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# Prospective Life Cycle Assessment of the Increased Electricity Demand Associated with the Penetration of Electric Vehicles in Spain

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**Abstract:** The penetration of electric vehicles (EV) seems to be a forthcoming reality in the transport sector worldwide, involving significant increases in electricity demand. However, many countries such as Spain have not yet set binding policy targets in this regard. When compared to a business-as-usual situation, this work evaluates the life-cycle consequences of the increased electricity demand of the Spanish road transport technology mix until 2050. This is done by combining Life Cycle Assessment and Energy Systems Modelling under three alternative scenarios based on the low, medium, or high penetration rate of EV. In all cases, EV deployment is found to involve a relatively small percentage (<4%) of the final electricity demand. Wind power and waste-to-energy plants arise as the main technologies responsible for meeting the increased electricity demand associated with EV penetration. When considering a high market penetration (20 million EV by 2050), the highest annual impacts potentially caused by the additional electricity demand are 0.93 Mt $CO_2$ eq, 0.25 kDALY, and 30.34 PJ in terms of climate change, human health, and resources, respectively. Overall, EV penetration is concluded to slightly affect the national power generation sector, whereas it could dramatically reduce the life-cycle impacts associated with conventional transport.

**Keywords:** climate change; electric vehicle; energy planning; energy systems modelling; human health; life cycle assessment; resources; road transport

## 1. Introduction

Nowadays, the transport sector accounts for a quarter of the global $CO_2$ emissions from fuel combustion. In particular, road transport, which is highly dependent on fossil fuels such as petrol and diesel, represents around 75% of the sectoral emissions [1]. According to a central document from the European Commission setting targets in terms of greenhouse gas (GHG) emission savings with milestones in 2030 and 2050 to decarbonise the energy system [2], GHG emissions associated with the transport sector must decrease between 54% and 67% with respect to the 1990 levels. Since the transport sector has a low share of renewable energy, considerable efforts are required for its transformation [3]. In this sense, alternative transportation fuels should be explored in order to mitigate the climate change impact linked to conventional fuels.

Within this context, the future transportation fuel mix is expected to involve alternative fuels such as natural gas, electricity, hydrogen, and biofuels. In particular, the penetration of electric vehicles (EV) could significantly contribute to achieve the decarbonisation of the transport sector [4]. Spain, as well as other member states of the European Union, is actively involved in the fight against climate change and contemplates EV penetration as a potential energy solution for the road transport sector, even though binding policy targets have not yet been set for Spain. There are several studies in the literature which estimate different penetration rates for EV in Spain, as summarised in Table 1 [5–9].

**Table 1.** Prospective stock of electric vehicles in Spain according to different literature sources.

| Year 2020 | Year 2030 | Year 2040 | Year 2050 | Source |
|---|---|---|---|---|
| - | 3,138,968 | - | - | [5] |
| - | 15,694,842 | - | - | [6] |
| 150,000 | 2,600,000 | - | - | [7] |
| 2,500,000 | 5,000,000 | - | 15,000,000 | [8] |
| 200,000 | 4,400,000 | 8,200,000 | 12,280,000 | [9] |
| 300,000 | 6,000,000 | 15,400,000 | 21,900,000 | [9] |

A massive implementation of EV will have consequences for the electricity production mix due to the need to satisfy an increased electricity demand. In other words, the additional electricity demand associated with EV penetration will be supplied by a set of power generation technologies, leading to modifications in the electricity production mix and thus implications on its sustainability performance. Besides, this deployment will have effects in terms of energy planning regarding capacity expansion, demand projections, peak load requirement, etc. In this regard, the combined use of well-known methodologies such as Energy Systems Modelling (ESM) and Life Cycle Assessment (LCA) [10] seems suitable to evaluate the prospective techno-economic and environmental performance of power generation all at once [11,12]. In the field of ESM + LCA, the benefits associated with an enriched analysis of energy systems should outbalance the current limitations in terms of results accuracy (e.g., lack of hard-linking approaches) and time consumption (e.g., in building energy systems models) [12,13].

Prospective EV penetration is a topic already studied by several authors. For instance, Liu et al. [14] evaluated the variability of the electricity demand under the hypothesis of full penetration of EV in the Scandinavian countries by 2050. Bohnes et al. [15] and Zhang et al. [16] carried out analyses of the environmental impacts resulting from EV deployment in Copenhagen and Beijing, respectively. Höltl et al. [17] analysed several scenarios including the electrification of the car fleet in Europe and its consequences. Within this context, this work addresses a prospective LCA study to evaluate the potential climate change (CC), human health (HH), and resources (Re) impacts of the increased electricity demand associated with EV penetration in Spain. As a novelty, this is done under three alternative scenarios of EV penetration and relying on the endogenous integration of life-cycle indicators into a national energy systems model (Section 2). In addition to the influence of EV penetration on the prospective electricity production mix and its evolution under life-cycle sustainability aspects, the potential environmental benefits linked to the substitution of electricity for conventional fuels are preliminarily assessed (Section 3). Although this study is especially useful for long-term energy planning at the national level, the methodological framework and the results presented are expected to be useful for a wide range of countries and actors facing similar decision- and policy-making concerns.

## 2. Materials and Methods

García-Gusano et al. [18] carried out the endogenous integration of several life-cycle indicators (viz., CC, HH, and Re) into an energy systems model of power generation in Spain based on LEAP-OSeMOSYS. This is an optimisation-based energy systems model that minimises the total system costs. The minimisation of the objective function—a sum of investment costs, fixed and variable costs, fuel costs, etc. of the existing and new electricity production technologies—is subjected to different constraints regarding emission reductions and capacity limits. The energy demand projections are entered exogenously into the model and are based on the behaviour of key socio-economic drivers such as gross domestic product (GDP), energy prices, and population. This type of model usually compares a set of scenarios against a reference case (business-as-usual, BaU).

In [18], the BaU scenario did not take into account EV penetration due to the lack of binding policy targets in this regard. Hence, as shown in Figure 1, this article proposes a framework based on the combined use of ESM and LCA for the analysis of the influence of EV penetration in Spain. In comparison with previous studies [18], the main novelty is the formulation and implementation of three transport-related scenarios for the corresponding prospective analysis of both the electricity production mix and life-cycle sustainability indicators with time horizon 2050. Thus, this work extends that in [18] by implementing three alternative scenarios of EV penetration in addition to the BaU one.

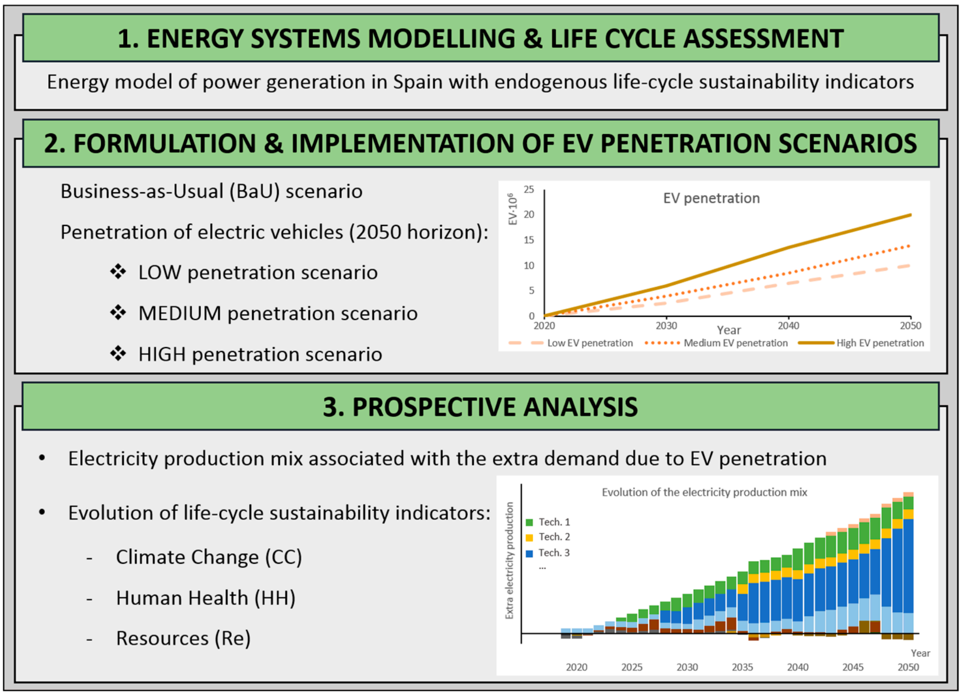


**Figure 1.** Framework for the prospective assessment of electricity production mix and sustainability indicators under alternative scenarios of EV penetration in Spain.

Regarding prospective electricity production mixes, the comparison of the results for the alternative scenarios with those for the BaU scenario allows the identification of the power generation technologies that are expected to satisfy the increased electricity demand of the Spanish road transport sector. According to the original energy systems model of electricity production in Spain [18], the following power generation technologies are included: coal thermal, natural gas combined cycle (NGCC; both with and without $CO_2$ capture), oil combustion engine, cogeneration (natural gas turbine), nuclear (pressurised water reactor –PWR– and boiling water reactor –BWR–, as well as generations III and IV and nuclear fusion), hydropower (dam and run-of-river, RoR), wind (onshore and offshore), solar photovoltaics (PV; both roof and plant), solar thermal (with and without storage), biomass power plants, waste-to-energy plants, biogas power plants, coal-based integrated gasification combined cycle (IGCC), proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), tidal power plants, wave power plants, and new geothermal power plants.

Thanks to the endogenous integration of a set of life-cycle indicators –CC, HH, and Re– into the energy systems optimisation model of power generation in Spain, the results also include the evolution of the cradle-to-gate impacts of the increased electricity demand associated with EV penetration. These life-cycle indicators—which represent quality changes of the environment affecting the ecosystem and/or human beings—are evaluated according to the IMPACT 2002+ method [19].

In order to calculate the extra demand of electricity caused by EV penetration, several vehicle categories are considered along with their corresponding distribution, energy consumption, and average annual mileage, as presented in Table 2. The values in this table are assumed to be constant during the whole time frame.

**Table 2.** Values assumed by vehicle category for the calculation of the extra electricity demand associated with EV penetration.

| Vehicle Category | Distribution [1] (%) | Energy Consumption [2] (kWh/100 km) | Annual Mileage [2] (km) |
|---|---|---|---|
| Motorcycles | 0.65 | 5 | 5000 |
| Cars | 79.74 | 18 | 10,000 |
| Vans | 6.33 | 14 | 10,000 |
| Trucks | 12.21 | 110 | 50,000 |
| Buses | 1.07 | 100 | 70,000 |

[1] Based on [20]; [2] Based on http://www.madrimasd.org/blogs/energiasalternativas/2018/03/02/133739.

Finally, Table 3 quantitatively presents the energy scenarios evaluated in this study. In particular, in addition to the BaU scenario (which is based on [18] with minor updates regarding the historical EV penetration for the period 2011–2015 [7]), three alternative scenarios are formulated according to the EV stock assumed in the road transport sector in Spain in 2020, 2030, 2040, and 2050. The formulation of these alternative scenarios is founded on the targets proposed in the studies included in Table 1. Thus, the scenario LOW is based on a slight penetration of 10 million EV in 2050, which results in an increased electricity demand of 9 TWh. On the other hand, the scenario MEDIUM considers a penetration of 14 million EV in 2050, which leads to an extra electricity demand of 12.6 TWh. Lastly, the scenario HIGH is based on a penetration of 20 million EV in 2050, which translates into an additional electricity demand of 18 TWh. In any case, EV deployment is found to involve a relatively small percentage (<4%) of the final electricity demand.

**Table 3.** Quantitative definition of alternative energy scenarios in Spain.

| | Year 2020 | | Year 2030 | | Year 2040 | | Year 2050 | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Total Electricity (GWh)** | | **Total Electricity (GWh)** | | **Total Electricity (GWh)** | | **Total Electricity (GWh)** | |
| BaU | 269,982 | | 312,688 | | 368,875 | | 437,666 | |
| | **Number of EV** | **Δ Electricity Demand (GWh)** | **Number of EV** | **Δ Electricity Demand (GWh)** | **Number of EV** | **Δ Electricity Demand (GWh)** | **Number of EV** | **Δ Electricity Demand (GWh)** |
| Low EV penetration | 50,000 | 45 | 2,600,000 | 2337 | 6,500,000 | 5842 | 10,000,000 | 8988 |
| Medium EV penetration | 75,000 | 67 | 4,000,000 | 3595 | 8,500,000 | 7640 | 14,000,000 | 12,584 |
| High EV penetration | 100,000 | 90 | 6,000,000 | 5393 | 13,500,000 | 12,134 | 20,000,000 | 17,976 |

## 3. Results and Discussion

Three main outcomes are reported in this section: (i) the evolution of the electricity production mix associated with the increased electricity demand due to EV penetration (Section 3.1); (ii) the corresponding evolution of the CC, Re, and HH impacts of the increased electricity demand (Section 3.2); and (iii) the preliminary estimation of the potential benefits associated with the substitution of conventional transportation fuels (Section 3.3).

### *3.1. Prospective Electricity Production Mix*

Figures 2–4 show the evolution of the electricity production mix that is expected to satisfy the additional electricity demand from the Spanish road transport sector in each EV penetration scenario. These figures refer to the difference between the results for each alternative scenario and those for the BaU scenario in terms of electricity production by power generation technology. Nevertheless, the evolution of the Spanish electricity production mix in the BaU scenario is detailed in the appendix (Figure A1).

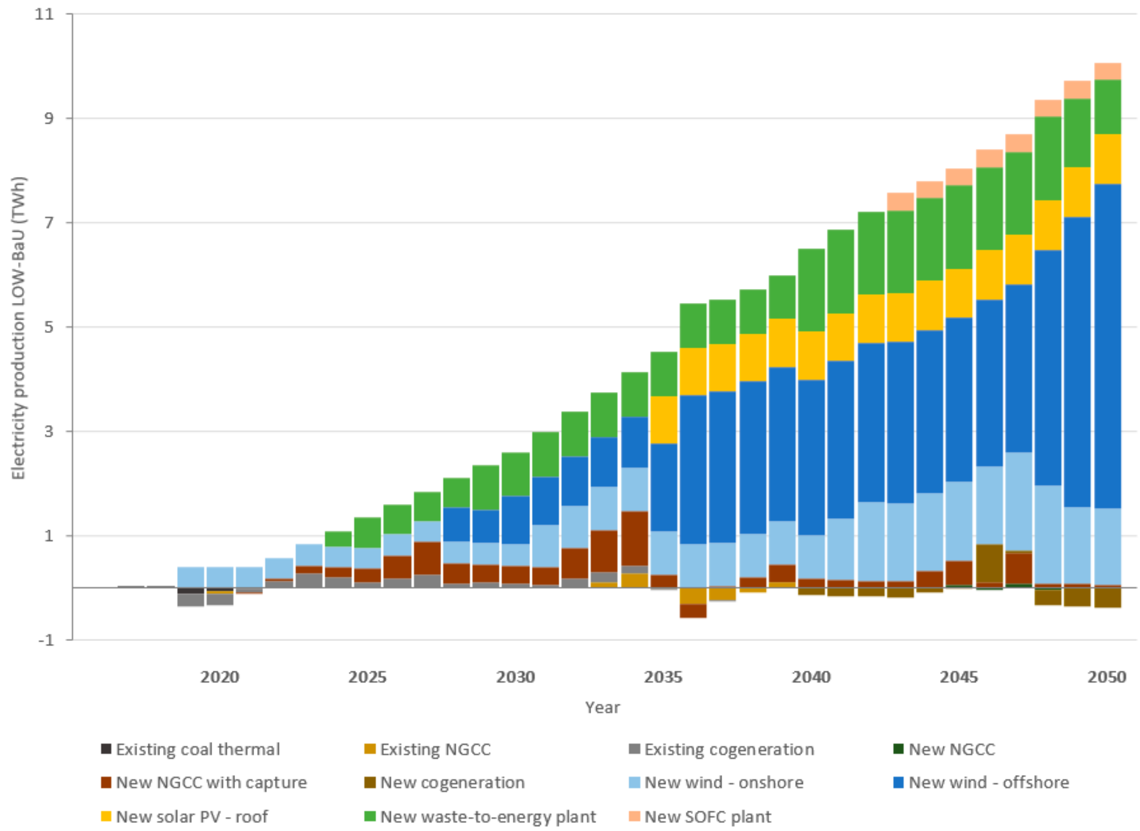


**Figure 2.** Evolution of the electricity production mix to satisfy the extra electricity demand due to EV penetration in the scenario LOW.

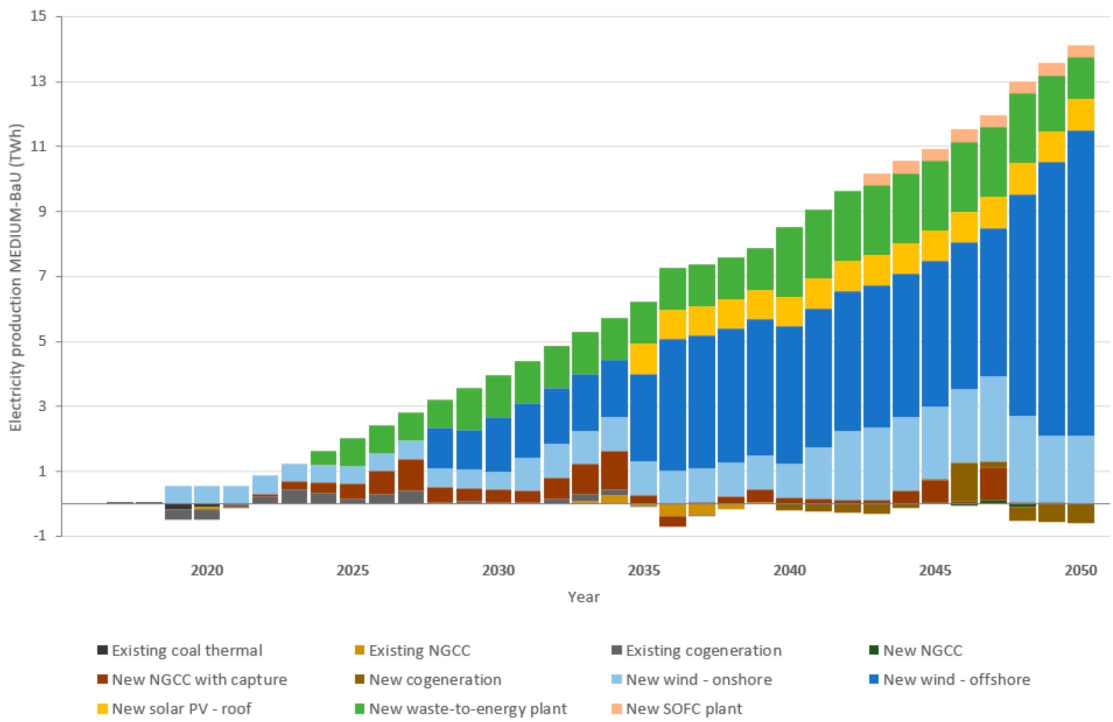


**Figure 3.** Evolution of the electricity production mix to satisfy the extra electricity demand due to EV penetration in the scenario MEDIUM.

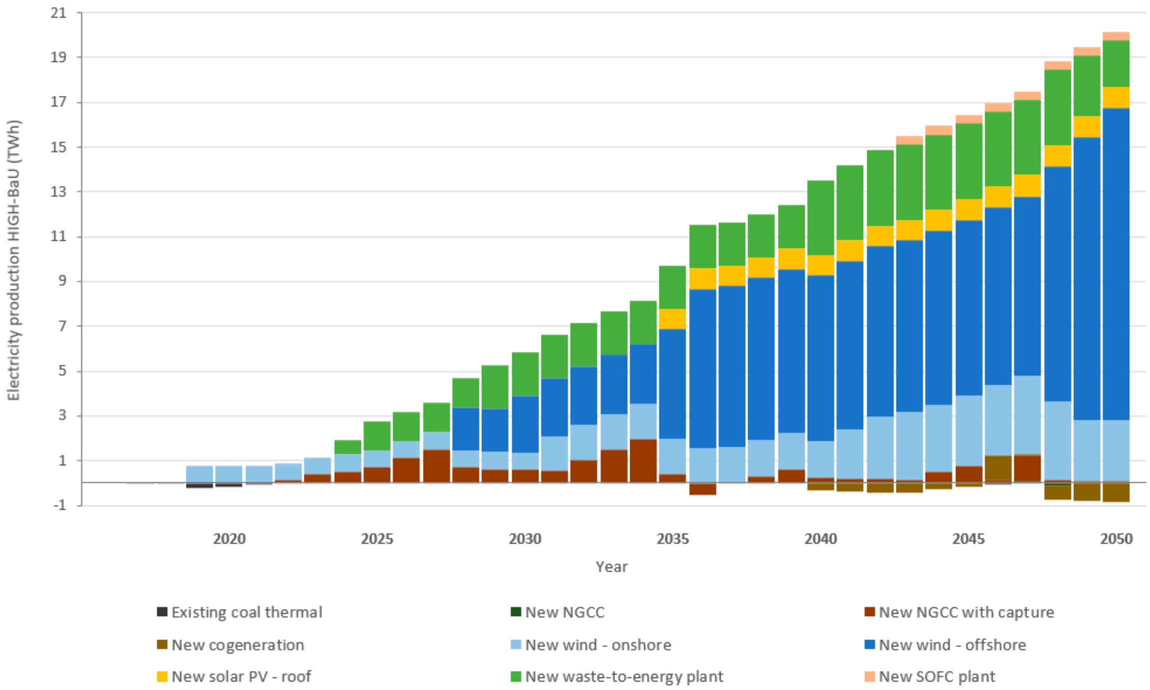


**Figure 4.** Evolution of the electricity production mix to satisfy the extra electricity demand due to EV penetration in the scenario HIGH.

The results shown in Figures 2 and 3 (LOW and MEDIUM scenarios, respectively) report a similar behaviour. In 2019 and 2020, both existing coal thermal and natural gas-based cogeneration plants are partly substituted, while the use of new wind onshore technology increases over the years. From 2024, waste-to-energy plants arise as a significant source of additional electricity. Furthermore, as of 2028, new offshore wind farms are used to supply most of the electricity demand associated with EV penetration from then on. For the period 2035–2050, solar PV emerges as another source of additional electricity, while SOFC plants play a minor role from 2043. Overall, it is found that the technology mix to supply the extra electricity demand caused by EV penetration in Spain may be almost 100% renewable by 2050. With regard to the environmental implications of this prospective performance, and unlike conventional ESM approaches limited to direct emissions, the combined ESM + LCA approach used in this article allows a deeper discussion on the evolution of certain life-cycle sustainability indicators as detailed later in Section 3.2 [18].

The behaviour observed in the scenario HIGH (Figure 4) is, to a large extent, similar to that reported for LOW and MEDIUM scenarios. However, existing NGCC and cogeneration plants do not emerge in the scenario HIGH, tipping the balance in favour of renewable options. Again, onshore and offshore wind farms—which are characterised by a favourable techno-economic and environmental performance—are found to play a leading role when it comes to meeting the extra electricity demand associated with the penetration of EV in Spain. Besides, the model introduces new waste-to-energy plants, which—according to the original study [18]—are free of environmental burdens since they involve a multifunctional system with 0% allocation to the energy production function and 100% to the waste management service [21].

Additionally, Figure 5 shows the prospective contribution of the main power generation technologies to the extra electricity production mix attributed to EV penetration. The contribution of these power generation technologies behaves similarly in the three alternative scenarios. New wind power generation (onshore + offshore) generally has the largest contribution to satisfy the extra electricity demand associated with EV penetration. This leading role of wind power technology is due to several reasons, such as the competitive investment costs (which are expected to decrease), the expected increase in technical efficiencies, and the null direct $CO_2$ emissions.

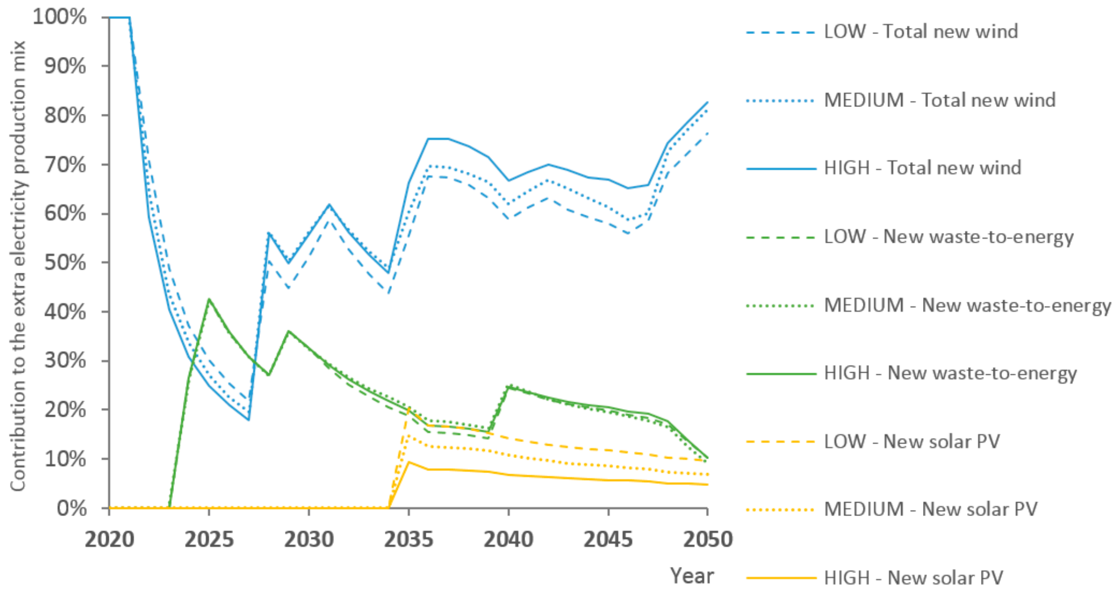


**Figure 5.** Contribution of key power generation technologies to the extra electricity production associated with EV penetration under three alternative scenarios.

Finally, it should be noted that—since electricity demand projections are introduced exogenously in the energy systems model—the results are highly conditioned by the assumed socio-economic drivers (e.g., GDP, electricity prices, and population). Thus, variations in the behaviour of these drivers could have significant effects on the performance of the indicators evaluated. In particular, according to [18], GDP would arise as a key aspect when analysing the sensitivity of the results.

### 3.2. Prospective Life-Cycle Profile

Figures 6–8 show the evolution of the life-cycle indicators CC, HH, and Re, respectively, in accordance with the prospective technology mixes detailed in Section 3.1 to satisfy the increased electricity demand. Hence, these figures report only the life-cycle impacts attributed to the additional electricity demand associated with EV penetration in Spain. Nevertheless, the total CC, HH, and Re impacts of the power generation sector in the scenarios BaU, LOW, MEDIUM, and HIGH are presented in Tables A1–A3 in the appendix.

As shown in Figure 6, the prospective performance in terms of CC is similar in the three scenarios. The CC indicator is found to evolve in line with the role of the fossil-based technologies observed in Figures 2–4 because of the their much higher CC compared to renewable options such as wind, solar PV, and waste-to-energy technologies.

The negative values (i.e., favourable impacts) observed for some years in Figure 6 are due to the subtraction of coal thermal, NGCC, and cogeneration plants with respect to the BaU scenario. Since this avoided electricity production is compensated by more onshore and offshore wind power technologies, which have low CC impact, a net negative value is found. While negative peaks are linked to reductions in the use of fossil-based technologies, positive peaks come from the increased use of natural gas-based technologies in specific years.

The prospective HH impact of the extra electricity production due to EV penetration is shown in Figure 7. Since coal-fired power plants typically are one of the most damaging power generation technologies in terms of HH, their partial avoidance gives rise to the negative (i.e., favourable) peak observed in Figure 7. On the other hand, the rest of the withdrawals of fossil-based power generation (e.g., in NGCC and cogeneration plants) play a less significant role. In fact, an overall trend of growing HH impact is found for the three scenarios after reaching the negative peak, i.e., when the avoidance of coal power generation is no longer observed.

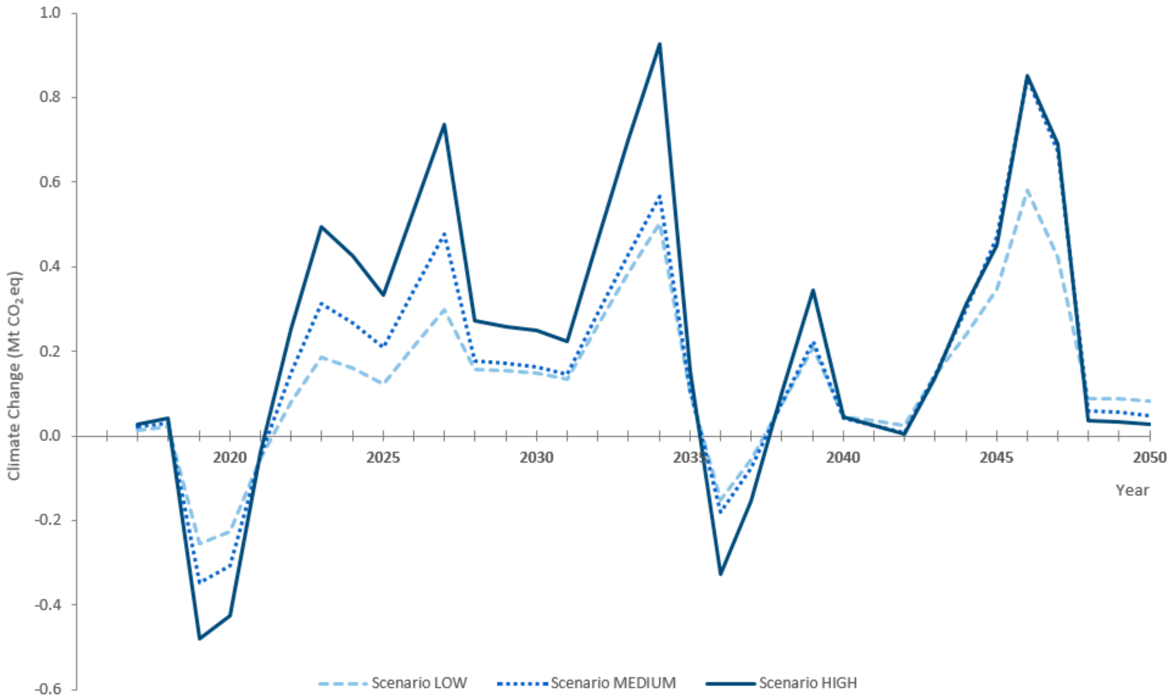


**Figure 6.** Evolution of the climate change indicator associated with the extra electricity demand due to EV penetration in Spain under three alternative scenarios.

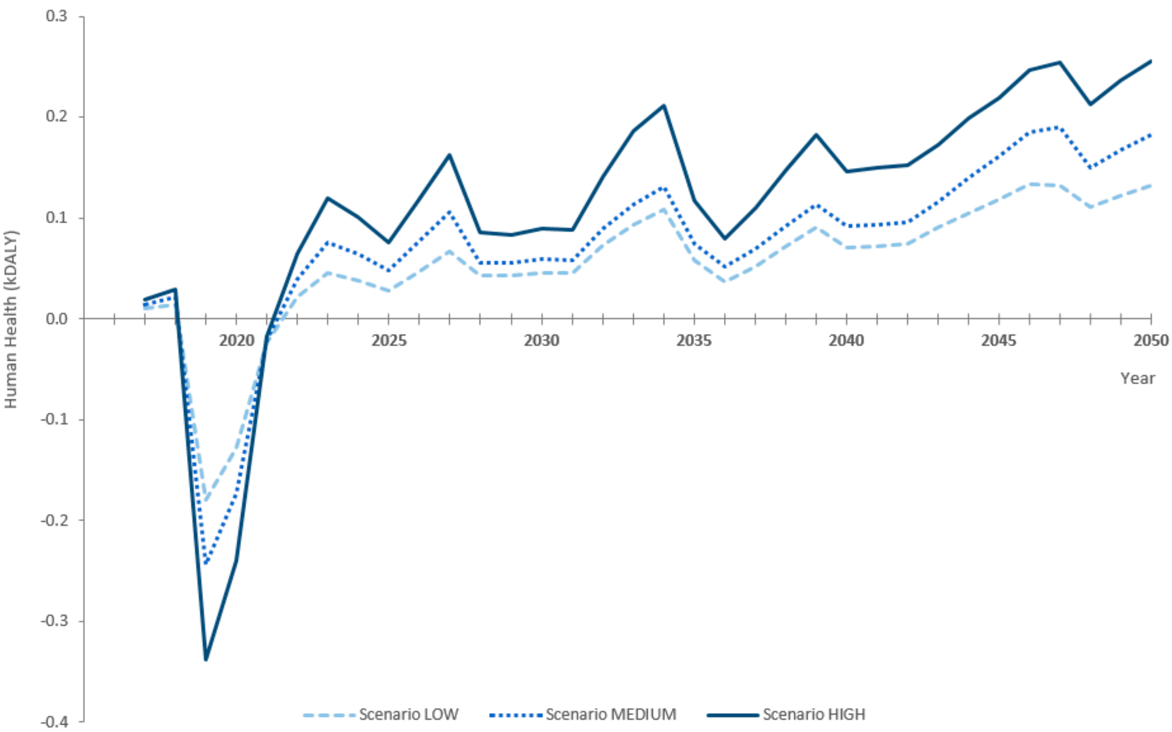


**Figure 7.** Evolution of the human health impact associated with the extra electricity demand due to EV penetration in Spain under three alternative scenarios.

Finally, the prospective performance of the Re indicator is shown in Figure 8. A very similar behaviour to that reported for the CC indicator is found. Thus, the peaks observed in the figure are closely linked to the contribution of the fossil-based technologies (coal thermal, NGCC, and cogeneration plants). It should be noted that NGCC with $CO_2$ capture plays a significant role in this category. In this respect, the energy penalty of capturing post-combustion $CO_2$ leads to a decrease in the overall efficiency of the NGCC plant, therefore increasing the impact in terms of Re. In contrast, renewable technologies barely contribute to this category.

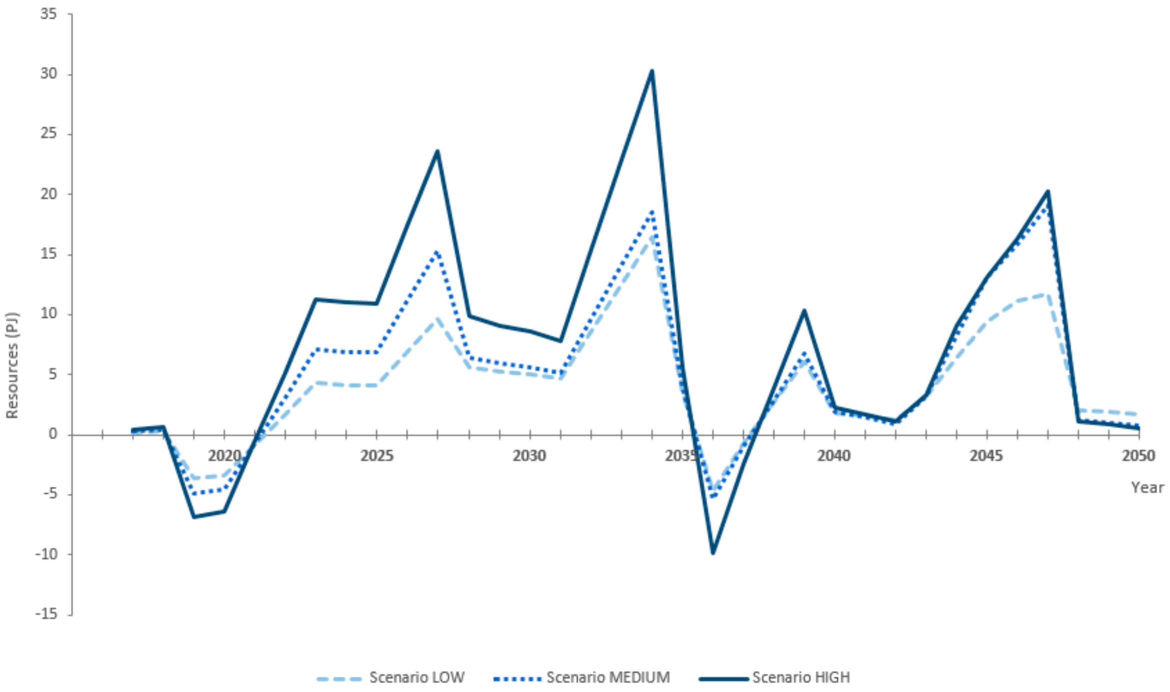


**Figure 8.** Evolution of the resources impact associated with the extra electricity demand due to EV penetration in Spain under three alternative scenarios.

### *3.3. Preliminary Comparison with Conventional Road Transport*

In addition to the interest in the prospective assessment of the life-cycle profile of the electricity demanded by EV (Section 3.2), the inclusion of the life-cycle consequences associated with the substitution of conventional fuels within the transport sector is especially interesting when it comes to further supporting decision- and policy-making processes on the suitability of EV deployment in Spain.

In this sense, Figures 9–11 show the quantification of the net potential benefits associated with the use of electricity instead of conventional fossil fuels in the Spanish road transport sector. For the sake of simplicity, this preliminary comparison assumes that the fleet of vehicles only consists of private passenger cars, which actually represent around 80% of the fleet. Moreover, for a fair comparison, both production [22] and combustion [23] of the avoided fossil fuels are taken into account. A typical fuel share of 60% diesel and 40% petrol for the Spanish car fleet is assumed [24]. The comparison takes into consideration that 100 kWh in EV provides the same transport function as the production and combustion of 28 kg of fossil fuels [25,26].

As shown in Figures 9–11, for the three life-cycle indicators, the potential impact savings ("net avoided impact" = "impact of the substituted fossil fuels" − "impact of the electricity demanded by EV") grow significantly when promoting the replacement of diesel and petrol vehicles with electric cars. The large differences in the scale of the *y*-axes in Figures 9–11 versus those in Figures 6–8 clearly show that the impacts of the electricity demanded by EV are negligible in comparison with those of the substituted fossil fuels on an equivalent functional basis. Hence, the highest benefits are found in the scenario HIGH. This finding shows the importance of decarbonising the transport sector. In particular, this preliminary comparison suggests the suitability of EV penetration as a potential solution to enhance the sustainability performance of this sector. However, additional issues about EV penetration—out of the scope of this study—should be taken into account, e.g., the technical difficulties in establishing complex demand-response schemes within the grid. In other words, EV penetration could be one of the solutions to achieve a significant reduction in the impacts associated with the high fossil dependence of the transport sector in countries such as Spain, but still requires further efforts to overcome techno-economic barriers. In this sense, the dynamic nature of the energy system—with high variability in production and consumption needs—makes the performance of additional analyses necessary to determine the actual sensitivity of the system to EV penetration.

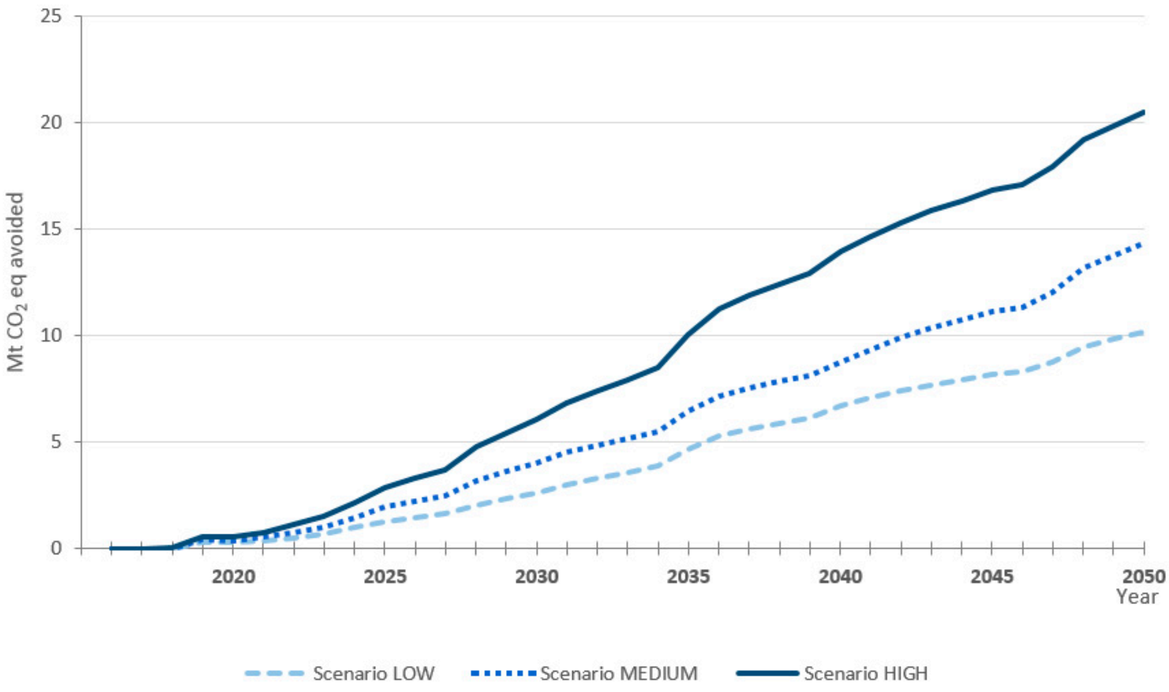


**Figure 9.** Net potential avoidance of CC impact under the three scenarios considered.

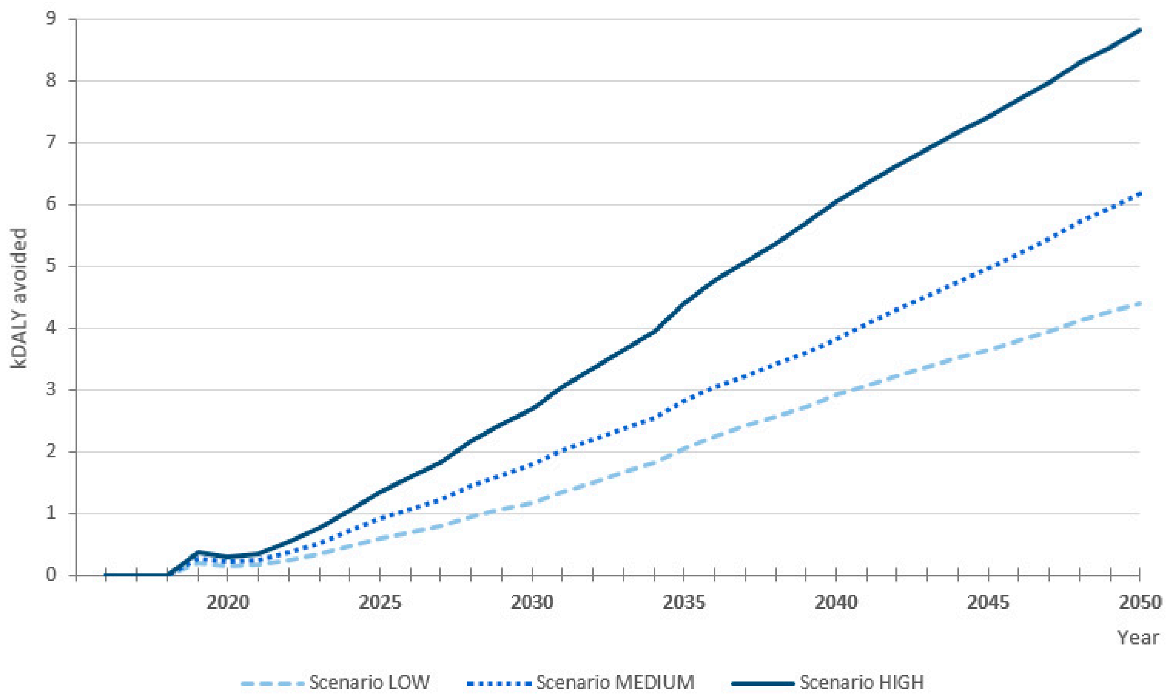


**Figure 10.** Net potential avoidance of HH impact under the three scenarios considered.

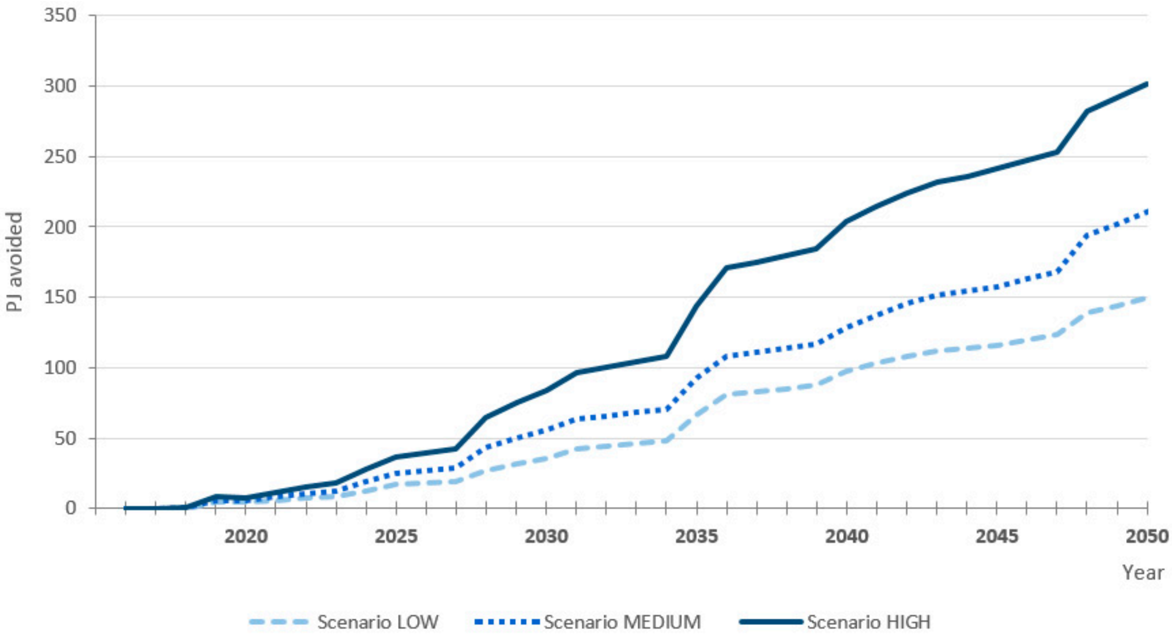


**Figure 11.** Net potential avoidance of Re impact under the three scenarios considered.

## 4. Conclusions

The electricity demand associated with the future penetration of EV in the Spanish road transport sector is expected to be mainly satisfied by an increased contribution of onshore and offshore wind power to the electricity production mix. This would generally lead to a slight increase in the annual life-cycle impacts of the power generation sector. In this regard, under a high market penetration of 20 million EV by 2050, the highest annual climate change, human health, and resources impacts of the EV-related electricity would be 0.93 Mt $CO_2$ eq, 0.25 kDALY, and 30.34 PJ, respectively. In fact, these minor impacts would be outshined by the high environmental benefits within the transport sector due to the avoidance of conventional fossil fuels to perform the same transport function. In this sense, net annual impact savings of up to 10–20 Mt $CO_2$ eq, 4–9 kDALY, and 149–301 MJ were estimated under three alternative scenarios on the penetration of EV in Spain (10–20 million EV by 2050). Overall, ambitious targets for EV penetration in countries such as Spain are deemed feasible and suitable from a life-cycle sustainability perspective.

**Author Contributions:** D.I. conceived the study; Z.N.-A. developed the scenarios; D.G.-G. implemented the scenarios in the Spanish energy model for power generation; all authors analysed the data and contributed to writing the paper.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix

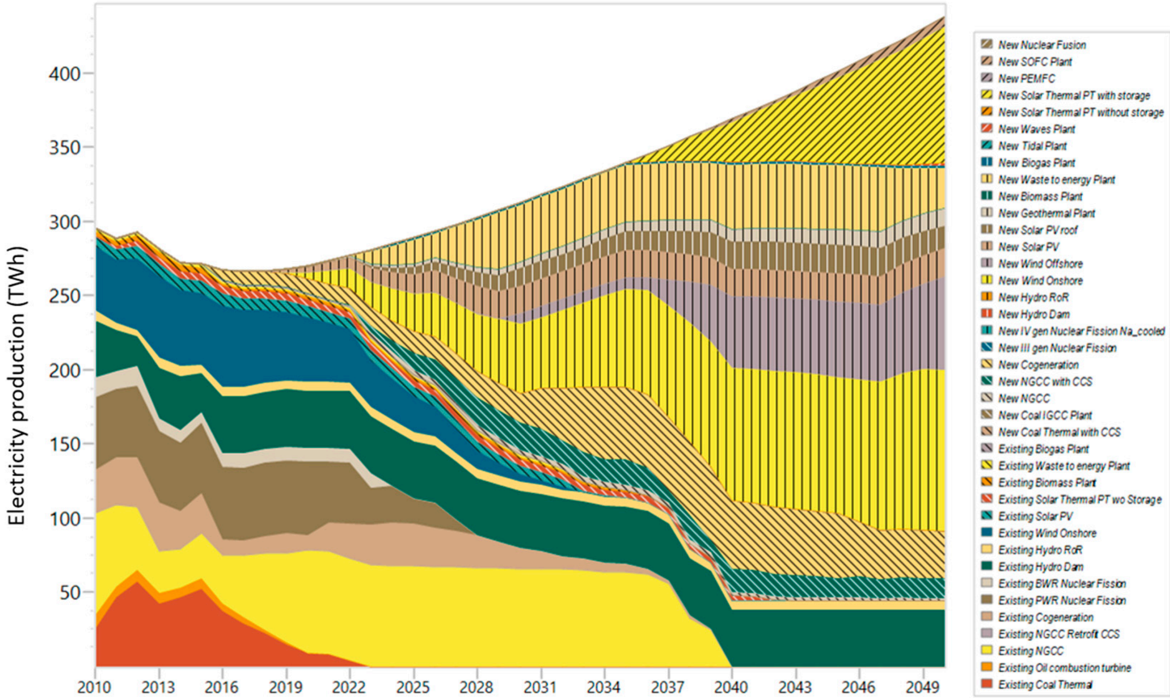


**Figure A1.** Evolution of the total electricity production by technology in the BaU scenario.

**Table A1.** CC impact of the power generation sector (Mt $CO_2$ eq).

| Scenario | Year 2015 | Year 2020 | Year 2025 | Year 2030 | Year 2035 | Year 2040 | Year 2045 | Year 2050 |
|---|---|---|---|---|---|---|---|---|
| **BaU** | 94.10 | 57.16 | 63.55 | 59.16 | 67.42 | 32.44 | 32.77 | 29.61 |
| **LOW** | 94.10 | 56.93 | 63.67 | 59.31 | 67.53 | 32.48 | 33.12 | 29.69 |
| **MEDIUM** | 94.10 | 56.85 | 63.76 | 59.33 | 67.53 | 32.48 | 33.24 | 29.66 |
| **HIGH** | 94.10 | 56.74 | 63.88 | 59.41 | 67.58 | 32.48 | 33.22 | 29.64 |

**Table A2.** HH impact of the power generation sector (kDALY).

| Scenario | Year 2015 | Year 2020 | Year 2025 | Year 2030 | Year 2035 | Year 2040 | Year 2045 | Year 2050 |
|---|---|---|---|---|---|---|---|---|
| **BaU** | 78.90 | 21.82 | 11.86 | 9.71 | 9.54 | 6.24 | 6.97 | 7.77 |
| **LOW** | 78.90 | 21.69 | 11.89 | 9.75 | 9.60 | 6.31 | 7.09 | 7.90 |
| **MEDIUM** | 78.90 | 21.65 | 11.91 | 9.77 | 9.61 | 6.33 | 7.13 | 7.95 |
| **HIGH** | 78.90 | 21.58 | 11.93 | 9.80 | 9.66 | 6.39 | 7.19 | 8.03 |

**Table A3.** Re impact of the power generation sector (PJ).

| Scenario | Year 2015 | Year 2020 | Year 2025 | Year 2030 | Year 2035 | Year 2040 | Year 2045 | Year 2050 |
|---|---|---|---|---|---|---|---|---|
| **BaU** | 1973 | 1666 | 1385 | 1157 | 1308 | 697 | 689 | 632 |
| **LOW** | 1973 | 1663 | 1389 | 1162 | 1311 | 699 | 698 | 634 |
| **MEDIUM** | 1973 | 1662 | 1392 | 1163 | 1312 | 699 | 702 | 633 |
| **HIGH** | 1973 | 1660 | 1396 | 1166 | 1313 | 699 | 702 | 633 |

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