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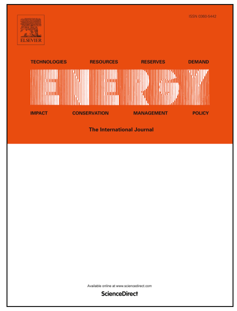

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Influence of climate change externalities on the sustainability-oriented prioritisation of prospective energy scenarios

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Abstract

The implementation of externalities in energy policies is a potential measure for sustainability-oriented energy planning. Furthermore, decisions on energy policies and plans should be based on the analysis of a number of potential energy scenarios, considering the evolution of key techno-economic and life-cycle sustainability indicators. The joint interpretation of these multiple criteria should drive the choice of appropriate decisions for energy planning. Within this context, this work proposes –for the first time– the combined use of Life Cycle Assessment, externalities calculation, Energy Systems Modelling and dynamic Data Envelopment Analysis to prioritise prospective energy scenarios. For demonstration and illustrative purposes, the application of this methodological framework to the case study of electricity production in Spain leads to quantitatively discriminate between 15 prospective energy scenarios by taking into account the life-cycle profile of the transformation path of the power generation system with time horizon 2050. When compared to the application of the framework without implementation of external costs, the internalisation of climate change externalities is found to affect the ranking of energy scenarios but still showing the rejection of those scenarios based on the lifetime extension of coal power plants, as well as the preference for those scenarios leading to a high penetration of renewable technologies.

Keywords: climate change; data envelopment analysis; electricity; energy systems modelling; externalities; life cycle assessment

1. Introduction

The current performance of the energy sector is unsustainable. For instance, at least two thirds of the anthropogenic greenhouse gas emissions come from activities within this sector [1]. In addition to environmental impacts, the continued and intense use of fossil resources is leading to economic and social concerns. Within this context, energy policies actually oriented towards sustainability targets become a critical need in most countries worldwide [2].

The development of sustainability-oriented energy policies requires taking into account multiple criteria and uncertainty. In this sense, in order to effectively support decision-makers, multi-criteria decision analysis (MCDA) methods could be used [3]. In particular, a growing interest in the use of MCDA tools for the selection of appropriate energy scenarios has recently been observed [4]. Furthermore, when emphasis is laid on compensating the damage caused by the pollution associated with an activity production such as power generation, the inclusion of external costs in the decision-making process emerges as a potential measure for sensible energy planning [5].

Thus, sensible energy planning demands information from different tools in order to carry out robust (i.e., science-based) assessments. In this regard, Energy Systems Modelling (ESM) is a valuable methodology to support energy planning and policy-making through the prospective evaluation of energy scenarios. Furthermore, for an actual orientation towards sustainability, current trends refer to the endogenous integration of life-cycle indicators into energy systems models [6]. These life-cycle indicators come mainly from the application of Life Cycle Assessment (LCA), a standardised methodology for the evaluation of the potential environmental impacts of a product system [7]. Beyond conventional techno-economic results, this hybrid procedure addresses the evolution of sustainability indicators in prospective energy scenarios. Moreover, unlike the separate use of LCA fed with ESM results [8], the endogenous integration of life-cycle indicators into energy systems models gives analysts the opportunity to affect the ESM optimisation problem with life-cycle indicators [9].

In addition to the quantification of life-cycle indicators and the prospective analysis of their evolution, an appropriate MCDA tool is needed when it comes to soundly prioritising prospective energy scenarios. In this sense, Martín-Gamboa et al. [4] proposed the use of dynamic Data Envelopment Analysis (DEA) –a linear-programming framework for the period-oriented computation of relative efficiency scores for a set of multiple similar entities [10]– in combination with ESM and LCA for the sustainability-oriented prioritisation of energy scenarios. The choice of dynamic DEA enhances other valuable practices in MCDA of prospective energy scenarios – e.g. for EU energy policy scenarios [11] and power generation scenarios in Tunisia [12] and Brazil [13]– by avoiding a static evaluation of energy scenarios. In other words, beyond the final picture of the energy system (e.g., in the year 2050), its transformation path over the period of analysis is considered in the prioritisation exercise [14].

While the combined use of LCA, ESM and dynamic DEA has already been proven to be a valuable tool for sustainability-oriented energy planning through a case study of power generation in Spain [14], the effect of the implementation of externalities (environmental external costs) on the prioritisation outcome has not yet been addressed. Since the internalisation of socio-environmental external costs in ESM could significantly affect prospective sustainability results [15], a detailed analysis of its influence on the prioritisation process should be conducted. Within this context, this article aims to assess the potential role of externalities in the prioritisation of prospective energy scenarios by (i) enlarging the methodological framework proposed in [14] through the inclusion of externalities calculation in addition to LCA, ESM and dynamic DEA (Section 2), and (ii) applying the novel, extended framework to the set of power generation scenarios in [14], thereby allowing the analysis of the influence of the externalities on the sustainability-oriented prioritisation of energy scenarios (Section 4). Thus, the case study of power generation in Spain was used herein to prove the feasibility of the novel methodological framework, which is of general use to thoroughly prioritise prospective energy scenarios.

2. Methodological framework

Previous studies addressed the internalisation of external costs in energy systems models to support energy plans and policies. For instance, Munksgaard and Ramskov [16] assessed the consequences of internalising externalities in an electricity market model of the Nordic countries. Kudelko [17] internalised the externalities of electricity production in Poland through a partial equilibrium model, concluding great improvements in social welfare. Klaasen and Riahi [18] examined the global effects of internalising the external costs related to SO_2, NO_x and particulates from power generation using a combined energy systems and macroeconomic model. Rentizelas and Georgakellos [19] performed a deep analysis of the life-cycle external costs of power generation technologies for the strategic decision of future electricity production mixes in Greece for the years 2012-2050, showing that the consideration of externalities leads to changes in the ranking order of cost-competitiveness of the energy sources. More recently, Rečka and Ščasný [20] carried out a detailed integration of the external costs associated with the use of brown-coal power in the Czech Republic using a TIMES model. Overall, these and other studies such as [5] focus on the consequences of internalising external costs on the long-term prioritisation of electricity production mixes. On the other hand, as a novel step forward, this article focuses on the influence of internalising external costs on the prioritisation of prospective energy scenarios. In other words, the focus is moved from energy production mixes to energy scenarios as the entities to be prioritised. In this sense, taking into account current initiatives in the integration of energy scenarios and LCA [21], the novel combination of ESM, LCA, externalities calculation and MCDA to prioritise prospective energy scenarios constitutes the cornerstone of this work.

As shown in Fig. 1, a novel methodological framework based on the combined use of LCA (Section 2.1), externalities calculation (Section 2.2), ESM (Section 2.3) and dynamic DEA (Section 2.4) was developed for the sustainability-oriented prioritisation of prospective energy scenarios. When compared to the methodological framework in Martín-Gamboa et al. [14], the main novelty lies in the consideration of external costs internalised in an updated version of the energy systems model. Thus, this work addresses the following research question: does the internalisation of environmental externalities affect the prioritisation of energy scenarios? This was explored by applying the novel framework to the same case study presented in [14], which consists of 15 prospective energy scenarios for power generation in Spain (Table 1). Regardless of the geographical scope of the study, answering this research question is relevant to a wide range of general actors such as energy systems analysts and decision-makers, especially energy policy-makers.

[**Fig. 1.** Methodological framework for the sustainability-oriented prioritisation of prospective energy scenarios based on life cycle assessment, externalities calculation, energy systems modelling, and dynamic data envelopment analysis]

Despite the need in Spain for addressing both the future gap of coal and nuclear power plants and the integration of sustainability aspects into prospective analyses [22], there is not a comprehensive energy strategy for power generation at the national level including sustainability indicators with a long-term perspective (2050 horizon). Hence, in addition to a business-as-usual (BaU) scenario, other 14 independent energy scenarios were used herein based on the three following topics of interest: lifetime extension of coal power plants, lifetime extension of nuclear power plants, and implementation of CO_2 capture technology. While the choice of this specific set of scenarios is in line with [14], alternative sets could be explored to address these and other issues affecting energy planning in Spain. “Coal extension” scenarios were assumed to affect 37% (3,560 MW) of the coal-based installed capacity in 2015 [23], with the remaining coal power plants being shut down by 2023. Two options of lifetime extension were considered: 10 years and 20 years. On the other hand, "nuclear extension" scenarios were assumed to affect ca. 60% of the nuclear-based installed capacity in 2015, also exploring two extension options (10 and 20 years). Finally, "fossil CCS" scenarios consider the mandatory installation of CO_2 capture systems in new fossil-based power plants from 2030, while "NGCC retrofit with CCS" scenarios consider the mandatory retrofit of existing natural gas combined cycle (NGCC) power plants with CO_2 capture systems by 2030.

[**Table 1.** List of energy scenarios for power generation in Spain according to Martín-Gamboa et al. [14]]

2.1. Life Cycle Assessment component

The standardised LCA methodology was used with two purposes: (i) to provide life-cycle indicators of power generation technologies for subsequent endogenous integration into the energy systems model; and (ii) to provide the inventory of life-cycle emissions for the calculation of power generation technologies' externalities.

It should be noted that the LCA studies of the power generation technologies involved in the current and future Spanish electricity production mix correspond to those already available in García-Gusano et al. [24]. In other words, the life-cycle indicators of each power generation technology were directly retrieved from [24]. These LCAs were carried out for a functional unit of 1 MWh of electricity produced (at plant) using SimaPro [25] and evaluating three damage categories according to the IMPACT 2002+ method [26]. These damage categories are climate change (CC, expressed in kg CO_2 eq), human health (HH, expressed in disability-adjusted life years, DALY), and resources (in MJ). Further details can be found in [24].

The analysis of the evolution of the life-cycle indicators of the power generation sector in each scenario (Section 3) can be classified as a prospective LCA relying on attributional LCA studies of each power generation technology. While the use of ESM enhances the analysis through a sound identification of the evolved electricity production mix [27], a pure consequential LCA of the power generation system is neither intended nor achieved [24]. It should also be noted that the distinction between current and future power generation technologies according to [24] partly mitigates the limitations associated with the use of constant inventories (not modified based on learning curves –e.g. [28,29]– and prospective energy mixes) and background databases.

2.2. Calculation of externalities

The calculation of externalities is limited to the climate change-related external costs of the power generation technologies involved in the current and future electricity production mix. It should be noted that the climate change external costs of the power generation technologies were updated from García-Gusano et al. [5] by using the industrial price index [30]. Therefore, they were calculated using the CASES project database [31] and the life-cycle emissions inventoried in the LCA study of each power generation technology. Table 2 presents the resulting climate change external costs. It is worth noting that, since externalities calculation requires the previous computation of life-cycle emissions, the abovementioned limitations and concerns on the LCA component (e.g., use of constant inventories) also apply to the calculation of externalities.

[**Table 2.** Climate change-related external costs of power generation technologies in Spain (€/MWh)]

2.3. Energy Systems Modelling component

The analysis of the evolution of performance indicators in each scenario is possible thanks to the use of an energy systems model in which techno-economic and life-cycle indicators are endogenously integrated. In particular, the Spanish power generation model reported in García-Gusano et al. [24] was used, but updated with historical data until 2019 for electricity production [32] and installed capacity [33], as well as with the capital costs reported in Table 3 [34-36]. Furthermore, the model was enriched through the internalisation of the climate change external costs gathered in Table 2 as well as through the implementation of the 15 energy scenarios listed in Table 1. This energy systems model is based on the Long-range Energy Alternatives Planning System modelling framework [37] coupled with the OSeMOSYS optimisation module [38]. The time horizon was set at 2050, with the period 2010-2019 based on historical values and 2020 as the first modelling year. The optimisation problem refers to the minimisation of the total system's costs associated with the technologies involved subject to a set of constraints regarding the inherent behaviour of the technologies, policy requirements, etc. [24]. Hence, the objective function consists of a sum of costs (investment costs, variable and fixed costs, fuel costs, external costs, etc.) to be minimised using a simplex algorithm and GLPK solver [14]. When running the scenarios to solve the optimisation problem, the computation time was below 5 minutes (Intel(R) Core(TM) i5-6300U CPU @ 2.40 GHz 2.50 GHz 8.00 GB RAM). Further details on the technical features of the original model and the endogenous integration of life-cycle indicators into the model (ESM and LCA soft-linking) can be found in [24], while further information on the internalisation of externalities can be found in [5].

[**Table 3.** Update of investment costs of power generation technologies in the Spanish power generation model (€/MW)]

The independent scenarios considered in this study were defined according to Martín-Gamboa et al. [14], thus involving a BaU scenario and a number of modifications of it. In this regard, it should be noted that neither the BaU scenario nor its modifications include a deep consideration of storage options in the model (beyond pumped hydroelectric energy storage and storage in solar thermal plants) despite flexibility issues on highly renewable systems [39]. This is due to the lack of a reference roadmap for the implementation of storage options in Spain, which is an incipient topic to be addressed in future versions of the national energy systems model used in this study [40].

Regarding the consideration of scenarios focused on 100% renewability in the power generation sector in 2050, as detailed later in Section 3, it should also be noted that most of the scenarios already considered (Table 1) would lead to high renewability, with some of them exceeding 97% and one of them reaching practically 100% renewability.

Finally, it is acknowledged that –even though the additional use of other energy tools is out of the scope of the study–, it could certainly enrich the analysis. As observed in Connolly et al. [41], there is no energy tool that addresses all issues related to e.g. the integration of renewables into the power generation sector (or into further integrated energy systems [42]), and the choice of the most appropriate energy tool is ultimately dependent on the specific objectives of the study. For instance, energy tools handling higher time resolution could be explicitly used to complement the study [43], e.g. in an hourly-resolution analysis [44].

2.4. Dynamic Data Envelopment Analysis component

A dynamic DEA model was used as MCDA tool due to its suitability for the prioritisation of prospective energy scenarios according to their performance over an extended period of time [4]. The analysis involves 15 independent energy scenarios (or decision-making units, DMUs, in DEA terminology) and 7 specific years (2020, 2025, 2030, 2035, 2040, 2045, and 2050). For every time term, each scenario was characterised by three DEA inputs (the life-cycle indicators: CC, HH, and resources) and one DEA output (electricity production). The input-oriented dynamic slacks-based measure of efficiency model with constant returns to scale (DSBM-I-CRS) was the specific DEA model used, as formulated in [10]. For the use of this model, power generation capacity was selected as a discretionary (free) carry-over [45]. In comparison with the MCDA study in [14], the present work involves a new DEA matrix due to changes in the prospective performance indicators as a consequence of both the update of the energy systems model and the internalisation of climate change externalities, as further explored in Section 3.

The main results from the resolution of the dynamic DEA problem (computation time below 1 minute) are both term-efficiency scores (i.e., the relative efficiency of each scenario for a specific time term) and the overall efficiency score (i.e., the comparative efficiency of each scenario taking into account all time terms). The latter can be understood as sustainability indices and lead to discriminate between efficient ($\Phi = 1$) and inefficient ($\Phi < 1$) scenarios. In this sense, it should be noted that best-performing scenarios are identified among the set of scenarios considered. In other words, this identification is inherently conditioned by the specific sample of DMUs. Moreover, the overall efficiency scores obtained herein for each scenario with internalisation of climate change externalities could be compared with the default ranking without externalities to elucidate the influence of environmental (climate change) externalities on the sustainability-oriented prioritisation of prospective energy scenarios.

3. Scenario analysis

While LCA results of power generation technologies are readily available in García-Gusano et al. [24], the results of this article focus on (i) the evolution of the selected performance indicators in the 15 scenarios with internalisation of externalities (Section 3), and (ii) the ranking of these energy scenarios according to overall relative efficiency scores (Section 4.1). In particular, this section addresses the evolution of both conventional (i.e., electricity production and power generation capacity) and unconventional (i.e., CC, HH, and resources) performance indicators as a result of the ESM exercise with internalisation of environmental externalities and endogenous integration of life-cycle indicators. The results without internalisation of externalities are included as Supplementary Material and constitute an update of those in [14].

Table 4 presents the evolution of the power generation capacity in each scenario. A general trend towards annual increases was identified until 2030, with a relatively stagnant behaviour thereafter. When comparing the different scenarios by period, coefficients of variation below 3% were always found. Additionally, prospective electricity production mixes are shown in Fig. 2 and 3. Overall, the transformation path of the power generation sector was found to be clearly led by renewable technologies in the mid and long term. In particular, wind and solar power plants were generally identified as key actors. Regarding total system costs, Fig. 4 shows –for each scenario and year– their relative change associated with the implementation of externalities in the optimisation model. As expected, the internalisation of externalities was found to result in an increase in the total system cost for every scenario and year. In general, this increase gradually falls as the use of low-carbon power generation technologies increases.

[**Table 4.** Evolution of the generation capacity (GW) per scenario and period when internalising climate change external costs]

[**Fig. 2.** Evolution of the electricity production mix when internalising climate change external costs: scenarios Sc1-9]

[**Fig. 3.** Evolution of the electricity production mix when internalising climate change external costs: scenarios Sc10-15]

[**Fig. 4.** Relative change in total system cost per scenario and year when internalising climate change external costs (relative change with respect to the scenarios without externalities)]

The evolution of the selected life-cycle indicators in each prospective energy scenario is presented in Tables 5-7. Overall, a significant improvement from the current to the mid/long-term life-cycle profile was observed, which is in line with the growing role of renewables. It is worth noting that, given the life-cycle approach followed in the study (i.e., inclusion of direct and indirect burdens), zero impact values should not be expected in spite of the high long-term renewability achieved in the scenarios assessed, which also applies to 100% renewable scenarios. In terms of CC, the most unfavourable values were found for those scenarios considering coal extension or NGCC retrofit, whereas the scenarios with restrictions on the installation of new fossil-based capacity seem to be associated with the lowest CC impacts. Similarly, the most important HH concerns were also linked to coal extension scenarios, which is in accordance with previous findings on the inappropriateness of coal-based prospective energy scenarios [46]. Finally, regarding the resources indicator, the most unfavourable values were found for nuclear extension scenarios, while the most favourable ones were associated with scenarios with restrictions on the installation of new fossil-based capacity.

[**Table 5.** Evolution of the climate change indicator (Mt CO_2 eq) per scenario and period when internalising climate change external costs]

[**Table 6.** Evolution of the human health impact (thousands of DALY) per scenario and period when internalising climate change external costs]

[**Table 7.** Evolution of the resources indicator (PJ primary) per scenario and period when internalising climate change external costs]

When compared to the results from scenarios without internalisation of climate change externalities in the energy systems model (Supplementary Material), the choice of internalisation was found to be often linked to a moderately higher penetration of wind power and a significantly lower climate change impact in the medium-to-long term for every scenario.

4. Further results and discussion

4.1. Ranking of energy scenarios

The main results from the DEA exercise include term-efficiency scores for each scenario and time term (Table 8) and the overall relative efficiency scores of each scenario (Fig. 5). The term-efficiency scores in Table 8 show that only two scenarios (Sc10 and Sc12) were found to be fully efficient over the whole period of analysis. Furthermore, these results highlight the convenience of taking into account the whole picture –i.e. the complete transformation path from 2020 to 2050– rather than the single picture of the final year of assessment (2050). For instance, the scenarios Sc3, Sc7 and Sc9 might involve a relatively good performance in 2050, whereas low term-efficiencies were found in previous years (e.g., in 2035 and 2040).

[**Table 8.** Term-efficiency scores (%) of the prospective energy scenarios when internalising climate change external costs]

The overall efficiency scores allowed the sustainability-oriented ranking of the set of energy scenarios as shown in Fig. 5. Three scenarios (viz., Sc10, Sc11, and Sc12) were found to involve an overall efficiency above 99%. Interestingly, these best-performing scenarios involve a restriction on the installation of new fossil-based capacity. Despite the formulation of these "fossil CCS" scenarios (Section 2), their suitability was found to be linked to an increased installation of renewable power plants rather than to an increased installation of CO_2 capture systems. The remaining scenarios were found to involve an overall efficiency below 90%, with the lowest scores found for the scenarios considering coal long-extension or NGCC retrofit.

[**Fig. 5.** Overall efficiency of the prospective energy scenarios when internalising climate change external costs]

When compared to the prioritisation study without consideration of externalities (Supplementary Material), Fig. 6 shows that the internalisation of climate change externalities leads to moderate changes in the ranking of energy scenarios. In particular, the ranking with internalisation of externalities shows a higher penalty on the scenarios addressing NGCC retrofit. Nevertheless, the identification of the best- and worst-performing scenarios was not affected, which is closely linked to the cost-competitiveness achieved by renewable technologies (in particular, wind and solar ones) to date. In fact, the overall recommendation that coal long-extension scenarios should be avoided and scenarios leading to a high penetration of renewable technologies should be supported is drawn both in the default study without externalities and in the study with internalisation of externalities.

[**Fig. 6.** Modification of the original ranking of energy scenarios due to the internalisation of climate change externalities]

4.2. Final remarks

The development of energy policies and plans should be aligned with the Sustainable Development Goals (SDGs) agreed by the United Nations in September 2015 in order to guide the decisions of governments throughout the forthcoming years [47]. However, there is an acknowledged need for tools that assist policy-makers in this task [48]. In this sense, the methodological advances proposed in this study for the sustainability-oriented prioritisation of prospective energy scenarios could contribute to defining energy strategies that actually meet key commitments according to the 2030 Agenda (e.g., affordable and clean energy and responsible production).

Fig. 7 represents the links identified between the proposed methodological advances for sustainability-oriented prioritisation of energy scenarios and a number of SDGs: SDG3 on good health and well-being, SDG7 on affordable and clean energy, SDG8 on decent work and economic growth, SDG11 on sustainable cities and communities, SDG12 on responsible consumption and production, and SDG13 on climate action. The checks in Fig. 7 highlight the role that methodological advances could play in strengthening the link with the above-mentioned SDGs.

As shown in Fig. 7, the strongest links were observed with SDG7 (energy) and SDG13 (climate). In other words, the features of the methodologies involved in this study on the prioritisation of prospective energy scenarios (i.e., ESM, LCA, environmental externalities calculation, and dynamic DEA) make their combined use suitable to facilitate the provision of plans that fit most of the targets related to both the access to affordable and clean energy (SDG7) and climate change mitigation (SDG13) [47]. In particular, ESM contributes to developing robust energy plans from a techno-economic point of view, while the remaining methodologies allow the sound integration of sustainability criteria into the plans in order to promote suitable power generation schemes oriented towards cleaner production and sustainability.

In the case of SDG3 (well-being) and SDG11 (sustainable regions), the usefulness of LCA and externalities calculation to identify clean energy systems leads to strengthen the link with those SDG targets focused on improving quality of life by reducing air pollution [47]. Furthermore, the link with SDG8 (economic growth) and SDG12 (responsible production) refers to specific SDG targets on decoupling economic growth from environmental degradation [47], which could be interpreted as the ability to meet the future energy demand while progressively reducing the use of natural resources and environmental impacts through the implementation of sustainable energy systems. In this regard, within the proposed methodological framework, LCA arises as a robust tool to evaluate energy systems from a sustainability and resource efficiency perspective, which is further enhanced by implementing environmental externalities and DEA.

[**Fig. 7.** Contextualisation of the methodological advances for the sustainability-oriented prioritisation of prospective energy scenarios and the United Nations Sustainable Development Goals (a higher number of checks indicate a harder link with the SDGs by broadening the analysis)]

Finally, it should be noted that the relevance of the outcomes of this research study are not limited to energy actors in Spain, but –beyond energy systems analysts– they are relevant to any decision- or policy-maker considering the development of sensible energy strategies, plans or policies under a scheme of life-cycle impacts and internalised external costs.

5. Conclusions

A novel methodological framework based on the combined use of LCA, externalities calculation, ESM and dynamic DEA was developed for the sustainability-oriented prioritisation of prospective energy scenarios, and applied to the case study of electricity production in Spain in order to shed light on the following research question of general interest: does the internalisation of environmental externalities affect the prioritisation of energy scenarios? Through the case study of prospective power generation scenarios in Spain with time horizon 2050, not only the feasibility and usefulness of the novel framework to quantitatively discriminate between scenarios considering the life-cycle profile of the transformation path of the power generation sector was shown, but also the role that externalities can play in such a prioritisation process. In this regard, the comparison with a default prioritisation without implementation of external costs proved that the internalisation of climate change externalities does affect the ranking of prospective energy scenarios. Nevertheless, in both cases (omission/internalisation of externalities), the main findings in terms of sensible energy planning showed a high level of agreement regarding the rejection of coal long-extension scenarios and the preference for those scenarios leading to a high penetration of renewable technologies. Future works in this field of research could deal with the enrichment of the analysis by integrating into the framework complementary tools that enhance aspects such as energy storage and time resolution in energy modelling, dynamic inventories in life cycle assessment, and uncertainty and weighting in multi-criteria decision analysis.

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Table and figure captions

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Fig. 1. Methodological framework for the sustainability-oriented prioritisation of prospective energy scenarios based on life cycle assessment, externalities calculation, energy systems modelling, and dynamic data envelopment analysis.

Fig. 2. Evolution of the electricity production mix when internalising climate change external costs: scenarios Sc1-9.

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Fig. 5. Overall efficiency of the prospective energy scenarios when internalising climate change external costs.

Fig. 6. Modification of the original ranking of energy scenarios due to the internalisation of climate change externalities.

Fig. 7. Contextualisation of the methodological advances for the sustainability-oriented prioritisation of prospective energy scenarios and the United Nations Sustainable Development Goals (a higher number of checks indicate a harder link with the SDGs by broadening the analysis).

Table 1. List of energy scenarios for power generation in Spain according to Martín-Gamboa et al. [14].

Code	Scenario description
Sc1	Business-as-usual scenario
Sc2	Coal extension scenario (10 years)
Sc3	Coal extension scenario (20 years)
Sc4	Nuclear extension scenario (10 years)
Sc5	Nuclear extension scenario (20 years)
Sc6	Coal extension (10 years) + nuclear extension (10 years) scenario
Sc7	Coal extension (20 years) + nuclear extension (10 years) scenario
Sc8	Coal extension (10 years) + nuclear extension (20 years) scenario
Sc9	Coal extension (20 years) + nuclear extension (20 years) scenario
Sc10	Fossil CCS scenario
Sc11	Fossil CCS + nuclear extension (10 years) scenario
Sc12	Fossil CCS + nuclear extension (20 years) scenario
Sc13	NGCC retrofit with CCS scenario
Sc14	NGCC retrofit with CCS + nuclear extension (10 years) scenario
Sc15	NGCC retrofit with CCS + nuclear extension (20 years) scenario

Table 2. Climate change-related external costs of power generation technologies in Spain (€/MWh).

Power generation technology[a]	Year 2015	Year 2020	Year 2025	Year 2030	Year 2035	Year 2040	Year 2045	Year 2050
Existing coal thermal	36.81	39.85	44.41	47.45	50.60	68.95	90.44	105.76
Existing NGCC	17.21	18.64	20.78	22.21	23.66	32.25	42.29	49.46
Existing cogeneration	19.47	21.06	23.46	25.06	26.75	36.44	47.82	55.90
Existing oil combustion engine	32.59	35.30	39.36	42.06	44.80	61.08	80.10	93.67
Existing nuclear BWR	0.24	0.26	0.29	0.31	0.34	0.46	0.60	0.70
Existing nuclear PWR	0.25	0.28	0.31	0.33	0.35	0.48	0.63	0.73
Existing hydropower – dam	0.18	0.19	0.22	0.23	0.25	0.34	0.44	0.52
Existing hydropower – RoR	0.12	0.13	0.15	0.16	0.17	0.23	0.30	0.36
Existing wind onshore	0.37	0.40	0.45	0.48	0.51	0.70	0.92	1.07
Existing solar PV	1.58	1.71	1.91	2.04	2.17	2.96	3.88	4.54
Existing biomass power	3.16	3.40	3.77	4.01	4.34	5.88	7.74	9.04
Existing waste-to-energy power	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Existing biogas power	3.62	3.92	4.36	4.65	4.98	6.77	8.89	10.39
New NGCC	16.25	17.61	19.63	20.98	22.35	30.47	39.95	46.72
New NGCC with CO_2 capture	8.95	9.69	10.79	11.53	12.30	16.76	21.98	25.70
New cogeneration	16.83	18.23	20.33	21.73	23.14	31.55	41.37	48.38
New wind onshore	0.25	0.27	0.30	0.32	0.34	0.47	0.61	0.72
New wind offshore	0.53	0.57	0.64	0.68	0.73	0.99	1.30	1.52
New solar PV – plant	0.94	1.01	1.13	1.21	1.29	1.75	2.30	2.69
New solar PV – roof	0.76	0.83	0.92	0.99	1.05	1.43	1.88	2.20
New solar thermal (with storage)	1.43	1.54	1.72	1.84	1.96	2.67	3.50	4.10
New solar thermal (without storage)	1.19	1.29	1.44	1.54	1.64	2.23	2.93	3.43
New biomass power	0.12	0.13	0.14	0.14	0.16	0.21	0.29	0.33
New waste-to-energy power	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New biogas power	2.78	2.99	3.32	3.54	3.81	5.17	6.81	7.95
New SOFC	14.20	15.37	17.13	18.30	19.52	26.60	34.90	40.80
New wave power	0.88	0.95	1.06	1.13	1.21	1.64	2.16	2.52
New geothermal power	0.14	0.15	0.16	0.17	0.19	0.25	0.33	0.39

[a] NGCC: natural gas combined cycle; BWR: boiling water reactor; PWR: pressurised water reactor; RoR: run-of-river; PV: photovoltaics; SOFC: solid oxide fuel cells

Table 3. Update of investment costs of power generation technologies in the Spanish power generation model (€/MW).

Power generation technology	**Year 2020**	**Year 2030**	**Year 2040**	**Year 2050**
New coal – integrated gasification combined cycle[a]	-	2540	2220	2180
New coal thermal with CO_2 capture[a]	-	2740	2590	2570
New NGCC with CO_2 capture[a]	-	1390	1310	1280
New hydropower – RoR[a]	3000	2990	2980	2970
New hydropower – dam[a]	3500	3490	3480	3470
New wind onshore[b]	1290	965	880	740
New wind offshore[b]	4690	4490	4330	4140
New solar PV – plant[c]	510	330	250	200
New solar PV – roof[c]	1050	720	550	450
New solar thermal (without storage)[a]	4500	3800	3500	3400
New solar thermal (with storage)[a]	4630	4040	3630	3420
New biomass power[a]	3810	3140	2840	2560
New biogas power[a]	2860	2740	2630	2510
New geothermal power[a]	6600	6190	5950	5720
New wave power[a]	6310	5320	4040	3240
New tidal power[a]	6260	5270	4000	3210

[a] Based on [34]; [b] Based on [35]; [c] Based on [36]

Table 4. Evolution of the generation capacity (GW) per scenario and period when internalising climate change external costs.

DMU code	Year 2020	Year 2025	Year 2030	Year 2035	Year 2040	Year 2045	Year 2050
Sc1	114.29	133.60	159.48	160.57	154.92	156.18	161.83
Sc2	115.21	132.85	159.39	164.00	158.52	159.76	164.46
Sc3	115.21	132.85	159.98	159.42	153.72	159.92	164.59
Sc4	114.29	133.60	157.22	157.88	154.99	156.23	161.86
Sc5	114.29	133.60	159.16	157.19	150.54	153.54	162.28
Sc6	115.21	132.85	157.11	161.32	158.60	159.82	164.52
Sc7	115.21	132.85	157.56	156.50	153.89	160.07	164.72
Sc8	115.21	132.85	157.57	160.61	154.14	157.28	164.92
Sc9	115.21	132.85	158.61	155.17	150.55	157.69	165.25
Sc10	114.31	133.02	160.58	161.01	155.77	156.99	162.50
Sc11	114.31	133.65	158.16	157.76	155.79	156.98	162.52
Sc12	114.31	133.18	158.54	156.73	151.43	154.55	163.12
Sc13	114.05	132.45	150.81	160.17	161.12	165.22	170.75
Sc14	114.05	132.45	146.48	153.12	161.41	165.22	170.75
Sc15	114.05	132.45	146.48	149.97	160.96	163.13	170.92

Table 5. Evolution of the climate change indicator (Mt CO_2 eq) per scenario and period when internalising climate change external costs.

DMU code	Year 2020	Year 2025	Year 2030	Year 2035	Year 2040	Year 2045	Year 2050
Sc1	49.93	33.12	28.44	19.37	10.78	10.69	11.93
Sc2	49.93	49.30	43.47	19.33	10.81	10.70	11.93
Sc3	49.93	49.30	43.36	40.21	25.53	11.02	12.30
Sc4	49.93	33.12	28.41	19.19	10.86	10.74	11.98
Sc5	49.93	33.12	28.34	19.01	9.29	9.99	13.29
Sc6	49.93	49.30	43.43	19.14	10.97	10.79	12.04
Sc7	49.93	49.30	43.30	39.19	26.14	11.29	12.52
Sc8	49.93	49.30	43.34	18.97	9.31	9.86	13.35
Sc9	49.93	49.30	43.27	38.91	23.75	9.67	14.48
Sc10	49.78	31.19	23.64	14.24	7.83	7.94	9.10
Sc11	49.78	31.14	23.55	13.64	7.85	7.95	9.13
Sc12	49.78	31.11	23.30	13.26	6.82	7.36	9.76
Sc13	50.02	33.20	32.32	29.18	24.64	19.85	18.74
Sc14	50.02	33.20	32.25	28.86	24.67	19.85	18.74
Sc15	50.02	33.20	32.25	28.29	21.74	19.13	19.75

Table 6. Evolution of the human health impact (thousands of DALY) per scenario and period when internalising climate change external costs.

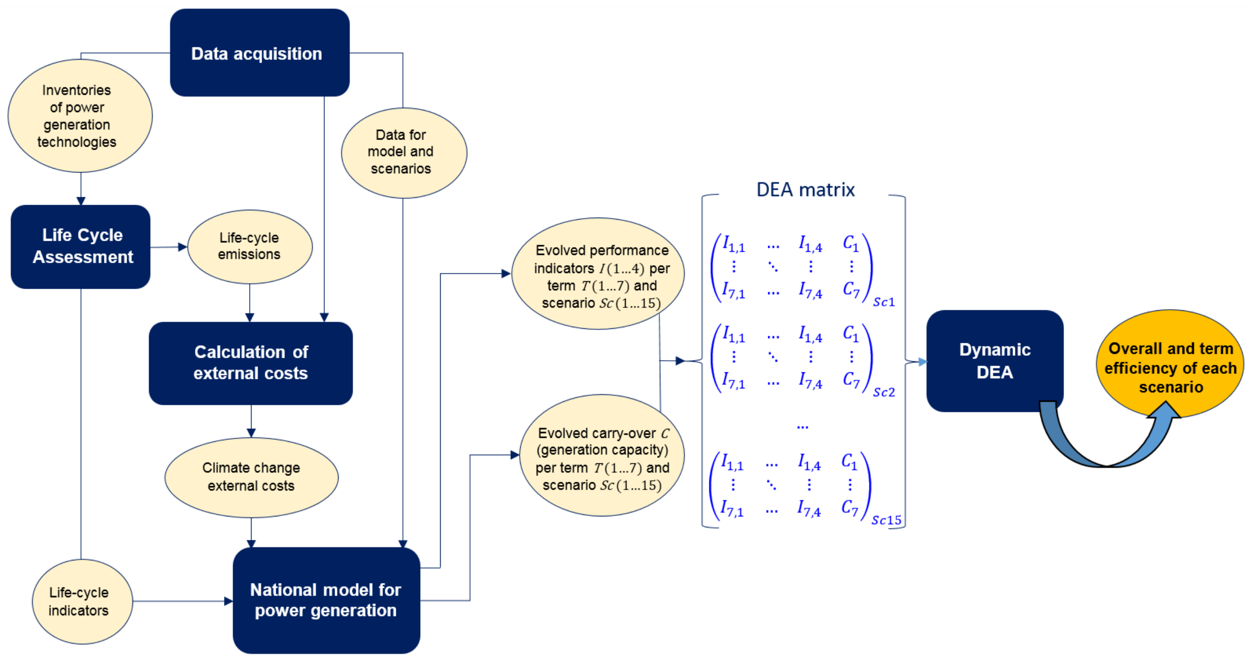
DMU code	**Year 2020**	**Year 2025**	**Year 2030**	**Year 2035**	**Year 2040**	**Year 2045**	**Year 2050**
Sc1	14.61	11.30	9.37	6.76	5.20	5.39	5.98
Sc2	14.61	33.09	30.85	6.73	5.20	5.40	5.98
Sc3	14.61	33.09	30.83	28.96	21.13	5.43	6.01
Sc4	14.61	11.30	9.73	7.62	5.21	5.40	5.98
Sc5	14.61	11.30	9.68	7.90	6.09	6.09	6.08
Sc6	14.61	33.09	31.20	7.58	5.21	5.41	5.99
Sc7	14.61	33.09	31.14	29.78	21.63	5.45	6.03
Sc8	14.61	33.09	31.15	7.88	6.09	6.08	6.08
Sc9	14.61	33.09	31.12	30.00	21.35	6.03	6.17
Sc10	14.90	11.24	9.15	6.41	5.07	5.26	5.82
Sc11	14.90	11.21	9.49	7.16	5.07	5.26	5.83
Sc12	14.90	11.19	9.33	7.37	5.97	5.95	5.92
Sc13	14.82	11.31	10.37	8.17	6.52	6.51	6.77
Sc14	14.82	11.31	10.71	9.12	6.56	6.51	6.77
Sc15	14.82	11.31	10.71	9.39	7.53	7.24	6.85

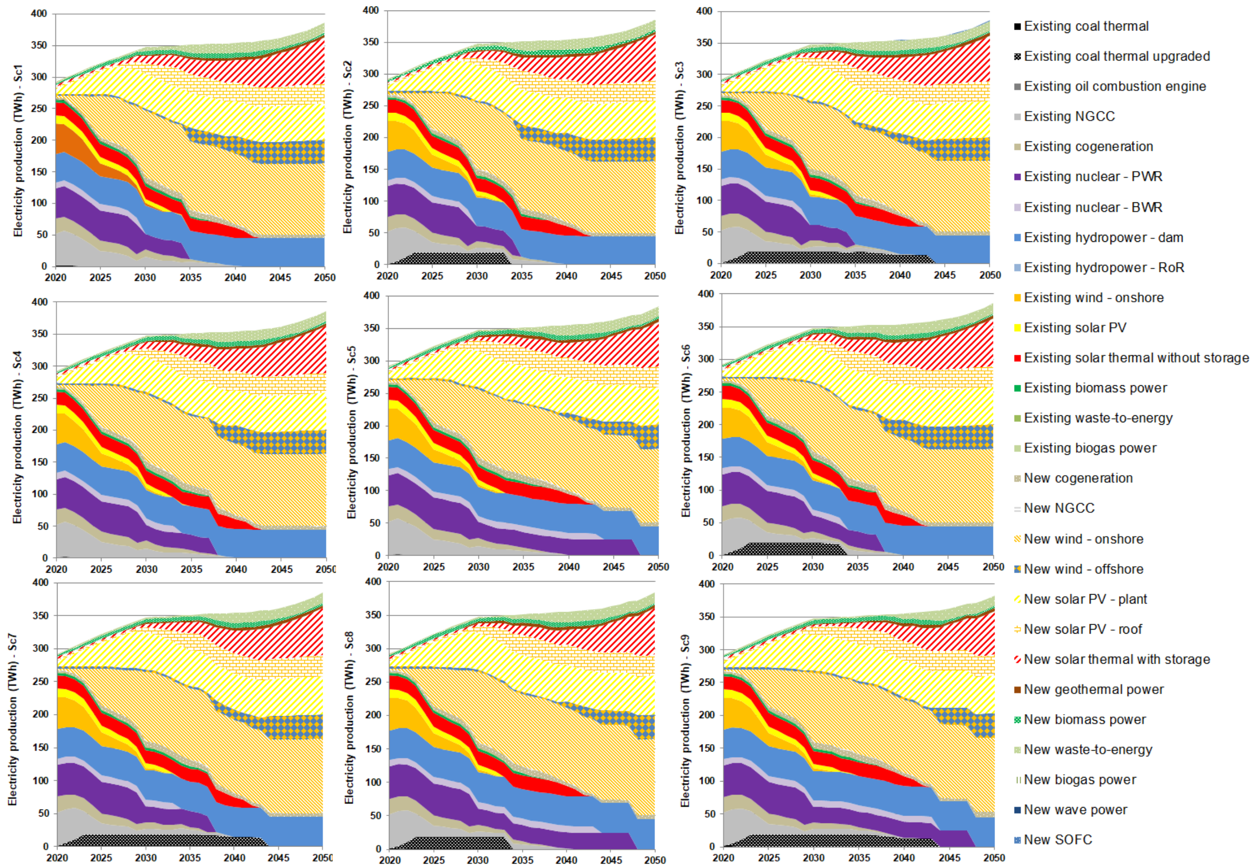
Table 7. Evolution of the resources indicator (PJ primary) per scenario and period when internalising climate change external costs.

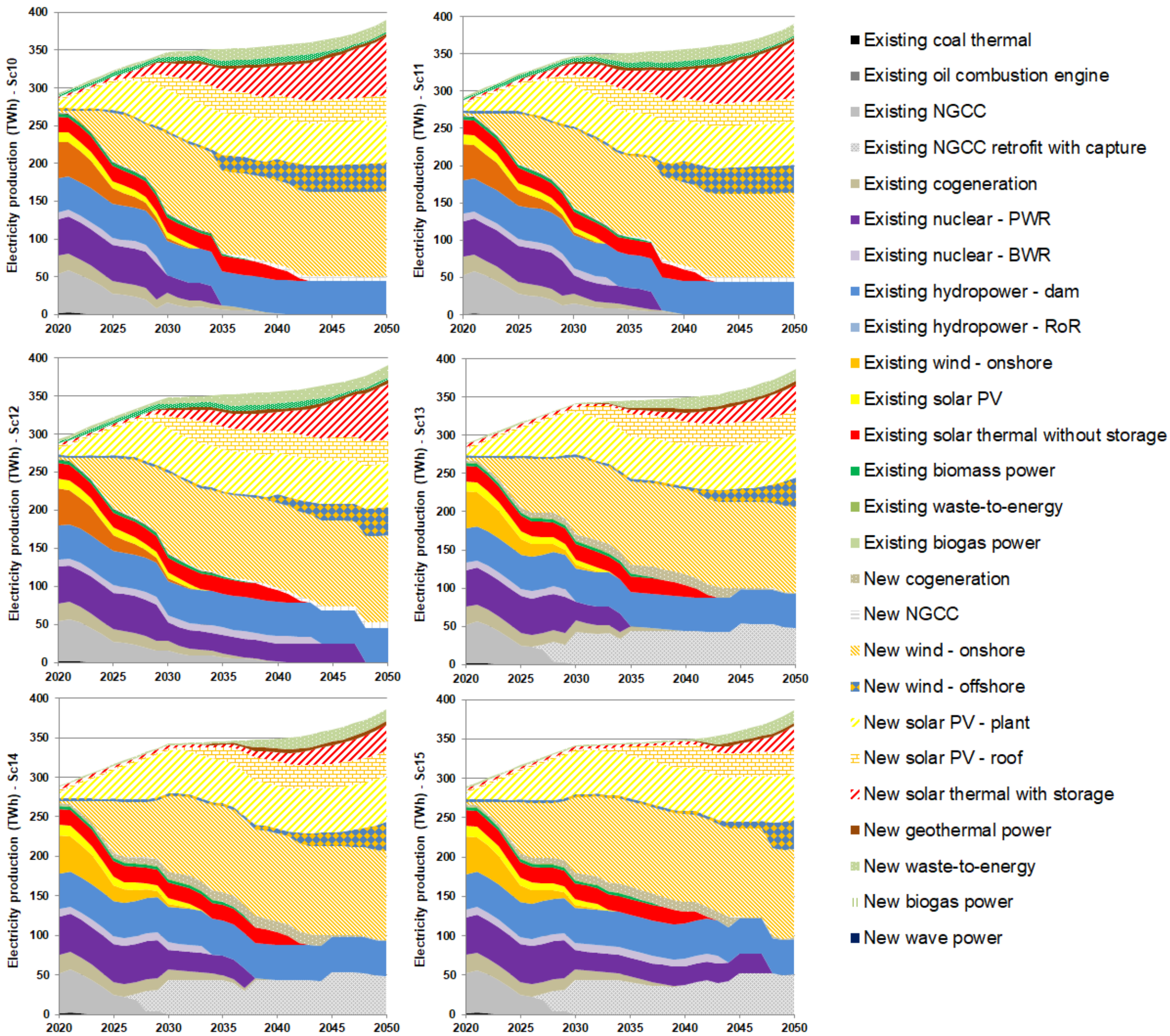
DMU code	**Year 2020**	**Year 2025**	**Year 2030**	**Year 2035**	**Year 2040**	**Year 2045**	**Year 2050**
Sc1	1572.63	1293.26	796.83	341.60	209.76	214.93	245.57
Sc2	1572.63	1413.26	897.24	340.53	210.31	215.21	245.70
Sc3	1572.63	1413.26	894.94	541.68	346.75	224.91	255.86
Sc4	1572.63	1293.26	917.14	641.80	212.00	216.41	247.21
Sc5	1572.63	1293.26	915.01	758.78	598.06	502.56	281.95
Sc6	1572.63	1413.26	1016.68	640.50	214.53	217.82	248.97
Sc7	1572.63	1413.26	1014.30	827.40	356.05	232.51	262.47
Sc8	1572.63	1413.26	1014.63	757.96	598.48	499.62	283.16
Sc9	1572.63	1413.26	1013.74	942.51	740.49	495.15	314.02
Sc10	1568.31	1265.03	716.92	264.13	175.75	182.96	209.90
Sc11	1568.31	1263.93	836.33	549.86	176.06	183.06	211.37
Sc12	1568.31	1263.24	830.80	662.18	569.91	471.43	244.50
Sc13	1573.37	1297.06	1176.61	825.37	754.09	737.55	675.69
Sc14	1573.37	1297.06	1296.58	1120.74	754.60	737.50	675.69
Sc15	1573.37	1297.06	1296.58	1219.26	1077.97	1020.93	716.94

Table 8. Term-efficiency scores (%) of the prospective energy scenarios when internalising climate change external costs.

DMU code	Year 2020	Year 2025	Year 2030	Year 2035	Year 2040	Year 2045	Year 2050
Sc1	100.00	97.14	90.23	81.87	84.64	85.63	86.39
Sc2	100.00	62.25	54.65	82.16	84.50	85.56	86.35
Sc3	100.00	62.25	54.77	35.44	35.12	83.40	84.29
Sc4	100.00	97.14	85.14	66.49	84.13	85.29	86.06
Sc5	100.00	97.14	85.44	63.59	65.64	67.42	79.55
Sc6	100.00	62.25	51.43	66.73	83.52	84.94	85.70
Sc7	100.00	62.25	51.55	29.93	34.25	81.84	83.08
Sc8	100.00	62.25	51.53	63.75	65.59	67.89	79.33
Sc9	100.00	62.25	51.59	28.66	26.82	68.74	74.69
Sc10	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Sc11	100.00	99.87	97.11	96.89	99.97	99.93	99.63
Sc12	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Sc13	99.47	96.94	74.09	53.06	44.28	48.53	55.22
Sc14	99.47	96.94	71.34	47.71	44.12	48.53	55.22
Sc15	99.47	96.94	71.34	46.75	39.90	44.02	53.45


Data acquisition
Inventories of power generation technologies
Data for model and scenarios
Life Cycle Assessment
Life-cycle emissions
Calculation of external costs
Climate change external costs
Life-cycle indicators
National model for power generation
Evolved performance indicators $I(1\ldots4)$ per term $T(1\ldots7)$ and scenario $Sc(1\ldots15)$
Evolved carry-over C (generation capacity) per term $T(1\ldots7)$ and scenario $Sc(1\ldots15)$
DEA matrix
Dynamic DEA
Overall and term efficiency of each scenario


Electricity production (TWh) - Sc1
Electricity production (TWh) - Sc2
Electricity production (TWh) - Sc3
Electricity production (TWh) - Sc4
Electricity production (TWh) - Sc5
Electricity production (TWh) - Sc6
Electricity production (TWh) - Sc7
Electricity production (TWh) - Sc8
Electricity production (TWh) - Sc9
Existing coal thermal
Existing coal thermal upgraded
Existing oil combustion engine
Existing NGCC
Existing cogeneration
Existing nuclear - PWR
Existing nuclear - BWR
Existing hydropower - dam
Existing hydropower - RoR
Existing wind - onshore
Existing solar PV
Existing solar thermal without storage
Existing biomass power
Existing waste-to-energy
Existing biogas power
New cogeneration
New NGCC
New wind - onshore
New wind - offshore
New solar PV - plant
New solar PV - roof
New solar thermal with storage
New geothermal power
New biomass power
New waste-to-energy
New biogas power
New wave power
New SOFC


Electricity production (TWh) - Sc10
Electricity production (TWh) - Sc11
Electricity production (TWh) - Sc12
Electricity production (TWh) - Sc13
Electricity production (TWh) - Sc14
Electricity production (TWh) - Sc15
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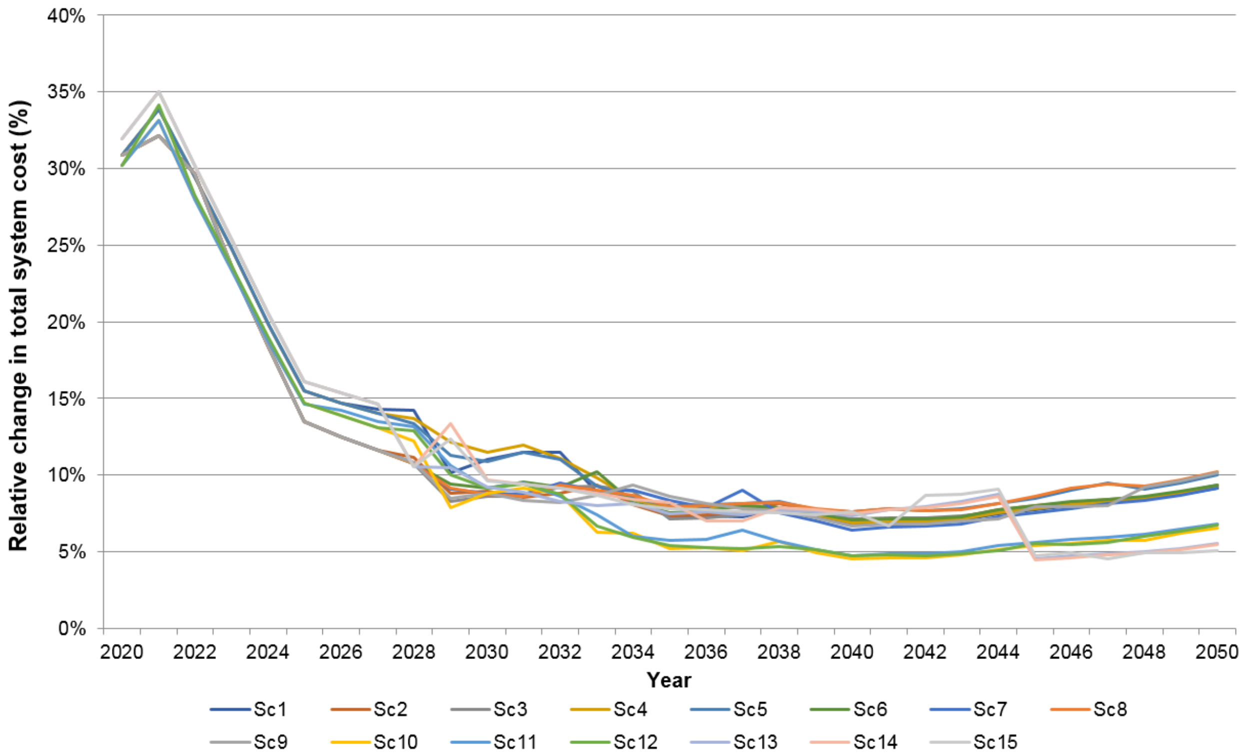
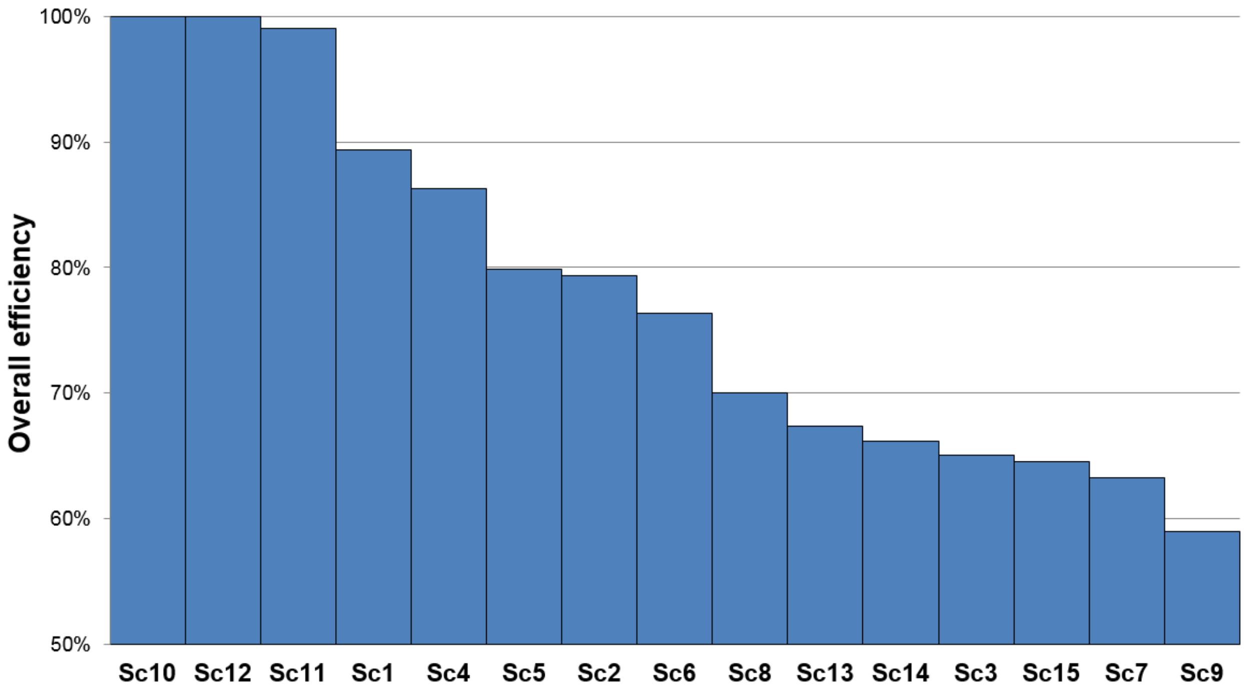
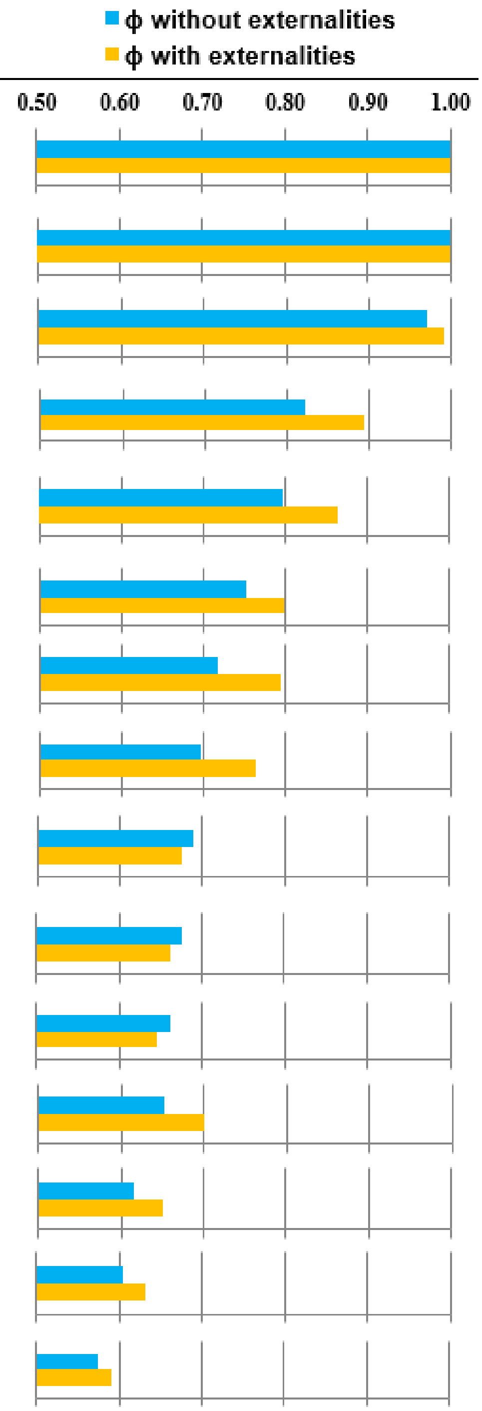
Existing coal thermal
Existing oil combustion engine
Existing NGCC
Existing NGCC retrofit with capture
Existing cogeneration
Existing nuclear - PWR
Existing nuclear - BWR
Existing hydropower - dam
Existing hydropower - RoR
Existing wind - onshore
Existing solar PV
Existing solar thermal without storage
Existing biomass power
Existing waste-to-energy
Existing biogas power
New cogeneration
New NGCC
New wind - onshore
New wind - offshore
New solar PV - plant
New solar PV - roof
New solar thermal with storage
New geothermal power
New waste-to-energy
New biogas power
New wave power

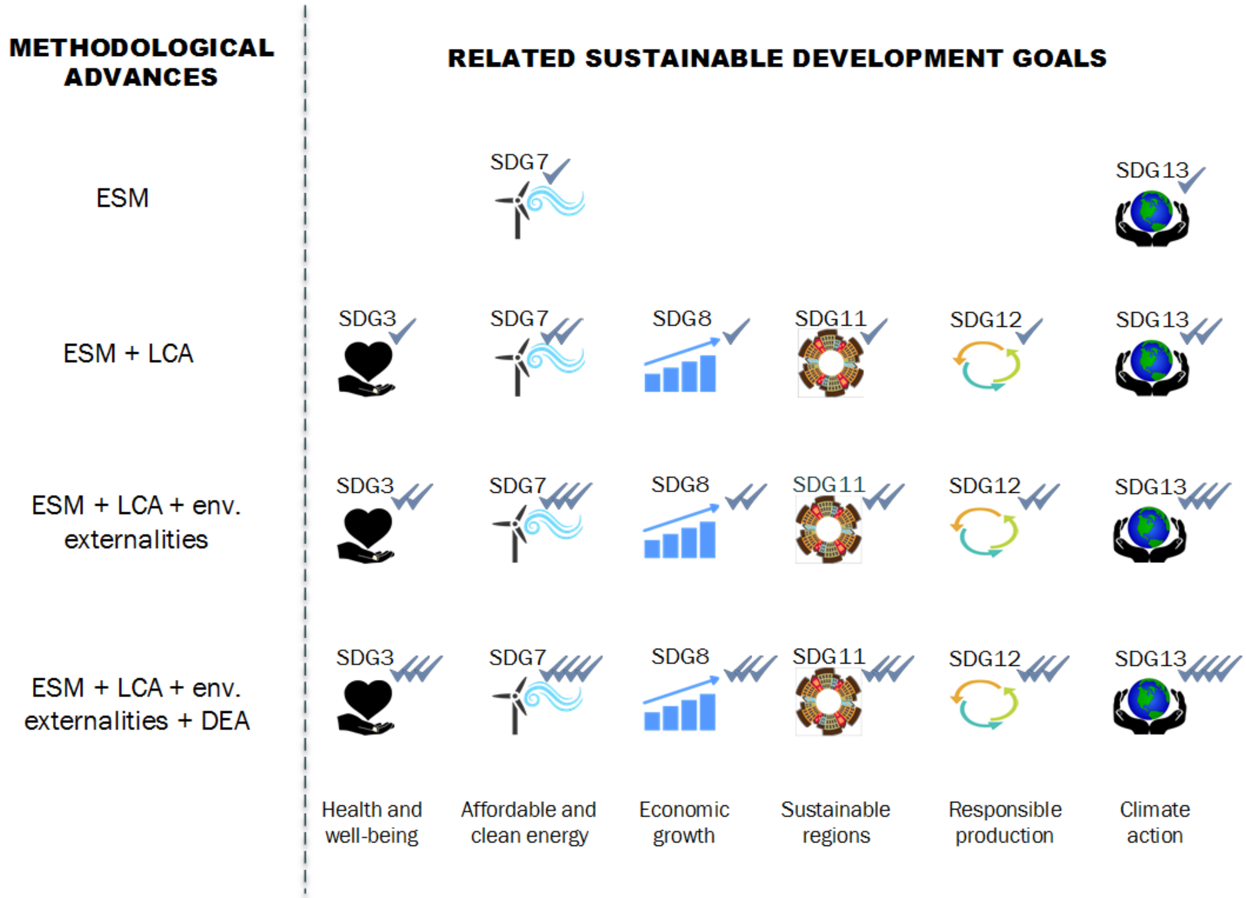


40%
35%
30%
25%
20%
15%
10%
5%
0%
Relative change in total system cost (%)
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
Year
Sc1
Sc2
Sc3
Sc4
Sc5
Sc6
Sc7
Sc8
Sc9
Sc10
Sc11
Sc12
Sc13
Sc14
Sc15


100%
90%
80%
70%
60%
50%
Overall efficiency
Sc10
Sc12
Sc11
Sc1
Sc4
Sc5
Sc2
Sc6
Sc8
Sc13
Sc14
Sc3
Sc15
Sc7
Sc9

Default position (without externalities)	Scenario	New position (with externalities)
1	Sc10	=
2	Sc12	=
3	Sc11	=
4	Sc1	=
5	Sc4	=
6	Sc5	=
7	Sc2	=
8	Sc6	=
9	Sc13	- 1
10	Sc14	- 1
11	Sc15	- 2
12	Sc8	+ 3
13	Sc3	+ 1
14	Sc7	=
15	Sc9	=




METHODOLOGICAL ADVANCES
RELATED SUSTAINABLE DEVELOPMENT GOALS
ESM
ESM + LCA
ESM + LCA + env. externalities
ESM + LCA + env. externalities + DEA
SDG3
SDG7
SDG8
SDG11
SDG12
SDG13
Health and well-being
Affordable and clean energy
Economic growth
Sustainable regions
Responsible production
Climate action

Influence of climate change externalities on the sustainability-oriented prioritisation of prospective energy scenarios

Diego Iribarren, Mario Martín-Gamboa, Zaira Navas-Anguita, Diego García-Gusano, Javier Dufour

Research highlights

- ✓ Energy modelling enriched with climate change externalities and life-cycle indicators
- ✓ Dynamic data envelopment analysis to prioritise prospective energy scenarios
- ✓ Case study of 15 prospective scenarios for power generation in Spain
- ✓ Ranking of scenarios moderately affected by climate change external costs
- ✓ Preference for scenarios leading to high penetration of renewables

Influence of climate change externalities on the sustainability-oriented prioritisation of prospective energy scenarios

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Conflict of Interest

The authors declare no conflict of interest.