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EV Market Development Pathways – An Application of System Dynamics for Policy Simulation

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Abstract

The transport sector, in particular road transport, is a major consumer of energy and a major source of greenhouse gas (GHG) emissions, contributing to climate change. There is increasing pressure to reduce CO_2 emissions from passenger cars (e.g. in the EU, the Regulation (EC) No 443/2009 sets the limit of CO_2 emissions of new passenger cars to 95 g of CO_2 from 2020 [1]). Today, the global vehicle stock has more than 1 billion units and relies almost entirely on oil-based energy. According to various projections, the global vehicle fleet could double or even triple by 2050. The energy and environmental implications of such increase would not be negligible. In this context, it is argued that the electrification of the global vehicle fleet emerges as a desirable goal. Electric vehicles (EVs) are expected to help meet key energy and environmental goals, leading to a decrease in oil imports, an increase in energy independency and to a decrease in CO_2 emissions.

This paper focuses on the EV market penetration in key OECD countries as well as in China and India, considering various vehicle technologies for passenger light-duty vehicles (PLDVs). In particular, the paper investigates the impacts of EVs on oil demand and CO_2 emissions in the countries of interest under various scenarios until 2050. For this purpose, a System Dynamics (SD) model is developed and the results of various simulations assessed. The output of the model includes possible future market shares of EVs as well as their specific energy and environmental impacts. Our results show to what extent EVs can potentially contribute to reduce oil dependency andCO_2 emissions in the countries analysed beyond 2030.

Keywords: electric vehicle market penetration, system dynamics, energy scenarios

1 Introduction

The transport sector is a major consumer of energy and a major source of emissions. In 2006, transport accounted for 27.5% of the world total final energy consumption and for 23% of global energy-related CO_2 emissions and 13% of greenhouse gas (GHG) emissions [2]. Within transport, road transport (especially road passenger) accounted for 72.9% and 74% of total transport energy consumption and CO_2 emissions, respectively [3]. In 2010, there were more than 1 billion vehicles on the world's roads [4], most of them running on oil-based fuels [5].

From an energy perspective, the oil needed to fuel road transport has to be imported in many countries, which represents a considerable economic cost and a challenge for their energy security. From an environmental perspective, excessive car exhaust CO_2 emissions contribute to global warming.

1.1 Challenge

Countries with high levels of vehicle ownership are faced with the task of reducing their oil imports and limiting their GHG emissions. In parallel, emerging economies are benefiting from solid economic growth, which in turn increases the demand for travel and vehicle ownership. In particular, China and Indiaare experiencing rapid motorisation which, given their large populations, is actively influencing the global vehicle market.According to various projections, the global vehicle stock could double or even triple by 2050 [6]. This projected trend entails important energy and environmental implications, representing a challenge and highlighting the need to improve sustainability in the road transport sector. Since car travel is a popular mode of transport (e.g. in the EU cars account for around 72% of all passenger kilometres [7]) and is expected to continue to be in the future, technological improvements, in combination with behavioural changes, are needed. One proposed technological solution towards this end is the deployment of electric vehicles (EVs), which are expected to gradually replace conventional internal combustion engine vehicles (ICEVs).

1.2 Objectives and outline

The main objective of this paper[1]is to explore several possible EV market development pathways and their corresponding impacts on oil demand and CO_2 emissions in key countries.
The scope of this paper is PLDVs[2], with a focus on EVs[3].
The geographical coverage of this paper includes key OECD with high motorisation rates (such as the USA, France, Germany and UK) as well as China and India (due to aforementioned reasons). These are countries that have shown a strong interest in promoting electric mobility. The timeframe of this study extends until the year 2050.
The proposed outline for the remaining part of the paper is the following: Section 2 provides a brief overview of EVs, focuses on the key concept of "total cost of ownership" and includes some declared targets for EVs; in Section 3, the method applied in this study is presented; Section 4 shows the model output for each individual country; in Section 5, conclusions are drawn from our results.

2 EV market penetration

2.1 Electric vehicle definition

From an energy efficiency and environmental perspective, EVs areconsidered to be superior technology than ICEVs [8]. EVs are expected to significantly contribute to oil independency and CO_2 mitigation in the road transport sector. Moreover, EVs are also more environmentally-friendly as they reduce local urban air pollution and noise, contributing to improved urban air quality and health.
Figure 1 compares, from the point of view of the propulsion system, the differences in vehicle technology that are of interest to us.
Hybrid electric vehicles (HEVs) differ from conventional vehicles (CVs) insofar they include an electric generator to improve fuel economy. Plug-in hybrid vehicles (PHEVs) go beyond that and can connect to an external source of electric power to recharge its battery. Extended range electric vehicles (EREVs) have in addition a combustion engine to provide extra mileage. Battery electric vehicles (BEVs) do not possess any combustion engine, but rely entirely on the electric motor and rechargeable battery pack. FCEVs use a fuel cell to generate electricity, from hydrogen stored in the tank,to power the electric motor.

CV HEV PHEV EREV BEVFCEV

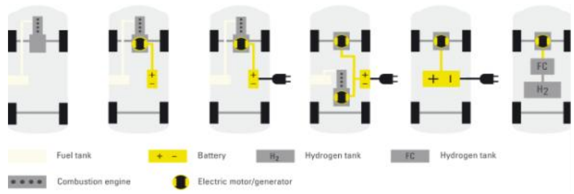

Figure1: Vehicle propulsion systems [9].

[1] The paper is the interim result of on-going doctoral work on this topic. The model used for this paper is a preliminary version of the final model, to be presented at the end of the PhD.
[2] According to IEA, this category includes automobiles, light trucks, sports utility vehicles (SUVs) and mini-vans.
[3]Although fuel cell electric vehicles (FCEVs) are not included in this paper, they will be incorporated into the model at a later modelling phase.

2.2 Total cost of ownership

ICEVs and EVs directly compete as durable products in the vehicle market. There are various key factors[4] influencing the decision of which vehicle technology to purchase, but our focus here is on cost for the potential buyer.

The vehicle purchase price is assumed to be the key factor affecting successful penetration of EVs. Today, consumers willing to buy an ICEV face in general lower upfront costs. The higher relative purchase price of an EV is attributed to the high cost of the battery (largely influencing the final purchase price of an EV) and the absence to date of economies of scale in EV production. Even under the assumption that the purchase price of EVs will not be (substantially) reduced during the next years[5], it can be argued that this is a myopic framework for assessing the full costs a potential buyer faces for eachvehicle technology. Instead, it is suggested that the analysis of the "total cost of ownership" (TCO) provides with the right cost evaluation framework, since it does not only consider upfront costs but also the whole cost of vehicle ownership and usage over the full product lifetime. Thus, from a consumer perspective, thinking in terms of the actual TCO emerges as a superior basis for making purchasing decisions that are thought to be, given a purely economic motivation,rational. Therefore, the TCO concept represents a more accurate framework for fairer cost comparisons between ICEVs and EVs.

Although the purchase price can make EVs look initially a more expensive option, the TCO analysis may give evidence that EVs are in fact overall cheaper than ICEVs.The result of the TCO is, however, highly dependent on a relatively large number of factors (e.g. annual mileage, vehicle lifetime), which makes its calculation slightly less straight-forward as merely considering the purchasing price. Figure 2 shows, in a stylised manner, the key factors affecting the TCO of ICEVs and EVs.

In broad terms, EVs face substantially lower usage or driving costs than ICEVs. Fuel represents a significant portion of ICEVs operating costs and, in the context of limited crude oil availability and high international oil prices, this important aspect is undoubtedly beneficial for EVs.

Furthermore, the introduction of fiscal incentives to promote the use of more energy efficient and environmentally cleaner technology can more evidently tip the scale in favour of EVs.

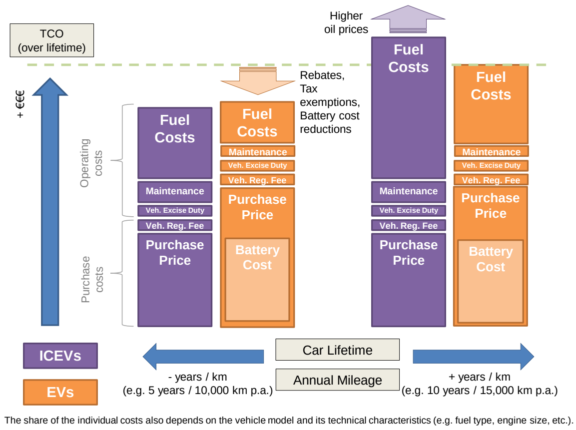

Figure 2: Stylised representation of the key factors affecting the "Total Cost of Ownership" (TCO) of ICEVsandEVs. Own work

2.3 Electric vehicle deployment targets

In recognition of the positive energy and environmental impacts that EVs can potentially deliver, governments have already started to lay out explicit plans for EV deployment, often crystallising into specific targets for EV market penetration. For example, India recently adopted its National Electric Mobility Mission Plan 2020 [10]. Table 1 shows the EV target for 2020 in key countries.

Table1: Examples of national targets for EVs (million vehicles). Own work based on [11]

Country	China	France	Germany	India	UK	US
Year 2020	5	2	1	7	1.5	1.5

It is uncertain how large the vehicle stock will grow over the next decades and, to what degree, it will reflect successful EV market penetration (see [12] for a recent overview of projections). It also remains to be seen whether the abovementioned EV targets will be achieved in those countries, but they do greatly reflect not only a recognition of the increasingly important role EVswill play in making transport more sustainable, but also a clear willingness to fulfil this goal.

[4] Other factors, such as the availability of infrastructure to recharge the EV battery and environmental considerations in the buying decision, though also expected to play a role, are for the purpose of our analysis out of the scope of this study.

[5] Due to e.g. technology improvements that lead to a reduction in battery costs, which can in turn be reflected in the EV's final purchase price.

3 Methodology

Much of the research conducted in the field of car ownership forecasting has relied on the theory of product life and the application of statistical techniques to historic data [13].Since our paper puts the focus on the exploration of future development pathways, with a long horizon until the year 2050, a research approach relying on simulation methods is preferred over a purely econometric approach. The required modelling approach should allow us to investigate, in a flexible manner, the key energy and environmental implications of future EV market development pathways. This entails the construction of various possible scenarios and the development of a simulation model. For our purpose, the System Dynamics (SD) framework emerges as a suitable modelling approach, because it enables us to better understand the complex behaviour of the road transport system and the interactions among vehicle fleets, road energy consumption and road CO_2 emissions. SD, used for policy analysis and design, is an approach to better understand complex dynamic systems characterised by interdependence, mutual interaction, information feedback and circular causality, andinvolves *inter alia* the identification of independent stocks and their inflows and outflows [14] [15] [16].

Figure 3reflects, in a simplified and schematic manner, an underlying mental model of the system affecting global vehicle stock, potentially useful to understand how the CV stock could be gradually replaced by EVs.

In order to assess the impacts of the various vehicle technologies, three basic scenarios have been created. Each scenario reflects different assumptions with regards to the share each technology holds:

- In Scenario 1, CVs (gasoline and diesel) hold 100% of the market. This is a very pessimistic view of new vehicle technology deployment but serves as a reference mode for comparisons between scenarios.
- Scenario 2 characterises a hybridisation of the vehicle market, where HEVs manage to acquire 60% of the market share at the cost of CVs. PHEV/EREVs and BEVs fail however to captivate consumers.
- In Scenario 3, an electric revolution is depicted, with PHEV/EREVs, BEVs and HEVs holding 40%, 30% and 20% of the market share, respectively, by 2050.

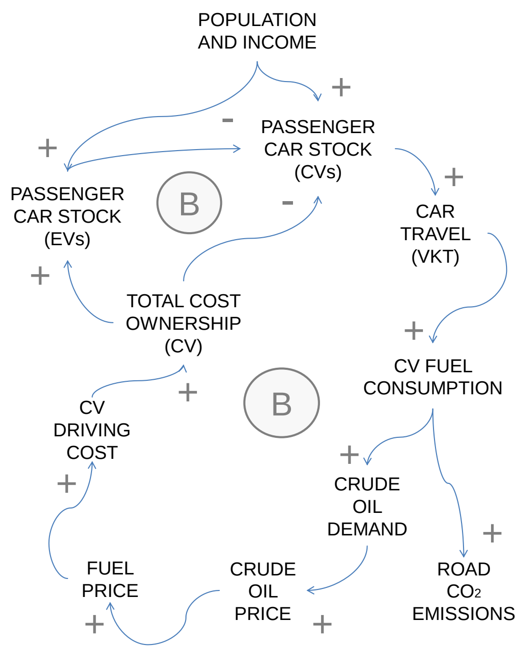

Figure3: Simplified causal diagram for the global vehicle stock. Own work following [17]

4 Results

The key output of the SD model for each of the countries analysed is shown below. With regards to the market development, only the output of Scenario 3 is included[6]. The output related to energy demand and CO_2 emissions, however, includes the output of the three scenarios to allow comparability.

4.1 USA

Figure 4-6 shows the key results for the USA.

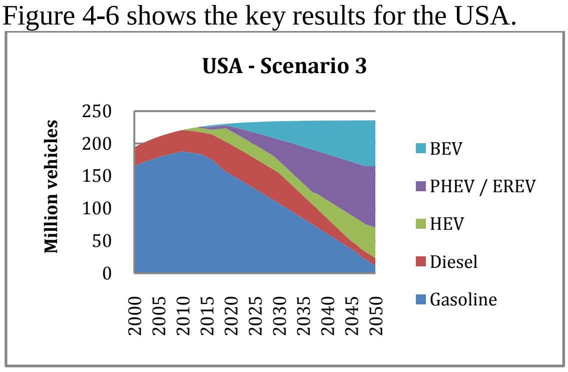

Figure4: USA market development until 2050

[6] The reason why is because Scenario 3, which reflects the successful market penetration of EVs, is the most interesting one to this paper.

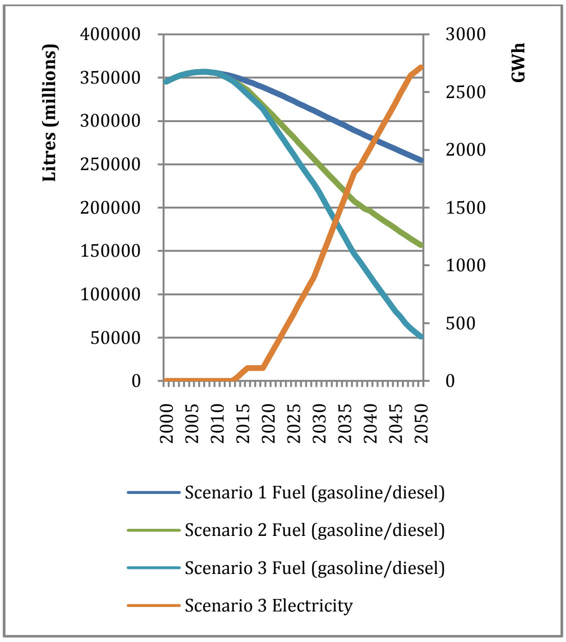

Figure5: USA energy demand until 2050

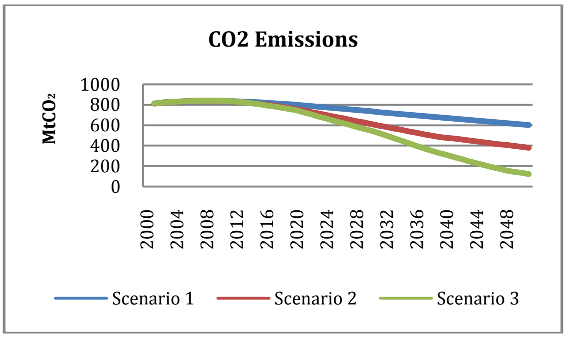

Figure6: USA CO_2 emissions until 2050

In the USA, the vehicle stock is projected to stabilise towards 2020 and remain relatively flat until 2050. From around 2015, a trend towards oil and CO_2 savings are expected to emerge. The size of these savings varies in accordance with the scenario under consideration.

4.2 China

Figure 7-9 shows the key results for the China.

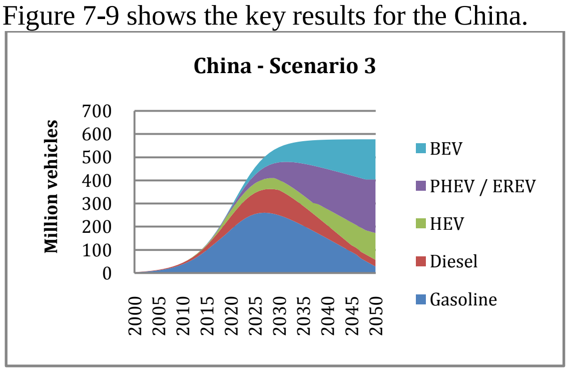

Figure7: China market development until 2050

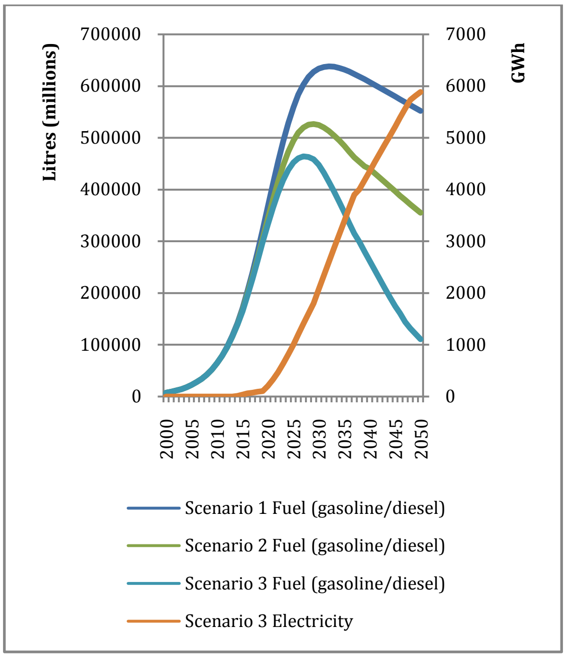

Figure8: China energy demand until 2050

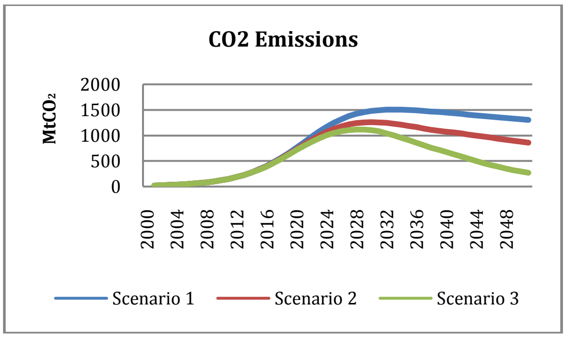

Figure9: China CO_2 emissions until 2050

In China, the vehicle stock is projected to increase strongly until around 2030 and show some signs of market saturation afterwards. As a consequence of this intense growth, oil demand and CO_2 emissions are expected to continue rapidly growing until at least the year 2025.

4.3 India

Figure 10-12 shows the key results for the India.

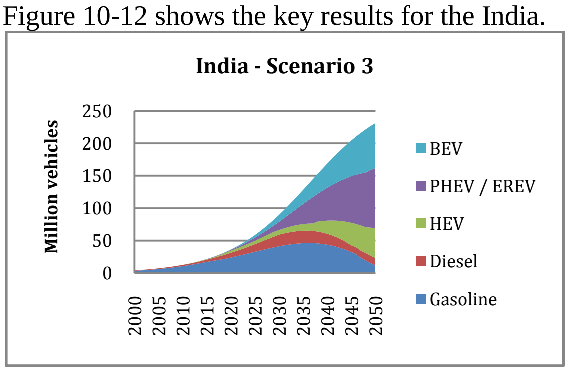

Figure10: India market development until 2050

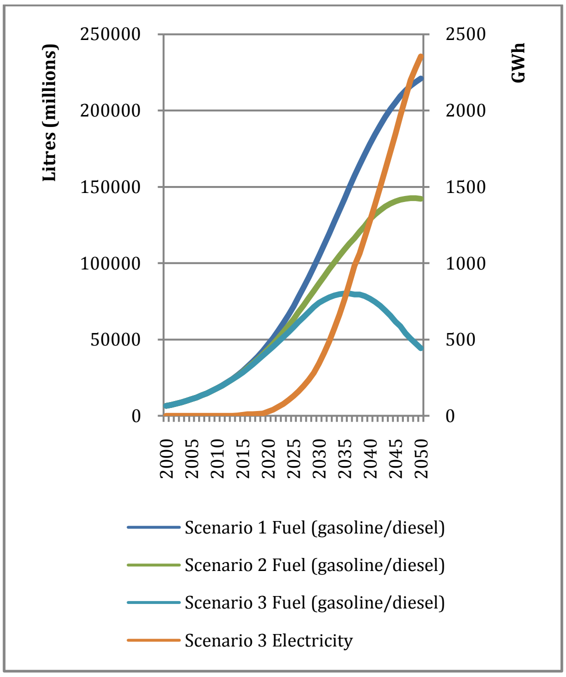

Figure11: India energy demand until 2050

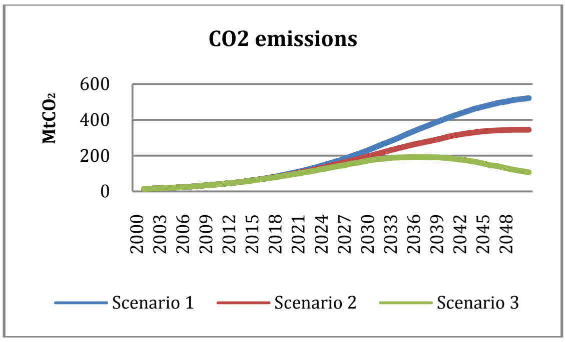

Figure12: India CO_2 emissions until 2050

India is expected to experience rapid motorisation and consequently growing oil demand and CO_2 emissions. In Scenario 3, the trend is reversed by mid-2030.

4.4 France

Figure 13-15 shows the key results for the France.

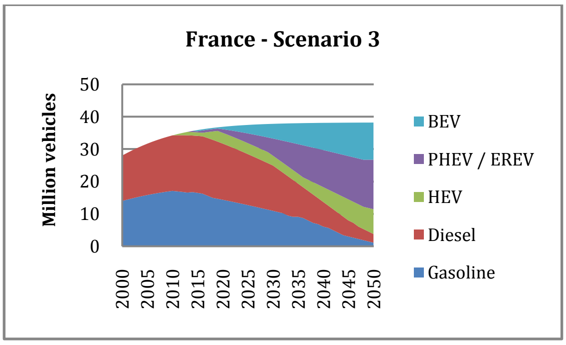

Figure13: France market development until 2050

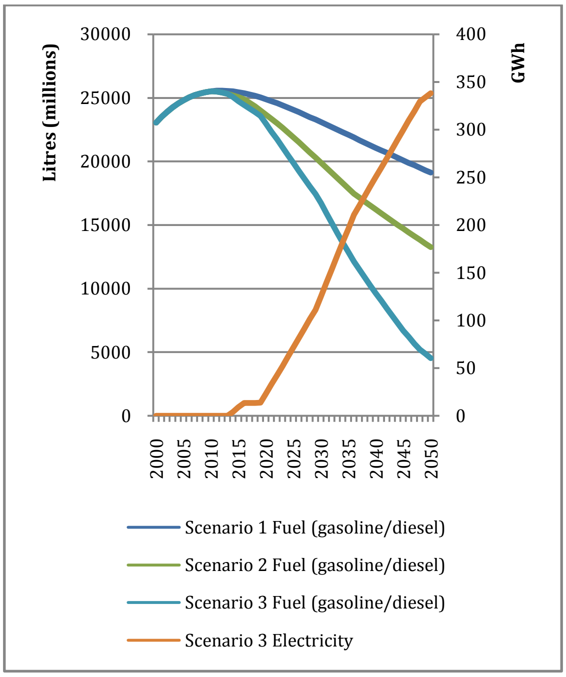

Figure14: France energy demand until 2050

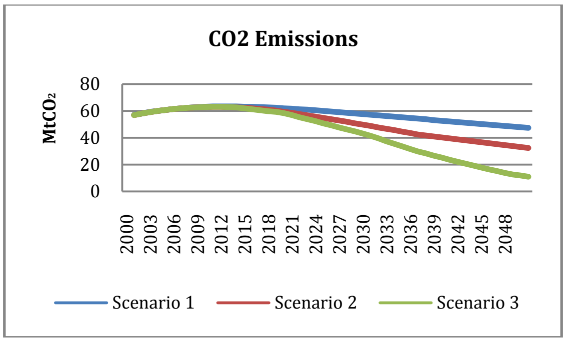

Figure15: France CO_2 emissions until 2050

In France, the oil and emissions trends, affected by very low vehicle growth, are characterised by a continuous decay.

4.5 Germany

Figure 16-18 shows the key results for the Germany.

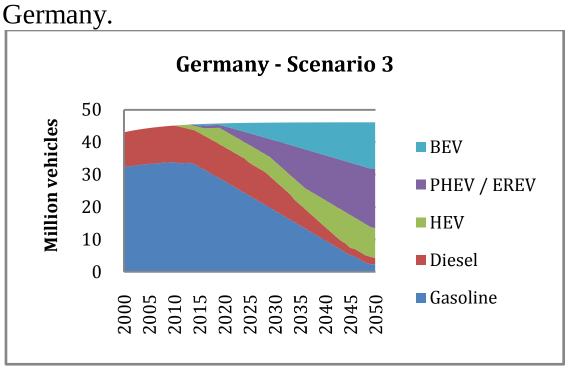

Figure16: Germany market development until 2050

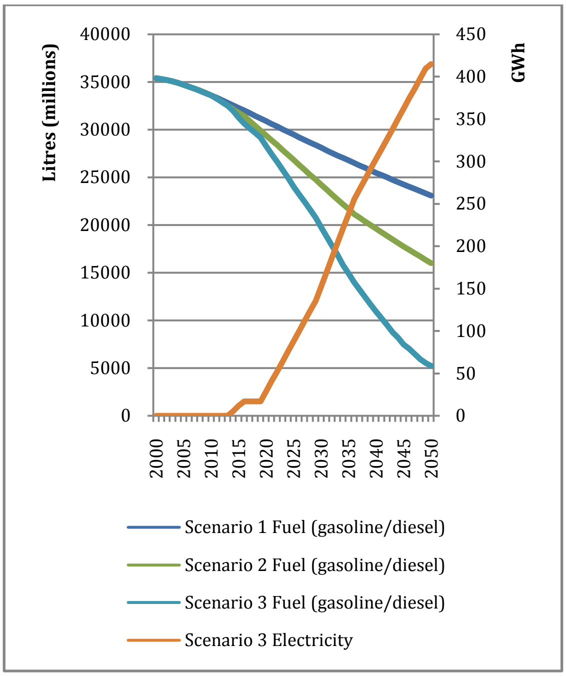

Figure17: Germany energy demand until 2050

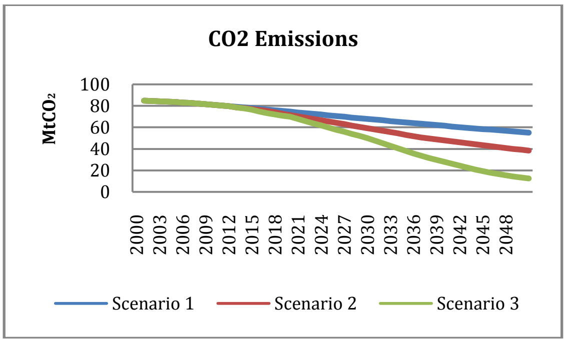

Figure18: Germany CO_2 emissions until 2050

Similar to the French case, vehicle stock in Germany is projected to remain relatively flat, which favours large oil and emissions reductions.

4.6 UK

Figure 19-21 shows the key results for the UK.

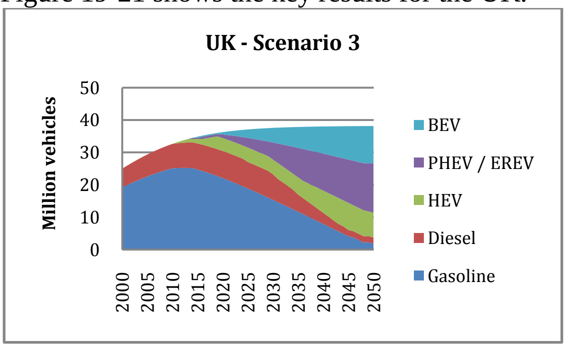

Figure19: UK market development until 2050

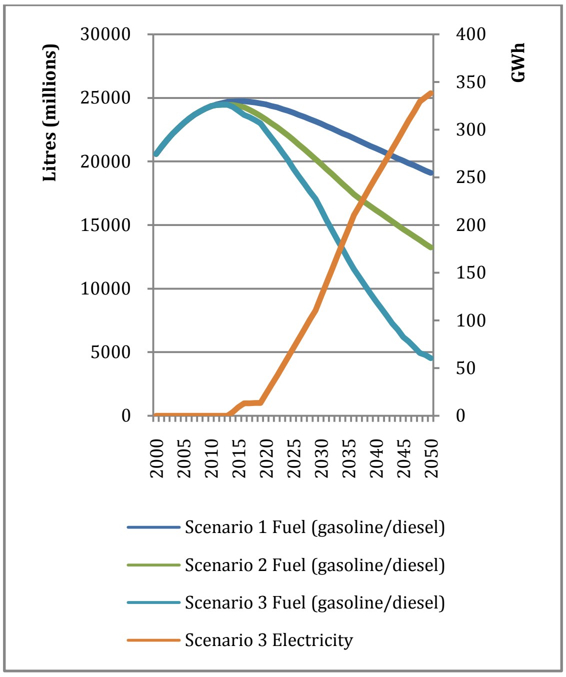

Figure20: UK energy demand until 2050

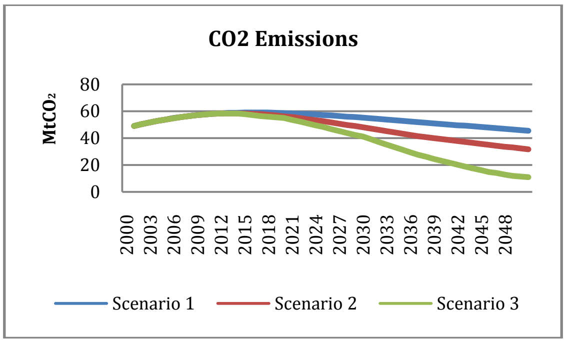

Figure21: UK CO_2 emissions until 2050

In the UK, the vehicle stock continues to growth during the next decade and seems to level off afterwards. In accordance, oil demand and emissions show a declining trend.

5 Conclusions

The need for increasing energy efficiency and reducing CO_2 emissions from the passenger road transport system, in line with specific energy and environmental policy objectives, has unleashed a strong movement towards the electrification of the vehicle stock. Today, EVs are competitive alternatives to ICEVs and are expected to become mass products over the next years, progressively replacing the latter. Theprocess towards the full scale electrification of road transport seems to have commenced.

This development is regarded as positive, since EVs are expected to contribute to reduce road oil consumption and its associated CO_2 emissions.

This hypothesis has been explored in this study, by analysing the impacts of EVs until 2050 in key countries. For our purpose, a simulation model based on the SD method has been developed, and the results of three scenarios have been assessed.
Our results show that EVs contribute to restrain oil demand and CO_2 emissions in the selected countries by 2030, and to significantly reduce them thereafter. Therefore, our analysis suggests that EVs can potentially assist in lowering energy dependency on non-renewable resources as well as in mitigating road CO_2 emissions, thus actively contributing towards the achievement of these key energy and environmental objectives.
Our results can be of interest to policy-makers and decision-makers responsible for improving the sustainability of the road transport system as well as to the private industry, in view of more stringent emission standards in the future.
It may be advisable to highlight, in particular, the important role effective policy instruments play to facilitate the vehicle electrification process, in view of the need to foster the demand for EVs at this crucial stage of EV market penetration, especially in advanced OECD countries. In this context, the introduction of adequate fiscal incentives, favouring cleaner technology that generate less negative externalities, may represent a valuable 'carrot-and-stick' policy instrument[7].
Finally, by adding together the emission savings that could be realised in the analysed countries, important conclusions with regards to global mitigation efforts in road transport can be drawn.

Acknowledgments

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[7]Especially in the case that a significant EV battery cost reduction does not actually occur in the future.

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