Prospective Assessment of the Carbon Footprint of a National Power Generation System

Zaira Navas-Anguita, Diego García-Gusano and Diego Iribarren

Abstract The global energy system is typically associated with severe environmental concerns, especially in terms of greenhouse gas emissions. In this regard, the transition to a low-carbon economy requires clean energy solutions for both the electricity and the transport sector. This chapter focuses on the prospective assessment of the carbon footprint of a national power generation system by combining life-cycle assessment (LCA) and energy systems modelling (ESM). Long-term energy planning is facilitated by considering not only a business-as-usual scenario, but also a number of alternative energy scenarios oriented towards (i) the extended operation of non-renewable power generation technologies, (ii) the implementation of novel energy policies on CO_2 capture, energy security and externalities, and (iii) cross-sectoral issues such as the deployment of electric vehicles. Through the case study of the Spanish power generation sector, the convenience of promoting the evolution to highly renewable electricity production mixes is shown.

1 Introduction

Nowadays, climate change is one of the main sustainability concerns from a global perspective. It usually refers to the negative consequences of the greenhouse gas emissions released from the different economic sectors. In this sense, it is important to set new policies and targets in order to mitigate climate change in the following years, which is especially relevant to the energy sector. In fact, the power generation and transport sectors account for around 25 and 14% of the global greenhouse gas emissions, respectively (IPCC 2014).

In Spain, the climate change context is similar. Regarding the power generation sector, 61% of the electricity produced in Spain is non-renewable, whereas the

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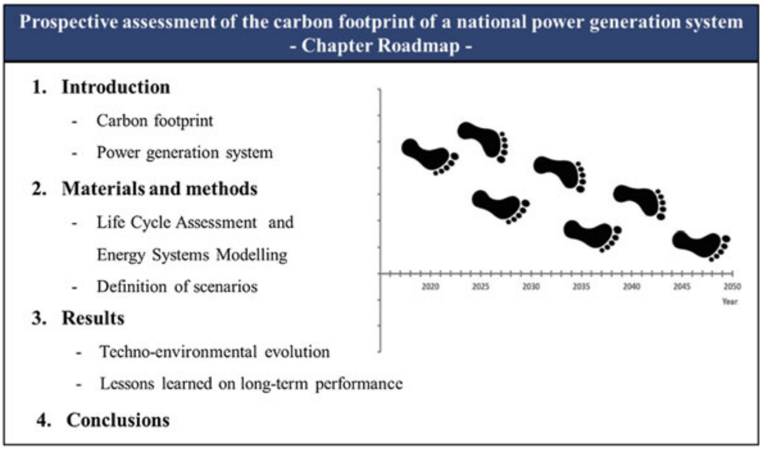

Fig. 1 Structure of the chapter

remaining 39% comes from renewable sources (REE 2019). Actually, the contribution of renewable sources to the Spanish electricity production mix has grown considerably during the last decades. Nevertheless, the electricity demand is expected to be higher in the future, thus being necessary to evaluate the technologies that could satisfy such a growing demand. Moreover, the transport sector should move from a fossil-based system (mainly diesel and gasoline) to a non-fossil-based one with a high share of alternative fuels and vehicles, e.g. electric vehicles (EV), which add an electricity demand to the power generation system.

When planning power generation systems from a long-term perspective, not only techno-economic aspects should be considered, but also socio-environmental issues. In particular, the environmental impact of the electricity produced should be taken into account through the implementation of life-cycle indicators in the power generation model (García-Gusano et al. 2016a). Among the indicators quantified through the life-cycle assessment (LCA) methodology (ISO 2006a, b), the most common one is the global warming impact or carbon footprint (CF). Within this context, this chapter focuses on the prospective assessment of the carbon footprint of the Spanish generation system under alternative scenarios. Figure 1 shows the roadmap of the chapter.

2 Materials and Methods

The goal of this chapter is to prospectively assess the carbon footprint of a national power generation system not only under a business-as-usual (BaU) scenario, but also under alternative energy scenarios oriented towards (i) the extended operation of non-renewable power generation technologies, (ii) the implementation of novel energy policies on CO_2 capture, energy security and externalities, and (iii) cross-sectoral issues such as EV deployment. Emphasis is laid on the evolution of the power generation technology mix as well as on the corresponding evolution of the system's carbon footprint. This is done by applying a combined Energy Systems Modelling (ESM) and LCA approach (Sect. 2.1) through the case study of Spain—a country characterised by a wide-ranging portfolio of power generation technologies—under a varied set of scenarios (Sect. 2.2).

2.1 The ESM + LCA Approach

The numerous ESM tools to assist decision-makers in developing energy plans involve different approaches in terms of interest, procedure, rationale, and method. For instance, it is possible to distinguish between simulation and optimisation models. The former are based on the connections between parameters and variables of technologies and commodities (fuels, materials, emissions), while the latter involve a more powerful calculation based on the minimisation of system costs. Thus, simulation-based models are usually oriented towards backcasting, whereas optimisation-based models are appropriate tools for forecasting. In between, there is a wide range of strategic combinations with the aim of answering "what if" questions, testing new measures, policies and/or technologies, or just exploring the relevance of key drivers in terms of demand or emission reductions.

According to Pfenninger et al. (2014), a key issue in energy systems models refers to scale, understanding in depth the dimensions of time and space. These authors established a three-level scale of decision-making interest. Accordingly, long-term energy planning is associated with low spatial and temporal resolution while providing a perspective oriented towards social aspects of energy systems. In this respect, it is frequently observed that most of the ESM tools focus only on techno-economic optimisation or accounting balances, considering energy flows and economic equilibrium. Environmental aspects are secondary in most energy systems models, if not neglected. In fact, the only environmental consideration usually consists in including the emission factors associated with the activity of the technologies and/or the use of fuels.

Hence, there is a need to broaden the scope of ESM by implementing a thorough sustainability perspective based on robust indicators. In this regard, the combined use of ESM and LCA—a methodology for the comprehensive evaluation of the environmental performance of product systems (ISO 2006a)—arises as a potential solution. For instance, the goal of the NEEDS project (www.needs-project.org) was to evaluate the full—direct and external—costs and benefits of energy policies and future energy systems. Assuming the availability of an optimisation-based energy systems model (e.g. MARKAL/TIMES models), the strategy followed in NEEDS pursued the internalisation of environmental parameters by including extra costs within the objective function to be minimised. Under this paradigm, the concept of externalities was used to deeply include the environmental dimension within the core of energy systems models. This requires externalities monetisation. The ExternE methodology (www.externe.info/externe_d7) was used to obtain the costs associated with the damages (to human health and environment) from electricity production technologies in European countries.

A key concern is the complexity linked to the combination of different areas of expertise: ESM (energy modellers, policy-makers), LCA (environmentalists, chemical engineers), and ExternE (environmental economists, sociologists, epidemiologists). These areas involve different approaches, entities, and rationales since they were conceived for different purposes. Hence, the idea of including in-depth LCA within the kernel of ESM before monetising damages could be a convenient research line. Assuming ESM as the starting point giving the opportunity to perform prospective analyses via techno-economic optimisation, a focus is placed on the (as deep as possible) integration of LCA into ESM. In principle, it would be possible to evaluate prospectively the environmental performance of life-cycle indicators through their robust integration into an energy systems model. However, there are some hurdles such as methodological inconsistencies, differences in temporal and spatial limits, and nomenclature dissimilarities.

The first works talking about the importance of mixing energy models and environmental methodologies appeared in the late 90s of the twentieth century. For instance, Wene (1996) discussed the need for soft-linking in ESM, while later Ekvall (2002) concluded the importance of mixing methodologies in order to broaden the field of LCA. Kypreos et al. (2008) described the main methodological advances behind NEEDS, and Pietrapertosa et al. (2009, 2010) applied these advances to the TIMES-Italy model. Pieragostini et al. (2012) discussed modelling approaches, concluding that the combination of LCA and ESM means an opportunity in the field of energy modelling.

In the field of power generation, Stamford and Azapagic (2014) carried out a prospective LCA of the UK electricity production mix pre-assuming future energy scenarios. Treyer et al. (2014) performed a similar study for the future EU mix but evaluating different life-cycle indicators. Other studies show a higher level of detail regarding the ESM component. For instance, Portugal-Pereira et al. (2016) performed an LCA of the electricity production mix in Brazil by means of a MESSAGE-based model with some indicators partly integrated. Recently, Volkart et al. (2017) developed an LCA study in connection with a TIMES-based model of the Swiss electricity sector, enriching the final results through multi-criteria decision analysis.

A singular advance in the combined field of ESM + LCA refers to the endogenous integration of life-cycle indicators into energy systems models. In this respect, García-Gusano et al. (2016a) endogenously integrated three life-cycle indicators (viz., climate change, human health, and ecosystem quality) into the TIMES-Norway model. This allowed a prospective analysis of the life-cycle performance of power generation in Norway.

In addition to TIMES-based models, alternative ESM frameworks have already been used in ESM + LCA studies. In particular, García-Gusano et al. (2016b) developed a LEAP-OSeMOSYS model of power generation in Spain endogenously integrating three life-cycle indicators (climate change, human health, and resources).

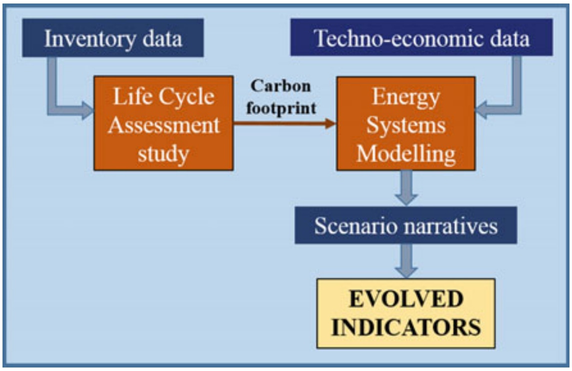

Fig. 2 ESM + LCA methodological approach

Figure 2 shows the methodological approach followed by the authors, herein adapted to the needs of the study carried out in this chapter. A key and time-consuming task in ESM + LCA studies is data acquisition. In this regard, it is necessary to collect a large number of techno-economic and life-cycle inventory data of each technology involved in the energy systems model. These data are endogenously implemented in the model, thereby enabling the analysis of the evolution of aspects such as the technology mix and the system's carbon footprint under different scenarios.

2.2 Energy Scenarios

The model of the Spanish power generation system detailed in García-Gusano et al. (2016b) is used in this chapter to prospectively assess the system's carbon footprint under several scenarios. The first one is the BaU or reference scenario, while the other five scenarios include alternative specifications regarding the retirement of non-renewable technologies, the implementation of novel policies for the power generation sector, and cross-sectoral issues. With the aim of assessing the environmental suitability of each alternative scenario, the study is based on the difference between a given alternative scenario and the reference (BaU) one in terms of the "evolved" share of renewable technologies and the "evolved" carbon footprint of the power generation system. The main specifications implemented in the model to define the alternative scenarios are explained in Sects. 2.2.1–2.2.3.

2.2.1 Retirement of Non-Renewable Technologies

The contribution of renewable energy technologies to the national electricity production is expected to increase in the coming years. However, nowadays the use of non-renewable sources such as coal and nuclear power is still relevant. In particular, decision- and policy-makers are interested in exploring the role played by coal within the fossil-renewable energy transition. In other words, they are interested in exploring coal extension scenarios. Hence, this chapter includes a "coal extension" scenario considering a 10-year extension for 3560 MW of the existing coal thermal capacity in Spain according to García-Gusano et al. (2018a).

2.2.2 Novel Policies for the Power Generation Sector

In the future, renewable technologies are expected to play the leading role in the Spanish electricity production mix, which would mean a minor role played by non-renewable technologies. Nevertheless, the implementation of CO_2 capture systems (CCS) could significantly affect this prospect by allowing a still significant use of fossil resources. Hence, policy- and decision-makers could be interested in exploring the potential consequences of novel policies forbidding fossil power options unless they include CO_2 capture. In this regard, based on García-Gusano et al. (2016b), the "CO_2 capture scenario" included in this chapter considers that no new fossil capacity installation is allowed beyond 2030 unless CCS options are implemented.

Regarding novel policies for the power generation sector, another relevant point of view could be based on the internalisation of external costs. In this sense, since sustainability is a key component of novel energy policies, the internalisation of externalities could be seen by energy policy-makers as an interesting option to promote a sustainable power generation system. Hence, the "externalities scenario" considers the implementation of the climate change externalities of each power generation technology in the model according to García-Gusano et al. (2018b).

Finally, energy security arises as another key concept concerning novel policies for the power generation sector. In this regard, under an ESM + LCA scheme, García-Gusano et al. (2017a) developed a new energy security indicator—the Renewable Energy Security Index (RESI)—oriented towards policy-makers. Following a life-cycle perspective, RESI measures the importance of indigenous renewable electricity production with respect to the national electricity demand. The use of RESI facilitates setting energy security restrictions that affect the optimisation procedure. In this respect, the "energy security scenario" included in this chapter sets a RESI target above 80% by 2030 according to García-Gusano and Iribarren (2018).

2.2.3 Cross-Sectoral Scenarios

While the harmonised hybridisation of LCA and ESM has mainly been proven in the power generation sector, Navas-Anguita et al. (2018) extended the Spanish power generation model to the road transport system in order to perform the prospective LCA of the increased electricity demand associated with EV penetration in Spain. In this regard, EV penetration arises as a cross-sectoral issue of growing interest to decision- and policy-makers. Figure 3 represents the extension of the methodological approach followed in the EV scenario considered in this chapter. This scenario takes into account a penetration of 14 million EV in Spain in 2050, which approximately

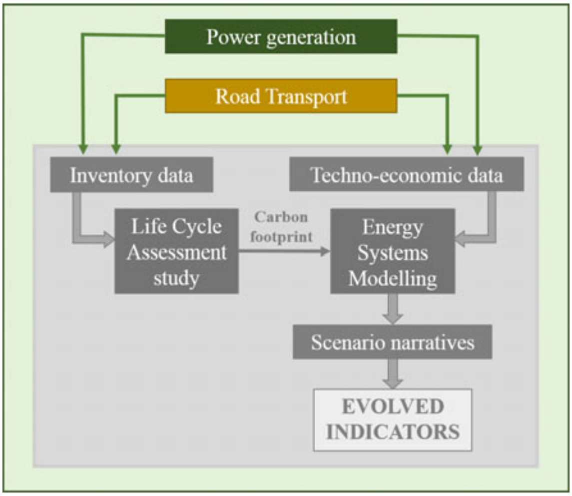

Fig. 3 ESM + LCA methodological approach involving power and transport sectors

means an extra electricity demand of 12.6 TWh (Navas-Anguita et al. 2018). It should be noted that technical issues on EV penetration such as the establishment of complex demand-response schemes within the grid remain out of the scope of this chapter.

Finally, Table 1 summarises the six scenarios assessed in this chapter. The aim of the study is to check the long-term suitability of each alternative scenario by comparing its system's renewability and carbon footprint with respect to the BaU scenario.

3 Results

Three main outcomes are reported in this section: (i) the techno-environmental evolution of the national power generation system under a scenario on the extended use of a non-renewable technology (COAL scenario; Sect. 3.1); (ii) the techno-environmental evolution under three scenarios on novel energy policies (CCS, Ext and RESI scenarios; Sect. 3.2); and (iii) the techno-environmental evolution under a cross-sectoral scenario (EV scenario; Sect. 3.3). Finally, the lessons learned are summarised in Sect. 3.4.

Table 1 List of scenarios under study

Code	Scenario	Description	References
BaU	Business-as-usual	Reference scenario including all current policies	Navas-Anguita et al. (2018)
COAL	Coal extension	10-year extension of existing coal thermal power in Spain	García-Gusano et al. (2018a)
CCS	CO_2 capture	No new fossil capacity installation is allowed beyond 2030 unless CCS options are implemented	García-Gusano et al. (2016b)
Ext	Externalities	Internalisation of climate change externalities	García-Gusano et al. (2018b)
RESI	Energy security	Renewable energy security index target above 80% by 2030	García-Gusano and Iribarren (2018)
EV	Electric vehicle	Increase in the electricity demand due to medium EV penetration (14 million EV in 2050)	Navas-Anguita et al. (2018)

3.1 Techno-Environmental Evolution Under Scenarios on the Retirement of Non-Renewable Technologies

Regarding the potentially extended use of coal power in Spain, Fig. 4 shows the prospective performance of the COAL scenario in terms of the contribution of renewable and non-renewable technologies to the national power generation. As long as coal power plants continue producing electricity, there is no new installation of alternative technologies. Thus, non-renewable electricity production in the COAL scenario increases around 7% during the period 2023–2033 with respect to the BaU scenario (which is also included in Fig. 4 as a reference).

On the other hand, when non-renewable power plants begin to be retired according to their lifespan, the system needs new capacity and production, which is mainly fulfilled by renewable technologies. This leads to a slight increase of approximately 1% in renewable electricity production in the COAL scenario with respect to the BaU scenario until the time horizon (year 2050).

Furthermore, Fig. 5 shows the corresponding evolution of the system's carbon footprint under the COAL scenario. In the period 2020–2033, the coal extension scenario is clearly associated with a significant increase in CF when compared to the BaU scenario. In fact, the COAL scenario involves a 19% increase in the system's CF in 2024. On the other hand, in the long term, a similar CF performance is observed for both the COAL scenario and the BaU one.

It should be noted that the behaviour observed herein for the extension of a specific non-renewable option (i.e. coal power) should not be generalised. For instance, the implementation of extension scenarios for nuclear power in the model has already

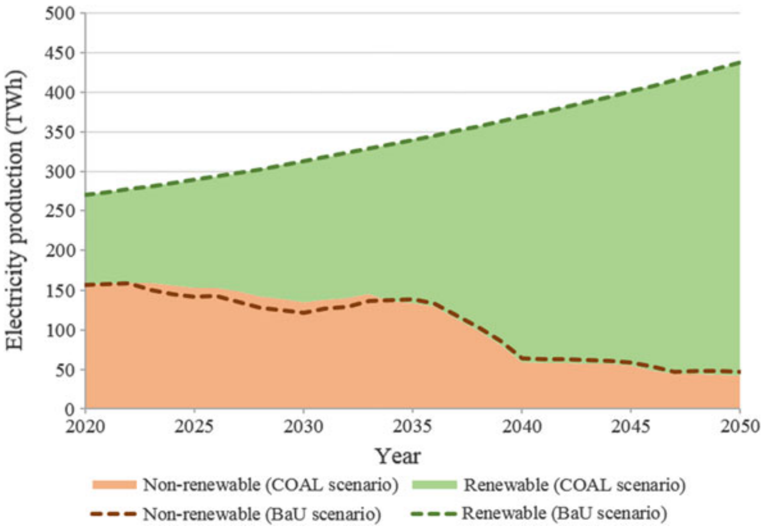

Fig. 4 Scenario "COAL": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2018a)

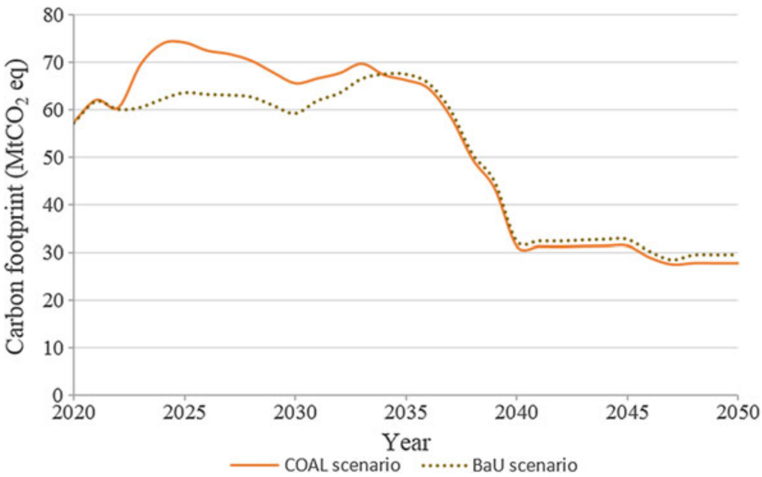

Fig. 5 Scenario "COAL": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2018a)

been reported to lead to opposite findings. In such a case, renewable technologies were found to be eventually favoured, enhancing the prospective CF performance accordingly (García-Gusano et al. 2017b).

3.2 Techno-Environmental Evolution Under Scenarios on Novel Energy Policies

Regarding novel policies potentially promoting CO_2 capture solutions for non-renewable power generation, Fig. 6 shows the results of the CCS scenario in terms of the contribution of renewable and non-renewable technologies to the national electricity production. Interestingly, the results show an average increase of 10% in power generation from renewable technologies—rather than from non-renewable technologies with CO_2 capture—with respect to the BaU scenario in the period 2020–2030, even reaching an average increase of 21% in the period 2030–2040. In this respect, the high investment costs of fossil options with CCS finally lead to a preference for the entrance of renewable energy technologies instead of fossil-based technologies with CCS (García-Gusano et al. 2016b).

Furthermore, Fig. 7 shows how the increase in the contribution of renewable technologies to the national power generation translates into a very significant reduction in the system's carbon footprint with respect to the BaU scenario. On average, CF

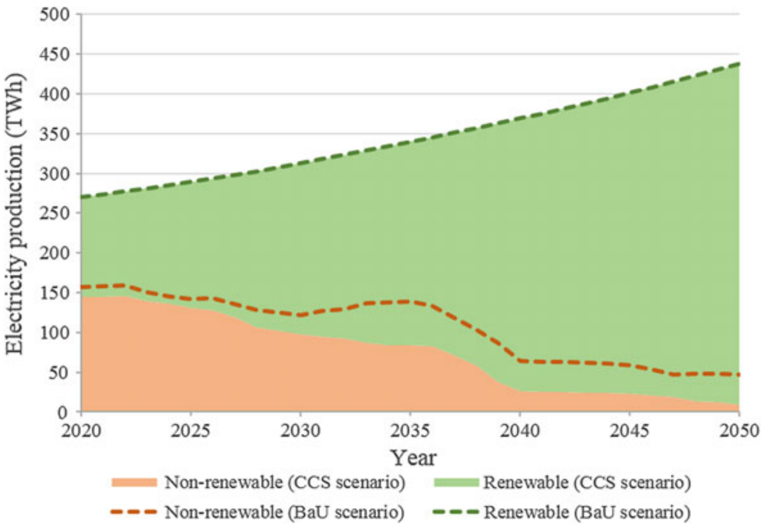

Fig. 6 Scenario "CCS": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2016b)

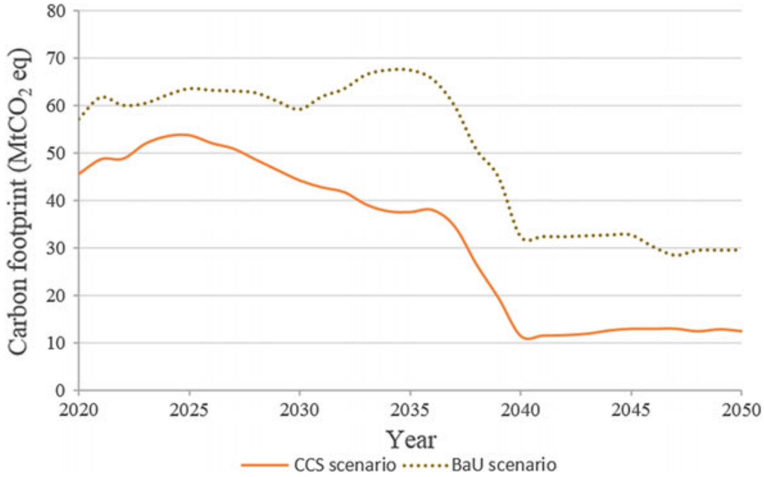

Fig. 7 Scenario "CCS": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2016b)

reductions of 20, 44, and 60% are observed for the periods 2020–2030, 2030–2040, and 2040–2050, respectively.

Regarding the internalisation of external costs as an alternative novel energy policy, Fig. 8 shows the contribution of renewable and non-renewable technologies to the national electricity production when climate change externalities are implemented in the model. As shown in Fig. 8, when compared to the BaU scenario, the internalisation of externalities leads to a faster retirement of non-renewable power plants, which translates into a faster penetration of renewable options. In this regard, average increases of 26 and 13% in renewable power generation are observed in the periods 2020–2040 and 2040–2050, respectively.

Moreover, Fig. 9 shows how the increased share of renewable electricity in the Ext scenario leads to significant reductions in the system's carbon footprint with respect to the BaU scenario. CF reductions in the period 2020–2035 ranges between 30 and 35%, reaching 60% in the period 2035–2050.

Concerning alternative novel policies based on energy security, Fig. 10 shows the contribution of renewable and non-renewable technologies to the national power generation under the RESI scenario. When compared to the BaU scenario, the implementation of a sensible energy security target leads to a faster and higher penetration of renewables. In fact, an increase of 40% in renewable power generation is observed in 2030.

Furthermore, Fig. 11 shows how the increased contribution of renewable technologies results in significant CF reductions with respect to the BaU scenario. Average CF reductions of 55 and 40% are observed in the periods 2030–2040 and 2040–2050, respectively.

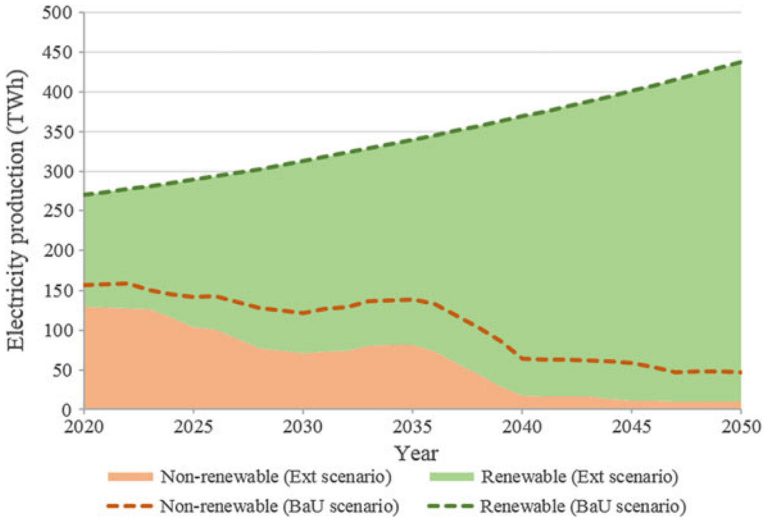

Fig. 8 Scenario “Ext”: evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano et al. (2018b)

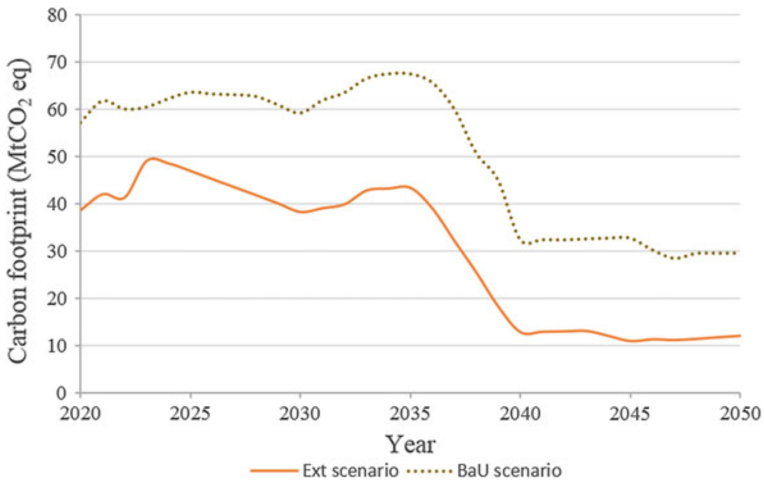

Fig. 9 Scenario “Ext”: evolution of the carbon footprint of the Spanish power generation system based on García-Gusano et al. (2018b)

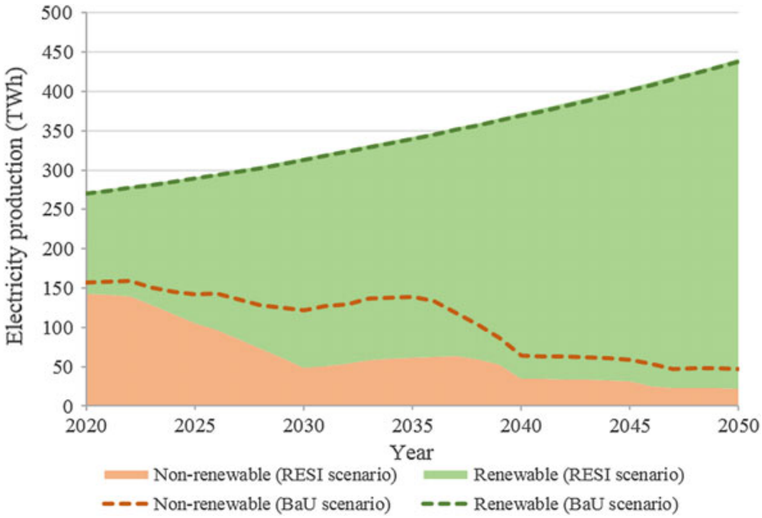

Fig. 10 Scenario "RESI": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to García-Gusano and Iribarren (2018)

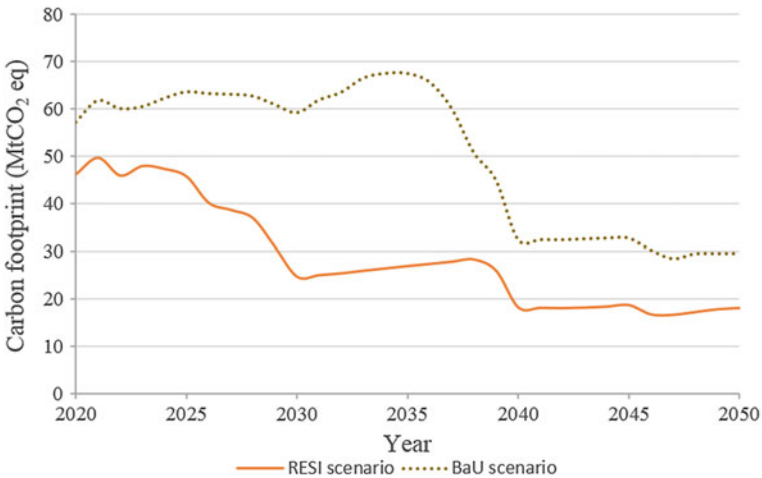

Fig. 11 Scenario "RESI": evolution of the carbon footprint of the Spanish power generation system based on García-Gusano and Iribarren (2018)

Overall, the implementation of novel, sustainability-oriented energy policies in the model is generally found to lead to an increased contribution of renewable technologies to the national electricity production and, as a consequence, to a reduced system's carbon footprint.

3.3 *Techno-Environmental Evolution Under Cross-Sectoral Scenarios*

As a cross-sectoral issue, the consideration of EV penetration in the power generation model (14 million EV in 2050) involves an increased electricity demand with respect to the BaU scenario. In the EV scenario, this extra demand associated with EV penetration means a low percentage of the total electricity demand (<5% for the whole time frame).

As shown in Fig. 12, the additional electricity demand related to EV penetration is fulfilled by renewable technologies. Furthermore, given the relatively low extra demand, Fig. 13 shows that the system's carbon footprint hardly varies in comparison with the BaU scenario.

Hence, the electricity demand associated with the future penetration of electric vehicles in the Spanish road transport system is expected to be mainly satisfied by a slightly increased contribution of renewable technologies to the national electricity production, with negligible effects on the carbon footprint of the power generation

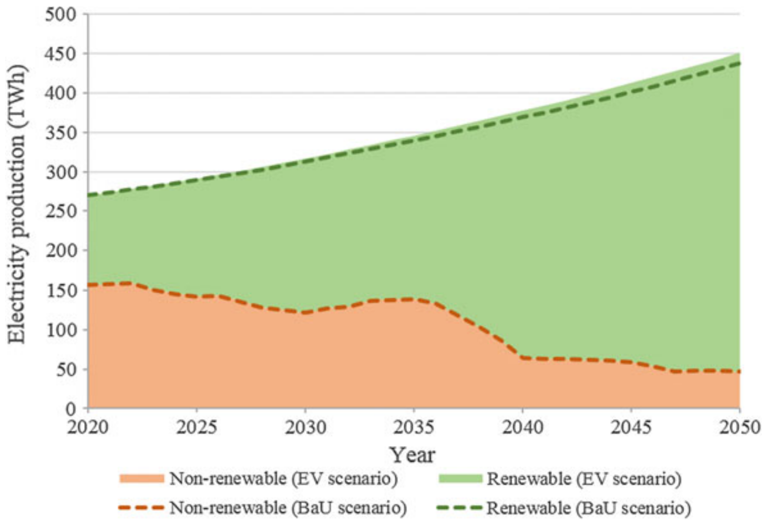

Fig. 12 Scenario "EV": evolution of the role of renewable power generation technologies in the prospective electricity production mix of Spain according to Navas-Anguita et al. (2018)

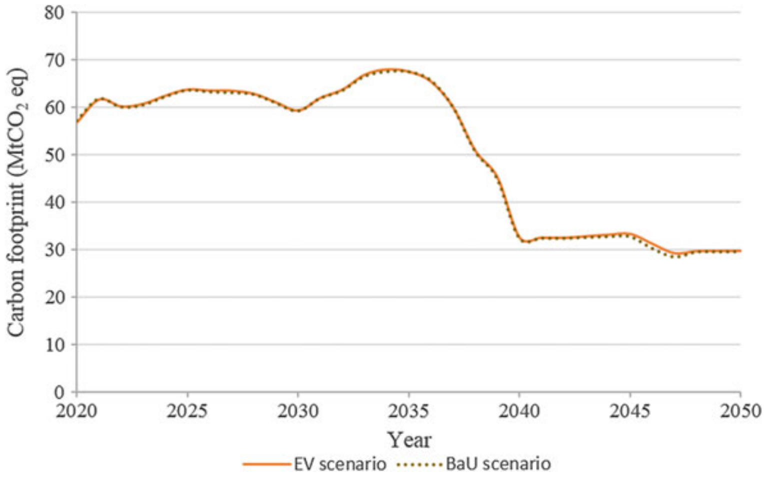

Fig. 13 Scenario "EV": evolution of the carbon footprint of the Spanish power generation system based on Navas-Anguita et al. (2018)

system. Furthermore, according to Navas-Anguita et al. (2018), EV penetration could bring about significant CF benefits within the transport system.

3.4 Lessons Learned

- The prospective assessment of the carbon footprint of the power generation system under alternative scenarios is feasible and can support decision-making processes.
- Extending the use of non-renewable technologies may lead to opposite techno-environmental outcomes depending on the selected option (e.g. coal or nuclear power).
- Coal extension is deemed not to be a sensible option for energy planning in Spain.
- The implementation of novel, sustainability-oriented energy policies generally leads to an increase in the contribution of renewable technologies to the national power generation, as well as to a decrease in the system's carbon footprint.
- When forbidding the installation of new fossil technologies without CO_2 capture, there is a preference for renewable technologies over fossil options with CO_2 capture.
- Policies internalising externalities or setting sensible energy security targets can hasten the retirement of non-renewable power plants, and thus the penetration of renewable options.
- The extra electricity demand associated with the future EV penetration is expected to be satisfied by renewable technologies, with negligible effects on the carbon

footprint of the power generation system but potentially significant CF benefits for the transport system.

Overall, the endogenous integration and prospective assessment of life-cycle indicators into energy systems models has the potential to assist energy policy-makers in performing sensible decision-making processes in the field of long-term energy planning.

4 Conclusions

The synergistic combination of ESM and LCA constitutes a research line of growing interest. The robust integration of life-cycle indicators such as the carbon footprint into energy systems models increases the utility of ESM for decision-making purposes, especially regarding sustainability-oriented energy planning by policy-makers. Nevertheless, it should be noted that the symbiotic story between ESM and LCA is still developing.

Given the current role of the life-cycle global warming impact as a central environmental indicator, prospective carbon footprinting might pave the way for sensible decision- and policy-making processes in the field of energy planning. For instance, through the case study of the Spanish power generation system, this chapter showed the techno-environmental suitability of policies hastening the transition to highly renewable electricity production mixes.

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References

Ekvall T (2002) Cleaner production tools: LCA and beyond. J Clean Prod 10:403–406

García-Gusano D, Iribarren D (2018) Prospective energy security scenarios in Spain: the future role of renewable power generation technologies and climate change implications. Renew Energy 126:202–209

García-Gusano D, Iribarren D, Martín-Gamboa M, Dufour J, Espegren K, Lind A (2016a) Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. J Clean Prod 112:2693–2696

García-Gusano D, Martín-Gamboa M, Iribarren D, Dufour J (2016b) Prospective analysis of life-cycle indicators through endogenous integration into a national power generation model. Resources 5:39

García-Gusano D, Iribarren D, Garraín D (2017a) Prospective analysis of energy security: a practical life-cycle approach focused on renewable power generation and oriented towards policy-makers. Appl Energy 190:891–901

García-Gusano D, Martín-Gamboa M, Iribarren D, Dufour J (2017b) A life-cycle perspective in energy systems modelling: nuclear extension scenarios for Spain. In: 8th international conference on life cycle management, luxembourg

García-Gusano D, Iribarren D, Dufour J (2018a) Is coal extension a sensible option for energy planning? A combined energy systems modelling and life cycle assessment approach. Energy Policy 114:413–421
García-Gusano D, Istrate IR, Iribarren D (2018b) Life-cycle consequences of internalising socio-environmental externalities of power generation. Sci Total Environ 612:386–391
IPCC (2014) Climate change 2014: mitigation of climate change—contribution of working group iii to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
ISO (2006a) ISO 14040:2006 environmental management—Life cycle assessment—principles and framework. International Organization for Standardization, Geneva
ISO (2006b) ISO 14044:2006 environmental management—Life cycle assessment—requirements and guidelines. International Organization for Standardization, Geneva
Kypreos S, Blesl M, Cosmi C, Kanudia A, Loulou R, Smekens K, Salvia M, Van Regemorter D, Cuomo V (2008) TIMES-EU: a pan-european model integrating LCA and external costs. Int J Sustain Dev Plan 3:180–194
Navas-Anguita Z, García-Gusano D, Iribarren D (2018) Prospective life cycle assessment of the increased electricity demand associated with the penetration of electric vehicles in Spain. Energies 11:1185
Pfenninger S, Hawkes A, Keirstead J (2014) Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 33:74–86
Pieragostini C, Mussati MC, Aguirre P (2012) On process optimization considering LCA methodology. J Environ Manage 96:43–54
Pietrapertosa F, Cosmi C, Macchiato M, Salvia M, Cuomo V (2009) Life cycle assessment, ExternE and comprehensive analysis for an integrated evaluation of the environmental impact of anthropogenic activities. Renew Sustain Energy Rev 13:1039–1048
Pietrapertosa F, Cosmi C, Di Leo S, Loperte S, Macchiato M, Salvia M, Cuomo V (2010) Assessment of externalities related to global and local air pollutants with the NEEDS-TIMES Italy model. Renew Sustain Energy Rev 14:404–412
Portugal-Pereira J, Köberle AC, Soria R, Lucena AFP, Szklo A, Schaeffer R (2016) Overlooked impacts of electricity expansion optimisation modelling: the life cycle side of the story. Energy 115:1424–1435
REE (2019) National statistical series—statistical series of the Spanish electricity system. Red Eléctrica de España, Alcobendas
Stamford L, Azapagic A (2014) Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy Sustain Dev 23:194–211
Treyer K, Bauer C, Simons A (2014) Human health impacts in the life cycle of future European electricity generation. Energy Policy 74:S31–S44
Volkart K, Weidmann N, Bauer C, Hirschberg S (2017) Multi-criteria decision analysis of energy system transformation pathways: a case study for Switzerland. Energy Policy 106:155–168
Wene CO (1996) Energy-economy analysis: linking the macroeconomic and systems engineering approaches. Energy 21:809–824