Energy Policy 178 (2023) 113592

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

An Integrated Assessment Model for comparing electricity decarbonisation scenarios: The case for Spain

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ARTICLE INFO

Keywords:
Climate change
Energy transition
Decarbonisation
Wind and solar energy
Integrated assessment models
Energy policy

ABSTRACT

The decarbonisation of electricity supply poses a major milestone in the mitigation of climate change. Integrated Assessment Models (IAMs) provide a relevant instrument for the quantification and comparison of the economic and environmental impacts of various electricity decarbonisation scenarios, despite having rarely been applied to a national context. In this paper, an IAM able to calculate such impacts on the electricity sector in Spain is presented. Developed using the latest IAM modelling literature, the proposed model is able to estimate changes in temperature, climate-induced economic losses, and investment needs for climate mitigation corresponding to a range of electricity decarbonisation scenarios on a time horizon to 2050. The findings show that scenarios that undertake deeper and earlier cuts in CO_2 emissions from electricity generation would achieve better welfare results, and that further reliance on fossil fuels would imply higher costs than the investment needed for renewable energy deployment in Spain. The findings constitute an insight towards the formulation of policies that address the decarbonisation of the Spanish electricity supply.

1. Introduction

The continuous increase in global anthropogenic Greenhouse Gas (GHG) emissions since the Industrial Revolution is setting climate change closer to a tipping point, beyond which the intensity and frequency of extreme weather events and sea-level rises will remarkably increase (IPCC, 2021). In Europe, such events will occur in the form of more frequent pluvial rain and floods in the North and extreme droughts and forest fires in the South and will cause disruptive economic losses if no significative policies are put in place sufficiently promptly (EEA, 2022; Feyen et al., 2020). Such negative impacts on the European Union (EU) Gross Domestic Product (GDP) can reach up to 4.7% by 2050 under a high emissions scenario (Galiano Bastarrica et al., 2023; Spano et al., 2021; van Vuuren et al., 2017). For the case of Spain, losses of similar magnitude related to climate change and extreme weather events are expected, especially in the form of heatwaves, desertification, and floods in fertile land (MITECO, 2020a; Moreno et al., 2005).

In order to tackle these prospects, climate policies have focused their efforts in the last two decades on setting mid- and long-term targets and climate-neutrality goals, with the Paris Agreement standing as one of the key milestones in setting the global objective of maintaining the projected increase of global temperature well below 2 °C and ideally below 1.5 °C (United Nations, 2015). Today, climate change policies seem to be entering a new field and most countries worldwide have adopted decarbonisation plans to become climate neutral, in most cases by 2050 (with the exception of China, by 2060) albeit with varying levels of commitment (Hale et al., 2021). The design of cost-effective and sufficiently ambitious mitigation pathways for the most emitting sectors has therefore become crucial.

With the power generation sector being the largest contributor to GHG emissions globally, whereby it accounts for approximatively 34% of global GHG emissions (IPCC, 2022), its decarbonisation constitutes the key to the success of the climate transition in Europe and beyond, since other regions may well follow suit to what is carried out by the European Union. In Spain, electricity accounted for 15% of total CO_2 emissions in 2019 (INE, 2022) and it is projected to become the main energy carrier by 2040 driven by the electrification of key end users, such as transport and industry (MITECO, 2020a). It is also portrayed as the sector where renewables bear maximum potential (MITECO, 2020b), thereby making it the single most important sector to

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https://doi.org/10.1016/j.enpol.2023.113592
Received 28 April 2022; Received in revised form 12 March 2023; Accepted 20 April 2023

decarbonise in the Spanish economy.

Europe has strongly increased the ambition level towards decarbonisation with the adoption of the European Green Deal and related legislation since 2019, and aims towards climate neutrality by 2050 (European Commission, 2019). The European Climate Law made such objective binding for the EU in 2021 (European Commission, 2021a). Additionally, the recently adopted "Fit for 55" package strives to deliver on an increased 2030 target of reduction of 55% GHG emissions compared to 1990 levels with a set of specific policy proposals that includes doubling the capacity of renewable energy sources (RES) within a decade from 2021 and increasing the presence of electricity as the main energy carrier before 2050 (European Commission, 2021b). In Spain, parallel objectives have been laid down in Spain's Long-Term Decarbonisation Strategy (MITECO, 2020a) and the Spanish National Energy and Climate Plan (MITECO, 2020b).

Additionally, the recent invasion of Ukraine by Russian forces and the ongoing war have increased the need for speed and depth in transforming the European Union energy system and has highlighted the considerable energy dependence of the continent towards non-EU energy providers. In particular, the perturbations in energy markets stemming from the conflict have resulted in an unprecedented energy crisis in Europe characterised by increasing energy prices and concerns over energy shortages to match domestic heating needs (Conti and Kneebone, 2022). Some of the very short-term measures planned by several EU Member States [1] include temporary re-starts of formerly closed coal power plants to cover gas supply shortages amounting to a 7% increase compared to 2021 levels according to the International Energy Agency prospects (IEA, 2022a, Sgaravatti et al., 2022). The impact of such short term increased use of coal is however unlikely to have significant long term impacts on GHG emissions in the EU power sector by 2050, as the trend in coal has been matched by similar increases in wind and solar on a year to year basis (Sgaravatti et al., 2022).

On the other hand, the European Commission aims to address the ongoing energy crisis through the recent REPowerEU plan. Proposed in May 2022 and currently reaching the final stages of interinstitutional negotiations, the plan aims at transforming the EU energy system and ending the dependence of the EU on Russian fossil fuels by 2027 through the combination of three main pillars: enhancing energy efficiency policies to reduce energy needs, accelerate the deployment of renewable energies (i.e. to replace up to 21 billion cubic meters per year of gas by wind and solar) and diversifying gas supplies needed in the short and mid-term (European Council, 2023; European Commission, 2022a; Conti and Kneebone, 2022; Sgaravatti et al., 2022). In this context, an accelerated deployment of renewable energy is in order not only needed for decarbonisation purposes, but also as a strategic investment to reduce Europe's energy dependence (European Commission, 2022a).

Regardless of the exact trajectory that GHG emissions from the EU power sector will follow in the coming decades, the implementation of decarbonisation plans entails complex impacts, positive and negative, that need to be measured and evaluated carefully. Modelling tools such as Integrated Assessment Models (IAMs) have a crucial role to play in supplying policymakers with an informed choice of optimal pathways for the deployment of such ambitions, by providing estimations on the economic costs of changes in GHG emissions under a range of scenarios (Capellán-Pérez et al., 2014; Estrada et al., 2019).

There are several advantages that can be drawn from the use of an IAM-based approach for the particular case of modelling the impacts of decarbonising electricity supply in Spain. First, IAMs constitute a widely used modelling approach for the quantification of interlinked impacts of different paths of action on climate change policies (Pietzcker et al., 2017). Moreover, IAMs are used by authoritative sources such as the Intergovernmental Panel on Climate Change (IPCC, 2022; IPCC, 2021) in their landmark reports and constitute an active field of academic research granted with increasing relevance and recognition in the literature (Weyant, 2017; van Beek et al., 2020). Thirdly, IAMs enable the integration of different disciplines (such as climate science and economics) and, even if their complexity varies greatly from one application to another, they can be calibrated more precisely than other numerical-based modelling tools that require the optimisation of complex interconnected systems such as global power system models (van Beek et al., 2020). Finally, within IAMs a calibration of the DICE-R model by Nordhaus and Sztorc (2013) was chosen as the basis to develop the presented model because of its relevance for its application to climate regional modelling (Ortiz et al., 2011) and from the fact that other types of IAMs (known as process-based) are mostly designed for global modelling and rely on assumptions that are not needed when modelling decarbonisation pathways for the case of one country (van Beek et al., 2020).

An adaptation and re-calibration of the DICE-R model seems therefore to be pertinent to the case at hand in this paper, aimed at replying to a simple, yet challenging research question: Can IAMs be applied to the specific case of one sector in the context of one EU Member State, such as the electricity sector in Spain? And in such case, what are the adjustments needed and the insights of relevance to policymaking that can be produced with it?

The IAM presented in this paper aims to calculate the environmental and economic costs of various scenarios of electricity decarbonisation in Spain in order to define a socially optimal renewable energy policy for electricity (Mathiesen et al., 2011). It does so by adapting the DICE-R model by Nordhaus and Sztorc (2013) to the particular case of electricity generation in one single country. In particular, the presented IAM uses as exogeneous input data the Lifecycle Costs of Energy (LCOE) for different energy sources as well as scenario projections on different energy mixes elaborated by the European Commission and the International Energy Agency to translate such scenarios to the particular case of the electricity generation sector in Spain and thus produce endogenous projections on the economic and environmental impacts of different electricity mixes by 2050.

Several contributions of the proposed approach can be outlined: first, economic modelling of climate change has seldom been utilised for the case of Spain in the literature, with very few and specific applications such as the water-energy nexus (Khan et al., 2016), land use change (Pulido-Velazquez et al., 2014), and the electricity market (Espinosa and Pizarro-Irizar, 2018; García-Gusano and Iribarren, 2018) whereby no IAMs have been employed. This paper, however, is a direct application of IAMs to electricity generation. Second, national applications of IAMs remain largely unexplored and with few adjustments and calibrations, as presented in this paper, IAMs can be adapted to produce important results for policymaking also at national level, relevant for the calibration of decarbonisation pathways. Finally, the proposed model is able to estimate economic costs and investment needed for the different scenarios: information that is needed at this stage by Spanish authorities to implement the plans outlined in the Long-Term Decarbonisation Strategy (MITECO, 2020a) and the National Energy and Climate Plan (MITECO, 2020b) as well as to tackle the ongoing energy crisis stemming from the invasion of Ukraine by Russian forces. The paper is structured as follows. Section 2 provides the theoretical framework for IAMs. Section 3 explains the characteristics and different modules of the model. The description of the data is given in Section 4. Section 5 presents and discusses the results and, finally, Section 6 draws the conclusions.

2. Integrated Assessment Models: benefits and limitations

The origin of IAMs is often traced to the Club of Rome and their "Limits to Growth" landmark publication in 1970, in which the assessment of a scenario called "World3" modelled climate change for the first

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[1] Austria, Denmark, France, Germany, Greece, Hungary, Italy, the Netherlands and Romania have planned measures in this direction (Sgaravatti et al., 2022).

time on a global scale and assessed the challenge of maintaining economic growth within a sustainable use of resources (Meadows and Randers, 2013; van Beek et al., 2020).

Integrated Assessment Models model the economic impacts of climate change by linking two sets of equations: a climate module representing the dynamics of CO_2 accumulation and their relative impacts on global temperature; and an economic section affected by the changes in temperature and abatement costs (Ortiz et al., 2011; Zhao et al., 2020). In IAMs, two concepts are key: the definition of damage functions and the intertemporal discount rate. Damage functions translate a change in global temperature to GDP loss by relying on a set of climate sensitivity parameters that connect the accumulation of CO_2 in the atmosphere with changes in average global temperature (Bretschger and Pattakou, 2019). A wide variety of approaches and functional forms have been explored in the relevant literature. Indeed, damage functions remain one of the most criticised elements of IAMs, the main criticism being that their formulation vastly affects the final estimations of the model and that approaches within the literature differ widely from each other (Diaz and Moore, 2017). The literature points out several caveats of damage functions. The use of quadratic forms fails to provide a realistic representation of climate dynamics, since tipping points of large economic losses appear too late in the temperature increase (Wouter Botzen & van den Bergh, 2012; Bretschger and Pattakou, 2019). Moreover, a careful assessment of impacts per sector has to be considered when estimating damage (Neumann et al., 2020), as well as adaptation policies (Estrada et al., 2019) or extreme weather events (Lempert et al., 2006; Zhang et al., 2021). However, in spite of these critiques, and as shown in Neumann et al. (2020), even if the feedback mechanisms taking place between economies and climate are simplified, damage functions continue to be the most straightforward and widely used way to calculate environmental impacts in IAMs.

Another challenge of IAMs lies in how to implement intertemporal discounting in the model specification (Weyant, 2017). In IAMs, various scenarios (often related to different mitigation pathways, plus a baseline that represents business as usual) are portrayed and placed in the decision-making process of a public agent. For the model to be useful for policymaking, a prioritisation logic between the welfare of the current generation and that of future generations needs to be implemented. This is carried out in IAMs by using an intertemporal social utility discount rate, which is used by the public agent to prioritise and compare scenarios from a social welfare standpoint (Espagne et al., 2018; Karp, 2005). Given the length of the time horizons involved in these models (often until 2100), a slight change in the discount rate can yield quite different results on the final estimates, which makes IAMs highly dependent on the chosen rate (Pindyck, 2013; Espagne et al., 2018). On this topic, and as shown in Weyant (2017) and Drupp et al. (2020), there is a dispute between Stern on one hand, who considers that any positive value of the discount rate in IAMs is purely unethical since the welfare of the current generation is valued more highly than future generations (Stern, 2007), and Nordhaus and Weitzman on the other hand, who propose a higher discount rate that sets climate investments in stronger competition with other investments, thereby allowing for a slower, market-driven transition (Nordhaus, 2007; Wouter Botzen & van den Bergh, 2012). Nevertheless, regardless of the final value chosen by the modeller, the discount rate decisively influences the ability of the remaining carbon budget to stay below specific temperature thresholds, such as 2 °C and 1.5 °C (Emmerling et al., 2019) and involves debates that go beyond purely economic decisions, such as to how to evaluate the welfare of future generations when precisely it is their future that seems increasingly unclear.

3. The model

The main features of the model are presented in the following subsections and in Graph 1 below. The model is composed of four modules: economy, climate, electricity, and social planner. The economic module includes a standard Cobb-Douglas production function in which productivity and capital accumulation are affected by climate change damage from the climate module that are estimated using the Weitzman damage function (Weitzman, 2010). Economic growth follows a Ramsey-Cass-Koopmans model, in which steady-state capital and consumption per capita are calculated as key variables for long-term forecasts as in the original specification of the DICE model (Nordhaus and Yang, 1996; Fankhauser and Tol, 2005; Nordhaus, 2007; Bauer et al., 2012; Diemer et al., 2019). The electricity module provides the mitigation pathways of the model, which are based on exogeneous projections under different scenarios designed by the European Commission and International Energy Agency (European Commission, 2011; IEA, 2021). The social planner module takes in the steady-state capital and consumption per capita to calculate total welfare under the various scenarios as a key factor in the choice of one decarbonisation pathway over the other. A visual representation of the interactions between modules is provided in Graph 1.

Several further elements related to the functioning and scope of the presented model can be outlined before presenting its modules and functioning in detail. Firstly, while the model focuses on one particular sector in one EU Member State (i.e. the electricity generation sector in Spain), it incorporates projections from different models that include cross-effects going much beyond the electricity generation sector itself, such as changes in transport, energy efficiency policies, energy system interconnections or innovation in different low-carbon energy sources resulting from the adoption of different energy mixes .[2] In addition, the changes foreseen in the electricity generation sector in Spain in the exogeneous data used in the model is in line with the Spanish National Energy and Climate Plan, which is defined in coherence with European policies in the field of energy. Thirdly, even if the presented model produces results at a relatively high level of integration (i.e. at national level), the exogeneous projections used for the baseline values of electricity uses in Spain coming from the EU Reference Scenario 2020 build on the PRIMES model, which is a bottom-up Partial Equilibrium Model that draws on microeconomic data to produce disaggregated results per sector and EU Member State. The modelling approach therefore consists of integrating the electricity generation in Spain with other policies and sectors by building on detailed bottom-up modelling results to assess the impacts of different electricity mixes by 2050 in the most accurately possible manner.

3.1. Economic module

The first part of the model is its economic module, composed by a Cobb-Douglas production function with constant returns to scale. As in the original DICE model (Fankhauser and Tol, 2005; Nordhaus, 2007; Ortiz et al., 2011), we consider a time horizon running from 2010 to 2050. The production function is sensitive to climate change damage (Nordhaus, 2007) and is expressed in terms of output per worker:

$$y_t = D_t A_t k_t^{\alpha} \tag{1}$$

where $D_t < 1$ is the value from the damage function from Weitzman (2010) at each point in time (see subsection 3.2); A_t is Hicks-neutral technical change or total factor productivity, and k_t^{α} is capital stock per worker. In our specification, α reflects the findings of Macías and Matilla-García (2015) and Bentolila and Saint-Paul (2003), with an income share of capital of approximately 40% for OECD countries .[3]

The model follows the usual assumptions in IAMs on all variables

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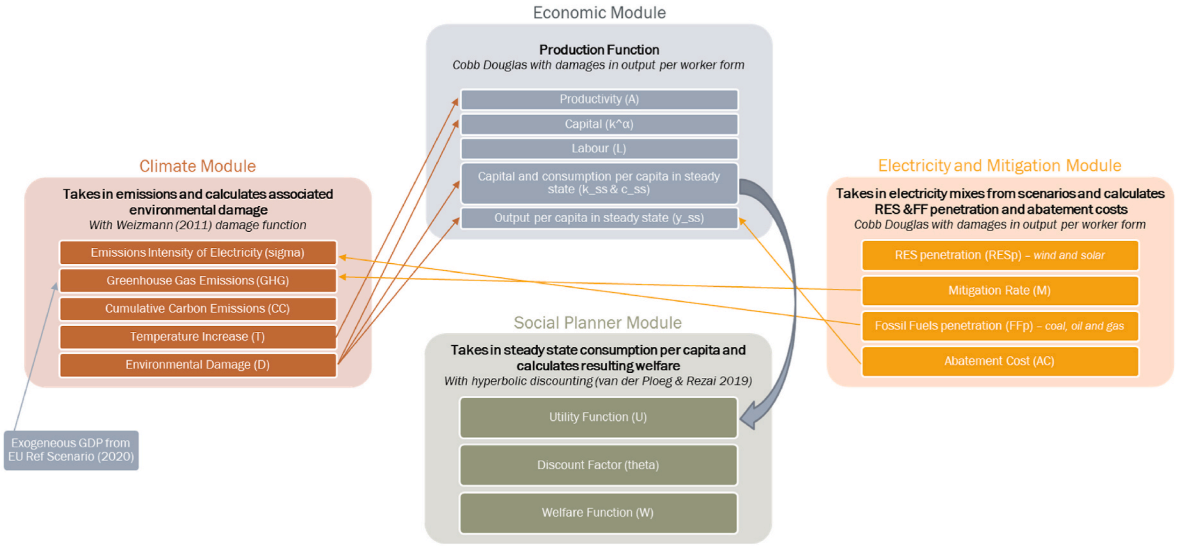
[2] In particular, we use i.e. the European Commission energy roadmap and the Net Zero by 2050 report by the International Energy Agency for the shares of the electricity mix under different scenarios and the EU reference scenario 2020 by the European Commission for the baseline of projected electricity needs in Spain.

[3] For the whole list of parameters, see the Appendix.



Graph 1. Model overview.

(Ortiz et al., 2011; Weyant, 2017; Espagne et al., 2018; van Beek et al., 2020): population increases at a decreasing rate $g_{L,t} = g_{L,t-1}/(1+\delta_L)$, where δ_L is the population growth rate (Tsigaris and Wood, 2016) that is added to the population in levels $L_t = L_{t-1} * (1 + g_{L,t})$, and reflects the trends in the European Union Reference Scenario report (European Commission, 2021c).

The dynamics of total factor productivity, A_t, are specified in a similar way to those of population, $A_t = A_{t-1} * (1 + g_{A,t})$, but with one major difference: the parameter measuring the growth rate on productivity, $g_{A,t}$, is negatively affected by temperature, $g_{A,t} = \frac{g_{A,0}}{(1+\delta_A)^t} - \gamma T_t$, where δ_A is a parameter that reflects technical change and γ links temperature increases to decreases in productivity growth (Nordhaus and Sztorc, 2013; Tsigaris and Wood, 2016). This is carried out on the basis of previous literature that argues for the specification of total factor productivity in IAMs in order to account for the opportunity cost regarding lost R&D that has been directed towards climate adaptation and mitigation, as well as for the negative impacts of extreme weather events (Nordhaus and Sztorc, 2013; Dietz and Stern, 2015; Diaz and Moore, 2017; Espagne et al., 2018; Zhao et al., 2020). Under this specification, total factor productivity, A_t, decreases over time as temperature increases. The speed of the trend ultimately depends on how fast temperatures rise over the time horizon.

The economic inputs module of the model is completed with the dynamics applied to the capital stock per worker (k_t), which are in line with the Ramsey-Cass-Koopmans and Solow-Swan economic growth model and the concept of convergence to a steady state (Solow and Swan, 1956), as in most of IAMs (Fankhauser and Tol, 2005; Hope, 2006; Bauer et al., 2012; Diemer et al., 2019). By taking the approach used in DICE, in which climate impacts are channelled mostly through the production function (Nordhaus, 2007; Fankhauser and Tol, 2005), a constant savings rate (s) is used together with the pathways outlined above to calculate the steady-state capital stock per worker regarding climate damage (D_t):

$$k_{ss,t} = \left(\frac{sA_tD_t}{\delta_k + g_{L,t}} \right)^{\frac{1}{1-\alpha}} \tag{2}$$

where capital stock per worker is also affected by temperature. In this case, the link with increasing temperatures is formed via a more accelerated depreciation of assets due to extreme weather events (Stern, 2013; Pietzcker et al., 2017). This link is carried out in the model via the specification of the capital depreciation parameter, $\delta_K = \delta_0 * \delta_1 T_t$, whereby δ_0 is the initial capital depreciation rate and δ_1 is a parameter that measures the change of depreciation from the temperature increase, T_t (Stern, 2013). With the steady-state capital stock per worker in place, the steady-state income and consumption per worker can be obtained in expressions (3) and (4) respectively:

$$y_{ss,t} = D_tA_tk_{ss,t}^{\alpha} \tag{3}$$

$$c_{ss,t} = (1-s)y_{ss,t} \tag{4}$$

The steady-state consumption per worker is a particularly relevant variable in the model, since it is the variable employed to compute the discounted utility to assess the social pertinence of each scenario.

3.2. *Climate module*

The second part of the model is the climate module, in which the environmental impacts of the various electricity decarbonisation scenarios are calculated based on the DICE and DICE-R models (Nordhaus 2008; Nordhaus and Sztorc, 2013).[4] The intensity of electricity (σ_t) of the greenhouse gas emissions provides the starting point. Since only one sector is addressed (i.e., electricity generation), σ_t is directly linked to the percentage of penetration of fossil fuels in the electricity mix (FFp_t) in the EU27 at each point in time:

$$\sigma_t = FFp_t \tag{5}$$

There are obvious advantages to specifying the intensity of electricity emissions in such a straightforward way instead of using an exogenous source. On the one hand, the model gains significant coherence, since emission intensity becomes directly linked to the policy choice on the presentation of renewables in the electricity mix. On the other hand, in this way the intensity of electricity emissions mirrors the results of the different scenarios evaluated with IAM, thereby making the overall tool more relevant for the policy decision-making.

The level of Greenhouse Gas Emissions is calculated as in the DICE-R model. An exogeneous level of projected GDP for the EU27 to 2050 ($\overline{Y}_t$) from the EU Reference Scenario report (European Commission, 2021c)

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[4] It is assumed that, since Spanish GHG emissions only account for a fraction of total GHG emissions, the endogenous levels of GHG emissions and mitigation pathways under scenarios at each point in time are calculated for the 27 Members of the European Union (EU27). The economic impacts of each scenario (i.e., climate losses) are then estimated at national level for the case of Spain.

is employed:

$$GHG_t = (1 - M_t)\sigma_t \overline{Y}_t \tag{6}$$

where σ_t is the intensity of electricity emissions (Equation (5)) and M_t is the cumulated abatement (see Subsection 3.3). It is easy to determine that the mitigation measures planned towards the decarbonisation of electricity supply (i.e., by increasing the penetration of renewables in the electricity mix) exert a direct effect on reducing the amount of GHG emissions in the model.

As in most IAMs, our focus is on cumulative carbon emissions (CC_t) as the main pollutant in the model to which changes in temperature are attributed (Nordhaus, 2007; Nordhaus and Sztorc, 2013), leaving aside other GHG emissions that are less relevant in the case of electricity generation (INE, 2022). The cumulative carbon emissions are calculated as follows:

$$CC_t = CC_{t-1} + \left(\frac{GHG_t}{CtoCO2_{cr}}\right) \tag{7}$$

where the level of carbon emissions grows cumulatively on a rate equal to the sum of the cumulated carbon emissions of the previous period (CC_{t-1}) and the carbon emissions taking place within the same period, which need to be calculated by dividing the GHG emissions from Equation (6) over the chemistry ratio of CO_2 to carbon ($CtoCO2_{cr}$) to focus only on carbon as the key pollutant. In order to treat carbon emissions as a global pollutant, the same initial value is taken for carbon emissions as in the DICE-R 2013 calibration: 530 billion tons already emitted globally (Nordhaus and Sztorc, 2013).

The climate module of the model is completed with the equations on temperature change and the damage function (Nordhaus, 2007; Weitzman, 2010; Nordhaus and Sztorc, 2013):

$$T_t = CC_t * CCR \tag{8}$$

$$D_t = 1 \bigg/ \left[1 + \left(\frac{T_t}{\theta_1}\right)^{\theta_2} + \left(\frac{T_t}{\theta_3}\right)^{\theta_4}\right] \tag{9}$$

where Equation (8) models the increase in projected temperature as a direct consequence of cumulative carbon emissions (Equation (7)), with the carbon-climate change response parameter (CCR)[5] as the parameter linking the temperature with the emissions (Matthews et al., 2012).

Equation (9) contains the climate change damage function proposed by Weitzman (2010). It includes four damage parameters, θ_1 to θ_4, which are calibrated using an expert panel to the values $\theta_1 = 20.46$, $\theta_2 = 2$, $\theta_3 = 6081$, and $\theta_4 = 6754$. As shown in Weitzman (2010) and Wouter Botzen & van den Bergh (2012), these calibrations yield a tipping point in economic growth at 6 °C beyond which disruptive climate events are triggered. Additionally, the application of this damage function results in climate policy that is significantly more stringent than that employed when applying the standard damage function used by Nordhaus (2008) in DICE, which tends to show only marginally small impacts on economic growth even when temperatures reach unconceivable thresholds beyond 8 °C of increase (Wouter Botzen & van den Bergh, 2012; Bretschger and Pattakou, 2019). Bretschger and Pattakou (2019) and Zhao et al. (2020) propose alternative specifications to the damage function, such as polynomial functions of up to quadratic form, which yield climate policy that is even more stringent for small increases of temperature. Although these new approaches appear promising and deserve attention, they have yet to be widely accepted as standard within the IAM literature.

We have opted for a climate change damage function exclusively dependent on temperature since temperature-denominated damage functions continue to be the most widely used in the IAM literature, largely because the increase in temperature remains the variable that attracts the most attention in climate science and international climate agreements, such as the Paris Agreement (Wouter Botzen & van den Bergh, 2012; Diaz and Moore, 2017; J.E. Neuman et al. 2020; IPCC, 2021). Although there are other approaches in the IAM literature to damage functions, such as those that are sensitive to extreme climate events (Zhang et al., 2021), sectoral climate impacts (Zhao et al., 2020), and abrupt climate change (Lempert et al., 2006), no consensus has yet been agreed in the literature as to how to include these effects in a standard way (Espagne et al., 2018).

3.3. Electricity and mitigation module

The third part of the model is its electricity and mitigation module, in which the impacts of different exogenous scenarios on the future evolution of the electricity mix for Spain are tested. Under each scenario, which will be described in Section 4, the model calculates the resulting proportions of renewables (including solar and wind) and fossil fuels (including coal, oil, and natural gas) in the electricity mix. The negative environmental impact from a higher presence of fossil fuels is captured by a higher intensity of electricity emissions, σ_t , which in turn results in higher cumulated emissions and climate damage. Conversely, a greater penetration of renewables in the electricity mix results in a higher cumulated abatement, which reduces cumulated emissions but entails abatement costs stemming from the deployment of the capacities required. These costs are calculated using the levelised cost of electricity (LCOE) of wind and solar generation, as calculated by the Fraunhofer study on LCOEs for renewable energies (Ueckerdt et al., 2013; Fraunhofer, 2021). The model focuses only on wind and solar technologies because all other renewables (i.e., hydropower, geothermal, tidal) are forecast to play a minor important role in the energy transition in Spain in all scenarios consulted (European Commission, 2011; European Commission et al., 2020; IEA, 2021; MITECO, 2020a).

Consequently, the cumulated abatement, M_t, under each scenario is calculated directly from the penetration in the electricity mix of wind [6] and solar power, $RESp_t$, which is taken as an exogeneous value under each scenario:

$$M_t = RESp_t \tag{10}$$

$$RESp_t = (SolESQ_t + WinESQ_t) \,/\, TotalESQ_t \tag{11}$$

where $SolESQ_t$ and $WinESQ_t$ are the exogeneous values under each scenario for electricity generation in Gigawatt-hours (Gwh) for solar and wind power in Spain, respectively, and $TotalESQ_t$ refers to the total exogeneous electricity generation in Spain, which is taken from the EU Reference scenario 2020 (European Commission, 2021c) in all scenarios of the model to ensure consistency of the calculations. The penetration of fossil fuels into the electricity mix is calculated in a similar way, and, as can be seen from Equation (5), it is taken as the endogenous value for the intensity of electricity emissions, which is in turn the main driver of cumulated emissions (and, therefore, of climate damage) in the model:

$$FFp_t = (CoalESQ_t + OilESQ_t + GasESQ_t) \,/\, TotalESQ_t \tag{12}$$

where $CoalESQ_t$, $OilESQ_t$, and $GasESQ_t$ refer to the exogeneous value

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[5] The CCR parameter yields an estimated linear relationship between cumulated CO_2 in the atmosphere and projected temperature increase, calibrated by Matthews et al. (2012) of 1.8 Celsius degrees increase in mean temperature for every 1000 Gigatons of cumulative CO_2 emissions released into the atmosphere. Such an estimation brings simplicity to the calculations in the model and is in line with recent proposals on the estimation of damage in climate change damage functions in IAMs (Bretschger and Pattakou, 2019).

[6] For the case of wind power, both offshore and onshore generation are considered by the IEA when calculating LCOEs. Since the model only accounts for wind in general, we have applied an arithmetic mean between the two LCOEs (for offshore and onshore wind) to obtain the LCOE used by the model.

under each scenario for electricity generation in Gigawatt-hours (Gwh) for coal, oil, and natural gas under each scenario for Spain.

As in all IAMs, the model needs to be completed by an abatement cost function that calculates the consequences of reducing emissions on the steady-state income per capita. To this end, the convex abatement cost function from the DICE-R 2013 model of Nordhaus and Sztorc (2013) has been employed in which the total abatement costs, AC_t, are a function of cumulated abatement, M_t, specified as follows:

$$AC_t = \omega_t M_t^{\theta_{AC}} \tag{13}$$

where: the cumulated abatement is weighted by an exponent, θ_{AC}, calibrated as 2.8 in the DICE-R 2013 model; and an abatement cost parameter, ω_t, declines at a rate equal to the change in the productivity rate in each period, $g_{A,t}$. This yields an abatement cost, AC_t, which shows very marginal values in the early decades of the period (mainly 2010 to 2020) and then gradually increases with the penetration of renewables in the electricity mix over the period. Abatement costs complete the model by entering the calculation of the steady-state output per capita given in Equation (3):

$$y_{ss,t} = (1 - AC_t) D_t A_t k_{ss,t}^{\alpha} \tag{14}$$

In this way, the trajectory of the level of output per capita is endogenously determined by two fundamental costs: the climate damage and the cumulated abatement, in which reducing units of the former implies an increase in the latter. The model is employed to compare how this relationship holds when variable compositions of the electricity mix are modelled for Spain over the period 2010 to 2050. Such changes are evaluated using Equation (4) (consumption per capita in steady state) for the calculations on utility and welfare, which we detail in the following subsection.

3.4. *Social planner module: A note on discounting and utility calculations*

An additional module representing the decision-making process of a public policy body is included in the model to compare results of the various scenarios. This module includes the utility calculations processed in most IAMs, which involve analysing the welfare of the current versus the future generation (Pindyck, 2013). The level of welfare is affected by the total abatement costs and the cumulated climate change damage at each point in time, which directly influence the level of consumption per capita, as shown in Equation (15): this is calculated as the discounted sum of the utility of steady-state consumption per capita over the entire time horizon, which in our case runs from 2010 to 2050:

$$W = \sum_{2010}^{2050} \theta_t L_t U(c)_t \tag{15}$$

where θ_t is the discount factor, which enables the inclusion of the intergenerational dilemma, calculated under the following form:

$$\theta_t = \frac{1}{1 + \rho(year - 2010)} \tag{16}$$

The discount factor displayed in equation (16) corresponds to hyperbolic discounting. As revealed in the Introduction, there is extensive debate in the literature on IAM regarding the way in which future welfare needs to be discounted when analysing climate scenarios. Hyperbolic discounting tends to place more policy effort in terms of the reduction in emissions reduction on closer generations than on more distant ones, which results in climate policy of a more stringent nature.[7] We deem this to constitute a realistic assumption for our model, in which the time horizon is comparatively shorter than in the usual IAMs[8] and is in line with the most stringent climate policy imposed in the European Union, through which a large part of the decarbonisation effort is going to be made over the next two decades (European Commission, 2021b).

Another key element frequently under discussion in IAMs is that of the calibration of the rate of pure time preference, ρ. In climate modelling, the value of this parameter determines the importance given to losses in future levels of consumption. Under such high values of ρ, the bulk of the emission reductions are placed on future generations, with the overall transition to climate neutrality taking place at a slower pace and with greater temperature increases (Wouter Botzen & van den Bergh, 2012; Emmerling et al., 2019). The Stern-Nordhaus controversy is particularly relevant in this matter: while in the DICE model by Nordhaus, ρ is set at a higher value to match interest rates, linking the pace of decarbonisation to market trends (Nordhaus, 2007; Espagne et al., 2018), in Hope's PAGE model, ρ is calibrated on ethical grounds, linked to the probability of disastrous events under higher temperatures (Stern, 2007, 2013; van der Ploeg and Rezai, 2019). An application of the Stern approach seems more up-to-date given the current context of repeated warnings of the consequences of increased temperatures and the extreme weather events that have already been set in motion globally (IPCC, 2021). Such choice is also in line with the most recent IAM literature, which seems to be shifting towards an institutionally-centred role of IAMs that aim to avoid previous underestimations of the potential impacts of accelerated climate change (Espagne et al., 2018; Estrada et al., 2019; Van Beek et al., 2020; Zhang et al., 2021). The approach taken in PAGE (Hope, 2006), with a rate of pure time preference equal to 0.015, is, therefore, the approach taken in our model.

The final element of the social planner module is the functional form of the utility function. As shown in Equation (16), welfare is calculated in IAMs as the sum of discounted utility, but the latter needs to be specified under a function. This topic is also the focus of significant debate in IAMs, as the choice of the rate in marginal utility for each level of per capita consumption (η) can greatly affect the sensitivity to income inequality. This form is normally stated as follows (Norstad, 1999):

$$U(c)_t = \begin{cases} \frac{c^{1-\eta}}{1-\eta}\, if\ \eta \neq 1 \\ \ln(c) if\ \eta = 1 \end{cases} \tag{17}$$

In this matter, we also follow the approach taken in the PAGE model by Hope (2006), in which an iso-elastic utility function is used. This corresponds to the $\eta = 1$ case, which enables the impacts of the different scenarios on per capita consumption to be aggregated in a more straightforward way (i.e., aggregating them in the welfare function, as in Equation (16), with no further adjustments). As a downside, this makes the model insensitive to distributional concerns and equity, although in our case the main focus of the model is to provide a common tool to compare aggregated costs of different electricity decarbonisation scenarios, while leaving out of the analysis the way in which those costs are distributed.

4. Data and scenario description

The model described in Section 3 has been applied to quantify the environmental and economic impacts of a variety of scenarios. The composition of the electricity mix therein is taken as an exogeneous input to the model, upon which such impacts are calculated.

A summary of the assessed scenarios is provided in Table 1. Four electricity sources have been considered, as these are projected to

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[7] See Karp (2005) and van der Ploeg and Rezai (2019) for more details on the application of hyperbolic discounting on climate change economics, and Laibson (1997) and Andersen et al. (2005) for general knowledge on hyperbolic discounting.

[8] Time horizons in IAMs tend to run until at least the year 2100. In our case, we opt for a shorter period because the objective is to analyse the economic consequences of different scenarios towards climate neutrality for the case of Spain, which, as across the entire European Union, is set to happen by 2050.

Table 1
Average electricity mix per scenario and costs per source.

Scenarios /Variables	BAU	IEA NZE	High RES	Low Nuclear	Energy Efficiency	LCOEs per source, US $/MWh, average	Additional costs per MWh for additional electricity interconnections for renewables, US $/MWh
Electricity mix (shares per source, %, average 2010–2050)							
Solar PV (incl. utility scale storage)	8.5%	19.2%	14%	11.4%	11%	79.6	2.86
Wind (incl. offshore and onshore)	24%	22%	31.3%	29.1%	28.3%	84.9	2.86
Nuclear	10.5%	9.2%	8%	7%	9.3%	128.3	N/A
Fossil fuels (incl. solids, oil, and gas fired)	40.6%	26.3%	30.65%	36%	34.1%	147.8	N/A
Data source	European Commission (2011), Current Policy Initiatives scenario	IEA (2021), Net Zero by 2050 report, Table A.3, total generation	European Commission (2011), High RES scenario	European Commission (2011), Low Nuclear scenario	European Commission (2011), Energy Efficiency scenario	Fraunhofer (2021) study on Levelized Cost of Electricity Renewable Energy Technologies for wind, solar and fossil fuels; IEA (2021) for nuclear	Red Eléctrica de España (2019b), 2021–2026 Electrical Networks Development Plan

Notes: BAU: Business as Usual scenario; IEA NZE: International Energy Agency's Net-Zero Emissions by 2050 scenario; RES: Renewable Energy Sources; LCOEs: Levelised Cost of Electricity, which are taken from the projections until 2040 given by the Fraunhofer (2021) study – for more information see Table 3 in the Appendix. The Fraunhofer study does not include nuclear in the analysis, which is why we rely on the figures given in IEA (2021) as LCOEs for nuclear in Europe. Finally, the values for the additional interconnections for renewables are calculated from the projections in Red Eléctrica de España (2019b), taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar renewables (1872 M€) for a period of six years (2021–2026).

increase or decrease the most in the decades up to 2050 in Europe (European Commission, 2011; IEA, 2021) and in Spain (MITECO, 2020b): solar photovoltaic (Solar PV) energy, wind energy (including offshore and onshore), nuclear fission, and fossil fuels. The latter is a joint category in which all fossil-fuel power plants are considered, including conventional power plants using solids (i.e., coal) and oil as well as those using gas turbines.[9]

In total, five scenarios have been considered. Four of these form part of the Impact Assessment of the European Commission's energy roadmap to 2050 (European Commission, 2011). Table 1 outlines the average shares on electricity generation and costs per source in each of the scenarios from 2010 to 2050. Fossil fuels and nuclear fission are more present in the BAU scenario than in any other, as the scenario only gathers the measures in place by EU Member States in the Energy 2020 strategy (European Commission, 2011, 2021b). The IEA NZE scenario outlines the changes needed to attain zero use of fossil fuels for power generation by 2050, but it does so by relying on nuclear power. The opposite case takes place for the Low Nuclear scenario. The High RES scenario gathers the largest average share of renewable energy.

Another fundamental component of the data and scenario description of the proposed model is the information related to costs of the different energy technologies involved, which need to be adapted to the particular case (i.e. Spain). Two fundamental characteristics of the Spanish electricity system have been identified: its relative isolation in terms of energy interconnections with the rest of Europe and a particular need for additional investments in terms of energy storage to integrate large shares of variable renewable energies (i.e. wind and solar) (Red Eléctrica de España, 2019a). These two characteristics act as framework conditions in which the model operates, and therefore needed to be clearly identified in the literature. To this end, a literature review for the Levelised Cost of Electricity (LCOEs) [10] of the four electricity sources of the proposed model has been conducted. Its sources, which were selected due to their relevance and pertinence to the presented model, include two landmark reports from authoritative sources in the energy sector at global level (i.e. IRENA and IEA) and two empirical literature surveys done by Fraunhofer and Lazard (Fraunhofer, 2021; IEA, 2021; Lazard, 2021; IRENA, 2022). The results, which can be consulted in Table 3 of the Appendix and that have been used for the sensitivity analysis on LCOEs presented in the Results section, point in all cases to remarkably lower LCOEs for renewable energies (solar and wind) than for fossil fuels and nuclear energy. Several factors can explain this. First, higher LCOEs for fossil fuels and nuclear energy can be due to the very nature of the assets used in power generation in these cases, which entail higher capital costs. Secondly and in particular for the case of fossil fuels, another set of explaining factors are of regulatory nature and largely include the assumed increasing price of coal and the influence of GHG emissions pricing mechanisms such as the EU Emission Trading Scheme (IEA, 2021).

Besides, the issue of intermittency in electricity generation of renewables such as solar and wind is well known and recognised, and so it is the need to accompany their deployment with grid-scale energy storage (European Court of Auditors, 2019; European Commission et al., 2020; Fraunhofer, 2021; IEA, 2021; IRENA, 2022). Such importance was already recognised by the European Commission in its 2018 Communication "A Clean Planet for All" which states that deployment of energy storage would need to increase by six times to accommodate large shares of variable renewable energies such as wind and solar (European Commission, 2018) and investments at the global level seem to be

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[9] Other electricity sources, such as hydropower, geothermal and tidal power, have not been considered because they are not projected to change as much in the next decades either for Spain or Europe. The bulk of the electricity decarbonisation efforts in Spain and Europe will be carried out by wide-scale deployment of renewables (mainly solar and wind) and the phase out of fossil fuels (including coal, oil, and gas) (European Commission, 2011; IEA, 2021; MITECO, 2020b).

[10] LCOE is equal to the Net present value of an electricity installation over its lifetime and is expressed in US dollars per megawatt hour. This allows for proper cost comparisons across different energy sources. We take values from Table B1 of the IEA Net Zero Report, EU series (IEA, 2021).

moving in that direction, as identified by the IEA (IEA, 2022b). In such context, a key objective of the literature review was to identify a set of LCOEs that would not only be representative of the different costs of the energy technologies in the model, but also would integrate the issue of energy storage deployment for the case of renewable energies. Incorporating cost information on energy storage in the model was not straightforward, as the LCOEs for utility-scale energy storage vary greatly across geographical locations in Europe and beyond due to the influence of complex and interconnected factors, such as the material composition of the batteries, the exact location of utility-scale storage plants or other elements such as solar irradiation patterns, grid losses and even regulatory obstacles in permitting (Chun Sing and Mcculloch, 2016; Ziegler et al., 2019; European Commission et al., 2020; Fraunhofer, 2021).

Among the sources consulted in the LCOE literature review, the study done by Fraunhofer on the Levelized Cost of Electricity Renewable Energy Technologies (Fraunhofer, 2021) seems to be the most pertinent, as it is the only source that includes sufficient and explicit data (i.e. able to be incorporated in the model) on energy storage for renewables. Several options are provided in the report (i.e. small, large and utility scale storage, of which we take the latter) with detailed explanations on the assumptions used. In addition, the Fraunhofer study considers the closest geographical scope to the case of the proposed model, as it focuses on one single European country (i.e. Germany) as compared to the other sources, which calculate LCOEs at global level (IEA, 2021; Fraunhofer, 2021; Lazard, 2021; IRENA, 2022). Finally, the most fundamental advantage of Fraunhofer (2021) compared to the rest of LCOE sources is the fact that it is the only study in the sample providing clear projections until 2040 with specific data on LCOEs for batteries, which makes it suitable to be integrated in the proposed model. A slight shortcoming, however, is that the Fraunhofer report does not include figures on LCOEs for nuclear energy in its scope. As a solution to this, the data for nuclear was obtained from IEA (2021), which provides detailed information on the assumptions and trends incorporated in the final LCOEs for nuclear.

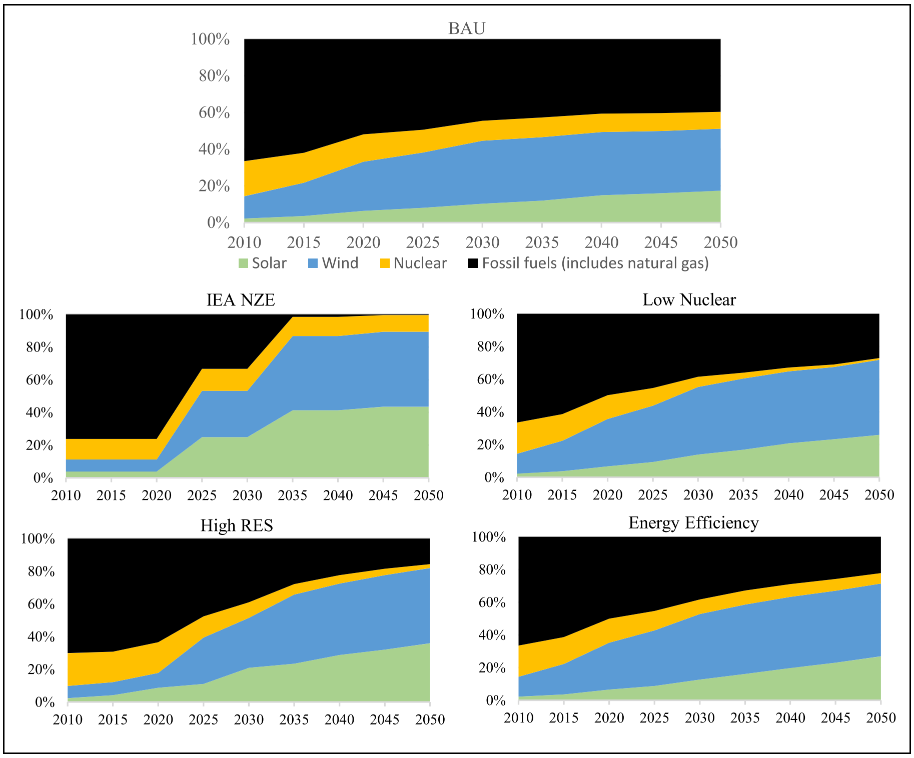
An additional fundamental factor to consider when integrating costs in the model is the issue of energy networks and interconnections. A highly-interconnected electricity system is necessary for the integration of higher shares of renewable energies in the electricity mix and the decarbonisation of energy supply as a whole, as it allows for dispatching clean energy to meet peak demand at a reduced cost for the electricity system (Crozier and Baker, 2022; Yang, 2022). Together with enhanced energy storage (as pointed out in the paragraph above), energy interconnections can bring the needed additional flexibility that the integration of renewables as the main electricity source will require to meet the goals of the Paris Agreement and the objective of climate neutrality by 2050 of the European Green Deal (European Commission, 2019; Mehigan et al., 2022). This is why the European Commission has set a target for interconnection of at least 15% of domestic electricity production able to be transported to neighbouring countries by 2030 among EU Member States (European Commission, 2017). After the invasion of Ukraine by Russian forces and the resulting energy crisis, the recent REPowerEU package has stressed the importance of speeding up the process of interconnection of national energy systems of EU Member States, in order to increase the EU's energy system resilience and flexibility to shocks such as the accelerated phase-out of Russian fossil fuels, as well as the integration of variable renewable energies as main generation technologies in the longer term (European Commission, 2022a).

The Spanish case, however, presents certain specificities when it comes to interconnections, which need to be incorporated in the proposed model as framework conditions. The electricity system in Spain is connected to France, Andorra, Portugal and Morocco, and its interconnection ratio to the EU electricity system only amounts to a maximum of 3.5 GW – only 3% of installed capacity and much below the 15% EU target for interconnection for 2030 (Red Eléctrica de España, 2019a; IEA, 2022c). Such lack of interconnections has given rise to the term "electricity island" to describe the Spanish electricity system. Furthermore, forecasts on expected cross-border electricity capacities for 2025, 2030 and 2040 elaborated by ENTSO-E (the association for cooperation of European Transmission System Operators), point out that the situation will not change significantly in the coming decades and that Spain will continue to be significantly isolated from the rest of Europe in the future (ENTSO-E, 2023). The recent suspension of the long-negotiated submarine electrical connection project with France through the Gulf of Biscay after an over 80% increase of the total expected cost of the project seems to confirm such forecasts (Monforte, 2023).

The isolated condition of the Spanish electricity system has been examined as well in the academic literature: Auguadra et al. (2023) find out that the small capacity in international interconnections of Spain makes energy storage play a more important role in energy decarbonisation than previously thought; Abadie and Chamorro (2021) elaborate on the economics of an additional France-Spain interconnectors and the impacts it would have on the market outlook for energy technologies in Spain; while Göransson et al. (2014) analysed that the congestion existing between isolated systems such as the Spanish one to the rest of Europe gave raise to congestion problems in the network, thereby negatively impacting the overall energy costs in the system.

It is therefore safe to establish for the purposes of the model that, due to its isolation, the changes in the Spanish electricity system in the coming decades towards energy decarbonisation will not be influenced in a great extent by fluctuations in the energy mix of neighbouring countries (France, Portugal, Andorra, Morocco) but rather by the changes taking place within the Spanish system itself. In particular, the isolated nature of the Spanish electricity system makes additional energy storage and electricity interconnections two fundamental pillars to ensure the necessary flexibility to accommodate an increasingly larger share of renewables in the electricity mix (Red Eléctrica de España, 2019b; Auguadra et al., 2023). As stated above, these elements needed to be integrated as framework conditions specific to the Spanish electricity system for the characterisation of the different scenarios. This has been incorporated in the proposed model through a second cost component complementary to LCOEs only for the case of wind and solar, expressing the need for additional electricity interconnections to accommodate renewables and ensure system flexibility. This cost component for interconnections has been calculated from the 2021–2026 Electrical Networks Development Plan of the Spanish TSO (Red Eléctrica de España, 2019b). All information on the input data on electricity mix per scenario and costs per source (including energy storage and interconnections for renewables) is provided in Table 1 below.

Graph 2 provides an overview of the dynamics in the various scenarios. While in all of these scenarios the presence of renewables (wind and solar) increases over the time horizon, the magnitude of the effect varies greatly. Under the BAU scenario, fossil fuels decrease their share in the electricity mix by only 20%, and still constitute 40% thereof by 2050. The picture is opposite in IEA NZE where, even if this is a scenario of global context instead of European, the biggest increase in both wind and solar power from among the scenarios assessed brings an electricity mix mostly based on renewables, with nuclear remaining relatively stable over the period and fossil fuels brought to net zero. The High RES scenario also portrays a large reduction on fossil fuels, which remain at 11% in the mix by 2050, while also achieving a significant reduction in nuclear dependence via an accelerated deployment of renewables, especially regarding wind energy. In the Low Nuclear scenario, bringing nuclear energy to a minimum within the mix comes at the cost of a lower deployment of renewable energy and further reliance on fossil fuels. The Energy Efficiency scenario achieves slightly higher reductions in the presence of fossil fuels than does the Low Nuclear option, which presents a moderate deployment of renewable energy. The Energy Efficiency scenario, however, has a differential point to all other scenarios thanks to its introduction of highly stringent commitments on energy savings, which leads to a decrease of 41% in final the energy demand by 2050



Graph 2. Electricity mix under different scenarios.

(European Commission, 2011), which, as will be presented in the Results section, entails lower investment costs for the implementation of the scenario in the Spanish case.

The shares in the electricity mix in each period under the different scenarios are expressed for the European Union in the case of the scenarios taken from the Impact Assessment of the European Commission (European Commission, 2011) (i.e., BAU, Low Nuclear, High RES, and Energy Efficiency scenarios) and for the world in the case of IEA NZE (IEA, 2021). The results for the Spanish electricity generation sector used in the model are calculated as follows:

$$Q_{ES,\varphi_i,t} = share(\%)_{scenario,\varphi_i,t} * Q_{ES-REF,total,t} \tag{19}$$

where $Q_{ES,\varphi_i,t}$ refers to the total amount of electricity generated in Spain (in gigawatt hours, Gwh) from a given technology φ_i (where φ represents all four available technologies in the model: $i = solar, wind, nuclear, fossil\,fuels$) at each point in time. $share(\%)_{scenario,\varphi_i,t}$ are the shares taken from each of the scenarios (BAU, IEA NZE, Low Nuclear, High RES, and Energy Efficiency, as presented above). $Q_{ES-REF,total,t}$ refers to the gross electricity generation in Spain (also in Gwh) and is taken from the EU Reference Scenario 2020 (European Commission, 2021c). The result of applying Equation (19) is the electricity mix in Spain under each of the scenarios at each point in time (2010–2050), which is used as an exogeneous input to the model calculations. Additionally, the LCOEs from Table 1 have been employed to calculate the required investment for the implementation of renewable energies in each period under the different scenarios ($IRES_{ES,t}$) by multiplying the forecast electricity necessary from solar and wind by their respective LCOEs. An exchange rate of US $ to € has been utilised to translate the LCOEs to € ($ER_{\$/€}$) (IEA, 2021; European Central Bank, 2023). This is summarised in the following expression:d

$$IRES_{ES,t} = \left[\left(LCOE_{solar,t} * Q_{ES,solar,t}\right) + \left(LCOE_{wind,t} * Q_{ES,wind,t}\right)\right] * ER_{\$/€} \tag{20}$$

A final indicator provided in Section 5 is that of the climate output gap (COG_t), which gives a measure of the foregone potential output given by environmental damage under each scenario. This indicator is an important output of IAMs, since it can allow for comparisons between the cost of the temperature increase to the mitigation costs under different scenarios (Weyant, 2017). In the proposed model, this is calculated as a simple benchmark between the modelled output per capita in steady state (as calculated in Equation (14) and multiplied by population, L_t) and the theoretical level of steady-state output per capita that would have been achieved in the absence of temperature change ($\widehat{y_{ss,t}}$), which is calculated using the same logic as in Equation (14) but removing the temperature from the specification of the total factor productivity and output itself. Therefore, the climate output gap is calculated as follows:

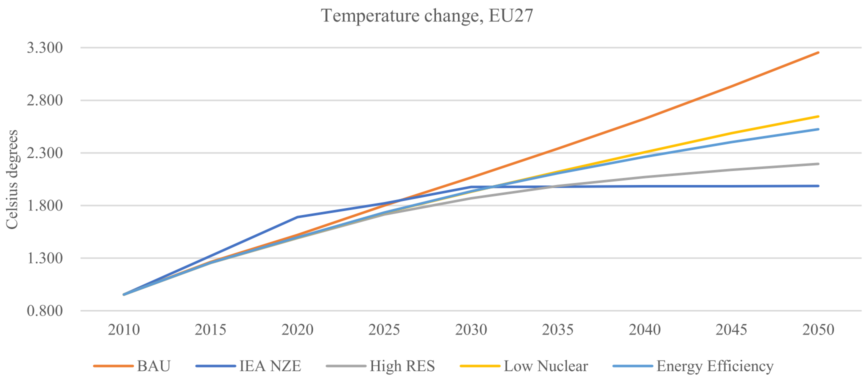
$$COG_t = \left(y_{ss,t} - \widehat{y_{ss,t}}\right) * L_t \tag{21}$$

The results of the model are presented in the following section.

5. Results

The model presented in the previous section has been applied to the electricity generation sector in Spain. The outcome is a forecast of the estimated economic and environmental impacts of introducing the electricity decarbonisation pathways foreseen in the BAU, IEA NZE, High RES, Low Nuclear, and Energy Efficiency scenarios, which are outlined in this section.

Graph 3 projects the changes in temperature over the time horizon under the different scenarios, calculated for EU27. The BAU scenario points to a remarkably higher temperature increase, of over 3 °C by 2050, which is explained by the large reliance on fossil fuels (never below 30% of the total electricity supply) that persists even at the end of the period and is in line with equivalent BAU scenarios shown in the IPCC AR6 report, which show similar temperature increases (IPCC, 2021). The policies considered in the BAU scenario are able to deliver only a moderate reduction of approximately 20% by 2030 (compared to 2010) of the share of fossil fuels: insufficient to maintain temperatures within safe levels by 2050. The result shows that additional policy efforts are needed to those summarised as current policy initiatives in the



Graph 3. Temperature change under various scenarios, EU27.

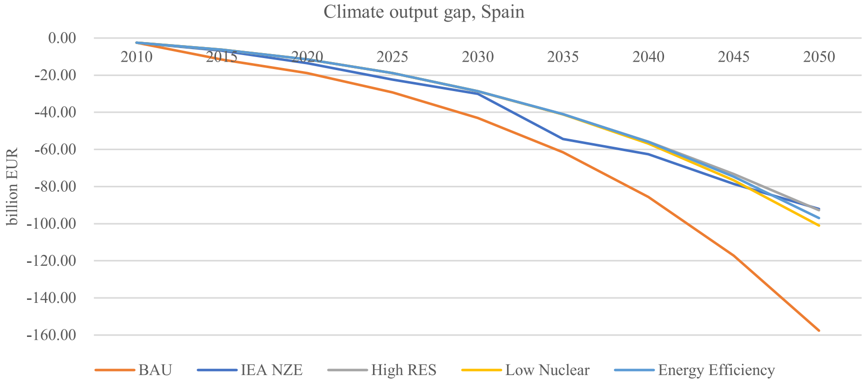
European Commission roadmap towards energy 2050 (European Commission, 2011).

Low Nuclear and Energy Efficiency scenarios show similar results in terms of temperature increase, by remaining above 2.3 °C by 2050. This shows that intermediate approaches, such as those pursued in scenarios where no steep decrease in the share of fossil fuels in electricity generation is introduced, also fall short in preventing temperature from increasing dramatically. Only the IEA NZE scenario manages to contain the temperature change, even though it does so by stabilising the temperature at 1.8 °C by 2050 and slightly lagging behind all the other scenarios at the beginning of the period. All of this shows that the effects of CO_2 emissions on temperature are persistent, and that containing temperature increase requires steep reductions in the share of fossil fuels in electricity generation.

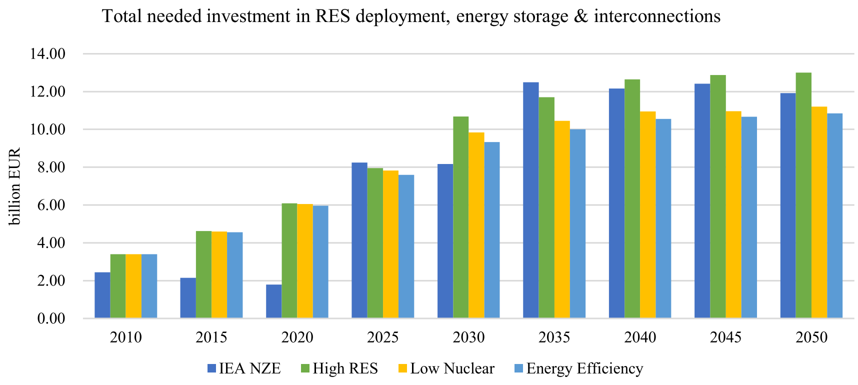
Nevertheless, caution needs to be exercised when reading these results. The proposed model focuses on the changes arising from one sector (electricity generation) by applying *ceteris paribus* reasoning, while if change were introduced in other sectors, such as transport, industry, and land use, the figures for temperature increase would certainly become worse. The fact that the temperature increases from BAU are remarkably higher than those of other scenarios (i.e., High RES, IEA NZE) indicates that electricity generation is a particularly influential sector on the overall trend of emissions and climate change. Additionally, the fact that none of the scenarios manage to maintain temperatures within the Paris Agreement ranges (well below 2 °C, and ideally less than 1.5 °C) indicates that a joint effort with measures placed in other sectors is needed. Electricity is, in short, a key sector in which deeper cuts of CO_2 emissions need to be achieved, but it is certainly not the only one in which such changes need to take place.

One key feature of IAMs is their potential to translate changes in temperature into forecast economic impacts. The damage function chosen in our model (Weitzman, 2010) is sufficiently sensitive to estimate such impacts in scenarios of moderate temperature increase, such as those presented in our results. Graph 4 provides a representation of the economic impacts of each of the scenarios and reveals that the gap between the potential steady-state output (i.e., where influence of temperature is not considered) and the actual output grows much higher when fossil fuels have a greater share in the electricity mix. The maximum losses take place in the BAU scenario, with a climate output gap equal to 105 billion euros by 2050. All other scenarios achieve significantly lower losses, of close to but still less than 70 billion euros by 2050. This shows that even in the scenarios where more climate ambition is brought forward in the form of the deployment of renewables, there is a deadweight loss that is potentially unavoidable in the long term. This finding can also be linked to the need for a fair transition, in which unavoidable costs should not be imposed on the most vulnerable sectors or income groups to prevent the climate crisis from generating further income inequalities.

Mitigation strategies differ across scenarios. Our proposed model also calculates the investment needed in the deployment of renewable energy (which in our case is limited to solar and wind) for the implementation of these scenarios for the case of Spain in real life, using LCOEs from Fraunhofer (2021) as in Equation (20) and including the complementary investments in energy storage and energy interconnections needed to integrate increasing levels of renewables in the electricity mix, as discussed in Section 4. As shown in Graph 5, the investment needed in solar and wind electricity generation including storage and interconnections grows by more than three times over the period across scenarios, from around 3 billion euros in 2010 to over 10 billion by 2050. However, such investment needs are still lower than the climate losses that the Spanish economy would incur if no measures were put in place (i.e., 160 billion euros by 2050, as shown in Graph 4).



Graph 4. Climate change losses under different scenarios.



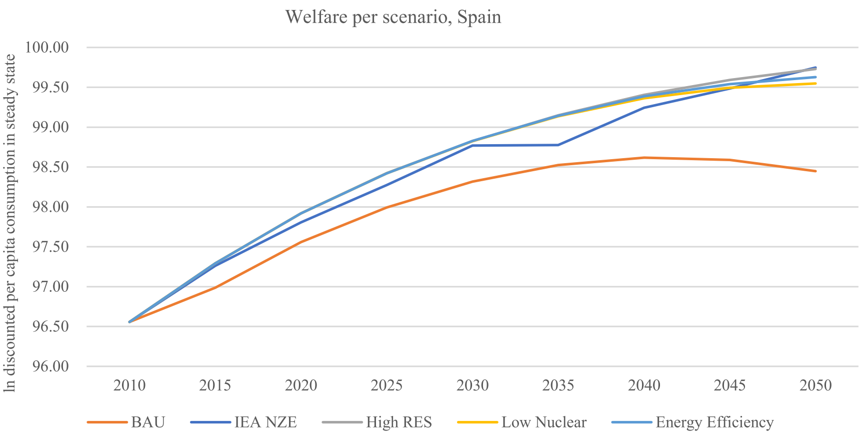
Graph 5. Investment required in solar and wind energy deployment, energy storage & interconnections.

The investment figures vary to some degree between scenarios, with High RES and IEA NZE tending to be those presenting the highest levels of investment in renewables: 13 and 11.9 billion euros by 2050, respectively. The enhanced energy efficiency policies in the Energy Efficiency scenario lead to a remarkable 20% decrease in the total investment needed: down to 10.8 billion euros, although with values very close to the Low Nuclear scenario. The reduction of final energy demand does therefore play a significant role in reducing the total costs of the transition in the Spanish electricity system.

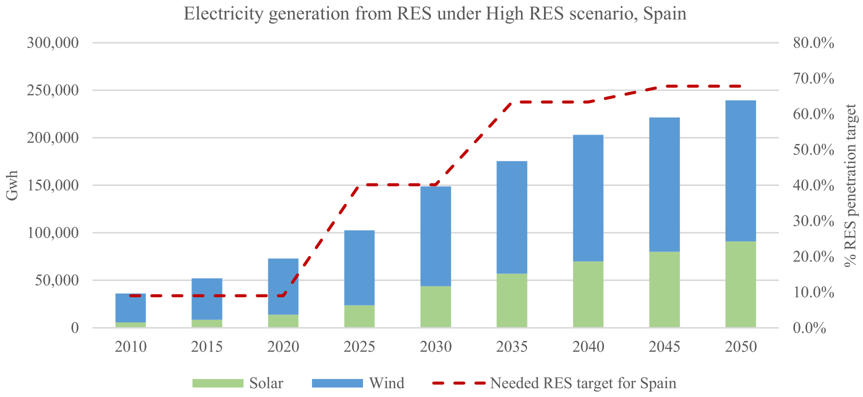
Having presented the results of the different scenarios, the social planner module described by Equations (16) to (18) is subsequently applied to compute the different welfare levels per scenario and therefore define the most preferable scenario. Graph 6 shows the results of the calculated discounted utility in each scenario over the period. The results reveal a clear outcome: the levels of welfare under the BAU scenario are systematically lower than all other scenarios over the entire time horizon, and they even enter a decreasing trend as from 2040. The persistence of fossil fuels in the electricity mix (and their associated damage in the form of temperature increase, harming total factor productivity and the steady-state levels of per capita income and consumption) seems to outweigh the abatement costs of all the decarbonisation scenarios. This is a key finding of the proposed model, as it shows that any policy option is preferable to maintaining the current state of play of the BAU scenario in terms of social welfare.

Conversely, the levels of welfare achieved in each of the policy scenarios are very similar over the period. When the levels of discounted utility are aggregated for the entire period to estimate total welfare (as in Equation (16)), the BAU scenario still gets the lowest value (equal to 881,6), while all decarbonisation scenarios (IEA NZE, High RES, Low Nuclear, and Energy Efficiency) obtain very similar results, with values around 886 of total welfare. High RES shows the highest level of total welfare (886.9) and seems to be the scenario that should be implemented by policymakers when economic and environmental concerns are assessed with our proposed model.

As a final assessment in the results of the model, a closer examination of the main metrics of the chosen scenario, High RES, is provided in Graphs 7 and 8. Graph 7 shows the composition and generation of the renewable electricity supply over the time horizon in the High RES scenario. Wind (including both onshore and offshore) is the dominate renewable energy at all times, although solar generation increases at a faster pace. By 2050, roughly one third of renewable electricity is supplied by solar power plants while the remaining two thirds come from wind energy. One major policy recommendation to be extracted from the model is that policymakers should ensure that the changes in electricity supply follow the same trajectory as that outlined in the High RES scenario. One possible way to do this is to follow the logic of European legislation, in which targets are frequently employed to guide policies and markets to a socially desirable outcome. For instance, the EU Renewable Energy Directive, currently under revision, intends to introduce an increased target of 40% of renewable energy at EU level by 2030 (European Commission, 2022b). According to the findings of the proposed model, electricity in Spain should follow a similar pathway: as can be observed in Graph 7, a minimum of 40% of electricity in Spain should originate from renewable sources. Spanish policymakers should, in addition to this, introduce specific targets, that is, 63% of renewable electricity by 2035 and 68% by 2050, in order to ensure that a minimum



Graph 6. Welfare per scenario.

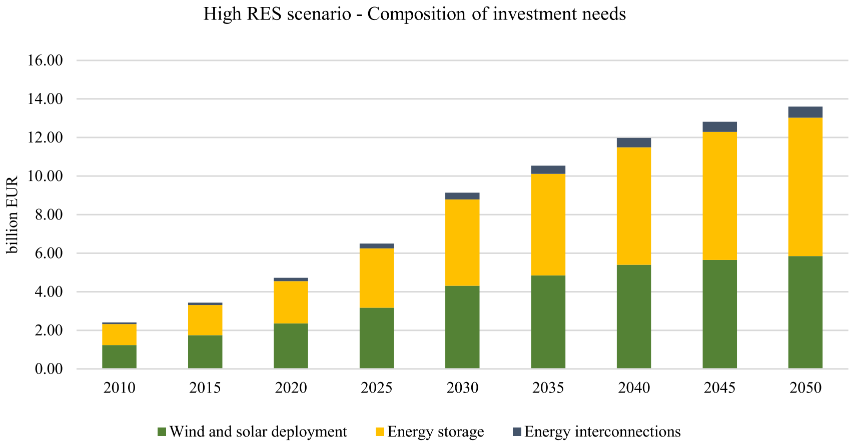


Graph 7. Electricity generation from RES under the High RES scenario and target required.

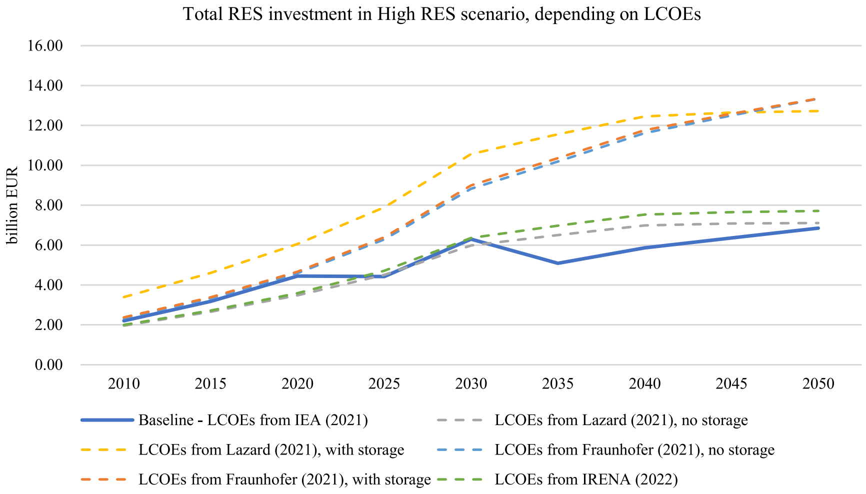
of 175 Gwh of electricity from renewable sources is installed by 2035 and 239 Gwh by 2050. As shown in Graph 5, achieving this in Spain would entail a total investment of 13 billion euros: this is but a small fraction of the total amount of investment in renewables for the entire energy sector foreseen in the Spanish National Energy and Climate Plan, that is, 91.76 billion euros (MITECO, 2020b).

The description of results achieved in High RES can be supplemented by analysing the composition of the needed investments to deploy the scenario in the Spanish electricity system. This is shown in Graph 8. As explained in Section 4, the use of LCOEs from Fraunhofer (2021), which foresee the deployment of energy storage to integrate solar energy at utility scale; together with the estimations from Red Eléctrica de España (2019b) on the additional interconnections for renewables allows us to decompose the subtotals of the needed investment in three categories: the deployment of wind and solar itself, energy storage and interconnections. Such three categories combine provide an estimation on the needed investments to implement the High RES scenario while accounting for the reality of the Spanish electricity system on the ground. As can be seen from Graph 8, for the implementation of the scenario it is equally important to secure sufficient investments in wind and solar deployment as for energy storage. This is coherent with the findings of Abadie and Chamorro (2021), which, as mentioned in Section 4, stress the specific importance of energy storage in Spain given the isolation of the Spanish electricity system. Finally, the needed investments in energy interconnections for the integration of renewables, even if sizeable (i.e. 570 million euros by 2050) represent a minor fraction of the total investment over the time horizon.

Lastly, and on the basis of the literature review presented in Section 4, a sensitivity analysis on the underlying LCOEs for the investment needed under the High RES scenario has been performed. The results are shown in Graph 9 below. As it can be observed, the required total investment for the deployment of renewables varies substantially depending on whether the LCOEs used in the model include or not energy storage, increasing remarkably when the latter is considered. However, and as explained in the LCOEs literature review in Section 4 and its results in the Appendix, an important caveat needs to be considered when relying on LCOEs for utility-scale storage solutions for renewables in the analysis of IAM results. The values of these indicators vary greatly across literature, as the total cost depends on different elements and assumptions such as the location of the renewable energy plants, the materials used in the batteries or other factors i.e. solar irradiation and energy grid losses (Chun Sing and Mcculloch, 2016; Ziegler et al., 2019; Fraunhofer, 2021; Lazard, 2021). In any case, in spite of these difficulties, when considering energy storage in the results from the High RES scenario of the presented model, the findings still point out at the fact that regardless of the potential LCOE options to be chosen for the modelling available across literature, deploying renewable energies to decarbonise electricity supply in Spain is always a more cost-effective option than continuing with the emissions associated with electricity generation and its associated losses in the BAU scenario (i.e., 160 billion euros by 2050, as shown in Graph 4).



Graph 8. Composition of investment needs of High RES scenario.



Graph 9. LCOE sensitivity analysis results.

6. Conclusion and policy implications

In this paper, an Integrated Assessment Model has been presented for the assessment of the economic and environmental impacts of various decarbonisation pathways for electricity generation in Spain from 2010 to 2050. The model has been developed using the DICE-R 2013 model by Nordhaus and Sztorc (2013) as a starting point, whereby the most up-to-date and relevant literature on damage functions and social welfare discounting is incorporated, together with the most adequate and widely used data sources on electricity shares and costs (European Commission, 2011; Red Eléctrica de España, 2019b; European Commission, 2021c; Fraunhofer, 2021; IEA, 2021). In addition, the specific situation of the Spanish electricity system (i.e. its isolation to the rest of the EU in terms of interconnections) as well as the needs for additional energy storage to accommodate intermittent renewable energies such as wind and solar have been integrated as framework conditions to the model.

The outcome is a model capable of comparing the potential consequences of introducing different levels of ambition in the decarbonisation of electricity, which constitutes a key pillar of climate change policies. This provides a highly relevant tool for policymaking, since it enables Spanish authorities to compare various policy options, anticipate their effects on social welfare, and foresee the investment needs for the deployment of renewables (wind and solar), energy storage and additional energy interconnections over a long time horizon.

A total of five scenarios have been compared with the proposed model. The results show a strong preference for scenarios in which deep cuts in CO_2 emissions from electricity generation are achieved. Conversely, the negative effects on social welfare from climate damage caused by the persistence of fossil fuels in the electricity mix are worthy of note: the BAU scenario, used as a baseline for the assessment, shows significantly lower social welfare values and cumulated losses in all periods of the time horizon. Such losses, estimated to be worth 160 billion euros by 2050 in the BAU scenario, are much higher than the mitigation costs of the most ambitious scenario (High RES), equal to 13 billion euros. The message is therefore clear: a polluting electricity mix has already become a much more expensive option in the long term than a renewable electricity mix.

Several extensions of this model can be applied, which provide room for further research. In addition to adding other possible scenarios or disaggregating the assessment to make the model granular to key electricity demand sectors (i.e., buildings, industry, transport), one possible improvement could be made upon introducing geographical data to enable the model to display optimal locations for the deployment of the scenarios, not only in terms of economic costs, but also environmental impacts on biodiversity, protected ecosystems, and landscape.

CRediT authorship contribution statement

Luis Antonio Galiano Bastarrica: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Eva M. Buitrago Esquinas:** Data curation, Supervision, Funding acquisition, Writing – review & editing. **María Ángeles Caraballo Pou:** Methodology, Validation, Resources, Writing – review & editing. **Rocío Yñiguez Ovando:** Project administration, Validation, Funding acquisition, Writing – review & editing.

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

We have attached the data and model file as additional material in the revised submission. We are willing to share this data and file in open access if the paper is published.

Acknowledgements

This research is partially supported by the SEJ258 and SEJ132 Research Groups in Applied Economics of the University of Seville. No specific grant was received from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix

Table 2 below summarises the parameters used in the model including their value and source.

Table 2
Modelling parameters, by source

General parameters				
Description	Symbol	Value	Unit	Source & notes
Initial population growth rate	g_L(0)	0,02300	2.3% annual increase	EU Reference Scenario 2020 (European Commission, 2021c)
Parameter affecting population growth	delta_L	0,052	parameter	Nordhaus and Sztorc (2013)
Spain population in 2010	L(0)	46,487	million people	INE (2022). Spanish National Statistics Institute
Initial TFP	A_0	3,80	parameter	Nordhaus and Sztorc (2013)
Initial TFP growth rate	g_A0	0,079	parameter	Nordhaus and Sztorc (2013)
Change in productivity growth rate	delta_A	0,006	parameter	Nordhaus and Sztorc (2013)
Parameter affecting productivity growth due to change in temperature	gamma	0,001	parameter	Nordhaus and Sztorc (2013)
Spain GDP in 2010	Y(0)	1078989	M€15	EU Reference Scenario 2020 (European Commission, 2021c)
Initial cumulated CO2 emissions	CC(0)	530	billion tons CO2 already emitted globally	Nordhaus and Sztorc (2013)
Carbon to CO2 conversion rate (44/12)	CtoCO2_cr	3667	parameter	Chemistry
Carbon-Climate Response parameter	CCR	0,0018	parameter showing temperature increase per cumulative 000 Gt of CO2eq emitted in the atmosphere	Matthews et al. (2012). Parameter showing a close to linear relationship at a 95% confidence for the model array studied in the paper
Weitzman damage function parameter 1	D_1	20,46	parameter	Weitzman (2010)
Weitzman damage function parameter 2	D_2	2	parameter	Weitzman (2010)
Weitzman damage function parameter 3	D_3	6081	parameter	Weitzman (2010)
Weitzman damage function parameter 4	D_4	6754	parameter	Weitzman (2010)
Savings rate	s	0,12	rate	Eurostat (2023). Average household saving rate from 2010 to 2020
Initial capital depreciation rate	delta_0	0,1	parameter	Nordhaus and Sztorc (2013)
Change in depreciation rate due to temperature	delta_1	0,001	parameter	Stern (2013)
Cobb-Douglas: exponent capital	alfa	0,4	parameter	Taken from literature review on the empirical range of this parameter among others done in Macías and Matilla-García (2015) where based on results from Bentolila and Saint-Paul (2003) they estimate an alpha of around 40% for OECD countries
Rate of pure time preference (for utility discounting)	rho	0,015	parameter	Various sources, mainly aligned with Stern review as welfare of future generations is highly valued and climate policy is more stringent
Rate of change in marginal utility for each level of per capita consumption - for utility function	eta	1	Parameter - change in marginal utility for each level of per capita consumption	Necessary level of "eta" to have an iso-elastic utility function (Norstad (1999), in which allocation results in the scenario are not sensible to the distribution of wealth. "eta". In our IAM we follow the example of the PAGE2002 model and take the case of eta = 1, as this allows the aggregation of the impacts in per capita consumption into the welfare function (Hope, 2006)
Exchange rate from US $ to €	N/A	0.9421	exchange rate USD vs EUR	European Central Bank (2023), from 04/03/2023.
Exchange rate from € to US $	N/A	1.0615	exchange rate EUR vs USD	European Central Bank (2023), from 04/03/2023.
Additional costs per MWh for additional electricity interconnections for renewables	N/A	2.55	US $ per MWh	Red Eléctrica de España (2019b). Calculated taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar (1872 M€) for a period of six years (2021–2026).
Mitigation parameters *(Used in scenarios other than BAU)*				
Description	**symbol**	**value**	**unit**	**source & notes**
Initial abatement cost parameter	omega_0	0,06	parameter	Nordhaus (2007)
Exponent abatement cost function	theta_AC	2,8	parameter	Nordhaus and Sztorc (2013)

Table 3 below summarises the results of the LCOE literature review referred to in Section 4.

Table 3
Literature review on LCOEs

LCOEs literature review results				
	IRENA (2022)	Fraunhofer (2021)	Lazard (2021)	IEA (2021)
Solar PV, no storage (US $/MWh, average)	46.31	46.65	34.00	37.00
Solar PV with storage (US $/MWh, average)	*N/A (not provided)*	77.75	70.50	*N/A (not provided as single data point)*
Wind (incl. offshore and onshore), no storage (US $/MWh, average)	52.09	82.93	53.00	47.00
Wind (incl. offshore and onshore) **with storage** (US $/MWh, average)	*N/A (not provided)*	*N/A (provided only for Solar PV)*	89.50	*N/A (not provided as single data point)*
Nuclear (US $/MWh, average)	*N/A (not in scope of the study)*	*N/A (not in scope of the study)*	167.50	128.30
Fossil fuels (incl. solids, oil, and gas fired) (US $/MWh, average)	*N/A (not in scope of the study)*	144.38	113.83	162.50

(*continued on next page*)

Table 3 (*continued*)

LCOEs literature review results

	IRENA (2022)	Fraunhofer (2021)	Lazard (2021)	IEA (2021)
% of LCOE decrease per year (used in LCOEs sensitivity analysis in case of no projection by 2050)	*5.7% for wind and 8% for solar per year for the period 2010-2021*	*Projections by 2040 for the particular case of Germany are already provided in the report: changing the units of the report to US $/MWh the results for 2040 are 44.5 for Solar PV, 46.65 for Solar PV with storage and 67.1 for wind (average including onshore and offshore)*	*6% for wind and 7.5% for solar per year for the period 2009-2021*	*Projections by 2050 are already provided in the report and are included in all scenarios in the model*
Does the report incorporate LCOE projections that evolve over time at least until 2050?	*No*	*No*	*No*	*Yes*
Does the report include figures to the particular case of Europe?	*Yes*	*No*	*No*	*Yes*
Notes on assumptions in each source	Data with no particular geographical scope. Data in energy storage is provided in Box 3.2 (page 94) of the report but for the particular case of behind-the-meter residential lithium-ion batteries in Europe, contrary to utility scale as the other reports which therefore cannot be compared with other figures.	Data for the particular case of Germany. As for all other cases, we take values for utility-scale PV. In this report, data on the LCOEs is provided only for the case of Solar PV utility scale and not as an independent data point. The values for the different LCOEs are taken as an estimation from the values in Figure 5 of the report (page 17). Nuclearslf is not part of the scope of the report.	Data with no particular geographical scope. For Solar PV, two types are provided: Crystalline Utility Scale and Thin Film Utility Scale - we take the average of the two. For wind, a higher LCOE is given for the particular case of offshore, which is included in the calculation of the average LCOE. For nuclear and fossil fuels, the LCOEs corresponding to fully depreciated assets is not considered. For gas, the case of using green or blue hydrogen reported by Lazard is not considered.	Data taken for the particular case of Europe. Table A3 includes data on battery storage at global level but only for the particular case of transport (EVs). In addition, in Figure 4.18 of IEA electricity system flexibility is considered as well – a large part of the flexibility is provided by a considerable deployment of batteries and demand response systems, but LCOEs on such storage is not provided.

The full code and parameters of the presented model has been made available in Excel format for full disclosure and further use by interested researchers in the following link of the files repository system of the University of Seville: https://idus.us.es/handle/11441/145566.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113592.

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