# Cost-Efficient Decarbonisation of Spanish Private Road Transportation: Biofuels vs. Electric Cars

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*- This is still ongoing work, please do not cite it. Any feedback received in my email (detailed below) would be very welcome -*

**Abstract:**

In order to address climate change threats, radical decarbonisation of the transportation sector is required. Within it, special emphasis must be put in cars, which account for a large share of emissions. This paper analyses which would be the most cost-efficient way of drastically reducing Spanish cars' CO2 emissions in 2030: electric cars or biofuels. We do it using a partial-equilibrium, linear programming, static model of the complete Spanish energy sector, created specifically in the BP Chair on Energy and Sustainability for energy policy strategic evaluation. According to our preliminary results, biofuels seem to be preferable unless drastic reductions in electric cars extra-costs are achieved.

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## 1. Introduction

Climate change is becoming a major threat, especially since those countries responsible for the problem are not acting with the required determination. Europe, however, has recently proposed an ambitious mitigation strategy that, if followed, should decarbonise Europe's economy almost completely by 2050. The precise objective is reducing Europe's carbon emissions in 2050 to less than a fifth of their level in 1990 (European Commission, 2011).

The transportation sector, due to its technological characteristics, is the toughest one to decarbonise. Mobility increases with wealth, so demand for transportation is now much larger than decades ago, and it is foreseen to keep growing, especially in developing countries. At the same time, vehicles have to be fuelled by high energy density products that must be, at the same time, cost-competitive, safe and easy to handle. Up to now, mainly oil products have succeeded in this. This has made carbon emissions from transport grow significantly, and this trend is expected to continue unless radical action is undertaken. Within transportation, one of the major sources of emissions is private road transportation, mainly cars.

The objective of this paper is to study the most cost-efficient way to severely cut carbon emissions from cars in Spain by comparing, for 2030, the two most promising alternatives: electric mobility and sustainable biofuels. This is done by using a bottom-up, static, partial equilibrium, linear programming model of the

Spanish energy sector, specially designed for answering energy policy questions. This paper's structure is the following one. In section 2, a brief overview of carbon emissions in Spain is given, and the objectives for private road transportation's decarbonisation are set; in section 3**¡Error! No se encuentra el origen de la referencia.**, the model is presented; section 4 deepens on the characterization of cars that has been done; in sections 5 and 6 the scenarios and results are presented; and finally conclusions are outlined in section 0.

## 2. Decarbonisation objectives and means

We calculate the Spanish 2030 carbon emissions target for private road transportation by car (motorbikes have not been considered), in order for this sector to be on the correct path towards the European 2050 ambitious objective. Total $CO_2$ emissions in 2010 from the Spanish energy sector accounted for 262Mt, which is 28% over 1990 levels. Prior to the present economic crisis, this value was 337Mt, i.e. 65% over 1990. Of these 2010 emissions, 83Mt (32%) came from road transportation. Private road transportation by car accounted for 43Mt, more than half of it. And this value is 54% higher than its 1990 level (28Mt), reflecting the large growth of mobility that has taken place in Spain during the last two decades of strong economic development.

The recently adopted European 2050 Roadmap sets the objective of reducing 2050 carbon emissions by 80% below 1990 levels. Given transportation's sector technological difficulties, its emissions should be in 2050 in the range of -54% to -67% compared to 1990. In 2030, their range should be +20% to -9% compared to 1990. These ranges depend on the assumptions of

technological development and fossil fuel prices. Assuming the central part of the range, 2030 emissions from the entire transport sector (including air, railway and sea transport) should be 5.5% over 1990 levels, which is 57Mt (they accounted for 90Mt in 2010). Of these, given the greater difficulty in reducing emissions in air transportation and freight transport modes, only 15Mt would correspond to cars. To sum up, for private road transportation by car in Spain to be on the virtuous path towards European 2050 objectives, its 2030 carbon emissions should not exceed 15Mt.

In the business as usual case private road mobility is expected to be mainly provided by internal combustion cars (annexes of European Commission, 2011). These would be mainly gasoline cars, according to latest European regulations that tend to diminish diesel use in order to reduce other pollutants such as particles and $NO_X$. These gasoline and diesel-based cars would be more efficient than today, due to increasing petroleum products' prices, technological advances, and efficiency policies. But demand for mobility would increase too, mainly driven by the increase in GDP per capita once the present economic crisis is over. The combined effect of greater efficiency but increased demand for transportation would keep emissions from cars in values similar to the present ones (around 45Mt), what is far from the needed value of 15Mt.

A radical decarbonization of private road mobility by car should thus take place and sustainable biofuels and electric mobility are presently the strongest candidates to achieve this target. Biofuels that comply with European sustainability regulations (Directive 2009/28/CE) can be considered to have null

carbon emissions. Electric mobility, apart from being far more efficient than combustion engines, results in lower emissions if the electricity mix has low carbon intensity. In this paper we compare both alternatives in terms of their cost-efficiency for achieving the 15Mt objective in 2030.

## 3. Methodology: overview of the model

To carry out the study, a model of the entire energy sector is needed, in order to be able to account for the emissions and costs not only of road transportation, but also of the other energy sub-sectors involved: electricity, oil products, natural gas, and biofuels. When electric cars are promoted, more electricity is consumed, so more emissions are expected from the electricity sector, more generation capacity and power networks may be needed, and more primary energy for electricity generation may be required, causing the total energy system costs to increase. Given the increasing importance of natural gas in power generation, this would affect the gas sector too: greater investments in gas networks, gas interconnections, or liquefied natural gas regasification may be needed. When biofuels use grows, they may be imported or, if domestically produced, greater production capacity may be needed, increasing costs in both cases. On the other hand, oil products demand would fall, diminishing crude and products importation, oil refining activity, costs and emissions.

For this study we have used a policy-oriented model of the entire Spanish energy system (López-Peña, Linares, & Pérez-Arriaga, 2011). It allows us to analyze the energy sector's evolution under different policy scenarios, specifically selected to answer our research question. It is a bottom-up, static,

partial equilibrium, linear programming model of the energy sector. For each scenario, we calculate the least-cost energy supply for the country in the considered year (in this case, 2030), given exogenous demands for each energy service (e.g. mobility, heating, lighting) in each subsector, and without exceeding a specified level of emissions. The cost to be minimized includes the main private costs (no externalities) involved in the energy sector: domestic primary energy purchases, energy imports and exports, investments in energy assets or their fixed and variable costs, among others. The main outputs of the model include the energy flows through the entire energy system, its emissions, the required investments, and all the associated costs.

The representation of demand sectors (industries, residential, services and transportation, mainly) has been done using externally-introduced energy services' demands which are supplied by a complete database of end-use technologies (e.g. cars, boilers, etc).

These energy services' demands calculation has been done based on official projections for energy services demand from the Spanish Government (Congreso de los Diputados, 2010; Ministerio de Industria, Turismo y Comercio, 2011) and research institutions (Centro Complutense de Estudios e Información Medioambiental & Fundación CONAMA, 2011; Economics for Energy, 2011; Greenpeace, 2011; Németh, Szabó, Císcar, & Soria, 2009; WWF Spain, 2010).

Each end-use technology consumes different types of final energy in order to produce energy services. The following final energy types are the main considered ones: electricity from the centralised national grid, electricity from

distributed grids, heat from district heating networks, coal, natural gas, gasoline, diesel, fuel-oil, liquefied petroleum gasses (LPG), kerosene, bioethanol, biodiesel, biomass, or solar thermal energy, among others.

End-use technologies are characterized through their technical and economic parameters, such as capacities, efficiencies (energy use of each type of final energy per unit of produced output), emission levels, or functioning costs. These functioning costs include the annual depreciation of overnight investment costs and the yearly non-energy operational costs. Their energy-use operational costs are not included because the complete upstream energy sector, which delivers final energy to them, is completely modelled and hence considers all the associated costs.

Next, the representation that has been done for each upstream energy subsector will be briefly introduced. For more details, refer to (López-Peña et al., 2011), where the complete mathematical formulation is explained.

The electricity subsector is modelled in detail to accurately consider the cost increments that would be brought by the increase in electricity demand that would be expected in the scenarios where electric cars are promoted. Power generation is represented by the twenty-nine technologies that are relevant to the Spanish case: nuclear, five coal types (domestic or imported, with or without carbon capture and sequestration, CCS), three types of hydro, hydro pumping stations, combined cycle and open cycle natural gas turbines (with and without CCS), fuel-gas generators, three types of onshore wind with different quality resource and different maximum potential, one type of offshore wind, three

types of biomass, solid waste, three types of solar photovoltaics and one of concentrated solar power, and two types of combined heat and power stations. 96 load levels are used, in order to represent electricity demand throughout the year with enough precision: 12 months, two day types within each month (week day/weekend), and four load levels per day (including a super-peak one representing the 1% hours with the highest demand values in each day type). Each generation technology is characterized by its technical and economic parameters: mainly efficiency; availability (or equivalent hours for intermittent technologies); investment, fixed and variable costs, rate of return on investment and economic life; or firmness and flexibility for electricity system's reliability constraints as explained in (Batlle, Vázquez, Rivier, & Pérez-Arriaga, 2007). The used costs for each technology are the median of the values foreseen by the most reliable international sources, such as the International Energy Agency (IEA), the European Commission or the US Energy Information Administration. The electricity network is represented as a single node, but average transportation costs are considered, which depend on total demand and on the installed intermittent generation. This dependence has been calculated through an econometric analysis of the evolution of Spanish electricity network costs over the last 10 years and allows us to explain electricity grid costs by an increment on demand and/or by an increment in connected intermittent generation. Two reliability constraints of the power grid are included too, as introduced above. The first one is an *adequacy* constraint, which imposes a 10% reserve margin of firm capacity over yearly peak demand. The second one is a *reserves* constraint, which forces the model to keep flexible generation providing

enough reserves to the system so as to cope with unexpected failure in large generators, demand uncertainty or intermittency in renewable generation. Interconnections with neighbouring countries are as well modelled. The model is provided as input with the current capacity that is expected to remain operative in 2030, and can invest in new assets depending on the electricity demand it has to supply and in all the other modelled restrictions.

The gas system is modelled too. Gas interconnections are represented, and the gas network is modelled in single node, with average costs depending on the total amount of gas delivered (a similar econometric analysis as the one explained above has been used). The technical constraints of the gas network are assumed to be well modelled by a simple energy balance, if constant pressure is assumed and the storage capacity of the gas pipelines is ignored. For modelling liquefied natural gas (LNG) regasification, a single reference regasification terminal is used. Its investment and operating costs, efficiencies and emissions are the average values of Spanish terminals. The minimum regasification (must-run) restrictions are included too. The model is provided, as input, with the current regasification capacity and can invest in more, if needed.

Concerning oil products, six are modelled, as mentioned above: diesel, gasoline, kerosene, liquefied petroleum gases, fuel oil and others. A single crude oil quality is represented. Oil refining is modelled through three benchmark refineries, according to their complexity: medium, high and very high. The greater the complexity, the greater the flexibility in obtaining different oil products and the larger the achievable proportion of high value added products

(such as gasoline and kerosene). However, greater complexity means larger investment and operating costs, higher losses and higher emissions. We have used the current Spanish refining capacity but the model can invest in new assets. Oil products distribution is modelled as a single node network with average costs that depend on the product and that have been obtained from official sources (liquefied petroleum gases are more expensive to distribute than diesel or gasoline, for instance).

Concerning biofuels, one bioethanol type and one biodiesel type have been included. They can be either imported or produced domestically. Benchmark bioethanol and biodiesel production plants have been used, with their average costs and efficiencies, and their current capacities (suitable for additional investment). Their inputs (mainly oil seeds and cereal) are assumed to be imported, as it is the case in Spain. For representing biofuels distribution to final demand sectors, average costs are considered, in a similar way as done with oil products' distribution.

Limitations on the annual availability of domestic primary energy have been introduced for domestic coal, biomass and hydropower. We have obtained their values through the extrapolation of average historical values. The costs associated with domestic primary energy production (coal mining and biomass processing) and coal mining emissions are considered too. We have assumed biomass for heat and electricity to be entirely domestic.

Unlimited import and export capacity is assumed for all primary and final energies traded in Spain, except for gas pipelines and electricity interconnections

with North Africa and Europe, where the foreseen 2030 capacity is used. For energy commodity prices, be it primary energy, final energy or biofuel production inputs, the IEA's latest projections are considered.

## 4. Modelling of private road transportation

Using the above-mentioned sources, demand for car mobility has been estimated to be the following:

| **Demand for Passengers Mobility by car in Spain in 2030** *(Mpkm, million passengers-kilometer)* | | |
|---|---|---|
| Urban (URB) | 118440 | Mpkm |
| Interurban metropolitan, less than 50km (L50) | 178736 | Mpkm |
| Interurban, more than 50km (G50) | 25157 | Mpkm |
| Intraregional, more than 100km (G100) | 79597 | Mpkm |
| Interregional, more than 500km (G500) | 54375 | Mpkm |

Thirteen car types are modelled, and each of them provides some or all of the above-described mobility types. Some of these car types do not produce long-distance mobility services due to technical constraints: battery electric vehicles are supposed to remain within urban and interurban environments, and something similar is true for compressed natural gas and liquefied petroleum gas cars, where the refuelling stations are not widely available in Spain. All car types are supposed to have the same occupancy rates (passengers/car), no matter their technology. These occupancy rates are supposed to increase with distance, because people tend to fill up their cars more in sporadic, long-distance trips. Refer to the next table for a complete list of modelled car types, their occupancy rates in each mobility service, and a relation of the services not being supplied in each case.

| **Occupancy rate per car type and mobility service** *(passengers/car)* | | | | | |
|---|---|---|---|---|---|
| **Vehicle type / Mobility service** | **URB** | **L50** | **G50** | **G100** | **G500** |
| Car gasoline standard 2030 | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car diesel standard 2030 | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car gasoline more efficient | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car diesel more efficient | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Compressed Natural Gas Car (50% CNG & 50% Gasoline) | 1.2 | 1.5 | - | - | - |
| Liquefied Petroleum Gas Car (50% LPG & 50% Gasoline) | 1.2 | 1.5 | - | - | - |
| Car bioethanol E85 (15% gasoline, 85% bioethanol) | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car biodiesel B85 (15% diesel 85% biodiesel) | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car gasoline non plug-in hybrid | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car diesel non plug-in hybrid | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car gasoline plug-in hybrid | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car diesel plug-in hybrid | 1.2 | 1.5 | 2.0 | 2.5 | 3.0 |
| Car battery electric vehicle | 1.2 | 1.5 | 2.0 | - | - |

In order to supply the mobility services, each car type uses a certain amount of energy, which for each car and mobility type have been estimated using values from the IEA's ETSAP Programme *Technology Brief* reports (International Energy Agency, 2010a, 2010b, 2010c, 2010d) and from the MIT's Report *On The Road 2035* (Bandivadekar et al., 2008). These values are represented below, along with the unitary cost of each car type, in €2010 per unit (values obtained from the same sources).

| **Unit cost and Mobility per consumed energy unit per car** | | | | |
|---|---|---|---|---|
| | *Cost (€/unit)* | *Mobility /energy (km/kWh)* | | |
| **Vehicle type** | **Cost** | **URB** | **L50** | **Longer** |
| Car gasoline standard 2030 | 16000 | 1.36 | 1.55 | 1.81 |
| Car diesel standard 2030 | 18000 | 1.55 | 1.74 | 1.97 |
| Car gasoline more efficient | 17500 | 1.64 | 1.79 | 1.97 |
| Car diesel more efficient | 19500 | 1.97 | 2.07 | 2.19 |
| Compressed Natural Gas Car (50% CNG & 50% Gasoline) | 18500 | 1.17 | 1.34 | - |
| Liquefied Petroleum Gas Car (50% LPG & 50% Gasoline) | 18500 | 1.17 | 1.34 | - |
| Car bioethanol E85 (15% gasoline, 85% bioethanol) | 16000 | 1.42 | 1.63 | 1.90 |
| Car biodiesel B85 (15% diesel 85% biodiesel) | 17500 | 1.63 | 1.82 | 2.07 |
| Car gasoline non plug-in hybrid | 21000 | 2.17 | 2.17 | 2.17 |
| Car diesel non plug-in hybrid | 22500 | 2.46 | 2.46 | 2.46 |
| Car gasoline plug-in hybrid | 28000 | 2.24 | 2.56 | 2.80 |
| Car diesel plug-in hybrid | 29000 | 2.71 | 2.95 | 3.05 |
| Car battery electric vehicle | 38000 | 2.24 | 2.56 | 2.98 |

Biofuel cars are supposed to have no extra cost, and their introduction has a null effect on the system (apart from biofuels' greater imports or production costs) because their only promotion policy is tax exemptions, and in our model taxes are supposed to be pure transfers and all energy products' prices are introduced without taxes.

The cost per kilometer of each car is needed in order to calculate the total cost of cars use. The cost per kilometer has been calculated the following way: (i) the annuity of the unitary investment cost is computed at 9% interest rate and for 12 years economic life; (ii.) yearly non-energy operation and maintenance costs are supposed to be 3% of the total unitary investment cost; (iii.) both annual values are added up, and divided by the total kilometers done by each car in a year, assumed to be 16000. These values are the same for all car types.

Finally, all the cars are supposed to emit the same amount of CO2 per each unit of consumed energy, but this depends on the energy type, of course. Biofuels are supposed to have null emissions (they are supposed to be fully compliant with the latest biofuel sustainability regulations). Electricity does not produce emissions in cars, but having a model of the complete energy sector allows us to account for them in power generation emissions,

| **Emissions per consumed energy unit** *(tCO2/MWh)* | |
|---|---|
| CNG | 0.204 |
| Gasoline | 0.256 |
| Diesel | 0.261 |
| LPG | 0.242 |
| Biodiesel | 0.000 |
| Bioethanol | 0.000 |
| Electricity | 0.000 |

## 5. Scenarios and relevant data

Four scenarios are used: a business as usual (BAU) one plus three decarbonization cases (refer to next table). The business as usual one represents the situation where emissions from car transportation are not restricted. The decarbonization scenarios are modelled by restricting cars emissions to 15Mt and forcing the model to provide private road transportation demand, apart from with gasoline and diesel cars, with only biofuel-powered cars, only with electric cars, or letting the model decide how much to use of each type (mixed case). In all four scenarios, the emissions of the rest of the energy system are restricted to be on the virtuous paths towards 2050 objectives. The constraint on emissions from electricity generation is critical in scenarios with penetration of electric cars, in order to avoid emissions leakage from transport to electricity generation. In the BAU case, biofuel-powered and electric cars are allowed, but the model is not expected to use them because their costs are higher than the gasoline or diesel options.

| | **BAU Case** | **Decarb_Bios** | **Decarb_Elec** | **Decarb_Bios+Elec** |
|---|---|---|---|---|
| **Emissions limit on cars (15Mt)** | No | Yes | Yes | Yes |
| **Emissions limit other energy sectors** | Yes | Yes | Yes | Yes |
| **Biofuels allowed** | Yes | Yes | No | Yes |
| **Electric cars allowed** | Yes | No | Yes | Yes |

## 6. Results

In the business as usual (BAU) case, which has been used for calibration purposes as well, all the demand is supplied with gasoline, and the total car emissions are 47Mt. These results allowed us to consider the model as correctly calibrated, because they are in line with our expectations (as described before). Another interesting preliminary result is that all results in the mixed case ("Bios+Elec") are exactly coincident with those of "Bios" case. This implies that the model is choosing biofuel-based decarbonisation over electric-cars one (because in the mixed scenario it can, indeed, choose). A more detailed description of the results will be done now.

The first result that will be commented on is total system costs (which is the objective value to be minimised). They are mainly composed by the total costs of car use and the total costs of final energy supply to end-use sectors. The first one does not include energy, as said before, and is calculated with the cost per kilometre and the total kilometres done by each type of car. The second cost component represents all the costs of the Spanish energy system in a year, excluding end-use technologies, and is composed of energy imports costs and exports revenues, energy assets depreciation and operation and maintenance costs, or energy transportation costs, among others. Both costs can be seen in the next table, expressed in billion € per year, as well as their addition (the total system cost to be minimised). It can be seen that all policies increment the costs of cars usage, because all cars are more expensive than the gasoline ones in the BAU case. This effect, however, is bigger with electric cars than with biofuel cars,

as could be expected from the table above where unit costs are given. Energy supply costs, however, are smaller in the case where electric cars are used, because of the lower average cost of electricity vs biofuels and higher energy efficiency of electric cars, causing less total final energy to be used. Biodiesel (the only used biofuel) is imported at a cost of 74€/MWh and its distribution costs around 6€/MWh, adding up around 80€/MWh. Electricity is mainly generated by 50%-efficiency combined cycle gas turbines which use liquefied natural gas (LNG) imported at 25€/MWh (world LNG market is considered to remain at low prices mainly due to the shale gas effect, in line with latest official forecasts). Then, this electricity delivery costs is around 15€/MWh, adding up around 65€/MWh.

| | **BAU case** | | **Decarb_Bios** | | **Decarb_Elec** | | **Decarb_Bios+Elec** | |
|---|---|---|---|---|---|---|---|---|
| **System costs (billion €2010/year)** | | | | | | | | |
| Total system costs (A): | 122.24 | | 125.36 | | 143.42 | | 125.36 | |
| - of which cars' non-energy costs (B): | 47.57 | | 50.90 | | 70.50 | | 50.90 | |
| - pure energy system costs (A-B) | 74.67 | | 74.45 | | 72.91 | | 74.45 | |
| **Emissions detail** | Mt | €/t | Mt | €/t | Mt | €/t | Mt | €/t |
| Emissions from energy conversions | 121.64 | N.A. | 121.64 | 46.91 | 121.64 | 48.69 | 121.64 | 46.91 |
| Emissions from cars | 47.16 | N.A. | 15.00 | 107.09 | 15.00 | 765.81 | 15.00 | 107.09 |

In the previous table, and after the costs, some detail of emissions is given: for each scenario, both emissions in energy conversions (mainly power generation and oil refining) and in cars are given in million tonnes (Mt). Both this values are capped (to 162.64Mt and to 15Mt), so the shadow prices of these constraints are given too (in €/tCO2). It can be seen that, in general, reducing carbon emissions in energy conversions is cheaper than in cars, because shadow prices are less than 50%. It is interesting to see the high value of cars' emissions

shadow price in the case with electric cars: this is due to the high over cost supposed for these cars. Shadow prices are smaller in the biofuels and the mixed case than in the only-electric cars case, what implies that it is cheaper achieving the emissions target through biofuels than through electric mobility. This result is confirmed by the fact that, in the mixed scenario (where the model can choose to use electric or biofuel cars), it only chooses biofuel cars, as was introduced above, and as can be seen in the next table. In this next table can be observed the use of each type of car that is used in each type of mobility, and it can be seen that traditional cars are kept for interurban trips, whereas electric or biofuel cars are used in metropolitan or urban trips. This is due to greater occupancy rates in interurban trips, which make each passenger-kilometer of mobility less intensive in emissions than a passenger-kilometer in the city, no matter the type of car used.

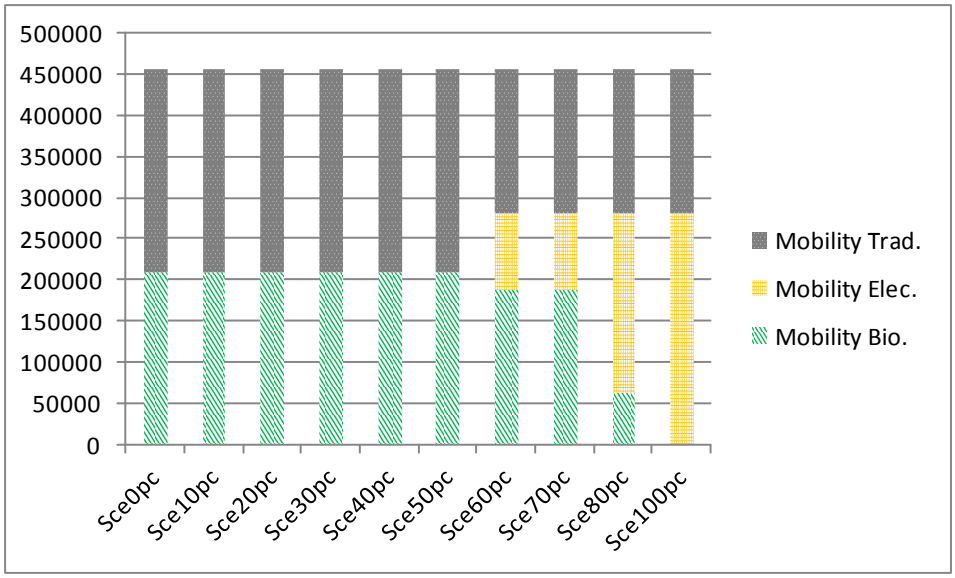
| **Car use (%)** | **BAU case** | **Decarb_Bios** | **Decarb_Elec** | **Decarb_Bios+Elec** |
|---|---|---|---|---|
| Urban | | | | |
| Traditional | 100% | 0% | 0% | 0% |
| Bio-cars | 0% | 100% | 0% | 100% |
| Electric-cars | 0% | 0% | 100% | 0% |
| Metropolitan (L50) | | | | |
| Traditional | 100% | 7% | 36% | 7% |
| Bio-cars | 0% | 93% | 0% | 93% |
| Electric-cars | 0% | 0% | 64% | 0% |
| Interurban (G50) | | | | |
| Traditional | 100% | 100% | 100% | 100% |
| Bio-cars | 0% | 0% | 0% | 0% |
| Electric-cars | 0% | 0% | 0% | 0% |

In the next table, some interesting insights about the total energy use in Spain in each scenario are provided. It can be seen that total consumed final energy is the smallest in the case with electric cars, as anticipated, due to these cars' higher energy efficiency. The same happens, although in smaller quantity, when biofuel cars are introduced: according to the IEA's Technology Brief on Biofuels, biofuel cars are more energy efficient (in energy/km, not in litres/km). Total domestic and exported energy remains constant in all cases, and energy dependence varies very slightly, remaining at high values. This is due because biofuels are entirely imported, and power is mainly generated with imported LNG.

| Energy use (EJ) | BAU case | Decarb_Bios | Decarb_Elec | Decarb_Bios+Elec |
|---|---|---|---|---|
| Total energy used (primary+final, domestic+imported) (A): | 5.86 | 5.78 | 5.75 | 5.78 |
| Total domestic energy used (primary+final) (B): | 0.68 | 0.68 | 0.68 | 0.68 |
| Total energy consumed in final sectors: | 4.37 | 4.29 | 4.19 | 4.29 |
| Total final energy exported: | 0.06 | 0.06 | 0.06 | 0.06 |
| Energy dependence [(A-B)/A], in %: | 88.4% | 88.2% | 88.1% | 88.2% |

According to our results, it may seem that biofuels are a less expensive means for decarbonization of cars. This is mainly due to electric cars' extra-cost over their reference fossil-fueled car (biofuel cars have no cost-premium over these, as seen). An extra case has been computed, in order to gain insights into this fact. We have seen how the flexible scenario ("Bios+Elec") evolves while electric cars' extra cost (over their reference fossil/biofuel car) is reduced

gradually, from no reduction (0%) to full reduction (100%, i.e. no extra-cost). The results can be seen in the next figure, where 10 scenarios are represented (all of them represent to the same "Bios+Elec" one, as said). Each of them represents a grade of decrement in electric cars' extra cost. It can be seen that, when these cost reductions are above 60%, the model chooses to use both types of cars in order to comply with the emissions constraint and that when the cost reduction is 100% (i.e. no extra cost of electric cars over biofuel and traditional cars), only electric cars are used.




## 7. Conclusions

A study of the costs of largely reducing CO2 emissions from Spanish cars in the 2030 horizon has been carried out. The first thing that is seen is that the costs of using these cars (investment and operational costs, excluding energy costs) are a key factor in the total costs to be minimised. The case where electric cars is paradigmatic: total energy supply costs are smaller (less energy being

delivered due to greater energy efficiency, and electricity cheaper, in average, than biofuels), but total system costs are bigger due to electric cars extra costs.

Following our model's results and taking into account our hypothesis, it seems that achieving large emissions reductions in private road transportation by cars through biofuels is cheaper than through electric cars. Hence the model, in the case where it can choose amongst both options, decides to go completely for biofuels. This result is mainly explained by the fact that electric cars have important cost-premiums over biofuel cars (which have been supposed to cost the same as an equivalent traditional car).

However, we find that this result is largely dependent on this extra cost of electric cars: as can be seen in the last graph, if electric cars' extra cost was null, decarbonisation through electric cars would be cheaper, due to the smaller average cost of electricity vs. that one of biofuels. Hence the electric car extra costs hypothesis is key in our research question. Some further research may be needed in this point, in order to obtain more robust conclusions.

Further research is needed as well to account for other advantages of electric cars for the system, such as the positive synergies with power grid operation in systems with large intermittent generation, the reduced local pollution (considering within the total system's cost the external costs of particles and $NO_X$ emissions), or the reduced energy dependence if biodiesel is imported and electricity is largely generated by renewable sources. In addition, further research will be soon conducted in order to consider transport demand

reduction policies, which have been omitted here, such as teleconferences promotion.

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