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Analysis of the Effects of Electrification of the Road Transport Sector on the Possible Penetration of Nuclear Fusion in the Long-Term European Energy Mix

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Abstract: The European Roadmap towards the production of electricity from nuclear fusion foresees the potential availability of nuclear fusion power plants (NFPPs) in the second half of this century. The possible penetration of that technology, typically addressed by using the global energy system EUROFusion TIMES Model (ETM), will depend, among other aspects, on its costs compared to those of the other available technologies for electricity production, and on the future electricity demand. This paper focuses on the ongoing electrification process of the transport sector, with special attention devoted to road transport. A survey on the present and forthcoming technologies, as foreseen by several manufacturers and other models, and an international vehicle database are taken into account to develop the new road transport module, then implemented and harmonized inside ETM. Following three different storylines, the computed results are presented in terms of the evolution of the road transport demand in the next decades, fleet composition and CO_2 emissions. The ETM results are in line with many other studies. On one hand, they highlight, for the European road transport energy consumption pattern, the need for dramatic changes in the transport market, if the most ambitious environmental goals are to be pursued. On the other hand, the results also show that NFPP adoption on a commercial scale could be justified within the current projection of the investment costs, if the deep penetration of electricity in the road transport sector also occurs.

Keywords: electric vehicles; energy scenarios; road transport; nuclear fusion; EUROfusion TIMES model

1. Introduction

According to the European Roadmap towards electricity from fusion [1], the European Demonstration Fusion Power Reactor (EU-DEMO) reactor project will follow the ITER experiment with the aim of demonstrating the possibility to produce net electricity from nuclear fusion reactions. In parallel, similar efforts to develop demonstration reactors or "fast pathways" to nuclear fusion are taking place in Korea [2], China [3], and in the US [4], where the issues of the lifetime of such a reactor when integrated in the energy grid are under investigation [5]. In Europe, while the cost analysis of a nuclear fusion power plant (NFPP) is being investigated based on simplified models of the physics, engineering and economical aspects [6], the EUROfusion socio-economic research on the role of nuclear fusion in the future energy mix aims to investigate the social acceptability of the technology and the conditions for its deployment once it is ready for the energy market, which may affect specific choices during the research and development stage [7]. The EUROfusion TIMES Model (ETM) is the tool used by the EUROfusion Socio-Economic Studies Work Package (WPSES) to explore scenarios for the evolution of the energy demand of the different sectors (agricultural, commercial, industrial, residential and transport) and generation systems, accounting for the production of electricity from fusion reactors. In order to achieve increasingly realistic results for the penetration of nuclear fusion, technological updates for the demand sectors are periodically needed.

The last update of the ETM transport sector module dates back to 2009 [8], when the level of technological advancement of electrified transport technologies was still very low, and called for a comprehensive update, which is described here. The ETM (global) spatial scale is subdivided into 17 regions, each one incorporating countries with similar conditions in terms of their economic development; the road transport sector update and subsequent scenario analysis presented in this paper is focused on the European region of the model, including the EU28 and the European Free Trade Association (EFTA) Countries, including Gibraltar, but with the exception of Croatia and Liechtenstein. The ETM time horizon goes from 2005 (the so-called "base year", where the initial demand for each sector is prescribed) to 2100, with an exogenous assignment of demand trends (based, in turn, on the results of other models such as GEM-E3 [9] or TIMES Integrated Assessment Model (TIAM) [10]), at each time step, namely at the beginning of each decade (2020, 2030, etc.). The characterization approach used by other TIMES family models, such as the JRC-EU TIMES Model [11], is followed here, by trying to stress the attention on both light-duty vehicles (LDVs) and heavy-duty vehicles (HDV), instead of on more specific vehicle categories, see [12] for cars, and [13] for LDVs. ETM is an optimization model, based on the minimum cost criterion. Instead, other similar models, such as the International Energy Agency (IEA) Mobility Model [14] (its results for medium-term scenarios until 2060 are extensively discussed in the IEA Energy Technology Perspectives 2017 [15]), are particularly suited and capable of depicting realistic alternatives for the evolution of the concerned end-use sector, being provided with a simulation model for the final demand. However, despite the fact that the literature concerning the analysis of nuclear fusion penetration is still quite poor, some remarkable works have used energy models to address this investigation. Some of them have been carried out inside the EUROfusion WPSES itself, such as the already mentioned work by Mühlich and Hamacher [8], which provided a preliminary assessment of the potential role of transportation in the evolution of the energy system, or the study in [16] about the contribution of fusion in low-carbon global energy scenarios. The analysis in [17] focused on the role of nuclear energy in the global energy system until 2100, using the World-TIMES Model and characterizing fusion via a set of exogenous assumptions, generally following an approach that is very similar to the one adopted in ETM, but with a characterization of transport technologies mainly based on the (limited) awareness about the actual recent progresses in the field at the time of writing. Instead, in [18] the role of nuclear fusion is assessed when breakeven prices, with respect to other electricity production costs, can be achieved via the Linearized Dynamic New Earth model [19].

The objective of this study is to provide a detailed and updated techno-economic characterization of road transport vehicles for use in technology-rich energy models, and to assess its impact on scenarios envisaging the adoption of fusion energy for electricity production.

This paper consists of the following sections. In Section 2, we present the approach used for the definition of parameters related to the modeling of road transport vehicles. In Section 3, we describe how the projection of the road transport sector demand is computed, then in Section 4 we assess its effects on the European energy system, with particular reference to the evolution of the energy mix and of CO_2 emissions from the transport sector. Moreover, an extensive comparison of ETM results with other optimization and simulation energy models is presented, aimed at assessing coherence and consistency. Finally, the conclusions and future perspective on the work are provided in Section 5, together with some remarks on the limitations of the current analysis.

2. The European Road Transport Reference Energy System

Following the approach already implemented in ETM, the road transport technologies are subdivided into eight transport modes, shown in Table 1; Table 2 shows the vehicle technologies currently considered in the ETM road transport module.

Table 1. Transport modes of the road transport processes, and associated features. The code is composed by three letters: TR stands for transport; the third letter uniquely identifies the transport mode.

Transport Mode	Code	Features
Passenger car	TRT	-
Light truck	TRL	Includes SUVs and pick-ups
Van	TRC	Up to 3.5 t Gross vehicle weight (GVW, for urban/regional freight transport)
Two-wheeler	TRW	-
Three-wheeler	TRE	-
Medium truck	TRM	From 3.5 t up to 12 t GVW, for regional/national freight transport
Heavy truck	TRH	From 12 t up to 60 t GVW, for national/international freight transport
Bus	TRB	-

Table 2. Vehicle technologies considered within the EUROFusion TIMES Model (ETM) road transport module; * is a placeholder for the third letter of the codes in Table 1.

Technology	Description	Fuel(s)
TR*GAS	Gasoline vehicle	Gasoline (GSL)
TR*DST	Diesel vehicle	Gas oil (DST)
TR*NGA	Natural gas vehicle	Natural gas (NGA)
TR*LPG	LPG vehicle	Liquefied petroleum gas (LPG)
TR*FLF	Flex-fuel vehicle	E85: GSL (15%) + ETH (85%)
TR*ELC	Full-electric vehicle	Electricity (ELC)
TR*GHE	Gasoline-electric hybrid vehicle	GSL
TR*DHE	Diesel-electric hybrid vehicle	DST
TR*GPH	Gasoline-plug-in electric hybridvehicle	Combination of gasoline and electricity (GSL (55%) + ELC (45%))
TR*DPH	Diesel-plug-in electric hybrid vehicle	Combination of gas oil and electricity (DST (55%) + ELC (45%))
TR*FCE	Fuel cell vehicle	Hydrogen (HH2)

In ETM, the road transport demand is measured in billion vehicle-kilometers (Bvkm). In order to calculate the sectoral demand over the model time horizon, the road transport technologies (and, more generally, all energy producer/consumer technologies) are split into two classes:

- Base year transport technologies, used to model the demand and the energy use at the beginning of the time horizon (year 2005), and displayed in Table 3. The base year demand is calculated by combining the total road transport energy consumption from IEA/Eurostat statistics [19] with dummy efficiency values and coefficients. In this way, the energy consumption is allocated to the different vehicle categories, which are then used as calibration parameters to meet total consumption in the base year, according to Equation (1):

$$D(\text{base year}) = \sum_{m,p} \left[\eta_{m,p}(\text{base year}) \cdot E_{m,p}(\text{base year}) \right] \tag{1}$$

  where $D(\text{base year})$ is the base year demand $[\text{Bvkm}]$, m is the transport mode, p is the process/vehicle technology, $\eta_{m,p}(\text{base year})$ is the base year (calibration) efficiency associated to the mode–process combination in $[\text{Bvkm/PJ}]$ and $E_{m,p}(\text{base year})$ is the base year energy consumption associated to the mode–process combination in $[\text{PJ}]$.
- New transport technologies, used to model the energy use throughout the model time horizon, are added to the existing fleet of the base year technologies from the second time step onwards.

In Section 3.2, the algorithm for the evaluation of the demand evolution will be illustrated; it has to be matched at any time step by the energy supply. The new technologies are characterized by five parameters:

1. Efficiency;
2. Lifetime;
3. Investment cost;
4. Fixed operation and maintenance (O&M) cost;
5. Variable O&M cost.

Table 3. Road transport base year technologies.

Technology	Initials	Fuel
Gasoline vehicle	TR*GAS	Gasoline
Diesel vehicle	TR*DST	Gas oil
Natural gas vehicle	TR*NGA	Natural gas
LPG vehicle	TR*LPG	LPG
Biofuel vehicle	TR*ETH	Ethanol
Electric vehicle	TR*ELC	Electricity
Hydrogen vehicle	TR*HH2	Hydrogen

For each kind of possible transport mode, all or some vehicle technologies reported in Table 2. have been selected and characterized at each time step after the base year, prescribing the trends for their future development.

2.1. Efficiency

Fuel economy specifications and, specifically, the energy efficiency of a particular vehicle, given as a ratio of the distance traveled per unit of fuel consumed, are widely accessible only for LDVs. A database based on [20], including 66 cars, 33 vans and 54 light trucks, has been built, subdividing vehicles into size categories (Mini, Small, Medium and Large for cars; Small, Medium and Large for vans; Small SUV, Compact SUV, Full-Size SUV and Pick-Up for light trucks), each one corresponding to a specific weight range. The fuel economy specifications are provided by manufacturers, on the basis of the New European Driving Test Cycle (NEDC), in $\mathrm{l}/100$ vehicle $-$ kilometres (vkm) (for gasoline, gas oil, LPG, ethanol), $\mathrm{kg}/100$ vkm (for natural gas and hydrogen) or $\mathrm{kWh}/100$ vkm (for electricity). These values are then properly translated in vkm/MJ, or equivalently $\mathrm{Bvkm}/\mathrm{PJ}$, as per the model convention for efficiency, using the fuel energy content properties retrieved from [21] and Equations (2)–(4):

$$\eta^*\left[\frac{\mathrm{Bvkm}}{\mathrm{PJ}}\right] = \frac{100}{E_c\left[\frac{l}{100\ \mathrm{vkm}}\right] \cdot LHV\left[\frac{\mathrm{MJ}}{l}\right]} \tag{2}$$

$$\eta^*\left[\frac{\mathrm{Bvkm}}{\mathrm{PJ}}\right] = \frac{100}{E_c\left[\frac{\mathrm{kg}}{100\ \mathrm{vkm}}\right] \cdot LHV\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right]} \tag{3}$$

$$\eta^*\left[\frac{\mathrm{Bvkm}}{\mathrm{PJ}}\right] = \frac{100}{E_c\left[\frac{\mathrm{kWh}}{100\ \mathrm{vkm}}\right] \cdot 3.6\left[\frac{\mathrm{MJ}}{\mathrm{kWh}}\right]} \tag{4}$$

In Equations (2)–(4), η^* is the vehicle efficiency, E_c is the declared fuel economy and LHV is the fuel lower heating value.

The fuel economy data collection highlights a decreasing efficiency trend with weight. For cars and light trucks, an average occupancy of 1.5 passengers has been considered (since they are mostly used for passenger transport), while vans have been supposed to be always driven at 80% of their maximum allowable capacity (since they are mostly suited to freight transport):

$$Weight_{car/light\ truck} = Curb\ weight + 1.5\ \cdot \text{Passenger}\ weight \tag{5}$$

$$Weight_{van} = Curb\ weight + 0.8\ \cdot GVW_{max} \tag{6}$$

Then, a factor ($f_{RD} = 1.39$) is applied to get the efficiency trends as a function of the vehicle weight for cars/light trucks. It takes into account the average gap between official fuel consumption figures and actual fuel use for new cars in the EU, which is actually 39% higher than official values (see [22]). The efficiency trends reported in Figure 1a (for gasoline, flex-fuel and diesel cars/light trucks), Figure 1b (for LPG and natural gas cars/light trucks), Figure 1c (for fully electric and fuel cell cars/light trucks) and Figure 1d (for gasoline-electric hybrid and plug-in hybrid electric cars/light trucks) are retrieved from the Deutsche Automobil Treuhand (DAT) database [20].

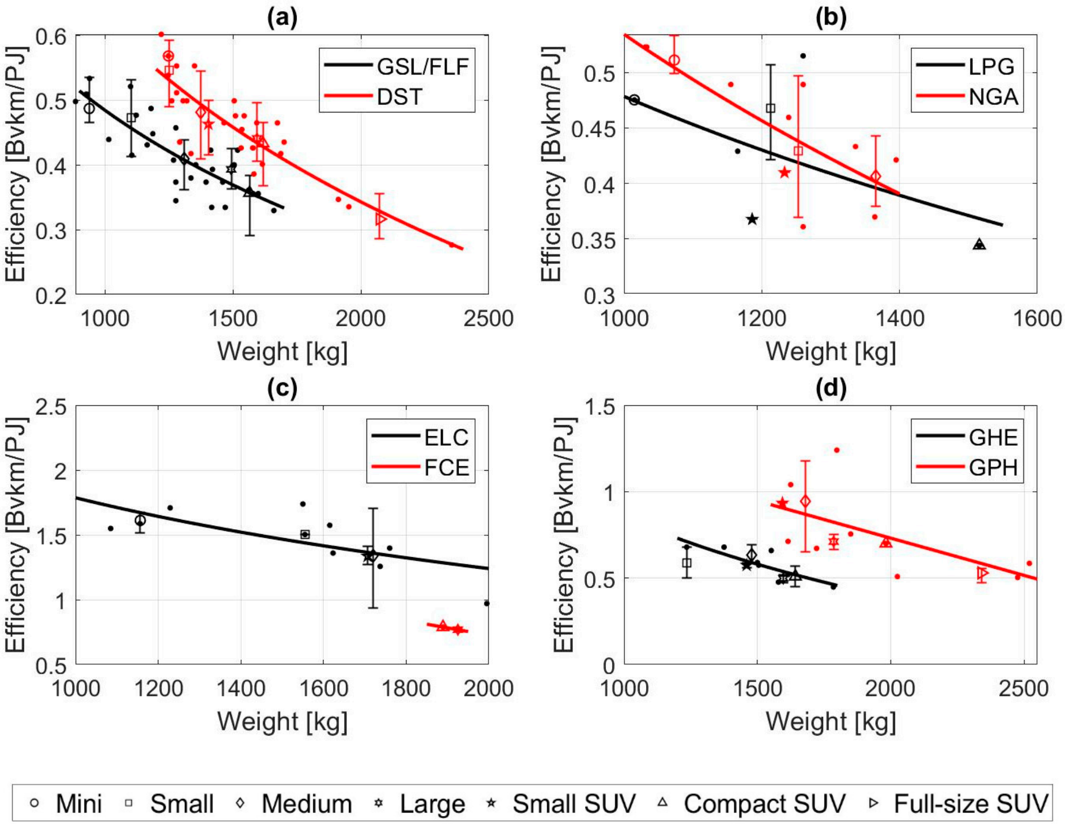

Figure 1. Efficiency trends as a function of vehicle weight for gasoline, flex-fuel and diesel cars/light trucks (**a**), for LPG and natural gas cars/light trucks (**b**), for fully electric and fuel cell cars/light trucks (**c**) and for gasoline–electric hybrid and gasoline–plug-in electric hybrid cars/light trucks (**d**), respectively: data-points represent the collected efficiency data, while the different size categories (Mini, Small, Medium, Large, Small SUV, Compact SUV and Full-Size SUV) are represented by the mean values of their respective weight-efficiency couple.

The van database is not sufficiently detailed enough for some technologies to provide separate trends. Nevertheless, the few data points available are well reproduced by the car and light truck trends. Since no trends can be retrieved for diesel-electric hybrid cars/light trucks, but this technology is considered for vans, trucks and buses, an average diesel-to-gasoline efficiency correlation factor $k_{DST/GAS}$, given by the ratio of gasoline and diesel car efficiencies, has been retrieved from the vehicle market database, highlighting a 20% higher efficiency for diesel cars ($k_{DST/GAS} = 1.2$), with respect to gasoline cars. The ratio $k_{DST/GAS}$, reported in Table 4, is used to increase the efficiency of gasoline–electric hybrid vehicles, in order to obtain the efficiency of diesel–electric hybrid vehicles.

Table 4. Efficiency ratios with respect to diesel cars/light trucks.

Efficiency Ratio	Value [−]
$k_{DST/GAS}$	1.20
$k_{DST/LPG}$	1.27
$k_{DST/NGA}$	1.20
$k_{DST/FLF}$	1.20
$k_{DST/ELC}$	0.36
$k_{DST/GHE}$	0.84
$k_{DST/DHE}$	0.78
$k_{DST/GPH}$	0.57
$k_{DST/FCE}$	0.67

Average efficiency values are then defined for each size category, and shown in Table 5, in order to get values for two- and three-wheelers (simply scaled down from Medium and Small cars, respectively).

Table 5. Average efficiency values (in billion vehicle-kilometers (Bvkm/PJ) for all car and light truck size categories.

Size Category	GAS	DST	LPG	NGA	FLF	ELC	GHE	GPH	FCE
Mini	0.49	-	0.46	0.48	0.49	1.68	-	-	-
Small	0.44	0.51	0.41	0.42	0.44	1.37	0.68	-	-
Medium	-	0.47	0.37	0.39	0.39	1.29	0.56	0.83	-
Large	0.36	0.42	-	-	0.36	1.09	0.52	0.76	0.70
Small SUV	0.39	0.46	0.41	0.43	0.39	1.30	0.56	0.83	-
Compact SUV	0.35	0.42	0.36	-	0.35	1.04	0.47	0.67	0.71
Full-Size SUV	0.30	0.35	-	-	-	-	-	0.54	-
Pick-Up	0.27	0.30	0.27	0.28	0.27	0.98	0.36	-	-

For HDVs (trucks and buses), an official document by Volvo Trucks [23] states guide values for the fuel consumption of their diesel trucks. Based on such data, and merging them with those for diesel LDVs, a new efficiency trend for HDVs is calculated, as reported in Equation (7) and displayed in Figure 2.

$$\eta_{HDV\ DST} = \{f_{RD} \cdot [2.41 \cdot \ln(Weight) - 15.96]\}^{-1} \tag{7}$$

where *Weight* (in *t*) corresponds to the selected representative weight for each HDV transport mode. From Equation (7), the efficiency can be computed for medium trucks (8 *t*), heavy trucks (30 *t*) and buses (16.5 *t*, including curb weight and 20 passengers, each one weighing 75 kg), respectively. For all other technologies, the diesel-to-other technology ratios observed from the average car, van and light truck efficiencies, as reported in Table 4, are adopted.

In order to reduce the level of disaggregation of the model, which would inevitably increase the computational time, representative size categories are then selected for cars (Medium car, e.g., Volkswagen Golf, for all kinds of cars except for 2020 fuel cell cars, which are actually larger cars, but will be considered as medium-size cars from 2025 onwards, assuming an extension of the size range expected for that technology), light trucks (Compact SUV, e.g., Toyota RAV4) and vans (Medium van, e.g., Ford Transit Connect). Two- and three-wheelers are each described by a single size category. Table 6 shows the updated efficiency values in year 2020.

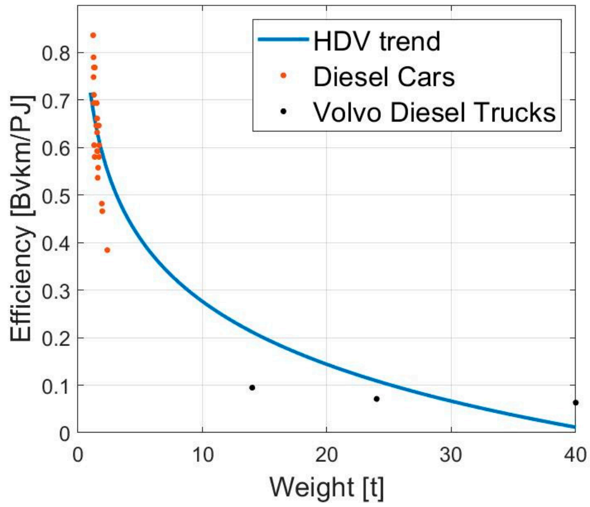

Figure 2. Efficiency trends for heavy-duty vehicles.

Table 6. Efficiency (in Bvkm/PJ) for the different modes/technolgies in the current road transport module.

	GSL	DST	LPG	NGA	FLF	ELC	GHE	DHE	GPH	DPH	FCE
TRT	0.39	0.47	0.37	0.39	0.40	1.29	0.56	-	0.76	-	0.70
TRC	0.30	0.34	0.30	0.28	0.30	0.98	-	0.33	-	0.72	-
TRL	0.35	0.42	0.36	-	0.35	1.04	0.47	-	0.67	-	-
TRW	1.19	1.40	-	-	-	3.81	1.77	-	-	-	-
TRE	1.12	1.35	-	-	-	3.60	-	-	-	-	-
TRM	0.09	0.11	0.09	0.09	0.09	0.31	-	0.11	-	-	-
TRH	0.04	0.05	0.04	0.04	0.04	0.13	-	0.05	-	-	-
TRB	0.05	0.06	0.05	0.05	0.05	0.16	-	0.06	-	-	0.10

Table 6 shows that, for all transport modes, the fully electric technologies (ELC) are the most energy efficient: they are on average ∼ three times more efficient than the corresponding gasoline and diesel technologies. Moreover, the modelled gasoline–electric hybrid car (GHE) allows for a significant gasoline fuel saving with respect to a traditional gasoline car (∼ 30%), thus reaching a higher efficiency. Caution should be used in the comparison between transport modes that are strictly adopted for passenger transport, namely cars (TRT) and buses (TRB): diesel buses show an eight times higher consumption with respect to diesel cars, but the modelled car efficiency is calibrated on 1.5 passengers, against the 20 passengers accounted for in the calculation of bus efficiency: this means more than 13 cars are needed to transport 20 people, consuming far more (∼ 70%) than a single bus.

The evolution of the efficiency over the time horizon analyzed in the present paper is assigned exogenously, keeping, for reference, the values assigned in the JRC-EU TIMES [11] for European LDVs, based on recent market trends. In JRC-EU TIMES, the fully electric LDVs are subdivided into three categories according to their battery size (15 kWh, 30 kWh, 60 kWh), due to the fact that the vehicle demand is subdivided into long and short distance, making some technologies suited for a specific demand category. The evolutions assigned to 30 kWh battery-electric vehicles (BEVs) have been taken into account for ETM fully electric LDVs. The efficiency variations, with respect to the 2020 values adopted in the present analysis, are represented in Figure 3: the same ratios for such parameters, between the characteristics of present and future technologies as in the JRC-EU TIMES, have been applied throughout the ETM timescale. From 2050 onwards, all efficiencies are kept constant until the end of the timescale, due to the lack of reliable estimations. Note that, as in JRC-TIMES, the efficiency has been considered constant for HDVs during the entire time horizon that we consider, mainly due to the poor amount of literature available.

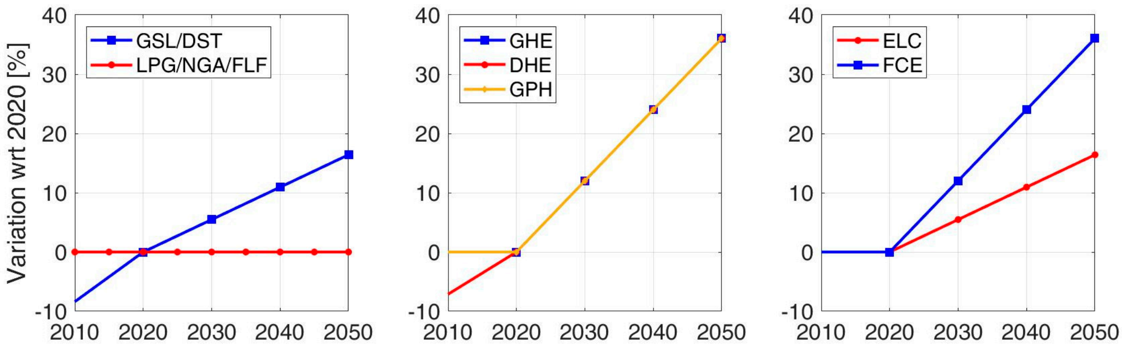

Figure 3. Efficiency variation with respect to 2020 applied to light-duty vehicles (LDVs), based on [11].

2.2. Lifetime

The vehicle lifetime for each transport mode and technology is difficult to retrieve from the literature, so the same assumption as in JRC-TIMES [11] is adopted, considering a 12-year lifetime for LDVs, and a 15-year lifetime for HDVs. The only exception to this concerns technologies with big batteries (fully electric and plug-in hybrid vehicles) or fuel cell vehicles), for which a slightly shorter lifetime has been assumed, i.e., 10 years for both LDVs and HDVs, before 2030. After 2030, a 12-year-long lifetime is considered for these vehicles as well.

2.3. Investment Cost

The sum of the manufacturer's suggested retail price and 21.3% Value Added Tax (average EUR value [24] in 2019) gives the purchase price of a single vehicle (in EUR/vehicle or USD/vehicle), translated into USD/year divided by the assigned vehicle lifetime. Table 7 reports the investment costs for all ETM vehicles.

Table 7. Investment cost (in USD/year) for the different modes/technologies in the current road transport module.

	GAS	DST	LPG	NGA	FLF	ELC	GHE	DHE	GPH	DPH	FCE
TRT	2′242	2′425	2′425	2′425	2′242	4′370	2′708	-	4′260	-	6′300
TRC	2′892	2′892	3′358	3′358	2′892	7′210	-	3′450	-	5′500	-
TRL	2′750	2′933	2′933	-	2′750	10′890	3′208	-	5′610	-	-
TRW	933	1′025	-	-	-	2′312	1′402	-	-	-	-
TRE	283	308	-	-	-	687	-	-	-	-	-
TRM	5′600	5′973	5′900	5′900	5′500	13′780	-	6′647	-	-	-
TRH	10′600	11′273	11′200	11′200	10′600	26′080	-	12′620	-	-	-
TRB	8′287	8′440	8′813	8′813	8′287	20′500	-	9′933	-	-	35′850

As expected, the annual price of fully electric, plug-in electric hybrid and fuel cell technologies is still far from being comparable with that of "traditional" technologies. One may think this is only due to the lower lifetime with respect to the other technologies (as explained in Section 2.2), but even when considering the same lifetime for gasoline and full-electric cars, the latter still cost 60% more than the former ones. Instead, the investment cost for a gasoline–electric hybrid car is 20% higher than a conventional gasoline car (against a 40% fuel saving, as reported in the caption of Table 6). Similar observations are applicable to all other transport modes.

Moreover, the evolution of the investment cost for the time horizon considered in our analysis is assigned exogenously, keeping, for reference, the same ratios between present and future costs of European LDVs as those assigned in JRC-TIMES [11], based on recent market trends; see Figure 4.

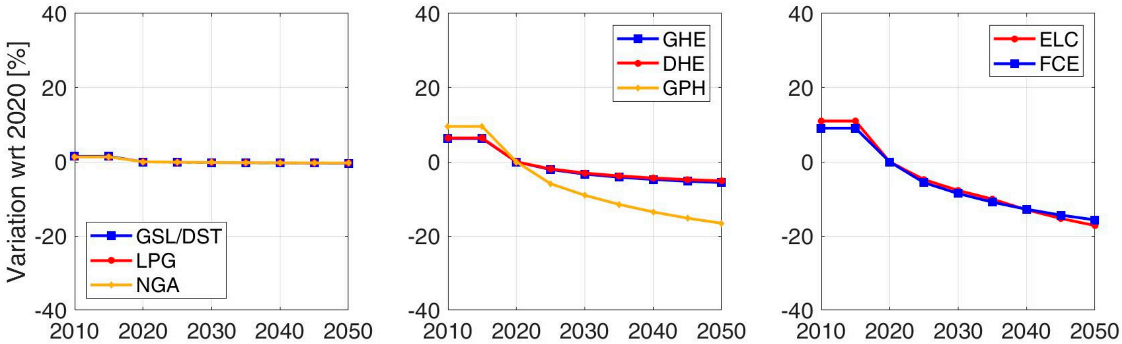

Figure 4. Investment cost variation with respect to 2020 applied to LDVs.

Moreover, since the 2020 fully electric Compact SUV corresponds to luxury vehicles (Tesla Model X), the costs of fully electric light trucks have been adjusted from 2030 so as to become representative of standard class vehicles. The same applies to fuel cell cars, which are assumed to be Medium cars (instead of Large cars only, as currently on the market) starting from 2030.

The variation in the investment cost considered for HDVs is due to the improved lifetime only; see Section 2.2.

2.4. Fixed O&M Cost

The Fixed O&M cost corresponds to the Maintenance and Repair (M&R) cost and it is derived from the analysis in [25], where M&R cost was evaluated for 2020 Medium cars. In [25], the definition of an internal combustion engine (ICE) includes gasoline and diesel vehicles only. For LPG, natural gas and flex-fuel cars, slightly increased costs are then adopted, due to the need for additional components with respect to a conventional ICE. The values obtained from [25] for cars, in $/vkm, are then properly scaled (considering the investment cost difference between transport modes) to be representative of all other vehicle types, and are reported in Table 8.

Table 8. Fixed operation and maintenance (O&M) cost (in USD/year) for the different modes/technologies in the current road transport module.

	GSL	DST	LPG	NGA	FLF	ELC	GHE	DHE	GPH	DPH	FCE
TRT	0.081	0.081	0.083	0.083	0.083	0.066	0.080	-	0.077	-	0.090
TRC	0.138	0.131	0.129	0.136	0.142	0.113	-	0.121	-	0.097	-
TRL	0.096	0.095	0.087	-	0.099	0.090	0.096	-	0.070	-	-
TRW	0.011	0.010	-	-	-	0.008	0.009	-	-	-	-
TRE	0.031	0.029	-	-	-	0.022	-	-	-	-	-
TRM	0.493	0.469	0.460	0.486	0.507	0.307	-	0.431	-	-	-
TRH	1.848	1.759	1.726	1.822	1.899	1.153	-	1.615	-	-	-
TRB	1.016	0.968	0.949	1.002	1.045	0.634	-	0.888	-	-	0.678

Regarding Fixed O&M costs, fully electric and plug-in hybrid electric vehicles allow substantial savings with respect to the other technologies. When fuel cell vehicles are assumed to be size-comparable with other technologies, they are ∼ 30% cheaper (e.g., buses) than conventional ICEs.

The fixed O&M costs have not been modified during the time scale of our analysis, except for fuel cell cars since size range extension has been forecast, so the fixed O&M have been adapted to be consistent with a Medium fuel cell car.

2.5. Variable O&M Cost

The variable O&M cost corresponds to the cost of energy/fuels, which is not given as an exogenous value to ETM, but rather is computed self-consistently at each time step, as the prices of all commodities in ETM are calculated according to Equation (8):

$$\frac{D}{D_0} = \frac{P}{P_0} \tag{8}$$

where $\{D_0, P_0\}$ is a reference pair of demand and price values for the energy service over the forecast horizon.

3. The EUROfusion TIMES Model

The EUROfusion TIMES Model (ETM) is an economic model of the global energy system [26], based on the TIMES framework [27]. Thus, it adopts an optimization strategy aiming to supply energy services at the minimum global cost (more precisely, at the minimum loss of total surplus) [28], with a partial equilibrium approach on a long-term time scale, starting from 2005 (the so-called "base year") up to 2100. ETM is particularly suited to the exploration of possible energy futures on the basis of alternative scenarios. Coherent driver (e.g., GDP, Population, GDPPP) trajectories, taken from validated sources, such as the International Energy Outlook 2014 by the U.S. Energy Information Administration [29] are allocated to each demand category, such as in the TIMES Integrated Assessment Model (TIAM) [10] to drive demand over the model time horizon, and are modified according to the storyline/scenario in order to analyze the impact of different elasticities of demand growth on the energy system. Different ETM scenarios are considered in the present study, based on three storylines, which are characterized by a diverse set of socio-economic, political and environmental features [16], as reported in Table 9 and presented in Section 3.1.

Table 9. Summary of the main features of the EUROFusion TIMES Model (ETM) storylines [16].

Storyline / Feature	A	B	C
Environmental responsibility	Strong, driven by RCP 2.6	Strong, driven by RCP 2.6	Weak, driven by RCP 6
Investment policies	Medium-term (medium disc. rate)	Long-term (low discount rate)	Short-term (high discount rate)
Demand elasticity	Medium	Low	High
Cooperation between countries	Moderate	High	Very low

3.1. The Storylines

Storyline **A** (corresponding to Paternalism 2.6 in [16]) is based on a strong environmental responsibility, where the composition of the road transport sector and, generally, of the overall energy system, has to adhere to restrictive environmental limits, defined according to the Representative Concentration Pathways (RCP) illustrated by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report [29]. Each RCP is a greenhouse gas (GHG) concentration trajectory until the end of the century, assigning maximum yearly values to GHG emissions from human activities in order to reach different GHG concentration targets. The so-called RCP 2.6, the only one able to keep the increase in global temperature well below 2 $^{\circ}$C with respect to pre-industrial levels, is applied to storyline A. The investment policies consider price as an important driver for the composition of the energy system, but the demand growth is moderately dependent on the socio-economic parameters. The countries grouped in the model regions show a moderate level of cooperation to reach the prescribed environmental goals, with some transfers of commodities allowed between the different regions.

In storyline **B** (corresponding to Harmony in [16]), a strong environmental responsibility (as in storyline **A**) is coupled to long-term investment policies. The demand growth, almost independent of the price, and the low discount rate, allow the market to be more sensitive to the prescribed environmental targets than to the mere economic affordability (cost) of supply processes. The international cooperation to reach the environmental goals is stronger than in storyline **A**.

Storyline **C** (corresponding to Fragmentation in [16]) is characterized by geo-politically constrained energy trade and subsequent difficulties to reach ambitious environmental goals. The environmental responsibility is thus much lower than in the other storylines, following the trajectory defined by RCP 6, in which some mitigation strategies and technologies are applied, but the CO_2 concentration reaches 660 *ppm* in 2100 (from a current value below 400 *ppm*), with a late stabilisation of emission levels. That is coupled to short-term investment policies, where prices are considered the most important drivers for the composition of the energy system and a demand growth tat is strongly dependent on socio-economic parameters.

3.2. Demand Projection

Each demand sector is coupled to one specific social or economic driver, which determines its growth or decline over the model time horizon. The ETM demand drivers for road transport are the Population (POP, used for two-wheelers, three-wheelers and buses), the gross domestic product by market exchange rates (GDP, used for vans, light, medium and heavy trucks) and the GDP per capita by purchasing power parities (GDPPP, used for cars). The trends for these drivers, as used for ETM demand projections in the EUR region, are exogenously taken from TIAM [10], and reported in Figure 5, where a slight population growth is forecast in Europe until the end of the 21st century, while GDP and GDPPP grow at different but positive rates.

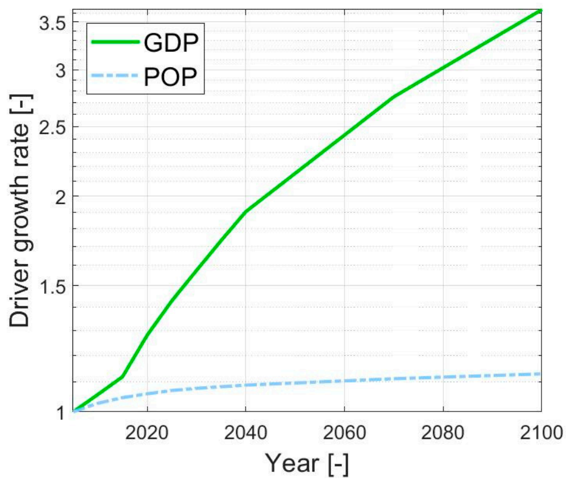

Figure 5. ETM Driver projections for EUR region [10].

The elasticities (e) of demand are considered in ETM, in order to reflect changing patterns in energy service demands in relation to socio-economic growth. These are yearly variables, different for each demand category and region, but generally allocated on three levels, according to the selected storyline, as shown in Figure 6. Conservatively, the elasticity is assumed not to decrease further in the long term, to avoid an excess of optimism about the growth of future demand. Note that the literature on the specific hypotheses made for elasticities of energy service demands is extremely poor, so they are constantly verified and updated, according to up-to-date statistics, to reflect changing patterns in the use of energy. Since the demand for transportation energy services in Europe is driven in ETM by constantly growing drivers, elasticities are kept constant from a certain time step onwards in order to reflect the saturation of the related energy service demand, which could ease the energy transition to a low-carbon system [30]. Indeed, in the most environmentally friendly storylines, **A** and **B**, the levels of elasticities are kept lower than in storyline **C**.

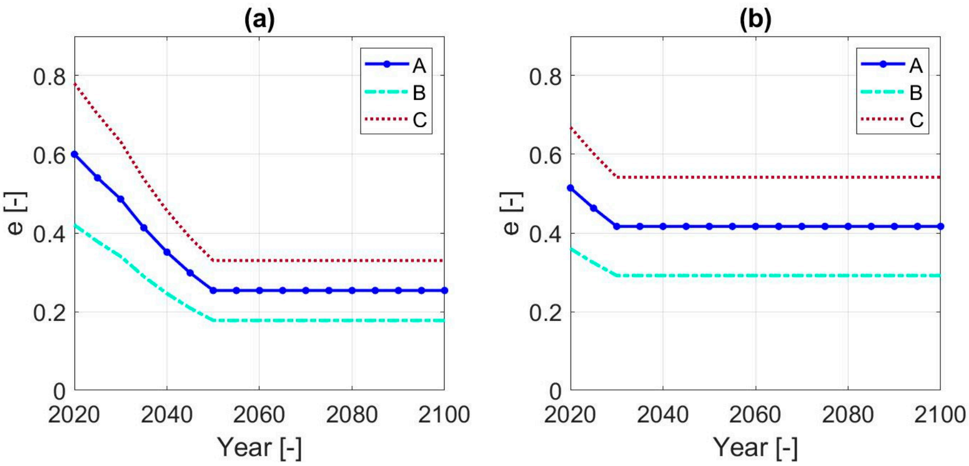

Figure 6. ETM elasticity trends for (**a**) gross domestic product and (**b**) population-associated demand categories [10] during the ETM time horizon, for the different storylines.

Moving from time t_{i-1} to time t_i, the demand increase is computed according to Equation (9):

$$D(d,r,t_i) - D(d,r,t_{i-1}) = D(d,r,t_{i-1}) \cdot [\delta(d,r,t_i)^{e(d,r,t_i,s)} - \delta(d,r,t_{i-1})^{e(d,r,t_{i-1},s)}] \quad (9)$$

where D is the demand, d the demand sector, r the region, t the time step and i the counter for time steps; δ is the driver growth factor, which is a function of the demand sector, region and time, while e is the elasticity, see Figure 6, that also changes with the storyline s.

According to Equation (9), the total road transport demand follows the trends illustrated in Figure 7 for the different storylines, during the ETM time horizon. In general, as visible from Figure 7, the road transport demand follows an increasing behavior, at different rates, for the three storylines, with cars (TRT) always keeping the highest share. As a general remark, the assigned values of elasticities are functional in relation to the reduction in the growth rate of demand with respect to the associated driver. In the specific case of road transportation demand, scenarios from the IEA Energy Technology Perspectives 2017 [15] highlight a plateau in the growth of the vehicle fleet until 2060, which is reflected here.

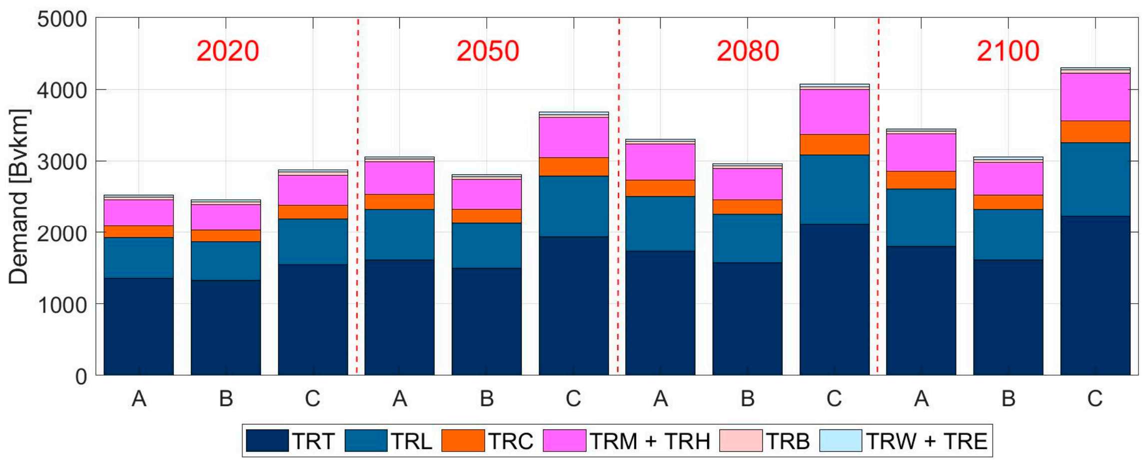

Figure 7. Road transport service demand projection for the different transport modes at selected time steps in the three storylines.

Note, however, that the model described by Equation (9) is subjected to the calibration at the base year, as illustrated by Equation (1): the efficiencies and energy consumption values of the different mode–process couples have been calibrated (and not computed) to match the 2005 total road transport sector consumption. A more accurate evaluation of the demand increase over the time horizon would require the use of more realistic efficiencies and energy consumption values for base-year technologies, thus implying a much more accurate description of the road transport sector in the year 2005, or a shift in the base year from 2005 to 2020 (which is beyond the scope of this paper).

3.3. Scenario Definition

Within a single storyline, typically, several scenarios can be analyzed, each assuming different degrees of technological advancement, in terms of new generation technology availability and the evolution of their costs, or specific policy measures (application of carbon taxes, consideration of external costs of energy production).

One scenario per ETM storyline is considered here (which will then be identified accordingly with the storyline name), characterized by the following main features:

- Carbon capture and storage (CCS) technology availability from 2030 in the EUR region;
- Reference investment and O&M costs for fusion technologies, derived from the fusion reactor cost estimation performed by means of the PROCESS code [6] (which aims to minimize the cost of electricity, accounting for constraints on engineering, physics and materials of the NFPP [30]); see Table 10. The NFPP availability for commercial purposes is assumed to start from 2070 in the EUR region; a 85% availability factor and a lifetime of 40 years is assumed;
- Optimistic prediction about nuclear fission potential evolution, in order to consider the possibility to increase, up to five times, the current global capacity, slightly reducing the investment costs by 0.26% per year;
- External costs of fusion and other electricity production sources are not included.

Table 10. Data adopted in the current analysis for the fusion technologies [16].

Type of Plant	Start	Inv. Cost	Fixed O&M	Var. O&M	Efficiency
		($/kW)	(M$/GWa)	(M$/PJ)	(%)
Basic plant A	2070	5910	65.8	2.2	42
Basic plant B	2080	4425	65.8	1.6	42
Advanced plant A	2090	4220	65.3	2.1	60
Advanced plant B	2100	3255	65.3	1.6	60

In all cases considered here, no constraints on material availability are taken into account.

4. Results

4.1. Energy Demand for the Road Transport Sector

The effects of the new road transport module bring a somehow comparable road transport energy demand trend for storylines **A** and **B**, as reported in Figure 8a,b. Indeed, a significant penetration of electricity is visible in both storylines: up to ∼ 31% (Storyline **A**) and ∼ 40% (Storyline **B**) of the total energy consumption in 2050, and ∼ 68% (Storyline **A**) and ∼ 96% (Storyline **B**), in 2100, significantly reducing the reliance on oil products, as expected. Apart from the demand, which is increasing less in terms of Bvkm for storyline **B**, if compared to **A** (see Figure 7), which leads to a lower energy demand, as both storylines **A** and **B** strongly reflect their environmentally friendly footprint.

A different path is found for storyline **C** when looking at the energy demand trends in Figure 8c. The larger service demand for that storyline, see Figure 7, is reflected in a large use of oil products and biofuel blends, which keep a robust share until the end of the century (the oil products show a share of 45% of total demand in 2050, reduced to ∼ 25% in 2100). Electricity reaches ∼ 24% of the total energy demand in 2050, and ∼ 42% in 2100, but the total installed electricity capacity at the end of the century is absolutely comparable to that of the other two storylines.

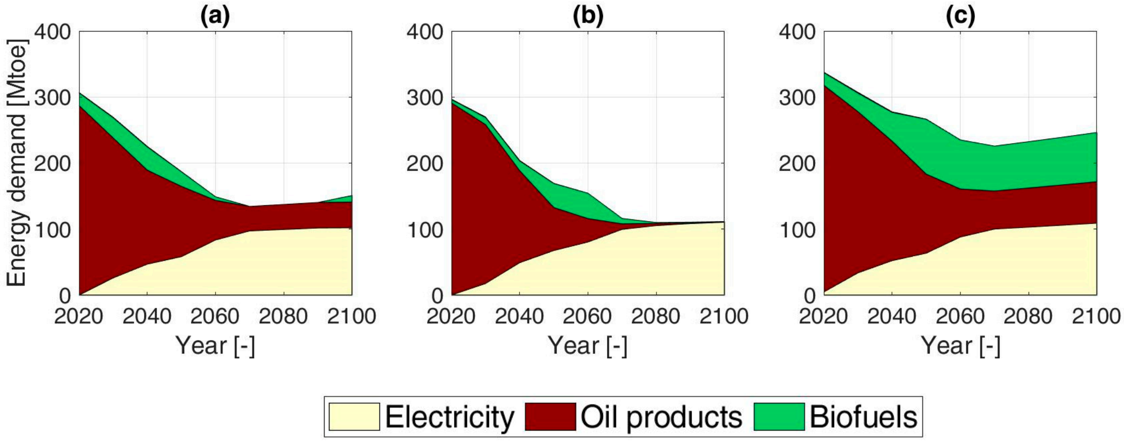

Figure 8. Road transport energy demand per type of fuel: storyline **A** (**a**), **B** (**b**) and **C** (**c**), respectively.

Table 11 shows a comparison between the results of the road transport energy consumption, as computed by ETM, and those from other models. Looking at the European Green Vehicle Initiative (EGVI) simulation scenarios [31] (referred to EU28 only), the corresponding ETM storylines with similar features compute a slightly higher total consumption in 2050. Such scenarios, not aimed at exploring the most effective transport solution in terms of both costs and environmental protection, but simply analyzing the possible effects of the adoption of an expert-base assumed road fleet, following the implementation of strong electrification policies ("High Electrification" and "High Electrification + Hydrogen" scenarios) or exploring a business-as-usual scenario ("Mix"), show that the strong efforts towards the penetration of electric vehicles are rewarded with a strong decline in total consumption, given the fact that electric vehicles (especially fully electrics) are the most energy efficient on the market, providing a huge reduction in the current consumption levels. On the other hand, the EGVI Mix scenario, proposing a road transport consumption pattern where gasoline and diesel still keep an 85% share in 2050 (due to a strong activity increase in the HDV fleet, which, instead, is not reflected in ETM demand trends; see Figure 7), but taking into account lower biofuel uptake, reflects the actual tendency to prefer traditional fuels; this is not completely verified in storyline **C**, the most environmentally careless one in ETM, where, instead, electricity is largely used for HDVs (see Figure 9), even from the beginning of the analyzed time period. The main explanation for this behavior can be simply found in the fact that ETM does not take into account the actual usage of vehicles, making electric HDVs attractive from an economic point of view, but neglecting the enormous difficulties involved in the recharge cycle of long haul vehicles, which would require a re-organization and optimization of road freight transport, in order to avoid economic losses and huge stress on the electricity grid [32].

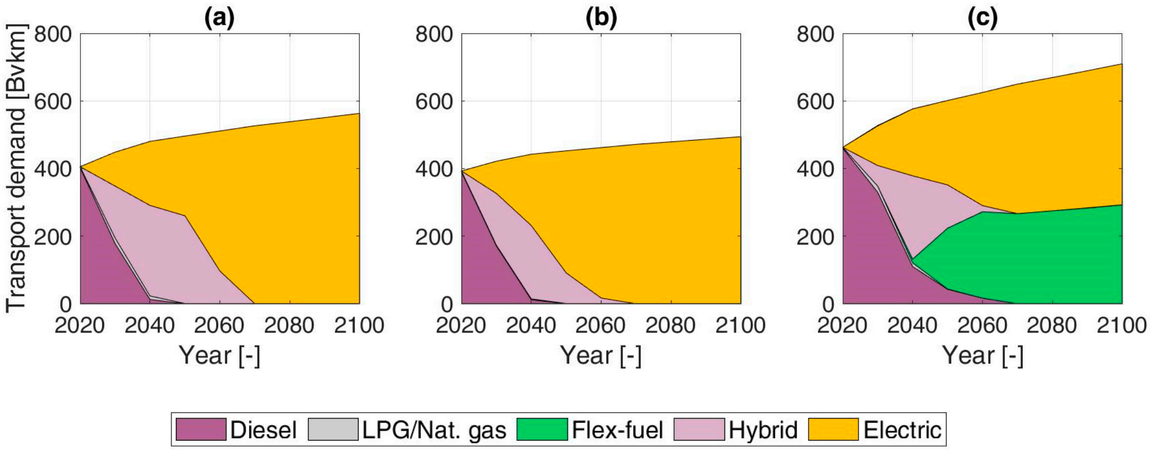

Figure 9. Heavy-duty vehicle (HDV) fleet composition in the three analyzed storylines: **A** (**a**), **B** (**b**) and **C** (**c**).

Table 11. Road transport energy consumption: ETM vs. other model results.

Specific Aspect	ETM Outcome	Other Model Results	Source
Road fleet total energy consumption @ 2050 [TWh]	A:~ 2200 B:~ 2000 C:~ 3100	HEH *: ~ 2000 HE **: ~ 1800 MIX ***: ~ 2800	[31]
Final energy demand (2050 wrt 2010)	A:−35% B:−41% C:−7%	(2050 wrt 2009) −38% ÷ −43% depending on the scenario	[34]
Final energy demand (2040 wrt 2010)	A:−21% B −29% C:−3%	(2040 wrt 2013) NPS #:−19%	[35]
Share of electricity in road transport energy demand (2040)	A:21% B:24% C:19%	NPS #: 4%	[35]
Share of biofuels in road transport energy demand (2040)	A:16% B:7% C:16%	NPS #: 15%	[35]
Share of electricity in transport energy demand (2040)	A:21% B:24% C:19%	NPS #: 12% CPS °°°: 5% SDS °°°°: 38%	[36]
Electricity demand for road transport in Europe (2030) [TWh]	A:~ 300 B:~ 200 C:~ 400	NPS #: ~ 110 EV30@30 $: ~ 200	[37]
Share of electricity demand in road transport @ 2030	A:10% B:7% C:11%	12% (2030)	[33]
Share of electricity demand in road transport @ 2050	A:31% B:40% C:24%	50% (2050)	[33]

* HEH (European Green Vehicle Initiative (EGVI)): High Electrification + Hydrogen scenario; ** HE (EGVI): High Electrification scenario; *** MIX (EGVI): Low electrification scenario; # NPS (IEA): New Policy scenario; $ EV30@30 (IEA): Scenario with 30% penetration of electric vehicles by 2030; °°° CPS (IEA): Current Policy scenario; °°°° SDS (IEA): Sustainable Development scenario.

On the other hand, the Greenpeace 2015 World Energy scenario [33] is far more optimistic than all ETM storylines: indeed, it considers a "transport [r]evolution" not only in the sense of a fuel switch from oil-based to electricity, but one that is achievable by means of the concrete and effective adoption of mobility solutions, solving environment-related issues. Of course, this is very hard—if not impossible—to implement in an optimization energy model.

4.2. Road Vehicle Fleet Composition

The composition of the fleet computed by ETM is shown in Figure 9 for heavy-duty vehicles and in Figure 10 for light-duty vehicles. The main results highlight how, for HDVs, the hybrid technology overcomes diesel during the transition towards a completely electrified fleet in storylines **A** and **B**, while in storyline **C**, fully electric and flex-fuel HDVs are chosen to cover the very high road demand, after an initial strong uptake of hybrid diesels, which, again, progressively substitute traditional diesels at the beginning of the ETM time horizon.

Regarding LDVs, the higher cost effectiveness is recognized for plug-in hybrids, which dominate the road transport sector in storylines **A** and **C** (that is the reason why oil products do not disappear, even at the end of the time horizon; see Figure 8), while more expensive fully electric vehicles progressively gain high shares in storyline **B**, where environmental awareness is put ahead of economic interests, and demand growth is not so marked as in the other storylines. Despite the fact that storylines **A** and **B** are characterized by the same environmental constraints (prescribed according to RCP 2.6), the evident difference in the composition of the fleet (compare Figure 10a,b) is driven by the different level of discount rate applied to the different technologies in each storyline, used to determine the investment policy perspective. Only a long-term investment policy (such as that implemented in storyline **B**) is able to allow for the penetration of more expensive fully electric LDVs, instead of the plug-in hybrids, which are slightly cheaper but less efficient, chosen as a consequence of the shorter-term investment policy adopted in storyline **A**.

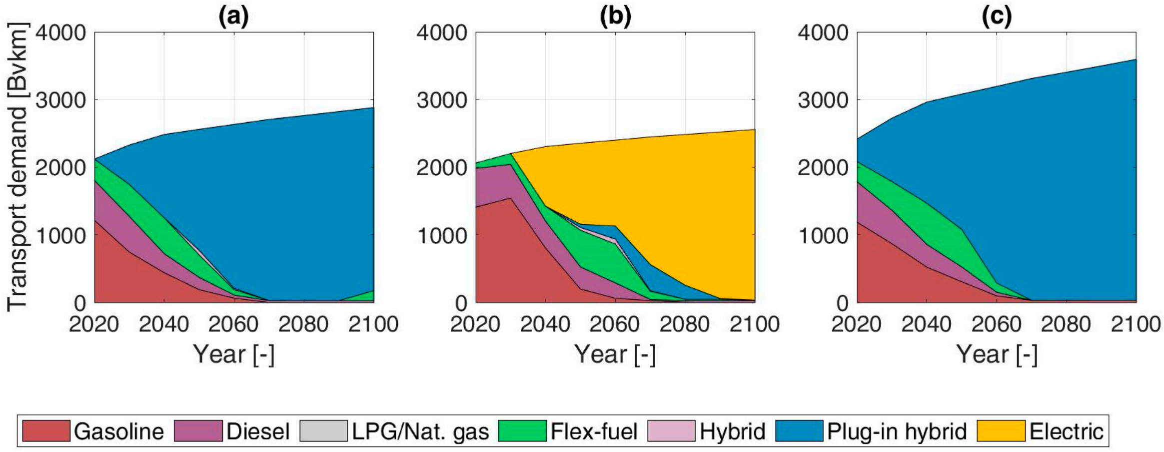

Figure 10. LDV fleet composition in the three analyzed storylines: **A** (**a**), **B** (**b**) and **C** (**c**).

It has to be noted that fuel cell technologies, despite being currently adopted, even at a very small scale for cars and buses, and forecast in major manufacturers' development plans to be potentially installed in all kind of vehicles, do not appear in any storyline, despite being highly efficient, mainly because of their extremely high investment costs. [38,39]

Table 12 shows the comparison of results concerning HDVs only: while transport and environment [40] are in line with ETM results, forecasting a 100% alternative fuel power HDV fleet by 2050, the 2016 edition of the EU Reference (business as usual) scenario only accounts for a 3% penetration of alternative fuel vehicles (AFV) in the heavy-duty fleet by 2030 (even in ETM storyline **C**; due to the strong uptake of biofuels, alternative fuels are able to cover 26% of the demand). As already explained in Section 4.1, the EU Reference scenario highlights how difficult the implementation of effective environmentally friendly initiatives for long-haul vehicles is in ensuring that there is no impact on the normal activity of goods transport. Furthermore, the first ever regulation standard to limit emissions from HDVs was adopted in 2019, setting targets for new vehicles starting from 2025 [41], thus leaving space for a short-term evolution of the sector in complete contrast with the urgent need to abate pollutant emissions.

Table 12. Heavy-duty vehicles: ETM vs. other model results.

Specific Aspect	ETM Outcome	Other Model Results	Source
Alternative fuel power share in the HDV fleet by 2050	A:100% (Mostly hybrid and fully electric) B:100% (Mostly fully electric) C:93% (Mostly flex-fuel + hybrid)	100% (electric + hybrid)	[40]
Alternative Fuel Power share in the HDV fleet by 2030	A:60% B:59% C:26%	3%	[42]

Table 13 shows the comparison of results concerning cars (therefore, both cars and light truck transport modes in ETM). The decarbonization scenarios of the European Commission Energy Roadmap to 2050 [34] accounts for a higher penetration of electric cars (80% of the fleet) with respect to all ETM storylines. Such a laudable result is realized by the application of strong energy measures like the increase in energy efficiency in all sectors, diversified supply technologies and the high penetration of renewable energy sources (RES) in the electricity production system, combined with the possibility to reduce the transport activity supplied by cars, realized by considering a modal shift to other types of passenger transport (e.g., public transportation). While the environmentally friendly ETM storylines are able to reproduce such behaviors in the composition of the electricity mix, the point concerning reduced car transport demand through a modal shift is not realized; actually, car demand increases in all ETM storylines, following GDPPP- (cars) or GDP-driven (light trucks) development trends. In any case, the increasing trend for GDP is also taken into account in the European Commission Energy Roadmap to 2050.

Table 13. Cars: ETM vs. other model results.

Specific Aspect	ETM Outcome	Value	Source
Electric car (fully electric + plug-in hybrid) share in 2050	A: 69% B: 58% C: 64%	80%	[34]
Electric car share in 2040	A:48% B: 42% C: 49%	NPS #: Negligible	[35]
Full-electric (BEV) and plug-in hybrid (PHEV) share among electric cars in Europe (2050)	A: 0%(BEV)–100%(PHEV) B: 96%(BEV)–4% (PHEV) C: 0%(BEV)–100% (PHEV)	C70 *: 0% (BEV)–60% (PHEV) REF **: 0% (BEV)–< 10% (PHEV)	[43]

NPS (IEA): New Policy Scenario. * C70 (PET36): Scenario with stringent carbon cap until 2050 and 25% cost reduction (2050 wrt 2020) for BEVs, 8% for plug-in hybrid electric vehicles (PHEVs, more efficient for long distances and modelled with 10% gasoline use, against 55% in ETM). ** REF (PET36): Less stringent carbon cap from 2030 to 2050, same cost trend as for C70.

The comparison with the IEA World Energy Outlook 2015 [35] New Policy scenario, reporting a negligible share of electric cars by 2040, highlights how almost half of the ETM car fleet is already completely electrified by 2050 in all storylines. This surprising IEA result was then reassessed in the following editions of the WEO, since results from the same scenario are far more positive concerning the penetration of electricity in the car fleet, highlighting how this sector is quickly and continuously progressing, affected by a huge number of variables.

The IEA Global EV Outlook, instead, introduced the EV30@30 scenario, where a 30% global share of cars in the fleet is assumed for the year 2030, in line with ETM storyline **B**, which takes into account an environmentally friendly characterization as well as a contained increase in transport activity and, above all, the uptake of fully electric vehicles. However, the uptake of fully electric vehicles in ETM is only forecast by this storyline due to economic reasons, which are fully confirmed by the results from another TIMES family model, Pan-European TIMES 36 (PET36), specifically focused on the optimization of the European energy system only (instead of the ETM global scale). The assessment of the cost effectiveness of EVs in Europe, by means of a such model [43], highlights that the penetration of fully electric cars is very difficult and subject to a strong investment cost reduction: indeed, BEVs are only able to gain market shares when their costs are reduced by more than 30% from current values; in a similar way, they are able to gain a robust market share in ETM only when a low transport demand is coupled with a reduced economic influence, such as in storyline **B**.

4.3. Electricity Production Mix

Given the results from the road transport sector, where an important contribution of electricity is present for all storylines, the composition of the electricity production mix, after the introduction of the NFPP technology (i.e., in years 2070, 2080, 2090, 2100), is shown in Figure 11. The electricity production sources have been grouped into five categories:

1. Nuclear, including fission and fusion power plants;
2. VRES, including solar PV and wind power plants;
3. Other RES, including biomass, hydroelectric, geothermal and concentrated solar power (CSP) plants;
4. Fossil fuels, including coal, oil and gas plants;

5. Fossil fuels w/CCS, including coal, oil and gas plants provided with CCS technologies.

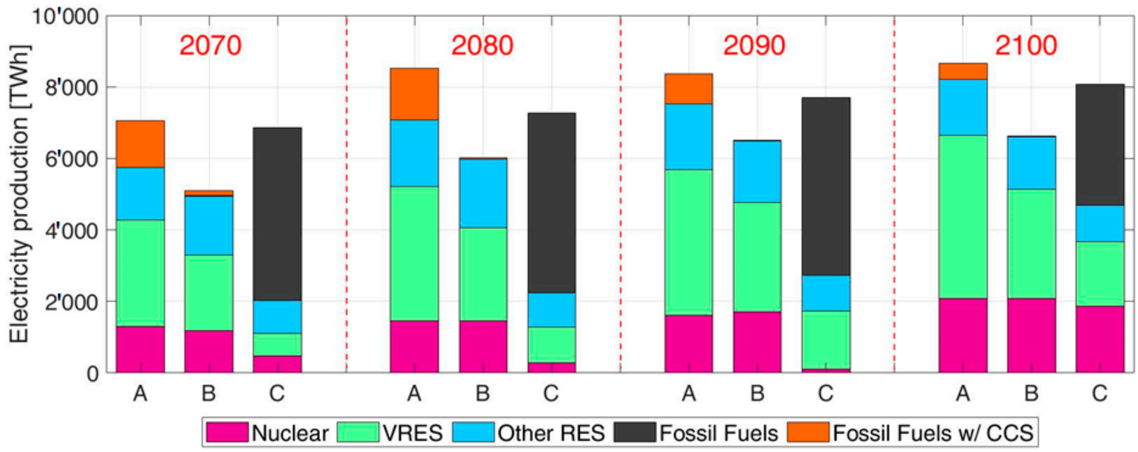

Figure 11. Evolution of the production mix for road transport electricity at selected time steps, for the different storylines.

The total electricity production reaches comparable levels in both storylines **A** and **C** in 2100 (~ 8000 TWh), while it does not exceed 7000 TWh in storyline **B**. When comparing these values with actual production in Europe (~ 3000 TWh [44]), the computed electricity production is more than doubled in all storylines in 2100, with respect to current levels.

In this framework, in any case, the three storylines show a very different production mix. In storylines **A** and **B**, fusion could reach its maximum penetration, contributing to ~ 25% of nuclear production in 2100, corresponding to ~ 530 TWh total production and 72 GW of installed capacity, a target which appears hard to reach based on the current perspective. Instead, fusion represents ~ 16% of nuclear production (~ 311 TWh, with 42 GW installed capacity) in 2100 in storyline **C**, still a very large capacity. The very high share computed for nuclear fusion, on one hand, highlights how the fusion technology can become easily competitive, but, on the other hand, calls for a careful revision of the factors that could constrain the penetration of fusion such as lithium and tritium availability and the feasibility of the resulting electricity fleets.

Electricity production from fossil fuels is already null in 2070 in storylines **A** and **B**, where, instead, RES dominate the electricity production system—above all, wind power. Fossil fuel power plants with CCS only appear in storylines **A** and **B**, but progressively reduce their share in the mix. On the other hand, not only is CCS not adopted in storyline **C**, but a strong uptake of fossil fuels is also preserved until 2100, when it reaches its lowest share, corresponding to 42% of total production. Thus, the uptake of electric vehicles, underlined by the strong electricity demand in this storyline, becomes useless and harmful, from an environmentally friendly point of view, when being coupled with a reckless electricity production system, dominated by fossil sources.

4.4. CO_2 Emissions

The strong environmental responsibility that characterizes storylines **A** and **B** is remarkable if looking at the computed evolution of CO_2 emissions from transport processes in Figure 12. Indeed, the strong uptake of electric vehicles (both plug-in hybrid and fully electric) in all road transport modes is reflected in the ~ 83% decline in yearly emissions from 2020 to 2100, reaching ~ 0.2 Gt_{CO_2} in 2100. A similar path is followed in storyline **B**, where yearly emissions are even lower than in storyline **A** in 2100 (< 0.1 Gt_{CO_2}), with a ~ 93% reduction from 2020 to 2100. This even larger reduction with respect to storyline **A** is due to the uptake of fully electric vehicles, instead of plug-in hybrids only, which are able to reach very low, but not null, emission levels. In storyline **C**, as the low environmental responsibility allows fossil fuels to be kept in the production mix during the whole ETM time horizon, the total CO_2 emission reduction is much less effective than in the others storylines, even if a $\sim$ 59% reduction occurs in the transport sector.

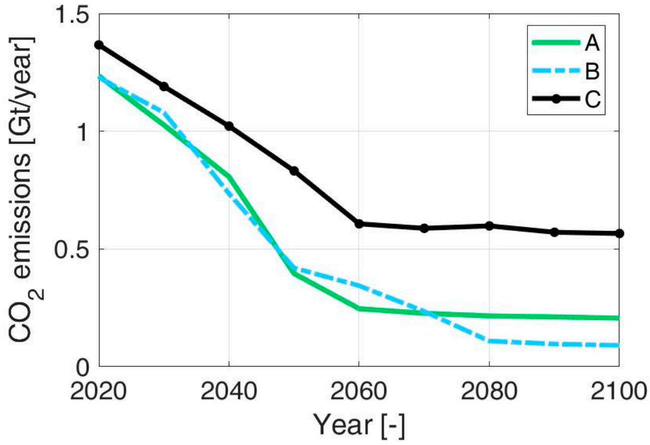

Figure 12. CO_2 emissions from the road transport sector.

The results regarding CO_2 emissions from the transport sector, compared in Table 14 to the outcome of other models, highlight that the ETM energy system optimization approach provides, as expected, far more pessimistic results with respect to the Greenpeace scenario [33] for Europe, but in line with the European Green Vehicle Initiative forecasts [31]. Indeed, if considering the transport sector alone, the hybridization and electrification of the whole fleet are undoubtedly the measures to be adopted for an effective reduction in pollutants. On the other hand, ETM storyline **C** and, similarly, the EGVI Mix scenario, particularly highlight how the increasing amount of biofuels in traditional fuel blending, and the application of strong efficiency measures on ICEs, are also not sufficient to realize short-term commendable CO_2 reduction targets, even when a considerable use of electricity is taken into account.

Table 14. CO_2 emissions from the transport sector: ETM vs. other model results.

Salient result	ETM Outcome	Value	Source
Transport CO_2 emission reduction from 2010 to 2050	A:−67% B:−65% C:−31%	(2009 to 2050) −94%	[33]
Transport CO_2 emission reduction from 2010 to 2050	A:−67% B:−65% C:−31%	(2015 to 2050) HE *:−70% HEH **:−80% MIX ***:−30%	[31]

* HEH (EGVI): High Electrification + Hydrogen scenario; ** HE (EGVI): High Electrification scenario; *** MIX (EGVI): Low electrification scenario.

As a consequence of the large uptake of electric vehicles, reflecting in good performances from the three storylines to lower CO_2 emissions from road transport (see Figure 12), the response from the electricity production system to bear this abrupt change should be analyzed. Figure 13 represents the comparison between CO_2 emission levels from both electricity production and road transport systems. While, at the first selected time step (2020), such levels are almost the same, the evolution in time highlights how, in the environmentally friendly storylines **A** and **B**—driven by RCP 2.6—the adaptation of the electricity production system to the uptake of electrified transport solutions is quite effective already, starting from 2050: thanks to the strong impact of renewable sources and the implementation of CCS in electricity production (mostly in storyline **A**, where the higher electricity demand cannot be fully sustained by renewable sources), net zero emissions are not reached until 2100. A stricter relationship between CO_2 emissions from the two sectors is highlighted in storyline

C, where the increase in electricity demand from road vehicles corresponds to a direct increase in emissions from electricity production, due to the additional fossil fuel-based capacity installed to cope with the higher electricity demand. Almost the same combined quantity of CO_2 emissions in 2020 is preserved until 2080. At the very end of the century, instead, RCP 6 prescribes a last-minute attempt to lower emission levels; thus, a larger uptake of nuclear, coupled with a reduction in fossil fuel-based production (see Figure 11) contributes to cut emissions from electricity production.

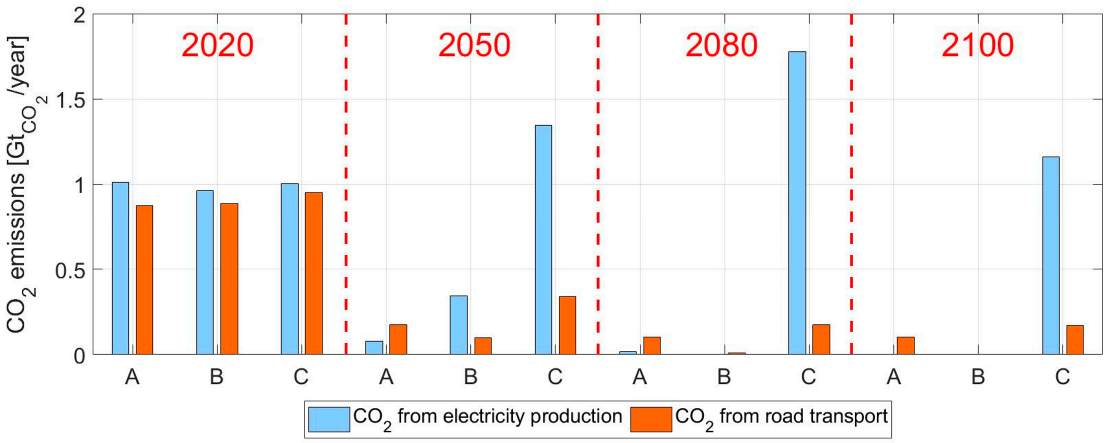

Figure 13. Comparison of CO_2 emissions from total electricity production and road vehicles at selected time steps, for the different storylines. The constantly growing electricity demand (above all from the transportation sector) reflects in an environmental-responsible adaptation of the production mix in storylines **A** and **B**, while the high uptake of electric vehicles in storyline **C** contributes to an uncontrolled growth of CO_2 (until 2080) from electricity production, making the radical changes in transportation almost ineffective.

5. Conclusions and Future Perspectives

A deep revision of the modelling of the road transport sector inside the EUROfusion TIMES Model has been carried out, in order to assess three storylines in ETM, which differ in the level of environmental responsibility, cooperation between countries, investment policies and demand elasticity of the behavior of the European transport sector and the implications for the future penetration of fusion power into the European energy system. This updated version of the model results in a deep penetration of electricity in the road transport sector in all the storylines. The electricity share is expected to be the highest in the energy consumption of the road transport system by the end of the century. The policy implications of this first conclusion are numerous. First, the results confirm that the electrification process initiated in the transport sector will probably continue in the future, irrespective of the pathway followed, as electricity will be the dominant energy carrier in the European transport sector at the end of the century. For the most ambitious pathways in terms of environmental goals, electricity would be the dominant energy carrier, even from the midpoint of the century. This calls for a deep change in the structure of the transport market itself, as well as a great and rapid deployment of electric vehicle charging infrastructure. Policies and economic instruments play a relevant role in accompanying and making possible this transition to electric mobility, especially in the early phases. Secondly, implications for the shape of the electricity demand curve could also be anticipated by looking at the results presented in this paper. Even if it is hard to achieve, the enormous fleet of electric vehicles present in the transport sector from the second half of the century onwards could play a role in the regulation of the electricity market as flexibility providers, and it could ease the penetration of variable renewable technologies foreseen in this work. Policies that regulate electricity markets should anticipate and enable this role for electric vehicles.

The second important conclusion of this work is that the larger electricity demand could help the penetration of nuclear fusion power plants in the European energy mix if the environmental responsibility is high enough to reward CO_2-free technologies, and provided that the investment cost does not exceed the current estimation much. The results obtained show that fusion is a valuable technology for the future European electricity system and the efforts pursued by the scientific community towards the adoption of this technology on a commercial scale are justified. The main policy implication of this second conclusion is that R&D programs currently running for the development of fusion technology should be continued, and strongly targeted to a cost-effective design.

However, some limitations are worth noting. First, neither the investment costs of the charging and refueling infrastructure, nor the costs for electric grid enhancement due to the shift towards a distributed renewable generation, are included in the costs considered for vehicles in the model: TIMES models are partial equilibrium models aimed at the estimation of the optimal energy system configuration that fits with the energy resources available and the energy demand. Therefore, ETM is not intended to carry out detailed analyses of the power system and energy infrastructure. The costs of the new refueling infrastructure, necessary for the diffusion of alternative fuels, are to be considered part of the costs of the transition, to be assessed separately to the TIMES framework. This is also valid for the assessment of the feasibility of ETM results regarding the development of the electricity system, which is actually performed via, e.g., dispatch models like PLEXOS on local geographical scales.

From another perspective, as far as the road transport sector model is strictly concerned, this work could be enhanced by looking at the effects of changes in the composition of the non-road vehicle fleet, and also by taking into account a possible increase in their electricity use, and considering alternative evolutions for (or by assessing the sensitivity to) the cost and efficiency parameters during the model timescale, through additional cost-driven scenario analyses. Furthermore, the revision of the regional calibration parameters, to extend the road transport sector review to all the other 16 regions, would make ETM able to depict global scenarios for the penetration of nuclear fusion into the energy mix.

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Abbreviations

The following abbreviations are used in this manuscript:

AFV	Alternative fuel vehicle
B2D	Below 2 Degrees
BEV	Battery-electric vehicles
CCS	Carbon capture and storage
CFV	Conventional fuel vehicle
DAT	Deutsche Automobil Treuhand
EGVI	European Green Vehicle Initiative
ETM	EUROfusion TIMES Model
EU-DEMO	European Demonstration Fusion Power Reactor
FCEV	Fuel cell electric vehicle

GDP	Gross domestic product
GHG	Greenhouse gases
GVW	Gross vehicle weight
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LDV	Light-duty vehicle
LPG	Liquefied petroleum gas
NEDC	New European Driving Cycle
NFPP	Nuclear fusion power plant
O&M	Operation and maintenance
PET36	Pan European TIMES 36
PHEV	Plug-in hybrid electric vehicle
POP	Population
RCP	Representative Concentration Pathway
RES	Renewable energy sources
TIMES	The Integrated MARKAL-EFOM System
VRES	Variable renewable energy source
WPSES	Work Package for Socio-Economic Studies

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