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Effect of Electrification of the transport sector for the EUROfusion TIMES Model

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Abstract

The EUROfusion TIMES Model (ETM) is an economic model of the global energy system, aiming at the exploration and optimisation of the future energy mix. In particular, it focuses on the possibility to have Nuclear Fusion power shares, starting from the second half of this century, at a cost competitive level with other electricity production technologies. This macro-scale model has been developed within the EUROfusion Socio Economic Research on Fusion (SERF) Group, starting from 2004.

The thesis focuses on the update of the EUROFusion TIMES Model (ETM) demand-side, with special reference to the Road transport sector.

The main aim of the work is the forecast of the future European energy mix, considering the possible role of Nuclear Fusion power plants for electricity production, related to the constantly growing interest on electrification of the vehicle fleet, which appears like the most suitable strategy to reduce GHG emissions from transport (provided that this electricity is produced from low/zero emitting sources).

In order to achieve that goal, the first step is the assessment of the present status of the vehicle usage. Indeed, the last version of the database included in the ETM, dating back to 2008, presents a lot of intolerable uncertainties and deficiencies, mainly related to the low technology readiness level of some of the technologies included in it. In particular, deep attention is paid to road transport, including passenger cars and light trucks, light, medium and heavy commercial vehicles, buses, two- and three-wheelers, with a special focus on Full-Electric and Plug-in Hybrid Electric vehicles, the ones requiring an increase in electricity production. This is fundamental for the re-running of the ETM code and the subsequent storyline and scenario analyses to find out which are the design choices that will allow the fusion technology to become competitive in the future European energy mix, in a sector which is, nowadays, increasingly oriented towards the use of electricity for the urgent environmental issues related with GHG emissions.

Since economic and population development will influence our energy system as well as climate change issues, resource depletion, technological development, demand development or political commitments, basing on three storylines included

in the Model, several scenarios with different consumption and emission trends up to the year 2100, under a set of constraints, are developed and analysed by means of the TIMES economic model generator in which ETM is implemented.

As a result of the update of the transport sector, which includes now more compelling cost and energy use trends for Road vehicles, a strong difference is highlighted in the allocation of electricity demand in Europe during the Model time horizon. Anyway, fusion is able to penetrate in the market with the Model hypotheses, even with a prominent role in the storylines with greater focus on environmental issues. However, most of the Model forecasts produce a somewhat utopian picture, in terms of installed Nuclear Fusion capacity by 2100. But those numbers are not to be interpreted according to their absolute value, since ETM does not take into account, by now, stringent assumptions about material availability, or delays in the building of large-scale fusion power plants (FPPs). An elementary sensitivity analysis on the cost parameters, integrated into the Model for FPPs, was carried out, in order to free market penetration from monetary constraints. Somehow, the Model shows the path to the realisation of a cost-competitive fusion power plant, in order to make it feasible for the integration in the electricity production mix.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The next decades are crucially important for putting the world on a path of reduced Greenhouse Gas (GHG) emissions. [9] [41] [162] [163] [164] [167] [168]

Population growth, increased urbanisation rate, expanding access to energy in developing countries and constantly increasing consumption in economically most developed countries will boost energy demand (to clearly of substantial efficiency improvements in all sectors). [12] [19] [76] [89] [95] [135] [150] [165] [166] [181]

The fossil fuels that shaped technological progress in the last centuries can only be relied on at the cost of no longer tolerable GHG emissions and pollution. Indeed, Article 2 of the Paris Agreement (2015), the world's first comprehensive climate agreement, states how GHG emission reduction and energy efficiency improvements are the main tool to hold the increase in the global average temperature to well below 2 $°C$ above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 $°C$ above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change. In order to do this, fossil fuel divestment is the most powerful weapon, unless rapid development of effective CCS technologies. [51] [73] [75] [84] [126] [133] [134] [174] [184]

A new large-scale, sustainable and carbon-free form of energy is urgently needed, especially to face the increasing demand of electricity. This new, revolutionary electricity production source can expected to be Nuclear Fusion. [43] [78] [107]

1.1 The essentials of a Nuclear Fusion reactor

According to the European roadmap [44] (see Figure 1.1) towards electricity from fusion [106] [183], the DEMO reactor project [43] will follow the ITER [107] ("The Way" in Latin) experiment with the aim of demonstrating the possibility to produce net electricity from Nuclear Fusion reaction. ITER has the aim of building the world's largest tokamak (Russian acronym for "toroidal chamber with magnetic coils" [11]), a magnetic confinement fusion device, designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy.

The principle at the basis of Nuclear Fusion is very simple, and it has been happening over and over, for billions of years, in the core of all stars forming the known Universe: light Hydrogen nuclei collide at very high speeds, favoured by the extremely high temperatures which make them overcome the natural electrostatic repulsion existing between their positive charges, fuse into heavier Helium atoms and release huge amounts of energy during the process (see Figure 1.2). Indeed, the mass of the resulting Helium atom is reduced with respect to the sum of the two original atoms, and this difference results in great amounts of gained energy, as stated by Einstein's famous formula $E = mc^2$: the tiny bit of lost mass m, multiplied by the square of the speed of light c^2, results in a very large energy figure E. Fusion can spontaneously occur in the extreme density and temperature of the stars, including our Sun. Nevertheless, fusion on Earth is not that easy, due to the absence of benefits provided by the gravitational forces at work all around the Universe. In laboratory, energy production from fusion can most efficiently take place through fusion reaction between two Hydrogen isotopes, Deuterium (D) and Tritium (T). Although this can produce the highest energy gain at the lowest temperatures, it requires nonetheless temperatures of $150 \cdot 10^6$ $[K]$, thus ten times higher than the Hydrogen reaction occurring in the Sun. [65] [107]

Plasma physics is at the core of fusion science. At extreme temperatures, electrons are separated from nuclei and a gas becomes a plasma. It is a ionized state of matter, very similar to a gas, but composed of charged particles. In a very tenuous plasma environment, with extremely low density, light elements are able to fuse and yield energy. In a laboratory, three conditions are needed to achieve fusion:

- high temperatures, to provoke high-energy collisions;
- sufficient plasma density, to increase collision probability;

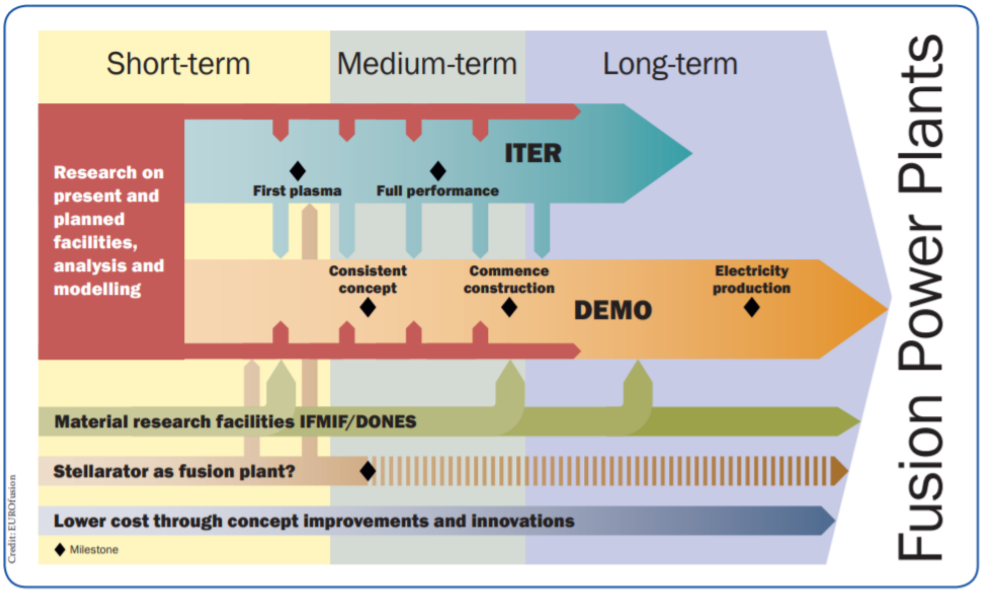

Figure 1.1: The European Roadmap towards Fusion Power Plants. Source: *European Research Roadmap to the Realisation of Fusion Energy*

- sufficient confinement time, to hold the plasma, which naturally tends to expand.

In ITER, fusion will be achieved in a tokamak device that uses magnetic fields to contain and control the hot plasma, at extreme levels of temperature and pressure. Inside the doughnut-shaped tokamak vacuum chamber, the gaseous Hydrogen fuel would become a plasma, controlled by the massive magnetic coils placed around the vessel, so that it would not enter in contact with the walls. Inside the tokamak, energy produced through DT fusion is absorbed as heat in the walls of the vessel, and just like it happens in conventional power plants, a fusion power plant will use this heat to produce steam, then electricity by means of turbines and generators. [107]

ITER's First Plasma is scheduled for December 2025. Today, project execution to First Plasma stands at 64.3 percent (July 2019 data). After that, Deuterium-Tritium operation beginning is scheduled for 2035. After ITER, a next generation machine, DEMO, aiming at producing the kWh, will bring fusion research towards the threshold of a prototype fusion reactor, which is planned as the following step (PROTO reactor). DEMO will explore continuous or steady-state operation, test the large-scale production of electrical power and

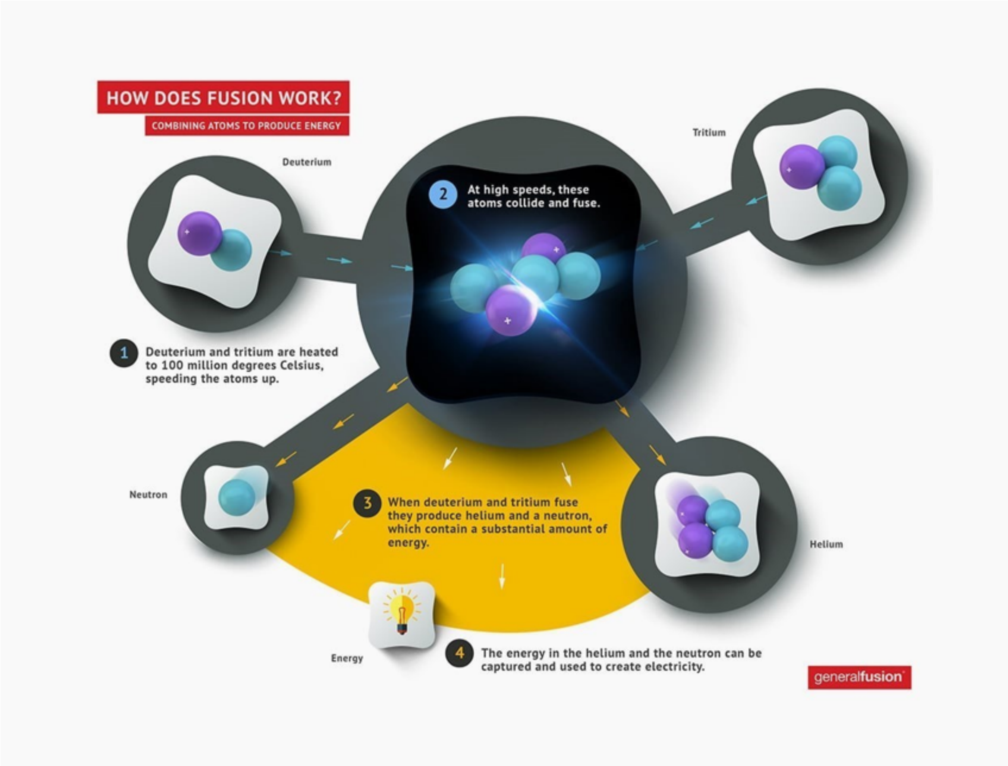

Figure 1.2: The working principle of Nuclear Fusion. Source: *General Fusion*

Tritium fuel self-sufficiency, in order to go beyond lab-based experiments, towards an industry-driven programme. EUROfusion, a Consortium of national fusion research organisations and universities, located in the European Union, Switzerland and Ukraine [43], is currently at work to lay the foundation for a EU-DEMO reactor. The term DEMO describes then more of a phase than a single machine, since different conceptual DEMO projects are under consideration. But there is cohesion around the timeline for the DEMO phase of fusion research: planning should continue throughout the early years of ITER fusion operation, while construction is foreseen to start in the 2030s, and operation in the 2040s. Within this context, EUROfusion's ITER Physics programme is designed to coordinate experiments to gather as much physics knowledge as possible to ensure the efficient experimentation in ITER once its operation begins. The central requirements for DEMO lie in its capability to generate $300 \div 500$ $[MW]$ net electricity to the grid, while operating with a closed fuel-cycle (reprocessing of spent Tritium fuel). In view of all this, large-scale fusion power production cannot be expected, in Europe, before 2070 (note, however, that in other countries, such as the US, a different path has been chosen, and fusion power could arrive earlier [26] [142]).

1.2 Advantages of Nuclear Fusion

A large number of advantages makes Nuclear Fusion worth pursuing [107]:

- Abundant energy, since controlled atom fusion releases nearly 4 million times more energy than a combustion reaction, and 4 times as much as Nuclear Fission reactions (at equal mass);

- Sustainability, since fusion fuels are widely available and nearly inexhaustible. (Deuterium can be distilled from water, while Tritium will be produced by neutron interaction with Lithium during the fusion process; indeed, Lithium is an abundant material on Earth, too).

- Absence of CO_2 emissions: fusion major product is Helium, an inert, non-toxic gas;

- Absence of long-lived radioactive waste, since the activation of components in a fusion reactor is low enough for the materials to be recycled or reused within 100 years;

- Limited risk of proliferation, since fusion does not employ fissile materials (Radioactive Tritium is neither a fissile nor a fissionable material); furthermore, there are no enriched materials in a fusion reactor that could be exploited to make nuclear weapons;

- No risk of meltdown, since any disturbance to the already extremely precise conditions, necessary to sustain fusion, would make plasma cool within seconds and the reaction stop. In addition, the low quantity of fuel present in the vessel at one time is not enough to trigger a chain reaction;

- Total cost comparable to Nuclear Fission, of course higher at the beginning of operation, when the technology is new, but then decreased thanks to the effect of economies of scale.

1.3 The need for macro-scale energy modelling

Macro-scale models generally analyse the energy system or a sub-system (e.g. the power generation system) at national, regional or global level, usually in the long-term, to achieve three main objectives:

- Energy market projections;
- Energy policy analysis;
- Analysis of climate change issues.

This kind of models applies different techniques, including mathematical programming (especially linear programming), econometrics and related methods of statistical analysis, and network analysis, and the main aim is to emphasise the need for co-ordinated developments between all the components of the energy system, in order to build cost-effective strategies for energy planning. [16]

Macro-models were born in the 1970s, mainly as a consequence of 1973 oil crisis: oil production was reduced by the Middle-East and price increased; at this point, resource allocation became to be very linked to their prices, thus energy system models were able to provide a reliable basis for beginning the discussion about resource dependence, as linked to economic growth. The focus shifted to energy-environment interactions in the mid-1980s, producing models for 20-25 years-long forecasts. In the 1990s, major attention began to be paid to climate change-related issues, as the natural extension of previously produced models, and the cost of mitigation strategies for damages to the environment were introduced in the new energy models. [16]

While basic accounting models are used to allocate energy use to the different components of the system (energy balance), a natural extension of this concept is the building of a network, the Reference Energy System (RES) describing the energy system and the relationships between its components (energy flows), from resource extraction to final use. This development took place in the early 1970s and has found extensive use until now. This approach is useful to analyse both existing technology and to explore alternative future developments (scenarios) of the RES from economic, technological and environmental point of views. Even though the increase of the number of involved technologies adds complexity to the system, the RES network is very useful for the application of optimisation or simulation strategies, to identify the best configuration for the solution of energy use-related problems, given a set of end-use demand. [16]

A major distinction between macro-scale models is related to the modelling approach; indeed, while engineering bottom-up models require a large technological database to characterise the energy system in all its components, macroeconomic top-down models analyse an aggregation of sectors to examine the influence of price variations on the markets. [16] [115]

In the framework of developing a successful fusion research programme, leading to the operation of a large-scale energy source, economical feasibility and social acceptance are parameters that cannot be disregarded. Indeed, as steps ahead are made towards the operation of fusion reactors, the integration of this new form of energy in the current system has to be explored. In the EUROfusion Consortium, the Socio-Economic Studies WorkPackage (WPSES) takes care of this matter. More in detail, the economic part of the studies analyses energy systems, energy markets and technologies, studying the dynamics of technological development and its implications for an integration of fusion in the energy system (e.g. dependence of production costs on plant engineering, learning and experience, internalisation of externalities, development of energy demands, regulations and policies), so macro-scale models, incorporating the four dimensions of economy, engineering, energy and environment, are the means able to develop "alternative images of how the future could unfold" [127], the so-called "energy scenarios". [16] [77]

1.4 Aim of the work

The aim of this work is to deeply analyse the present situation of the Road transport sector, which is one of the most carbon-intensive human activities today, with special reference to the European framework, as it is characterised in the framework of the EUROfusion TIMES Model (ETM) [45], which is the tool used by the EUROfusion WPSES, in order to develop sustainable future trends for its energy demand. The key point of ETM is to analyse the way fusion and future energy use relate, in order to justify the adoption of a completely new electricity production technology, involving unprecedented scientific, social and economic efforts. Even if it is supposed to be available after the first half of the current century, thus not before 30 years, but maybe even later, the exploration of future energy trends is not premature. Indeed, radical changes in the energy system are only possible if considering very long periods, due to path dependency on economic growth and traditional forms of energy, leading to a seemingly-unbreakable inertia, which is cause of the increasingly difficult sustainability challenge [182]. An additional, important motivation for this work, and more in general for the entire EUROfusion WPSES, is the fact that Nuclear Fusion has been rarely considered in long-term energy scenarios, in the literature.

Environmental control agencies, manufacturers and governments all over the world identify electrification of the Road transport sector as the main strategy for the resolution of many problems related to pollutant emissions, after a century of total reliance on ICE [159] [17] [55] [86] [95]. Indeed, besides brand new vehicle producers - it is impossible not to mention Tesla as a leader in this framework [156] - putting Electric vehicles in the core of their business, even historical manufacturers - above all the Renault-Nissan-Mitsubishi Alliance, the Volkswagen Group (Volkswagen, Audi, SEAT, Škoda) [175], the PSA Group (Peugeot, Citroën, DS, Opel, Vauxhall) [144], BMW [18] and Mercedes-Benz [121] - are now shifting their focus towards the production of new generation Electric vehicles, even stopping the development of new ICE vehicles [113], in order to entirely allocate R&D budget for Electric powertrains. Europe is today already a main actor in the world (just behind China) for what concerns the uptake of Electric vehicles, with Norway leading the regional ranking, but the numbers are still incomparable with the ones regarding Conventional ICE vehicles. [91] [92]

The last version of ETM Road transport sector dates back to 2008 [123], when undying reliance on fossil fuels was a matter of fact, and the embrionic stage of Electrified (but not only) transport technologies, at the time, made it not feasible to track the ongoing process towards "cleaner" technologies. Even if today the world is still slowly starting to deal with these new transport solutions, the process is certainly going to dramatically increase electricity request in the next few years, and the electricity system as it is today will undergo an unprecedented stress. Then, a re-assessment of the electricity production system, with subsequent effects on the whole energy system, is required.

With this background, where the increase of electricity need is taken for granted, basing on energy and economic indicators, the possible future role of Nuclear Fusion in the European energy mix will be explored by means of ETM. Since Nuclear Fusion is neither ready for commercial stage nor a specific date is set for the commissioning of such installation, the Model is designed to explore energy scenarios and analyse the economic convenience of technologies requiring electricity. The outcome of the Model will be then used to drive design choices for fusion reactors, to make them convenient when they will be ready for large-scale applications.

So to recap, this work has two main objectives:

- Update of ETM Road transport technological repository, through the analysis of 2016 European vehicle market and usage, to depict the current situation and plausible evolutions, in order to update and possibly re-calibrate the Model;

- Investigate the possible role of Nuclear Fusion in the future European energy mix, which accounts for a more accurate modelling of the transport sector, through scenario analysis, in order to draw the optimal evolution of the energy mix, and verify the degree of penetration of Nuclear Fusion power production, depending on the ETM cost drivers.

Chapter 2

EUROfusion TIMES Model

2.1 General features of the Model

The EUROfusion TIMES Model (ETM) is an economic model of the global energy system based on the TIMES (the Integrated MARKAL-EFOM System) framework [45].

The TIMES economic model, in which ETM is implemented, adopts an optimisation approach, oriented to produce the least-cost combination of energy demand and supply to picture the possible evolution of the energy system, under user-defined constraints regarding GHG emissions, socio-economical and technological development, over a long-term time horizon. In doing this, the general equilibrium approach is followed, thus the energy system is built with the logic of meeting exactly the demand, maximising profits for producers, and utility for consumers. [23] [115] [137]

Models belonging to the TIMES class encompass all the steps interposed between primary resources production and final use of energy. Indeed, TIMES is a deterministic bottom-up model requiring the elaboration of a huge database to get up to few aggregate values describing the energy system. Therefore, it requires detailed technological information about all the components of the Reference Energy System (RES). The Reference Energy System is the definition of the set of all the available energy conversion technologies that are included in the Model. [115] [117]

The general structure of the TIMES Reference Energy System (see Figure 2.1) is characterised by:

- Energy supply-side (*producers*), including domestic and imported primary sources; inputs for this section are energy prices and inland resource availability;

- Energy demand-side (*consumers*), which includes the energy end-use sectors. The input for this section is the final energy demand for each sector. In particular, ETM defines a list of energy carriers and technologies involved in each sector of the energy system, which is divided into Upstream, Industry, Transport, Residential-Commercial-Agriculture and Electricity and Heat production sectors.

The connection between the two sides is described by means of mathematical, economic and engineering relationships, including user-defined constraints, regarding fossil resource availability, minimum and maximum limits of final energy production from different sources and yearly GHG emissions.

Each model of the TIMES family is based on three fundamental pillars:

- Commodities;

- Processes;

- Commodity flows.

Commodities represent energy carriers, energy services, materials, monetary flows and emissions, therefore they can be either produced or consumed by technologies.

A process is the Model implementation of a physical device or technology, which transforms one or more commodities into other commodities. In ETM, over 1400 technologies are modelled, of which more than 200 belonging to the transport sector.

Commodity flows are the links between processes and commodities, thus they represent the way energy is used by both production and consumption technologies, namely the input, output and efficiency of a process.

As an example, for the specific case of the analysis of the road transport sector (see Figure 2.2): a Diesel truck (technology) is fuelled by Gas Oil (commodity) coming from Oil extraction (technology) and refinement (technology), and is used to produce freight transport (commodity in terms of freight kilometers), generating other commodities in terms of CO_2, NO_x, PM, HC and CO emissions, that are obviously subject to user-defined constraints, driven by IPCC trajectories on GHG atmospherical concentrations. The commodity flows link extraction to refinement,

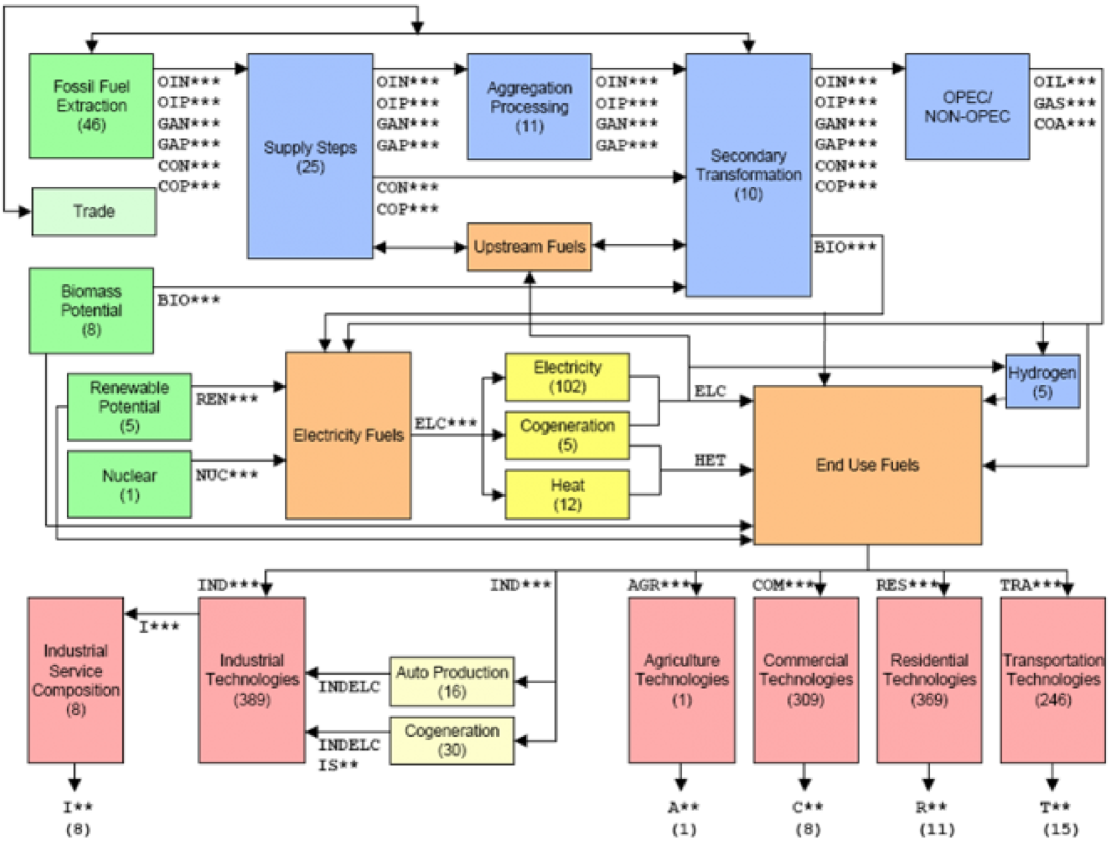

Figure 2.1: ETM Reference Energy System. Source: *EFDA World TIMES Model Final Report*

then fuel use to the production of final commodities (a certain amount of Diesel fuel in a Diesel truck produces a fixed value of vehicle kilometers and emissions).

The current composition of the energy supply system, given the existing out-fading of fossil fuel power plants and the increasing unpopularity of Nuclear Fission (a recent fact is the closure of the majority of nuclear sites in Japan [85] [101], after the Fukushima accident, while the Land of the Rising Sun is well known to be strongly dependent on electricity from nuclear power plants), is likely to soon become inadequate to face the continuously increasing demand. [67] [97]

The final aim of ETM trends identification and scenario analysis is to create and manage all the components of an energy market, where a perfect competition among commodities is assumed, in order to supply energy services in general equilibrium conditions (i.e. to meet *exactly* the demand), at the minimum global cost, trying to generate the maximal net economical surplus, but satisfying all given constraints.

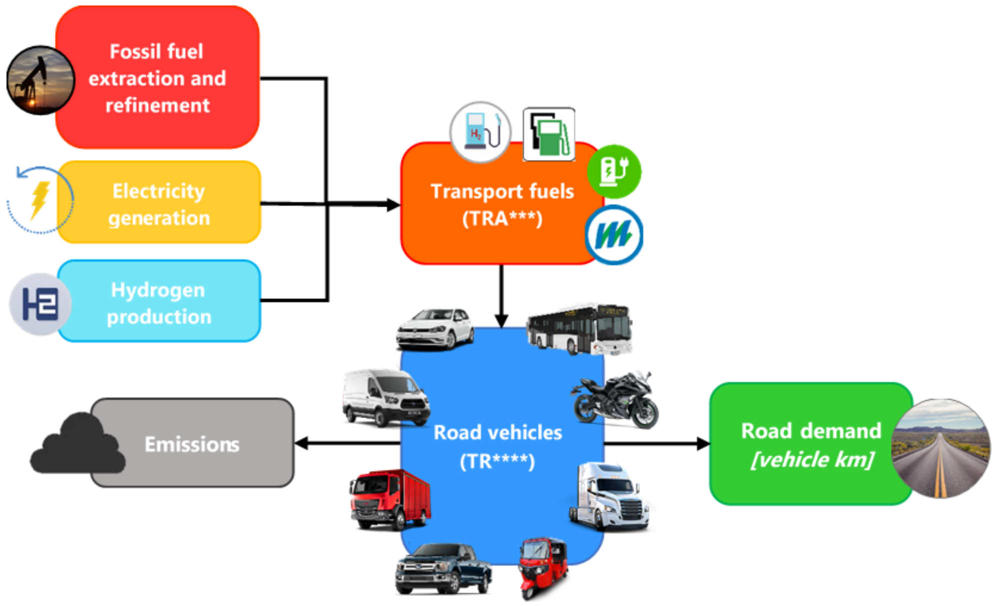

Figure 2.2: Road transport sector structure in ETM

[23] [45] [137]

2.2 Model architecture

ETM analyses the evolution of the global energy system on a long-term time scale, starting from the base year 2005, up to 2100.

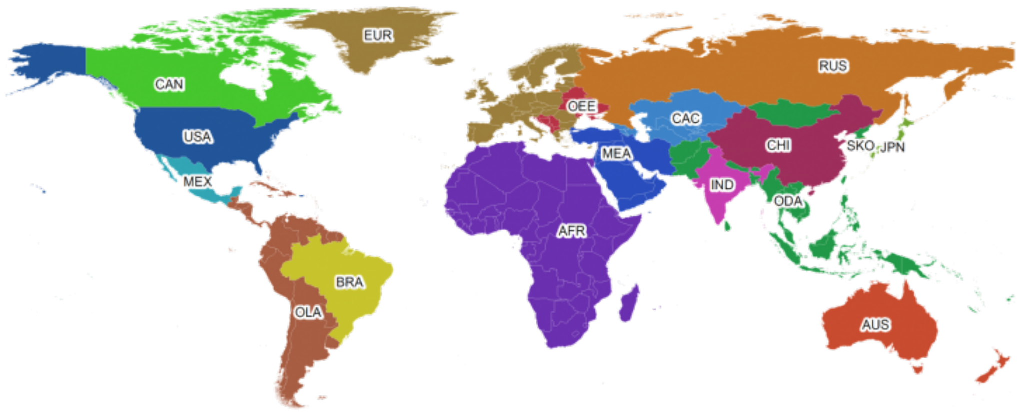

Figure 2.3: ETM World regions. Source: `https://collaborators.euro-fusion.org`

Table 2.1: List of World regions in ETM. Source: *EFDA World TIMES Model FINAL REPORT*

Code	**Region**
AFR	Africa
AUS	Australia and New Zealand
BRA	Brazil
CAC	Central Asian Countries
CAN	Canada
CHI	China
EUR	Western Europe
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East Asia
ODA	Other Developing Asian countries
OEE	Other Eastern Europe
OLA	Other Latin America
RUS	Russia
SKO	Korean Peninsula
USA	United States of America

In ETM, the global energy system is subdivided into 17 regions, as visible in Figure 2.3, listed in Table 2.1, connected via trade processes. Each region incorporates single countries with similar conditions in terms of economical developments.

The EUR region, which is analysed in the context of the analysis of Electrification of the transport sector to picture the role of Nuclear Fusion in a future European energy mix, includes 27 out of the 28 EU Member States (excluding Croatia) and EFTA countries (Iceland, Liechtenstein, Norway and Switzerland).

The ETM Reference Energy System (RES), represented in Figure 2.1, accounts for a set of technologies, for each ETM region: each box represents a technological subset, and the number of included processes is indicated in brackets, while colors differ according to the sector role in the system (green for primary production, blue for primary resource transformation, orange for fuel production, yellow for power/heat generation and red for end-use sectors). The links matching sectoral boxes represent commodity flows, then each one is accompanied by a generic commodity name, standing for a number of fuels. For instance, the generic name TRA*** stands for the set of fuels considered in the transport sector (Gasoline TRAGSL, Gas Oil TRADST, LPG TRALPG, etc.), and the detailed structure of the Road transport sector is reported in Figure 2.2.

Table 2.2: Socio-economic drivers. Source: *Global transportation scenarios in the multi-regional EFDA-TIMES energy model*

Code	**Description**
GDP	GDP
GDPP	GDP per capita
GDPPHOU	GDP per household
HOU	Number of households
PAGR	Value Added Agriculture
PCHEM	Value Added Chemical sector
PINSF	Value Added Iron and Steel and Non Ferrous metals
POEI	Value Added Other Energy Intensive Industries
POI	Value Added Other Industries
POP	Population
PSER	Value Added Service sector

In order to picture a balanced setup of the future energy system, ETM relies on some exogenous drivers of two types: the ones regarding efficiency and cost assumptions for the different modelled technologies, and the ones related with energy demand evolution (socio-economic drivers, see table 2.2). Future trends for drivers, as considered in ETM, are based on implicit regional demographic and socio-economic assumptions, making reference to validated models, such as TIAM [116], and renowned energy reports, such as the International Energy Outlook (IEO) (2014 edition, for the current ETM version) by EIA [36].

2.3 Storylines and scenario definition

Since a future knowledge of the future development of the energy system is impossible to be clearly depicted, three different storylines are distinguished in ETM, to establish comparatively the broad outlines of policies and behaviours [137]. Differentiated environmental responsibility is one of the main characteristics of each storyline, and it is defined according to the Representative

Concentration Pathways (RCP), adopted by the IPCC for its Fifth Assessment Report (AR5) [104], in 2014.

2.3.1 Emission reduction targets

Each RCP is a GHG concentration trajectory, and is characterised by a number representing the total maximum allowed radiative forcing in 2100, that is fixed as aim for each RCP scenario. The official definition of radiative forcing, as given in the IPCC Fourth Assessment Report [103] is the following: "The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in W/m^2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values". Indeed, the total radiative forcing is the cumulative measure of GHG emissions from human activities. Total radiative forcing and concentration trajectories for the different RCP scenarios are reported in Figure 2.4.

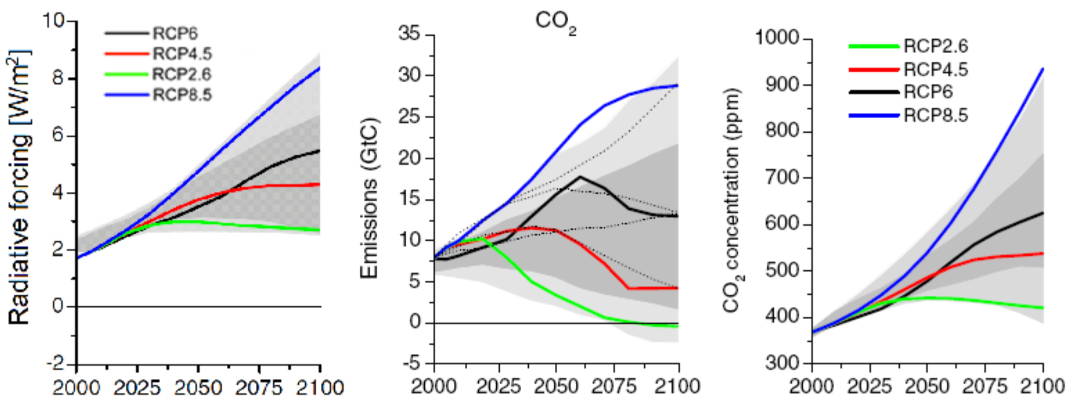

Figure 2.4: Radiative forcing, Carbon emissions and CO_2 concentration trajectories according to the RCP scenarios. Source: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

- RCP 2.6 is a scenario where the peak in radiative forcing is at 3 W/m^2

before 2100, where an ongoing decline is foreseen for the after-2100; this is the most ambitious RCP, requiring early participation from all emitters, including developing countries, as well as the application of carbon capture technologies, as well as the only RCP in line with the aim of containing global temperature increase well below $2°C$;

- RCP 4.5 is a scenario where, after emission peak in 2040, CO_2 concentration stabilises at 540 *ppm* in 2100;
- RCP 6 is a scenario where some mitigation strategies and technologies are applied, but emission still reach 660 *ppm* by 2100, with a late stabilisation of the radiative forcing;
- RCP 8.5 is a scenario with little emission curbing late in the century, where CO_2 concentration grows up steadily by 2100.

2.3.2 ETM storylines and scenarios

ETM, as more in general macro-scale models, is particularly suited to the exploration of possible futures based on contrasted scenarios. A scenario consists of a set of coherent assumptions about the future technological development, basing on energy service demands, primary resource potential and available technological set, leading to a coherent organization of the system under study. Following the approach described in [69], prior to scenario building, credible storylines are designed, driven by several important forces in the environment affecting the future role of fusion, weighted based on their uncertainty and importance: public acceptance, GDP, climate change and energy costs. [21] [137]

As stated in the introduction to this section, three storylines are distinguished in ETM, each one characterised by a diverse set of economic, social, political and environmental assumptions.

- Paternalism: this storyline joins pronounced awareness to the environmental themes and the lack of adequate planning for reaching the goals on a global scale. Indeed, it is characterised by regionally diversified ecological responsibility (RCP 2.6 or RCP 4.5), with medium-term investment policies (medium discount rate) and a sufficient level of cooperation between all regions of the world. A medium level of price elasticity of the demand is fixed;

- Harmony: this storyline is characterised by strong environmental responsibility and long-term investment policies (low discount rate). Constraints on emission targets are very stringent (RCP 2.6) and the possibility of achieving ambitious goals is fostered by global cooperation. A low level of price elasticity of the demand is fixed;
- Fragmentation: this storyline represents the continuation of the present world situation, with high elasticity of energy service demands to their drivers, pointing out weak environmental responsibility (RCP 6), with a short-term view in investment policies (high discount rate) and a range of regional partial agreements on carbon emission targets and geopolitically constrained energy trade. A high level of price elasticity of the demand is fixed.

Then, starting from each storyline, several technological development scenarios are drawn. Figure 2.5 represents all the 24 possible combinations for scenario definition, per each storyline (for a total number of 96 storylines).

Those storylines have been afterwards quantified using different parameters. To introduce the environmental responsibility, elasticity of energy service demands to their drivers has been used in a way that the stronger the responsibility, the lower the elasticity. "Base-case" elasticities were retrieved from the GEM-E3 Model. The term view used by operators or investors was instead introduced by means of the technology specific hurdle rate, in a way that the longer the term view, the lower the rate. Finally, CO_2 emission targets are assigned according to the RCP scenarios in section 2.3.1, and translated into annual CO_2 emission limits (14.5 [$Million\ Gt$] in 2050 and 1 [$Million\ Gt$] in 2100 for RCP 2.6, 48.2 [$Million\ Gt$] in 2050 and 50.4 [$Million\ Gt$] in 2100 for RCP 6). [21]

In this work, for 3 out of 4 storylines (Paternalism 2.6, Harmony and Fragmentation), scenario no. 2, from the scenario tree in Figure 2.5, will be analysed. It is characterised by the following technological features:

- Nuclear Fusion power plants are available starting from 2070, in Europe;
- Reference Investment and O&M costs for fusion technologies are prescribed, as in Table 2.3), and derived by the fusion reactor cost estimation, performed by means of the PROCESS code [40] [108] [109], reducing it by 30 [%], taking into account optimistic cost reduction factors, in order to dictate the terms for Nuclear Fusion penetration in the energy mix [34];

- Carbon Capture and Storage (CCS) technologies are available starting from 2030;
- Optimistic prediction of Nuclear Fission potential evolution, involving matters linked with mainly good social acceptability, in order to multiply, up to 5 times, the current global capacity;
- External costs of fusion and other electricity production sources are not included.

Table 2.3: Data for fusion technologies. Source: *Fusion power in a future low carbon global electricity system*

Type of plant	**Start**	**Inv.** [$\$/kW$]	**Fixed O&M** [$M\$/GWa$]	**Var. O&M** [$M\$/PJ$]	**Efficiency** [%]
Basic plant	2070	5910	65.8	2.2	42
	2080	4425	65.8	1.6	42
Advanced plant	2090	4220	65.3	2.1	60
	2100	3255	65.3	1.6	60

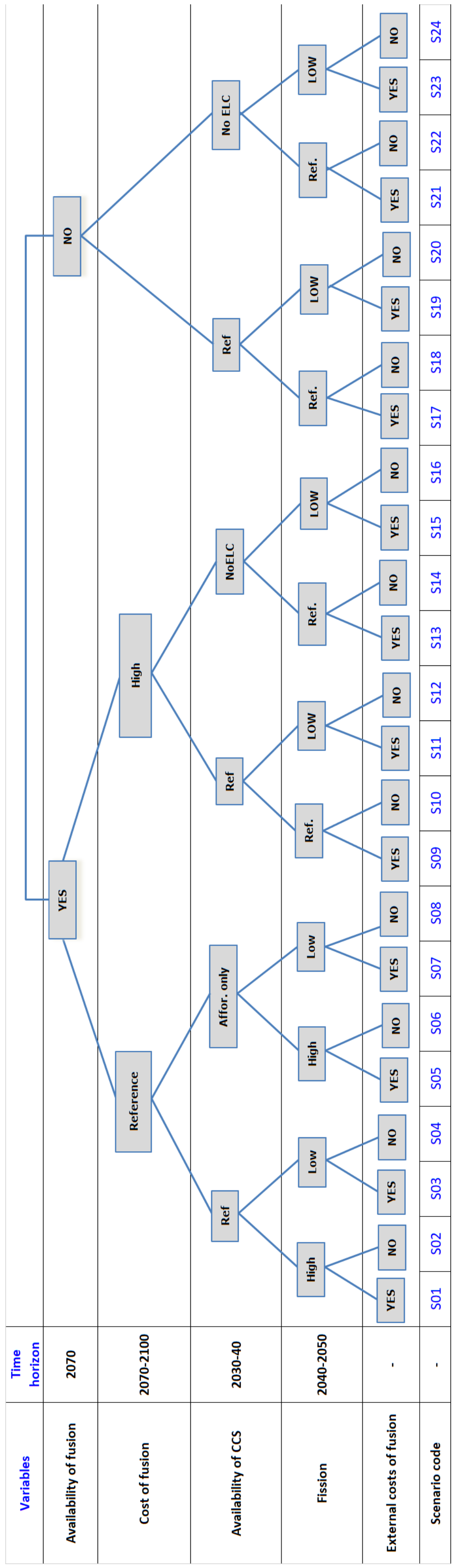

Figure 2.5: ETM Scenario tree. Source: *EUROfusion TIMES Model*

Chapter 3

Road transport Reference Energy System

The last update of the ETM transport sector [123] dates back to 2008, when the EUROfusion TIMES Model was still called as "EFDA-TIMES Model" (EFDA stands for "European Fusion Development Agreement"). Since then, however, the situation has profoundly changed, due to the need for cleaner transport forms, in order to reduce pollution from both fuel production and tailpipe emissions, the impending depletion of fossil sources, which up to date by far dominate the transportation sector, and an impressive technological progress. [5] [89] [38] [52] [103]

Today, a set of new competitive technologies is clearly defined, has already faced market entry, then is ready to drive Road transport sector towards a large diffusion of GHG (almost) neutral engines. Therefore, a revision of the ETM Road transport module is needed to assess forecasts about the future role of electricity production technologies, in particular Nuclear Fusion, given the ongoing transition of this sector towards an increasingly widespread use of electricity. [55] [56] [58] [59] [91] [112] [123]

The main limitations characterising the latest available version of ETM Transport sector, devised by Pascal Mühlich and Professor Thomas Hamacher [123], from the Max-Planck-Institut für Plasmaphysik (Garching, Germany), concerns the low level of technological awareness about Electric, Hybrid and Hydrogen vehicles.

3.1 Road transport RES components

The structure of the EFDA-TIMES/ETM transportation sector is characterized by an explicit modelling of transportation demands, in terms of available technologies. In practice, rather than end-energies, actual transportation demands, measured as vehicle kilometres per year, form the back-end of the Transport sector Reference Energy System. The technologies satisfying these demands are coupled to the residual energy system via the consumption of various types of energy carriers and the production of GHG emissions. Here follows an accurate description of the components of the RES which are directly relevant to the Road transport sector:

- Input commodities: fuels used for Road transportation;
- Output commodities: Road transport demand and produced emissions;
- Technologies: vehicle fleet;
- Commodity flows: how the energy is used to supply transportation processes.

3.1.1 Commodities

IEA/Eurostat energy statistics [60] and balances are used to identify the relationship between primary fuels and energy-end use. In particular, for the aim of this work, the link between commodities relevant to Road transport and their actual consumption is useful. Since these commodities are all used for the same purpose, indeed to provide energy to power transport machines, they can be simply associated to transport fuels.

Fuels currently used in Road transport sector can be ranked within 5 macro-categories, according to the classification made in the Eurostat energy balances [60]:

- Oil and petroleum products, including Liquified Petroleum Gases, Motor Gasoline, Gas Oil and Industrial spirits;
- Natural Gas;
- Renewables and biofuels, including Biogas, Biogasoline, Biodiesel and other liquid Biofuels;
- Electricity;

- Hydrogen, which is still not included in the Eurostat energy balance, even in its latter version, dating to April 2019. Indeed, request of hydrogen as fuel is still not so common, even though some Fuel Cell Cars and Buses are there on the market. Hydrogen for transport is used after compression at 350 or 700 *bar*. [61]

In the continuation of this work, Motor Gasoline and Gas Oil will be referred to as "Traditional fuels", while the remaining ones will be called "Alternative fuels".

For the purpose of ETM, the large number of fuels included in the Eurostat energy balance is re-arranged in accordance with the modelled fuel categories, corresponding with the commodities associated with Road transport sector [123], namely:

- Motor Gasoline TRAGSL, including Motor Gasoline;
- Gas Oil TRADST, including Diesel Oil and Gas Oil, and Industrial spirits;
- Liquified Petroleum Gases (Autogas) TRALPG, including LPG;
- Natural Gas and Biogas TRANGA, including Natural Gas and Biogases;
- Ethanol, under which all liquid Biofuels (Biogasoline, Biodiesel and other liquid Biofuels) can be found, TRAETH. Although, today Biofuels are not used as pure fuels, but usually blended with Gasoline or Gas Oil. Since several Biofuels with diversified properties are coupled under the same category, properties of Ethanol are taken as reference for describing all Biofuels in ETM. Ethanol is actually used as fuel in some European countries, but pure Ethanol use is practically nil, as for all other Biofuels. Indeed, it is typically used in a mix with conventional Gasoline at various percentages, otherwise known as "blends". While all Gasoline sold in Europe contains up to 5% Ethanol (E5, where "5" stands for the maximum percentage of Ethanol content) and the most of Petrol vehicles sold since 2000 can run on E10, cars defined as running on Ethanol are actually fuelled with E85; [147] [153]
- Electricity TRAELC;
- Hydrogen TRAHH2.

Since the fuel production chain is modelled inside the Reference Energy System, fuel properties are given endogenously, while prices (i.e. marginal prices) are obtained as a result by the Model, according to the different storyline/scenario. Adopted emission factors for fuels are reported in Table 3.1. Table 3.2 reports fuel properties, as used for the evaluation of 2016 vehicle

Table 3.1: Emission factors for modelled fuels. Source: *EUROfusion TIMES Model*

Fuel	**Initials**	**Emission factor** $[g_{CO_2}/MJ]$	$[g_{CH_4}/MJ]$	$[g_{N_2O}/MJ]$
Gasoline	TRAGSL	69.30	6.92	6.60
Gas Oil	TRADST	74.07	1.32	3.36
LPG	TRALPG	63.07	1.18	9.00
Natural Gas	TRANGA	56.10	1.10	1.00
Ethanol	TRAETH	0.00	0.02	0.10
Electricity	TRAELC	0.00	0.00	0.00
Hydrogen	TRAHH2	0.00	0.00	0.00

efficiency (the adopted methodology will be explained in the continuation of this chapter).

Table 3.2: Fuel properties. Source: `https://www.engineeringtoolbox.com`

Fuel	**Initials**	**Specific energy content** $[MJ/l]$	$[MJ/kg]$	$[MJ/kWh]$
Gasoline	TRAGSL	32.10	-	-
Gas Oil	TRADST	35.16	-	-
LPG	TRALPG	23.30	-	-
Natural Gas	TRANGA	-	47.5	-
E85	TRAGSL + TRAETH	23.40	-	-
Electricity	TRAELC	-	-	0.28
Hydrogen	-	120	-	

3.1.2 Technologies

Within ETM all transportation processes are subdivided into two classes [123]:

- Base year technologies, which are actually used in the beginning of the Model time horizon (2005), representing the whole vehicle fleet. They are used to model base year vehicle demand. Since 2016 is taken as reference year for this ETM update, the base year technology stock has not been modified in its structure within the framework of this work, but some adjustments were made, as it will be soon reported;

- New technologies, which are introduced from the second time step on (2007), and representing the new vehicle stock, added to the existing fleet or substituting a part of it, at the end of their lifetime. They are used to model energy use and vehicle demand during the Model time horizon. They are characterized by investment and fixed operation and maintenance costs (variable costs, such as fuel cost, are a result of the Model). The update of the new technologies repository has been the core of the carried out activity, and will be carefully described. Further modifications and improvements could still be needed, by adding even more technologies and reviewing the cost evolution of implemented processes.

3.1.3 Categories and Modes of transport

All classifications of vehicles composing the Road transport fleet, adopted in this work, are performed in accordance with the European Commission classification, and coherently adapted for the purposes of ETM. A first classification of road vehicles modelled inside ETM can be done according to the purpose [48] [49]:

- Passenger transport: it accounts for vehicles exclusively adopted for people transport. The unit of measurement specifically adopted to characterise this type of vehicles is the passenger-kilometre pkm, representing the transport of one passenger over one kilometre.

- Freight transport: it accounts for vehicles used for transport of freight of diverse nature. The unit of measurement specifically adopted to characterise this type of vehicles is the tonne-kilometre tkm, representing the transport of one tonne of goods over a distance of one kilometre.

However, this distinction is merely indicative. Indeed, the Model does not make distinction among these two categories, and the final demand in terms of driven distance is given as result in vehicle kilometres vkm (or billion vehicle kilometres $bvkm$). In this sense, passenger occupancy (in case of vehicles for passenger transport) and payload (in case of vehicles for freight transport) will be only useful for the estimation of on-road fuel economy.

A second classification is driven by vehicle size. The 2008 EFDA-TIMES version, which will be referred to as "OldTRA ETM" from now on (in contrast with the "RevTRA ETM" version produced by the application of the outcomes of this review), divided vehicles into two macro-categories: Light-Duty Vehicles and Other Vehicles. In RevTRA ETM, instead, the two macro-categories are re-arranged according to their energy consumption characteristics [48] [49]:

- Light-Duty Vehicle (LDV), including vehicles with a Gross Vehicle Weight (GVW) lower than 3.5 t, which represent the majority of vehicle stock but are characterised by a generally low individual energy consumption;
- Heavy-Duty Vehicle (HDV), including vehicles with a Gross Vehicle Weight higher than 3.5 t, which constitute a significantly lower presence in the stock, but are characterised by sensibly higher consumption with respect to LDVs.

Inside these two macro-categories, vehicles are then distinguished among several subcategories, according to dimensions, usage and specific characteristics, each one referred to by three specific initials in EFDA-TIMES/ETM, generally TR*, since they are modelled in the framework of transport sector. These subcategories are defined as "transport modes".

Table 3.3: ETM transport modes. Source: *Global transportation scenarios in the multi-regional EFDA-TIMES energy model*

Purpose	**Macro-category**	**Mode**	**Initials**
Passenger	Light-Duty	Passenger Cars	TRT
Passenger	Light-Duty	Light Trucks	TRL
Freight	Light-Duty	Light Commercial Vehicles	TRC
Passenger	Light-Duty	Two-Wheelers	TRW
Freight	Light-Duty	Three-Wheelers	TRE
Freight	Heavy-Duty	Medium Trucks	TRM
Freight	Heavy-Duty	Heavy Trucks	TRH
Passenger	Heavy-Duty	Buses and Coaches	TRB

As the base year vehicle stock has been preserved for the purpose of this work, 8 transport modes are both present in OldTRA and RevTRA ETM:

- Cars (TRT);

- Light trucks (TRL);
- Light Commercial Vehicles (TRC);
- Two-Wheelers (TRW);
- Three-Wheelers (TRE);
- Medium trucks (TRM);
- Heavy trucks (TRH);
- Buses (TRB).

However, in OldTRA ETM [123] they were characterised by some ambiguities, thus precise characteristics will be clearly defined during the prosecution of this report for each transport mode.

3.1.4 Vehicle technologies

In each transport mode, several vehicle technologies is considered. Each technology is basically characterised by the type of fuel(s) it runs on, which determines its behaviour inside the Model.

Table 3.4: ETM Base year vehicle technologies. Source: *Global transportation scenarios in the multi-regional EFDA-TIMES energy model*

Technology	**Initials**	**Fuel**
Gasoline	TR*GAS	TRAGSL
Diesel	TR*DST	TRADST
LPG	TR*LPG	TRALPG
Natural Gas	TR*NGA	TRANGA
Ethanol	TR*ETH	TRAETH
Methanol	TR*MET	TRAMET
Electric	TR*ELC	TRAELC

Table 3.4 shows the Road transport base year technologies, as modelled in ETM. Then, additional technologies were considered for the new technologies repository, and they are reported in Table 3.5. They were all supposed to be available in the Model starting from 2007, except for Diesel Hybrid Cars (2015). From a first glance at Table 3.5, several inconsistencies arise, highlighting the need for the update

Table 3.5: OldTRA ETM new technologies repository. Source: *EUROfusion TIMES Model*

Technology	Initials	Fuel(s)	Mode(s)
Gasoline	TR*GAS	TRAGSL	All
Diesel	TR*DST	TRADST	All, exc. TRW
LPG	TR*LPG	TRALPG	TRB, TRC, TRH, TRM
Natural Gas	TR*NGA	TRANGA	All, exc. TRE, TRW
Biofuel	TR*BIO	TRAMET	All, exc. TRE, TRW
Electric	TR*ELC	TRAELC	All, exc. TRE, TRW
Hydrogen	TR*HH2	TRAHH2	All, exc. TRE, TRW
Gasoline Hybrid	TR*HYBG	TRAGSL + TRAELC	TRT
Diesel Hybrid	TR*HYBD	TRADST + TRAELC	TRT

Table 3.6: RevTRA ETM new technologies repository

Technology	Initials	Fuel(s)	Mode(s)
Gasoline	TR*GAS	TRAGSL	All
Diesel	TR*DST	TRADST	All
LPG	TR*LPG	TRALPG	All, exc. TRE, TRW
Natural Gas	TR*NGA	TRANGA	All, exc. TRE, TRW
Flex-Fuel	TR*FLF	TRAGSL + TRAETH	All, exc. TRE, TRW
Full-Electric	TR*ELC	TRAELC	All
Gasoline-Hybrid	TR*GHE	TRAGSL	TRL, TRT, TRW
Diesel-Hybrid	TR*DHE	TRADST	TRB, TRC, TRH, TRM
Plug-in Hybrid	TR*GPH	TRAGSL + TRAELC	TRL, TRT
Fuel Cell	TR*FCE	TRAHH2	All, exc. TRE, TRW

of ETM Road transport sector. For example, new technologies included in the OldTRA repository only accounted for Gasoline Hybrid and Diesel Hybrid Cars, which were characterised by a 50% Gasoline/Gas Oil - 50% Electricity fuel use. That is inconsistent with the actual existing technology, as will be soon explained in the upcoming detailed description. Furthermore, existing Hybrid-Electric vehicles concern almost all transport modes. Table 3.6 reports all technologies, as present on the vehicle market in 2016, included in RevTRA ETM.

A brief description of all currently available technologies follows here.

Conventional Gasoline vehicles

Conventional Gasoline vehicles run on a spark-ignition engine, an internal combustion engine fuelled by petrol, where the combustion process of the air-fuel mixture is ignited by a spark from a spark plug and the fuel is Gasoline. Due to regular Gasoline composition, the exhaust gases resulting from the combustion process in a spark-ignition engine have high CO_2 content, in quantities generally variable with the vehicle load [30]. Approximately 50% of Light-Duty vehicles on the European road run on this type of engine, which is characterised by low efficiency, therefore is more adapt to small vehicles that are usually driven for short distances, but just for economical evaluations on the fuel cost. [2] [3] [90] [122]

Conventional Gas Oil vehicles

Conventional Gas Oil vehicles (or more commonly called as Diesel vehicles) run on an internal combustion engine where spontaneous ignition of the fuel, Gas Oil, which is injected into the combustion chamber, is caused by the elevated temperature of in the cylinder due to mechanical compression of air. Diesel engines have the highest thermal efficiency of any other internal or external combustion engine, due to the very high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. Diesel engines are adopted by almost the totality of heavy vehicles on the road today. [2] [3] [90] [122]

LPG vehicles, Natural Gas vehicles

Vehicles running on LPG and Natural Gas (commonly Compressed Natural Gas CNG) are called "Bi-fuel vehicles". Indeed, as this name suggests, they cannot run on LPG or CNG only, but are coupled together with Gasoline or Gas Oil to supply an internal combustion engine. The two fuels are stored in separate tanks and the engine runs on one fuel at a time in some cases, in others both fuels are used in unison. LPG and CNG vehicles are the most diffuse among all Alternative fuel vehicles, especially in Europe. The Netherlands and the Baltic area have a large number of cars running with LPG, while Italy currently has the largest number of CNG vehicles [60]. Conventional Gasoline vehicles are usually aftermarket retrofitted in authorised workshops, in a process which involves the installation of the gas cylinder in the trunk, the LPG/CNG injection system and electronics, although some vehicles already come out of factory as Bi-fuels. [8] [28]

Flex-Fuel vehicles

Flex-Fuel (or Dual-Fuel) vehicles can work with any Gasoline-Biofuel mixture, without the need for separate fuel tanks. Nevertheless, the most adopted solution is to make them run on E85, a fuel with a maximum 85% Ethanol in a Gasoline blend. Flex-Fuel engines are capable of burning the blend in the combustion chamber as fuel injection and spark timing are adjusted automatically according to the actual blend detected by a fuel composition sensor. The technical distinction between Flex- and Bi-fuel vehicles is the presence, in the former, of two fuels stored in the same tanks, while the engine runs on two fuels at a time. Instead, where Flex-Fuel vehicles are sold, they are practically identical to their Gasoline correspondent, with the only difference lying in the technical issues related with the adopted fuel. Regarding fuel economy and emissions, depending on the variable blend composition and the Ethanol production process, it is not possible to outline a clear picture, even though the situation can be described as not so different for Gasoline vehicles. On the market side, while American countries as U.S. and Brazil (the first country to introduce Flex-Fuel vehicles in 2003 and today the best market for cars running on Ethanol, with more than 90% of new car sales), Europe is still lagging behind and needs large infrastructure improvements to enable the increased uptake of E85. Indeed, E85 is very common in Sweden, where biofuel diffusion policies have been very effective during the years, with tax reductions on the purchase of Flex-Fuel vehicles and ownership costs, too, but it is also diffuse in Germany, France and Netherlands. [42] [96] [147] [153] [155]

In Figure 3.1 the European E85 filling stations map is reported [99].

The next items represent the strongholds of this work, then special attention will be paid to the description of their technical and historical aspects, to help the identification of the most likely future scenarios.

Full-Electric vehicles

A Full Electric vehicle is propelled by one or more electric motors, which work using energy stored in rechargeable batteries. While the first non rechargeable Full Electric cars date back to the end of the 19^{th} century, their mass marketing was

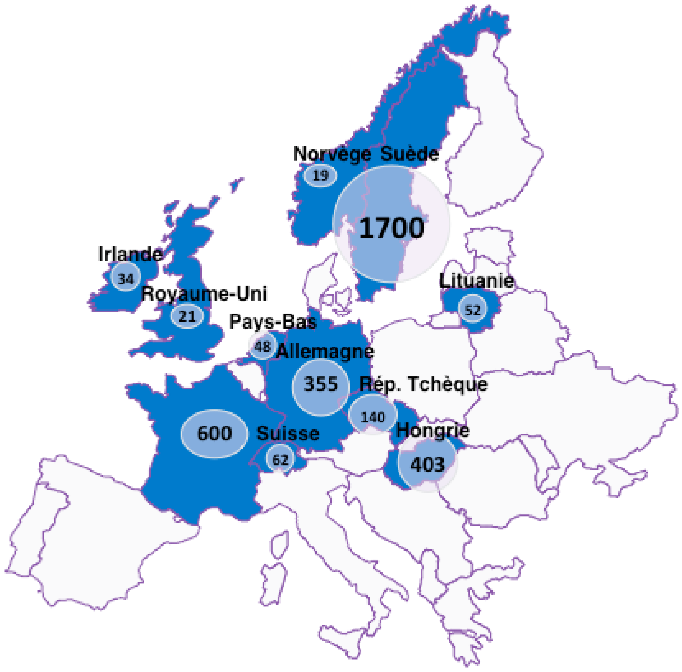

Figure 3.1: Number of E85 filling stations per country in 2015 in Europe. Source: `https://www.epure.org`

restrained by the impressive advances in cheaper internal combustion engines. With respect to traditional engines, Full Electric vehicles present undeniable advantages:

- Self-starting: indeed, besides combustion engine, traditional vehicles need additional components for starting;
- High efficiency;
- Quiet operation;
- Zero tailpipe emissions;
- High torque adjustability;
- Simple construction;
- Low maintenance;
- High reliability and lifetime.

Although it may seem that Full Electric vehicles are actually perfect, they are also characterised by some serious issues, mainly related with the energy source:

nowadays, batteries for automotive purposes are characterised by relatively low capacity, directly related with the vehicle autonomy, big size (including weight), high recharge time with the scarce present infrastructure, non-constant performances and limited reliability and durability. Furthermore, their cost is strongly related with the increased purchase price for Electric vehicles with respect to traditional ones. To sum up, the main advantage given by traditional mobility is the possibility to own a vehicle to go where you want as and when you want, with a lot of on-board available energy and immediate fuel restoration. On the other hand, the energy, environmental and technical benefits of Electric propulsion have not been able to overcome cost and battery limitations over the entire 20th century. Nevertheless, following the oil crisis in the 1970s [140] and the first attempts to focus on health and environmental impacts of GHG emissions, along with technological ripeness of power electronics (AC electric motors), a new Renaissance of electric vehicles comes to light since the 1990s. Despite important efforts by the California Air Resource Board (CARB) [22] to push for more fuel-efficient, lower-emitting transportation in the early 1990s, vehicles as the GM EV1, the first modern electric car produced since 1996, were not very successful and never got into the global limelight. Less then ten years after, in 2004, the visionary American automotive and energy company Tesla (at that time called as "Tesla Motors"), founded just one year before, began development on what would become the Tesla Roadster [156]. The Roadster was the first highway legal serial production Full Electric car to use Lithium-ion battery cells, declaring 320 km per charge (EPA range). That was the beginning of an unprecedented global interest about Electric vehicles, with more and more car manufacturers targeting to produce Battery Cars and Vans to be placed on the mass market, exploiting economies of scale to reduce cost, with the aim of making Pure Electric vehicles competitive with combustion engines on a purchase price basis. [17] [37] [91] [172]

However, the main issue related with the boost of Electric vehicles, especially cars, is due to the lacking infrastructure, in Europe as in the rest of the world. Strictly related to this, there is the so-called "range anxiety", even though some high-range Electric vehicles are today existent. According to many national surveys, these two are the main reasons why Full Electric vehicles are still not considered sufficiently reliable to substitute traditional ones [35] [94] [129] [119]. In this sense, Tesla is again the main actor to show the way, with its Supercharger network, counting hundreds of recharge stations all over the world and a total of more than

12’000 Supercharger posts (in Figure 3.2 the European Supercharger stations are represented) [156].

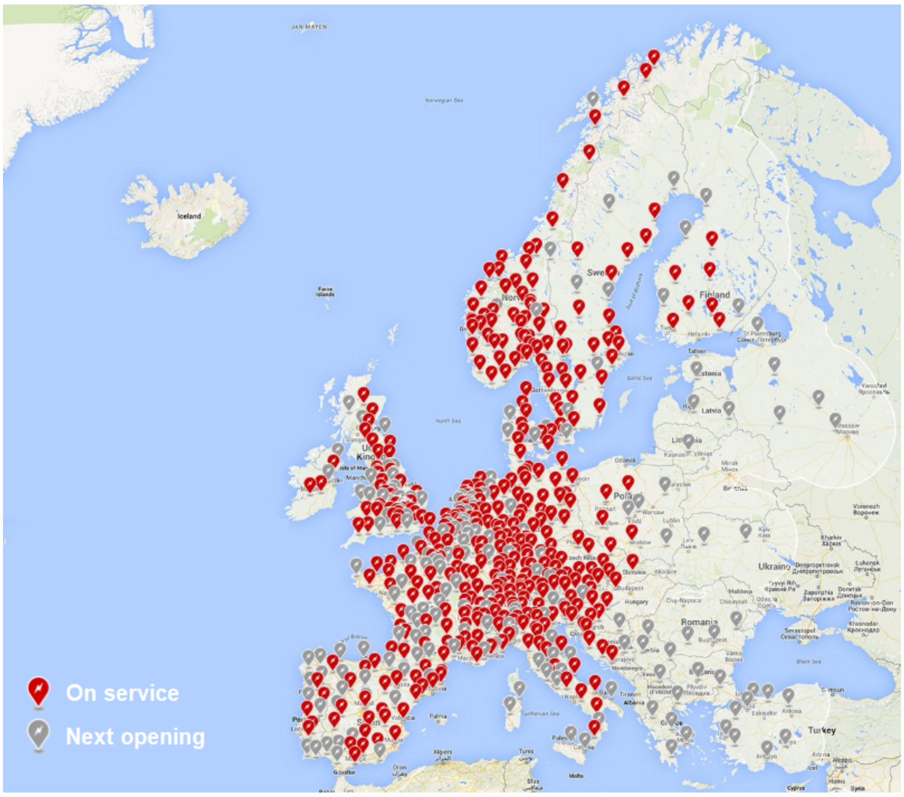

Figure 3.2: Tesla Supercharger network in Europe. Source: `https://www.tesla.com`

While Light-Duty vehicles and Buses are the ones currently on the market with electrified versions, Commercial Heavy-Duty Electric vehicles commercialisation stage is forthcoming, too. Indeed, Tesla has already presented its Class 8 Electric Truck, the Tesla Semi, that is about to be released at the end of 2019. This started a chain reaction and now basically all major truck manufacturers forecast the imminent production of electrified Heavy-Duty vehicles. [29] [121] [156]

A distinction concerning Full-Electric cars depends on their origin: some of them are adapted from existing traditional models (the Volkswagen e-Golf is derived from the traditional Golf, the Renault Zoe comes from Renault Clio), while others can be classified as "Native-Electric" cars (the whole Tesla’s line-up, or other models as Nissan Leaf and BMW i3); although, these definitions are not reflected in technical implications, but are important for market observations, since adapted models can be useful to make the "Oil-to-Electricity" transition more awkward.

Nowadays, the global leader in Full-Electric sales is the Renault-Nissan Alliance, counting a wide and expanding range of vehicles, in particular Cars and Vans. Renault Zoe (represented in Figure 3.3) is indeed one of the most representative All-Electric cars, exceeding 37'000 sold examples in 2018 all over Europe. It will now be taken as baseline for a technical explanation about present Electric vehicles main characteristics. The first difference that jumps immediately to the eye with respect to traditional vehicle is the absence of the grille, due to the fact that there is no a thermal engine needing cooling. Indeed, the battery, anyway provided with a cooling air interface, is located on the car floor (see Figure 3.4). As visible, electric driving implies constructional simplicity, but the battery pack requires wide space, and it is also characterised by heavy weight, reaching over 300 kg in current models. All electric cars derived from a traditional correspondent (Renault Zoe, for instance, is the Full-Electric version of Renault Clio), indeed, are characterised by substantially higher empty weight. With the coupling of an electric powertrain with a rated power of 65 kW, that can generate a maximum 220 Nm torque, and a 41 kWh battery working at a 360 V nominal voltage, a Renault Zoe R90 (2016 version), equipped with a Z.E. 40 battery, can guarantee up to 400km driving range, according to NEDC specifications. The Z.E. 40 battery pack is made of 12 Lithium-ion modules, containing 192 cells, that can provide up to 80 kW maximum power. Therefore the electric motor has a 81% efficiency, putting it on another level with respect to any internal combustion engine. But what's even more striking is the impressive technological evolution of this car since it was first produced, in 2013. Indeed, at the beginning, the declared autonomy was just 210 km, and in three years only, it was almost doubled by only making Battery Management System modifications and pack design improvements, without increasing the battery size. This optimised cell is then characterised by a 240 Wh/kg/500 Wh/l energy density, and current plans forecast to reach 350 Wh/kg/800 Wh/l until 2025. Further improvements, after that, only seem possible with new cell technologies. While cell design has been the key for recent improvements, and other enhancements are certainly possible (space optimisation, thinner foils, high loading, separators), for achieving higher energy density, cell chemistry modifications are needed, i.e. Si-based anode, Ni-rich cell, solid electrolyte and additives. Furthermore, Lithium stocks have not endless availability, even though estimations foresaw the possibility to produce 4.8 billion Plug-in Electric Cars worldwide, in 2009 [152]. On the durability side, currently used Li-ion batteries are characterised by a relatively short lifetime of 5 years (some producers, Renault included, offer battery hire on favourable terms, in fact), but with the advantage of no memory effect: they do not need complete recharge/use cycles, but can be partially recharged and used without potential losses due to this. In addition, recharge time is strongly dependent on the recharge site power (the higher the power, the shorter the time). Standardisation of charging cables and adaptation of batteries to the increasing power output of ever-expanding charge points play a key role for the improvement of the public charging infrastructure. Finally, Li-ion batteries for automotive purposes correctly work in a $-10°C \leq T_{op} \leq 40°C$ temperature range, which is actually adherent to any driving style [145] [31]. Basically, all manufacturers adopt this solution for their vehicles, excluding different electrode materials and minor cell design specifications. The next steps for enhancing vehicle electrification almost certainly include the development of solid-state batteries, using solid electrolyte in place of liquid ones, as the Toyota-Panasonic joint venture is planning, from 2020 on. The main advantage in this batteries is the improved energy density. [5] [141] [156]

Figure 3.3: Renault Zoe. Source: `https://www.renault.com`

Mild-Hybrid vehicles

Present Mild-Hybrid vehicles (or less commonly Battery-assisted hybrid vehicles), run on Petrol internal combustion engines, with the support of a compact electric machine ($< 20\ kW$), usually a motor or generator in a Parallel-Hybrid configuration, allowing the engine to be turned off whenever the car is coasting,

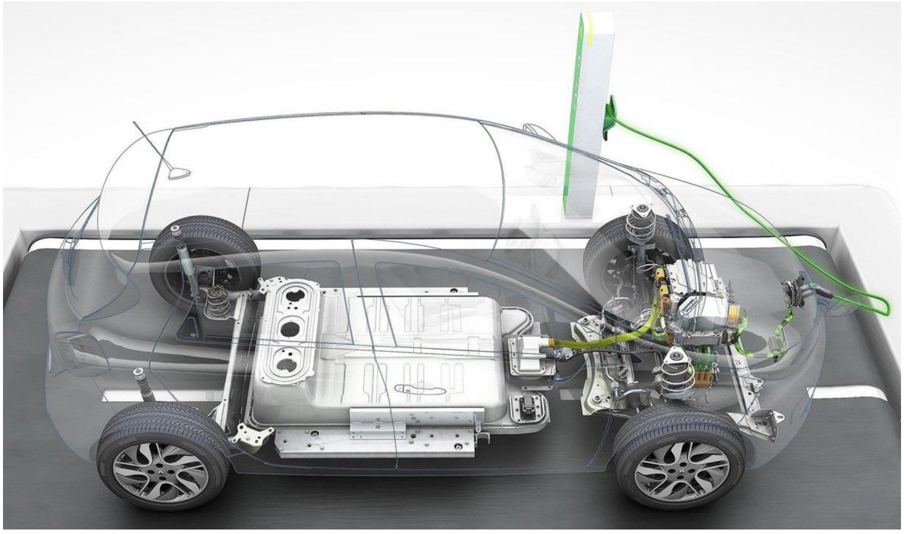

Figure 3.4: Renault Zoe e-powertrain and battery. Source: *Zoe Battery Durability, Field Experience and Future Vision*

braking, or stopped, yet restart quickly. Even though Mild-Hybrids may employ regenerative braking and some level of power assist to the internal combustion engine, they are not able to run on an electric-only mode of propulsion, therefore their operation is almost identical to Gasoline vehicles, even in terms of fuel consumption and GHG emissions, even if they can be considerably reduced. Although they are classified as Hybrid vehicles by present regulations. Indeed, fuel economy improvements on Gasoline vehicles have been directed towards the direction of Mild-Hybrid engines, in the last years, and the same is happening for Diesel ones. [64] [154]

Full-Hybrid vehicles

Gasoline-/Diesel-Hybrid Electric vehicles, generally called Full-Hybrid or Series-Hybrid Electric vehicles, use an internal combustion engine to drive an electric generator that powers an electric motor (see Figure 3.5 for the schematics of a Full-Hybrid vehicle). The Full-Hybrid concept is based on the fact that the different motors work better at different speeds: the electric motor is more efficient when producing torque, while the combustion engine is better for maintaining high speed. A Series-Hybrid vehicle is driven by an electric motor, and the internal combustion engine is tuned to run as a generator when the battery pack cannot provide sufficient energy. Since the charge battery

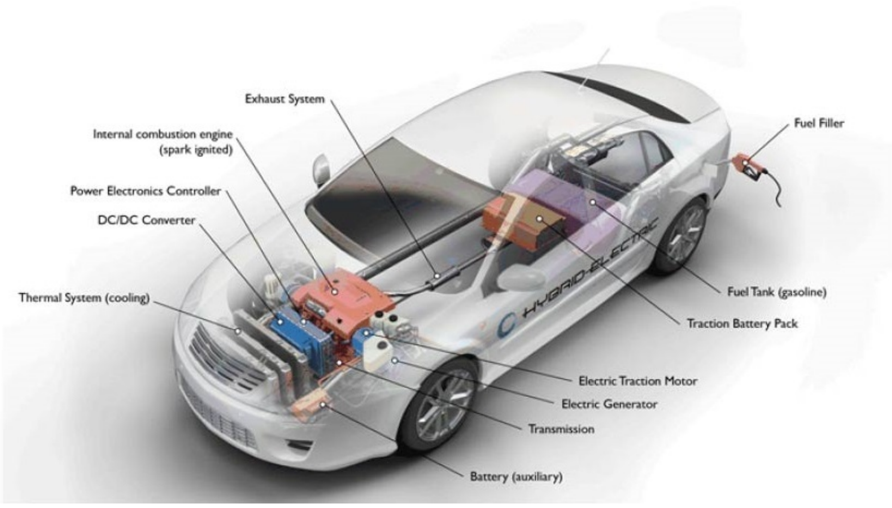

Figure 3.5: Full-Hybrid Electric vehicle schematics. Source: `https://afdc.energy.gov`

functioning is practically identical to a Full-Electric vehicle, the primary purpose of the engine actually acts like a range extender. Indeed, Series-Hybrid are also referred to as "Extended Range Electric vehicles" (EREV). While Full-Hybrid for cars totally relies on Gasoline engines, Diesel-Hybrid is adopted for heavier vehicles, mainly to exploit the higher thermal motor efficiency. A balance between advantages and disadvantages of Full-Hybrid vehicles is not so simple. [8] [159] [172] Indeed, their main characteristics are:

- Powertrain complexity, due to the presence of the internal combustion engine, one or more electric motors (including inverters) and a power split device;
- Small battery;
- No need for recharge infrastructure;
- Not so impressive fuel economy improvements with respect to traditional vehicles.

Plug-in Hybrid Electric vehicles

Plug-in Hybrid Electric vehicles (PHEVs) combine the characteristics of Full-Electric and Full-Hybrid (see Figure 3.6 for the schematics of a Plug-in Hybrid Electric vehicle). They are actually Extended Range Electric vehicles

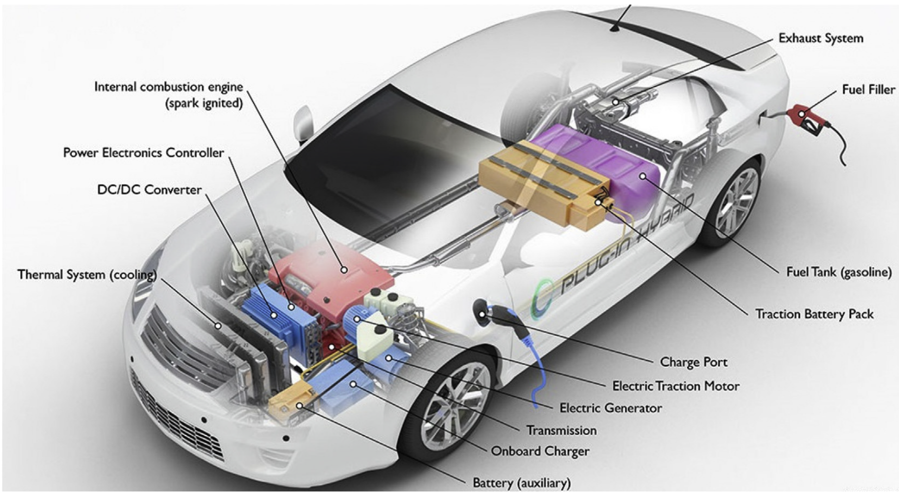

Figure 3.6: Plug-in Hybrid Electric vehicle schematics. Source: `https://afdc.energy.gov`

whose battery can be recharged by both plugging it into an external electricity source and by its own on-board engine and generator. These are charging processes that use different currents: Alternating Current (AC) is used for on board chargers, as happens for Full-Hybrids, while Direct Current (DC) is used for external charging, as for All-Electric vehicles. PHEVs on the European market today are all passenger cars, but this is an interesting and mature technology to be soon extended to a wider vehicle range (the first PHEV to be sold in Europe was an EREV version of the Renault Kangoo, called as "Renault Elect'road" [145], marketed since 2003 in France, Norway and UK, but it did not became successful, mainly due to its still immature technological level). [8] [70] [149]

The PHEV powertrain is even more complex than the Full-Hybrid one: a Series-Hybrid is propelled by electric motors only, a Parallel-hybrid is propelled both by its engine and by electric motors operating concurrently and a Series-Parallel hybrid operates in either mode. Even if the battery is not as powerful as the one of a Full-Electric vehicle, it can receive a quite high energy amount from the external source. Even in this case, Lithium-ion increasingly appears to be the current chemistry of choice for PHEVs. [8] [37]

Since the main aim of this technology is to improve sustainable transport [5], coupling congenial characteristics for combustion engine-fanatics and the need for cleaner transportation modes, the Battery Management System has to be optimal [72]. A PHEV can operate in charge-depleting and charge-sustaining modes, and the combinations of the twos is termed "blended/mixed mode": since they are designed to be able to drive in All-Electric mode for an extended range of distance and speed, the operational modes manage the battery discharge strategy, therefore their balance has a direct effect on the size and type of battery required.

- Charge-depleting mode allows a fully charged PHEV to operate almost exclusively, except during very hard acceleration, on electric power until the battery state of charge is depleted to a predetermined level. After that, the vehicle's internal combustion engine will be engaged. Since the battery has not very impressive autonomy, this mode is commonly used for short travels;

- Mixed mode is, instead, commonly used for longer travels: the trip usually begins in low speed Charge-Depleting mode, but when speed increases, Blended mode intervenes. The switch is immediate and automatically regulated, according to the vehicle speed. PHEV fuel economy specifications are generally given for Mixed mode.

Even though PHEV sales in Europe surpassed Full-Electric vehicles (a trend that is not reflected on the global scale), the main problem for a larger diffusion of this technology (in this case cars) is the limited model range and the high purchase cost. [3] [122]

Fuel Cell vehicles

A Fuel Cell Electric vehicle FCEV uses a fuel cell to power its on-board electric motor (see Figure 3.7 for the schematics of a FCEV powertrain). The adopted solution is to provide the vehicle with a low temperature fuel cell PEMFC (Proton Exchange Membrane Fuel Cell) stack, due to clear thermal management issues, fuelled with air and compressed hydrogen, at 350 or 700 bar. The main improvement provided by Fuel Cell vehicles with respect to All-Electric ones is the higher energy density (up to one order of magnitude higher than the one of a traditional Lithium-ion battery for automotive purposes), therefore the driving range of a FCEV can be comparable to them with significantly reduced dimensions of the energy generator. [178]

FCEVs are zero-GHG emission vehicles that only emit water and heat, originated during the fuel cell operation. Differently from traditional vehicles, FCEVs centralise pollutant generation during the Hydrogen production process,

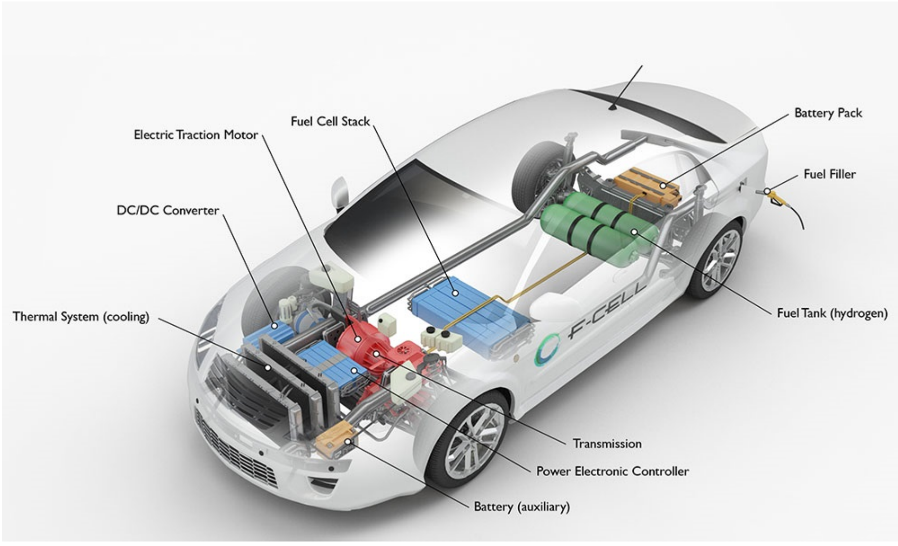

Figure 3.7: Schematic diagram of the powertrain of a FCEV. Source: `https://afdc.energy.gov`

since hydrogen is today typically derived from steam reforming of natural gas. Hydrogen production from Renewable Sources or by thermochemical processes is the key for the improving the environmental aspects of this technology, but there is still some way to go, especially on the cost side. [173] [178]

Fuel cells have been used in various kinds of vehicles. While the first commercially produced FCEV is a car, the Hyundai Tucson FCEV (2013), Toyota Mirai (2015) has become the symbol of this technology. Some FC Buses are also being tested in some European large cities, while the first Fuel Cell truck, the Nikola One, is upcoming. [130] [146] [178]

If the public recharging infrastructure for Electric cars has been already considered insufficient for a meaningful growth of All-Electric vehicle sales, only 107 Hydrogen stations are present in Europe, to date, of which 70 in Germany, 13 in UK and others sparse around the continent. Hydrogen refuelling only takes only 3 minutes and can assure up to 800 km range, with the present technology level. [6] [79]

Critics of this technology doubt about the cost effectiveness, both on purchase and operational sides, and difficulties in "clean" Hydrogen production are deterrent, too. [131]

3.2 Commodity flows

This section will focus on the methodology adopted to obtain efficiency figures of both reference year and new technologies, for all transport modes.

Table 3.7: Average transport mode efficiency. Source: *Global transportation scenarios in the multi-regional EFDA-TIMES energy model*

Technology	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$
TRT	0.25
TRL	0.21
TRW	0.67
TRE	0.35
TRC	0.12
TRM	0.08
TRH	0.06
TRB	0.10

Weighted average efficiency for each transport mode, as evaluated for the year 2000, and reported in Table 3.7, is considered for base year technologies in ETM. These values are given as calibration parameters, therefore can be variable according to regional correction parameters. These figures will be also used as a baseline for the evaluation of reference year 2016 efficiency by transport mode.

Regarding new technologies, deeply analysed as present on the European market in 2016 (thus the Model will be only solved for the EUR region, for the purpose of this work, before a needed revision of regional calibration parameters), a precise methodology has been followed, basing on real consumption data.

3.2.1 Fuel economy specifications in Europe

The *Car labelling Directive* [47] is a directive by European Commission aimed at helping drivers choose new cars with low fuel consumption, encouraging, on the other hand, manufacturers to improve fuel efficiency of the vehicles they produce [50]. EU countries are then required to ensure that relevant information is provided to consumers, including a label showing a car's fuel efficiency and CO_2 emissions. Besides, an important transition is under way in Europe regarding fuel economy evaluations for new produced cars and vans. The "New European

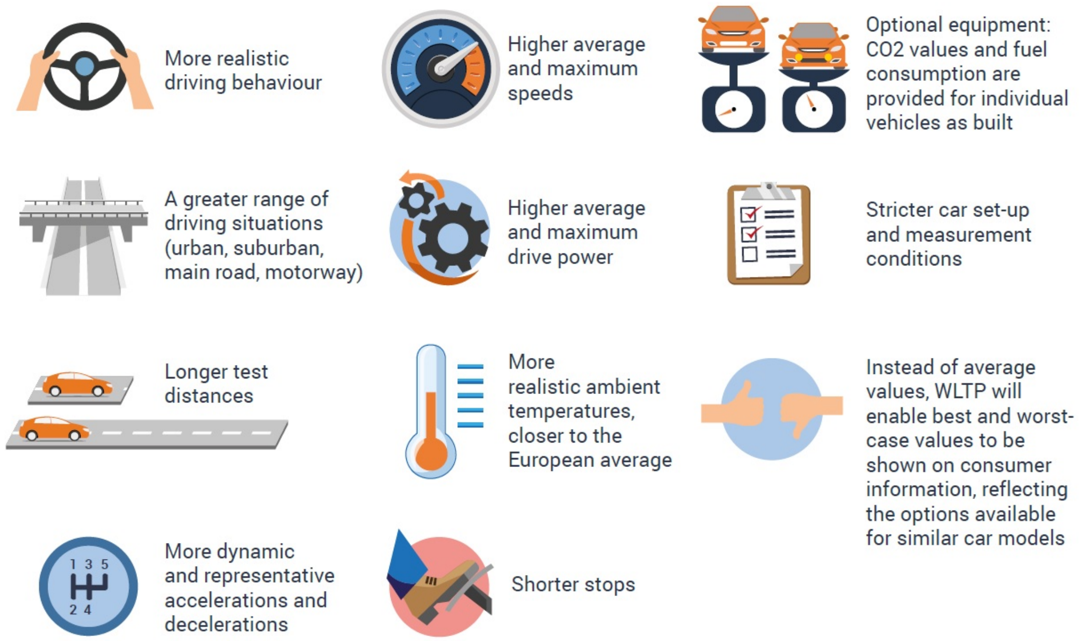

Figure 3.8: The benefits of WLTP. Source: `https://wltpfacts.eu`

Driving Cycle" (NEDC) lab test, designed in the 1980s, has being gradually replaced by the "Worldwide-Harmonised Light Vehicle Test Procedure" (WLTP), due to evolutions in technology and driving conditions [180]. Both tests provide results in terms of fuel economy, measured in $l/100\ km$, $kg/100\ km$ or $kWh/100\ km$, depending on the type of fuel(s), CO_2 emissions, in g/km, and electric range, in km (obviously for Electric vehicles only). The WLTP is generally a more stringent procedure, characterises by much more realistic conditions with respect to NEDC. Indeed, IPCC has measured a very negative displacement between NEDC and real driving conditions [82] [15], with a difference up to 39%, that can hardly continue to be tolerated. Figure 3.8 summarises the changes introduced by the WLTP shift, with respect to the previous regulation. The overall effect results in worse performances by tested vehicles, which may be translated into market bans, with consequent economic repercussions on manufacturers [7] [13]. Therefore, the EU automotive producers have a full interest to fit their new models into the WLTP regulatory limits. Although, being the transition still in act, even though from 1 January 2019 all cars in dealership should present WLTP values only to avoid any confusion among consumers, up to date an exhaustive WLTP specifications database does not exist, while NEDC-derived values are still universally provided by manufacturers [30]. Therefore, almost all the fuel economy, emission and electric range information provided in this work refer to NEDC test specifications, but properly translated to reproduce, as far as possible, real driving conditions.

However, there is also a distinct lack regarding Heavy-Duty vehicles [88] [161], which are certainly subject to blander regulatory limits. Indeed, in May 2018, the European Commission presented a legislative proposal [54] setting the first ever CO_2 emission standards for HDVs, provided in terms of percentage reductions by new trucks. Against this background, clear fuel economy specifications for HDVs are still not easily accessible. Thus, the approach used in OldTRA ETM, which adopted a simple scaling up of LDVs' efficiency values, cannot be condemned, but rather adapted to the available information.

In the following sections, transport modes and the approach used to calculate their efficiency figures will be accurately described.

3.2.2 The future of mobility in Europe

Several hypotheses can be done for the future of such a consuming sector, even though constant fuel economy improvements and the deployment of less energy intensive vehicles (in terms of energy per kilometre) have to be taken into account [89], in contrast with the increase in the number of vehicles [3], strictly related with economic growth [32] [33] [57] [60] [136]. In particular, the interest for better performing vehicles is strictly related with the increasingly stringent GHG emission targets [52] [84]: it has to be remarked that GHG emissions are strictly related with fuel consumption of engine vehicles [89], therefore emissions and efficiency improvements run on close parallel roads.

Is Diesel on its way out in Europe?

Since 2009, both Light- and Heavy-Duty vehicles are subject to mandatory emission reduction targets [52] [54]. In particular, Cars only are responsible for around 12 [%] of the total European CO_2 yearly emissions [53]. In Figure 3.9 the 2017 European car fleet situation is represented. Regarding cars, while the 2015 regulation target has been fully satisfied (the prescribed limit was 130 g/km for the new car fleet and it was reached in 2013, while in 2017 the average new car emits 118.5 g/km

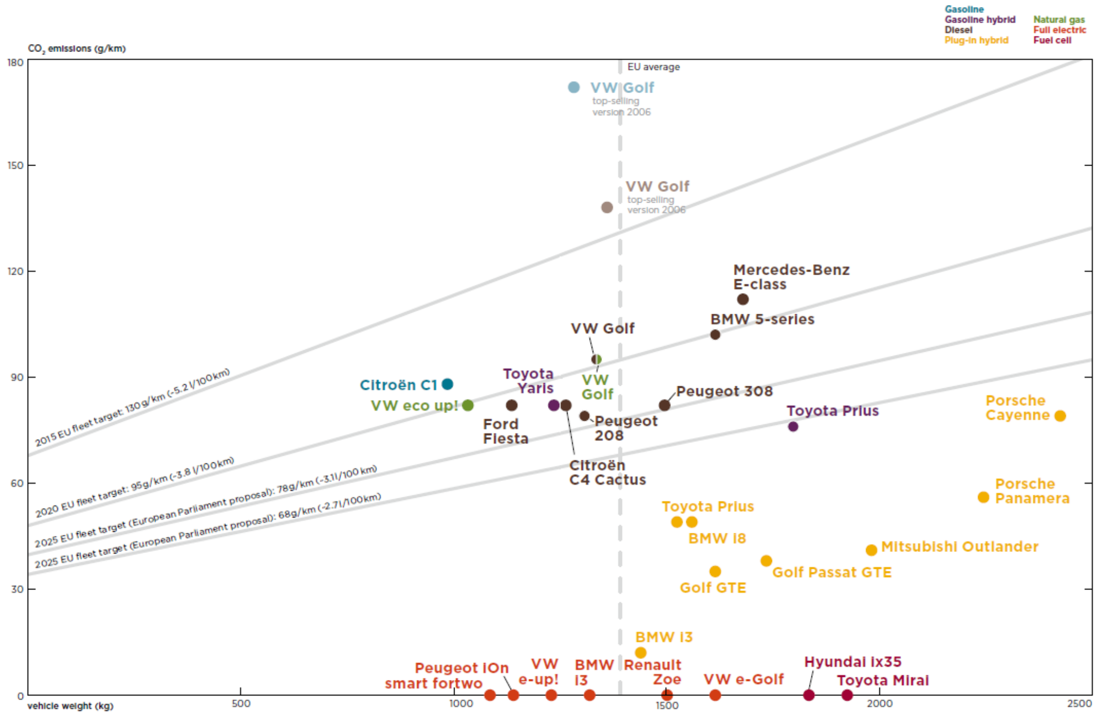

Figure 3.9: CO_2 emissions of selected new passenger cars. Source: *European vehicle market statistics - Pocketbook 2017-2018*

of CO_2) [53], in 2020 a new policy will enter into force, to abate the limit on the car fleet limit under 95 g/km. From 2021 on, the average emissions of all newly registered cars must be below this target. [52]

Concerning the remaining Light-Duty vehicles and all Heavy-Duty vehicles, a weight-driven approach is considered for the emission reduction targets, obviously increasing with the weight of the vehicle. Nevertheless, despite this policy-driven increasing interest for cleaner vehicles, an unprecedented event, now famous as "*Dieselgate*", shook the automotive, and more in general the whole road transport manufacturing world, in 2015. The name *Dieselgate* refers to the widespread use of a defeat device for circumventing the EPA (the U.S. Environmental Protection Agency) rules about NO_x emissions, by several European car manufacturers, mainly gravitating towards Volkswagen Group. [24] [27] [170] [171] Being the Euro 6 [179] European regulation far more lenient than the American one, providing for a limit of 0.08 g/km of NO_x, the already extremely serious environmental impact turns very worrying, as visible from Figure 3.10. The discussed cheat relates to the defeat device that VW embedded in its software

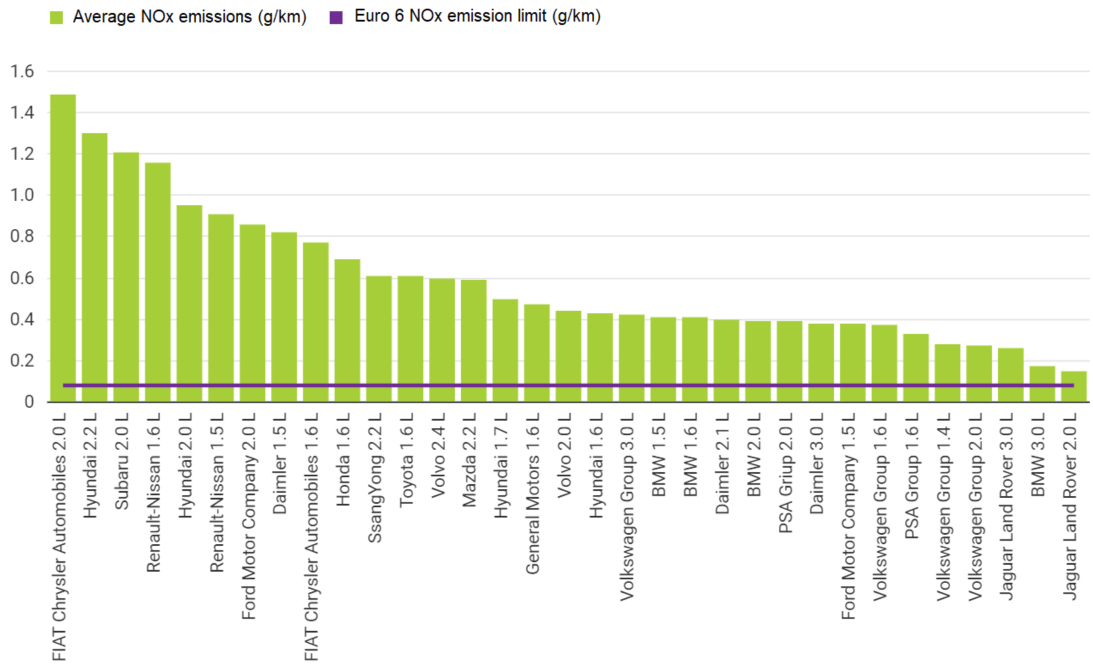

Figure 3.10: On-road NO_x emissions, by manufacturer and engine displacement. Source: *Explanation of the TRUE real-world passenger vehicle emissions rating system*

calibrations, starting from 2009, for all its produced diesel cars. This device was in charge of reducing the effectiveness of the emission control system recognising particular test conditions, and returning NO_x emission levels in line with regulation. While VW has paid a steep bill for this in the U.S., Europe has a structural problem with law enforcement, and the required defeat device remedies are far less effective than the American ones. Moreover, continuing this investigation, even more manufacturers have been involved in the scandal [68] [15]. The devastating environmental and economic impact of this fraud, and the consequent loss of confidence on the part of consumers with respect to Diesel cars, lead to decision, by part of several manufacturers, to stop the production and commercialisation of new Diesel vehicles in many European countries [25] [63] [125] [157] (e.g. the 2019 Toyota lineup in Italy is totally Diesel-free [100] [160]). In addition, driving bans, mainly in large city centers, act as leverage for limiting Diesel cars use. In the end, the combination of these facts is a valid justification to forecast the substitution of the present Diesel fleet in the mid-term, with emerging environmentally-friendly technologies. [5] [68] [60] [122]

3.3 Base year 2005 technologies

As already explained in 3.1.2, base year technologies are used to model vehicle demand at the beginning of the Model time horizon, thus in base year 2005.

In OldTRA ETM, base year efficiencies were assigned as calibration parameters to each base year technology for every transport mode, and these values are preserved. Then, these figures were reported to base year 2005 by means of regionally variable efficiency multipliers (calibration parameters), ranging from 1.01 (TRTMET, TRTETH) to 1.21 (All other Cars and Light trucks, while a 1.11 efficiency multiplier was used for all other vehicles) for EUR, meaning from 0.2 $\%/year$ to 4.2 $\%/year$. However, as highlighted by Figure 3.11, from 2000 to 2015, the average annual efficiency (measured in $lge/100\ km$ or MJ/km) improvement of the Car stock in EU28 was of 0.819 [$\%/year$], much less than even the lowest efficiency improvement considered in OldTRA ETM. Anyway, the assigned efficiency multipliers were used to make the modelled vehicle stock meet the final energy consumption value, stated by IEA/Eurostat energy balances, thus they will be preserved, too. Tables from 3.8 to 3.15 report all the information about base year Road transport technologies in Europe.

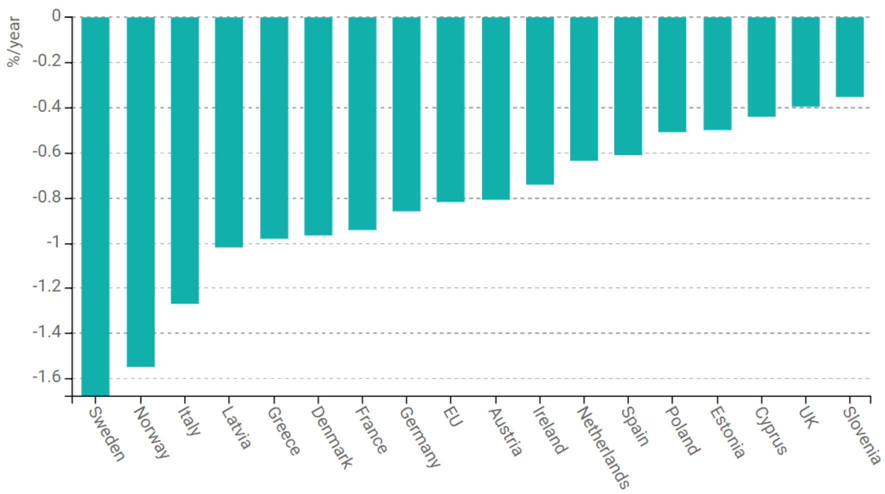

Figure 3.11: Trends in specific consumption of Cars by country (2000-2015). Source: `https://www.odyssee-mure.eu`

Table 3.8: Base year TRT technologies

Technology	Fuel	Efficiency$_{2000}$ $[Bvkm/PJ]$	Efficiency$_{2005}$ $[Bvkm/PJ]$
TRTGAS	TRAGSL	0.25	0.30
TRTDST	TRADST	0.29	0.35
TRTLPG	TRALPG	0.28	0.33
TRTNGA	TRANGA	0.28	0.33
TRTELC	TRAELC	0.47	0.57
TRTMET	TRAMET	0.37	0.37
TRTETH	TRAETH	0.37	0.37

Table 3.9: Base year TRL technologies

Technology	Fuel	Efficiency$_{2000}$ $[Bvkm/PJ]$	Efficiency$_{2005}$ $[Bvkm/PJ]$
TRLGAS	TRAGSL	0.21	0.25
TRLDST	TRADST	0.20	0.26
TRLLPG	TRALPG	0.16	0.20
TRLNGA	TRANGA	0.16	0.20
TRLELC	TRAELC	0.47	0.57
TRLMET	TRAMET	0.16	0.20
TRLETH	TRAETH	0.16	0.20

3.4 Passenger Cars (TRT)

Passenger Cars serve the general purpose of individual transport of passengers on public roads and, unlike commercial vehicles, are not primarily designed and hardly adopted for commercial use.

3.4.1 Reference year 2016 technologies

On the basis of the most recent data by ACEA [1], the EUR Car fleet counted over 265 million vehicles in 2016, meaning about one car per 2 inhabitants. The average car lifetime is increasing year on year, contrasting the diffusion of more efficient and cleaner vehicles. In 2016, it stands at 11.5 $years$.

Actual market trends [132], which highlight how Sweden, Norway and Italy are leaders in Europe in the adoption of efficient Cars, reflect the situation depicted in

Table 3.10: Base year TRB technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TRBGAS	TRAGSL	0.089	0.099
TRBDST	TRADST	0.098	0.109
TRBLPG	TRALPG	0.080	0.089
TRBNGA	TRANGA	0.080	0.089
TRBELC	TRAELC	0.134	0.149
TRBMET	TRAMET	0.080	0.089
TRBETH	TRAETH	0.080	0.089

Table 3.11: Base year TRH technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TRHGAS	TRAGSL	0.056	0.064
TRHDST	TRADST	0.058	0.062
TRHLPG	TRALPG	0.052	0.057
TRHNGA	TRANGA	0.052	0.057
TRHMET	TRAMET	0.052	0.057
TRHETH	TRAETH	0.052	0.057

Figure 3.11, but it is very difficult to draw a common framework. Indeed, factors acting on efficiency improvements are vehicle lifetime, type of fuel and car size. Here follows the analysis of the most interesting regional situations concerning fleet efficiency:

- Sweden leads the ranking, and the large number of Petrol Cars (~ 60 [%] of the total) is counterbalanced by low lifetimes, 9.9 *years* in average, and a strong presence of Alternative Fuel Vehicles AFVs, of which 4.7% are Flex-Fuel Cars;

- Norway is even more interesting: only 3.7% cars are AFVs, all coming from the Electric class, while Petrol and Diesel cars are almost equally shared. Average lifetime stands at 10.6 *years*, but a slight presence, even if constantly increasing, of Electric vehicles, especially BEVs, has a significant effect;

- Italy follows a still different pattern: average lifetime (10.8 *years*) is still below the European average, but the consistent presence of LPG and Natural Gas as

Table 3.12: Base year TRM technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TRMGAS	TRAGSL	0.072	0.080
TRMDST	TRADST	0.077	0.085
TRMLPG	TRALPG	0.068	0.075
TRMNGA	TRANGA	0.068	0.075
TRMMET	TRAMET	0.068	0.075
TRMETH	TRAETH	0.068	0.075

Table 3.13: Base year TRC technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TRCGAS	TRAGSL	0.12	0.13
TRCDST	TRADST	0.12	0.14
TRCLPG	TRALPG	0.11	0.12
TRCNGA	TRANGA	0.11	0.12
TRCMET	TRAMET	0.11	0.12
TRCETH	TRAETH	0.11	0.12

fuels, and a market trend directed towards small vehicles (Italy is a flourishing market for City Cars) implies quite good savings.

- UK plays the role of the villain; indeed, a strong presence of ICE Cars, accounting for $\sim$ 98.9 [%] of the total, is the main reason for a stagnation in fuel economy improvements, even if the average car lifetime is one of the lowest in Europe, 7.8 $years$.

- Latvia is a quite surprising example: while Diesel cars are up a leg with 53.6% against the 44.9% of Gasoline, and the average Car lifetime reaches 16 $years$, it provide an impressive result. It may be a signal of the fact that the presence of Gasoline Cars is the strongest factor to take into account for efficiency improvements.

At EUR level, the situation is strongly different from OldTRA ETM Transport sector update, which considered 2000 as reference year, as visible from the comparison between figures 3.12 and 3.13). Besides an unsurprisingly AFVs

Table 3.14: Base year TRW technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TRWMPG	TRAGSL	0.90	1.00
TRWMCG	TRAGSL	0.63	0.70

Table 3.15: Base year TRE technologies

Technology	**Fuel**	**Efficiency$_{2000}$** $[Bvkm/PJ]$	**Efficiency$_{2005}$** $[Bvkm/PJ]$
TREGSL	TRAGSL	0.35	0.39
TREDST	TRADST	0.28	0.31

growth, where new technologies based on the Electric concept gain a consistent share, the Diesel exploit is impressive. Indeed, the introduction of the TDI (Turbocharged Direct Injection) engine by Volkswagen Group in the early 2000s has been the spark for the big success of this technology [68] [122] [176]. However, following the Dieselgate (see section 3.2.2), this flame seems to be destined to burn out within some years. Three new technologies entered the market, even if still playing marginal roles in the total fleet, but with a considerable uptake of Gasoline Full-Hybrids [3].

Within the Car sector, vehicles are generally classified according to technology and size category.

Table 3.16 shows the reference year 2016 technologies considered within the Passenger Car sector, where Fuel Cell Cars are included, even though their number is so small to be considered as negligible; strictly related to this is the fact that compressed Hydrogen demand is still not considered within the IEA/Eurostat energy balances, then its reference year demand will be assumed as 0, in terms of both energy demand, thus vehicle demand.

Size categories (or segments) distinguish cars in terms of body, dimensions and fuel economy. However, considering different features according to the size, in the Model, would result in a pointless, too high, level of disaggregation. Nevertheless, a detailed analysis is reported here. Although the definition of size category, for Cars, is not unambiguous, and overlaps are possible between one or more categories, Car segments (reported in Table 3.17; Volkswagen Group models are

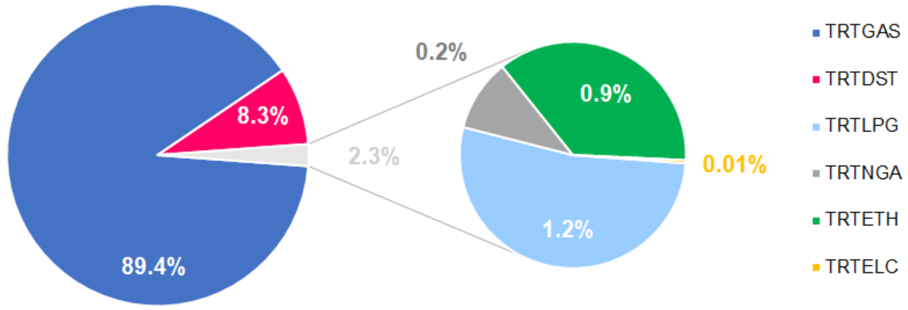

Figure 3.12: 2000 EUR TRT fleet by type of technology (in terms of % over the total number of Cars)

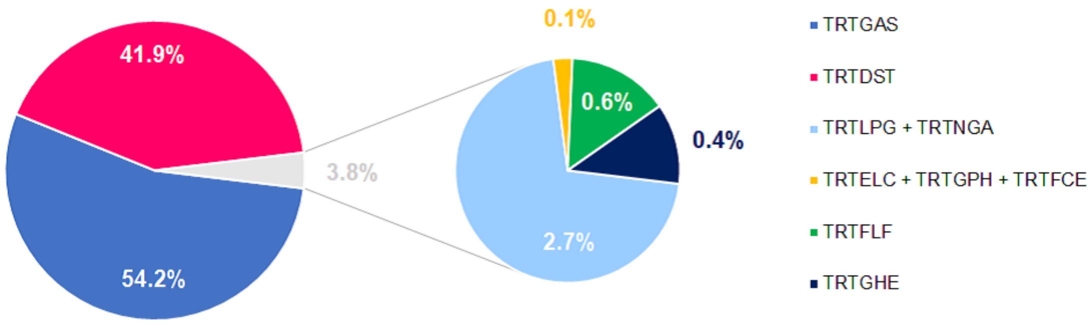

Figure 3.13: 2016 EUR TRT fleet by type of technology (in terms of % over the total number of Cars)

given as example, for line-up completeness and uniform comparison) were just mentioned in an official document by European Commission in 1999 [46], but not specifically described, therefore manufacturers tend to split production basing on simple comparison with other well-known brand models. The main problem with that categorisation is the recent SUV class market uptake. SUVs of very diverse dimensions (and fuel economy characteristics, in fact) have been spreading, filling the existing gaps among different segments [3]. Therefore, the J segment is no more sufficient to give a full representation of the SUV class. For instance, Volkswagen's J class Cars include specimens ranging from Volkswagen T-Cross (4.11 m × 1.76 m × 1.58 m and 1250 kg in its base version) to Volkswagen Touareg (4.9 m × 1.98 m × 1.72 m and 2020 kg in its III series base example). A more coherent categorisation, based on market observations and joining vehicles with similar fuel economy and weight, is then reported in Table 3.18.

Table 3.16: Reference year 2016 Passenger Cars in use: technologies, fuels and fleet composition

Technology	**Initials**	**Fuel(s)**	**Share %**
Gasoline	TRTGAS	TRAGSL	54.25
Diesel	TRTDST	TRADST	41.94
LPG	TRTLPG	TRALPG	1.90
Natural Gas	TRTNGA	TRANGA	0.81
Flex-Fuel	TRTFLF	TRAETH/TRAGSL	0.56
Full-Electric	TRTELC	TRAELC	0.10
Gasoline-Hybrid Electric	TRTGHE	TRAGSL	0.44
Gasoline Plug-in Hybrid Electric	TRTGPH	TRAGSL/TRAELC	0.04
Fuel Cell	TRTFCE	TRAHH2	0.00

Table 3.17: Car segmentation by European Commission. Source: *Case No COMP/M.1406 HYUNDAI / KIA REGULATION (EEC) No 4064/89 MERGER PROCEDURE*

Segment	**Type of car**	**Example**
A	Mini Car	Volkswagen up!
B	Small Car	Volkswagen Polo
C	Medium Car	Volkswagen Golf
D	Large Car	Volkswagen Passat
E	Executive Car	Volkswagen Arteon
F	Luxury Car	Audi A8
S	Sport Coupé	Porsche 911
M	Multi Purpose Car	Volkswagen Sharan
J	SUV (including off-road vehicles)	Volkswagen Touareg

Efficiency of the Passenger Car fleet

In OldTRA ETM, the weighted average efficiency, used to represent Passenger Cars, stood at 0.25 $[Bvkm/PJ]$, as visible from Table 3.7.

The application of the 0.819 $[\%/year]$ (see 3.3) improvement for the 16 years from 2000 to 2016 results in a 13 $[\%]$ average efficiency growth. Given that, a further step is needed in order to characterise all vehicle technologies for reference year 2016.

Exact fuel economy information can be retrieved by specifications that

Table 3.18: Passenger Car size categories

Size category	**Initials**	**EC Segment**	**Example**
Mini Car	A	A	Volkswagen up!
Small Car	B	B	Volkswagen Polo
Medium Car	C	C	Volkswagen Golf
Large Car	D	D, E, F, S, M	Volkswagen Passat
Small SUV	BS	J	Volkswagen T-Cross
Compact SUV	CS	J	Volkswagen Tiguan
SUV	DS	J	Volkswagen Touareg

manufacturers are obliged to provide to consumers [30]. A database, including 119 Passenger Car models on sale in 2019, selected in such a way to represent the totality of Cars sold nowadays, has been built and used as starting point for the evaluation of efficiencies of both reference year 2016 fleet and new vehicles.

Fuel economy specifications, as mentioned in 3.2.1, are provided in terms of $l/100\ km$, $kg/100\ km$ and $kWh/100\ km$, depending on the type of fuel. Thus, in order to give uniformity and coherence with the purpose they will be used for (evaluation of Road transport demand in terms of driven distance), they are properly translated into km/MJ, or equivalently $Bvkm/PJ$, values, by means of the fuel properties reported in Table 3.2:

$$\eta^*_{new\ TRT***,2019}\left[\frac{km}{MJ}\right] = \frac{100}{E_c\ \left[\frac{l}{100\ km}\right] \cdot e_i\ \left[\frac{MJ}{l}\right]} \tag{3.1}$$

$$\eta^*_{new\ TRT***,2019}\left[\frac{km}{MJ}\right] = \frac{100}{E_c\ \left[\frac{kg}{100\ km}\right] \cdot e_i\ \left[\frac{MJ}{kg}\right]} \tag{3.2}$$

$$\eta^*_{new\ TRT***,2019}\left[\frac{km}{MJ}\right] = \frac{100}{E_c\ \left[\frac{kWh}{100\ km}\right] \cdot 3.6\ \left[\frac{MJ}{kWh}\right]} \tag{3.3}$$

where $\eta^*_{new\ TRT***,2019}$ is the vehicle efficiency evaluated from 2019 NEDC specifications, E_c is the vehicle consumption and e_i is the specific energy content of fuel i. Equation 3.1 is used for TRTGAS, TRTDST, TRTLPG, TRTFLF and TRTGHE, equation 3.2 is used for TRTNGA and TRTHH2 and equation 3.3 is used for TRTELC. TRTGPH fuel economy specifications, instead, are provided as if the vehicle always works in mixed mode (see 3.1.4). For all analysed PHEVs, about 55% energy from Gasoline and the remaining 45% from Electricity per kilometre are required, as fuel economy specifications are provided for mixed mode use (see 3.1.4). Therefore, equations 3.1 and 3.3 are properly combined to reproduce this consumption splitting and provide actual TRTGPH efficiency values. This approach is not replicated for TRTFLF because E85 is modelled as a fuel with its own properties, therefore equation 3.1 can be directly applied.

For each technology, size categories are defined as in Table 3.18, trying to include a sufficient number of samples to define a clear efficiency pattern. Once efficiency has been evaluated for all vehicle technologies and size categories, where available, values are re-arranged through a weight-driven increasing trend.

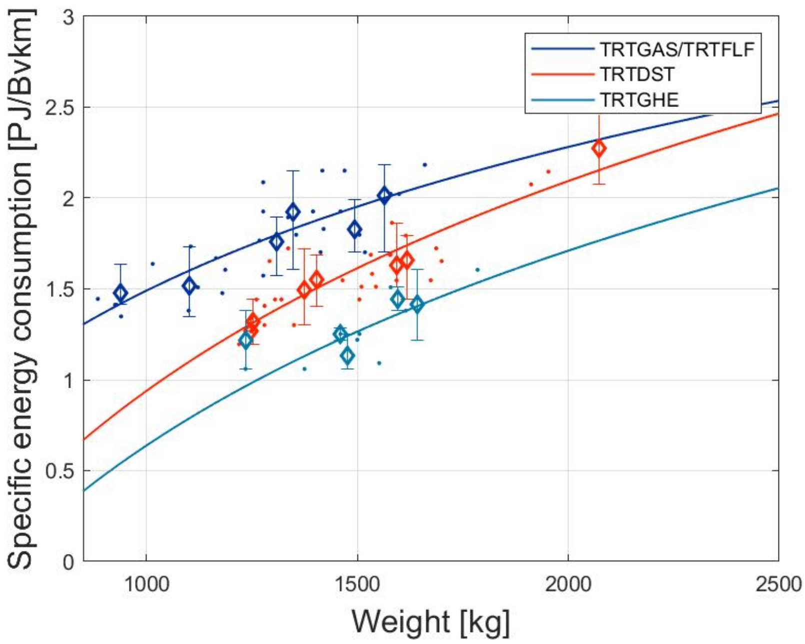

Figure 3.14: Efficiency trend for TRTGAS, TRTDST and TRTGHE

The results of this data collection are summarised in figures 3.14, 3.15 and 3.16. Then, statistically derived empirical equations are obtained, to describe the

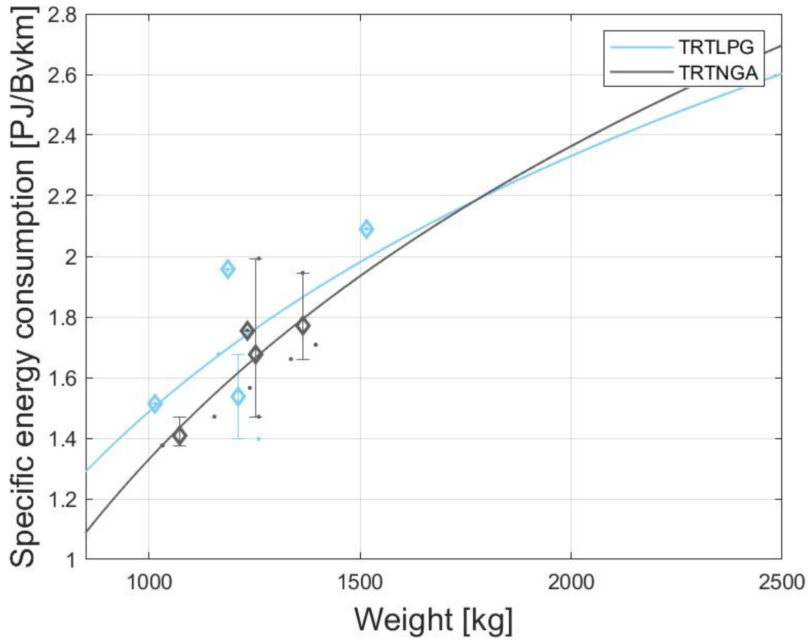

Figure 3.15: Efficiency trend for TRTLPG and TRTNGA

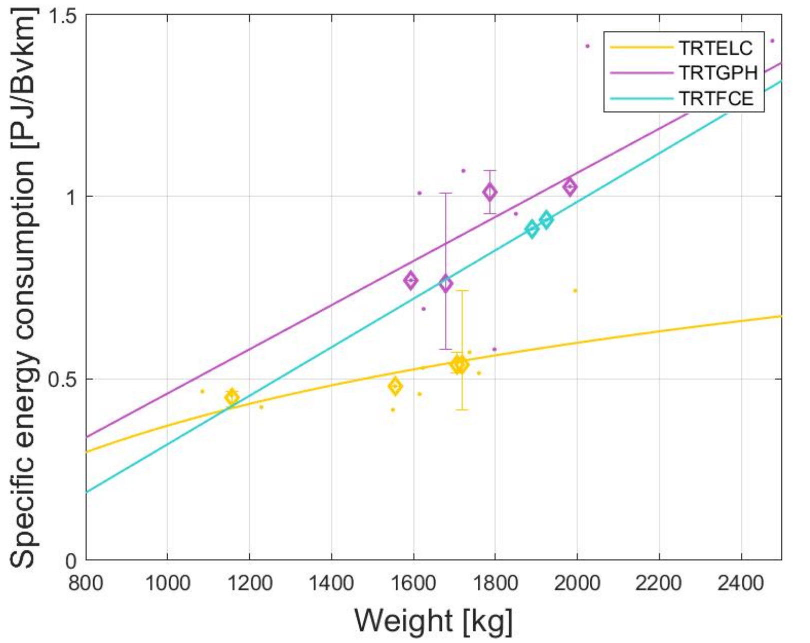

Figure 3.16: Efficiency trend for TRTELC, TRTGHE and TRTHH2

efficiency behaviour for each specific Car technology:

$$\eta^*_{new\ TRTGAS,2019} = \eta^*_{new\ TRTFLF,2019} = [1.14 \cdot \ln(Curb\ weight) - 6.39]^{-1} \quad (3.4)$$
$$\eta^*_{new\ TRTDST,2019} = [1.25 \cdot \ln(Curb\ weight) - 7.56]^{-1} \quad (3.5)$$
$$\eta^*_{new\ TRTLPG,2019} = [1.08 \cdot \ln(Curb\ weight) - 5.92]^{-1} \quad (3.6)$$
$$\eta^*_{new\ TRTNGA,2019} = [1.49 \cdot \ln(Curb\ weight) - 8.97]^{-1} \quad (3.7)$$
$$\eta^*_{new\ TRTELC,2019} = [0.33 \cdot \ln(Curb\ weight) - 1.90]^{-1} \quad (3.8)$$
$$\eta^*_{new\ TRTGHE,2019} = [1.32 \cdot \ln(Curb\ weight) - 8.41]^{-1} \quad (3.9)$$
$$\eta^*_{new\ TRTGPH,2019} = [7.00 \cdot 10^{-4} \cdot Curb\ weight - 0.34]^{-1} \quad (3.10)$$
$$\eta^*_{new\ TRTFCE,2019} = [7.00 \cdot 10^{-4} \cdot Curb\ weight - 0.35]^{-1} \quad (3.11)$$

where $Curb\ weight$ is measured in kg.

- Gasoline and Flex-Fuel Cars (equation 3.4) require the same energy amount per km, therefore their efficiencies are modelled according to the same logarithmic trend, even though the market analysis only included Gasoline vehicles. The observation of market data (Figure 3.14) highlights a tendency to choose Gasoline for smaller Cars, with respect to Diesel; indeed, this is mainly due to the currently higher Gasoline price, which lowers the appeal for large energy consuming Cars;

- Diesel Cars (equation 3.5, Figure 3.14) show lower specific energy consumption with respect to Gasoline ones for all size categories;

- Gasoline-Hybrid Electric Cars (equation 3.9, Figure 3.14) are generally substantially heavier than their Gasoline size category correspondents. However, the efficiency improvement is evident, even if not dramatic;

- LPG (equation 3.6) and Natural Gas (equation 3.7) Cars are characterised by lack of available data (Figure 3.15), mainly due to the fact that most of Bi-fuel cars vehicles are retrofitted in post-market phase (see 3.1.4), then only a few vehicle specifications are available for these technologies. Nonetheless, a logarithmic trend seems to be a reasonable choice;

- Full-Electric Cars (equation 3.8, Figure 3.16) show the highest efficiency among all technologies all over the covered sizes, with low dependence on weight;

- Regarding Gasoline Plug-in Hybrid Electric Cars (equation 3.10, Figure 3.16), the battery provides 45% of the required energy amount per km, helping to improve the overall vehicle performance. The analysis of the few Plug in Hybrids on the market today shows that a linear trend could be a good solution to approximate their behaviour, and the presence of the Electric motor gives an impressive enhancement to the performances of this type of vehicles, with respect to traditional ones;
- Fuel Cell Cars (equation 3.11, Figure 3.16) are present on the market with 2 examples only then the derived linear trend is reported just for uniformity with all other technologies, but it cannot be considered as representative of the real situation.

Once the efficiency trends are obtained, a specific weight value is needed to be applied to each size category. These weights are calculated, for each technology and size category, as:

$$Weight = Average\ curb\ weight + 0.5 \cdot Passenger\ weight \tag{3.12}$$

where $Average\ curb\ weight$ is evaluated by Car market data, and $0.5 \cdot Passenger\ weight$ is considered to account for a 1.5 Passenger occupancy (1 is already considered for NEDC test), each passenger weighting 75 kg. These values will replace $Curb\ weight$ inside the equations from 3.4 to 3.11, in order to obtain representative efficiencies:

$$\eta_{new\ TRTGAS,2019} = \eta_{new\ TRTFLF,2019} = [1.14 \cdot \ln{(Weight)} - 6.39]^{-1} \tag{3.13}$$

$$\eta_{new\ TRTDST,2019} = [1.25 \cdot \ln{(Weight)} - 7.56]^{-1} \tag{3.14}$$

$$\eta_{new\ TRTLPG,2019} = [1.08 \cdot \ln{(Weight)} - 5.92]^{-1} \tag{3.15}$$

$$\eta_{new\ TRTNGA,2019} = [1.49 \cdot \ln{(Weight)} - 8.97]^{-1} \tag{3.16}$$

$$\eta_{new\ TRTELC,2019} = [0.33 \cdot \ln{(Weight)} - 1.90]^{-1} \tag{3.17}$$

$$\eta_{new\ TRTGHE,2019} = [1.32 \cdot \ln{(Weight)} - 8.41]^{-1} \tag{3.18}$$

$$\eta_{new\ TRTGPH,2019} = [7.00 \cdot 10^{-4} \cdot Weight - 0.34]^{-1} \tag{3.19}$$

$$\eta_{new\ TRTFCE,2019} = [7.00 \cdot 10^{-4} \cdot Weight - 0.35]^{-1} \tag{3.20}$$

However, for each technology Medium Cars-referred values are taken as landmarks for the estimation of the reference year 2016 Car fleet efficiencies (except for TRTHH2, which does not include any Medium Car, thus Large Car is taken as reference). Table 3.19 summarises weights, calculated from equation 3.12, and efficiencies, evaluated from NEDC specifications and equations from 3.13 to 3.20, used as representative of 2019 new Cars.

Table 3.19: 2019 Car market key data

Technology	**Size category**	**Weight** $[kg]$	**Efficiency** $[Bvkm/PJ]$
TRTGAS	C	1310	0.39
TRTDST	C	1380	0.47
TRTLPG	C	1440	0.37
TRTNGA	C	1370	0.39
TRTFLF	C	1370	0.39
TRTELC	C	1720	1.29
TRTGHE	C	1480	0.56
TRTGPH	C	1680	0.83
TRTFCE	D	1930	0.70

The last needed element is a factor taking into account the presence of old vehicles in the fleet. In order to do this, a combination of the average efficiency value used for year 2000, reported in Table 3.7 ($\overline{\eta}_{TRT\ fleet,2000} = 0.25\ [Bvkm/PJ]$) and the 2019 Car market data in Table 3.19 is performed.

The total improvement factor from 2000 to 2016 is calculated as:

$$I_{\eta,LDV,2000-2016} = \left(1 + 0.819\ \left[\frac{\%}{year}\right] \cdot 16\ [years]\right) = 1.13 \tag{3.21}$$

Therefore, the average efficiency of the 2016 Car fleet is:

$$\overline{\eta}_{TRT\ fleet,2016} = \overline{\eta}_{TRT\ fleet,2000} \cdot I_{\eta,LDV,2000-2016} = 0.28\ \left[\frac{Bvkm}{PJ}\right] \tag{3.22}$$

From a simple comparison of efficiencies from Table 3.19, weighted according to the actual corresponding share of vehicles for each technology from Table 3.16, and coupling them with the efficiency trend equations from 3.13 to 3.20, an adjustment factor is obtained, to be applied universally in order to take into account the presence of old vehicles in the fleet. This factor, called $f_{old,TRT}$, is used to decrease efficiencies of 2019 new Cars, in order to make them represent the 2016 fleet:

$$f_{old,TRT} = \frac{\overline{\eta}_{new\ TRT,2019}}{\overline{\eta}_{TRT\ fleet,2016}} = 2.10 \tag{3.23}$$

This means that, if the 2016 fleet was only composed of vehicles with the present grade of technology and the same technology share, it would have an average efficiency increased by 210%, even though the majority of the fleet still relies on Gasoline and Diesel Cars.

The factor $f_{old,TRT}$ is then applied to all Car technologies:

$$\eta_{TRT***\ fleet,2016} = \frac{\eta_{new\ TRT***,2019}}{f_{old,TRT}} \tag{3.24}$$

and results are illustrated in Table 3.20, along with the technology share over the total fleet for reference year 2016. These values will be then used for illustrating a new, alternative method for the estimation of base year demand.

Since this pejorative factor is applied to all technologies as it is, this will obviously lead to a pessimistic underestimation of the efficiency value for recent technologies (TRTELC, TRTGHE, TRTGPH, TRTFCE), but they do represent a very small fraction of the Car stock, therefore this "forcing" could be acceptable, by now.

Table 3.20: Reference year 2016 Passenger Car fleet

Technology	**Fuels**	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$	**Share** [%]
TRTGAS	TRAGSL	0.26	54.25
TRTDST	TRADST	0.31	41.94
TRTLPG	TRALPG	0.25	1.90
TRTNGA	TRANGA	0.26	0.81
TRTFLF	TRAGSL + TRAETH	0.26	0.56
TRTELC	TRAELC	0.86	0.10
TRTGHE	TRAGSL	0.37	0.44
TRTGPH	TRAGSL/TRAELC	0.55	0.04
TRTFCE	TRAHH2	0.49	0.00

3.4.2 New technologies

Efficiency of new Passenger Cars in 2019

Efficiency of new Cars, as sold in 2019, is far more simple to be calculated, now that its estimation procedure for the reference year 2016 fleet has been performed. Indeed, the bases are still NEDC specifications, properly modified to meet the assumed vehicle occupancy (equations from 3.13 to 3.20 using as weight the one calculated with equation 3.12) and adjusted to take into account real driving conditions. Indeed, according to ICCT, the International Council on Clean Transportation, the average gap between official fuel consumption figures and actual fuel use for new cars in the EU stands at 39%:

$$f_{RD} = 1.39 \tag{3.25}$$

Thus, efficiency of new 2019 TRT technologies $\eta_{TRT***,2019}$ is evaluated as:

$$\eta_{TRTGAS,2019} = \eta_{TRTFLF,2019} = \frac{\eta_{new\ TRTGAS,2019}}{f_{RD}} = \frac{\eta_{new\ TRTFLF,2019}}{f_{RD}} \tag{3.26}$$

$$\eta_{TRTDST,2019} = \frac{\eta_{new\ TRTDST,2019}}{f_{RD}} \tag{3.27}$$

$$\eta_{TRTLPG,2019} = \frac{\eta_{new\ TRTLPG,2019}}{f_{RD}} \tag{3.28}$$

$$\eta_{TRTNGA,2019} = \frac{\eta_{new\ TRTNGA,2019}}{f_{RD}} \tag{3.29}$$

$$\eta_{TRTELC,2019} = \frac{\eta_{new\ TRTELC,2019}}{f_{RD}} \tag{3.30}$$

$$\eta_{TRTGHE,2019} = \frac{\eta_{new\ TRTGHE,2019}}{f_{RD}} \tag{3.31}$$

$$\eta_{TRTGPH,2019} = \frac{\eta_{new\ TRTGPH,2019}}{f_{RD}} \tag{3.32}$$

$$\eta_{TRTFCE,2019} = \frac{\eta_{new\ TRTFCE,2019}}{f_{RD}} \tag{3.33}$$

Cost characterisation

New technologies are characterised by their own value of Investment and O&M costs, that would drive choices during the Model time horizon (since ETM is an economic model tending to the minimisation of the total system cost). While in OldTRA ETM all costs were assigned as "educated guesses", the approach used for RevTRA ETM will be more accurate, in order to catch real cost differences between vehicles, and to make the Model more precise for the definition of cost-effective future trends:

Country	VAT	Registration Tax
Austria	20%	Based on CO2 emissions (max 32% + bonus/malus)
Belgium	21%	Based on cylinder capacity and age (Brussels-Capital) Fuel, age, emission standards and CO2 (Flanders) Cylinder capacity, age and CO2-based bonus/malus scheme (Wallonia)
Bulgaria	20%	Plate costs (BGN 25) + eco tax (BGN 160)
Cyprus	19%	Based on CO2 emissions and cylinder capacity
Czech Republic	21%	Registration tax (max CZK 800) + eco tax based on emission standards
Denmark	25%	85% of vehicle's value up to DKK 193,400 + 150% of the rest. Reductions based on safety equipment and fuel consumption.
Estonia	20%	Registration label (€62) + registration card (€130)
Finland	24%	Based on retail value and CO2 emissions (min 2.7%, max 50%)
France	20%	Registration tax (varies by region) + CO2-based bonus/malus scheme
Germany	19%	Registration fees (€26.3)
Greece	24%	Based on net retail price, emissions technology and CO2
Hungary	27%	Based on cylinder capacity and emission standards
Ireland	23%	Based basic price and CO2 emissions
Italy	22%	Based on vehicle type and horsepower + registration fees (+ €145.00) + CO2-based bonus/malus scheme
Latvia	21%	Registration costs (€43.93) + national resources tax (€55)
Lithuania	21%	Based on vehicle type
Luxembourg	17%	Registration stamp (€50) + supplement (€24 or €50)
Malta	18%	Based on vehicle's value, CO2 emissions and length
Netherlands	21%	Based on CO2 emissions and fuel efficiency
Poland	23%	Based on cylinder capacity (up to 18.6% of vehicle's value)
Portugal	23%	Based on cylinder capacity and CO2 emissions
Romania	19%	Registration fees (€8.6)
Slovakia	20%	Registration fees (min €33 based on vehicle's value, engine power and age) + plate costs (€16.5)
Slovenia	22%	Based on selling price, CO2 emissions and fuel type
Spain	21%	Based on CO2 emissions (max 14.75% for 200g/km or more)
Sweden	25%	None
United Kingdom	20%	First registration fee (£55)

Figure 3.17: Taxes on Car acquisition in EU. Source: *ACEA Tax Guide*

- Investment cost, to be paid by drivers at the moment they buy a new vehicle, is made up of several components:

$$Inv.\ cost\ [€/vehicle] = MSRP + V.A.T. + Other\ taxes \pm Bonus/Malus \tag{3.34}$$

Let us give a meaning to these cost components:

- $MSRP$ is the Manufacturer's Suggested Retail Price (or list price) and it is evaluated with the intention of helping standardise prices among different locations. Italian price lists, provided by manufactures, have been consulted for the same Car models involved in the previous Car market analysis; there, not MSRP, but the sum of that plus V.A.T. plus a tax for getting the car on the road, which depends on engine power, and here estimated as 10 $[€/kW]$, is displayed, so MSRP is retrieved;
- V.A.T. is the Value Added Tax, a consumption tax placed on a product whenever value is added at each stage of the supply chain, from production to the point of sale. According to the ACEA Tax Guide, taxes on acquisition are very diversified among the different EU countries (see Figure 3.17, which provides an overview on the situation as at 1 January 2019), therefore here an average 21.3 [%] V.A.T., to be applied to MSRP, is considered;
- Other taxes are very difficult to be estimated in such a way to represent the actual, very varied situation, as highlighted by Table 3.17 for Registration taxes; thus, the sum of a 150 € One Time Registration Tax plus Road Tax, evaluated as 10 $[€/kW] \cdot Engine\ power\ [kW]$, is considered in the "Other Taxes" contribution to Investment cost;
- Bonus and Malus are usually applied basing on CO_2 emissions as declared by manufacturers, but they are characterised by strong regional variability and can be seen as an important policy instrument to guide customers' choices during the transition to "cleaner" vehicles, thus as temporary measures. Since the aim of this work is not to show the convenience of clean vehicles, bonus and malus on car purchase will be not considered, to guarantee uniformity among the different technologies.

- O&M costs are obtained by the sum of three elements:

$$O\&M\ cost\ [€/vkm] = c_e + c_{M\&R} + Ownership\ taxes \tag{3.35}$$

– Energy cost c_e is a variable O&M cost, corresponding with fuel price, evaluated on a per km basis:

$$c_e\ [€/vkm] = c_f\ [€/MJ] \cdot e\ [MJ/km] \tag{3.36}$$

where c_f is the fuel price and e_f is the specific energy consumption by fuel, such as the reciprocal for efficiency. Anyway, this variable O&M cost is a result of the Model;

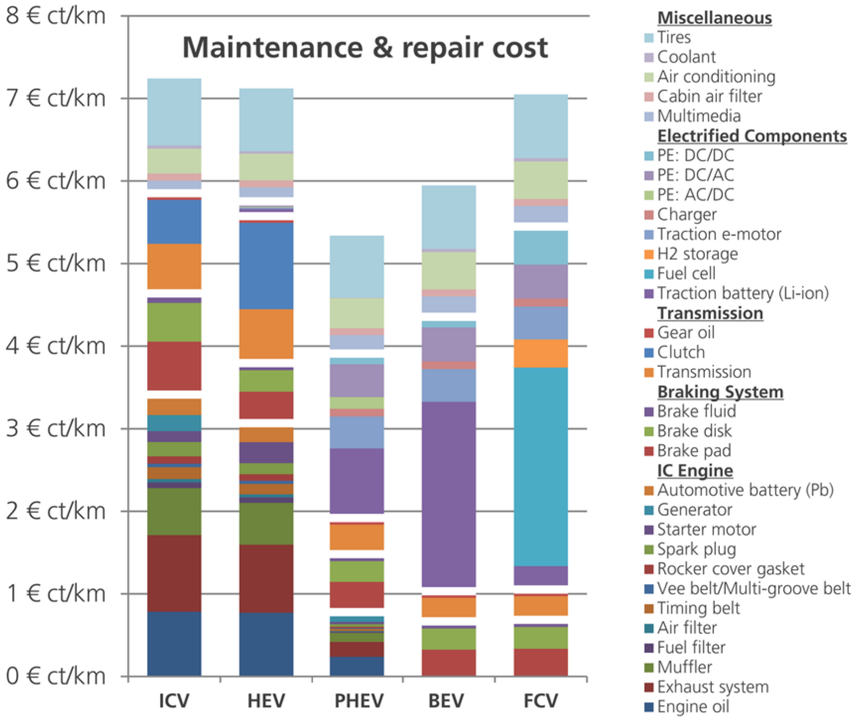

Figure 3.18: M&R costs for Medium Cars. *Cost analysis of Plug in Hybrid Electric Vehicles including Maintenance & Repair costs and Resale Value*

– Maintenance & Repair cost $c_{M\&R}$ is retrieved from [143], where it was evaluated for year 2020 Medium cars and for 31 assessed drivetrain components (see Figure 3.18); although, LPG, Natural Gas and Flex-Fuel Maintenance cost is not compared with the one considered for the macro-group Internal Combustion Vehicles (ICV), since the need for additional components with respect to a conventional Gasoline or Diesel

Vehicle should be taken into account; thus, while Medium Gasoline and Diesel Cars are characterised by a 7.2 $c€/vkm$ M&R cost, it has been chosen to characterise the above mentioned Medium Cars with a 7.4 $c€/vkm$ M&R cost.

Moreover, in order to take rid of the fact that those M&R cost was evaluated for Medium Cars, a size category factor, evaluated as:

$$f_{size}\ [-] = \frac{Weight_{size\ cat.\ TR****,\ cat.\ *}\ [kg]}{Weight_{size\ cat.\ TRT***,\ C}\ [kg]} \tag{3.37}$$

is evaluated in order to adapt values, retrieved from the above mentioned document to vehicles of all sizes (not only Cars); finally, M&R cost is estimated as:

$$c_{M\&R,\ TRT***,\ size\ cat.\ *}\ [€/vkm] = c_{M\&R,\ TRT***,\ C}\ [€/vkm] \cdot f_{size}\ [-] \tag{3.38}$$

– Ownership taxes, as visible from Figure 3.19, are characterised by high diversity on regional level, thus they are excluded from this evaluation.

Table 3.21: TRT New vehicles on the market in 2019

Technology	**Size cat.**	**Investment** $[€/vehicle]$	**Fixed O&M** $[€/vkm]$	**Efficiency** $[Bvkm/PJ]$
TRTGAS	A	13'000	0.05	0.49
TRTLPG	A	14'000	0.05	0.46
TRTNGA	A	15'000	0.06	0.48
TRTFLF	A	13'000	0.05	0.49
TRTELC	A	27'000	0.04	1.68
TRTGAS	B	16'000	0.06	0.44
TRTDST	B	18'000	0.07	0.51
TRTLPG	B	16'000	0.06	0.41
TRTNGA	B	18'000	0.07	0.42
TRTFLF	B	16'000	0.06	0.44
TRTELC	B	26'000	0.05	1.37
TRTGHE	B	29'000	0.06	0.68
TRTGAS	C	24'000	0.07	0.39

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Table 3.21 – continued from previous page

Technology	Size cat.	Investment [€/*vehicle*]	Fixed O&M [€/*vkm*]	Efficiency [*Bvkm*/*PJ*]
TRTDST	C	26’000	0.07	0.47
TRTLPG	C	24’000	0.07	0.37
TRTNGA	C	26’000	0.07	0.39
TRTFLF	C	24’000	0.07	0.39
TRTELC	C	39’000	0.06	1.29
TRTGHE	C	29’000	0.07	0.56
TRTGPH	C	38’000	0.05	0.83
TRTGAS	D	35’000	0.08	0.36
TRTDST	D	36’000	0.08	0.42
TRTFLF	D	35’000	0.08	0.36
TRTELC	D	95’000	0.07	1.09
TRTGHE	D	40’000	0.08	0.52
TRTGPH	D	46’000	0.06	0.76
TRTFCE	D	82’000	0.08	0.70
TRTGAS	BS	22’000	0.07	0.39
TRTDST	BS	23’000	0.07	0.46
TRTLPG	BS	20’000	0.06	0.41
TRTNGA	BS	20’000	0.07	0.43
TRTFLF	BS	22’000	0.08	0.39
TRTELC	BS	41’000	0.06	1.30
TRTGHE	BS	28’000	0.07	0.56
TRTGPH	BS	38’000	0.05	0.83
TRTGAS	CS	30’000	0.09	0.35
TRTDST	CS	32’000	0.08	0.42
TRTLPG	CS	32’000	0.08	0.36
TRTFLF	CS	30’000	0.09	0.35
TRTELC	CS	99’000	0.08	1.04
TRTGHE	CS	35’000	0.09	0.47
TRTGPH	CS	51’000	0.06	0.67
TRTFCE	CS	77’000	0.08	0.71

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Table 3.21 – continued from previous page

Technology	**Size cat.**	**Investment** $[€/vehicle]$	**Fixed O&M** $[€/vkm]$	**Efficiency** $[Bvkm/PJ]$
TRTGAS	DS	50’000	0.12	0.30
TRTDST	DS	52’000	0.11	0.35
TRTGPH	DS	81’000	0.16	0.54

Table 3.21 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Cars in 2019.

RevTRA New technologies repository (TRT mode)

It is evident that such a number of information in the Model would result in a very high level of disaggregation. Thus, as already applied for the evaluation of reference year 2016 fleet efficiency, the same vehicles as in Table 3.19 will be used to represent 2019 new Car technologies in RevTRA ETM.

Furthermore, the Model also requires vehicle lifetime, and cost information in $[M\$/cap]$, where a *cap* unit is defined as 19312 $[Bvkm/year]$:

- Vehicle lifetime is generally preserved with respect to OldTRA ETM, while it has been slightly reduced for technologies involving a large battery (Full-Electric, Plug-in Hybrid vehicles) or a fuel cell (Fuel Cell vehicles);
- Investment cost is, by definition, not suitable to be measured on a *perkm* basis. Anyway, it has been evaluated by taking into account vehicle lifetime and assigning a yearly driven distance to each vehicle category. Medium Cars (size category C) are then supposed to be driven for $d_{TRT***,C} = 15'000$ $[Bvkm/year]$, while Large Cars (size category D) for $d_{TRT***,D} = 20'000$ $[Bvkm/year]$. Therefore:

$$Inv.\ cost \left[\frac{M\$}{cap}\right] = \frac{Purchase\ price \left[\frac{M\$}{vehicle}\right]}{lifetime\ [years]} \cdot \frac{d_{TRT***,\ size\ cat.\ *}}{1\ [cap]} \tag{3.39}$$

  But in the OldTRA database a 1000 $[M\$/cap]$ value was assigned to the generic TR*GAS new technology. Therefore, this way of acting was borrowed, but keeping the observed cost differences between technologies.

Country	Ownership taxes
Austria	Engine power (kW)
Belgium	Cylinder capacity, CO2 emissions, fuel type and emission standards
Bulgaria	Engine power (kW), year of production and emission standards
Cyprus	CO2 emissions
Czech Republic	Engine size
Denmark	Fuel consumption and weight
Estonia	None
Finland	CO2 emissions, weight and fuel type
France	Fiscal power (hp) and CO2 emissions
Germany	CO2 emissions and cylinder capacity
Greece	Engine capacity or CO2 emissions
Hungary	Engine power and year of production
Ireland	Cylinder capacity or CO2 emissions
Italy	kW, emission standards and fuel type
Latvia	GVW, engine capacity (cc), power (kW)
Lithuania	None
Luxembourg	CO2 emissions or cylinder capacity
Malta	CO2 emissions and age
Netherlands	GVW, province, fuel, CO2 emissions
Poland	None
Portugal	Cylinder capacity and CO2 emissions
Romania	Cylinder capacity (cc)
Slovakia	Cylinder capacity and age
Slovenia	None
Spain	Engine rating (hp)
Sweden	Weight, fuel type and CO2 emissions
United Kingdom	Engine size or CO2 emission

Figure 3.19: Ownership Taxes for Cars in EU. Source: *ACEA Tax Guide*

- Fixed O&M cost is converted from $€/vkm$ to $M\$/cap$, by simply applying a monetary conversion and considering the same yearly driven distance as for Investment cost. Therefore:

$$Fixed\ O\&M\ \left[\frac{M\$}{cap}\right] = Fixed\ O\&M\ \left[\frac{M\$}{Bvkm}\right] \cdot \frac{d_{TRT***,\ size\ cat.\ *}}{1\ [cap]} \tag{3.40}$$

Table 3.22 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model.

Table 3.22: RevTRA TRT New technologies (2020)

Technology	Start	Lifetime $[years]$	Investment $[M\$/cap]$	Fixed O&M $[M\$/cap]$	Efficiency $[Bvkm/PJ]$
TRTGSL	2007	12.5	1000	56	0.39
TRTDST	2007	12.5	1083	56	0.47
TRTLPG	2007	12.5	1000	57	0.37
TRTNGA	2007	12.5	1083	57	0.39
TRTFLF	2007	12.5	1000	60	0.40
TRTELC	2007	10	2031	46	1.29
TRTGHE	2007	12.5	1510	55	0.56
TRTGPH	2015	10	2111	61	0.74
TRTFCE	2015	12.5	3203	81	0.70

Then, the Model is able to catch, in a rudimentary way, details about the cost/efficiency evolution of each technology during the time horizon. This information can be provided by defining new values at selected time steps, so that the Model can create a simple linear connection between them. Taking as baseline the observed values for 2019 Car market, and allocating them to the new technologies to be introduced in the Model starting from 2020, values for 2050 new technologies have been assigned, considering several factors, such as the effect of economies of scale and lifetime improvements on currently-emerging technologies and penalties on the purchase of pollutant vehicles and the halting of efficiency improvements on ICE vehicles, mainly basing on observations of vehicle market made by IEA in its *Energy Technology Perspectives 2017* [86], *World Energy Outlook 2018* [95] and *The Future of Trucks* [88]. Fixed O&M costs have not been modified during the time scale. Table 3.23 reports the percentage variation of Investment cost and efficiencies in 2050, with respect to 2020. Those values are used not only for Cars, but for all transport modes. As visible from Figure 3.20, for example, investment cost (as it is defined in the Model, thus this not necessarily corresponds with price parity) parity between Full-Electric Cars and Conventional ICEs is supposed to be reached around 2030 (Diesel Cars) or 2040 (Gasoline Cars). This represents a marked distinction on the method used for efficiency projection in OldTRA ETM. Indeed, while costs were simply modified through educated guesses, vehicle fuel economy was simply improved by a 0.8 [$\%/year$] growth factor, used for all transport modes and technologies from 2003 until 2100, bringing to a 117 [%] total improvement. Roughly speaking, considering one of the most famous Full-Electric Cars, a Tesla Model S Long Range, with a 75 [kWh] battery pack (Large Car, declared performance 5.3 [km/kWh]):

- In OldTRA ETM, it would be able to cover 11.5 [km/kWh] in 2100 (declared performance for a Renault Zoe R90 Z.E. - 41 kWh, Small Electric Car, is currently 7.5[km/kWh]);

- In RevTRA ETM, where a less optimistic specific consumption improvement is prescribed (+20 [%] for Electric Car efficiency, by 2050), the same Tesla Model S would cover 6.4 [km/kWh] in 2050 (and the same in 2100).

In general, a more cautious approach has been adopted: even though emerging technologies have been on the market for a few years only, some of them (Hybrids and Full-Electrics) already reached high performance level in a very short time, and it appears difficult to breach, unless revolutionary technological advancement (for example, in the field of batteries); on the other hand, Plug-in Hybrids and Fuel Cell vehicles, due to the currently limited size range and the early commercial stage, have been supposed to undergo more significant improvements.

Trends in new Car sales

Regarding new Car registrations, the automotive market seems to be finally breathing new life after the Great Recession. Over 13 millions per year new vehicles, in average, are added to the existing fleet, without considering the ones at the end of their useful life. If just considering the post-crisis period, the yearly increase is substantial. Referring to Figure 3.21, 13 million or even more Cars have been sold in EU28 every year in that period, with almost 4 million vehicles

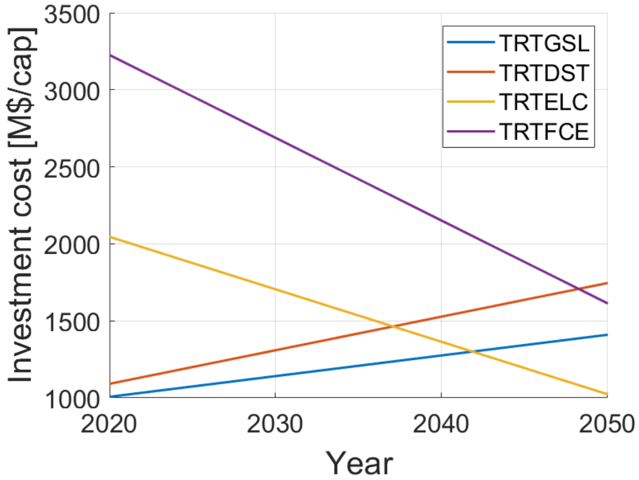


Figure 3.20: Selected Investment cost trends for Cars

Table 3.23: Supposed investment cost and efficiency variations (from 2020 to 2050)

Technology	Inv. cost variation [%]	Efficiency variation [%]
TR*GAS	+40	0
TR*DST	+60	0
TR*LPG	+60	+10
TR*NGA	+60	+10
TR*FLF	+20	+10
TR*ELC	-50	+20
TR*GHE/TR*DHE	-10	+20
TR*GPH	-30	+30
TR*FCE	-50	+30

per year to be added to account for the presence of the EFTA countries and the absence of Croatia (basing on the Cars/inhabitants trend, see 3.4.1) in the EUR region. An increasing tendency to buy larger cars, especially SUVs, exists, then this leads to slower fuel economy improvements if keeping a traditional vehicle-dominated stock, since consumption increases with size. [3]

Nonetheless, the Medium Car (C) size category can be still considered as representative of the whole fleet, at least in the short term, for two main reasons:

- Small SUVs (BS) and Compact SUVs (CS) are not so far from Medium Cars

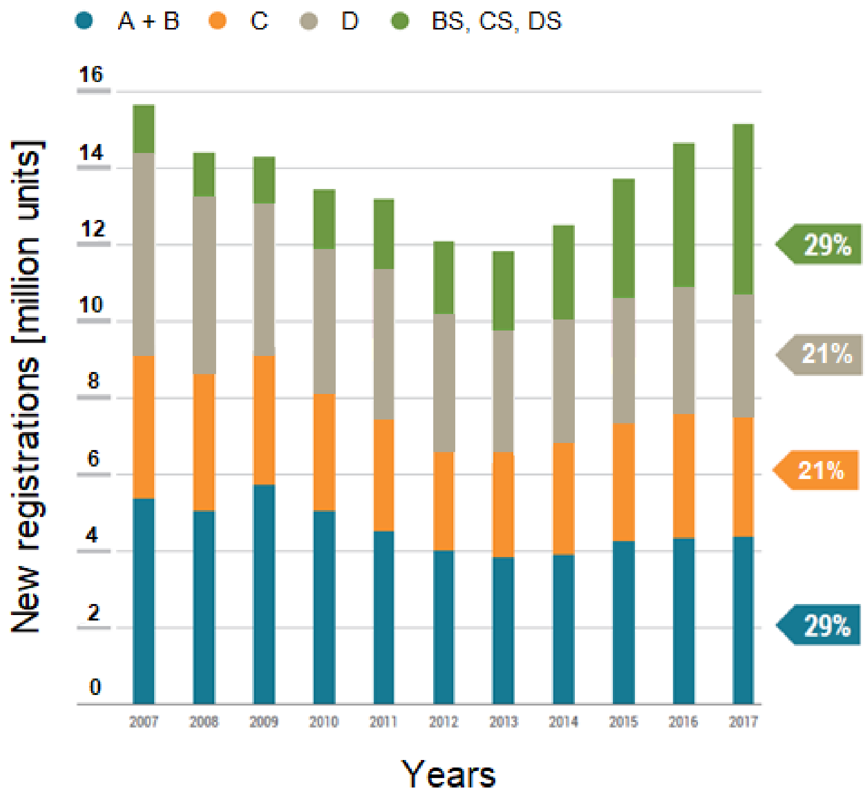


Figure 3.21: Trends in Car market share by size category (EU28). Source: *The Automobile Industry Pocket Guide*

in terms of specific energy consumption [30];

- Mini (A) and Small (B) Cars keep being very popular in Europe, balancing this "large-size tendency" [3].

Observing Figure 3.22, the effects of Dieselgate are visible on Diesel Car sales, mainly resulting from the loss of customers' trust. Furthermore, scheduled bans on Cars with Internal Combustion Engines only are a powerful policy instruments to drive market choices. 7 EUR countries (France, Ireland, Netherlands, Norway, Slovenia, Sweden, United Kingdom) officially announced bans on ICE-only Car sales by 2040 [86] [95]. Although the recent sales displacement is favouring Gasoline Cars sales in the short term, as electricity-based technologies still considered as immature, for the several reasons already explained in 3.1.4, and their purchase prices are still out of market. Nevertheless, AFVs are playing an important role in thinning the TRTDST share. While the TRTLPG + TRTNGA

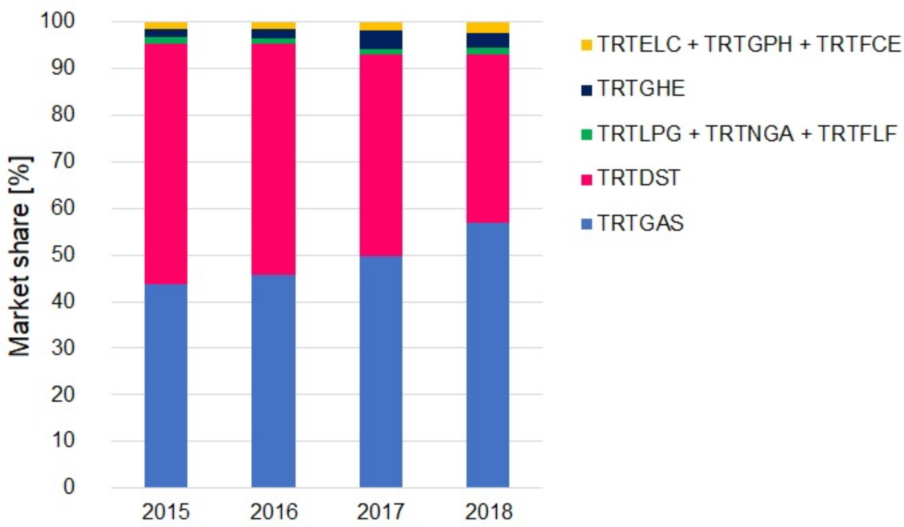


Figure 3.22: Trends in Car market share by type of fuel (EUR). Source: *ACEA*

+ TRTFLF coalition keeps an average 1.4% annual sales share, and Full-Hybrids have gone up and down, the electricity-based technologies are gaining increasing interest. In particular, data about how the Electric category sales are split among TRTELC + TRTFCE and TRTGPH are only available starting from 2017: while Fuel Cell Cars still play a very marginal role (they are only available in Germany, France and Netherlands, and their total number is just above 1000 examples), the remaining two categories share their market between them on almost equal terms. Even though PHEVs can be considered more reliable then BEVs on the autonomy side, their sales are not so impressive. Indeed, this is due to the fact that PHEVs are mainly present on the market with large size Cars, produced by luxury-oriented manufacturers (BMW and Volvo are major players in this technology) and, if not (Mitsubishi, Volkswagen), they are only available with premium class equipment (this was true for the first Full-Electric Cars, too, but the situation has evolved rapidly, with the production of cheaper vehicles). It is not a chance, in fact, that the Mitsubishi Outlander PHEV, a Compact SUV (CS) far from being a luxury car, is the world's all-time best selling Plug-in Hybrid. Cumulative global sales reached 200'000 units in April 2019, with more than 20000 specimens sold in Europe during 2018 (almost 20% of all PHEVs sold in Europe in the same year). However, the rising share of Electric vehicle sales in higher-price countries, such as Norway, Germany and the United Kingdom, is determining a decreasing price trend. In general, there is not yet a clear decline in average Electric Car prices for either BEVs or PHEVs in most countries as variations in market composition, especially the sales of luxury vehicles, dominate the trend. What is curious about Full-Electric vehicles is that, for instance, Renault Zoe (Small Car B) and Nissan Leaf (Medium Car D) purchase prices are 25 [%] and 33 [%] lower than they were in 2012, despite strong improvements in the battery range. The trend towards higher battery ranges is clear across all BEV models in all countries. In 2017, the sales-weighted average worldwide range is 100 *km* higher than in 2010. [37] Concerning Mini BEVs (Figure 3.23), they

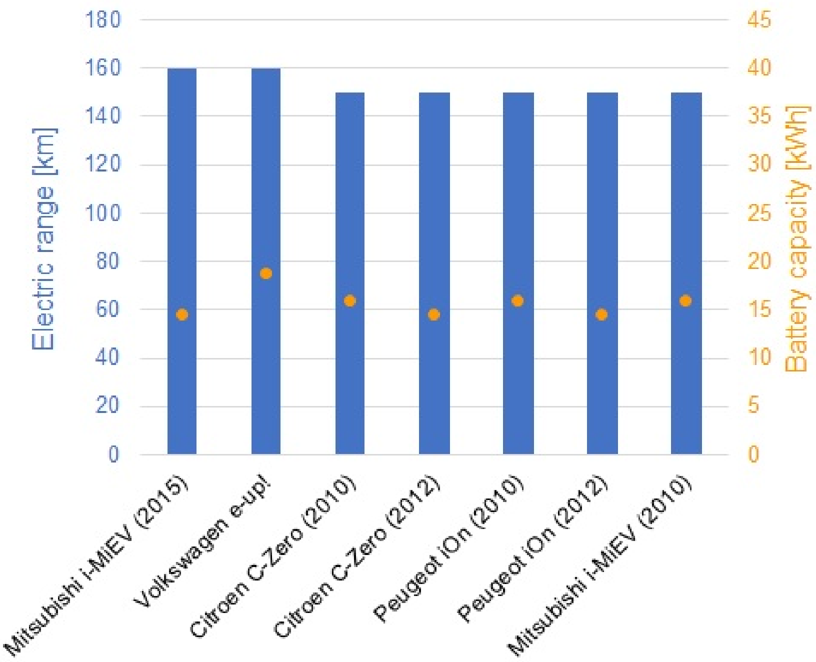


Figure 3.23: Electric range (NEDC) of selected Mini BEVs (A)

are all characterised by short NEDC ranges and small batteries, anyway making them feasible for urban use. However, they are all characterised by out-of-market upfront cost, starting from around €20000.00, which makes them comparable with traditional Compact SUVs. When coming to Small BEVs, the range choice is wider, and while the Renault Zoe line-up is characterised by reasonable costs with respect to its traditional competitors, BMW i3 represents a premium choice, in terms of equipment, motor power and costs. Nevertheless, it turns out to be the fourth best-selling BEV in Europe during 2018 (after Nissan Leaf, Renault Zoe

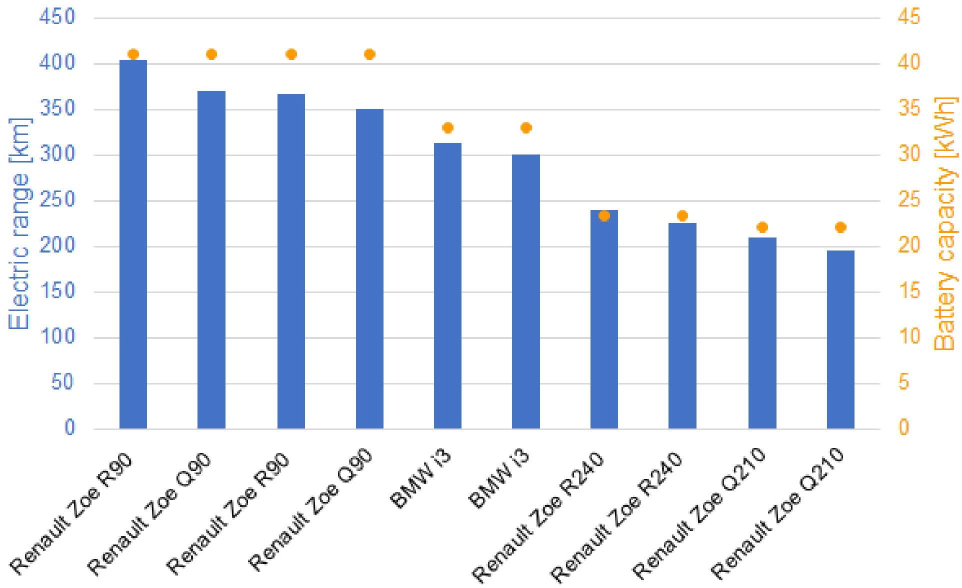


Figure 3.24: Electric range (NEDC) of selected Small BEVs (B)

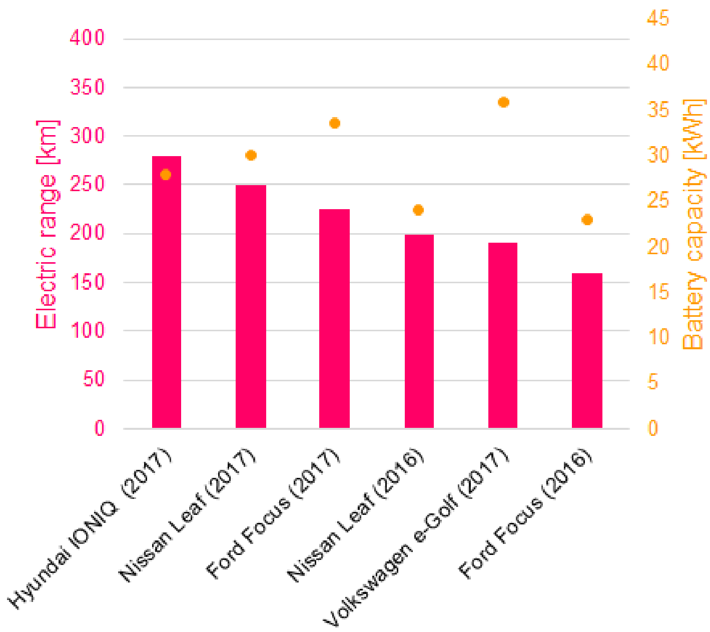


Figure 3.25: Electric range (NEDC) of selected Medium BEVs (C)

and Volkswagen e-Golf). Instead, Medium BEVs are currently characterised by non impressive range performances, mainly due to their bigger dimensions and weight, which strongly affect usability; they are largely adopted for family use and

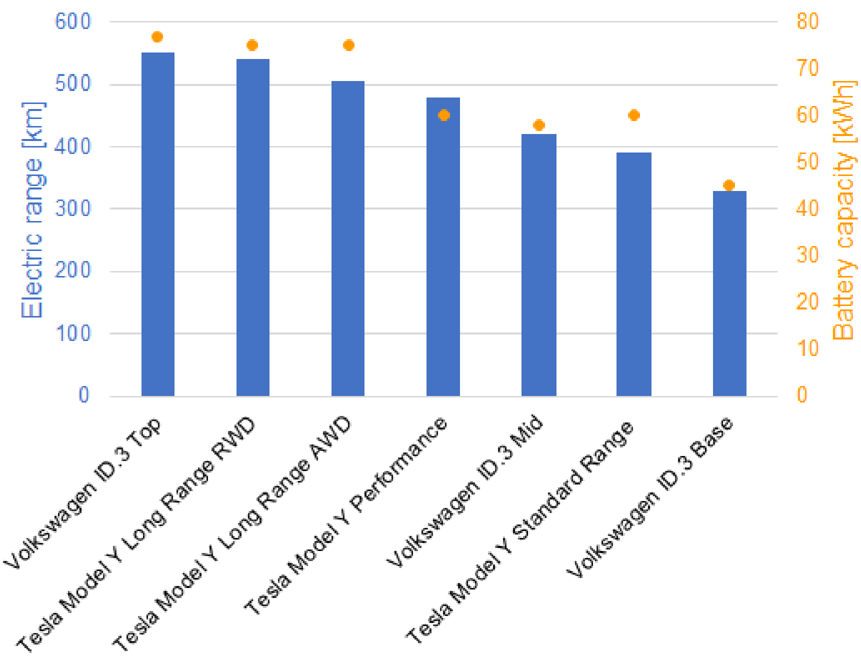


Figure 3.26: Electric range (WLTP) of upcoming BEVs

travelling long distances in Europe, therefore they appear unsuitable for this use, even thinking about the fact that NEDC specifications overestimate vehicle performances. [37] Instead, when observing the characteristics of upcoming

Figure 3.27: Tesla Model Y. Source: `https://www.tesla.com`

Native-Electric cars, the progress is evident. Indeed, the already presented Tesla Model Y [156] (Compact SUV CS, Figure 3.27) and Volkswagen ID.3 [175]

Figure 3.28: Volkswagen ID.3. Source: `https://www.volkswagen.com`

(Medium Car C, a sort of "new-generation Volkswagen Golf", Figure 3.28), ready to be launched on the market in the late 2020, provide impressive WLTP electric ranges (WLTP is far more restrictive than NEDC, therefore lab ranges are expected to be very close to real ones [180]), especially in their top-class examples, with high-capacity batteries in an installation space anyway limited. Therefore, expectations about new Full-Electric models with satisfying ranges for several kinds of use should not be disregarded in the next years, along with a technological advance in battery energy density, anticipating range extension.

3.5 Light Commercial Vehicles (TRC) and Light trucks (TRL)

Light Commercial Vehicles LCVs, as defined by EU regulations [49], are all commercial carrier vehicles with a Gross Vehicle Weight (GVW) not exceeding 3.5 *tons*.

TRC transport mode, as taken into consideration for RevTRA ETM, includes Commercial Vans only. According to European Regulations, Pick-up Trucks are also sold as LCVs, but ETM includes the Light truck mode, too, so they are placed there. The LCV concept, indeed, portrays a vehicle built as a compact truck and usually optimised to be tough-built and economically convenient, and to be utilised in intra-city operations. Therefore, LCVs and Pick-ups are commonly driven to meet indistinctly Passenger and Freight transport purposes.

3.5.1 Reference year 2016 technologies

On the basis of the most recent data by ACEA [1], the EUR LCV fleet counted over 32 million vehicles in 2016, most of all Vans. The average LCV lifetime is increasing year on year, standing at 10.6 *years* in 2016.

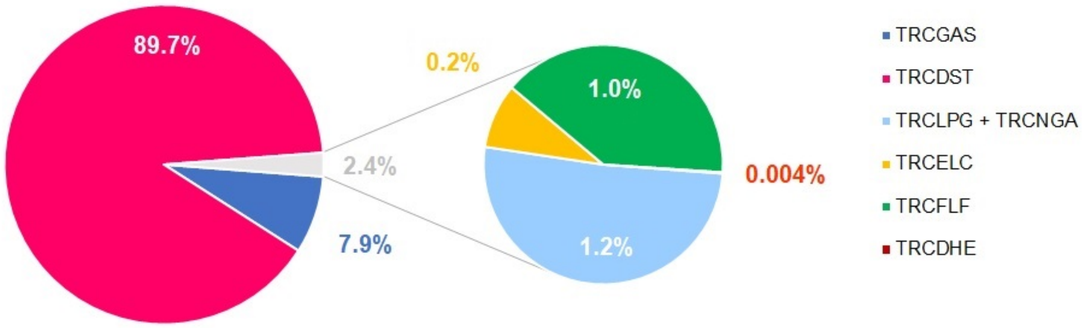


Figure 3.29: 2016 EUR TRC fleet by type of technology (in terms of % over the total number of LCVs)

While the fleet composition for 2000 is not available from [123], a Diesel dominance in 2016 is evident from Figure 3.29.

Table 3.24: Reference year 2016 LCVs in use: technologies, fuels and fleet composition

Technology	**Initials**	**Fuel(s)**	**Share %**
Gasoline	TRCGAS, TRLGAS	TRAGSL	7.86
Diesel	TRCDST, TRLDST	TRADST	89.74
LPG	TRCLPG, TRLLPG	TRALPG	0.86
Natural Gas	TRCNGA, TRLNGA	TRANGA	0.37
Flex-Fuel	TRCFLF, TRLFLF	TRAGSL + TRAETH	0.96
Full-Electric	TRCELC	TRAELC	0.21
Diesel-Hybrid Electric	TRCDHE	TRADST	0.00

Again, within TRC sector, vehicles are classified according to technology and size category. TRL mode only includes Pick-ups, then no size category is included. Table 3.24 shows the reference year 2016 technologies considered within the LCV sector, where Diesel-Hybrid Electric LCVs are included, even though their number is so small to be considered as negligible. Size categories for TRC vehicles are

Table 3.25: TRC size categories

Size category	**Initials**	**Example**
Small Van	S	Ford Transit Connect
Medium Van	M	Ford Transit Custom
Large Van	L	Ford Transit Van

reported in Table 3.25, and the distinction is much more evident and marked than for Cars (Ford vehicle models are given as examples, for line-up completeness and uniform comparison).

Efficiency of the LCV fleet

In OldTRA ETM, the weighted average efficiency of TRC and TRL modes stood at 0.12 $[Bvkm/PJ]$, and 0.21 $[Bvkm/PJ]$ respectively, as visible from Table 3.7. Since the considered LCVs for the new TRC transport mode are very resembling Passenger Cars, the most appropriate value to represent the actual LCV fleet seem to be the one associated with TRL, thus 0.21 $[Bvkm/PJ]$, that will be used as baseline for the evaluation of reference year 2016 efficiency (in the new method for the calculation of base year demand, TRL energy consumption will be assumed as 0 $[PJ]$, since Light trucks are included in the LCV class).

Since all LCVs can be $I_\eta = 1.13$ (equation 3.21) again.

Exact fuel economy information can be retrieved by specifications that manufacturers are obliged to provide to consumers for LCVs, too. Therefore, a database, including 39 LCV models on sale in 2019 has been built. Although, it is very lacking if compared with the one compiled for Passenger Cars, but it highlights that trends elaborated for the TRT transport mode are still valid for TRC, too. Thus, equations from eq:trtgas* to 3.8 are used again to model LCV energy consumption behaviour. Anyway, Full-Hybrid TRC are Diesel-based (TRCDHE), while this technology is not present for Passenger Cars, thus a Gasoline-Diesel correlation coefficient is derived from the Car market analysis, comparing efficiency of the modelled Diesel Car η_{TRTDST} and the one for the modelled Gasoline Car η_{TRTGAS}:

$$k_{DST/GAS} = \frac{\eta_{TRTDST}}{\eta_{TRTGAS}} = 1.20 \tag{3.41}$$

Thus, equation 3.9 is used, but adjusted in order to represent a Diesel-Hybrid Electric vehicle:

$$\eta^*_{new\ TRCDHE,2019} = k_{DST/GAS} \cdot [1.32 \cdot \ln{(Curb\ weight)} - 8.41]^{-1} \tag{3.42}$$

For TRC and TRL, since a specific weight value characterises each size category, $Curb\ weight$ is replaced by:

$$Weight = 0.8 \cdot GVW_{max} \tag{3.43}$$

and equations from 3.14 to 3.17 are obtained again for TRC transport mode, while equation 3.42 is modified in:

$$\eta^*_{new\ TRCDHE,2019} = k_{DST/GAS} \cdot [1.32 \cdot \ln{(Weight)} - 8.41]^{-1} \tag{3.44}$$

Thus, Light Commercial Vehicles are assumed to always run at 80% of their maximum allowable Gross Vehicle Weight (2000 kg for Small Vans, 2800 kg for Medium Vans and 3500 kg for Large Vans and Pick-Ups).

This time, Medium Vans are taken as landmark to represent the reference year 2016 fleet.

The average efficiency of the 2016 LCV fleet is:

$$\overline{\eta}_{TRC\ \ fleet,2016} = \overline{\eta}_{TRC\ \ fleet,2000} \cdot I_{\eta,LDV,2000-2016} = 0.24\ \left[\frac{Bvkm}{PJ}\right] \tag{3.45}$$

The adjustment factor to take into account old vehicles is obtained comparing the efficiency of the average 2019 TRC (Table 3.26) and the efficiency of 2016 TRC fleet, just obtained from equation 3.45, as:

$$f_{old,TRC} = \frac{\overline{\eta}_{new\ TRC,2019}}{\overline{\eta}_{TRC\ \ fleet,2000}} = 1.99 \tag{3.46}$$

The factor $f_{old,TRC}$ is then applied to all technologies:

$$\eta_{TRC***\ \ fleet,2016} = \frac{\eta_{new\ TRC***,2019}}{f_{old,TRC}} \tag{3.47}$$

and results are illustrated in Table 3.27, along with the technology share over the total fleet for reference year 2016. These values will be then used for the estimation

Table 3.26: 2019 LCV market key data

Technology	Size category	Weight $[kg]$	Efficiency $[Bvkm/PJ]$
TRCGAS	M	2800	0.30
TRCDST	M	2800	0.34
TRCLPG	M	2800	0.29
TRCNGA	M	2800	0.28
TRCFLF	M	2800	0.30
TRCELC	M	2800	1.19
TRCDHE	M	2800	0.43

of the reference year 2016 TRC demand in terms of vkm.

Table 3.27: Reference year 2016 LCV fleet

Technology	Fuels	Efficiency $[Bvkm/PJ]$	Share [%]
TRCGAS	TRAGSL	0.21	7.86
TRCDST	TRADST	0.24	89.74
TRCLPG	TRALPG	0.21	0.86
TRCNGA	TRANGA	0.20	0.37
TRCFLF	TRAGSL + TRAETH	0.21	0.96
TRCELC	TRAELC	0.79	0.21
TRCDHE	TRADST	0.33	0.00

3.5.2 New technologies

Efficiency of new LCVs in 2019

Efficiency of new LCVs, as sold in 2019, is evaluated from equations from 3.26 to 3.30, already considering the real driving coefficient $f_{RD} = 1.39$, provided by ICCT analyses, while 3.44 has to be adjusted to take it into account:

$$\eta_{TRCDHE,2019} = \frac{\eta_{new\ TRCDHE,2019}}{f_{RD}} \tag{3.48}$$

Cost characterisation

Investment and fixed O&M costs are calculated as described in section 3.4.2.

Table 3.28: TRC and TRL New vehicles on the market in 2019

Technology	**Size cat.**	**Investment** $[€/vehicle]$	**Fixed O&M** $[€/vkm]$	**Efficiency** $[Bvkm/PJ]$
TRCGAS	S	21’000.00	0.09	0.36
TRCDST	S	21’000.00	0.08	0.43
TRCLPG	S	21’000.00	0.08	0.36
TRCNGA	S	26’000.00	0.09	0.35
TRCFLF	S	21’000.00	0.09	0.36
TRCELC	S	36’000.00	0.05	1.37
TRCDHE	S	25’000.00	0.08	0.43
TRCGAS	M	31’000.00	0.12	0.30
TRCDST	M	31’000.00	0.12	0.34
TRCLPG	M	31’000.00	0.12	0.30
TRCNGA	M	36’000.00	0.12	0.28
TRCFLF	M	31’000.00	0.13	0.30
TRCDHE	M	37’000.00	0.11	0.33
TRCDST	L	39’000.00	0.15	0.30
TRCLPG	L	37’000.00	0.14	0.27
TRCNGA	L	46’000.00	0.15	0.25
TRCELC	L	81’000.00	0.10	1.01
TRCDHE	L	47’000.00	0.13	0.28
TRLGAS	-	35’000.00	0.16	0.27
TRLDST	-	39’000.00	0.15	0.30
TRLLPG	-	35’000.00	0.15	0.27
TRLNGA	-	32’000.00	0.15	0.28
TRLELC	-	50’000.00	0.11	0.98
TRLGHE	-	41’000.00	0.16	0.36

Table 3.28 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Vans and Pick-ups in 2019.

RevTRA New technologies repository (TRC, TRL modes)

For the purpose of the update of the ETM Road transport sector, Medium Vans (size category M) have been selected as representative of the TRC mode. Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRC***,M} = 20'000\ [Bvkm/year]$ for Medium Vans (size category M) and

$d_{TRL***} = 25'000$ $[Bvkm/year]$ for Light trucks. Tables 3.29 and 3.30 report all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model. In addition, further new technologies have been added (TRCFCE, TRLFCE, starting from 2025), to represent upcoming vehicles in the TRC and TRL modes.

Table 3.29: RevTRA TRC New technologies (2020)

Technology	Start	Lifetime $[years]$	Investment $[M\$/cap]$	Fixed O&M $[M\$/cap]$	Efficiency $[Bvkm/PJ]$
TRCGSL	2007	15.0	1000	128	0.30
TRCDST	2007	15.0	1000	121	0.34
TRCLPG	2007	15.0	1000	119	0.30
TRCNGA	2007	15.0	1161	126	0.28
TRCFLF	2007	15.0	1000	131	0.30
TRCELC	2015	12.0	2274	83	1.19
TRCDHE	2015	15.0	1194	111	0.33

Table 3.30: RevTRA TRL New technologies (2020)

Technology	Start	Lifetime $[years]$	Investment $[M\$/cap]$	Fixed O&M $[M\$/cap]$	Efficiency $[Bvkm/PJ]$
TRLGSL	2007	12.5	1000	207	0.27
TRLDST	2007	12.5	1114	199	0.30
TRLLPG	2007	12.5	1000	190	0.27
TRLNGA	2007	12.5	914	190	0.28
TRLLFLF	2007	12.5	1000	207	0.25
TRLELC	2020	10.0	1786	142	0.98
TRLGHE	2015	12.5	1172	208	0.36
TRLGPH	2020	10.0	2000	152	0.45

3.6 Two-Wheelers (TRW)

TRW transport mode includes vehicles commonly known as "Motorcycles" and "Mopeds". A large variety of Motorcycles (Size category MC) and Mopeds (Size category MP) exists, but they are generally characterised by good fuel economy and lower weights with respect to Passenger Cars, that are used for the same purpose, individual Passenger transport, even though Cars allow more than one passenger per travel (from a minimum of 1 up to 7 in some cases), while Two-Wheelers are limited for the transport of 1 or 2 people at most.

3.6.1 Reference year 2016 technologies

On the basis of the most recent data by ACEM [4], the EUR Two-Wheeler fleet counted over 34 million vehicles in 2014 (no more recent data are available), where 24 million are motorcycles and 10 million mopeds. The term "moped" generally describes a vehicle with an engine capacity below 50 *cc*. The *E.U. moped* is a scooter, moped (or similar) with two, three or four wheels, a maximum speed of 45 km/h and an obligatory license plate as proof of insurance.

Due to the small size and low fuel consumption, most of Two-Wheelers run on Gasoline, with a very small share of Diesel Two-Wheelers; thus, given the lack of data regarding that, the 2016 TRW fleet is supposed to be composed by 90% Gasoline (TRWGAS) and 10% Diesel Two-Wheelers (TRWDST).

Even though a large range of engine displacements exist, all Motorcycles and Mopeds can be summarised in two size categories: Motorcycle MC and Moped MP.

Efficiency of the Motorcycle fleet

In OldTRA ETM, the weighted average efficiency, used to represent Two-Wheelers, stood at 0.67 $[Bvkm/PJ]$, as visible from Table 3.7. It is reported to 2016 by using the $I_{\eta,LDV,2000-2016}$ factor:

$$\overline{\eta}_{TRW\ fleet,2016} = \overline{\eta}_{TRW\ fleet,2000} \cdot I_{\eta,LDV,2000-2016} = 0.76\ [Bvkm/PJ] \tag{3.49}$$

Thus, knowing the assumed vehicle fleet composition, TRWGAS and TRWDST efficiencies are calculated by simply scaling up values for TRTGAS and TRTDST (Table 3.20), in order to meet the calculated $\overline{\eta}_{TRW\ fleet,2016}$:

$$f_{s,TRW} = \frac{\eta_{TRTGAS\ fleet,2016} \cdot 0.9 + \eta_{TRTDST\ fleet,2016} \cdot 0.1}{\overline{\eta}_{TRW\ fleet,2016}} = 0.35 \tag{3.50}$$

Then efficiency of the reference year TRW fleet is calculated:

$$\eta_{TRWGAS\ fleet,2016} = f_{s,TRW} \cdot \eta_{TRTGAS\ fleet,2016} \tag{3.51}$$

$$\eta_{TRWDST\ fleet,2016} = f_{s,TRW} \cdot \eta_{TRTDST\ fleet,2016} \tag{3.52}$$

Results are illustrated in Table 3.31, along with the (assumed) technology share over the total fleet for reference year 2016. These values will be then used for the estimation of the reference year 2016 TRW demand.

Table 3.31: Reference year 2016 Motorcycle fleet

Technology	**Fuels**	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$	**Share** [%]
TRWGAS	TRAGSL	0.74	90.00
TRWDST	TRADST	0.89	10.00

3.6.2 New technologies

In addition to the already present Gasoline and Diesel Two-Wheelers, Electric and Gasoline-Hybrid Electric Motorcycles and Mopeds are considered as new technologies to be introduced in the Model.

Efficiency of new Motorcycles in 2019

Efficiency of new Motorcycles and Mopeds, as sold in 2019, is then evaluated from equations 3.26, 3.27, 3.30 and 3.31, already considering the real driving coefficient $f_{RD} = 1.39$, provided by ICCT analyses, and scaled up by using the $f_{s,TRW}$ factor from equation 3.50 (efficiency of Medium Cars is scaled down to represent Motorcycles, while Small Cars are scaled down to represent Mopeds).

$$\eta_{TRW***,MC,2019} = \eta_{TRT***,C,2019} \cdot f_{s,TRW} \tag{3.53}$$

$$\eta_{TRW***,MP,2019} = \eta_{TRT***,B,2019} \cdot f_{s,TRW} \tag{3.54}$$

Cost characterisation

Investment and fixed O&M costs are calculated as described in section 3.4.2. Although, MSRP is calculated, for each new technology, as the half of the corresponding Medium Car purchase price for Motorcycles, and the half of the corresponding Small Car purchase price for Mopeds. Weights used for the calculation of the size category factor are:

- $Weight_{MC} = 150\ kg + 1\ Passenger\ Weight\ (75\ kg)$
- $Weight_{MP} = 50\ kg + 1\ Passenger\ Weight\ (75\ kg)$

Table 3.32: TRW New vehicles on the market in 2019

Technology	Size cat.	Investment [€/*vehicle*]	Fixed O&M [€/*vkm*]	Efficiency [*Bvkm/PJ*]
TRWGAS	MC	12’000	0.01	1.12
TRWDST	MC	13’000	0.02	1.35
TRWELC	MC	20’000	0.01	3.70
TRWGHE	MC	14’000	0.01	1.60
TRWGAS	MP	8’000	0.01	1.26
TRWDST	MP	9’000	0.01	1.46
TRWELC	MP	13’000	0.01	3.93
TRWGHE	MP	14’000	0.01	1.94

Table 3.32 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Cars in 2019.

RevTRA New technologies repository (TRW mode)

For the purpose of the update of the ETM Road transport sector, an average Two-Wheeler is selected as representative of the TRW mode. Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRW***} = 6000\ [Bvkm/year]$. Table 3.33 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model.

3.7 Three-Wheelers (TRE)

TRE transport mode includes vehicles commonly known as "Motorised Tricycles" (e.g. Piaggio Ape) or "Auto-Rickshaws". They are nowadays barely adopted in Europe, indeed the official number of Three-Wheelers is unknown. Their purpose is mainly commercial, for urban/rural scale delivery.

Table 3.33: RevTRA TRW New technologies (2020)

Technology	Start	Lifetime $[years]$	Investment $[M\$/cap]$	Fixed O&M $[M\$/cap]$	Efficiency $[Bvkm/PJ]$
TRWGSL	2007	10.0	1000	3	1.19
TRWDST	2007	10.0	1107	3	1.40
TRWELC	2015	6.5	2527	2	3.81
TRWGHE	2020	10.0	1500	3	1.77

3.7.1 Reference year 2016 technologies

A very small presence of Three-Wheelers can be assumed and quantified in about 2 million vehicles in the EUR region.

Due to the small size and low fuel consumption, most of the Three-Wheelers run on Gasoline, with a very small share of Diesel Three-Wheelers; thus, given the lack of data regarding that, the 2016 TRE fleet is supposed to be composed by 90% Gasoline (TREGAS) and 10% Diesel Three-Wheelers (TREDST), as for Two-Wheelers.

All Three-Wheelers can summarised in a single size category, due to their overall reduced contribution in terms of energy consumption.

Efficiency of the Three-Wheeler fleet

In OldTRA ETM, the weighted average efficiency, used to represent Three-Wheelers, stood at 0.35 $[Bvkm/PJ]$, as visible from Table 3.7. It is reported to 2016 by using the $I_{\eta,LDV,2000-2016}$ factor:

$$\overline{\eta}_{TRE\ fleet,2016} = \overline{\eta}_{TRE\ fleet,2000} \cdot I_{\eta,LDV,2000-2016} = 0.40\ [Bvkm/PJ] \tag{3.55}$$

Thus, knowing the assumed vehicle fleet composition, TREGAS and TREDST efficiencies are calculated by simply scaling up values for TRTGAS and TRTDST (Table 3.20), in order to meet the calculated $\overline{\eta}_{TRE\ fleet,2016}$:

$$f_{s,TRE} = \frac{\eta_{TRTGAS\ fleet,2016} \cdot 0.9 + \eta_{TRTDST\ fleet,2016} \cdot 0.1}{\overline{\eta}_{TRE\ fleet,2016}} = 0.67 \tag{3.56}$$

Then efficiency of the reference year 2016 TRE fleet is calculated:

$$\eta_{TREGAS\ fleet,2016} = f_{s,TRE} \cdot \eta_{TRTGAS\ fleet,2016} \tag{3.57}$$

$$\eta_{TREDST\ fleet,2016} = f_{s,TRE} \cdot \eta_{TRTDST\ fleet,2016} \tag{3.58}$$

Results are illustrated in Table 3.34, along with the (assumed) technology share over the total fleet for reference year 2016. These values will be then used for the estimation of the reference year 2016 TRE demand.

Table 3.34: Reference year 2016 Three-Wheeler fleet

Technology	**Fuels**	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$	**Share** [%]
TREGAS	TRAGSL	0.39	90.00
TREDST	TRADST	0.47	10.00

3.7.2 New technologies

In addition to the already present Gasoline and Diesel Three-Wheelers, an Electric TRE technology is considered to be introduced in the Model.

Efficiency of new Three-Wheelers in 2019

Efficiency of new Three-Wheelers, as sold in 2019, is evaluated from equations 3.26, 3.27 and 3.30, already considering the real driving coefficient $f_{RD} = 1.39$, provided by ICCT analyses, and scaled up by using the $f_{s,TRE}$ factor from equation 3.56:

$$\eta_{TREGAS,2019} = \eta_{new\ TRTGAS,2019} \cdot f_{s,TRE} \tag{3.59}$$

$$\eta_{TREDST,2019} = \eta_{new\ TRTDST,2019} \cdot f_{s,TRE} \eta_{TREELC,2019} = \eta_{new\ TRTELC,2019} \cdot f_{s,TRE} \tag{3.60}$$

Cost characterisation

Investment and O&M costs are calculated as described in section 3.4.2. Although, MSRP is calculated, for each new technology, as one third of the corresponding

Medium Car purchase price. Weight used for the calculation of the size category factor is $Weight_{MT} = 500\ kg$).

Table 3.35: TRE New vehicles on the market in 2019

Technology	Size cat.	Investment [€/*vehicle*]	Fixed O&M [€/*vkm*]	Efficiency [*Bvkm/PJ*]
TREGAS	-	3’000	0.03	1.12
TREDST	-	4’000	0.03	1.35
TREELC	-	6’500	0.02	3.60

Table 3.35 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Three-Wheelers in 2019.

RevTRA New technologies repository (TRE mode)

For the purpose of the update of the ETM Road transport sector, Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRE***} = 2000\ [Bvkm/year]$. Table 3.36 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model.

Table 3.36: RevTRA TRE New technologies (2020)

Technology	Start	Lifetime [*years*]	Investment [*M$/cap*]	Fixed O&M [*M$/cap*]	Efficiency [*Bvkm/PJ*]
TREGSL	2007	10.0	1000	3	1.12
TREDST	2007	10.0	1000	3	1.35
TREELC	2020	8.0	2527	2	3.60

3.8 Medium Trucks (TRM)

Medium trucks are mainly used for small scale distribution, at regional or national level (in case of small nations), and they are also largely used for special purposes, like garbage or fire trucks.

3.8.1 Reference year 2016 technologies

ACEA [1] does not provide a distinction among Medium and Heavy Trucks, thus from the total number of Trucks (6'415'375) 70% are supposed to be Medium Trucks and the remaining 30% Heavy Trucks. According to this subdivision, the EUR Medium Truck fleet counted nearly 4.5 million vehicles in 2016.

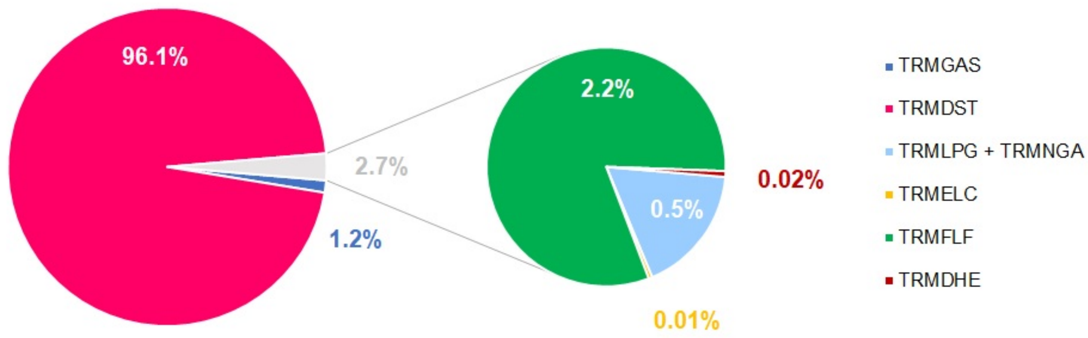


Figure 3.30: 2016 EUR TRM fleet by type of technology (in terms of % over the total number of Medium Trucks)

While the fleet composition for 2000 is not available from [123], a Diesel dominance in 2016 is evident from Figure 3.30. Although, since ACEA data do not provide distinction among Medium and Heavy trucks, the same fleet composition is considered for both Medium and Heavy Trucks, but Electric Trucks are all belonging to the Medium Trucks transport mode, since the first All-Electric Heavy Trucks is still going to enter the market, presumably in 2020 [156].

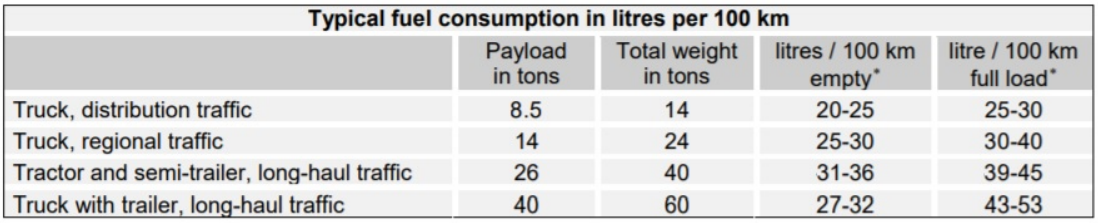
Within TRM sector, vehicles are classified according to technology, but not according to size category. Indeed, they differ according to the maximum allowable Gross Vehicle Weight (from 3.5 t up to 12 t). Thus, a reference Gross Vehicle Weight of 8 t is assumed to describe the whole transport mode, since loads and configurations can be combined in so much different ways that would lead to an unmanageable number of size categories.

Efficiency of the Medium Truck fleet

In OldTRA ETM, the weighted average efficiency, used to represent Medium Trucks, stood at 0.08 $[Bvkm/PJ]$, as visible from Table 3.7.

Since no efficiency improvement trends for TRM fleet are available, and these vehicles belong to the Heavy-Duty Vehicles category, thus they are very different with respect to all vehicles studied until now, the 0.819 [$\%/year$] from 2000 to 2016 increase may be too optimistic, above all due to the deficient regulations about Heavy-Duty Vehicles fuel economy. In OldTRA ETM, efficiency of TRM fleet. A $0.5\%/year$ is now assumed and will be used for all Heavy-Duty transport modes. Therefore, the total improvement factor from 2000 to 2016 would result in:

$$I_{\eta,HDV,2000-2016} = \left(1 + 0.5 \left[\frac{\%}{year}\right] \cdot 16\ [years]\right) = 1.08 \tag{3.61}$$



Typical fuel consumption in litres per 100 km				
	Payload in tons	Total weight in tons	litres / 100 km empty*	litre / 100 km full load*
Truck, distribution traffic	8.5	14	20-25	25-30
Truck, regional traffic	14	24	25-30	30-40
Tractor and semi-trailer, long-haul traffic	26	40	31-36	39-45
Truck with trailer, long-haul traffic	40	60	27-32	43-53

Figure 3.31: Fuel consumption of Volvo Trucks. Source: *Emissions from Volvo's Trucks*

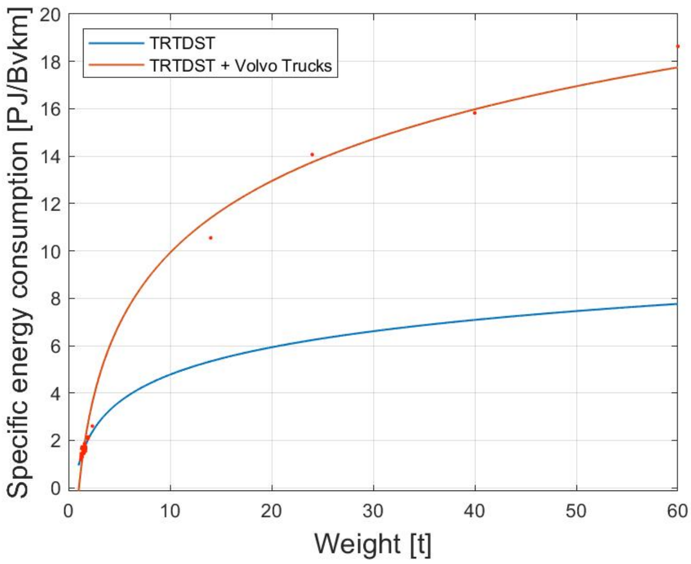


Figure 3.32: Specific energy consumption trend including Volvo Trucks

As already mentioned in section 3.2.1, Heavy-Duty transport modes are very information poor, but a simple scaling-up approach (as performed in OldTRA ETM) is not the best solution for the evaluation of Heavy-Duty Vehicles efficiency. An official document by Volvo Trucks [177] stated guide values for fuel consumption of their Diesel trucks, with different payloads and total weights, then a new consumption trend for Heavy-Duty Diesel vehicles is derived basing on this information. Figure 3.31 shows these values. The maximum consumption is selected for each total weight, converted in energy consumption per energy unit by inverting equation 3.1 and the specific energy consumption trend in Figure 3.32 is obtained. It is very evident that using the same consumption trend used for cars would lead to a gross underestimation for Heavy-Duty Vehicles.

Thus, equation 3.14 is modified to represent Heavy-Duty Vehicles:

$$\eta_{new\ HDVDST,2019} = \left[4.37 \cdot \ln\left(GVW\right) - 30.34\right]^{-1} \tag{3.62}$$

From this new trend, efficiency is retrieved for Diesel Trucks and Buses, then derived for other technologies by taking into account the Diesel-to-Other technology efficiency ratios observed for Cars; e.g. to obtain Gasoline HDVs efficiencies:

$$k_{DST/GAS} = \frac{\eta_{TRTDST}}{\eta_{TRTGAS}} = 1.20 \tag{3.63}$$

$$\eta_{HDVGAS} = \eta_{HDVDST} \cdot k_{DST/GAS} \tag{3.64}$$

and so on for all other involved technologies. Results for this approach are summarised in Table 3.37 for the modelled 8 t GVW Medium Truck.

The average efficiency of the 2016 Medium Truck fleet is:

$$\overline{\eta}_{TRM\ fleet,2016} = \overline{\eta}_{TRM\ fleet,2000} \cdot I_{\eta,HDV,2000-2016} = 0.086\ \left[\frac{Bvkm}{PJ}\right] \tag{3.65}$$

The adjustment factor to take into account old vehicles is obtained comparing the efficiency of the average 2019 TRM (Table 3.37) and the efficiency of 2016 TRM fleet, just obtained from equation 3.65, as:

$$f_{old,TRM} = \frac{\overline{\eta}_{new\ TRM,2019}}{\overline{\eta}_{TRM\ fleet,2000}} = 1.29 \tag{3.66}$$

Table 3.37: 2019 Medium Truck key data

Technology	**Weight** $[kg]$	**Efficiency** $[Bvkm/PJ]$
TRMGAS	8000	0.09
TRMDST	8000	0.11
TRMLPG	8000	0.09
TRMNGA	8000	0.09
TRMFLF	8000	0.09
TRMELC	8000	0.31
TRMDHE	8000	0.16

The factor $f_{old,TRM}$ is then applied to all technologies:

$$\eta_{TRM***\ fleet,2016} = \frac{\eta_{new\ TRM***,2019}}{f_{old,TRM}} \tag{3.67}$$

and results are illustrated in Table 3.38, along with the technology share over the total fleet for reference year 2016. These values will be then used for the estimation of the reference year 2016 TRM demand in terms of vkm.

Table 3.38: Reference year 2016 Medium Truck fleet

Technology	**Fuels**	**Efficiency** $[Bvkm/PJ]$	**Share** [%]
TRMGAS	TRAGSL	0.07	1.24
TRMDST	TRADST	0.09	96.06
TRMLPG	TRALPG	0.07	0.33
TRMNGA	TRANGA	0.07	0.14
TRMFLF	TRAGSL + TRAETH	0.07	2.20
TRMELC	TRAELC	0.24	0.01
TRMDHE	TRADST	0.12	0.02

3.8.2 New technologies

Efficiency of new Medium Trucks in 2019

Efficiency of new Medium Trucks, as sold in 2019, is evaluated as just seen above, applying 3.62 for Diesel Trucks and the efficiency ratios for all the other technologies (as seen for Gasoline HDVs in equations 3.63 and 3.64). No factors for driving conditions are applied due to lacking information, so efficiencies from 3.37 are already sufficient to represent new Medium Trucks.

Cost characterisation

Investment and O&M costs are calculated as described in section 3.4.2. MSRP of Medium Trucks are only easily accessible for Diesel Trucks with different maximum allowable GVWs. Figure 3.33 shows this cost component trend, which will be applied to all Heavy-Duty Vehicles, according to the prescribed Gross Vehicle Weight:

$$MSRP_{HDV} = 44331 \cdot \ln(GVW) - 332858 \qquad (3.68)$$

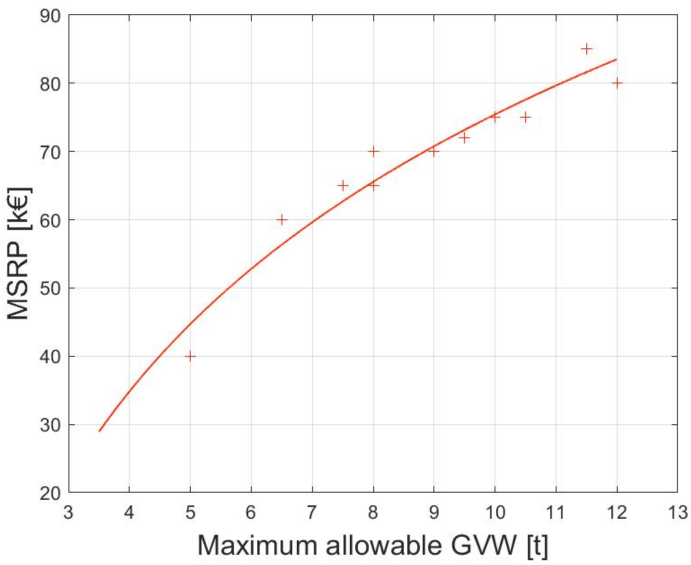


Figure 3.33: Medium Trucks MSRP trend

Other categories cost information are derived by them, considering the cost difference observed for Medium Car technologies.

Table 3.39 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Medium Trucks in 2019.

Table 3.39: TRM New vehicles on the market in 2019

Technology	Investment $[€/vehicle]$	Fixed O&M $[€/vkm]$	Efficiency $[Bvkm/PJ]$
TRMGAS	75'000	0.85	0.09
TRMDST	80'000	0.76	0.11
TRMLPG	75'000	0.66	0.09
TRMNGA	79'000	0.65	0.09
TRMFLF	75'000	1.01	0.09
TRMELC	123'000	0.41	0.31
TRMDHE	89'000	0.65	0.11

RevTRA New technologies repository (TRM mode)

For the purpose of the update of the ETM Road transport sector, Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRM***} = 30000$ $[Bvkm/year]$. Table 3.40 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model. In addition, a further new technology has been added (TRMFCE, starting from 2025).

Table 3.40: RevTRA TRM New technologies (2020)

Technology	Start	Lifetime $[years]$	Investment $[M\$/cap]$	Fixed O&M $[M\$/cap]$	Efficiency $[Bvkm/PJ]$
TRMGSL	2007	15.0	1000	684	0.09
TRMDST	2007	15.0	1067	651	0.11
TRMLPG	2007	15.0	1000	639	0.09
TRMNGA	2007	15.0	1053	674	0.09
TRMFLF	2007	15.0	1000	702	0.10
TRMELC	2020	12.0	2050	426	0.31
TRMDHE	2015	15.0	1186	597	0.11

3.9 Heavy Trucks (TRH)

Heavy trucks are mainly used for large scale distribution, at national or international level.

3.9.1 Reference year 2016 technologies

ACEA does not provide a distinction among Medium and Heavy Trucks, thus from the total number of Trucks (6'415'375) 30% are supposed to be Heavy Trucks. According to this subdivision, the EUR Medium Truck fleet counted nearly 2 million vehicles in 2016.

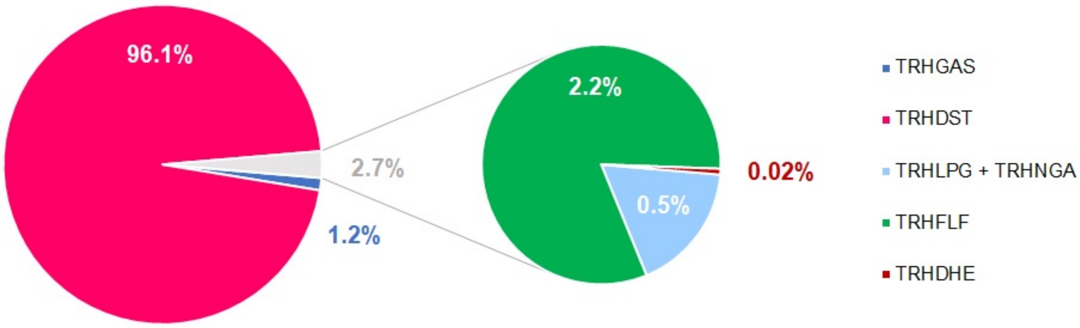


Figure 3.34: 2016 EUR TRH fleet by type of technology (in terms of % over the total number of Heavy Trucks)

While the fleet composition for 2000 is not available from [123], a Diesel dominance in 2016 is evident from Figure 3.34. Although, ACEA data do not provide distinction among Medium and Heavy trucks, therefore the same fleet composition is considered for both Medium and Heavy Trucks, but Electric Trucks are all belonging to the Medium Trucks transport mode, since the first All-Electric Heavy Trucks should enter the market in 2020, thus the share that was previously assigned to Electric Trucks is now added to Diesel Heavy Trucks.

Within TRH sector, vehicles are classified according to technology, but not according to size category. Indeed, they differ according to the maximum allowable Gross Vehicle Weight (from 12 *t* up to 60 *t*). Thus, a reference Gross Vehicle Weight of 30 *t* is assumed to describe the whole transport mode, since loads and configurations can be combined in so much different ways, that would lead to an unmanageable number of size categories. Furthermore, maximum allowable Gross Vehicle Weights differ from country to country (e.g. 56 *t* in Italy, 40 *t* in France, even though 44 *t* is the most common limit).

Efficiency of the Heavy Truck fleet

In OldTRA ETM, the weighted average efficiency, used to represent Medium Trucks, stood at 0.06 $[Bvkm/PJ]$, as visible from Table 3.7.

Thus, the approach already described in section 3.8.1 will be used again to evaluate efficiency of the TRH fleet. Results are shown in Table 3.41 for the modelled 30 t GVW Heavy Truck.

The average efficiency of the 2016 Heavy Truck fleet is:

$$\overline{\eta}_{TRH\ \ fleet,2016} = \overline{\eta}_{TRH\ \ fleet,2000} \cdot I_{\eta,HDV,2000-2016} = 0.065 \left[\frac{Bvkm}{PJ}\right] \tag{3.69}$$

The adjustment factor to take into account old vehicles is obtained comparing the efficiency of the average 2019 TRH (Table 3.41) and the efficiency of 2016 TRH fleet, just obtained from equation 3.69, as:

$$f_{old,TRH} = \frac{\overline{\eta}_{new\ \ TRH,2019}}{\overline{\eta}_{TRH\ \ fleet,2000}} = 1.02 \tag{3.70}$$

Table 3.41: 2019 Heavy Truck key data

Technology	**Weight** $[\boldsymbol{kg}]$	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$
TRHGAS	30’000	0.06
TRHDST	30’000	0.07
TRHLPG	30’000	0.05
TRHNGA	30’000	0.06
TRHFLF	30’000	0.06
TRHDHE	30’000	0.09

The factor $f_{old,TRH}$ is then applied to all technologies:

$$\eta_{TRM***\ \ fleet,2016} = \frac{\eta_{new\ \ TRM***,2019}}{f_{old,TRH}} \tag{3.71}$$

and results are illustrated in Table 3.42, along with the technology share over the total fleet for reference year 2016. These values will be then used for the estimation of the reference year 2016 TRH demand.

Table 3.42: Reference year 2016 Heavy Truck fleet

Technology	Fuels	Efficiency [$Bvkm/PJ$]	Share [%]
TRHGAS016	TRAGSL	0.06	1.24
TRHDST016	TRADST	0.07	96.07
TRHLPG016	TRALPG	0.05	0.33
TRHNGA016	TRANGA	0.06	0.14
TRHFLF016	TRAGSL + TRAETH	0.06	2.20
TRHDHE016	TRADST	0.09	0.02

3.9.2 New technologies

Efficiency of new Heavy Trucks in 2019

Efficiency of new Heavy Trucks, as sold in 2019, is evaluated as seen in section 3.8.2, so efficiencies from 3.41 are already sufficient to represent new Heavy Trucks.

Cost characterisation

Investment and O&M costs are calculated as described in section 3.4.2. MSRP of Heavy Trucks is modelled according to equation 3.68 for Diesel Heavy Trucks, applying a 30 t GWV. Other categories cost information are derived by them, considering the cost difference observed for Medium Car technologies.

Table 3.43: TRH New vehicles on the market in 2019

Technology	Investment [€/$vehicle$]	Fixed O&M [€/vkm]	Efficiency [$Bvkm/PJ$]
TRHGAS	142’000	2.60	0.04
TRHDST	151’000	2.35	0.05
TRHLPG	141’000	2.12	0.04
TRHNGA	150’000	2.13	0.04
TRHFLF	142’000	2.97	0.04
TRHDHE	169’000	2.05	0.05

Table 3.43 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Heavy Trucks in 2019.

RevTRA New technologies repository (TRH mode)

For the purpose of the update of the ETM Road transport sector, Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRH***} = 50000$ $[Bvkm/year]$. Table 3.44 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model. In addition, a further new technology has been added (TRHFCE, starting from 2025).

Table 3.44: RevTRA TRH New technologies (2020)

Technology	Start	Lifetime $[\boldsymbol{years}]$	Investment $[\boldsymbol{M\$/cap}]$	Fixed O&M $[\boldsymbol{M\$/cap}]$	Efficiency $[\boldsymbol{Bvkm/PJ}]$
TRHGSL	2007	15.0	1000	4272	0.04
TRHDST	2007	15.0	1063	4066	0.05
TRHLPG	2015	15.0	993	3991	0.04
TRHNGA	2007	15.0	1056	4211	0.04
TRHFLF	2007	15.0	1000	4390	0.04
TRHELC	2020	12.0	1492	2649	0.08
TRHDHE	2015	15.0	1190	3733	0.05

3.10 Buses (TRB)

Buses and Coaches are used for passenger transport at different scale. A Coach is a Bus used for longer-distance service, in contrast to Transit Buses that are typically used within a single metropolitan region. Often used for touring, intercity and international bus service, Coaches are also used for private charter for various purposes. Although, Buses and Coaches have not structural differences, therefore are modelled in the same transport mode.

3.10.1 Reference year 2016 technologies

On the basis of the most recent data by ACEA [1], the EUR Bus fleet counted over 770 thousand vehicles in 2016.

While the fleet composition for 2000 is not available from [123], a Diesel dominance in 2016 is evident from Figure 3.35, as for all other Heavy-Duty Vehicles.

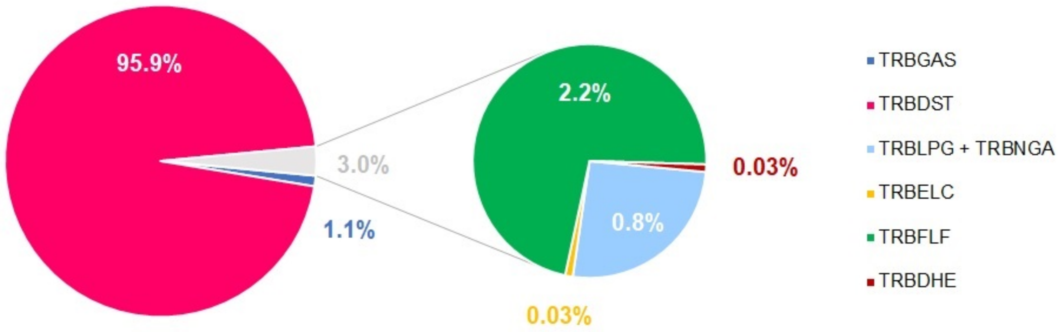


Figure 3.35: 2016 EUR TRB fleet by type of technology (in terms of % over the total number of Heavy Trucks)

Within TRB sector, vehicles are classified according to technology, but not according to size category. Indeed, they differ according to the maximum allowable Gross Vehicle Weight, depending on state regulations; in general, in Europe, Buses with total weights not exceeding 21.5 t are allowed. Thus, a reference Gross Vehicle Weight is assumed to describe the whole transport mode:

$$GVW = Curb\ Weight + 20 \cdot \ Passenger\ weight \tag{3.72}$$

where $Curb\ Weight$ is assumed as 15 t and $PassengerWeight$ as 75 kg; thus, GVW of the modelled Bus is 16.5 t. Then, Buses are simply treated as Heavy-Duty Vehicles, just like Trucks.

Efficiency of the Heavy Truck fleet

In OldTRA ETM, the weighted average efficiency, used to represent Medium Trucks, stood at 0.11 $[Bvkm/PJ]$, as visible from Table 3.7. Although, this value seem to be excessively high, if compared with $\overline{\eta}_{TRM\ fleet,2000} = 0.08\ [Bvkm/PJ]$. Thus, no comparison will be performed with the 2000 efficiency value through the $I_{\eta,HDV,2000-2016}$, but equation 3.62 is used, and scaled to represent all technologies, then the obtained values are adjusted through a $f_{old,TRB}$ factor assumed as 1.1 (intermediate value between $f_{old,TRM}$ and $f_{old,TRH}$. Results are illustrated in Table 3.45, along with the technology share over the total fleet for reference year 2016. These values will be then used for the estimation of the reference year 2016 TRB demand in terms of vkm.

Table 3.45: Reference year 2016 Bus fleet

Technology	Fuels	Efficiency $[Bvkm/PJ]$	Share [%]
TRBGAS	TRAGSL	0.06	1.11
TRBDST	TRADST	0.09	95.90
TRBLPG	TRALPG	0.05	0.54
TRBNGA	TRANGA	0.06	0.23
TRBFLF	TRAGSL + TRAETH	0.06	2.16
TRBELC	TRAELC	0.21	0.03
TRBDHE	TRADST	0.10	0.03

3.10.2 New technologies

In addition to the already present Bus technologies, Fuel Cell Buses are considered as new technologies to be introduced in the Model. [62]

Efficiency of new Buses in 2019

Efficiency of new Buses, as sold in 2019, is evaluated as seen in section 3.8.2.

Cost characterisation

Investment and O&M costs are calculated as described in section 3.4.2. MSRP of Buses is modelled according to equation 3.68 for Diesel Buses, applying a 16.5 t GWV. Other categories cost information are derived by them, considering the cost difference observed for Medium Car technologies.

Table 3.46 summarises results, in terms of Investment cost, Fixed O&M cost and efficiency for all available new Buses in 2019.

RevTRA New technologies repository (TRH mode)

For the purpose of the update of the ETM Road transport sector, Investment and fixed O&M costs have been adapted, as seen in section 3.4.2. The only difference stays in the assigned annual driven distance, that is $d_{TRB***} = 50000$ $[Bvkm/year]$. Table 3.47 reports all the information about new technologies, properly adapted to be feasible to be correctly read and processed by the Model.

Table 3.46: TRB New technologies on the market in 2019

Technology	**Investment** [€/*vehicle*]	**Fixed O&M** [€/*vkm*]	**Efficiency** [*Bvkm/PJ*]
TRBGAS019	111'000	1.69	0.05
TRBDST019	113'000	1.50	0.06
TRBLPG019	111'000	1.32	0.05
TRBNGA019	118'000	1.31	0.05
TRBFLF019	111'000	1.98	0.05
TRBELC019	183'000	0.82	0.16
TRBDHE019	133'000	1.29	0.06
TRBFCE019	379'000	1.58	0.10

Table 3.47: RevTRA TRB New technologies (2020)

Technology	**Start**	**Lifetime** [*years*]	**Investment** [*M$/cap*]	**Fixed O&M** [*M$/cap*]	**Efficiency** [*Bvkm/PJ*]
TRBGSL	2007	15.0	1000	2350	0.05
TRBDST	2007	15.0	1018	2237	0.06
TRBLPG	2007	15.0	1000	2195	0.05
TRBNGA	2007	15.0	1063	2316	0.05
TRTLFLF	2007	15.0	1000	2415	0.05
TRBELC	2015	12.0	2061	1465	0.16
TRBDHE	2015	15.0	1198	2053	0.06
TRBFCE	2020	12.0	4268	1568	0.10

Chapter 4

Calibration and validation of the Model

4.1 Road transport sector base year demand

In ETM, annual Road transport demand is expressed in $[Bvkm]$, therefore it corresponds with the yearly total travel distance, allocated to each transport mode.

In both OldTRA ETM and RevTRA ETM, base year demand is evaluated by the following formula:

$$Base\ year\ demand\ [Bvkm/year] = \sum_m \sum_p \eta_{m,p,\ base\ year} \cdot E_{m,p,\ base\ year} \tag{4.1}$$

where m refers to transport mode, p refers to process (technology), while $\eta_{m,p,\ base\ year}$ and $E_{m,p,\ base\ year}$ are the base year efficiency and energy consumption, respectively, for each mode and technology. In ETM, yearly energy consumption is retrieved from IEA/Eurostat energy balances, but the voice "Road transport" is not further detailed, thus do not provide a subdivision into different transport modes, but the total value only is shown. In order to overcome this, ETM adopts a complex system of regionally-variable calibration parameters, to assign different values of energy consumption to each technology, for each different model region. In the new method for the calculation of base year demand that will be proposed in the continuation of this work, this is the point that will be modified.

4.2 A new method for base year demand calculation

This section regards a new proposed method for the evaluation of base year demand for EUR region. It is based on the line of reasoning which is applied for the calculation of base year transport demand in OldTRA ETM, thus the same procedure is followed, but trying to eliminate most of the sources of uncertainties and the assumptions that were involved in that. Indeed, calibration parameters were used in OldTRA ETM to assign possibly coherent final energy consumption values to each transport mode, in order to meet the IEA/Eurostat energy balances total consumption figures, but not to represent the real composition of the vehicle fleet. The new method is here applied with reference to year 2016, since 2016 fleet efficiency has been calculated (see sections 3.4.1, 3.5.1, 3.6.1, 3.7.1, 3.8.1, 3.9.1 and 3.10.1). Keeping faith to formula 4.1, the change is in the estimation of the term $E_{m,p,\ base\ year}$, that will be now calculated on the basis of official (or assumed, where lacking) vehicle statistics, instead of regional calibration parameters. By the way, since 2016 efficiencies have been retrieved from 2000 values, that were subjected to calibration, a complete review of base year efficiencies should be considered, in order to increase reliability of the Model.

4.2.1 Energy balance and vehicle statistics

Table 4.1 shows the 2016 EUR region Road transport energy-end use breakdown by type of fuel. Actual energy use is obtained by summing up EU28, Norway and Iceland values and subtracting Croatia ones, while Switzerland and Liechtenstein are not included, as already mentioned in section 5.1. These figures are then put together, as already explained in section 3.1.1, to obtain the data reported in Table 4.2. In 2016, Oil and petroleum products covered 90% of transport total final energy consumption, with an impressive Gas Oil dominance (67.3% of the total). Indeed, the motivation relies in the fact that Gas Oil is largely used as fuel for Heavy-Duty Vehicles, which are the most energy consuming ones. On the other hand, Motor Gasoline (25.7% of the total) is more common for lighter vehicles, which represent the majority of the fleet in terms of number of vehicles, though the consumption figure accounts for not even half of Diesel. Energy consumption from Alternative fuels is still not even quantitatively comparable with respect to traditional ones.

Table 4.1: Energy balance for the EUR Road transport sector. Source: `https://ec.europa.eu`

EUR, 2016	**Final energy consumption** [***ktoe***]	[***PJ***]
Total	302'668.4	12'672.1
Oil and petroleum products	287'031.8	12'017.4
LPG	5'741.2	240.4
Motor Gasoline	77'648.3	3'251.0
Gas Oil and Diesel Oil	203'630.2	8'525.6
Industrial spirits	12.1	0.5
Natural gas	1'757.6	73.6
Renewables and biofuels	13'749.0	575.6
Biogases	142.7	6.0
Pure biogasoline	10.6	0.4
Blended biogasoline	2'667.1	111.7
Pure biodiesels	368.0	15.4
Blended biodiesels	10'556.2	442.0
Other liquid biofuels	4.5	0.2
Electricity	130.1	5.4

Table 4.2: Energy balance for the EUR Road transport sector after fuel aggregation

EUR, 2016	**Final energy consumption** ***PJ***
Total	12'672.1
TRAGSL	3'251.0
TRADST	8'526.1
TRALPG	240.4
TRANGA	79.6
TRAETH	569.7
TRAELC	5.4
TRAHH2	N.A.

Keeping faith to the original ETM methodology, even if applying some reasonable differences, the final energy breakout by transport mode is obtained. For this purpose, the original ETM adopts an approach driven by specific weight of each vehicle kind over the total fleet. Although, they were further divided into Light-duty and a more general definition of Other Road vehicles. Light-duty vehicles included Passenger Cars, Light Trucks, Two- and Three-Wheelers, while Other Road vehicles grouped Buses, Medium, Heavy and Commercial Trucks, mainly to have them divided according to their similar energy consumption characteristics. However, it was decided to modify that classification in order to better take into account substantial differences between Light-Duty and Heavy-duty vehicles. Light-duty vehicles are now all the vehicles with a Gross Vehicle Weight (GVW) below 3.5 t, while Heavy-Duty Vehicles have a Gross Vehicle Weight exceeding 3.5 t. Therefore, Commercial Trucks (TRC) were moved from the Other Road Vehicles class to the Light-Duty Vehicles one, since they are intended as belonging to this category by regulatory definition.

Then, basing on databases provided by ACEA *Association des Constructeurs Européens d'Automobiles* [1], the European Automobile Manufacturers' Association, and ACEM (*Association des Constructeurs Européens de Motocycles*) [4], the European Motorcycle Manufacturers' Association, actual quantitative information and fuel usage framework for each type of modelled vehicle have been retrieved. In the original ETM, instead, these figures were all based on assumptions and regionally-variable calibration parameters. Nevertheless, ACEA vehicle classification by type of technology slightly differs from the one adopted in this work. According to it, existing vehicles technologies are grouped in:

- Petrol;
- Diesel;
- LPG and Natural Gas;
- Hybrids (including Mild-Hybrids and Full-Hybrids);
- Electric (including Full-Electric, Plug-in Hybrid Electric and Fuel Cell vehicles);
- Others, such as Flex-Fuel vehicles.

In order to get rid of this, ACEA statistics have been coupled with the minimum possible number of assumptions, which will be now listed and explained:

- 40% of ACEA's Electric Cars are considered as Plug-in Hybrid Electric Vehicles, 0.25% of them are Fuel Cell vehicles (about 700 Cars all over Europe) and the remaining part are Full-Electric vehicles;
- ACEA's LPG and Natural Gas vehicles, due to the similar properties of the two fuels, can be separated from each other according to the energy consumption values of Table 4.2; thus, 70% vehicles of this type are classified as LPG vehicles, while the remaining 30% are Natural Gas vehicles;
- ACEA does not provide a distinction between Medium and Heavy trucks, for the main reason that this separation does not follow uniform rules among all European countries. However, due to the fact that some restrictions exist on the maximum allowable vehicle weight in some European countries' roads and that Heavy Trucks are only used for long-range hauling, a predominance of Medium Trucks can be supposed, considering that they represent the 70% of all Trucks (and obviously Heavy Trucks are the remaining 30%).

Moreover, ACEM information does not provide facts about the type of fuelling for Two- and Three-Wheelers, so that a reasonable 90% Gasoline - 10% Diesel fuelling is considered for both transport modes.

Given all these assumptions, Table 4.3 reports the fuel and transport mode breakdown as it will be used for the next calculation steps. Information about the total number of vehicles is very straightforward. Indeed, it is not a surprise that Light-Duty vehicles cover the most of the total fleet, thus they play an important role from the consumption side: in particular, Passenger Cars (TRT) represent alone almost 80% of the vehicle stock in the EUR region. On the other hand, each category/mode-fuel couple is represented by a percentage indicating the share of vehicles of that category/mode and running on that fuel. For instance, 54.5% of Light-Duty Vehicles are Gasoline-fuelled, while, inside this category, 80.6% of Light-Duty Gasoline-fuelled vehicles are Passenger Cars, and so on.

After that, energy breakdown by transport mode is obtained, by coupling energy balances (Table 4.2), vehicle statistics (Table 4.3) and reference year vehicle energy consumption (in tables 3.20, 3.27, 3.31, 3.34, 3.38, 3.42 and 3.45 2016 fleet efficiency values can be read, and energy consumption is simply derived by inverting those values), and normalising according to the category in which the selected mode falls into:

$$E_{m,i} = \frac{n_m/n_c}{n_c/N} \cdot E_i \cdot \frac{\eta_i}{\overline{\eta}_c} \tag{4.2}$$

where:

- $E_{m,i}$ is the transport mode m final energy consumption relative to fuel i;
- n_m/n_c is the fraction of the number of vehicles of transport mode m over the total number of vehicles in Category c (Light-Duty or Heavy/Duty);
- n_c/N is the fraction of the number of vehicles belonging to Category c over the total vehicles in the fleet N;
- E_i is the final energy consumption by type of fuel i (as in Table 4.2);
- $\eta_i/\overline{\eta_c}$ is the consumption specific weight of fuel i inside the vehicle category c. In the original ETM all vehicles of the same category were assumed to have the same efficiency, for the purpose of the calculation of base year demand). Therefore, this lead to an overestimation of the actual fuel consumption for some transport modes (e.g. Two- and Three-Wheelers inside the Light-Duty Vehicle Category) and underestimation for other ones (e.g. Light trucks inside the Light-Duty Vehicle Category), since a sing average efficiency was considered for each category.

The way the term $\frac{n_m/n_c}{n_c/N}$ (from equation 4.2) is estimated is one of the basic differences with respect to OldTRA ETM. Indeed, it was simply assigned, for each region and each transport mode, on the basis of assumed calibration parameters. Then, vehicles belonging to the same category (Light Vehicles and Other Road vehicles in OldTRA ETM), were treated as if they were characterised by the same consumption behaviour: practically, the term $\frac{\eta_i}{\overline{\eta_c}}$ from equation 4.2 was assumed as equal to 1.

Table 4.4 shows the results of the new methodology, that will be soon applied to calculate transportation demand, for each type of Road transport mode. From that table and from Figure 4.1, the huge impact of Trucks on energy demand is noticeable. Indeed, less than 7 million Trucks on EUR roads overcome the energy demand by over 265 million Cars, according to this calculation. The situation is far more dramatic if considering that almost the totality of this request relies on Gas Oil, therefore the environmental issues about Diesel vehicles require strong policies for Trucks, too, while Diesel Cars represent a priority problem, but not the only one and not even the worst one.

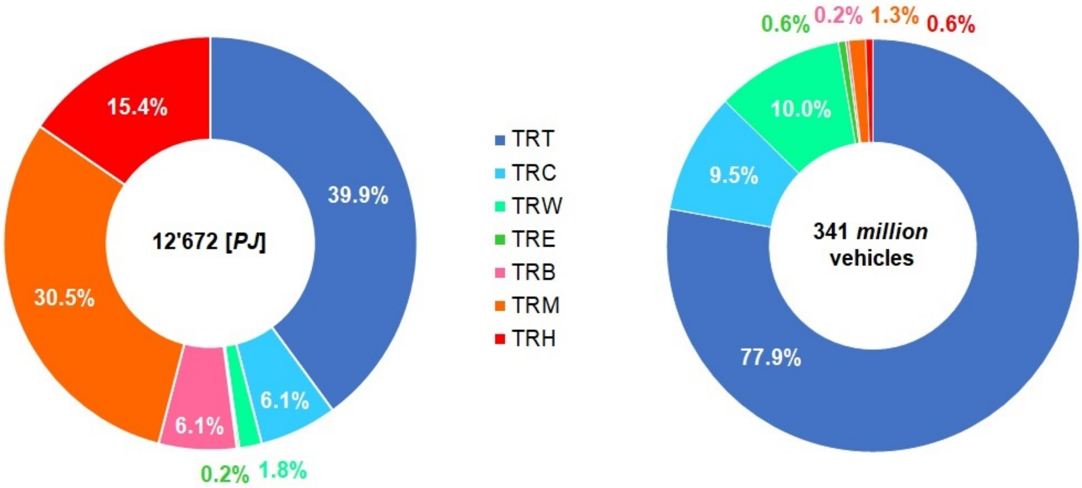


Figure 4.1: Energy breakdown vs. Fleet composition by transport mode

4.2.2 The new method for calculation of the demand applied to Reference year 2016

What is still needed for the evaluation of the Road transport sector demand, for each transport mode, is to couple the reference year 2016 fleet efficiency with final energy consumption.

Travel demand will be specifically calculated for each transport mode and technology, present in the fleet during the reference year. For base year 2000 all technologies only required a single fuel, and no fuel overlaps were present inside the technology repository. Because of that, energy demand for each mode m and technology p was calculated using (i stands for fuel):

$$E_{m,p} = E_{m,i} \tag{4.3}$$

In 2016, instead, fuel combinations are present (e.g. TR*FLF use both Gasoline and Ethanol, TR*GPH use both Gasoline and Electricity). In order to overcome this issue, 4.3 is better replaced by a more general formulation:

$$E_{m,p} = \sum_{i=1}^{N_{fuels}} x_i \cdot E_{m,i} \tag{4.4}$$

where x_i is the fuel share, considered for "hybrid" technologies.

Furthermore, a fuel can be used in more than one technology (e.g. TR*GAS and TR*GHE both use Gasoline, TR*DST and TR*DHE both use Gas Oil), and in this case the technology share in each transport mode is used to split energy consumption of the involved Fuels (Gasoline and Diesel). In general:

$$E_{TR*GAS} = E_{TRAGAS} \cdot (1 - \%_{TR*FLF} - \%_{TR*GHE} - \%_{TR*GPH}) \tag{4.5}$$

$$E_{TR*DST} = E_{TRADST} \cdot (1 - \%_{TR*DHE}) \tag{4.6}$$

Finally, travel demand can be calculated for each transport mode and technology:

$$D_{m,p} = E_{m,p} \cdot \eta_{mp,2016\ fleet} \cdot CF_{m,p} \tag{4.7}$$

where CF_{mt} is the capacity factor and it is assumed as 1 for all modes and technologies (for Full-Electric Vehicles, this is true if charge cycles are optimised by users).

Results are shown in tables 4.5, 4.6, 4.7, 4.8, 4.9, 4.10 and 4.10.

Table 4.3: Vehicle statistics by transport mode and type of fuel

Vehicle	Number	Vehicle share						
		TRAGSL	**TRADST**	**TRALPG**	**TRANGA**	**TRAETH**	**TRAELC**	**TRAHH2**
	[*Million*]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
LDV	334.1	54.5	43.1	1.6	0.7	0.5	0.1	0.0
TRT	265.7	80.6	77.4	94.8	94.8	82.7	80.4	100.0
TRT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRC	32.3	1.6	20.1	5.2	5.2	17.3	19.6	0.0
TRW	34.1 [1]	16.8	2.4	0.0	0.0	0.0	0.0	0.0
TRE	2.0 [2]	1.0	0.1	0.0	0.0	0.0	0.0	0.0
HDV	7.2	3.4	96.1	0.4	0.2	2.2	0.0	0.0
TRM	0.8	62.8	62.5	58.4	58.4	62.6	71.3	0.0
TRH	4.5	26.9	26.8	25.0	25.0	26.8	0.0	0.0
TRB	1.9	10.2	10.7	16.5	16.5	10.6	28.7	0.0

[1] 2014 data.

[2] Assumption.

Table 4.4: Final energy consumption breakdown by transport mode

Mode	**Final energy consumption**							
	TRAGSL [PJ]	**TRADST** [PJ]	**TRALPG** [PJ]	**TRANGA** [PJ]	**TRAETH** [PJ]	**TRAELC** [PJ]	**TRAHH2** [PJ]	**Total** [PJ]
TRT	2765.8	1955.2	185.0	60.8	88.6	3.8	0.0	5059.2
TRC	67.2	662.7	11.9	4.4	23.1	1.1	0.0	770.3
TRW	203.2	20.9	0.0	0.0	0.0	0.0	0.0	224.1
TRE	22.8	2.3	0.0	0.0	0.0	0.0	0.0	25.2
TRM	20.7	664.1	7.5	2.5	74.8	0.2	0.0	769.8
TRH	109.7	3344.3	23.0	7.6	383.2	0.4	0.0	3868.3
TRB	61.5	1876.5	12.9	4.3	0.0	0.0	0.0	1955.2

Table 4.5: Reference year 2016 Passenger Car travel demand

Technology	**Fuel 1**	**Fuel 2**	**Fuel share** [%]	[%]	**Energy consumption** $[\boldsymbol{PJ}]$	**Efficiency** $[\boldsymbol{Bvkm/PJ}]$	**Demand** $[\boldsymbol{Bvkm}]$
TRTGAS	TRAGSL	-	1.00	-	2726.2	0.26	708.4
TRTDST	TRADST	-	1.00	-	1955.2	0.31	610.0
TRTLPG	TRALPG	-	1.00	-	185.0	0.25	45.4
TRTNGA	TRANGA	-	1.00	-	60.8	0.26	15.8
TRTFLF	TRAGSL	TRAETH	0.85	0.15	104.2	0.26	27.1
TRTELC	TRAELC	-	1.00	-	2.3	0.86	1.9
TRTGHE	TRAGSL	-	1.00	-	22.2	0.37	8.2
TRTGPH	TRAGSL	TRAELC	0.55	0.45	3.4	1.15	3.9
TRTFCE	TRAHH2	-	1.00	-	0.0	0.49	0.0
Total					5059.2		1420.5

Table 4.6: Reference year 2016 LCV travel demand

Technology	Fuel 1	Fuel 2	Fuel share [%]	Fuel share [%]	Energy consumption [PJ]	Efficiency [$Bvkm/PJ$]	Demand [$Bvkm$]
TRCGAS	TRAGSL	-	1	-	51.6	0.21	10.8
TRCDST	TRADST	-	1	-	662.7	0.24	158.7
TRCLPG	TRALPG	-	1	-	11.9	0.21	2.5
TRCNGA	TRANGA	-	1	-	4.4	0.20	0.9
TRCFLF	TRAGSL	TRAETH	0.85	0.15	38.7	0.21	8.1
TRCELC	TRAELC	-	1	-	1.1	0.79	0.9
TRCDHE	TRADST	-	1	-	0.0	0.33	0.0
Total					770.3		181.8

Table 4.7: Reference year 2016 Motorcycle travel demand

Technology	Fuel 1	Fuel 2	Fuel share [%]	[%]	Energy consumption [PJ]	Efficiency [$Bvkm/PJ$]	Demand [$Bvkm$]
TRWGAS	TRAGSL	-	1	-	203.2	0.74	151.0
TRWDST	TRADST	-	1	-	20.9	0.89	18.7
Total					224.1		169.6

Table 4.8: Reference year 2016 Three-Wheeler travel demand

Technology	Fuel 1	Fuel 2	Fuel share [%]	[%]	Energy consumption $[PJ]$	Efficiency $[Bvkm/PJ]$	Demand $[Bvkm]$
TREGAS	TRAGSL	-	1	-	22.8	0.39	8.9
TREDST	TRADST	-	1	-	2.3	0.47	1.1
Total					25.2		10.0

Table 4.9: Reference year 2016 Medium Truck travel demand

Technology	Fuel 1	Fuel 2	Fuel share [%]	Fuel share [%]	Energy consumption [PJ]	Efficiency [$Bvkm/PJ$]	Demand [$Bvkm$]
TRMGAS	TRAGSL	-	1	-	42.1	0.07	0.5
TRMDST	TRADST	-	1	-	3344.3	0.09	49.9
TRMLPG	TRALPG	-	1	-	23.0	0.07	0.4
TRMNGA	TRANGA	-	1	-	7.6	0.07	0.2
TRMFLF	TRAGSL	TRAETH	0.85	0.15	450.8	0.07	5.5
TRMELC	TRAELC	-	1	-	0.4	0.24	0.0
TRMDHE	TRADST	-	1	-	0.0	0.12	0.0
Total					3868.3		56.5

Table 4.10: Reference year 2016 Heavy Truck travel demand

Technology	**Fuel 1**	**Fuel 2**	**Fuel share** [%]	[%]	**Energy consumption** [PJ]	**Efficiency** [$Bvkm/PJ$]	**Demand** [$Bvkm$]
TRHGAS	TRAGSL	-	1	-	61.5	0.06	3.4
TRHDST	TRADST	-	1	-	1876.4	0.07	124.7
TRHLPG	TRALPG	-	1	-	12.9	0.05	0.7
TRHNGA	TRANGA	-	1	-	4.3	0.06	0.2
TRHFLF	TRAGSL	TRAETH	0.85	0.15	0.0	0.06	0.0
TRHDHE	TRADST	-	1	-	0.0	0.09	0.0
Total					1955.2		129.0

Table 4.11: Reference year 2016 Bus travel demand

Technology	Fuel 1	Fuel 2	Fuel share [%]	[%]	Energy consumption [PJ]	Efficiency [$Bvkm/PJ$]	Demand [$Bvkm$]
TRBGAS	TRAGSL	-	1	-	7.5	0.06	0.5
TRBDST	TRADST	-	1	-	664.1	0.08	49.9
TRBLPG	TRALPG	-	1	-	7.5	0.06	0.4
TRBNGA	TRANGA	-	1	-	2.5	0.06	0.2
TRBFLF	TRAGSL	TRAETH	0.85	0.15	88.0	0.06	5.5
TRBELC	TRAELC	-	1	-	0.2	0.21	0.0
TRBDHE	TRADST	-	1	-	0.0	0.10	0.0
TRBFCE	TRAHH2	-	1	-	0.0	0.12	0.0
Total					769.8		56.5

Chapter 5

Demand projection and scenario analysis

5.1 Road transport end-use energy demand: historical trends

The examination of what happened in the past is the first step for the definition of trends in any energy system. A strong issue regarding the Road transport sector is due to its quiescence, mostly related with the fact that it has known a very long period of reliance on fossil fuels, since the advent of cheap combustion engines in the 19th century. Energy consumption for both individual and freight transport has grown steadily, and the only major change in the structure of this sector has been noticeable during the Gasoline-to-Diesel partial turnover, mainly regarding Cars, at the beginning of the XXI century.

Therefore, the analysis of the evolution of final energy consumption breakdown generally ends in itself, due to the Gasoline and Diesel dominance, but it is useful for outlining demand needs, provided that it is coupled with the proper market facts, and economic and demographic indicators. Energy statistics and balances, provided by Eurostat for the EUR region, are useful to identify the relationship between primary fuels and energy end-use. Unfortunately, Eurostat Energy balances do not include Switzerland and Liechtenstein, therefore, despite not being so relevant in the overall final energy, their absence from statistical data implies a first underestimation of the actual final energy consumption for Road transport in the EUR region.

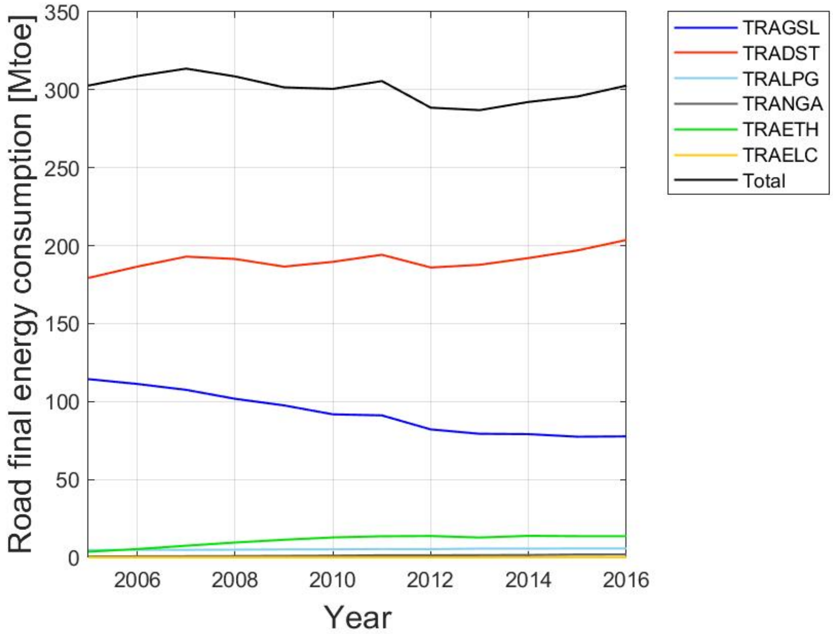


Figure 5.1: Road transport sector final energy consumption trend (2005 to 2016)

Starting from 2005, base year ETM, the historical evolution of energy demand for Road transport until 2016 (that is the reference year for this ETM update, due to the fact that official data stop at this year) has been obtained from the elaboration of past Eurostat energy balances. Figure 5.1 shows how the total energy demand has been almost the same all over the 11 years from 2005 to 2016, with a generally stable request for all fuels, despite some visible but non dramatic variations. The impact of the economic crisis in 2009 is evident, with negative effects on both vehicle and fuel sales, concerning the individual transport demand, and blowback on goods production, obviously impacting on freight transport. Although, the consumption recovery in recent years, starting from 2012, is noticeable, too.

5.2 Demand projections

5.2.1 Drivers for demand projection

Transportation demands are supposed to vary along with specific socio-economic indicators, such as population, personal income and urbanisation for Passenger

Table 5.1: ETM demand drivers allocation. Source: *Global transportation scenarios in the multi-regional EFDA-TIMES energy model*

Transport mode	Driver
TRT	GDPPP
TRC	GDP
TRL	GDP
TRW	POP
TRE	POP
TRM	GDP
TRH	GDP
TRB	POP

transport demand, while Freight transport will greatly depend on the overall economic development. In TIMES-based models each demand is coupled to one specific social or economic driver, which determines its growth or decline over the Model time horizon. OldTRA ETM demand drivers in the Road transport sector are Population (POP), Gross domestic product (GDP) by market exchange rates and GDP per capita (GDPPP) by purchasing power parities. The same applies to RevTRA ETM. The allocation of these drivers to the particular transportation demand is reported in Table 5.1.

In Figure 5.2, driver trends until 2100, as assumed for ETM projections for EUR region, are reported. While almost all future projections of the world population show substantial ongoing growth until the end of the 21st century, this increase most regards developing countries, while Europe sees a very slight Population growth, 13% from 2005 to 2100 only. Also GDP will grow in all world regions at different but positive rates, and this is true for EUR region, too. Nevertheless, demand does not directly depend on the associated driver, but price elasticity of demand is considered inside ETM, too. It is used as a parameter to reflect changing patterns in energy service demands in relation to socio-economic growth. Despite being a yearly variable, and different for each demand category and region, price elasticity is allocated on three levels, according to the selected storyline (see 2.3.2):

- Paternalism: medium price elasticity of the demand;
- Harmony: low price elasticity of the demand;
- Fragmentation: high price elasticity of the demand.

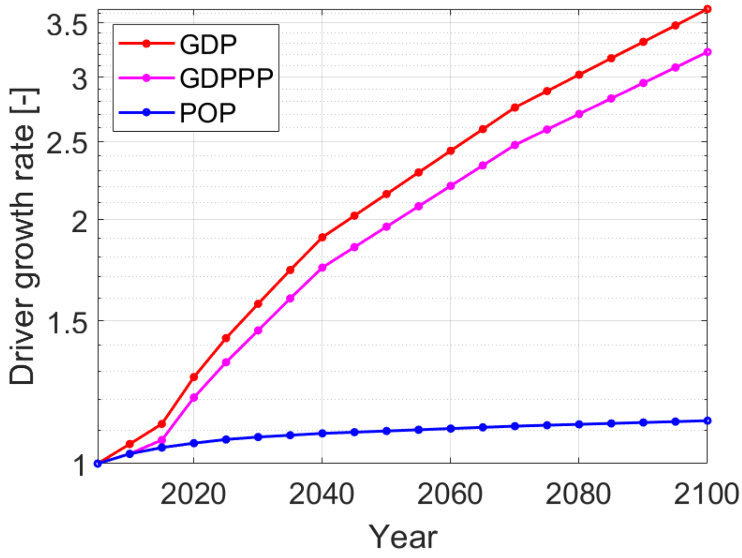


Figure 5.2: ETM Driver projections for EUR Region. Source: *EUROfusion TIMES Model*

Therefore, during the Model time horizon, demand is projected depending on demand category d (in this case transport modes), region r (in this case EUR) and time t. A regionally-variable sensitivity constant k, depending on the demand sector (for EUR Road transport demand it is fixed at 0.9 during the whole time horizon) is applied, too:

$$Demand\ (d, r, t) \propto k \cdot Driver\ (d, r, t)^{elasticity\ (d,r,t)} \tag{5.1}$$

While a new method for the evaluation of base year demand has been presented in section 4.2, formula 5.1 is still valid for the evaluation of future demand during the Model time horizon.

5.2.2 Road transport demand projection in the ETM storylines

As already stated in 3.4.1, the unrealistically high efficiency improvement factors, used in OldTRA ETM, could have been the outcome of a subsequent re-calibration of the transport sector, to meet actual energy demand, as a result of attempts to track real consumption. Thus base year efficiencies for 2005 will be kept and demand will follow the trends in figures 5.3, 5.4 and 5.5, according to equation 5.1.

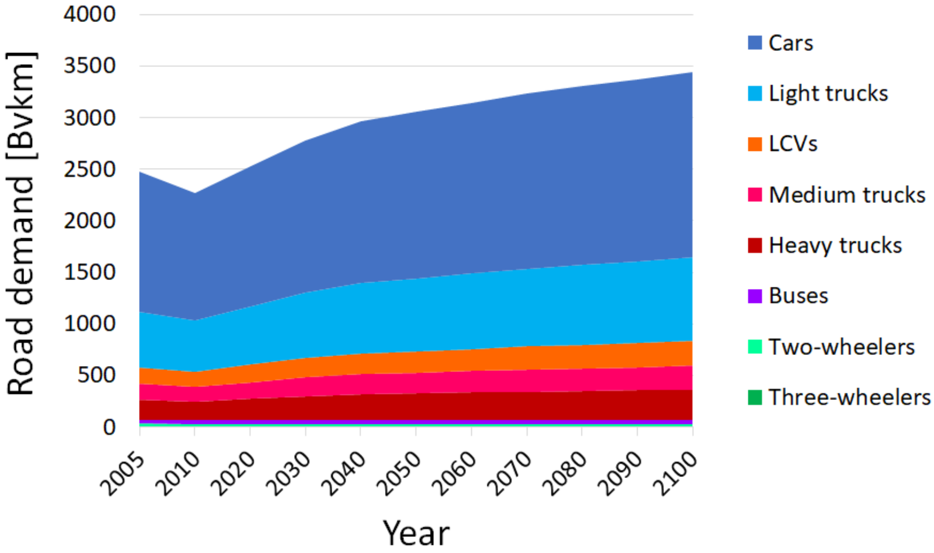


Figure 5.3: Road transport demand projection: Paternalism

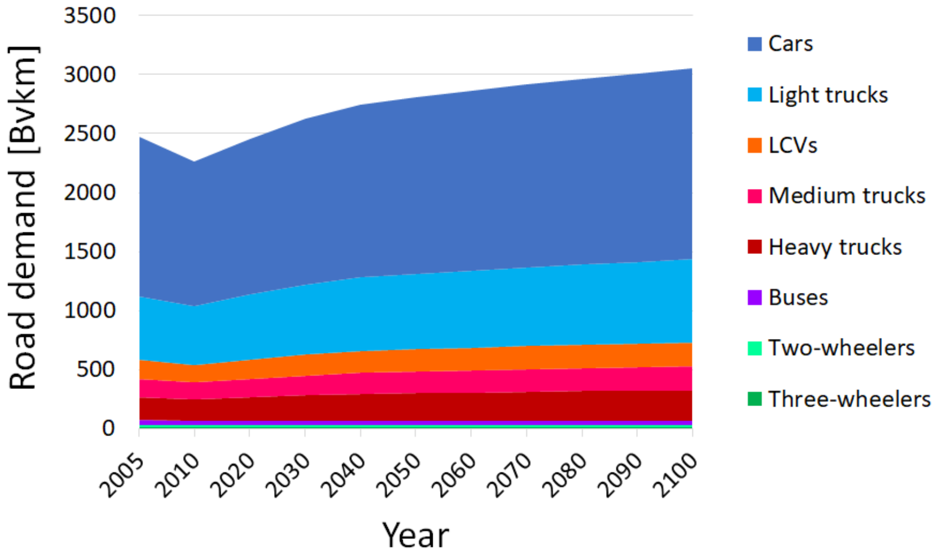


Figure 5.4: Road transport demand projection: Harmony

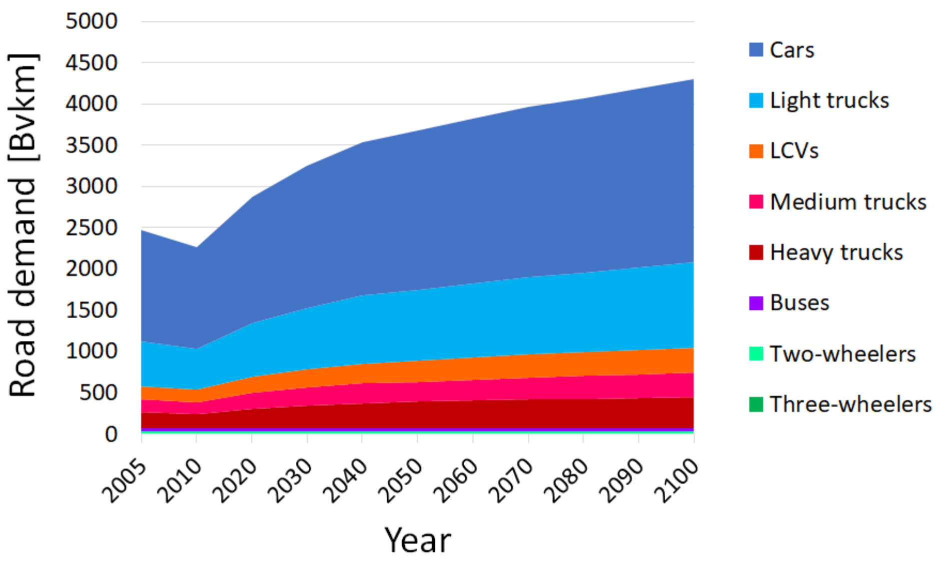


Figure 5.5: Road transport demand projection: Fragmentation

5.3 Scenario analysis

The selected scenario (n. 02 of the ETM scenario tree) for this analysis was described in section 2.3.2.

The aim of this scenario analysis is to show how a considerable uptake of electric vehicles, favoured in the Model by the revision of the technological repository, could modify the need for electricity from fusion, making it more or less convenient with respect to traditional sources, in different storylines characterised by diversified economic and environmental frameworks.

Thus, for each storyline, a comparison between the results of the Model, mainly regarding the Road transport sector only, or strictly related production branches, for the original (OldTRA ETM) version and the updated one including the revision of transportation technologies (RevTRA ETM), will be performed. Then, benefiting for a more coherent representation of future trends in Road transportation, the RevTRA ETM results will be deeply analysed.

5.3.1 Paternalism RCP 2.6

Energy consumption

Figure 5.6 shows the comparison between results for total energy consumption by Road transport sector in OldTRA e RevTRA ETM. Despite being results of the same storyline (same demand trend), the distance between total consumption is very pronounced, starting from 2040, reaching almost 70 [$Mtoe$] in 2100. Looking at the historical series, instead, ETM is quite able to track actual Road final consumption as far as it is available. Nevertheless, an explanation of the very different behaviour can be provided if looking at figures 5.7 and 5.8. Indeed, it is evident how, in OldTRA ETM, Electricity for Road transport was not a good choice due to the very high prices of (especially) Electric HDVs. At the contrary, RevTRA ETM forecasts an almost totally electricity-fed Road transport system by 2100, with an electricity consumption resulting in 133 [$Mtoe$] (1547 [TWh]), representing 88 [%] of total Road consumption; on the other hand, electricity use for Road transport processes stood at just 8 [%] of total Road consumption in OldTRA Paternalism 2.6, due to the ever increasing growth of both Traditional and Alternative Vehicle efficiencies, not justifying the uptake of more expensive Electric vehicles. RevTRA ETM results highlight how Electric HDVs are already convenient starting from 2020 (indeed existing Electric trucks and Buses are actually cost-comparable with their Diesel competitors, while the Tesla Semi, that will be the first Heavy truck to be launched on the market in 2020, has been announced that it will be in line with competition from traditional vehicles, in terms of price [156]). In this framework, the complete disappearance of all Diesel vehicles is scheduled for 2070, while LPG gains the highest share among Oil Products, especially for Cars and Vans, due to both low prices and higher efficiencies with respect to Gasoline and Diesel. It should be noted that the Model completely excludes Hybrid-Electric vehicles, considering their combination of costs, efficiency and GHG emissions uneconomical and quite useless from the environmental point of view, even if compared to traditional and LPG vehicles, which are picked during the whole time horizon.

Electricity production and use

As predictable from the consumption path, RevTRA electricity production capacity has to be increased, with respect to OldTRA ETM results (Figure 5.9),

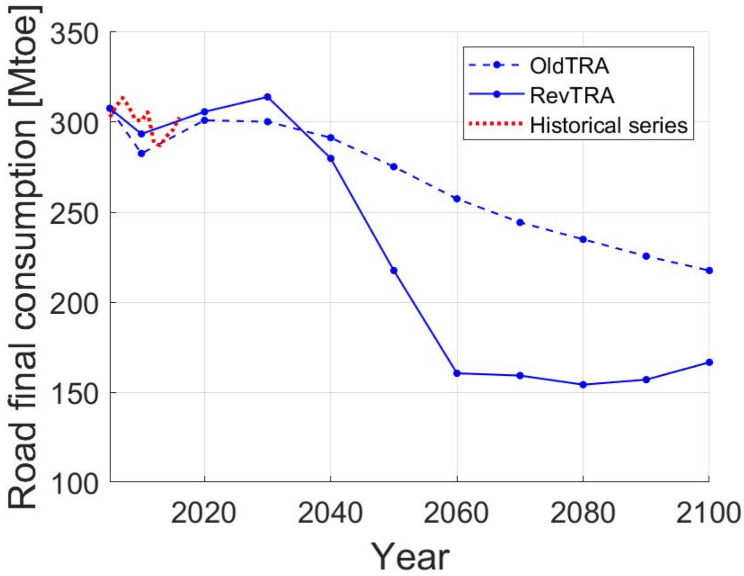


Figure 5.6: Road transport final energy consumption: Paternalism 2.6

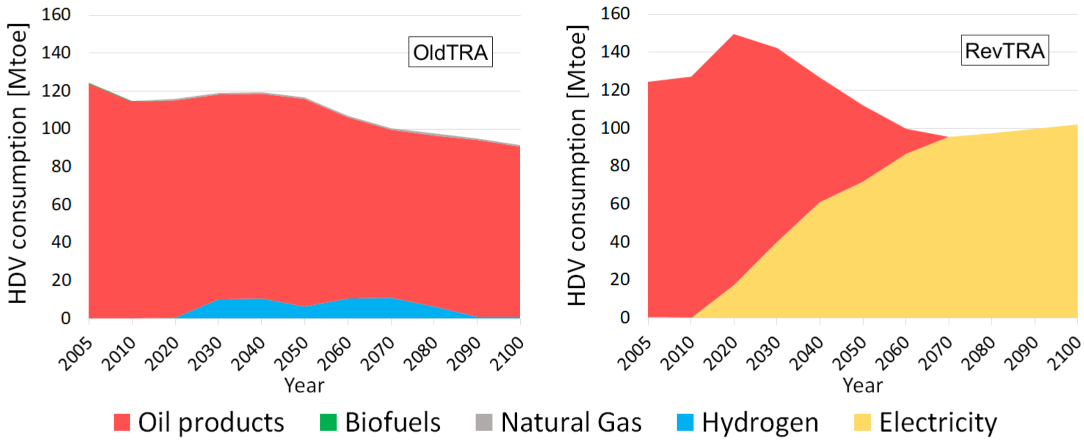


Figure 5.7: HDV energy consumption: OldTRA Paternalism 2.6 vs RevTRA Paternalism 2.6

and a more considerable uptake of Electric vehicles is the main reason for that. RevTRA Paternalism 2.6 Total Electricity demand goes from 3300 $[TWh]$ (in line with the IEA statistics [83]) to 5200 $[TWh]$ in 2100 (almost 1 $[PWh]$ more than 2100 OldTRA Paternalism 2.6). In this framework, where a demand increase of 60[%] is realised with respect to the starting point, and this has to be coupled to clean energy forms (due to the restrictive environmental limits of the RCP 2.6)

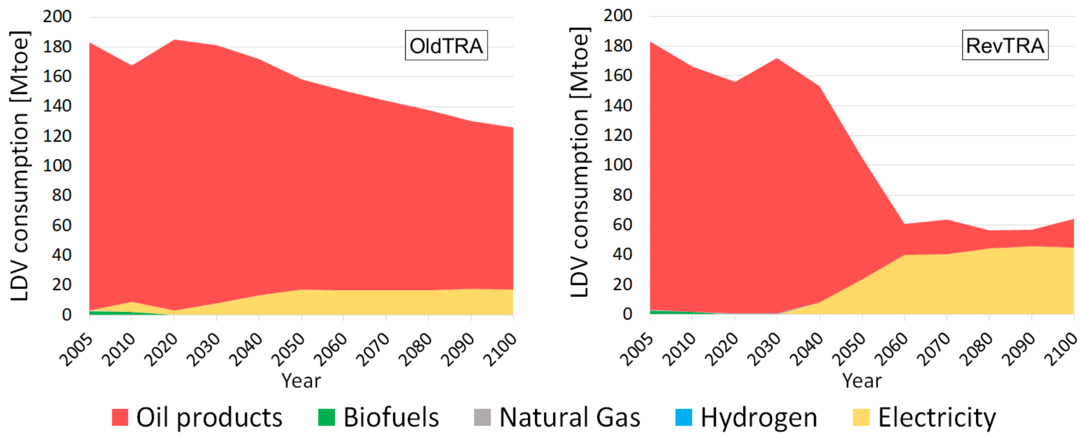


Figure 5.8: LDV energy consumption: OldTRA Paternalism 2.6 vs RevTRA Paternalism 2.6

electricity production from fusion (Figure 5.10) conquers a much more important place in the energy mix, passing from 209 $[TWh]$ (4.9 [%] of total production) to 533 $[TWh]$ (10.6 [%] of total production) in 2100, justifying the cost-effectiveness of this form of energy. Table 5.2 shows the composition of the electricity production mix in 2100. In RevTRA ETM, the high electricity demand, as expected, is balanced with a strong presence of zero-emission electricity production forms (Fossil Fuels represent less than 3 [%] of total production), while a dramatic reduction of Nuclear Fission electricity production, with respect to OldTRA ETM, has to be reported.

The evolution, during the Model time horizon, of the electricity generation sector is showed in Figure 5.11. In both generations of the Paternalism 2.6 storyline, electricity production from fossil sources is progressively reduced, leaving space for a huge growth of VRES. Anyway, the much higher electricity request in RevTRA Paternalism 2.6 translates into a higher fusion uptake, with the exclusion of Nuclear Fission plants from the energy mix, apart from a very slight allocated demand.

CO_2 emissions from transport

The strong environmental responsibility which characterises the Paternalism 2.6 storyline is for sure much more remarkable in RevTRA ETM. Indeed, the strong uptake of Full-Electric vehicles (zero tailpipe emissions) in all Road transport modes reflects itself in the strong decline of CO_2 emissions from transport (almost 90%

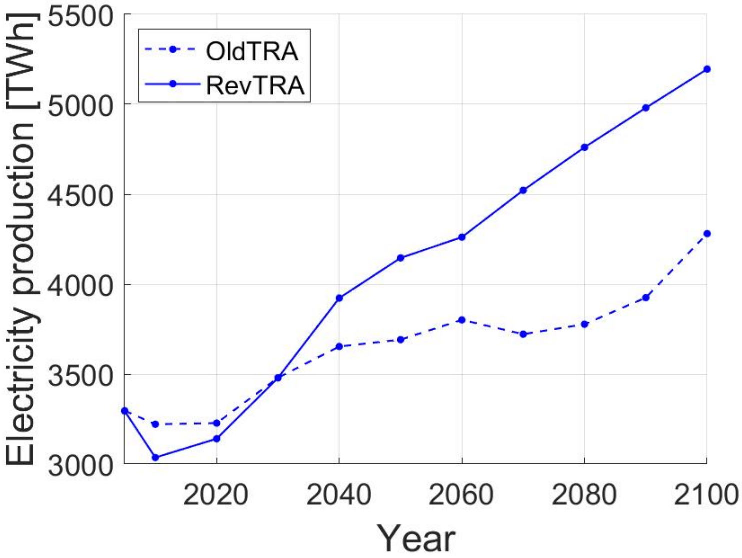


Figure 5.9: Final electricity use: Paternalism 2.6

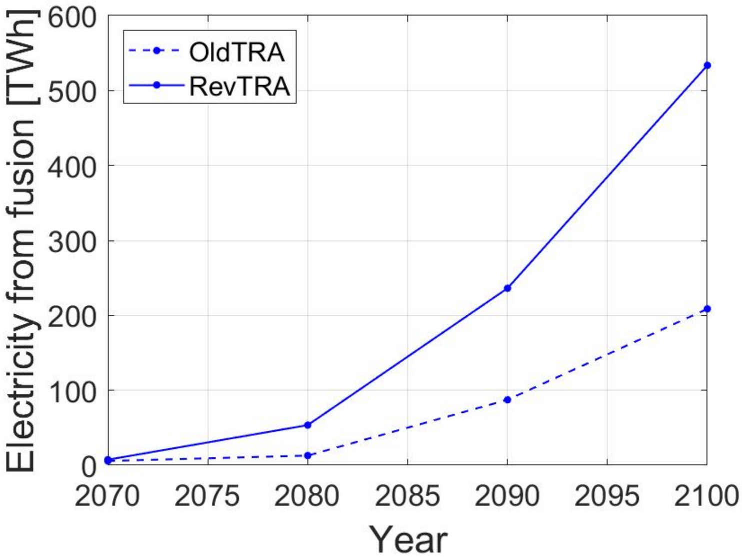


Figure 5.10: Electricity production from fusion: Paternalism 2.6

decline in yearly emissions from 2005 to 2100), reaching 0.15 [$MillionGt_{CO_2}$] in 2100.

Table 5.2: Composition of the electricity production system (2100): Paternalism 2.6

Technology	OldTRA share [%]	RevTRA share [%]
Biomass	1.1	2.6
Coal	3.2	2.3
Fission	36.4	4.7
Fusion	4.9	10.3
Geothermal	1.5	12.4
Hydroelectric	18.6	15.3
Oil & Gas	0.5	1.0
Wind	31.1	48.7
Solar PV	2.7	1.8
CSP	0.0	0.9

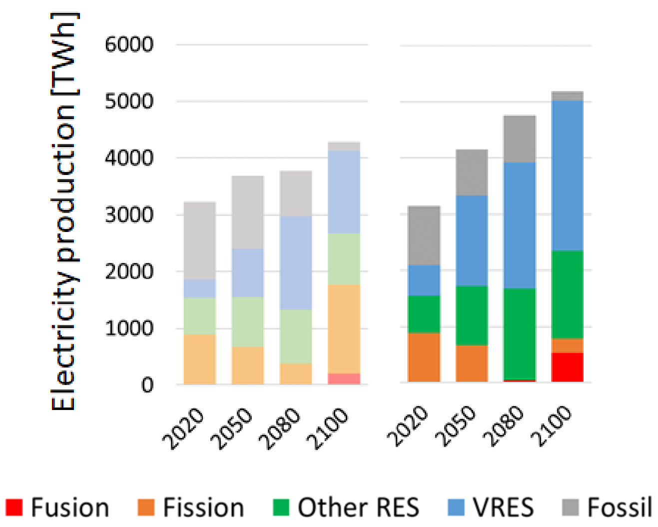


Figure 5.11: Electricity generation system evolution: OldTRA Paternalism 2.6 vs RevTRA Paternalism 2.6

CO_2 emissions from electricity production

Figure 5.13 highlights how the RevTRA Electricity production system, despite a considerable demand increase, is able to keep emission generation at very low levels during the whole time horizon, even reaching almost the same value (less than 0.1 [$MillionGt_{CO_2}$]), in 2100, but with a trend more complying with the prescriptions of RCP 2.6, avoiding a worrying emission peak in 2040, and

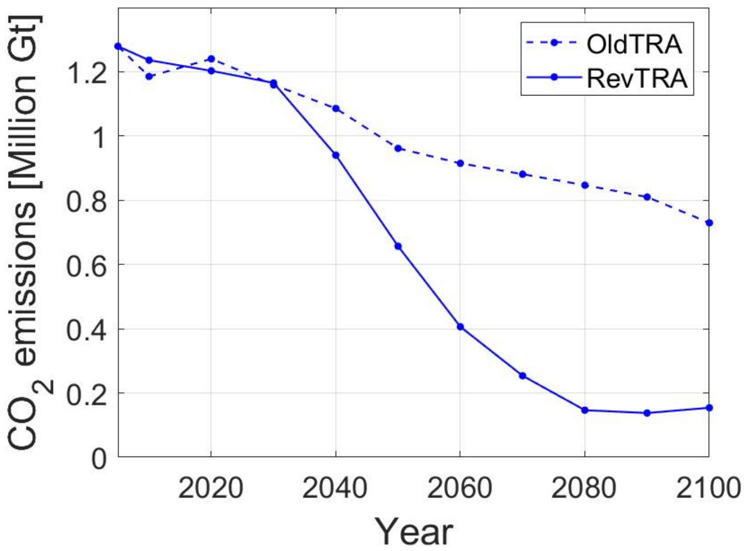


Figure 5.12: CO_2 emissions from transport: Paternalism 2.6

emphasising the role of fusion in abating annual CO_2 emissions, since its introduction in 2070.

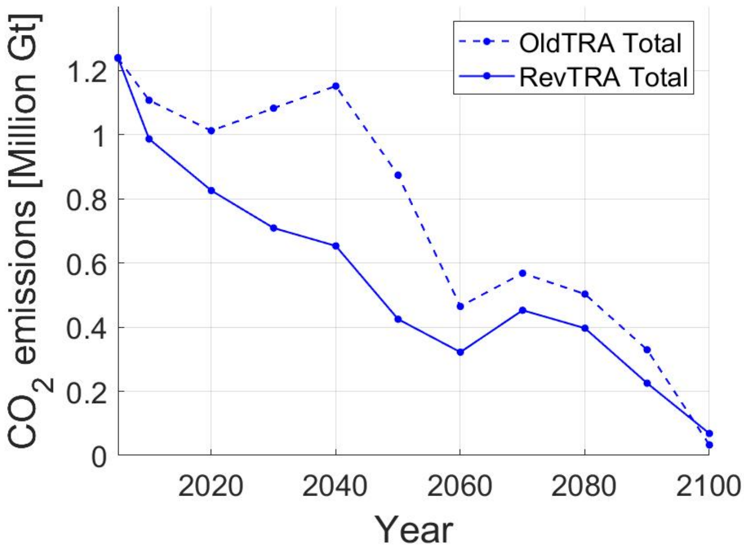


Figure 5.13: CO_2 emissions from electricity production: Paternalism 2.6

5.3.2 Harmony

Energy consumption

Figure 5.14 shows the comparison between results for total energy consumption by Road transport sector in OldTRA e RevTRA ETM. In this case, the difference in total consumption, by 2100, is not so noticeable. Anyway, during the Model time horizon, the total Road transport consumption is considerably lower in RevTRA ETM, with respect to OldTRA ETM. Strong environmental responsibility and long-term investments play an important role in this storyline, thus progressive Electrification of Road transport is the identified solution in both cases, even for HDVs (figures 5.15, 5.16). Electricity consumption from Road transport processes stands here at 118 [$Mtoe$] (1376 [TWh], the highest value among the analysed storylines) in 2100, representing 92 [%] of total road consumption; on the other hand, electricity use for Road transport processes stood at 96 [%] of total Road consumption in OldTRA Paternalism 2.6. On the other hand, RevTRA Harmony forecasts a more rapid decline of Oil products use for transport. However, expensive Hydrogen vehicles are only picked by OldTRA ETM. RevTRA ETM

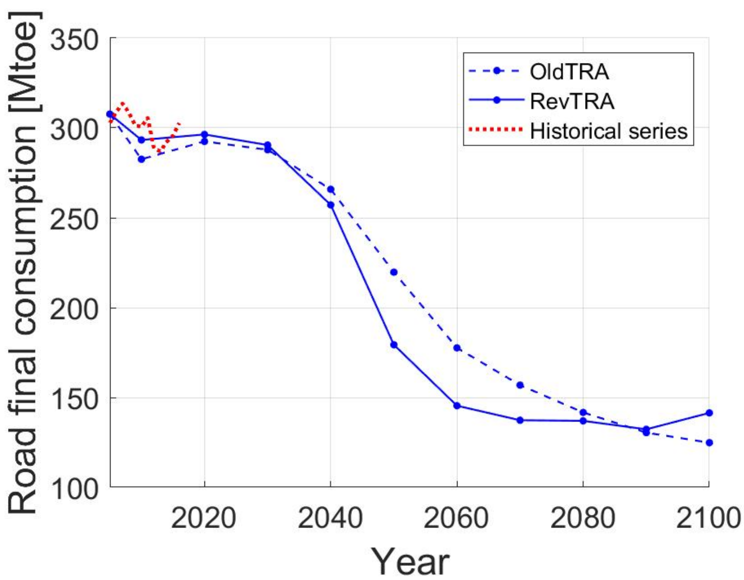


Figure 5.14: Road transport final energy consumption: Harmony

prescribes a total turnover between Electric and Conventional HDVs, starting from 2010 and completed by 2070, while the shift towards Electric LDVs is slower, and a small share of LPG Light-Duty Vehicles is present until 2100. Anyway, it is

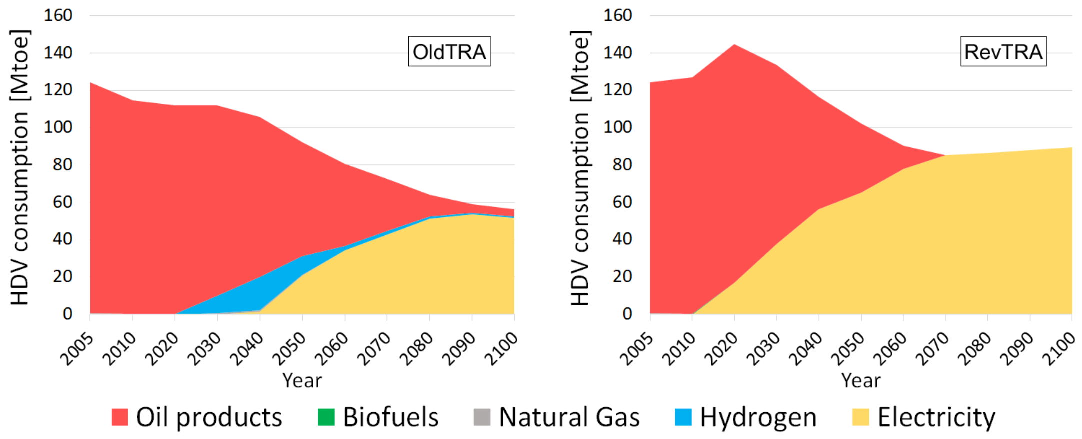


Figure 5.15: HDV energy consumption: OldTRA Harmony vs RevTRA Harmony

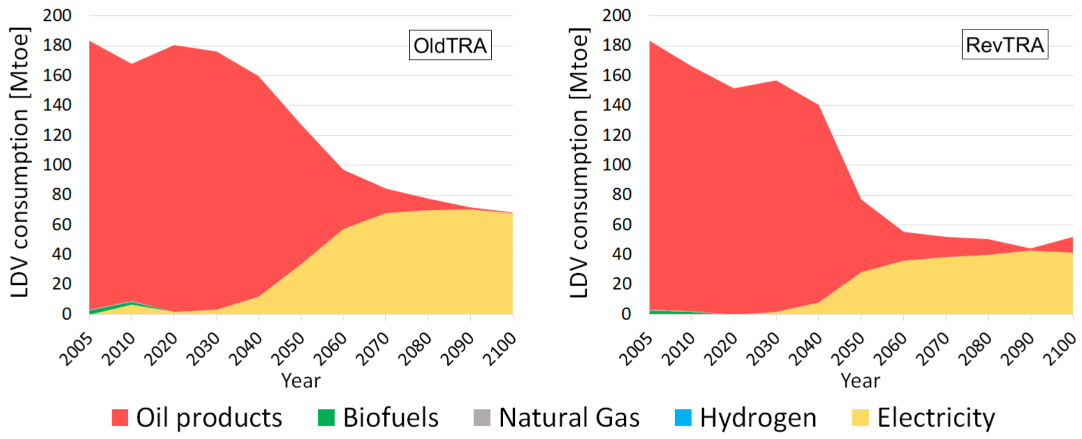


Figure 5.16: LDV energy consumption: OldTRA Harmony vs RevTRA Harmony

quite impressive how total consumption is very reduced when efficient Electric Light-Duty Vehicles are picked by the Model, despite the (little) increasing demand. Hybrid vehicles are not taken into consideration, even in this storyline.

Electricity production and use

RevTRA electricity production is progressively reduced, with respect to OldTRA ETM results (Figure 5.9), starting from 2040, reaching 4400 $[TWh]$ in 2100 (with respect to 5800 $[TWh]$ in OldTRA Harmony). On the other hand, demand from Road transport sector stays quite the same (1500 $[TWh]$) during the Model time horizon, even though its use is more allocated to HDVs in RevTRA ETM. The explanation for this result can be found in the strong mismatch between the efficiency projections in the two ETM Road transport sector versions. In this framework, electricity production from fusion (Figure 5.10) is reduced by extension, but its share in the production mix stays almost the same (from 280 [TWh], corresponding to the 4.8 [%] over total production, to 209 [TWh] but 4.9 [%] over total production) in 2100. However, the trend is ever increasing since the introduction of the technology, ensuring for its convenience. Table 5.2 shows the composition of the electricity production mix in 2100. In RevTRA ETM, Nuclear Fission leads the ranking in electricity production, immediately followed by Wind power.

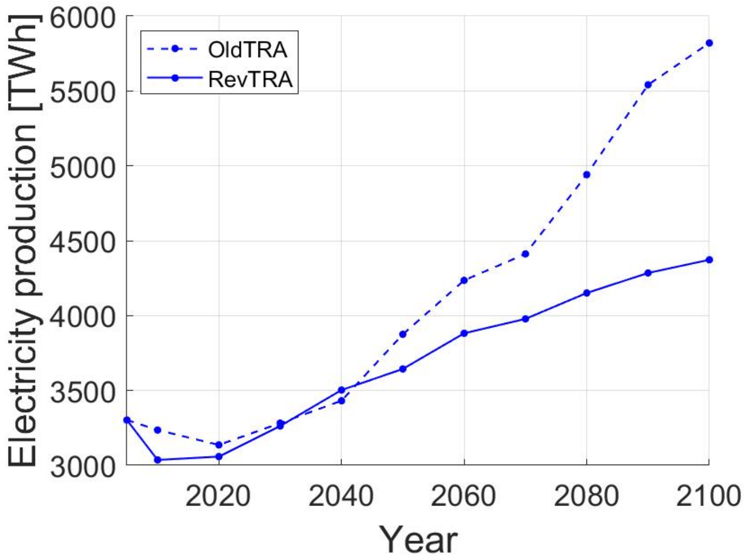


Figure 5.17: Final electricity use: Harmony

The evolution, during the Model time horizon, of the electricity generation sector is showed in Figure 5.19. In both generations of the Harmony storyline, electricity production from fossil sources never reach complete fade-out, but they represent a minor resource, even starting from 2050. Instead of Paternalism 2.6, here Nuclear Fission is considered as an important technology to achieve the environmental protection objectives, while the rise of fusion is balanced against reduced Renewable Energy Source production.

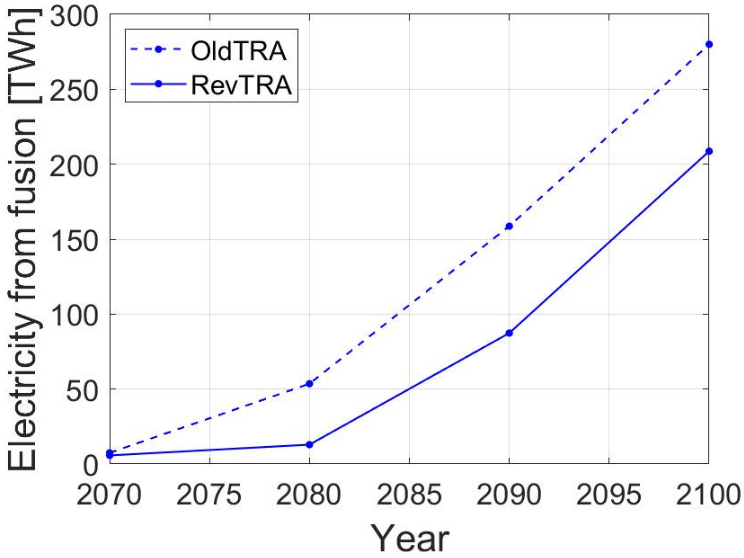


Figure 5.18: Electricity production from fusion: Harmony

Table 5.3: Composition of the electricity production system (2100): Harmony

Technology	OldTRA share [%]	RevTRA share [%]
Biomass	0.7	1.7
Coal	0.9	0.9
Fission	26.8	35.6
Fusion	4.8	4.8
Geothermal	1.1	1.5
Hydroelectric	13.7	18.2
Oil & Gas	0.0	0.0
Wind	35.3	35.1
Solar PV	16.7	2.2

CO_2 emissions from transport

The strong environmental responsibility which characterises the Harmony storyline leads to the same value of very low emissions from Road transport, $\sim$ 0.1 [$MillionGt_{CO_2}$] in 2100, for both OldTRA and RevTRA ETM, despite a more rapid decline in the beginnings of the time horizon, in RevTRA ETM. Of course, this 90% decline in yearly emissions from transport between 2005 and 2100 is due to the very considerable uptake of both Electric LDVs and HDVs,

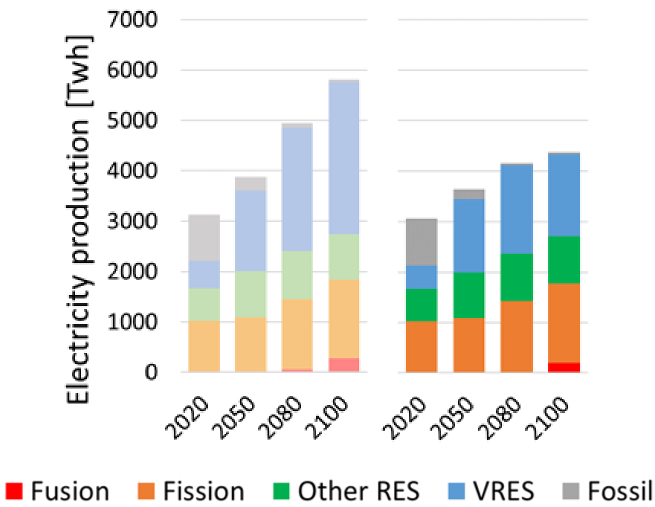


Figure 5.19: Electricity generation system evolution: OldTRA Harmony vs Harmony

coupled with a slightly increasing demand.

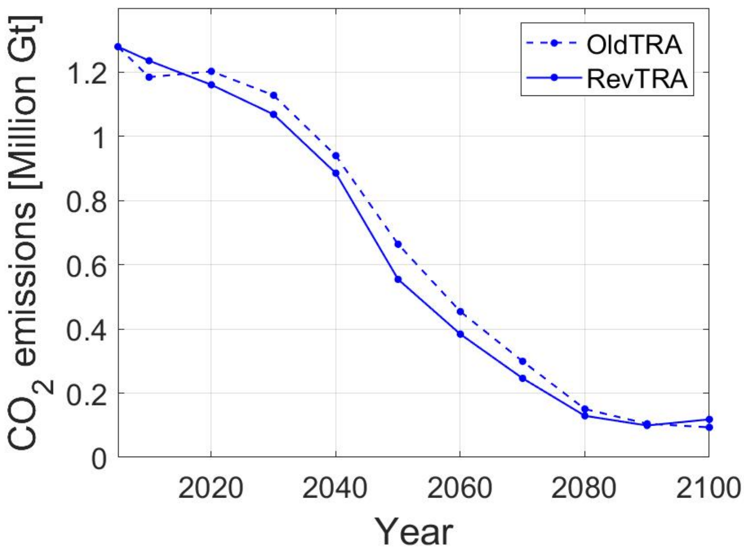


Figure 5.20: CO_2 emissions from transport: Harmony

CO_2 emissions from electricity production

Figure 5.21 highlights how the RevTRA Electricity production system, even if coupled with much lower demand, is not able to always keep emissions below the OldTRA threshold, with a ~ 0.6 [$Million\ Gt_{CO_2}$] peak in 2040. However, starting from 2060, a zero-emissions electricity production system is achieved, one time step before the one prescribed by OldTRA ETM, mainly due to the complete fade-out of Oil and Gas electricity production.

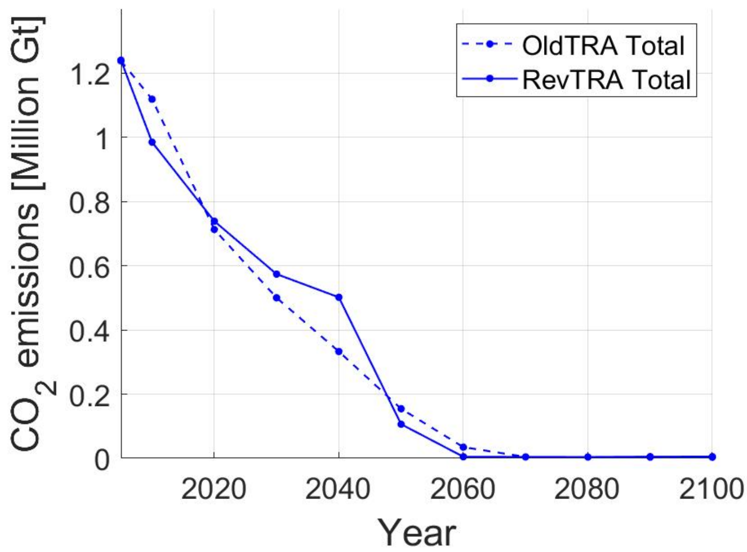


Figure 5.21: CO_2 emissions from electricity production: Harmony

5.3.3 Fragmentation

Energy consumption

Figure 5.22 shows the comparison between results for total energy consumption by Road transport sector in OldTRA e RevTRA ETM. Despite being results of the same storyline, the prescribed consumption trend highlights strong differences. Indeed, watching at figures 5.23 and 5.24, in RevTRA ETM, the progressive achievement of price parity between Conventional and Alternative fuel vehicles makes Electricity a considerable solution for HDVs during the Model time horizon, while Electric LDVs have no place in this forecast. Road transport electricity consumption results in 100 [$Mtoe$] (1160 [TWh], the lowest value among the analysed storylines), representing 88 [%] of total Road consumption; this time, the effect of Electrification of Road transport sector is again impressive, if compared to the 10 [%] over total Road consumption in OldTRA Paternalism 2.6, in 2100. Even expensive (but more efficient than traditional vehicles) Hydrogen HDVs are picked by the Model. The only explanation for this can be found in the achievement of the maximum capacity limit for electricity production, so the Model prefers to allocate the maximum possible Electricity to HDVs (which generally have lower efficiencies with respect to LDVs), and the remaining demand gap is filled by FCEV, since 2050, while Oil demand for LDVs sees a dramatic increase, due the prescribed stagnation in efficiency improvements for CFVs, after 2050. In this storyline, Diesel vehicles keep an important share (almost 800 [$Mtoe$] Gas Oil consumption in 2100) during the whole time horizon, despite the increasing price.

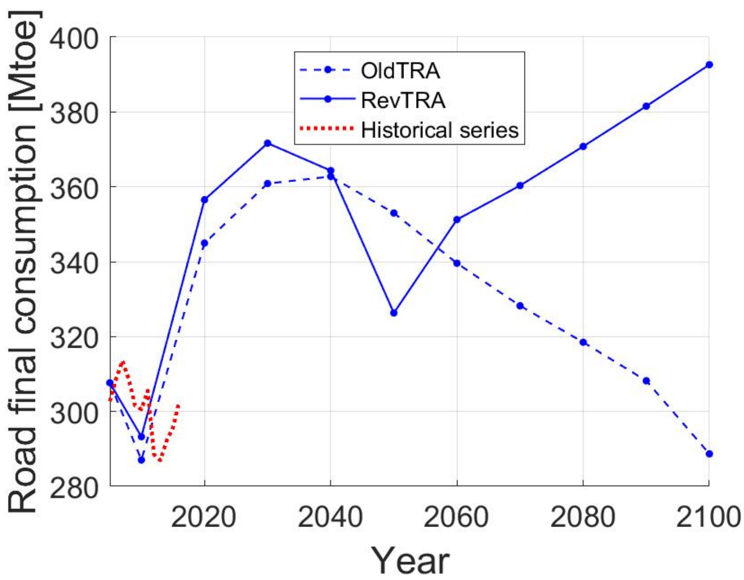


Figure 5.22: Road transport final energy consumption: Fragmentation

Electricity production and use

As already announced in the analysis of energy consumption trends, a saturation of electricity production capacity seems to be reached in RevTRA ETM Fragmentation (annual electricity demand is nearly tripled during the Model time horizon), with a small growth with respect to OldTRA ETM, despite the strong

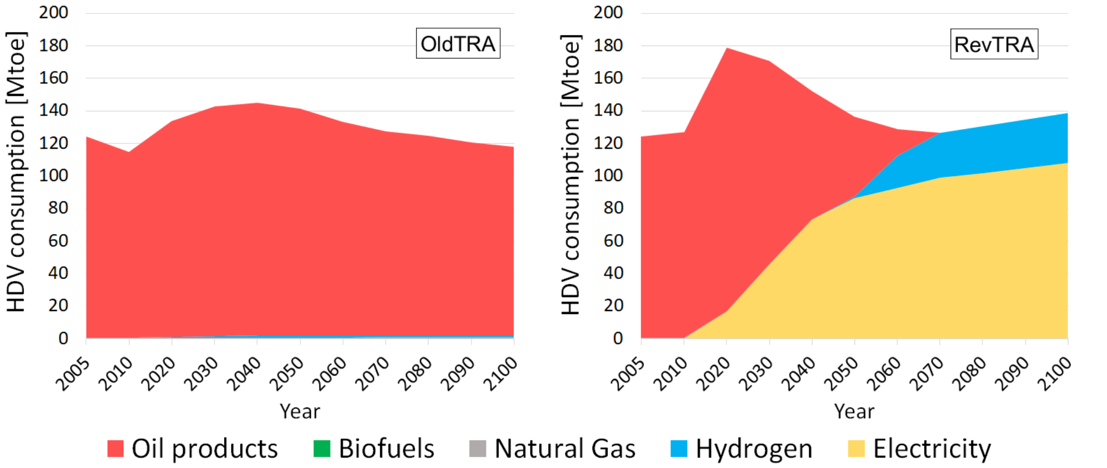


Figure 5.23: HDV energy consumption: OldTRA Fragmentation vs RevTRA Fragmentation

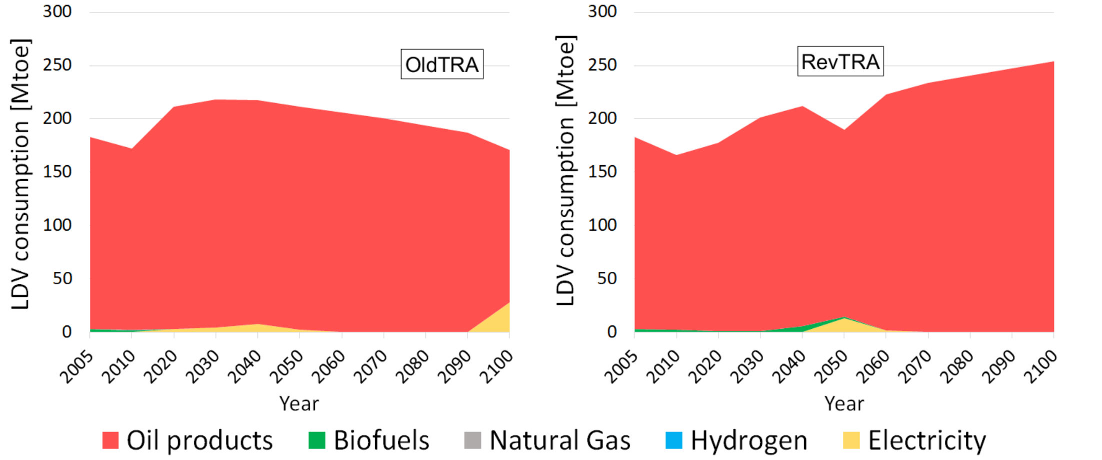


Figure 5.24: HDV energy consumption: OldTRA Fragmentation vs RevTRA Fragmentation

difference in electricity demand from Road transport sector (over 800 $[TWh]$ in 2100). In this framework, where the electricity production system faces a huge stress, fusion (Figure 5.26) surprisingly gets a very little place in the energy mix, passing from 209 $[TWh]$ (3.4 $[\%]$ of total production) to less than 8 $[TWh]$ (0.1 $[\%]$ of total production) in 2100. The very weak environmental responsibility, highlighted by the fact that the electricity production system is dominated by Coal, Oil and Gas even in 2100 (over 55 $[\%]$ of production), and profit consideration that drive this storyline are the main reasons for this pattern. Table 5.4 shows the composition of the electricity production mix in 2100.

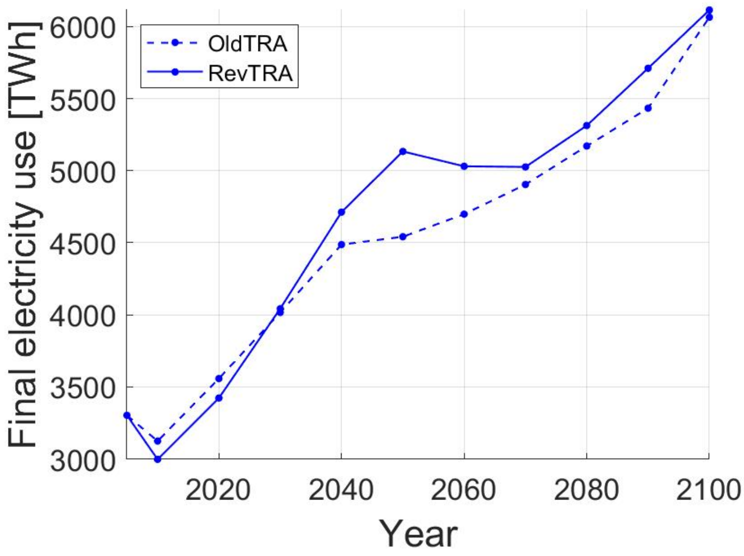


Figure 5.25: Final electricity use: Fragmentation

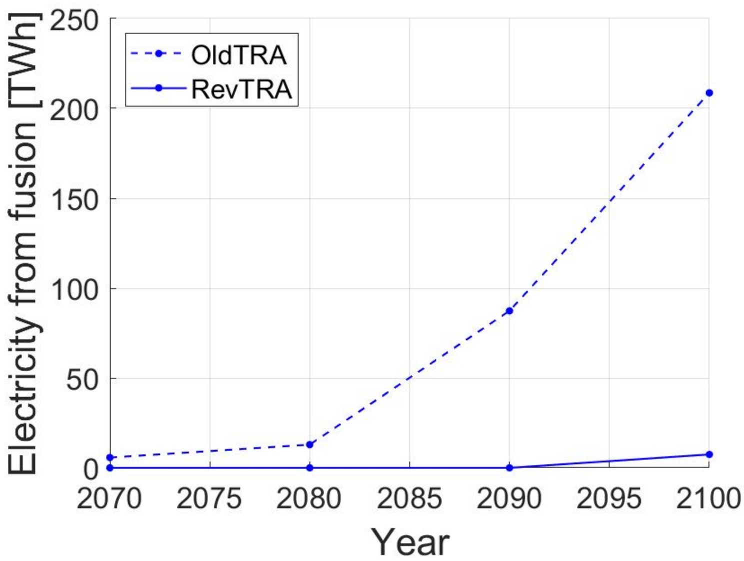


Figure 5.26: Electricity production from fusion: Fragmentation

The evolution, during the Model time horizon, of the electricity generation sector is showed in Figure 5.27. Here, the Fossil production trend undergoes a

Table 5.4: Composition of the electricity production system (2100): Fragmentation

Technology	OldTRA share [%]	RevTRA share [%]
Biomass	2.5	2.1
Coal	4.9	32.4
Fission	21.2	0.0
Fusion	3.4	0.1
Geothermal	1.1	1.1
Hydroelectric	12.9	12.6
Oil & Gas	24.8	23.8
Wind	28.1	27.8
Solar PV	1.2	0.1

considerable reduction, by 2100, in the OldTRA Fragmentation, while a strong increase is observed in RevTRA Fragmentation fossil power production, despite a not so different demand increase between the two generations of the Model. However, this is related to the high Electric vehicle uptake in RevTRA Fragmentation, since a positive move, such as abatement of tailpipe emissions from High-Duty transport processes, is contrasted by the necessity to increase electricity production, relying on traditional generation sources. In this troubling framework, the weak environmental responsibility and a highly desired return on investments make the deployment of fusion power generation very difficult.

CO_2 emissions from transport

Despite the weak environmental responsibility and the Oil products dominance in LDVs energy mix, CO_2 emissions from Road transport are very reduced in RevTRA ETM (64 [%] reduction in annual emissions from 2005 to 2100), due to the total turnover between Conventional and zero-emission technologies, concerning HDVs. However, this good result is counterbalanced by a reckless production system, mainly based on Fossil Fuels, coupled with a considerable increase of travel demand.

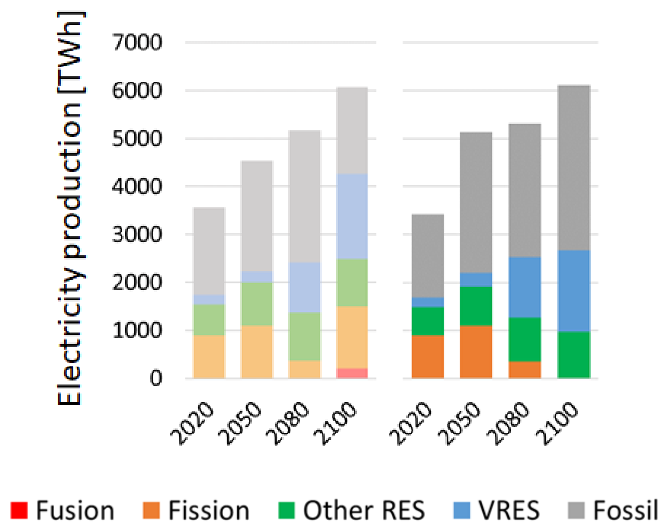


Figure 5.27: Electricity generation system evolution: OldTRA Fragmentation vs RevTRA Fragmentation

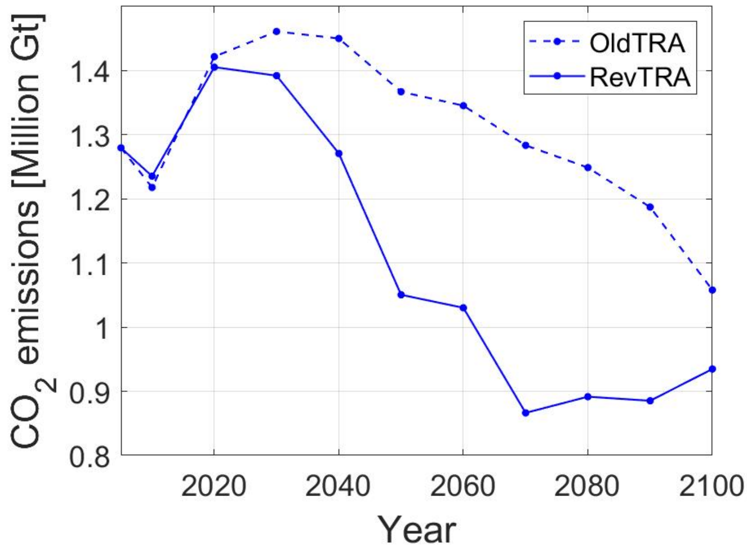


Figure 5.28: CO_2 emissions from transport: Fragmentation

CO_2 emissions from electricity production

Figure 5.29 highlights how the RevTRA Electricity production system, due to the strong uptake of Electric HDVs, which dramatically decrease tailpipe emissions from transport processes, is instead much less environmentally-sustainable. Indeed, the high, increasing share kept by electricity from coal in the production system, to sustain the unprecedented diffusion of Electric vehicles, defeats the purpose of zero-emission vehicles, keeping annual emissions from the sum of the two sectors at even higher levels, with respect to the base year. Instead, in OldTRA ETM, thanks to the almost total depletion of the Oil and Gas production share, which was progressively substituted by Wind and Hydroelectric, the sum of the two sectors was able to return a ~ 28 [%] decrease in annual emissions in 2100, with respect to 2005.

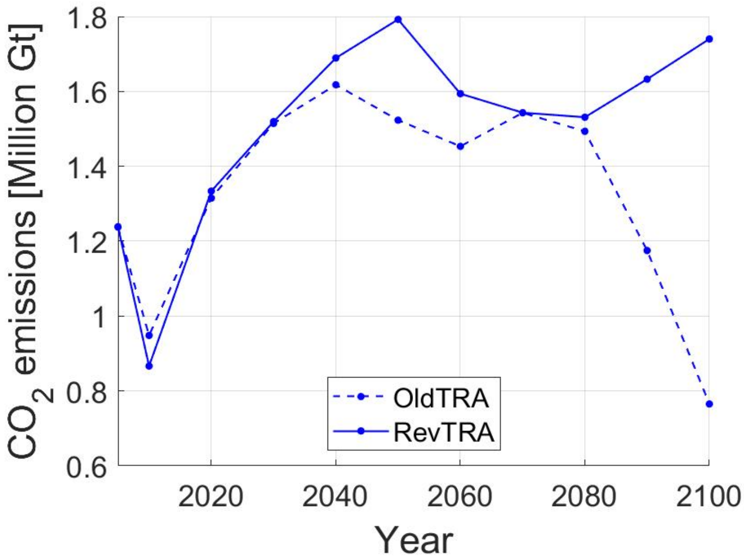


Figure 5.29: CO_2 emissions from electricity production: Fragmentation

5.3.4 Focus on Nuclear fusion

Currently, 131 Nuclear Fission reactors are operating in Europe, for a total of 121 [GW] installed capacity [81]. In the three RevTRA ETM storylines, different pictures are forecast for the development of Nuclear Fission capacity:

- Paternalism 2.6: in 2100, Nuclear Fission contribution is quantified in 33 [GW] installed capacity, mirroring the ongoing tendency towards Nuclear phase-out.
- Harmony: in 2100, Nuclear Fission contribution is quantified in 209 [GW] installed capacity, thus current available power is almost doubled during the ETM time horizon;

- Fragmentation: in 2100, Nuclear Fission sees complete phase-out, with 0 [GW] installed capacity.

Here follows the analysis of the forecast evolution of Nuclear Fusion power. The EU-FPP is supposed to be able to provide $300 \div 500$ [MW] net electrical power to the grid [43]. In the three RevTRA ETM storylines, different pictures are forecast for the development of Nuclear Fusion capacity:

- Paternalism 2.6: 72 [GW] Nuclear Fusion installed capacity is reached in 2100 (10.6 [%] of total electricity production), through a progressive growth since 2070. This means that 144 500 [GW]-FPPs need to be installed in Europe, by 2100.
- Harmony: Nuclear Fusion is supposed to reach a good electricity production share (4.8 [%]), with 28 [GW] installed capacity in 2100, requiring the equivalent of 56 500 [GW]-FPPs.
- Fragmentation: A very slight share electricity production is allocated to fusion (0.1 [%]), with just 1 [GW] installed capacity, corresponding to 2 500 [GW]-FPPs operating on commercial scale.

5.3.5 Cost dependency of Nuclear Fusion penetration

As stated in the Introduction, the main aim of ETM is to set the conditions for the penetration of Nuclear Fusion in the energy mix. Leaving aside the several and previously discussed benefits of this energy form, the system integration of a new technology is subject to restrictive cost constraints, especially in the first years of operation (as happened with Wind and Solar PV power plants, which are now undergoing considerable cost reduction, with consequent penetration in the production mix [105]). [93] [98]

The ETM-prescribed Nuclear Fusion economic parameters, as explained in 2.3.2, represent a target for plants of this type, and have been proved to be able to forecast a considerable penetration of Nuclear Fusion in the electricity production system, both for the scenarios analysed in this thesis and in previous works [20] [21] [71] [114] [124].

After the review of the European Road transport sector, which has provided a new and different energy mix forecast, Paternalism 2.6 is the only storyline where a noticeable increase in fusion demand is seen. By the way, the effect of a cost increase of Nuclear Fusion technology could be interesting to be observed, in order to analyse the role of competitors and to establish a threshold for the price of electricity production from fusion.

Base-case Capital and O&M costs are reported in Table 2.3. Since Investment cost represents the most important economical parameter for FPPs [34], an elementary sensitivity analysis has been carried out on the prescribed values, for the three different storylines. Results are represented in Figures 5.30, 5.31 and 5.32. In general, strong dependence from the Investment cost variation is highlighted:

- Paternalism 2.6: the same number of fusion reactors as in the Base-case (144 500 [GW]-FPPs) is here obtained with a 20 [%] increase in Investment cost. Moreover, Nuclear Fusion finds a place in the mix with an increase in capital cost up to 80 [%] (the first plant appears in 2090, reaching 54 [TWh] production in 2100, corresponding to 1 [%] of total electricity generation, and a 7.2 [GW] installed capacity, with almost 15 500 [GW]-FPPs).

- Harmony: again, the same number of fusion reactors as in the Base-case (56 500 [GW]-FPPs) is here obtained with a 20 [%] increase in Investment cost. Moreover, Nuclear Fusion finds a place in the mix with an increase in capital cost up to 30 [%] (the first plant appears in 2090, reaching 54 [TWh] production in 2100, corresponding to slightly more than 1 [%] of total electricity generation, and a 7.2 [GW] installed capacity, with almost 15 500 [GW]-FPPs).

- Fragmentation: here, the Base-case fusion cost scenario already sets a maximum threshold for Nuclear Fusion penetration in the mix. Instead, the role of Fusion is strongly enhanced when even a 10 [%] capital cost decrease is taken into account, with the number of Plants passing from 2 to 26, and a share in the total production mix increasing from 0.1[%] to 2.3 [%]. This trend is even confirmed when applying a 20 [%] cost decrease, when Nuclear Fusion is able to reach the 5 [%] of total electricity generation.

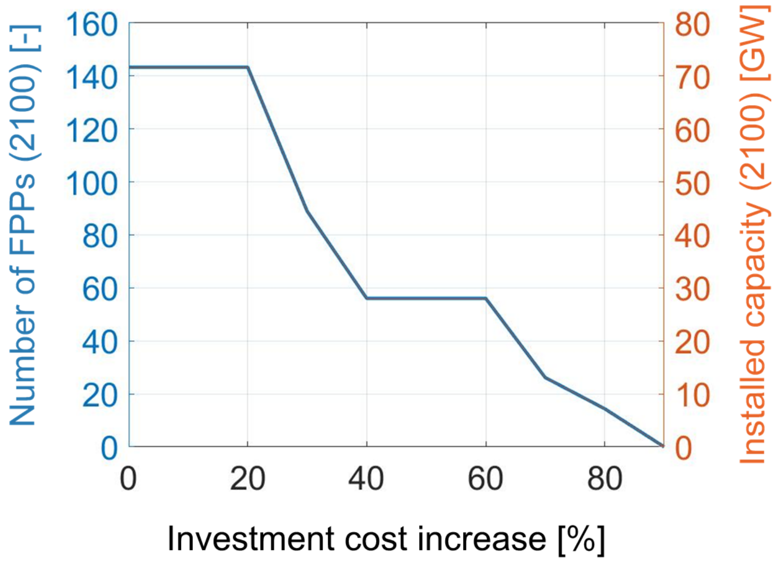


Figure 5.30: Cost dependency of Nuclear Fusion penetration: RevTRA Paternalism 2.6

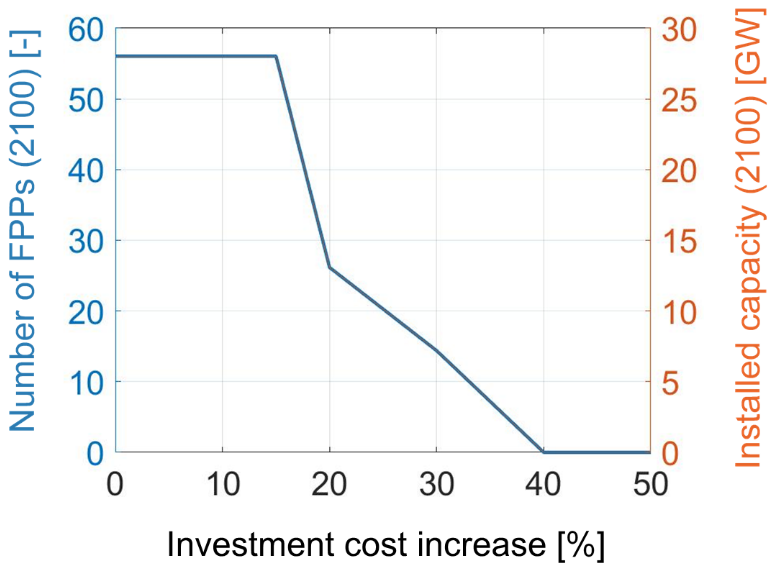


Figure 5.31: Cost dependency of Nuclear Fusion penetration: RevTRA Harmony

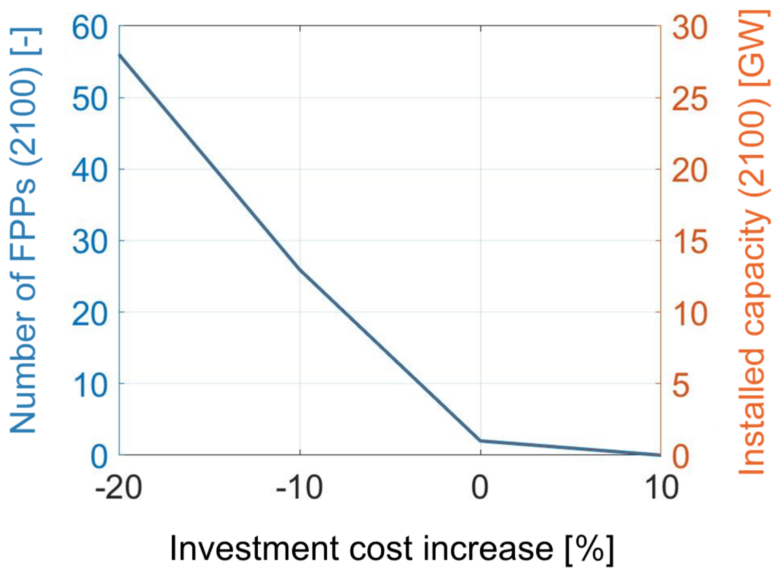


Figure 5.32: Cost dependency of Nuclear Fusion penetration: RevTRA Fragmentation

Chapter 6

Conclusions

6.1 Is Road transport sector going in the right direction?

ETM is not a mobility model, not being able to catch substantial differences in vehicle usage, even in the same transport mode, and furthermore does not allow modal shift (i.e. it is not able to transfer part of the transport demand from one transport mode to another, taking into account users' behaviour change or economic advantages). For these reasons, it provides a picture of how the Road transport should - not may - look in a long-term future in order to accomplish a set of different economic and environmental goals. Instead, other models, such as the IEA MoMo [87], which are specifically designed to evaluate trends for the evolution of the global vehicle fleet, provide results which are more in line with real adaptation of the vehicle usage to environmental constraints.

In this framework, the almost total exclusion of Hybrid and Plug-in Hybrid Electric vehicles from any future mix is a result that stands out. Being a general equilibrium model, ETM works in the logic of maximising profits and utility, this outcome translates into a simple conclusion: Hybrid vehicles can be seen as a "transition technology", with the main aim of helping the transition to a new type of Electric mobility, avoiding a clean break with the past, dominated by an unconditioned reliance on ICEs. In addition, Hybrid and Plug-in Hybrid Electric vehicles do not provide outstanding fuel economy, thus environmental, improvements to current conventional vehicles. On the other hand, today they provide unquestionable range security, due to the widespread penetration of diesel and petrol stations, and do not require refuelling scheduling due to the immediacy of the procedure, making them a suitable choice for driving longer distances. These are all features that the Model cannot catch, thus an undisputed growth of Electric vehicle use is outlined, especially in the RPC 2.6 storylines, since economic convenience of these transport technologies is realised. Indeed, Electric vehicles can be actually a good choice in the predictable future if progresses in battery capacity, recharging time and upfront cost reduction (fixed operational costs are already competitive with the most common technologies) are achieved. A direct effect of these observations on the Model is the need for Re-calibration to a new base year, in order to take into account the effective presence, in the current fleet, of technologies which are not picked by the Model, since it now starts working on the building of the energy system, beginning from 2005.

Anyway, the Model identifies Electric vehicles as the most appropriate technology to get significant environmental responses. In particular, even though today mainly Electric Cars are under the spotlight, it highlights how the Electrification of HDVs, which represent in it a contained demand share (and this is also reflected in the actual number of HDVs on the road today), should be one of the measures to adopt, in order to allow the transition towards sustainable mobility. However, RevTRA ETM results (section 5.3.3) highlight how this process of Electrification of the transport sector must be coupled with a responsible evolution of the electricity generation system: the diffusion of clean technologies (in which Fuel Cell vehicles are included, too, with the consequent environmental issues about Hydrogen production) is hoped-for, but it has to be realised in order to abate GHG emissions from both sides.

6.2 Nuclear Fusion in the future European energy mix

RevTRA ETM results highlight how, in order to accomplish the Below 2 Degrees (B2D) temperature goal (RCP 2.6 scenarios) [158] [163], the higher is the electricity demand, the higher is the uptake of Nuclear Fusion in the power generation mix. However, the results of the Model, in terms of penetration of this new technology, should be proved to be viable. Besides, the aim of the Model is to set conditions and drive design choices for the reactors that will be put on the market, in order to make them effective on the economical point of view.

RevTRA Paternalism 2.6 is characterised by good feasibility and for a large adoption of Nuclear Fusion. Indeed, it involves not so ambitious economic limitations, coupled with substantial increase in electricity demand and a good adoption of fusion-based power generation. Indeed, it prescribes, for EUR Region, a 72 [*GW*] Nuclear Fusion installed capacity in 2100, reached through a progressive growth since 2070. This means that more than 140 FPPs need to be installed in Europe, by 2100. This involves undoubtedly progresses which are very difficult to be implemented, just think that 131 Fission reactors are currently present in Europe, and this technology has a history of more than 50 years. On the other hand, this is a heartening storyline from the fusion point of view, since the cost which would justify the presence of Fusion capacity in the market is very large. Instead, Nuclear Fission capacity is significantly reduced, in RevTRA Paternalism, until 2100, reaching 30 [*GW*] from the current 120 [*GW*]. This could represent a big step forward for social acceptability problems [14] [138] [139], provided that this type of issues would not arise for fusion, too.

Regarding the Harmony storyline, where a Nuclear Fission capacity increase is prescribed, up to 209 [*GW*] installed in 2100, meaning for a nearly doubled capacity with respect to current values, fusion is supposed to reach a good production share with the prescribed costs, with 28 [*GW*] installed capacity in 2100, requiring the equivalent of slightly less than 60 FPPs. While this number is far more ambitious than in the Paternalism 2.6 storyline, even if they are characterised by the same emission reduction path, the realisation of the Harmony FPP fleet is characterised by a higher dependence on cost variation. Indeed, a 40 [%] deviation from the ETM prescribed value for Investment cost would prevent the realisation of Fusion capacity by 2100. As a final remark, Harmony could be seen as a more optimistic storyline towards energy from Nuclear Fission, and with less ambitious goals for the realisation of a very large fusion reactor fleet.

Instead, analysing the less desirable storyline, Fragmentation, where a disproportionate increase of Fossil power generation is realised and Nuclear Fission does not find a place in the mix, a very slight electricity production capacity is allocated to Nuclear Fusion, just 1 [*GW*] installed capacity, corresponding to 2 fusion reactors operating on commercial scale, but reflecting the expected viability of Fusion.

It is not a fatality that the Model, at any rate, allocates a more or less substantial share to Fusion electricity capacity. Indeed, the logic of cost minimisation which is behind it recognises how, with the implemented parameters about FPPs, they could gain a noticeable presence, even in scenarios characterised by advanced technological development and optimistic prescriptions regarding electricity from Nuclear Fission, and in some cases even when the price would see an increase with respect to the set targets. In this respect, it should be noted that ETM still does not take into account limits on the availability of materials such as Tritium and Lithium, which could set serious restrictions on the feasibility of a large number of FPPs. On the other hand, given the possibility to respect economical parameters, the introduction of Fusion in the mix is not only positive for environmental or social purposes, but its effect on the stability of the grid, in contrast with VRES, should be stressed, too. [10] [111] [148]

The final effect of this update of the Road transport sector shows how, in every storyline, the influence of new cost and efficiency trends brings to a very noticeable increase in electricity demand from transport, but not necessarily related to the uptake of power generation from Nuclear Fusion, at least when its costs are not sustainable by the economic system. On the other hand, the strong effect of uncontrolled Electrification undermines the environmental purpose of clean transport technologies, if the energy system is expected to continue to rely on the same structure, for at least the next 50 years. In this framework, Nuclear Fusion echoes all the features requested to a new electricity source, but the Model tells financial gain needs to be put aside, in the early years of operation, in order to make it get a consistent market share and to make it able to contribute to the desired environmental purposes. However, over-optimism about a rapid and effective growth of fusion plants should be avoided, because while commendable efforts are made on the technical side, a model, also in its "representation of an ideal world", has to keep an eye on reality, and it tells that fusion is still at a stage where the large required production capacities could not be available, even in a time horizon pointing to 2100.

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Acronyms

AFV Alternative Fuel Vehicle.

AR5 Fifth Assessment Report.

B2D Below 2 Degrees.

CCS Carbon Capture and Storage.

CFV Conventional Fuel Vehicle.

D Deuterium.

EFDA European Fusion Development Agreement.

EFOM Energy Flow Optimisation Model.

EIA Energy Information Administration.

ETM EUROfusion TIMES Model.

FCEV Fuel Cell Electric Vehicle.

FPP Fusion Power Plant.

GDP Gross domestic product.

GDPPP GDP per capita.

GHG Greenhouse Gas.

HDV Heavy-Duty Vehicle.

ICE Internal Combustion Engine.

IEA International Energy Agency.

IEO International Energy Outlook.

IPCC Intergovernamental Panel on Climate Change.

LCV Light Commercial Vehicle.

LDV Light-Duty Vehicle.

MARKAL Market Allocation.

POP Population.

RCP Representative Concentration Pathway.

RES Reference Energy System.

T Tritium.

TIAM TIMES Integrated Assessment Model.

TIMES The Integrated MARKAL-EFOM System.

TRADST Gas Oil.

TRAELC Electricity for transport.

TRAETH Ethanol for transport.

TRAGSL Motor Gasoline.

TRAHH2 Hydrogen for transport.

TRALPG Liquified Petroleum Gases for transport.

TRANGA Natural Gas for transport.

TRB Buses.

TRC Light Commercial Vehicles.

TRE Three-Wheelers.

TRH Heavy trucks.

TRL Light trucks.

TRM Medium trucks.

TRT Cars.

TRW Two-Wheelers.

VRES Variable Renewable Energy Sources.

WPSES Socio-Economic Studies WorkPackage.

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