Henke *et al. Energy, Sustainability and Society* (2024) 14:41
https://doi.org/10.1186/s13705-024-00469-w

Energy, Sustainability and Society

RESEARCH Open Access

Exploring European decarbonisation pathways in the Power Decisions Game

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Abstract

Background Article 12 of the Paris Agreement summons the signing parties to co-operate in improving the education of their citizens on climate change and related matters. The article thereby acknowledges the importance of citizens' support and understanding of climate change and needed measures to fight climate change. This work aims to inform European citizens on how climate change-related policies affect the power sector in Europe. For this purpose, a serious game, based on sound principles of energy systems analysis, has been developed to allow players to explore how key policy decisions affect capacity mix, investment needs, and electricity costs.

Results The game is based on more than 1700 scenarios run through an open-source and accessible, yet technologically detailed, myopic energy system optimisation model for the electricity supply in the EU27 + 3. The game allows the user to take the role of a decision-maker and make decisions in 2020, 2030, and 2040 regarding the usage of CCS, biomass imports, cross-border electricity transmission and the pace of emission reductions. The user is then presented with economic, social, and environmental impacts of these choices. These impacts are, for example, measured and illustrated in the development of accumulated CO_2 emissions per capita, levelised cost of electricity, and investment need per citizen.

Conclusion The Power Decisions Game provides a first-of-its-kind open-source infrastructure that allows non-modellers to explore the impact of key decisions and preferences on the design of the future European power system. Furthermore, it provides insights on the consequences of short-sighted decision making. The game can be used to facilitate policy-science discussions.

Keywords Energy transition, OSeMOSYS, Decarbonisation pathways, Modelling, OSeMBE

Background

The Paris Agreement acknowledges in Article 12 that fighting climate change will only work if citizens understand the potential consequences. Only with this understanding, they will support needed actions and measures [1]. This has since also been identified by the European Commission (EC) as a priority. The EC aims, therefore, to strengthen policy support, policy understanding and societal cohesion around measures to reach climate neutrality [2]. The involvement of citizens in the process of policy creation can generate understanding of the issues to be addressed and can improve the support and response to decarbonisation policies.

The energy transition with the goal to tackle climate change is a process that will affect the lives of most European citizens. Therefore, it is crucial that the policies that are made in relation to the energy transition are explained, discussed and supported. In this context, not only communication between policymakers and society is important, but also communication between

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the research community and society. The results and findings of researchers can stimulate discussions and highlight the implications of political decisions and of wait-and-see-strategies on society and the environment. To communicate results, findings and insights to energy and climate systems, researchers have produced a series of Serious Games, Scenario Explorers, and energy and climate calculators. These tools allow users in different ways to explore the insights from energy and climate research; My2050 allows users to browse through scenarios designed by researchers and policymakers [3, 4]. In EUCALC, users can design their own scenarios by setting levers for technology use and behaviour [5]. And a series of tools allows to calculate the personal carbon footprint [6]. EUCALC [5] and My2050 calculator [4] allow the user to develop a very comprehensive and detailed idea about the effect of different levers in relation to decarbonisation. These levers go beyond the electricity or the energy sector and cover, for example, travel patterns, human diet, and resource and land use. These levers are mostly non-binary decisions, but the user needs to indicate the degree to which certain developments will happen, e.g., "How much wind power will we generate in 2050?" [5]. Another category of serious games are board games like, for example, the Energy Safari [7]. The Energy Safari focuses on local implications and trade-offs of the decarbonisation of the energy system in the Dutch region of Groningen. While aiming at a very different scale and using different gaming tools, these approaches highlight for the players how holistic a task the decarbonisation is for our societies and how many aspects there are to work on.

The calculations and data processing of these tools happen either in Excel without optimisation [3, 4] or in simulation models [5]. Simulation models provide insights into how systems will behave under user-defined boundary conditions, but they are not optimising the modelled system [8]. In contrast to simulation models, optimisation models provide solutions that are relatively closer to systems that developed in a market setting [9]. Important for the quality of results is the representation of the boundary conditions of the represented market. In the literature the linking of an energy systems optimisation model to a Serious Game has not been described yet.

In this paper, we investigate the question 'How can the dynamics and insights provided by analysing the impact of policy decisions using a power system optimisation model be explored in an engagement tool?' To answer this question, we developed the Power Decisions Game, in the EU Horizon 2020 project 'Role of technologies in an energy efficient economy—model-based analysis of policy measures and transformation pathways to a sustainable energy system' (REEEM). The Power Decisions Game is a tool that rests on the basis of a scientifically developed energy systems model [10], yet allows non-energy analysts, like policymakers, academia, and an interested public to explore the implications of selected policy and investment decisions on the European power system. In particular, the effect of decisions on pace of emission reductions, use of carbon capture and storage (CCS) technologies, import of biomass, and expansion of cross-border electricity transmission lines on the accumulated emissions per capita, the needed investments, and the levelised cost of electricity are being explored. These are representative sets of decisions and impacts chosen by the authors aiming to illustrate key decisions with significant impact on the future European power system. The decisions are selected with the aim to represent policy decisions, where policymakers have near-binary options or a very strong impact on the power system depending on their choice. However, the infrastructure is open-source, flexible, and modular, and more decisions and impacts can be added for investigation, by running additional sets of scenarios.

The Power Decisions Game differentiates itself from other serious games in that:

- It takes the perspective of an optimising agent, which meets the projected electricity demands by minimising the system costs and complying with a number of constraints. Furthermore, the optimisation is stepwise with limited foresight, to represent more realistic decision patterns, as compared to more common long-term, perfect foresight optimisation models.
- It is based on the results of a large set of scenarios of the Open Source electricity Model Base for Europe (OSeMBE), an open-source and accessible, yet technologically detailed and accurate long-term energy investment optimisation model for the power sector of the EU [10]. This model is based on OSeMOSYS, a modelling framework specifically designed for lowering the threshold of energy systems analysis and engaging large communities of practitioners [11–13].
- It is built on a technologically detailed techno-economic model, with up to 45 power generation technologies per country and interconnections between them. It spans the years 2015–2050 and covers all EU member countries, Switzerland, Norway, and the United Kingdom.
- It considers critical national and EU legislation like the EU ETS, nuclear phase-outs, and coal phase-outs.
- The engine of the game is a modular model, that can be expanded to see how the outcomes change if more elements are considered.

The model and the Power Decisions Game are published following the FAIR criteria [10]. Therefore, even though they currently cover only the electricity system, the infrastructure is ready for the model and the Power Decision Game to be expanded.

The remaining part of this paper is structured into the following sections. The "Methods" section presents the developed game, its logic and the underlying connection to the OSeMBE model. The "Results" section presents the insights that the game offers, and the last section draws conclusions on how the presented work answers the above stated research question.

Methods

The Power Decisions Game is a serious web-game following the definition of a serious game by Dörner et al. [14]. Thus, the goal is to entertain and facilitate the user to explore implications of key policy decisions on the future European power system design.

The objective of the game is to allow the player to explore and develop an understanding of the economic, social, and environmental implications of a set of key decisions in the power sector of the EU up to 2050. At the same time, the player shall be able to explore how societal priorities might affect what system design would be considered optimal. The player might come from policy-making, academia or other energy-involved stakeholder groups, but the audience is not limited to these groups.

This section describes how the Power Decisions Game is set up and structured. In the game, the player is asked to adopt a specific profile of preferences related to environment, economy, and society. Once the game has started, the player needs to make decisions related to the future European electricity system, considering his or her profile of preferences. By making these decisions, the player is exploring scenarios modelled upfront in the long-term energy planning model OSeMBE. Given the complexity of the underlying optimisation model, the scenarios are not run live. They are pre-run in a myopic set-up, i.e. step-by-step from decision to decision. More details on this procedure are provided in section "Myopic setting".

Figure 1 shows the entire process that underlies the creation of the Power Decisions Game. At the top of the figure, the process starts with the data collection for the OSeMBE model. The central box illustrates the process of running the underlying scenarios for the game with OSeMOSYS_step. The lower box illustrates the process of calculating the KPIs that are fed into the game. The core software and data components of this process, the OSeMBE data, the OSeMOSYS model, the OSeMOSYS_step scripts, and the code for the Power Decisions Game, are in four GitHub repositories under open-source licences [15–18]. Therefore, they can be picked up for the reproduction of our results or for the further development of the entire system or single components of it.

Game context

The Power Decisions Game and the underlying model cover the electricity sectors of the 27 EU member states, Norway, Switzerland, and the United Kingdom. Each of the countries covered is modelled individually as one node. The starting year of the game is 2015 and the end year 2050. Each national electricity system is represented individually, while considering the links for exchanging electricity between countries. The model covers energy sources and power plants ranging from biofuels, biomass, coal over natural gas, geothermal heat, oil, nuclear power to solar, wind, ocean, and waste. For each of the commodities the model provides multiple technology options. For example, for biomass a combined cycle, a combined heat and power, a carbon capture and storage, and a steam cycle are available. In total, the model contains 1251 power generation technologies. Also resource availability constraints and national policies, for example, regarding nuclear or coal phase-out are considered, as detailed in the publication describing the OSeMBE model [10].

In the interface, the users are guided through the steps in the game with explanatory texts and descriptions, to also allow audiences with limited modelling expertise an insightful experience.

The game is currently only available in single-player mode. The addition of a multi-player mode would be possible, but require a much larger number of scenarios to be run, since multiple players imply that more decision combinations are possible.

Game logic

At the beginning of each round, the user gets assigned a randomly determined point of view (POV) which weighs the player's priorities between economic, social, and environmental aspects. For instance, if the player's point of view requires that the player should care equally for all three dimensions, the categories will be weighted equally with 33%. If the player should focus on one category only, that category will be weighted with 100% and the other two with 0%. The weights are randomly determined. After this initial step, the player is called to make decisions regarding alternative policy and investment developments in the EU at different points in time, from 2020 to 2040. The decisions are detailed in the section "The decisions". The assigned POV of the player is used to calculate, after each step, the score of the currently selected scenario in 2050. The goal of the game is to maximise the score in the year 2050, after all decisions are taken. This implies that, during the game,

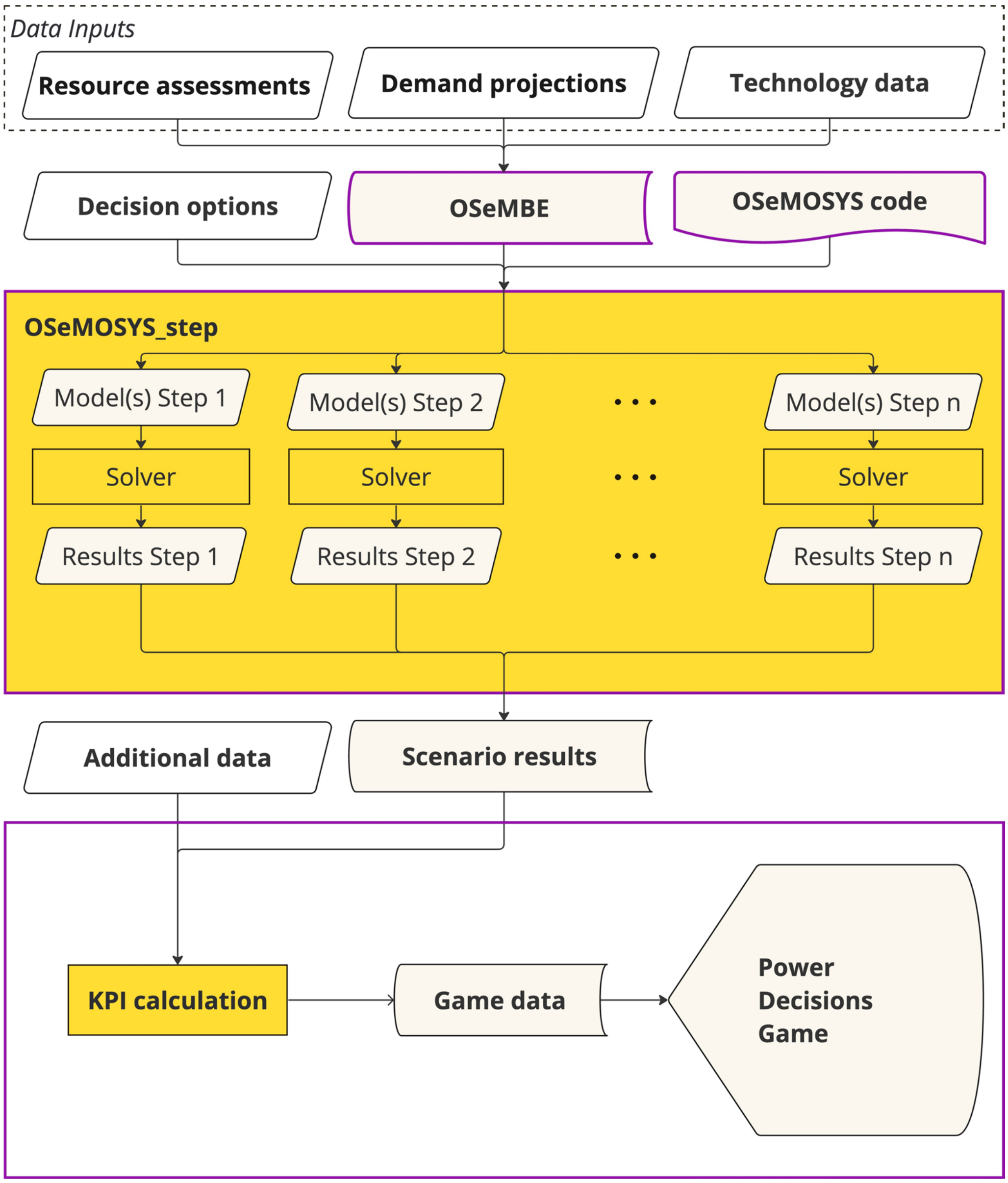

Fig. 1 The background process of the Power Decisions Game. The purple frames indicate the GitHub repositories related to the process. Links to these repositories are listed in the declarations section

the player should make decisions that are expected to maximise the outcomes for the dimensions that are weighed most, so that the final score may be high. The final score then represents the player's 'perception' of how optimal the outcomes of the decisions are, based on the assigned POV. The formula with which the score is determined is shown in Eq. (1):

Equation (1): score calculation

$$\mathrm{Score}(s) = \frac{100 * wK(s)}{\max(\{wK(s) : s = 1, \ldots, n\})}. \quad (1)$$

Here, $wK(s)$ is the weighted KPI, as outlined by Eq. (2):
Equation (2): weighted KPI

$$\begin{aligned} \mathrm{wK}(x) = & \mathrm{weight}_{env} * \mathrm{ENV}_{\mathrm{norm}}(x) \\ & + \mathrm{weight}_{\mathrm{eco}} * \mathrm{ECO}_{\mathrm{norm}}(x) \\ & + \mathrm{weight}_{\mathrm{soc}} * \mathrm{SOC}_{\mathrm{norm}}(x). \end{aligned} \quad (2)$$

Weight is here defined as the weight from the POV assigned for the corresponding dimension of sustainability, while ENV, ECO, and SOC stand for the normalised indicators of the sustainability dimensions. The

Table 1 Abbreviations used in score equation

Abbreviation	Meaning
ENV	Environmental
ECO	Economic
norm	Normalised
s	Scenario
SOC	Social
wK	Weighted KPIs

variables and abbreviations used in Eqs. (1) and (2) are spelled out in Table 1. All abbreviations used throughout the paper are also listed and spelled out in Abbreviation section at the end of the paper.

The impacts of the decisions are shown through a number of indicators. The scenario that performs best in relation to the point of view gets a score of 100. All other scenarios are graded proportionally less. Since the point of view changes from round to round, the best scoring scenario changes from round to round, i.e., each round a different combination of decisions might be required to achieve the highest score. The reason for requiring the player to change decisions for reaching the best scoring scenario is to facilitate the achievement of the main intended learning outcome: that is the player building an understanding of how the point of view or in other words the setting of priorities changes the solution perceived as ideal. The idea of the 'point of view' is not to create a competition between social, environmental, and economic aspects, but rather to highlight how on the one hand a change in priorities might change the optimal solution, but on the other hand to also show that there are good solutions that satisfy multiple interests.

The score, the decisions, and the POV are recorded in the score board. This allows the user to compare how decision combinations and POVs are affecting the score. Since playing a round of the game does not require much time, it is easy to quickly generate a score board with decision combinations and POVs from a series of rounds, which allows the reflection on how decisions and POV affect the score.

The decisions

The game asks the player to make decisions at three points in time 2020, 2030, and 2040. The questions deal with the introduction of CCS, speed of emission reductions, expansion of cross-border electricity transmission lines, and biomass imports. Table 2 shows in which year the player must make decisions on what. The decisions create a decision tree with 1728 possible final states in 2050. A visualisation of the decision tree is available in Fig. 7 in Appendix B.

The number of scenarios determines the computational capacity required. Every decision in the game increases the number of scenarios. Therefore, the goal was to have a limited number of decisions, as to keep the computational effort manageable. In these, we put the focus on a set of key decisions that have the character of a game changer specifically for the European power system. We selected decisions that alter key boundaries of the system, e.g., the speed of emission reductions is the central policy component for decarbonisation. Furthermore, we selected decisions that affect the flexibility of the system, but which have been to a limited extent at the centre of the recent European policy debate, e.g., CCS legislation is rather restrictive in most parts of Europe, even though many models in the literature anticipate a role for the technology [19].

By default, carbon capture and storage (CCS) technologies are not allowed in the scenarios. This aims to reflect that the legislation on CCS within the EU is still not comprehensive and with certain gaps [20]. However, at all three decision points the player can allow the installation of power plants with CCS. Furthermore, in all three decision points the player can decide at what rate the emission limit in the model shall be reduced. Slow means in this context that the emissions are being reduced at the current rate of the EU Emissions Trading System (EU ETS), The EU ETS currently uses a linear reduction factor of 2.2% per year, where 2.2% refers to the year 2005. The carbon budget and the reduction rate in the model are adjusted to the power sector, since the EU ETS covers more sectors. The medium reduction rate refers to a linear reduction factor of 3.4%, which leads to (net-)zero emissions in the power sector by 2045. The fast emission

Table 2 Decisions in power decisions game

Decision	2020	2030	2040
CCS	Yes/no	Yes/no	Yes/no
Emission reduction speed	Slow/medium/fast	Slow/medium/fast	Slow/medium/fast
Transmission expansion	Yes/no		
Biomass imports		Yes/no	Yes/no

reduction rate applies a linear reduction factor of 5.6% annual reduction, which would result in (net-)zero emissions in 2035. The player can only once make a decision related to the expansion of cross-border transmission lines in 2020. This relates to the expansions and additions suggested in the Ten-Year-Network-Development-Plan from ENTSO-E [21]. If the player opts for the transmission expansion, the cross-border electricity transmission capacities are increased as suggested in the TYNDP 2018 by 2035. The last decision that the player must make is on biomass imports and it is offered in 2030 and 2040. By default, biomass imports are allowed. However, the player can decide to ban them, for example, to address sustainability concerns around the environmental impacts of imported biomass.

The underlying modelling infrastructure

As mentioned, the scenarios with 1728 possible pathways and outcomes are not modelled 'live' as users play the game. Instead, an underlying optimisation model has been used to run all scenarios ahead of publishing the Serious Game.

OSeMBE

The Open-Source electricity Model Base for Europe (OSeMBE) is a long-term planning model of the European power system, built using the modelling system OSeMOSYS [10]. It covers the 27 EU member states, plus Norway, Switzerland, and the United Kingdom and models the years 2015–2050.

The modelling system OSeMOSYS is by default a least-cost optimisation program that assumes perfect foresight. It provides least-cost solutions for satisfying externally defined energy demands, based on technological options provided and boundary conditions like emission limits or resource availability [11]. Furthermore, OSeMOSYS is dynamic and assumes perfect competition [22]. It is available for probabilistic scenario design, but it is here used in its original, deterministic form.

Myopic setting

The aforementioned perfect foresight in OSeMOSYS implies that the model, by default, minimises the total net present cost of the entire EU27 + 3 electricity system at once for the entire modelling period (in the case of OSeMBE, from 2015 to 2050). The perfect foresight is valuable when the purpose of a model and scenario is to show a 'best' type of outcome. However, it does not reflect many real-world policy and investment decisions, which are commonly based on information over a short period of time and get updated as more information becomes available. Here, a myopic perspective is more suitable, meaning that optimising the model horizon in steps of suitable length reflects better real-world decision patterns. The effect of perfect foresight on the results has been documented in the literature. For example, Fuso-Nerini et al. show the effect of perfect foresight on investment decisions related to decarbonisation of the transport sector in the UK. They find that myopia can lead to delayed investments in key technologies and infrastructure [23]. A myopic setting in models leads to a stronger focus on the short to medium-term benefits of decisions, because the model is optimised in consecutive steps, while perfect foresight in models optimises decisions over a long-term horizon. Fuso-Nerini et al. and Heuberger et al. highlight the importance of both perfect foresight models and myopic models when investigating pathways to a decarbonised energy system [23, 24].

Since the aim of the Power Decisions Game is to call the users onto making decisions at several points in time, with limited information and be confronted with their outcomes, we decided to implement a myopic perspective in the model. This is done for the first time with OSeMOSYS and therefore required new infrastructure. To run OSeMBE with myopic foresight, we developed a Python package called OSeMOSYS_step [17]. OSeMOSYS_step allows the user to run a model, while considering possible decisions at certain decision points. It breaks the modelling period into a series of consecutive steps. The first step is six years long. The following steps are each ten years long. The steps have a foresight horizon of ten years, i.e. the models cover 20 years. Between each step, new data can be provided to create alternative scenarios relating to decisions or new technological developments, while residual capacities are devised from the results of the previous step and the original model data, and all other data are provided from the original model. OSeMOSYS_step allows to run OSeMOSYS models under myopia with limited foresight. The current steps of 10 years with 10-year foresight need on average 16 minutes to run. With a shorter step length of 5 years, which implies that the model length shortens to 10 years, the running time is reduced to an average of ten minutes. These run times are measured using OSeMOSYS_step with the solver Gurobi.

Indicators

The score in the Power Decisions Game is calculated based on three indicators, one for each of the categories in the player's perspective—economic, social, and environmental. The indicators are not direct outputs of OSeMBE, but are calculated based on the models results and partly with additional input, e.g., for future country populations. The indicators are:

- Accumulated CO_2 emission per citizen as a proxy for the environmental dimension.
- Discounted investment per citizen as a proxy for the economic dimension.
- Levelised cost of electricity (LCOE) as a proxy for the social dimension.

It must be noticed that in future implementations of the game, the indicators could be changed, to represent different perspectives.

In the following subsections the calculation of the indicators is described.

Environment: accumulated CO_2 emissions per citizen The chosen proxy for the environmental dimension is CO_2 emissions. While it certainly is a 'proxy' of importance, it is not the only one. Nevertheless, CO_2 is the most important Greenhouse gas (GHG), due to the large amounts emitted by humanity and its longevity in the atmosphere.

The accumulated CO_2 emissions per citizen, $\mathrm{AE}\left(\frac{\mathrm{t\ of\ CO_2}}{\mathrm{capita}}\right)$, indicate the CO_2 emissions from the power sector between 2020 and the current year divided by the number of citizens, as shown in Eq. (3). The used variables are explained in Table 3.

Equation (3): accumulated CO_2 emissions per citizen

$$\mathrm{AE}[c,y] = \frac{\sum_{2021}^{y} ae_{c,y}}{p_{c,y}}. \tag{3}$$

The accumulated CO_2 emissions per capita indicate the CO_2 emissions that the power sector of a single country or entire Europe has emitted between the current year and 2020. This means, the emissions from the year of the first decision by the player till the year that the player is currently in. This indicator goes into the score calculation as the environmental dimension. It highlights the importance of early action on emission reductions, since it is not only crucial to have a net-zero power sector in 2050, but also how much CO_2 is still emitted on the way till there.

Table 3 Abbreviations and variables of accumulated CO_2 emissions calculation

Abbreviation	Meaning	Unit
AE	Accumulated CO_2 emissions	Tonnes of CO_2 per citizen
ae	Annual CO_2 emissions	Tonnes of CO_2
c	Country	–
p	Population	Citizen
y	Year	–

Economy: discounted investment per citizen The discounted investment per citizen, $I\left(\frac{\mathrm{EUR}}{\mathrm{citizen}}\right)$, indicates the annualised investment per citizen, where all investments across the entire time domain of the model are accounted for. It gives an indication that is comparable between countries on how much investment countries need to realise to meet the growing demand for electricity by their citizens in the chosen scenario. The comparability between countries gives indications on which countries will need to realise or attract more or less investments in the power sector. As such, I is a suitable proxy for Economy because it allows the comparison of capital requirements for the future power system across countries and across scenarios.

Equation (4) indicates how the discounted investment per citizen is calculated: it is the ratio between an output variable of OSeMBE called Capital Investment (defined for each country-specific technology and year), discounted and annualised, and the population forecast, as with the previous indicator from Fouré et al. [25]. Discounted means, future cash-flows are converted to today's value and annualised refers to the even distribution of investment cost over the technical lifetime of the related technology. The abbreviations used in Eqs. (4) and (5) for the variables are listed in Table 4.

Equation (4): formula for the discounted investment per citizen

$$I[c,y] = \frac{\frac{\sum_{t}^{T}\sum_{y-ol_t}^{y}\frac{ci_{t,y}}{PA[t]}}{(1+i)^{y-y_0}}}{p_{c,y}}. \tag{4}$$

Here, $\mathrm{PA}(t)$ is the present value of the annuity, as outlined in Eq. (5).

Table 4 Abbreviations and variables of investment per citizen calculation

Abbreviation	Meaning	Unit
c	Country	–
ci	Capital investment	€
I	Discounted investment per citizen	€ per citizen
i	Discount rate	%
ol	Operational life	Years
p	Population	Citizen
PA	Present value annuity	€
t	Technology	–
T	All technologies	–
y	Year	–
y_0	First year of the modelling period	–

Equation (5): formula present value annuity

$$\mathrm{PA}[t] = \left(1 - (1+i)^{-ol_t}\right) * \frac{1+i}{i}. \tag{5}$$

Society: levelised cost of electricity (LCOE) The LCOE is taken as the proxy for scenario performance in the social dimension since it indicates the cost that are related to each unit of electricity and that the consumers will face. The calculation of the LCOE is shown in Eq. (6). The abbreviations used for the variables in Eq. (6) are explained in Table 5.

The LCOE does not represent market prices, hence it does not directly correspond to the actual electricity tariffs consumers will face. The consumer prices include commonly large components of taxes and levies, which are considered neither in the OSeMBE model nor in the Power Decisions Game. However, the assumption is made that the costs occurring in the power system are reflected in the electricity tariffs, and that therefore the differences between LCOEs in different scenarios give indications of increased or decreased pressure on the final consumers. The equation is somewhat more comprehensive than for the previous two indicators. This is caused by the consideration of the electricity cross-border flows. The if clause in Eq. (6) adds the cost of electricity for imported electricity and subtracts the cost of electricity exported. The detailed formulas for the variables used in the equation of the LCOE can be found in Appendix A, including a list of variables and their abbreviations in Table 10.

Equation (6): formula of the levelised cost of electricity (LCOE)

$$\mathrm{LCOE}[c,y] = \frac{DP[c,y]}{\frac{\mathrm{sad}_{c,y}}{0.95}} * \mathrm{LCODE}[c,y] + \sum_{x}^{X} \mathrm{LCOTE}(c,x,y). \tag{6}$$

Here, the $\mathrm{LCOTE}(c,x,y)$ is the LCOE of electricity transferred between countries, as outlined in Eq. (7).

Equation (7): calculation of the cost related to the net-imports of electricity

$$\mathrm{LCOTE}(c,x,y) = \begin{cases} \frac{\mathrm{NI}[c,x,y]}{\frac{\mathrm{sad}_{c,y}}{0.95}} * \mathrm{LCODE}[x,y] & \text{if}\, \mathrm{NI}[c,x,y] > 0 \\ \frac{\mathrm{NI}[c,x,y]}{\frac{\mathrm{sad}_{c,y}}{0.95}} * \mathrm{LCODE}[c,y] & \text{otherwise.} \end{cases} \tag{7}$$

Linking between the model and the Power Decisions Game

The Power Decisions Game and OSeMBE are linked statically, i.e. all scenarios that are possible based on the decisions available to the player are modelled and run in advance. The results and the already calculated scores are stored in the game's backend. This stands in contrast to other tools like EUCALC [5] or my2050 [4] where at least the calculations for extreme scenarios are performed after the player has made a choice. The static connection is necessary due to the long calculation times for the optimisation of the technically detailed model to converge. Model and game are available on GitHub under open-source license [15, 18].

Results

This section provides an overview of what insights the game can provide the player. In the first part of the section, we analyse the impact of the POV on the score. In the second part of the section, we analyse the impact of the decisions available in the game on the indicators that constitute the score.

In Fig. 2, we show how the score distribution of all scenarios underlying the game changes depend on the assigned POV. While the weights for the POV in the game are randomly assigned to values between zero and one that add up to one, the POVs shown in Fig. 2 represent a selection of possible weight combinations.

Table 5 Abbreviations and variables of LCOE calculation

Abbreviation	Meaning	Unit
c	Country	–
DP	Domestic production	kWh
LCODE	Levelised cost of domestic electricity	€ cent per kWh
LCOE	Levelised cost of electricity	€ cent per kWh
LCOTE	Levelised cost of transferred electricity	€ cent per kWh
NI	Net imports	kWh
sad	Specified annual demand	kWh
x	Country with which country c exchanges electricity	–
X	All countries with which country c exchanges electricity	–
Y	Year	–

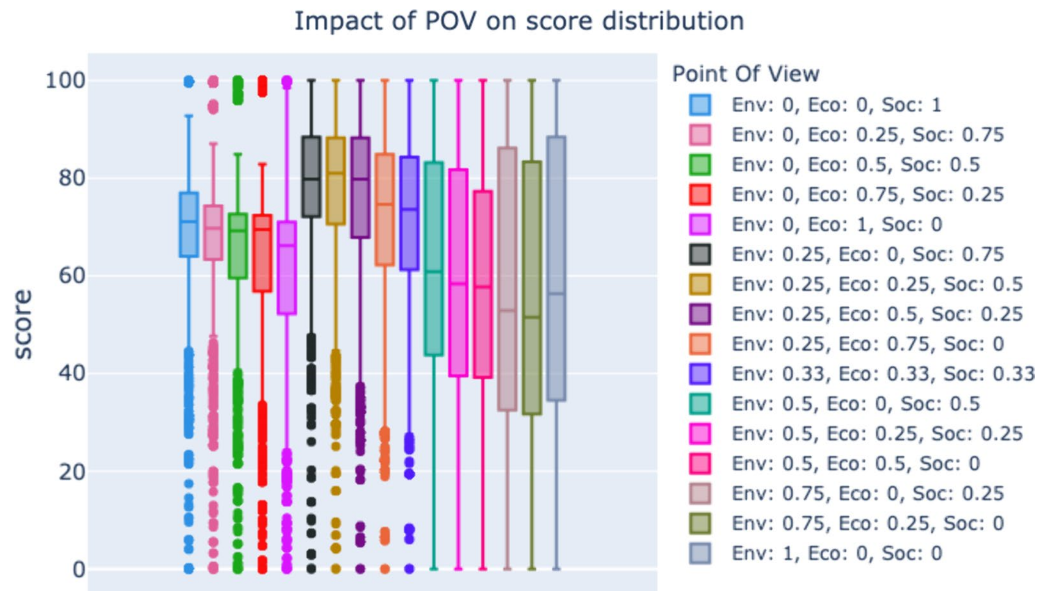

Fig. 2 Impact of the point of view on the overall score distribution

There are several interesting observations that we can make in Fig. 2.

Firstly, we can notice that the score distributions indicated by the box plots vary noticeable in their distribution. This is best visible on the score distributions for which the POV is focusing solely on one of the sustainability dimensions. The social dimension is rather concentrated, see blue box plot on the left. The economic dimension shows a similar, but more stretched pattern. Lastly, the environmental dimension, in grey on the right-hand side of the graph, shows the widest spread of scores.

Knowing the above described score distributions, where the POV focuses solely on one dimension, allows to analyse the distributions when the POV gives weight to multiple dimensions of sustainability. We notice that the POVs that give weight only to the economic and social dimension create score distributions that compare well with the distributions when the weight is fully on one of these two dimensions. Also, the five box plots next to the one focusing on the environmental dimension show similar characteristics as the one focusing on the environment only. But in between, the five box plots at the centre of the graph are interesting. These box plots concentrate in the upper half of the graph. They illustrate how for certain POVs it is easier to achieve a high score. However, it does not imply that each individual dimension of sustainability scores well under these POVs, but that the dimensions complement each other well, and therefore reach a high score across scenarios, e.g., in some scenarios the environmental dimension might score well and the social and economic less well and vice versa. This illustrates how the perspective on and the priorities given to the dimensions of sustainability, in the game illustrated by the POV, lead to favouring scenarios that create a decent compromise between the different dimensions of sustainability, but do not necessarily score best in all individual dimensions.

To further analyse the determinants of the score, we analyse in Figs. 3, 4, 5 and 6 and the accompanying tables, Tables 6, 7, 8 and 9, how selected decision patterns affect the three indicators described in "Indicators" section, from which the score is calculated.

The wide variety of decision combinations in the Power Decisions Game allows the user to investigate how different decisions, taken in a specific sequence, affect each other. In Figs. 3, 4, 5 and 6, we illustrate how the indicator distribution varies for selected decision patterns, with the goal to show what insights the player might derive from the game. The decision patterns selected are:

- All scenarios.
- No cross-border transmission expansion.
- Increased cross-border transmission.
- No biomass imports.
- No CCS.
- No biomass, no CCS.
- Slow CO_2 reduction.
- Fast CO_2 reduction.

The distributions of the indicators LCOE and discounted investment per citizen, in Figs. 3 and 4, are illustrated for the entire modelling region. In contrast, for the

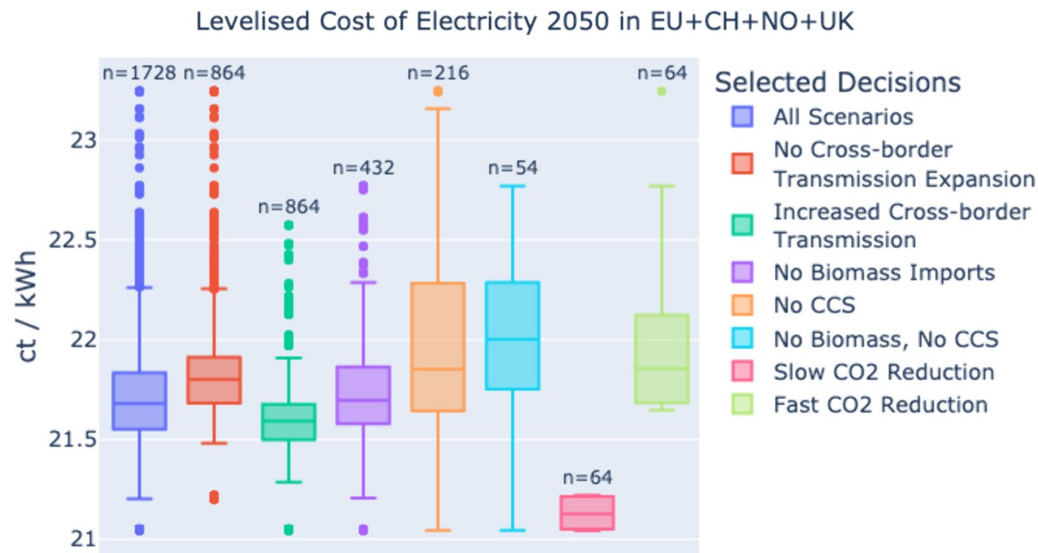

Fig. 3 Box plots for the LCOE distribution in 2050 under selected decision patterns, with n indicating the number of scenarios covered by each box plot

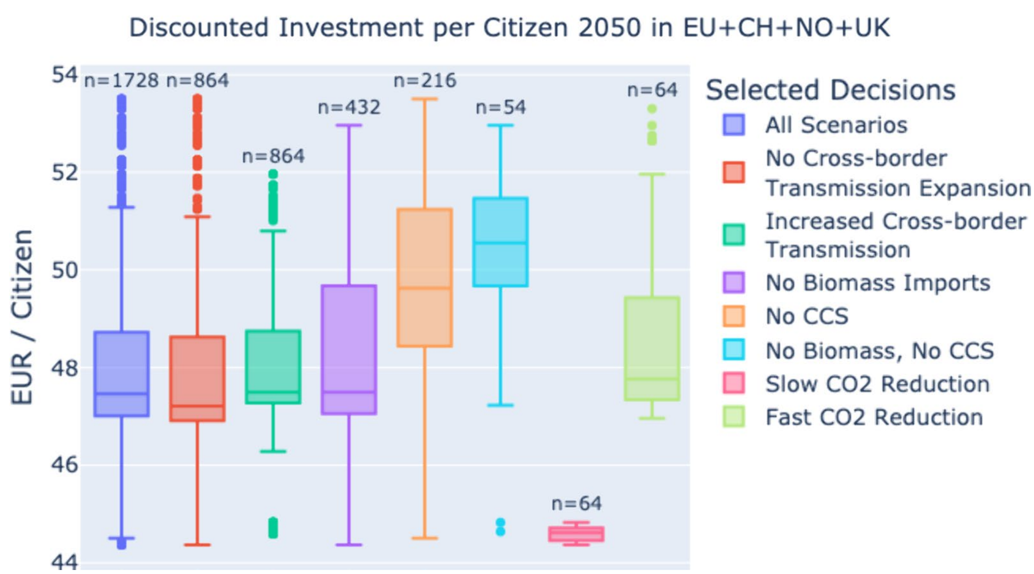

Fig. 4 Box plots for the discounted investment per citizen in 2050 under selected decision patterns, with n indicating the number of scenarios covered by each box plot

accumulated CO_2 emissions per citizen we selected two countries, the United Kingdom and Italy. By doing so, we can illustrate how the CO_2 emissions from the optimisation model are affected differently by the decisions in the game depending on the country, while complying with the emissions limit for the entire modelling region. In the game, the player can make such observations by clicking on the countries in the map, which opens a bar plot of the currently selected indicator for the clicked country.

In all indicator distribution figures, the blue box plot on the left shows the indicator distribution for all scenarios, i.e. the box plot covers the entire range of possible values for the illustrated indicator. The red and green box plots show the indicator distributions for scenarios without increased cross-border electricity transmission capacity (red) and with increased cross-border transmission capacity (green). In purple, orange, and turquoise the indicator distributions of decision patterns related

Fig. 5 Box plots for the accumulated CO_2 per citizen in Italy under selected decision patterns, with n indicating the number of scenarios covered by each box plot

Fig. 6 Box plots for the accumulated CO_2 per citizen in the United Kingdom under selected decision patterns, with n indicating the number of scenarios covered by each box plot

to biomass imports and CCS are illustrated. Lastly, the two box plots on the right side of the figures illustrate the indicator distributions of slow emission reduction rate scenarios (pink) and fast emission reduction scenarios (light green). Note that, since the box plots show results for different selections of decisions, also the number of scenarios they include is different.

Figures 3, 4, 5 and 6 are each accompanied by a table—Tables 6, 7, 8 and 9—in which the number of scenarios with a certain decision pattern, the standard deviation (σ) for each box plot, and the p-value, indicating the significance of the change between decision patterns and all scenarios, are listed. The lower the p-value, the higher the statistical significance, with everything smaller than 5% considered significant, i.e. everything with a p-value larger than 5% does not show a statistically significant change. By default, the p-values are calculated using the Alexander Govern test [26]. Only in the case of

Table 6 Standard deviations of Fig. 3 and significance of change by decisions on the LCOE in 2050 in the entire modelling region

Selected decisions	No. scen.	σ	*p*-value (%)
All scenarios	1728	0.33	–
No cross-border transmission expansion	864	0.36	0.00
Increased cross-border transmission	864	0.23	0.00
No biomass imports	432	0.33	10.33
No CCS	216	0.49	0.00
No biomass, No CCS	54	0.41	0.00
Slow CO_2 reduction	64	0.08	0.00
Fast CO_2 reduction	64	0.34	0.00

Table 7 Standard deviation of Fig. 4 and significance of change by decisions on the discounted investment per citizen in 2050 in the entire modelling region

Selected decisions	No. scen.	σ	*p*-value (%)
All scenarios	1728	1.65	–
No cross-border transmission expansion	864	1.89	55.25
Increased cross-border transmission	864	1.36	46.19
No biomass imports	432	1.84	0.28
No CCS	216	1.99	0.00
No biomass, no CCS	54	1.76	0.00
Slow CO_2 reduction	64	0.16	0.00
Fast CO_2 reduction	64	1.84	0.35

Table 8 Standard deviation of Fig. 5 and significance of change by decisions on the accumulated CO_2 emissions per citizen between 2021 and 2050 in Italy

Selected decisions	No. scen.	σ	*p*-value (%)
All scenarios	1728	4.76	–
No cross-border transmission expansion	864	5.02	0.00
Increased cross-border transmission	864	4.27	0.00
No biomass imports	432	4.59	42.12
No CCS	216	5.35	0.00
No biomass, No CCS	54	5.26	0.00
Slow CO_2 reduction	64	0.85	0.00
Fast CO_2 reduction	64	4.49	0.00

Accumulated CO_2 in the UK, the p-values for the decision patterns 'No CCS', 'No Biomass, No CCS', and 'Slow CO_2 reduction' are calculated using the Kruskal–Wallis H-test [27].

In Fig. 3 we observe that the highest LCOEs are observed when cross-border electricity transmission capacities are not increased, when no CCS is available, and when CO_2 emissions are reduced fast, whereas the lowest LCOEs are observed when reducing emissions slowly. Furthermore, the p-value in Table 6 indicates that a ban on biomass imports has no significant effect on the LCOE distribution. This shows that the model is not relying on biomass imports from outside Europe. However, the ban of CCS leads to increased LCOEs, which implies that the model uses CCS, if available. In the game, the player can observe this, for example, when selecting the accumulated CO_2 emissions of the UK, which are reducing after 2030 if the emission limit is reduced fast and CCS is available. This in turn allows, for example, Italy to keep emitting CO_2.

Table 9 Standard deviation of Fig. 6 and significance of change by decisions on the accumulated CO_2 emissions per citizen between 2021 and 2050 in the United Kingdom

Selected decisions	No. scen.	σ	*p*-value (%)
All scenarios	1728	1.13	–
No cross-border transmission expansion	864	1.13	16.94
Increased cross-border transmission	864	1.11	16.45
No biomass imports	432	1.13	86.80
No CCS	216	0.53	0.00
No biomass, no CCS	54	0.53	0.00
Slow CO_2 reduction	64	0.00	0.00
Fast CO_2 reduction	64	0.80	0.00

Furthermore, it is interesting to observe that slow emission reductions lead to lower LCOEs, while fast emission reductions lead to a significant but not strong increase of the LCOE median in comparison to the distribution of all scenarios, mainly the upper half of the box plot shows a wider spread. This is an important observation, since it not only shows that a European net-zero power sector in 2050 is possible, but also that the cost difference between several decarbonisation pathways does not need to be large. However, this insight is aggregated. There are more significant differences across the continent.

In Fig. 4 we can observe that the decision patterns show similar patterns for the discounted investment as for the LCOE, shown in Fig. 3. However, the scenarios with and without increased cross-border electricity transmission (shown in red and green) do not show a statistically significant change to the distribution of all scenarios—see Table 7. Important to consider is that the decision on transmission in 2020 becomes effective in 2030, 20 years before 2050. One could expect a stronger effect on the investment if there would be also later decisions on transmission capacities. In contrast to the LCOE, for the discounted investment per citizen Table 7 indicates that the decision on biomass imports has a statistically significant impact. In Fig. 4 we can observe this in form of a longer distance between the median and the third quartile.

Figure 5 shows the accumulated CO_2 emissions per citizen from power generation in Italy from 2021 to 2050 for the above described decision patterns. We can observe that the Italian power sector accumulates at least 10.5 tonnes of CO_2 per citizen from 2021 to 2050 and can emit up to 30 tonnes of CO_2 per citizen. In Fig. 6, we show the accumulated CO_2 emissions per citizen from power generation in the UK. The UK power sector accumulates at least 1 tonne of CO_2 per citizen between 2021 and 2050 and can emit up to 4.9 tonnes of CO_2 per citizen depending on the scenario.

This means that even in a scenario with high emissions, the UK emits less than half of what Italy emits in a scenario with low emissions. This gives an indication on how decarbonising the Italian power supply is more costly than in the UK. As mentioned before, in the game the player can explore this by selecting the respective countries from the map.

We can also note the accumulated emissions are most strongly affected by decisions on the emission reduction pace, see the box plots in pink and light green on the right-hand side in both graphs. Furthermore, it is notable that apart from the emission decisions, the effects of decisions on the accumulated emissions seem contrarily for the two countries, while in Italy the decision not to increase cross-border electricity transmission capacities leads to statistically significantly higher emissions, the UK emissions are not significantly affected, see Tables 8 and 9. And while banning CCS lowers the Italian emissions, it increases the emissions in the UK.

These observations indicate that the repeated playing of the game can make the dynamics of the underlying model observable, showing how a joint emission limit allows countries to reduce emissions in line with their capabilities, based on resource availability and demand levels. In the discussed case of Italy and the UK, the results indicate better availability of fossil free energy sources in the UK than in Italy.

For all three indicators we can notice that the decisions on the emissions pace have the strongest impact on the results. This reflects the fact that the decisions on the CO_2 emissions reduction speed are directly affecting a limiting constraint of the model, which represents a key parameter in the design of the future power system.

In overall, we can see that the game allows the player to explore how decisions affect the cost of electricity, the need for investment, and the CO_2 emissions per capita, at the European level, but also at the country level. It is also observable how different countries are differently affected by decisions, e.g., if CCS is available, Italy keeps emitting CO_2 while the UK has negative emissions; or while the increase of cross-border electricity transmission capacity has a significant effect on emissions in Italy, it does not for the UK.

Discussion

The main question investigated and described is how well the Power Decisions Game reaches its goal of facilitating the engagement and the exploration of the dynamics of a European power system (optimisation) model and the impacts of key policy decisions on the design of the future power sector, by analysing their effect on key performance indicators. The game offers the opportunity for non-modellers to see how the results from a power system optimisation model are affected when changing key boundary conditions. By doing so, the game user gets an interactive exploration process, like the one that a modeller has when working and modifying a model. Beyond this, the 'Point-of-View' feature aims to overcome the misperception that optimisation models deliver one optimal solution and showcases that the solution that is perceived as optimal can depend on the priorities of the model user. Results presented herein show, for example, how the need to balance competing interests in the POV can lead to preferring scenarios that do not excel in the individual sustainability dimensions, but together build a good compromise. However, the POV feature could still be improved. Currently, the POV is randomly determined and indicated as a percentage. This could be difficult for users to interpret. One option to overcome this is to randomly assign pre-defined POVs, such as 'balanced', 'pro-environment', and similar. Additionally, the explanation of how the POV affects the achieved score could be improved.

The Power Decisions Game distinguishes itself from existing engagement tools in multiple aspects. It illustrates the implications of delayed decision making, through the introduction of limited foresight in the underlying model, and how these might affect the achievement of certain climate-related goals. This becomes, for example, clear to players via higher investment needs when reducing emissions later instead of early.

Another difference to existing tools is the use of an optimisation model instead of a simulation model. An optimisation model provides results of a more normative nature in relation to meeting defined objectives and indicates when objectives cannot be met. The least-cost optimisation used provides a solution that is closer to a system developing in a market setting than the solution of a simulation model would be. To a certain extent, the game also provides insights into how different societal priorities can affect the power system design. For example, the ban on CCS technologies will most likely lead to higher electricity costs, since emissions that are hard to abate cannot be compensated for by negative emissions, but need to be avoided entirely. However, the use of CCS will cause a demand for biomass, which raises the question: how is the biomass sourced? In regard to this, the techno-economic nature of the underlying model sets certain limits on how far the social implications of decisions can be reflected. The indicators currently used for the social dimension and the economic dimension, the discounted investment per citizen and the LCOE, are strongly related. The main difference is that the LCOE considers the operational and fuel costs that are not considered in the discounted investment costs per citizen. The investment costs, therefore, illustrate well that the shift to a renewable-based power system is capital intensive. But the two indicators also strongly correlate. Model expansions such as accounting for jobs linked to the application of technologies, or the linking with other tools could strengthen the representation of social aspects and would allow the modeller to change the indicators. Furthermore, the game could be expanded to indicate how delayed decisions can cause existing assets to be stranded, using already available results from the underlying model. In the context of decarbonisation pathways, stranded assets indicate economic inefficiencies of a pathway. The indication of stranded assets is facilitated by the limited foresight set-up of the model. A model with perfect foresight would better avoid investments that do not pay off, since under perfect foresight the investments over the entire modelling period are optimised. Such aspects, which either have already been covered in the model, e.g., how a ban of CCS might lead to higher electricity cost, or could be covered by future additions to the model, are currently hardly visible to the player. Future work on the game should focus on integrating more model indicators into the game's interface. They could also cover some visualisations in relation to the decisions offered, e.g., when is net-zero reached with selected emission reduction speeds?

Currently, the game covers the power sector. Hence, interactions with other sectors of the energy system are neglected. This neglects potential synergies, such as the option that the heating and cooling sector could absorb production peaks of variable renewable energy sources. But it also neglects potential challenges, like high electrification in transport or other sectors, which would require more bulk electricity supply. This could be overcome by expanding the coverage of the underlying model OSeMBE.

Currently, the Power Decisions Game only offers a single-player mode. However, particularly for use with students, it could be interesting to have the option for a multi-player mode. In such a mode, each player could make decisions for groups of countries or individual countries. Crucial to the implementation would be to carefully decide how many decisions would be offered, since the corresponding number of scenarios to be run would increase exponentially with each additional player.

It becomes clear that time requirements for running the scenarios for the game are an important factor to consider when further developing the Power Decisions Game. A compromise would be needed between model detail, sectoral coverage and number of decisions offered. But also, enhancements of the OSeMOSYS_step package, improving its capabilities of using the full potential of high-performance computing infrastructure, could be a viable option to expand the Power Decisions Game. Another potential improvement to OSeMOSYS_step could be to develop the possibility to provide decision options that are conditional on the decisions in the previous steps. For example, if the emission limit has reached zero one might want to remove options for emission reduction speeds.

A different development direction for the game could be to overcome the static link between model and game. Recent developments around OSeMOSYS have reduced the time required to solve models. If this trend continues, one could reach conveniently short solution times with a low-resolution model. This would enable the developers to offer more decisions to the player. However, it would require a redesign of the game's logic, particularly the score calculation, as the score is currently normalised over all possible scenarios, thereby enabling the comparison between different decision patterns.

Conclusions

This paper presents the open-source Power Decisions Game, as an engagement tool, where the dynamics and insights of the impact of key policy decisions on the results of a European power system optimisation model can be explored. In the previous section, we have highlighted and discussed the current version of the game and its limitations. Considering these limitations and potential expansions, one could consider the current version of the Power Decisions Game a proof of concept, i.e., it is a fully functioning game, but it would develop its full potential if it were to be expanded. For a meaningful expansion of the game, the involvement of stakeholders in the development process could be valuable to receive input on the relevance of the decisions in the game or potential sectoral expansions. A guiding example for such a stakeholder involvement could be the development process of the Energy Safari [28].

The Power Decisions Game has not yet been systematically tested. However, various potential use cases can be envisioned. A possible use case could be in workshops that discuss energy policies. In this setting, the users would be stakeholders from different disciplines, such as policymaking, industry, and academia. The game could act as a starting point for discussing potential policy options and their implications.

A second setting in which the game could be used are courses in higher education, e.g., at Bachelor's or Master's level. In this context, the game could be used to let students explore the dynamics of energy systems models and the potential implications of key decisions on the system design.

In both cases, the focus on a few key decisions and levers facilitates a quick understanding of the rules of the game and gives the possibility for all participants to individually play it several times during one workshop session or class. This quickly creates a large set of outcomes, which are recorded for each player on a 'Score' page of the online application. It thereby allows participants to adjust their decisions recursively to obtain better outcomes for different POVs and creates statistics to be used for plenary discussion and for reaching common conclusions on the potential outcomes of key choices. This is the type of application and exploration that the game in its current design mostly targets. The game thereby facilitates non-modellers to explore, in an interactive manner, the dynamics of a power system optimisation model. An aspect that could be improved, to make the game more user-friendly for non-expert players, is the explanation of technical terminology, such as Emission Trading System or Carbon Capture and Storage.

The game and all associated tools and infrastructure are published under open-source licence, which allows the adaptation of the game. This means that developers can update the questions and decisions or the data of the model, for instance.

Appendix A: Formulas

Equations for the calculation of the LCOE

$$\mathrm{LCOE}[c,y] = \frac{\mathrm{DP}[c,y]}{\mathrm{sad}_{c,y}} * \mathrm{LCODE}[c,y] + \text{for x in} X \left(\text{if } \mathrm{NI}[c,x,y] > 0\left(\frac{\mathrm{NI}[c,x,y]}{\mathrm{sad}_{x,y}} * \mathrm{LCODE}[x,y]\right)\right), \tag{8}$$

$$\mathrm{DP}[c,y] = \mathrm{sad}_{c,y} - \text{if} \sum_{x\, in\, X} \mathrm{NI}[c,x,y] > 0\left(\sum_{x\, in\, X} \mathrm{NI}[c,x,y] * 0.95\right), \text{else}\left(\sum_{xinX} \mathrm{NI}[c,x,y]\right), \tag{9}$$

Table 10 Abbreviations and variables of LCOE calculation

Abbreviation	Meaning
AFOC	Discounted annual fixed operating cost
afoc	Annual fixed operating cost
AIC	Annualized investment cost
AVOC	Discounted annual variable operating cost
avoc	Annual variable operating cost
c	Country
ci	Capital investment
CRF	Capital recovery factor
DP	Domestic production
LCODE	Levelised cost of domestic electricity
LCOE	Levelised cost of electricity
NI	Net imports
PA	Present value annuity
pbta	Production by technology annual
sad	Specified annual demand
t	Technology
T	All technologies in country c
x	Country electricity is exchanged with
X	All countries country c is exchanging electricity with
y	Year

$$\mathrm{LCODE}[c,y] = \frac{\mathrm{AIC}[c,y] + \mathrm{AFOC}[c,y] + \mathrm{AVOC}[c,y]}{\mathrm{DP}[c,y] * 277.778}, \tag{10}$$

$$\mathrm{AIC}[c,y] = \sum_{t \text{ in } T} \sum_{y-OL_t}^{y} \frac{\mathrm{ci}_{t,y}}{\mathrm{PA}[t]}, \tag{11}$$

$$\mathrm{AFOC}[c,y] = \sum_{t\, in\, T} \mathrm{afoc}_{t,y}, \tag{12}$$

$$\mathrm{AVOC}[c,y] = \sum_{t \text{ in } T} \mathrm{avoc}_{t,y}, \tag{13}$$

$$\mathrm{NI}[c,x,y] = \mathrm{pbta}_{c,x,y} - \mathrm{pbta}_{x,c,y}, \tag{14}$$

$$\mathrm{PA}[t] = \left(1 - (1+i)^{-ol_t}\right) * \frac{1+i}{i}. \tag{15}$$

Appendix B

See Fig. 7.

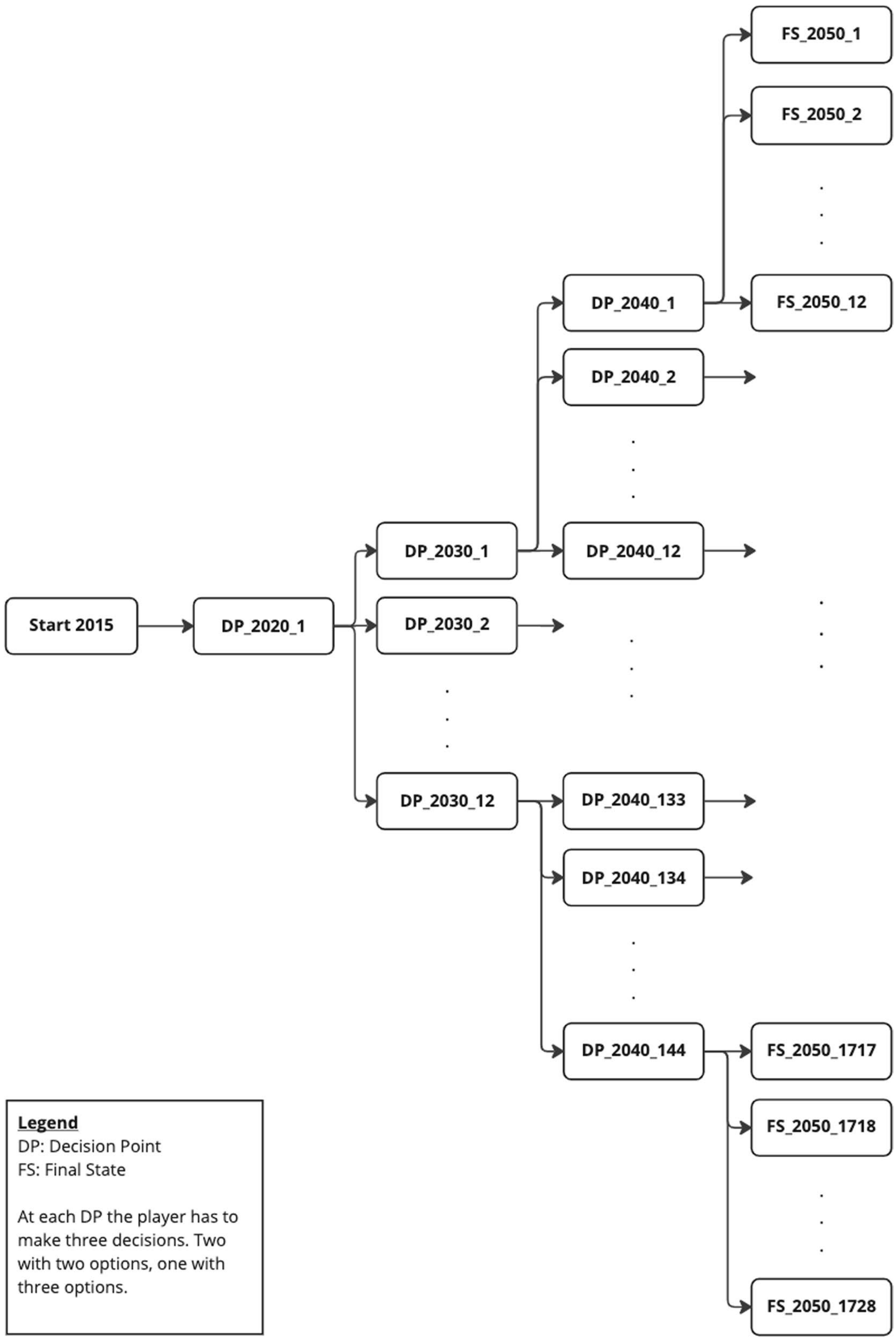

Fig. 7 Decision tree of game

Abbreviations

AE	Accumulated CO_2 emissions
ae	Annual CO_2 emissions
AFOC	Discounted annual fixed operating cost
afoc	Annual fixed operating cost
AIC	Annualised investment cost
AVOC	Discounted annual variable operating cost
avoc	Annual variable operating cost
c	Country
CCS	Carbon capture and storage
ci	Capital investment
CO_2	Carbon dioxide
CRF	Capital recovery factor
DP	Domestic production
EC	European commission
ECO	Economy
ENTSO	European Network of Transmission System Operators for Electricity
ENV	Environment
ETS	Emission trading system
EU	European Union
EUCALC	European calculator
FAIR	Findable, accessible, interoperable, and re-usable
GHG	Greenhouse gas
KPI	Key performance indicator
KTH	Kungliga Tekniska Högskolan
LCODE	Levelised cost of domestic electricity
LCOE	Levelised cost of electricity
LCOTE	Levelised cost of transferred electricity
NI	Net imports
OSeMBE	Open Source electricity Model Base for Europe
OSeMOSYS	Open Source energy Modelling System
PA	Present value annuity
pbta	Production by technology annual
POV	Point of view
REEEM	Role of technologies in an energy efficient economy—model-based analysis policy measures and transformation pathways to a sustainable energy system
sad	Specified annual demand
SNIC	Swedish National Infrastructure for Computing
SOC	Society
t	Technology
T	All technologies in country c
TYNDP	Ten-Year Network Development Plan
UK	United Kingdom
WWF	World Wide Fund for Nature
x	Country electricity is exchanged with
X	All countries country c is exchanging electricity with
y	Year

Acknowledgements
The authors would like to thank the European Commission for funding the REEEM project that allowed this work. The computations were enabled by resources provided by the Swedish National Infrastructure for Computing (SNIC) at PDC Center for High Performance Computing partially funded by the Swedish Research Council through grant agreement no. 2018-05973. We also acknowledge the various staff members at the PDC Center for assistance concerning the use of software, placing jobs and in making our code run on Dardel at the PDC Center. We would also like to thank our former colleagues Mark Howells and Georgios Avgerinopoulos for their contributions in discussions on the game design and the management of the REEEM project. Furthermore, we would like thank Jan Frederik Köster for the support in updating the score board in the game and lastly, we would like to thank Haluk Akay for proofreading the paper.

Author contributions
HH designed the decisions in the game, drafted the paper, developed the OSeMOSYS_step package, ran the scenarios, and set up the score calculation. FG designed the decisions in the game and reviewed the draft. OE developed the game logic and interface and reviewed the paper draft. ML developed the game interface and reviewed the paper draft. BL developed game logic and game interface. KK contributed to the design of the decisions in the game and reviewed the paper.

Funding
Open access funding provided by Royal Institute of Technology. This work was funded by the European Union [Grant Number 691739].

Availability of data and materials
The datasets and scripts used for this study are available in the below repositories. The archived versions are on Zenodo. The OSeMBE models is the power system planning model used in this study. The power decisions game repository contains the coding of the game interface and the indicators illustrated in it. The repositories of OSeMOSYS_step contain the scripts to run OSeMOSYS models in a myopic setting with limited foresight.

OSeMBE model
GitHub repository: https://github.com/kTH-dESA/osembe.
Archived version: https://doi.org/10.5281/zenodo.5032445.

Power Decisions Game
Playable game: https://powerdecisionsgame.com/.
GitHub repository: https://github.com/olavurellefsen/reeemgame.
Archived version: https://doi.org/10.5281/zenodo.8332745.

OSeMOSYS_step
GitHub repository: https://github.com/KTH-dESA/OSeMOSYS_step.
Archived version: https://doi.org/10.5281/zenodo.7962909.

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Competing interests
The authors declare that they have no competing interests.

Received: 2 June 2023 Accepted: 23 June 2024
Published online: 11 July 2024

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