyad et al. [21]. They concluded that one option for reducing emissions is to replace coal power plants by hydropower (PP6). This coincides with the results here presented. A region in the same country was analysed by Handayani et al. [89]. Although the authors focus only on CO_2 emissions, they found that natural gas (PP8) would have to replace coal power plants. Indonesia, Philippines and Vietnam were addressed by Das and Ahlgren [51]. The authors concluded that renewables and gas substitute coal when CO_2 constraints are established. Finally, Shahid et al. [93] proposed a scenario for Pakistan mainly based on wind, hydro and nuclear energy. They estimated that this would serve to reduce CO_2 emissions by 75 %, compared to the baseline case.

5. Conclusions

A great number of authors have addressed different energy planning problems. Each problem involves a decision-making process that can be carried out according to various criteria. Cost assessment or minimisation is the most common approach. However, a great number of existing studies still overlook environmental issues at the time of facing and solving energy planning problems. Even studies that consider the environmental dimension often present several shortcomings. On the one hand, they are usually limited to the emission of certain pollutants (CO_2, NO_x, SO_2, among others), although a pollutant can contribute to more than one environmental impact category. Consequently, direct quantification of pollutants can lead to both difficult-to-interpret results and biased conclusions. On the other hand, a reduced number of studies analyse environmental impact categories instead of directly working with pollutants. However, in most of these cases, the number of environmental impacts is reduced, climate change being the most common one. In other words, most authors usually overlook impacts, such as acidification, eutrophication, ionising radiation, human toxicity, or resource depletion, among others. Existing energy planning studies usually adopt a local, regional or national scope. A few studies avoid the deficiencies mentioned above. However, their environmental results have not been integrated into a common index, a limitation that hinders the decision-making process. These are the gaps filled in this study.

In this article, a multi-criteria decision making model based on the MIVES method was employed to assess the environmental performance of the most relevant types of power plants in European (EU-27 and UK) countries. The input values for this model are the results obtained for 15 environmental midpoint indicators, including acidification, eutrophication, climate change, ozone depletion or land use, among others. These input values were estimated through several LCA studies developed with GaBi software. The MIVES model returns a numerical value between 0 and 1, the worst and best possible results. Thirteen types of power plants were studied adopting an approach from cradle-to-grave, in particular, biogas, biomass, coal gas, hard coal, oil, hydro, lignite, natural gas, nuclear, peat, solar photovoltaic, waste and onshore and offshore wind alternatives. By using the electricity production percentage for each type of power plant in each region for 2017, it was possible to estimate an environmental index for each country (Country Environmental Index, *CEI*). It is a dimensionless parameter that falls within the interval [0, 1], the worst and best possible results. This index provides a numerical idea of the extent to which each country's electricity sector damages the environment. To the best of the authors' knowledge, this is the first time that the environmental performance of each type of power plant and each electricity sector belonging to EU-27 and UK countries is estimated. With the corresponding *CEIs* and the production percentages of each country in relation to the European total, an environmental index for Europe's electricity sector (European Environmental Index: *EEI*) was estimated, also for 2017. Once again, no similar application has been found in the specialised literature.

A linear optimisation problem was proposed and solved, in three different scenarios with common and uncommon mixed constraints, where *EEI* was the objective function and the generation percentage of each energy source in each country were the variables. The constraints, depending on the scenario, make it possible to have different variations in the production percentage from each type of power plant. Never before has solving an optimisation problem in the energy sector taken into account 15 environmental impacts, a further contribution of this study. The need to include comprehensive environmental analysis when solving energy planning problems has been addressed. Furthermore, the potential usefulness of integrating the MIVES model used here into other existing energy planning tools has also been shown. The main conclusions drawn from the results are:

- In general terms, hydro and onshore and offshore wind alternatives appeared to be the best alternatives from an environmental point of view. They boasted environmental indices above 0.95, being 1 the best possible solution. Natural and nuclear power plants were the best non-renewable options with acceptable results (environmental indices varying between 0.68 and 0.89 and between 0.69 and 0.80, respectively). Biogas and oil had the poorest performances, with indices often below 0.5. The results for the remaining energy sources are usually far from those enjoyed by the best options.
- Certain countries, such as Austria, Croatia, Ireland, Lithuania, Luxembourg, Latvia or Sweden, achieved outstanding environmental results for 2017. Their country environmental indices are always above 0.85. They have a considerable share of renewables in their electrical networks. For example, Austria, Luxembourg and Latvia produced more than 50 % of their electricity from hydro power plants in 2017. With the exception of Ireland, all of these countries generated more than 10 % of their electricity from wind farms, also in the same year. Regarding non-renewables, their production from natural gas and nuclear was generally higher than that derived from other options.
- Some countries obtained discouraging results for 2017. This is the case of Bulgaria, Cyprus, Estonia or Poland. Their country environmental indices were 0.5721, 0.5075, 0.4857 and 0.5461, respectively. All of these based their production on energy sources, such as lignite (about 77 % of the total generation in Estonia), oil (91 % of the total production in Cyprus) or hard coal (46 % in the particular case of Poland in 2017) that greatly contribute to the deterioration of the environment. The remaining countries were halfway between the best and worst groups.
- It is possible to optimise the environmental index of the European electricity sector without worsening the environmental performance of each country. In fact, in this study the European Environmental Index was improved by 7.24 % compared to the base year, even with the constraints defined in the optimisation problem.
- After solving the optimisation problem, only hydro, onshore and offshore wind and natural gas power plants increased their production in Europe as a whole. This does not mean that other options may not have experienced occasional increases in certain countries. The opposite is also possible.
- From an environmental point of view, EU-27 countries and UK should promote, to the best of their respective possibilities, the use of hydro, wind and natural gas alternatives. This can lead to the reduction of several impacts.
- A small improvement in the European Environmental Index or in a Country Environmental Index translates into significant reductions in several emissions and, in general, into less pressure on the environment. For instance, one of the scenarios considered in this study would serve to halt the emission of 124 million tonnes of equivalent CO_2 in Germany.
- For achieving better results, both individually and as a whole, certain countries must adopt new technologies and leave behind others they are using. Nevertheless, better results are possible, even with the technologies they are currently using.
- The results of this study may be of great interest because it provides a way to consider environmental externalities in the electricity sector.

On the other hand, there are many possible future developments based on the results presented here. The most immediate one is to model and solve an optimisation problem similar to the one in this paper. However, in this case, it would be for a limited number of neighbouring countries with real constraints including, among other aspects, electricity exchanges among countries. Similar problems can also be defined and solved for neighbouring regions within the same country.

CRediT authorship contribution statement

Juan José Cartelle Barros: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Software, Writing – original draft, Visualization, Writing – review & editing, Validation. **Fernando de Llano Paz:** Conceptualization, Investigation, Formal analysis, Writing – review & editing, Validation. **Manuel Lara Coira:** Formal analysis, Writing – review & editing, Validation, Supervision. **María Pilar de la Cruz López:** Formal analysis, Writing – review & editing, Validation, Supervision. **Alfredo del Caño Gochi:** Formal analysis, Visualization, Writing – review & editing, Validation, Supervision. **Isabel Soares:** Formal analysis, Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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