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The impact of the EU car CO_2 regulation on the energy system and the role of electro-mobility to achieve transport decarbonisation

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HIGHLIGHTS

- Car CO_2 regulation effective policy to reduce transport CO_2 emissions.
- Learning rate above 12.5% can lead to sharp increase in electric vehicle deployment.
- Electric vehicles can foster the deployment of variable renewable electricity.
- Policies for other modes needed to curb transport CO_2 growth.

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ABSTRACT

We analyse the impact of the current and an alternative stricter EU CO_2 car legislation on transport related CO_2 emissions, on the uptake of electric vehicles (EV), on the reduction of oil consumption, and on total energy system costs beyond 2020. We apply a TIMES based energy system model for Europe. Results for 2030 show that a stricter target of 70 g CO_2/km for cars could reduce total transport CO_2 emissions by 5% and oil dependence by more than 2% compared to the current legislation. The stricter regulatory CO_2 car target is met by a deployment of more efficient internal combustion engine cars and higher shares of EV Total system costs increase by less than 1%. The analysis indicates that EV deployment and the decarbonisation of the power system including higher shares of variable renewables can be synergistic. Our sensitivity analysis shows that the deployment of EV would sharply increase between 2020 and 2030 at learning rates above 12.5%, reaching shares above 30% in 2030. Finally, the study highlights that, besides legislating cars, policies for other transport sectors and modes are needed to curb transport related CO_2 emission growth by 2030.

1. Introduction

Significant improvements in the specific fuel consumption of passenger cars in the EU (European Union) have been achieved over the last years (Fontaras and Dilara, 2012). Nevertheless, because of the growth of car transport, this has not fully translated into the same level of reduction of CO_2 emissions from passenger cars in the EU. The transport sector is the only sector which emissions were growing in the EU (by 19%) when comparing 2013 to the baseline year 1990 (Eurostat, 2016). Moreover, passenger car transport is expected to further grow over the next decades (European Commission, 2013a). Therefore, the EU recently adopted a CO_2 legislation, setting specific CO_2 emission targets of the average new fleet at 130 g/km for 2015 (EC, 2009a) and 95 g/km by the end of 2020 and onwards (EU, 2014a). This legislation is currently based upon type approval values and CO_2 emission measurements, done according to the New European Drive Cycle (NEDC). Historically (up to 2005), the CO_2 emissions measured in the NEDC were in average around 15% lower than the real drive CO_2 emissions on the road. Publications indicate that this gap may have increased recently (Fontaras and Dilara, 2012; EEA, 2014; ICCT et al., 2014), however the European Commission proposed a package including new testing procedures to limit the emission gap between test

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and real driving conditions (European Commission, 2016). Furthermore, the European Commission has proposed to reduce the total greenhouse gas (GHG) emissions in the EU by 40% in 2030 over the 1990 levels (European Commission, 2014a).

This policy has an impact on the technological mix in the transport sector, but also affects the overall energy sector due to the substitution of fuels: oil may be substituted by e.g. natural gas or electricity, when new technologies enter the market. In particular, an increased use of electricity by car transportation may have impacts on costs and CO_2 emissions in the electricity generation sector, which could trigger changes in other sectors due to changes of relative costs of energy sources – and due to the restrictions of the European Emission Trading Scheme (ETS). The assessment of the impact of the CO_2 car regulation policy on total GHG emissions in the energy sector therefore has to rely on a systemic approach.

In the past, many legislative measures and scenarios in the transport sector were primarily analysed with tools focussing on the transport sector only, which often use exogenous scenario assumptions for the evolution of fuel or energy supply (Fontaras et al., 2007; Pasaoglu et al., 2012; Sorrentino et al., 2014; Thiel et al., 2014; Bauer et al., in press). A number of publications have analysed various aspects of different powertrain technologies, such as (i) well-to-wheel emissions, efficiencies, and total cost of ownership (Thiel et al., 2010; Bishop et al., 2014; Millo et al., 2014; Waller et al., 2014), (ii) impacts on air pollution in cities (Donateo et al., 2015), and (iii) behavioural aspects (Tran, 2012). Brouwer et al. (2013); Foley et al. (2013); Loisel et al. (2014); Verzijlbergh et al. (2014) study the interaction between electric vehicles and power supply, markets, and interconnection, but do not assess impacts on the whole energy system.

Some studies have taken a systemic view into account and employed energy system optimisation models in order to analyse future vehicle scenarios in the context of an overall energy decarbonisation strategy (Ichinohe and Endo, 2006; Bahn et al., 2013; Anandarajah et al., 2013; Rösler et al., 2014; Seixas et al., 2015). The use of these models has the advantage that, rather than using prescriptive exogenous scenario assumptions, the cost-optimal deployment of technologies is endogenously determined by the model. However, those studies have been conducted with a low disaggregation of the vehicle technologies, which limits the capability of the models to fully explore the potential of the most important available low-carbon technologies in the sector. Additionally, only Rösler et al. (2014) and Seixas at al. (2015) had a look at Europe specifically, and none of the studies assessed the EU car CO_2 regulation.

In this exploratory study we therefore use a TIMES[2] based energy system model (Loulou et al., 2005) to analyse, how a specific policy, the EU CO_2 car legislation, can contribute towards an overall EU 40% GHG reduction target and how it may foster the deployment of electro-mobility in Europe. While this analysis starts from the basis of the impact assessment that accompanied the proposal of the 40% GHG reduction target (European Commission, 2014b) and builds upon earlier other studies that were performed with TIMES/MARKAL energy system models (Ichinohe and Endo, 2006; Bahn et al., 2013; Anandarajah et al., 2013; Rösler et al., 2014; Seixas et al., 2015), we study the car sector at a much higher technology detail in the context of the car CO_2 legislation. We discuss in detail the role that electro-mobility could play in order to achieve the EU's objectives on decarbonisation and energy independence and we perform sensitivity analyses to test the robustness of the model outcomes under variations of assumed learning rates for EV technologies, considering recent evidence of increased progress in battery cost reduction (Nykvist and Nilsson, 2015). EV in this study comprises battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and hydrogen fuel cell (HFC) cars.

The remainder of the article is structured as follows: Section 2 describes the data and methods applied in this analysis, Section 3 describes the results while Section 4 discusses these. Section 5 draws conclusions and highlights policy implications.

2. Methods and data

This chapter describes in sub-Section 2.1 the JRC-EU-TIMES energy system optimisation model and in sub-Section 2.2 the design of scenarios as well as the design of the sensitivity analysis.

2.1. JRC-EU-TIMES energy system optimisation model

The JRC-EU-TIMES model is used for this study that focusses on passenger cars and does not consider differentiated scenarios for other modes of transportation. JRC-EU-TIMES is a linear optimisation bottom-up energy system model generated with the TIMES model generator. Its objective function minimises the total energy system costs over the entire modelling horizon. The minimisation is subject to constraints, for example primary resources supply bounds, technical constraints, balance constraints for energy and emissions, timing of investment, and the satisfaction of a set of demands for the energy services of the economy. TIMES based model applications are used by numerous research teams for a variety of analyses at a sector, country, region or multi-region level that require an energy system perspective. See besides the above mentioned publications for example Vaillancourt et al. (2014), Daly et al. (2014) and Cayla and Maïzi (2015), or for a wider overview of recent TIMES model applications Giannakidis et al. (2015). The JRC-EU-TIMES model represents the EU28 (the 28 member states of the EU) energy system plus Switzerland, Iceland, Norway, and the Western Balkan countries from 2005 to 2050, where each country is modelled as one region. It includes the following sectors: primary energy supply; electricity generation; industry; buildings; agriculture; and transport (Fig. 1).

As a partial equilibrium model, JRC-EU-TIMES does not model the economic interactions outside of the energy sector. Nevertheless, they are considered to some extent via price elasticities of service demands. In this analysis, JRC-EU-TIMES' demands are sensitive to price changes as described in Kanudia and Regemorter (2006). The price elasticity for car passenger kilometres is assumed to be -0.3 and symmetrical. A 10% increase in the endogenous total cost of a passenger kilometre will lead to a 3% decrease of this particular demand and vice versa. For cost reductions, this feature reflects rebound effects that would typically not be considered in supply oriented cost-minimisation models.

The most relevant model outputs are the annual stock and activity of energy supply and demand technologies for each region and period, with associated energy and material flows including emissions to air and fuel consumption for each energy carrier. Besides these, the model computes operation and maintenance costs, investment costs, energy and materials commodities prices. Each year is divided in 12 time-slices that represent an average of day, night and peak demand for every one of the four seasons of the year.

The model is supported by a detailed database, with the following main exogenous inputs: (1) end-use energy services and materials demand; (2) characteristics of the existing and future energy related technologies, such as efficiency, stock, availability, investment costs, operation and maintenance costs, and discount

[2] TIMES: *T*he *I*ntegrated *M*ARKAL-*E*FOM *S*ystem; MARKAL: *Mark*et *Al*location; EFOM: *E*nergy *F*low *O*ptimisation *M*odel.

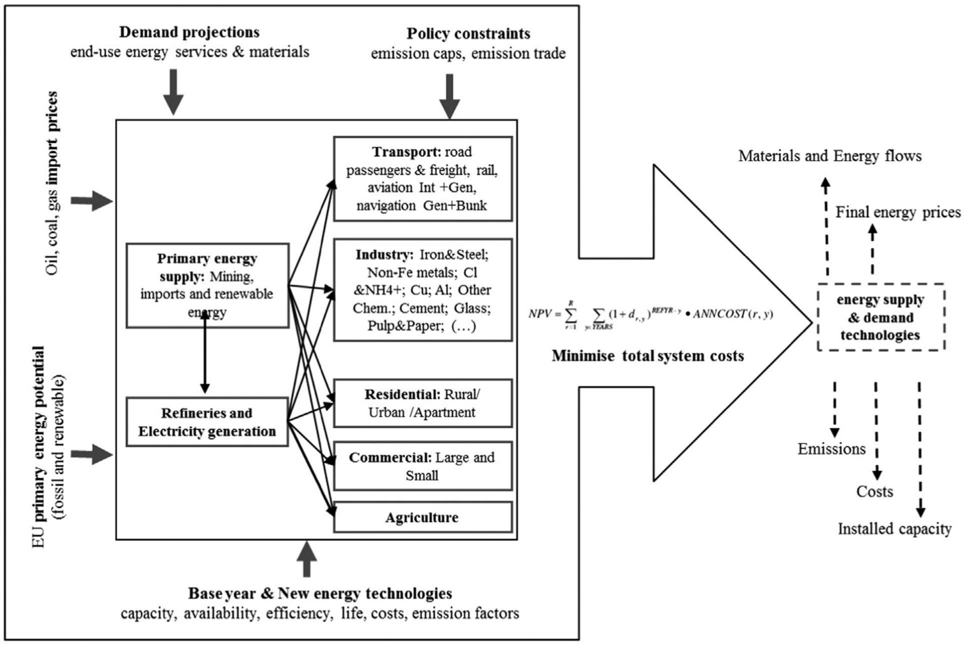

Fig. 1. Simplified structure of the JRC-EU-TIMES model (adapted from Simoes et al., 2013).

rate; (3) present and future sources of primary energy supply and their potentials; and (4) policy constraints and assumptions. In this section we present a rather condensed version of the detailed model inputs which are further described in Simoes et al. (2013).

(1) The materials and energy demand projections for each country are differentiated by economic sector and end-use energy service, using as a starting point macroeconomic projections from the GEM-E3 (General Equilibrium Model for Energy-Economy-Environment interactions) model; for a description of GEM-E3 see EC4MACS (2012);
(2) The energy supply and demand technologies for the base-year are characterised considering the energy consumption data from Eurostat to set sector specific energy balances. The new energy supply and demand technologies are compiled in a database with detailed technical and economic characteristics;
(3) The present and future sources (potentials and costs) of primary energy and their constraints for each country are from the GREEN-X[3] model for bioenergy. For other renewable energy sources, for uranium, and fossil fuels the primary energy potentials are taken from several sources as detailed in Simoes et al. (2013). It is possible to import energy commodities from outside the EU, with import prices taken from European Commission, (2013a);
(4) The policy constraints as CO_2 emission caps and ETS, are presented in Section 2.2.

For this analysis a number of updates were done on the JRC-EU-TIMES model from what is described in Simoes et al. (2013): (i) energy service demands were updated according to the latest EU reference scenario (European Commission, 2013a), (ii) the techno-economic assumptions of the generation and conversion technologies were updated according to the “Energy Technology Reference Indicator projections for 2010–2050″ (Joint Research Centre, 2014), (iii) the hydrogen production and distribution pathways were updated as described in Sgobbi et al., submitted for publications, (iv) biomass based pathways and biomass resource potentials were updated as described in Ruiz et al. (2014), and (v) energy storage technologies and the handling of variable renewable technologies was modified along with the addition of flexibility constraints for the power sector, as explained in Nijs et al., (2014a, 2014b). To address flexibility issues, each of the 12 time-slices of the power sector is further split into two sub-periods. In 12 out of the 24 sub-periods, there is a possible excess generation of electricity, endogenously calculated for each country based on the installed power of photovoltaic panels, wind and wave technologies as well as on demand profiles. This allows modelling the competition amongst curtailment and different transformation and storage options in case of excessive variable renewable electricity production (Sgobbi et al., 2015). In this context, up to 10% of the energy capacity of the batteries of BEV and PHEV are added as a flexible power resource that can provide load shift or V2G (vehicle-to-grid) services. A schematic representation of this mechanism is shown in Fig. 2.

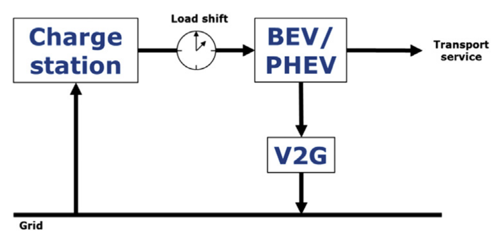

Fig. 2. Schematic representation of flexibility services that BEV can provide within the JRC-EU-TIMES model.

Investment costs for the alternative fuel distribution and refilling infrastructure (including charge points) are included in the model. They have been derived from investment costs published by European Commission, (2013b); European Expert Group on Future Transport Fuels, (2011), Fraunhofer ISE (2013), and Department of Energy, 2012. We have converted these values to energy related delivery costs and in the model they are added as a mark-up to the energy costs (i.e. the fuels) delivered to the cars. Table 1 shows the investment costs and the mark-up costs, as

[3] GREEN-X: Simulation model to determine the RES-E (electricity from renewable energy sources) potential, for more information see Huber et al. (2004)

Table 1.
Costs for alternative fuel distribution and refilling/ charging infrastructure.

	LPG	CNG	EV charge station	Hydrogen
Mark-up on energy (in Euro/GJ)	0.40	3.80	15.00	8.35
Investment cost in Euro per facility	30,000	2,50,000	1500	11,00,000
Assumed annual minimum energy delivery (GJ/year)	7000	7000	10	14,000

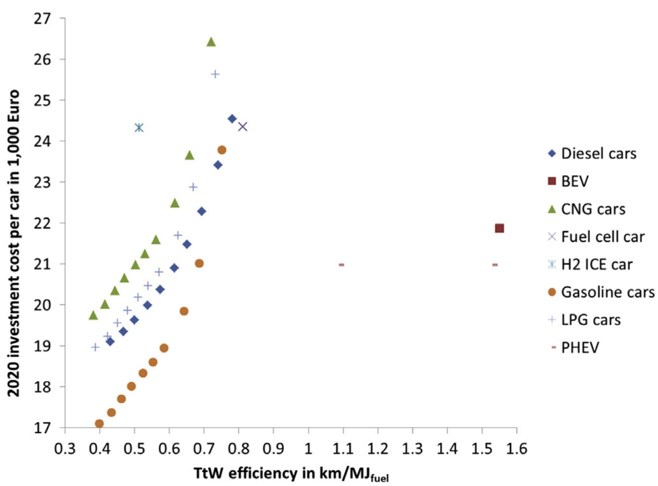

Fig. 3. Techno-economic parameters for 2020 car technologies (example Germany, short distance trips).[4]

applied in the model. The BEV/ PHEV charge station is the sum of one private charge point per EV and one public charge point per ten EV. No learning is applied to any of the alternative fuel refilling/ charging infrastructure costs. The model allows flexible blending of biofuels and fossil fuels up to a maximum of 85% biofuel content. The blending levels are endogenously determined by the model and are scenario dependent.

Different to Simoes et al. (2013), we have disaggregated the car technologies further in this analysis. We differentiate between 45 car powertrain variants including several improvement levels for conventional cars, alternatively fuelled cars, such as compressed natural gas (CNG) cars, liquefied petroleum gas (LPG) cars, BEV, PHEV for short and long range, and hydrogen fuel cell (HFC) cars. The techno-economic assumptions for these technologies are based on Thiel et al. (2014). Technology specific learning over time is considered as an exogenous model input, translated as lower costs over time. A learning rate of 10% for the costs of the EV specific powertrain components is used as standard in all scenarios. Assumed global cumulative sales volumes by 2030 underlying the cost calculation are 206 million BEV, 77 million PHEV, and 33 million HFC. An average sized car model is taken as a basis for the development of efficiency and costs of the car technologies. Member state specific differences in the vehicle fleet composition in terms of size, average mileage, and real drive efficiency are implicitly considered in the model through the base year (2005) data from EUROSTAT, TREMOVE and explained in Simoes et al. (2013). In 2005 there was in average a gap of roughly 15% between type approval tested and real drive energy efficiency of cars. This gap remains constant in the scenarios employed for this study as the European Commission has adopted measures to keep this gap within reasonable limits (European Commission, 2016). In order to reflect the member state differences in diesel car deployment, we have applied a country specific constraint to ensure minimum shares of diesel fuelled cars out of the internal combustion engine (ICE) propelled cars based on extrapolating recent trends in powertrain shares. The model differentiates between efficiency levels for short and long trips as described in Simoes et al. (2013). Specifically for BEV, the average electricity consumption for long distance travel was assumed to be 15–20% higher than for short distance travel. Similarly to Seixas et al. (2015) we assume that PHEV and HFC can deliver long distance travel as other non-electric cars. For BEV we assume that in 2010 their share of delivered long distance travel to short distance travel is limited to 15%. This limit increases linearly from 2010 to 2030 to 60% since in that time frame more BEV with fast charging capability and more fast chargers will be deployed.

Fig. 3 shows for the example of Germany the techno-economic parameters of the different car powertrain technologies as applied for the 2020 car investment costs and corresponding tank-to-wheel (TtW) efficiencies of short distance trips. The efficiencies for long trip distances are usually slightly higher (except for BEV). Because of the different portfolios (with in average differently sized vehicles) each member state has slightly different efficiency values. Fig. 3 shows the 10 different efficiency levels and associated costs that are implemented for each of the gasoline, diesel, CNG, and LPG propelled variants. The figure reveals the design of the cost curves that lead to a higher slope of the cost-efficiency curve at higher efficiencies. The very efficient ICE propelled cars require full hybridisation as well as other advanced technologies such as waste heat recovery through thermo-electric generators. Additionally, Fig. 3 shows the hydrogen driven cars, fuel cell and ICE based. Finally, it shows the BEV and the two PHEV variants, one with more electric driving share than the other. The vehicles that are mainly driving on electricity have the highest TtW efficiencies since most of their efficiency losses occur upstream in the generation processes. In the appendix is as an example a table with the techno-economic assumptions for 2020 car technologies for Italy.

2.2. Design of scenarios and sensitivity analysis

We run the model up to 2050 with the policy scenarios as described in Table 2: (i) reference aligned to European Commission (2013a, 2014a, 2014b), including a 10% renewable energy target for 2020 (EC, 2009b), which is currently not extended beyond 2020, and including a CO_2 car legislation with a new fleet average target of 130 g CO_2/km by 2015 (EC, 2009a), (ii) current CO_2 car legislation with a new fleet average target of 95 g CO_2/km by 2021 (95 g scenario), in accordance to EU (2014a), (iii) an exploratory scenario of an alternative stricter future CO_2 car legislation with a new fleet average target of 70 g CO_2/km by 2030 (70 g scenario) on top of the 95 g scenario, inspired by a European Parliament (2013) report . The previous legislation (EC, 2009a) included a provision for crediting the use of E85 (blended gasoline with 85% bio-ethanol content) by up to 5% for each E85 car. This provision expired at the end of 2015. This crediting has not been considered in the model. The CO_2 car legislation has been implemented in the model as a constraint on the new car sales fleet, in which the EU sales weighted average CO_2 emissions of the new car fleet has to be lower or equal to 130 g CO_2/km from 2015 onwards (Ref scenario), lower or equal to 95 g CO_2/km from 2021 onwards (95 g scenario) and then lower or equal to 70 g CO_2/km from 2030 onwards (70 g scenario) under the type approval conditions of the NEDC. For this we have assigned CO_2 values to each of the vehicle configurations, which are based on the 2010 fleet

[4] For interpretation of the references to the colour in the the reader is referred to the web version of this article.

Table 2.
Scenario design.

Scenario	Energy system CO_2 target	ETS sector	Energy efficiency target	New car TtW CO2 fleet target (in g/km)	EV learning rate
Ref	2020: at least 20% reduction; linear interpolation between 2020 and 20,302,030–2050, in each year: at least 40% reduction (all versus 1990)	At least 21% reduction in 2020; at least 43% reduction in 2030 and at least 60% reduction in 2050 (all versus 2005), linear interpolation 2020–2030 and 2030–2050	2030–2050 in each year: total primary energy consumption reduced by at least 27% versus no policy scenario	130 from 2015	Standard (i.e. 10%)
95 g	as Ref but transport excluded from overall target			As Ref and 95 from 2020	
70 g				as 95 g and 70 from 2030	

average value of 142.5 g CO_2/km for the new gasoline car and 139.3 g CO_2/km for the new diesel car in that year (EEA, 2014) and respective lower CO_2 values for the more efficient vehicle configurations. The exact formulation of the constraint is given in the Appendix. It is important to note that this constraint influences only the deployment of the vehicle configurations. The (real drive) energy use and emissions of these configurations are modelled as described in Section 2.1.

Recent publications and industry statements indicate that battery costs may decline faster than originally anticipated in previous studies (Weiss et al., 2012; Nykvist et al., 2015). Therefore, we have performed a sensitivity analysis for 2030 on the basis of the 70 g scenario: varying the learning rate for the costs of the EV specific powertrain components. The exogenous learning rates in the sensitivity analysis are 5%, 7.5%, 10% (i.e. standard in all scenarios), 12.5%, and 15%. A 10% learning rate relates in the model to specific battery costs of approximately 190 $€_{2010}$/kW h in 2030, while a 12.5% learning rate relates to costs of approximately 140 $€_{2010}$/kW h in 2030.

In line with European Commission, (2013a), the passenger transport activity increases in the JRC-EU-TIMES model for passenger cars from 5340 billion person-km (bpkm) in 2010 to 6620 bpkm in 2050. For the EU this is an average annual increase of approximately 0.65% for the 2010–2050 time-frame. From member state to member state it varies significantly reaching values between 0.2% and ca. 1.5% for the same time-frame.

3. Results

This Section is divided in the following sub-Section 3.1 Scenario results and sub-Section 3.1.1 Results of the sensitivity analysis.

3.1. Scenario results

We analyse the following car related model outputs for the three scenarios for the EU. (i) Car transport needs satisfied by the different powertrain technologies from 2010 to 2050. (ii) CO_2 well-to-wheel (WtW) emissions caused by cars from 2005 to 2050. (iii) Final energy demand by cars, broken down by fuel. For the wider energy system related indicators, we analysed the: (1) Development of total CO_2 emissions and the transport part of it (only direct CO_2 emissions for transport), both compared to 1990 levels. The 1990 CO_2 emission levels were taken from values of the European Environment Agency (EEA, 2013), (2) for 2030 a more detailed look at direct transport CO_2 emissions, oil based fuel consumption and final electricity consumption. Energy data for 1990 was taken from Eurostat (2014). Finally, (3) we have compared the total energy system costs for 2030 for the three different scenarios.

3.1.1. Car portfolio and EV share

Based on the CO_2 car target of the legislation and the cost-effectiveness of the available technologies, the model deploys a different portfolio of car powertrains across scenarios. The model deploys more EV (BEV, PHEV, HFC) earlier with a stricter regulatory CO_2 car target.

Fig. 4 shows the evolution of the car technologies as they are deployed within the JRC-EU-TIMES model under the total system cost optimisation paradigm in the three regulatory scenarios to meet the transport demand. LPG and CNG fuelled cars play a negligible role in the model results due to their higher costs and emission factors compared to the other cars. Fig. 4 reveals that in all scenarios, EV become the major powertrain option by 2050. In 2050 BEV contribute with roughly 50% to satisfy the long distance trip and roughly 80% to satisfy the short distance trip demand. Even in the reference scenario, within the model, EV become a

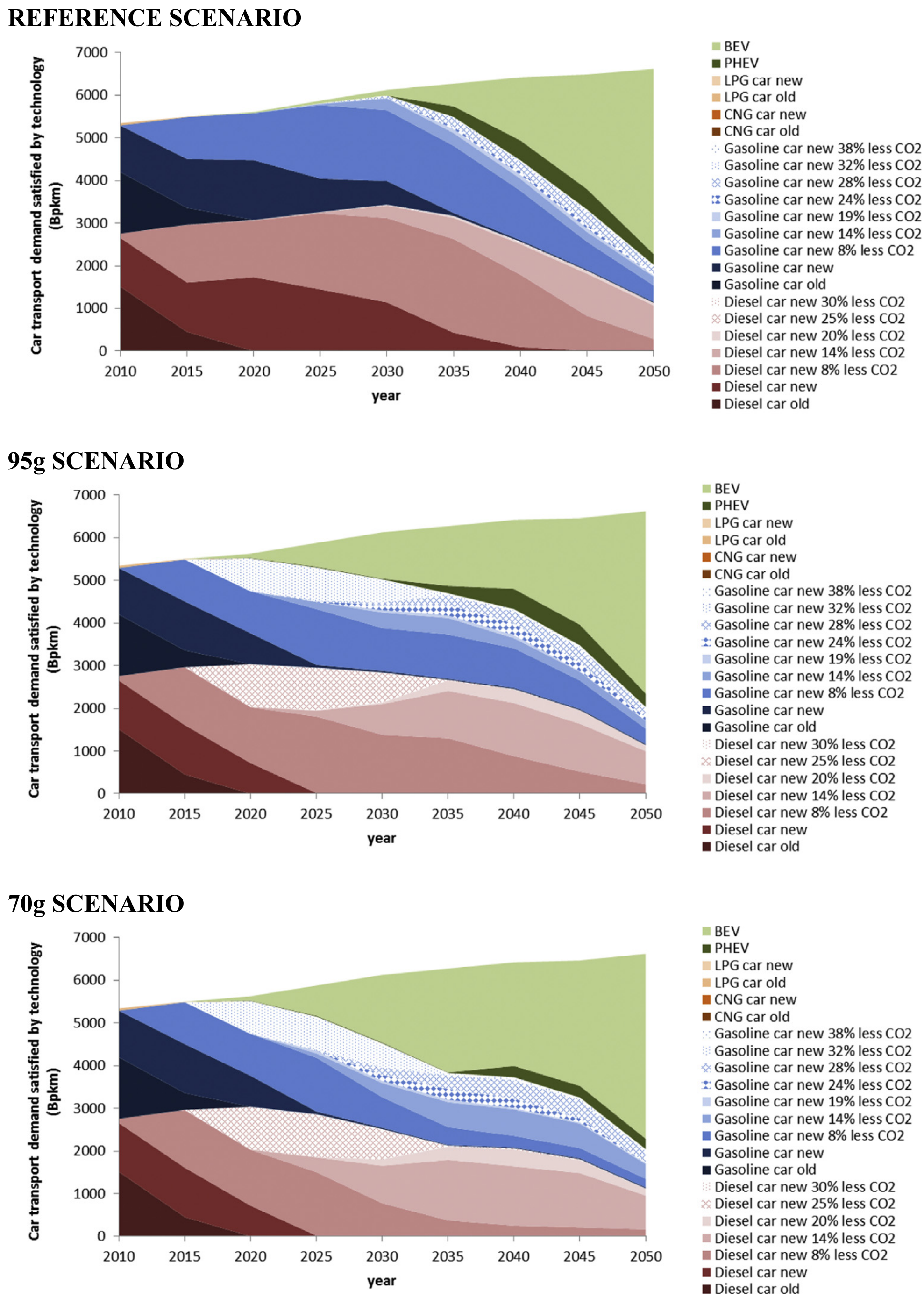

Fig. 4. Evolution of technology shares in passenger cars by scenarios.

cost-efficient technology for decarbonising the energy system beyond 2035. EV are more cost effective than fossil cars because the gasoline and diesel prices increase more than the power price. This price increase of fossil fuels can be mainly attributed to increased import prices (exogenous factor) and the cap on total use of EU primary energy (endogenous factor resulting in a penalisation). In all scenarios, EV do not reach significant mobility shares before 2020 i.e. a 2% share in the 70 g and 95 g scenarios. Especially the transition period between 2020 and 2040 reveals big differences among the three scenarios. In the reference scenario, significant deployment of EV starts only in 2030. Their deployment is advanced to 2020 in the 95 g and 70 g scenarios. However, it is more rapidly growing in the 70 g scenario than in the 95 g scenario. Nevertheless, gasoline and diesel based cars remain dominant throughout 2030 in all scenarios. Even in the 70 g scenario they satisfy close to 75% of the car transport demand in 2030. Without target for renewable energy in transport after 2020, a negligible amount of biofuel is used in car transport. In 2030, the biofuel production amounts to 1.4 mtoe or nearly 1% of total final energy demand for cars. After 2030, the biofuel production gradually phases out because the limited available biomass is used mainly for heat and power production. In the model results, HFC do not enter the market in any of the scenarios also due to the costs associated with hydrogen production. Fig. 4 also reveals how a future stricter CO_2 target for cars would lead to a more rapid deployment of more advanced conventionally fuelled cars. The car

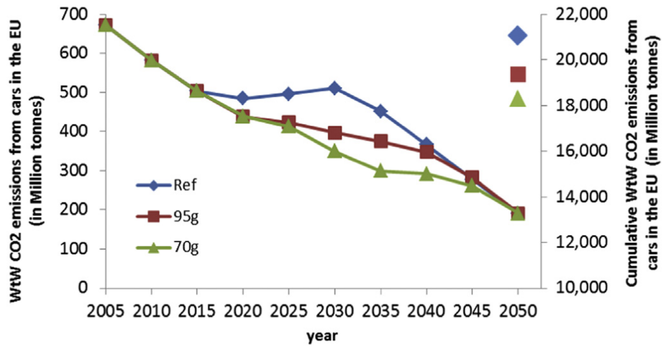

Fig. 5. Evolution of WtW CO_2 emissions from cars in the EU by scenarios. Note: The markers in 2050 show the cumulative WtW CO_2 emissions (i.e. the integral of the lines) and refer to the right axis.

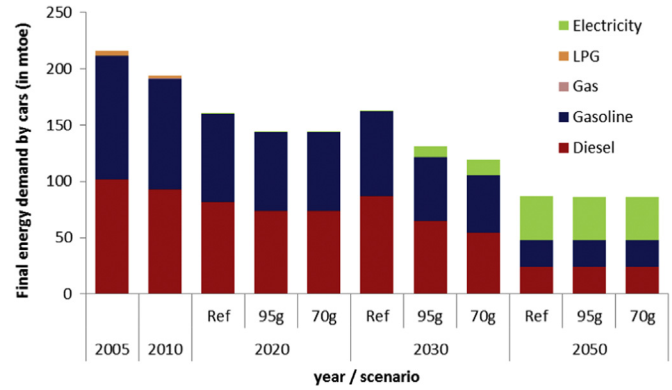

Fig. 6. Evolution of final energy demand for cars (TtW) by fuel type and scenarios.

related CO_2 targets (95 and 70 g) in the model are met by a faster deployment of mainly EV and more efficient gasoline and diesel fuelled cars. PHEV are penalised as they still feature TtW emissions. Their deployment stays small compared to BEV. Because of the high number of powertrain configurations available in the model, the JRC-EU-TIMES is capable of making choices of high technology and economic detail for deploying the optimal portfolio meeting the model constraints. This is visible in Fig. 4 in the 95 and 70 g scenario beyond 2030. From this moment on the larger uptake of BEV, which account as zero TtW emission cars, allows the choice of slightly less efficient conventional car options within the boundaries of the overall fleet target.

3.1.2. CO_2 emissions and energy demand from cars

Fig. 5 shows the evolution of car related WtW CO_2 emissions in the studied scenarios. For the calculation of the CO_2 WtW car emissions we allocated the fuel supply and conversion related CO_2 emissions for a given year and scenario, proportional to the fuel/energy demand for the car fleet and as derived from the JRC-EU-TIMES for the same year and scenario. This is a simplification as the daily/seasonal profile of the CO_2 emissions, especially relevant in power generation, is omitted in this calculation. The upstream emissions are normally accounted for in the supply and generation sectors of the model results and we only did the WtW calculation in order to verify if a further tightening of the TtW based CO_2 target for cars could cause significant WtT (well-to-tank) CO_2 emissions and offset the gains in TtW emissions. As in all three scenarios EV are a large part of the cost minimal solution for decarbonising the EU energy system by 2050, the car WtW CO_2 emissions of all scenarios are similar in this year. They go down from roughly 670 million tonnes CO_2 in 2005 to approximately 145 million tonnes CO_2 in 2050. This progress is also facilitated by the decarbonisation of the power sector. For example according to the modelled scenarios the EU average specific CO_2 emissions of power generation in 2030 are 0.146 t CO_2/MW h in the reference, 0.141 in the 95 g and 0.140 t CO_2/MW h in the 70 g scenario. These emissions vary significantly among the member states, with ranges between 0.005 and 0.421 t CO_2/MW h in 2030. Driven by the 2015, 130 g CO_2 fleet target for cars all scenarios display a reduction of car WtW CO_2 emissions until 2020. The scenarios diverge in the transition period from 2020 to 2040. While the reference scenario shows an increase of car WtW CO_2 emissions from 2020 to 2030, the two other scenarios feature steady reductions of these emissions until 2050. Hence, only the stricter CO_2 targets beyond 2015 warrant continuous CO_2 reduction from cars. The 70 g scenario, imposed by its stricter CO_2 target for the new car fleet, displays consistently lower car WtW CO_2 emissions than the two other scenarios. The JRC-EU-TIMES results indicate that the biggest difference between the modelled scenarios is in 2030, between the reference scenario with around 510 million tonnes, and the 95 g scenario with around 400 million tonnes CO_2. After 2030 the differences between scenarios are gradually attenuated. In 2035 the biggest difference is between the 95 g scenario with around 375 million tonnes and the 70 g scenario with around 300 million tonnes CO_2. The fleet dynamics can explain this evolution in time across scenarios. A stricter fleet target from 2030 onwards will have the greatest effect on the total stock of vehicles after 2030, when over a period of roughly 15 years the total car stock is replaced with more efficient cars, in-line with the stricter fleet target. From 2035 onwards the three scenarios converge again as more EV are deployed in all scenarios causing the CO_2 of the average new fleet to be lower than 70 g. Total cumulative WtW CO_2 emissions from cars in the EU from 2005 to 2050 amount according to the model results to around 21 billion tonnes in the reference scenario, 19.3 billion tonnes in the 95 g scenario, and 18.3 billion tonnes in the 70 g scenario.

Fig. 6 shows the evolution of the final energy demand for cars, broken down by fuel type, as calculated by the JRC-EU-TIMES model for the three scenarios. The total final energy demand from cars more than halves from 2005 to 2050, despite the increasing passenger mobility demand. In 2005 it is at roughly 215 mtoe[5] and around 86 mtoe in 2050 in all scenarios. The figure reveals the importance of the CO_2 car regulation to increase the energy efficiency of cars and reduce the EU's dependence from oil based fuels, especially in the mid-term. In 2030 we can observe large differences between the three scenarios. The final energy demand of cars in the reference scenario in this year is 163 mtoe, a higher value than in 2020. For the 95 g scenario and the 70 g scenario it is at around 131 and 119 mtoe respectively in 2030. Interesting to note is that because of their high TtW efficiency, the EV in 2050 need less than half of the final energy than the ICE propelled vehicles, although EV satisfy almost 70% of the car transport demand in the same year (see Fig. 4).

3.1.3. Energy system impacts

Fig. 7 shows the total CO_2 emissions and share of total transport CO_2 emissions, disaggregated by modes, versus 1990 values in the studied scenarios. It also displays the level of the 1990 transport CO_2 emissions in comparison to the scenarios. In Fig. 7, WtT emissions are not added. Hence, the transport CO_2 emissions reported in this figure are only direct CO_2 emissions. The more stringent the CO_2 emission target from cars, the more reductions are also achieved in total CO_2 emissions and, most notably, on transport CO_2 emissions. The difference of the three scenarios regarding the total CO_2 emissions, because of the scenario design, is small. The total CO_2 emissions in the reference scenario, as imposed by the applied carbon constraint for this scenario, decrease in 2030 to 60% of the 1990 value. The 95 g and 70 g scenarios are very close to this reduction with values of 58% and 57% respectively in 2030. The total CO_2 emissions reduce further until 2050 to values around 53% versus 1990. The development beyond 2030 is

[5] mtoe: million tonnes oil equivalent

mainly caused by the constraint on total use of EU primary energy as this forces the use of more efficient transformation and end-use technologies. However, Fig. 7 also reveals that the transport CO_2 emissions are in all three scenarios higher in 2020 and 2030 than in 1990. Only in 2050 they are slightly lower than in 1990. Fig. 7 indicates that regulating only cars cannot guarantee that transport will deliver a fair share of CO_2 reductions in the EU. According to the model results, even with the 70 g target, the transport CO_2 emissions in 2030 would still be approximately 4% higher than in 1990. The figure also shows that the CO_2 emissions of the other transport modes and sectors continue to increase in the future, if no policies are applied to them. This seems to indicate that policy measures for other transport modes or sectors, such as goods transport, are urgently needed in order to achieve substantial CO_2 reductions in transport.

Fig. 8 shows the transport CO_2 emissions, fossil oil consumption, and final electricity consumption in 2030 versus 1990 values as calculated by the JRC-EU-TIMES model for the three scenarios. Overall, in addition to the scenario differences, this figure displays some general features of the evolving energy system. Firstly, the transport sector, despite specific efficiency improvements, may not deliver CO_2 reductions in 2030 versus 1990, mainly driven by expected increasing transport demand since 1990. Secondly, despite this transport growth and continuous reliance of transport on oil derived fuels, oil consumption will, according to the model results, decrease by 2030. Besides some electrification of cars, this is mainly due to the replacement of oil based heating in the residential, commercial, and industrial sectors with other alternatives such as gas-, district-, electric-heating, or heat pumps. Thirdly, the JRC-EU-TIMES model shows a general trend towards more electrification in various end use sector applications, besides

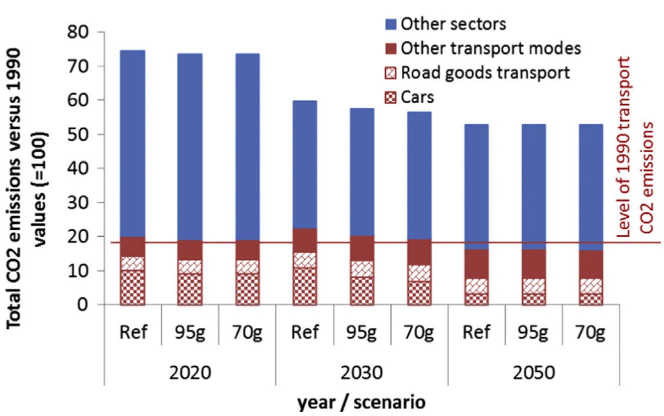

Fig. 7. Total CO_2 emissions and share of direct transport CO_2 emissions versus 1990 values in the studied scenarios.

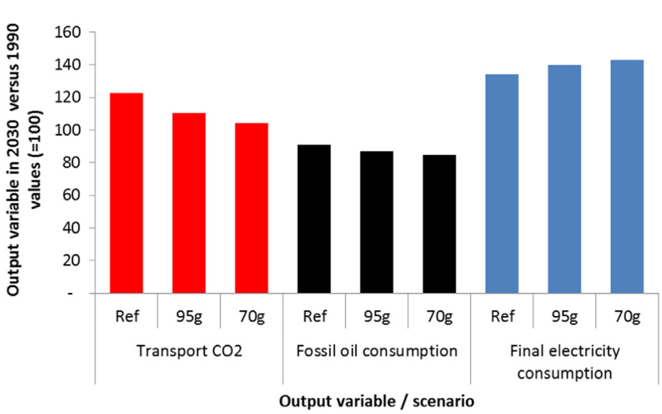

Fig. 8. Direct transport CO_2 emissions, fossil oil consumption, and final electricity consumption in 2030 relative to 1990 values (=100) by scenarios.

car transport. In terms of scenario differences, Fig. 8 reveals that the transport CO_2 emissions in 2030 are in the 95 g scenario about 10% lower than in the reference scenario. For the 70 g scenario this difference amounts to 15%. For energy system wide fossil oil consumption, the differences between the three scenarios are smaller. Here the 95 g scenario features about 5% lower oil consumption than the reference scenario, while the 70 g scenario shows a reduction of slightly more than 7%. Because of higher EV shares the consumption of electricity as final energy carrier increases from the reference to the 95 g and 70 g scenarios in 2030. This increase is around 4% for the 95 g scenario and 6.5% for the 70 g scenario.

The JRC-EU-TIMES model, being a cost minimisation model, solves the 40% CO_2 reduction target for the entire energy system (without sector break-down) with a cost-minimal technology mix. Constraining the system further through specific car CO_2 targets necessarily leads to an increase in total system costs as a side effect of reducing CO_2 emissions below the reference level. The annualised 2030 energy system costs increase in the 95 g scenario by 0.45% or 0.09% of GDP and in the 70 g scenario by 0.73% or 0.14% of GDP over the reference scenario. Typically, because of the relatively high turn-over of the car fleet (complete turn-over in 15 year time intervals) and the relatively high costs of cars, the car sector has a large share of the energy system costs according to the JRC-EU-TIMES model results. In comparison, the cost increases induced by the stricter CO_2 target appear modest. Dividing the difference in the total system costs by the total reduced CO_2 emissions over all modelled periods, the comparison of the 70 g and 95 g scenarios results in an abatement cost of 60 €$_{2010}$ per tonne CO_2 for the tighter emission limits. In 2030 the marginal system cost for an additional tightening of the TtW CO_2 emissions new car fleet target by 1 g is 15 €$_{2010}$ per car.

3.2. Results of the EV learning sensitivity

In the context of the sensitivity analysis we analyse the impact of the EV learning rate assumptions on the indicators electric vehicle share, transport CO_2 emissions, oil based fuel consumption, and total energy system costs for the 70 g scenario. Furthermore, we look in more detail at the car transport demand, the deployed car portfolio, the electricity generation portfolio including carbon capture and storage (CCS), the power demand from EV, and its flexible portion, as requested by the JRC-EU-TIMES for load shift and V2G.

Fig. 9 reveals that the variation of the learning rate between 5% and 12.5% has a rather minor effect on the system costs, transport CO_2 emissions and oil consumption in 2030, with the higher learning rates leading to a gradual reduction. This is accompanied by an increasing share of car transport satisfied by EV that ranges from 14% with a 5% learning rate to 32% with a 12.5% learning rate

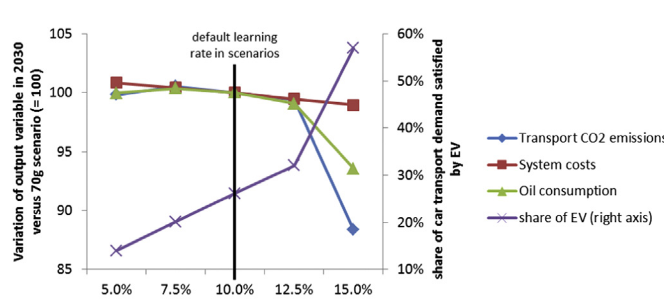

Fig. 9. Sensitivity of model outputs by varying learning rates for EV. Note: variation versus 70 g scenario in 2030 (with 10% learning rate). Left axis: transport CO_2 emissions, total system costs, oil consumption (70 g scenario =100). Right axis: share of 2030 car transport demand satisfied by EV (in %).

in 2030. The reduced car transport demand (more details below) has a small but measurable impact on transport CO_2 emissions and oil consumption, which reduce very slightly (less than 0.2%) in the 5% learning rate case. This sensitivity analysis shows that the car CO_2 regulation is an effective tool to ensure that mid- and long-term energy and climate targets can be met, even under uncertainty of technology costs as even with higher EV costs (lower learning rate) the CO_2 emissions do not grow and additional system costs are low, 0.9% higher in 2030 with a 5% learning rate versus the standard learning rate case. When EV become more expensive, the model chooses alternative cars relying on fossil fuels that are so efficient that the oil consumption does not grow.

Between a learning rate of 12.5% and 15% a tipping point is reached. Beyond this tipping point the deployment of EV would drastically increase between 2020 and 2030. Accordingly, this electrification has a large impact on oil consumption and transport CO_2 emissions, with respectively 6.5% and 12% reduction. The car TtW emissions are lower than the imposed 70 g/km. The learning rate of 15% reduces the total system costs in 2030 by 1%.

3.2.1. *Sensitivity of car transport demand*

As explained in chapter 2.1 the JRC-EU-TIMES model is run with demand elastic to prices of the reference scenario. We only observe changes in the demand in the most extreme cases of the sensitivity analysis. Under the 5% learning rate, the cost for the 70 g constraint increases to a level at which demand reduction takes place. The demand for passenger car transport in 2030 is reduced by nearly 4% when compared to the 10% learning rate case. Also in 2050, Fig. 10 reveals that the car transport demand in 2050 is reduced by approximately 5%. In contrast a 15% learning rate displays a very slight demand increase by 0.2% in 2050 versus a 10% learning rate.

3.2.2. *Sensitivity of car portfolio and EV share*

Fig. 10 shows the evolution of the car portfolio over time for the two most extreme cases, the one with 5% and 15% technology learning rate for EV. We observe large impacts of the employed learning rate on the deployed car portfolio. With a 5% learning rate the higher costs of the EV effectively limit its deployment. Their share, entirely supplied by BEV, remains at 26% even in 2050. Instead, more efficient ICE based vehicles are deployed in fast succession in order to ensure compliance with the car CO_2 fleet regulation. The most expensive and most efficient ICE based car technologies are only deployed in very small amounts. In the 15%

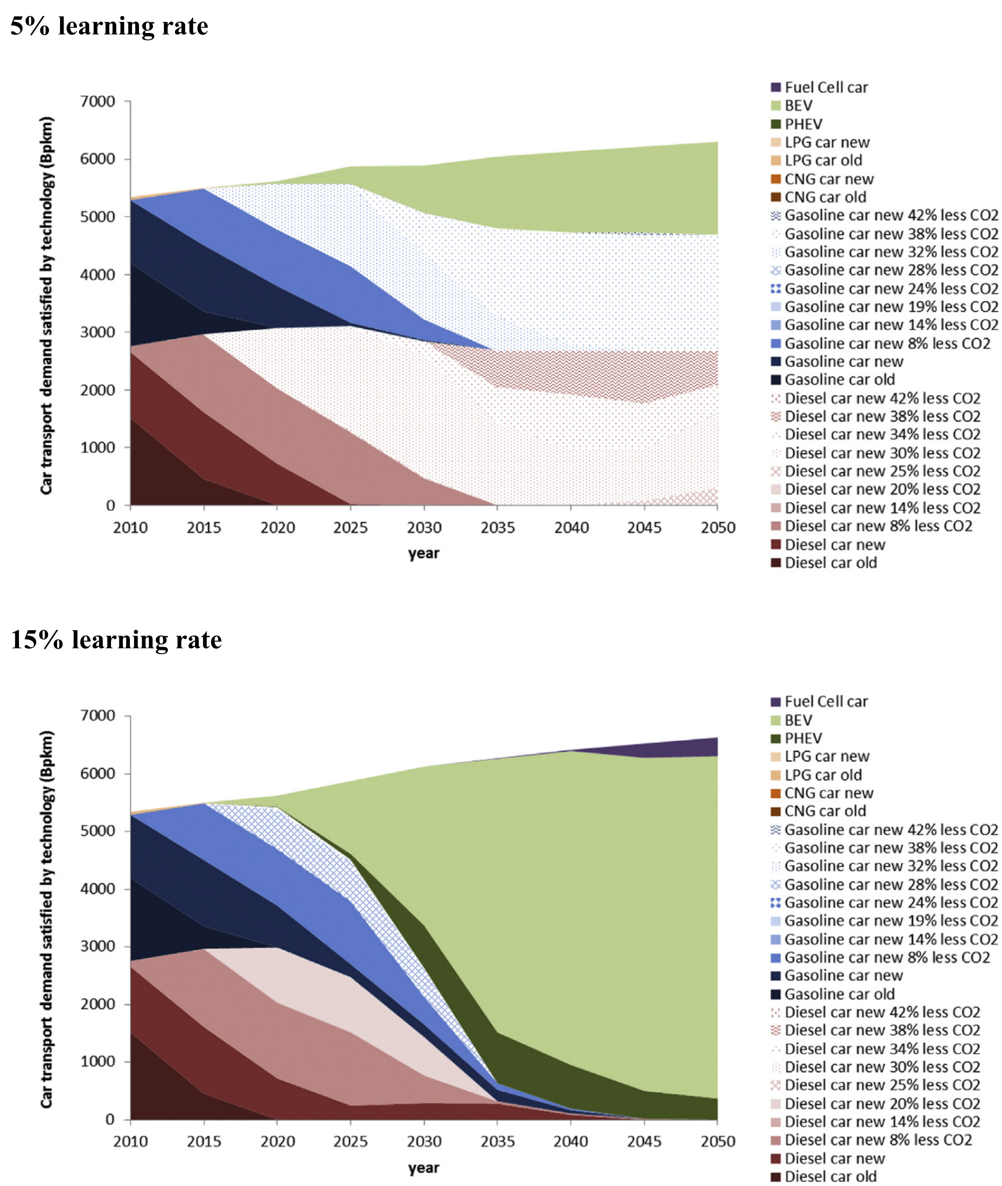

Fig. 10. Evolution of technology shares in passenger cars with a 5% and a 15% technology learning rate.

learning rate case we observe a massive deployment of EV with the highest growth rates between 2020 and 2035. The deployed EV are to a large extent BEV, but there are also significant shares of PHEV and FCV. The latter deploy mainly after 2040, substituting PHEV. This indicates that FCV, provided that there is significant learning, can complement other EV options in the longer term, especially for the delivery of long distance travel. In the 15% learning rate case, the highest efficiency ICE cars play a minor role. Instead, a mix of low to medium efficient ICE cars and EV fulfil the 70 g constraint in 2030. In 2050, the standard 10% learning rate is sufficient to reach the car TtW emissions target below 70 g/km.

3.2.3. *Sensitivity of electricity generation and interaction with EV*

We analyse the impact of the EV learning rate on the total electricity generation mix as well as the electricity demand required by EV. Fig. 11 shows the 2050 annual electricity generation by technology and EV electricity demand for different EV learning rates. The electricity demand from EV in 2050 shows the biggest increase from the 7.5% to the 12.5% learning rate case. The amount of total electricity generation follows closely this trend. Mainly three generation sources increase their share in 2050 from the 5% case to the 15% case to satisfy the increasing EV power demand. These are biogas, gas, and solar PV. Lignite reduces its share. This is a direct effect of the ETS cap which limits the CO_2 emissions from power generation and the model responds to it with a fuel switch from lignite to lower carbon fuels and gas power plants with CCS. The largest changes naturally occur between the 7.5% and 12.5% learning rate case as in 2050 the share of EV display the steepest growth in this learning rate interval.

Fig. 12 shows the variation of electricity generated by gas/ solar sources, CO_2 stored, electricity for EV, EV load shift, and V2G in 2050 as calculated by the JRC-EU-TIMES for different EV learning rates. It becomes visible that while the power demand from EV increases from the 5% learning rate case to the 15% learning rate case, the model uses the EV load shift option and V2G as additional flexibility sources that allow a larger deployment of variable solar power. This indicates that higher shares of EV can foster the deployment of variable renewable sources, especially PV. Parts of the higher power demand by EV are also covered through gas power plants. The CO_2 emissions from this generation source are off-set by an increase of CCS.

4. Discussion and comparison with other studies

As mentioned in the introduction, we have identified five other studies (Ichinohe and Endo, 2006; Bahn et al., 2013; Anandarajah et al., 2013; Rösler et al., 2014; Seixas et al., 2015) that analyse in more detail transport decarbonisation through EV deployment in an energy system context with the help of TIMES/MARKAL based models. Although the scope of the studies is very different, it can be useful to compare some overall characteristics. We present the main outcome of this comparison in Table 3. The comparison is based on four recent publications, which are all based on TIMES model analyses. Besides their different scope, the studies differ regarding their car powertrain technology detail and assumed or derived battery costs. All studies employed learning rates exogenous to the model except Anandarajah et al. (2013) who applied endogenous technology learning in their scenarios. Our study employs the highest technology detail in terms of car powertrain technologies. It also employs the lowest specific battery costs as recent industry statements and publications (Nykvist and Nilsson, 2015) indicate already for today lower battery costs than the other studies had assumed for 2050. Nykvist and Nilsson (2015), for example, estimate that BEV market leaders may source their batteries already now at specific costs of ca. 210 €$_{2010}$/kW h. In order to make the comparison more complete we also analysed a "no-policy" scenario to identify the dominant car technology in 2050. The "no policy" scenario is equivalent to the BAU (business as usual) scenarios of the other publications. All studies come to the conclusion that under a BAU scenario ICE propelled cars will remain the dominant technology throughout 2050. The studies deviate regarding the dominant car powertrain technology under the decarbonised scenario. In Rösler et al., 2014 HFC become the dominant car powertrain technology by 2050. In all other studies plug-in vehicles either in the form of BEV or PHEV become the dominant technology by 2050. Rösler et al. (2014) assume the highest specific battery costs in comparison to the other studies. In

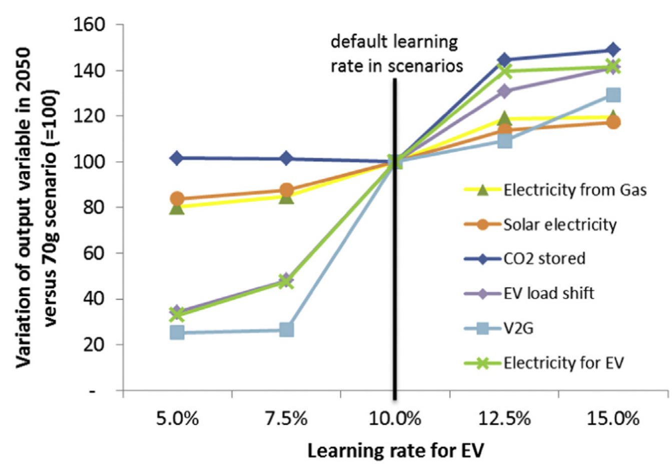

Fig. 12. Variation of electricity generated by gas/ solar sources, CO_2 stored, electricity for EV, EV load shift, and V2G in 2050 with different EV learning rates.

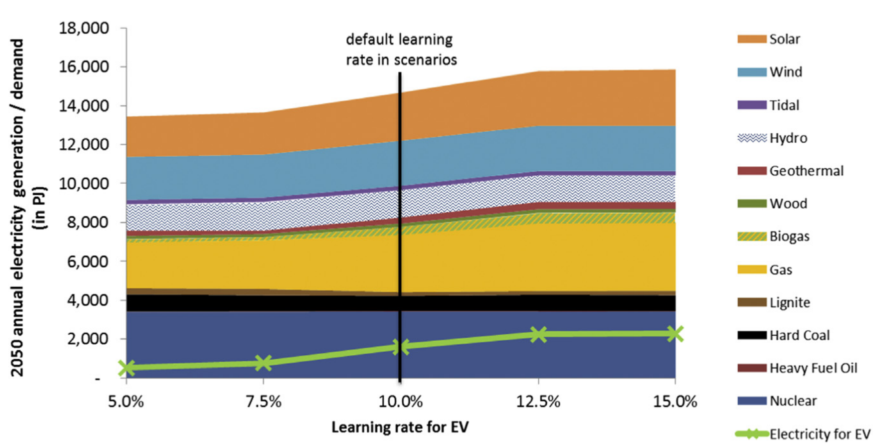

Fig. 11. 2050 annual electricity generation by source and EV electricity demand under various EV learning rates.

Table 3.
Comparison of studies.[6.]

Study	Regional scope	Nr of car technologies	battery costs in Euro $_{2010}$ / kW h		dominant technology in 2050	
			2030	2050	BAU	Decarbonised scenario
Anandarajah et al. (2013)	Global	12	266	258	–	(P)HEV
Bahn et al. (2013)	Canada	38	271	271	Conventional	BEV
Rösler et al. (2014)	Europe	13	335	284 (in 2040)	Conventional	HFC
Seixas et al. (2015)	EU28	11	330	230	Conventional	PHEV
Our study	EU28	45	190	153	Conventional	BEV

Bahn et al. (2013), similar to our study, BEV become the dominant technology by 2050.

In a theoretical static setting, a uniform pricing of CO_2 over all sectors would deliver the most cost-effective reduction in CO_2-emissions compared to any other policy (e.g. Schmidt et al., 2011). However, in a dynamic setting this may not be the case as a cost-effective technology or sector neutral policy in the short term could lock out emerging energy technologies in the long term (e.g. BEV) (de Mello Santana, 2016). Learning effects, as highlighted in our study, play a crucial role – they can, however, not be triggered by financing research & development alone, but may need the massive introduction of the technology on industrial scale to allow for learning along the whole supply chain (Sandén et al., 2005). Besides triggering technological learning, sector or technology specific policies may also have other advantages, such as being easier to implement and monitor than system wide taxes. We have shown that the sector specific car CO_2 regulation is a robust policy that allows the achievement of CO_2 reductions at low costs even under technological uncertainty.

5. Conclusion and Policy Implications

The model results reveal that the legislation of the EU car CO_2 emissions plays an important role to mitigate the CO_2 impact of expected growing transport demand in the EU. According to the scenario analysis, total transport related CO_2 emissions are expected to increase in 2020 and 2030 versus the 1990 levels. However, a stricter limit of 70 g in 2030 could effectively reduce these emissions versus current legislation by 5% already in 2030. Under the assumption that significant cost reductions of currently available EV are achieved by a learning rate of 10%, the analysis indicates that the deployment of EV is a viable option to attain these CO_2 reductions. Under the most stringent scenario (70 g) more than one quarter of the passenger car transport demand is satisfied by EV in 2030. A stricter CO_2 legislation and deployment of EV can also have a positive impact on energy security aspects as it can reduce the consumption of fossil oil based fuels in the EU by more than 2% in 2030 versus the current legislation. A more stringent CO_2 target for cars (70 g scenario) has, according to the model results, only a small effect on total system costs of below 1% in 2030.

The model results are dependent on the assumed learning rate for cost reductions of electrified vehicles. They exhibit gradual small changes when applying a learning rate between the interval 5–12.5%. This indicates that the CO_2 car regulation seems to be a robust policy to achieve CO_2 reductions at low costs also under uncertainty of technology costs and performance. A learning rate beyond 12.5% results in a massive deployment of electrified vehicles and pushes the car tank-to-wheel emissions below 70 g/km without additional system costs. The ETS target ensures that the higher electricity demand from EV is covered by low carbon electricity sources, including CCS. According to the scenario analysis, EV are able to provide flexibility services to the grid through load shifting or V2G. As a result, higher EV uptake is accompanied by more deployment of variable renewable electricity sources, especially PV.

From this analysis the following major conclusions on policy implications are drawn: (i) regulating CO_2 emission from cars is an effective CO_2 mitigation policy regarding the total emission abatement that can be achieved not only in cars but also via increased renewable power; (ii) specifically addressing car emissions is a robust policy approach since it is effective in abatement even if considering the future uncertainty on car technologies evolution; (iii) a stricter limit of 70 g in CO_2 emissions in 2030 can effectively reduce passenger car emissions earlier than the current legislation, without a significant cost increase for the whole energy system and with positive impacts in EU's energy security; (iv) although legislating CO_2 emissions from cars can have an important impact on total transport CO_2 emissions, other modes of transport should likewise be targeted by policies to ensure greater transport CO_2 emission reductions in the future. Besides, the role of sustainable biofuels for decarbonising transport should be further explored.

In future research it will be necessary to analyse scenarios for other transport modes and scenario variations of the CO_2 car legislation. Further methodological improvements within the JRC-EU-TIMES model could enhance the accuracy of this analysis: (i) explicit disaggregation of car segments similar to Thiel et al. (2014), (ii) explicit modelling of the fleet average CO_2 target for light commercial vehicles in accordance to EU (2014b), and (iii) scenarios for CO_2 improvements in heavy duty vehicles and other transport modes. Finally, as in all technology based analysis, it is fundamental to address consumer behaviour which was not in the scope of this paper. Behaviour plays a major role in passenger car options both regarding investing in certain technologies and in the way they are used, including modal shifts between cars and public transport, for example. An interesting future avenue for research could be combining the cost-optimal technology based analysis done in this paper with other approaches such as agent based models that could better explore modal shifts and passenger car acquisition.

Acknowledgements

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Appendix A. – Example for detailed car techno-economic assumptions

See Table A1.

Appendix B. - Constraint for car regulation

See Table B1.

[6.] Battery costs for other studies converted from other currency years.

Table A1.
Techno-economic assumptions for new cars in Italy in 2020.

Car technology	Input fuel	TtW efficiency[a] in km/MJ_{fuel}		Investment cost in $Euro_{2010}$	Annual maintenance cost in $Euro_{2010}$
		Long distance travel	Short distance travel		
Diesel car new	Diesel	0.558	0.397	19,106	573
Diesel car new 8% less CO_2	Diesel	0.606	0.431	19,345	580
Diesel car new 14% less CO_2	Diesel	0.649	0.461	19,625	589
Diesel car new 20% less CO_2	Diesel	0.697	0.496	19,989	600
Diesel car new 25% less CO_2	Diesel	0.744	0.529	20,378	611
Diesel car new 30% less CO_2	Diesel	0.797	0.567	20,901	627
Diesel car new 34% less CO_2	Diesel	0.845	0.601	21,480	644
Diesel car new 38% less CO_2	Diesel	0.900	0.640	22,282	668
Diesel car new 42% less CO_2	Diesel	0.962	0.684	23,408	702
Diesel car new 45% less CO_2	Diesel	1.014	0.721	24,545	736
BEV	Electricity	1.360	1.404	21,868	656
CNG car new	Natural Gas	0.488	0.346	19,746	592
CNG car new 8% less CO_2	Natural Gas	0.531	0.376	20,017	601
CNG car new 14% less CO_2	Natural Gas	0.568	0.402	20,341	610
CNG car new 19% less CO_2	Natural Gas	0.603	0.427	20,651	620
CNG car new 24% less CO_2	Natural Gas	0.642	0.455	20,973	629
CNG car new 28% less CO_2	Natural Gas	0.678	0.480	21,247	637
CNG car new 32% less CO_2	Natural Gas	0.718	0.509	21,588	648
CNG car new 38% less CO_2	Natural Gas	0.787	0.558	22,485	675
CNG car new 42% less CO_2	Natural Gas	0.842	0.596	23,660	710
CNG car new 47% less CO_2	Natural Gas	0.921	0.653	26,423	793
HFC	Hydrogen	1.080	0.735	24,353	731
Hydrogen ICE car	Hydrogen	0.684	0.465	24,130	724
Gasoline car new	Gasoline	0.509	0.360	17,106	513
Gasoline car new 8% less CO_2	Gasoline	0.553	0.392	17,377	521
Gasoline car new 14% less CO_2	Gasoline	0.591	0.419	17,701	531
Gasoline car new 19% less CO_2	Gasoline	0.628	0.445	18,011	540
Gasoline car new 24% less CO_2	Gasoline	0.669	0.474	18,333	550
Gasoline car new 28% less CO_2	Gasoline	0.706	0.500	18,607	558
Gasoline car new 32% less CO_2	Gasoline	0.748	0.530	18,948	568
Gasoline car new 38% less CO_2	Gasoline	0.820	0.581	19,845	595
Gasoline car new 42% less CO_2	Gasoline	0.877	0.621	21,020	631
Gasoline car new 47% less CO_2	Gasoline	0.959	0.680	23,783	713
LPG car new	LPG	0.496	0.352	18,956	569
LPG car new 8% less CO_2	LPG	0.539	0.382	19,227	577
LPG car new 14% less CO_2	LPG	0.577	0.409	19,551	587
LPG car new 19% less CO_2	LPG	0.613	0.434	19,861	596
LPG car new 24% less CO_2	LPG	0.653	0.463	20,183	605
LPG car new 28% less CO_2	LPG	0.689	0.488	20,457	614
LPG car new 32% less CO_2	LPG	0.730	0.517	20,798	624
LPG car new 38% less CO_2	LPG	0.801	0.567	21,695	651
LPG car new 42% less CO_2	LPG	0.856	0.606	22,870	686
LPG car new 47% less CO_2	LPG	0.936	0.664	25,633	769
PHEV[b]	Electricity	1.398	1.424	20,982	629
	Gasoline	0.479	0.390		

[a] Eficiency varies with biofuel blends.
[b] Different shares of energy applied depending on the ratio of long to short distance travel.

Table B1.
Values for a_x.

x: Car technology	a: CO_2 factor	x: Car technology	a: CO_2 factor
Diesel car new	139	Gasoline car new	143
Diesel car new 8% less CO_2	128	Gasoline car new 8% less CO_2	131
Diesel car new 14% less CO_2	120	Gasoline car new 14% less CO_2	123
Diesel car new 20% less CO_2	111	Gasoline car new 19% less CO_2	115
Diesel car new 25% less CO_2	104	Gasoline car new 24% less CO_2	108
Diesel car new 30% less CO_2	98	Gasoline car new 28% less CO_2	103
Diesel car new 34% less CO_2	92	Gasoline car new 32% less CO_2	97
Diesel car new 38% less CO_2	86	Gasoline car new 38% less CO_2	88
Diesel car new 42% less CO_2	81	Gasoline car new 42% less CO_2	83
Diesel car new 45% less CO_2	77	Gasoline car new 47% less CO_2	76
BEV	0	LPG car new	131
CNG car new	117	LPG car new 8% less CO_2	120
CNG car new 8% less CO_2	108	LPG car new 14% less CO_2	112

Table B1. (*continued*)

CNG car new 14% less CO_2	101	LPG car new 19% less CO_2	106
CNG car new 19% less CO_2	95	LPG car new 24% less CO_2	99
CNG car new 24% less CO_2	89	LPG car new 28% less CO_2	94
CNG car new 28% less CO_2	84	LPG car new 32% less CO_2	89
CNG car new 32% less CO_2	80	LPG car new 38% less CO_2	81
CNG car new 38% less CO_2	73	LPG car new 42% less CO_2	76
CNG car new 42% less CO_2	68	LPG car new 47% less CO_2	69
CNG car new 47% less CO_2	62	PHEV more short distance travel	40
Hydrogen ICE car	0	PHEV more long distance travel	50
HFC	0		

Table C1.
2030 EV investment costs under different learning rate assumptions:.

Learning rate	Investment cost in $Euro_{2010}$		
	BEV	PHEV	FCV
5.0%	25,583	23,768	27,009
7.5%	22,808	21,715	24,546
10.0% (i.e. standard)	20,690	20,087	22,527
12.5%	19,085	18,804	20,881
15.0%	17,879	17,801	19,546

$$Target_z \geq \frac{\sum a_x * s_{x,y,z}}{\sum s_{x,y,z}}$$

where.

z is the specific year,

a is the car technology specific CO_2 factor (expressed in g CO_2 /km),

x is the subscript for the car technology,

y is the subscript for each of the 28 EU member states,

s is the new car sales as deployed by the model.

For the Ref scenario the target in 2015 is 130 g CO_2/km and beyond,

For the 95 g scenario the target is as Ref and 95 g CO_2/km in 2020 and beyond; linear interpolation of target between 2015 and 2020,

For the 70 g scenario the target is as 95 g and 70 g CO_2/km in 2030 and beyond; linear interpolation of target between 2020 and 2030.

Appendix C. – EV investment costs under different learning rate assumptions

See Table C1.

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