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MASTER OF SCIENCE - SUSTAINABLE ENERGY TECHNOLOGY

Modelling of Global Energy Demand in the Transportation Sector

A Country by Country Approach

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Abstract

This study deals with the modelling of the future global energy demand in the transportation sector, how and in what extend this could be limited and which low carbon fuels and technologies could contribute to the mitigation of the energy demand. In the introduction of the current report, the greenhouse effect, the global warming and the climate change are defined. Then, the actions taken and the agreements made to deal with global warming and climate change are presented and the need for combating them is highlighted.

After the introduction, a literature review is conducted in order to spot the knowledge gap and formulate the research questions. In the literature review, the ICCT's and IEA's studies are mainly discussed due to their high quality research and the big amount of published reports. More specifically, their models, scenarios, policies and results are discussed in detail in order to accurately define the knowledge gap and formulate the research questions. Thus, the goal and the main research question of this research is to answer how could the future global energy demand be mitigated and which low carbon fuels and technologies could significantly penetrate into the transportation sector.

In the beginning of this research, the conceptual and the theoretical frameworks are presented in order to assist with the outline of the thesis and create the theoretical background for the development of the model. Then, in order for the research questions to be answered, a forecasting model calculating the transportation future energy demand by country, transport mode, technology and energy carrier throughout the period 2015-2050 is developed. The main features that distinguish this model from models used in similar studies are the strong focus on the diffusion of low carbon fuels and technologies, the use of a different diffusion model (the Bass s-curve) and the country by country with one-year time increments approach.

After the model is verified and validated through comparison with similar studies and a sensitivity analysis, results are presented for two different scenarios. The first scenario is called Current Policies scenario and aims to show a potential pathway of the future global energy demand in the transportation sector that could happen if no more policies are applied after 2020 and the second scenario is called Accelerated Policies scenario and its target is to represent a pathway that could happen if new policies are adopted and stricter implementation is applied.

The results of the two scenarios show that it is possible to achieve a bending of the energy demand and a diffusion enhancement of low carbon fuels and technologies if new and stricter policies that motivate technology improvements and fossil vehicles ban are applied. In particular, the results indicate that the implementation of new and stricter policies, which could lead to efficiency improvements, and to more effective diffusion of low carbon fuels and technologies could achieve reduction of the energy demand after

2029. Moreover, according to the results, electricity is expected to dominate in the transportation sector, while biofuels, hydrogen and ammonia are also expected to be highly used. However, without further policy action, the global energy demand is expected to follow a constantly increasing trend in the future while the penetration of low carbon fuels is expected to be significantly lower.

1 Introduction

Limiting global warming is a target of crucial importance. Global warming is the continuous heating of the planet which is caused by human activity, mainly because of the burning of fossil fuels which lead to greenhouse gas emissions, and it affects the climate change in ways which could be disastrous for the human and the planet (NASA, n.d.-b).

In order to combat climate change caused by global warming and deal with its effects, countries joined the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 (UNFCCC, 2020a). The UNFCCC entered into force in 1994 and today it counts 197 members which are called Parties of the Convention. The ultimate purpose of the UNFCCC is to stop the dangerous human activities that affect the climate system (UNFCCC, 2020d).

The first action of the UNFCCC was the Kyoto Protocol which was adopted in Kyoto, Japan, in 1997 but came into force in 2005 due to complex ratification process. The main target of the Protocol was to reduce greenhouse gas emissions by asking the countries to apply measures and policies in this direction. The Protocol is based on the principle of "common but differentiated responsibility and respective capabilities", since it acknowledges that the developed countries are mostly responsible and are more capable of dealing with the problem (UNFCCC, 2020c).

The latest international treaty that was adopted by the Parties of the UNFCCC is the Paris Agreement. It was adopted in Paris, in 2015 by 196 countries. Its target is to keep global warming below 2^oC, and if possible below 1.5^oC, compared to pre-industrial levels (UNFCCC, 2020b).

1.1 Greenhouse Effect

Joseph Fourier, in 1824, was the first to observe that some components of the earth's atmosphere were able to affect the temperature at the surface of the earth (Fourier, 1824). In the 1860s, John Tyndall, proved that CO_2 was able to absorb greater amounts of heat than other atmospheric gases. So, Tyndall was able to connect his findings with J. Fourier's findings and reach the conclusion that CO_2 is the component of the atmosphere which mainly influences the temperature at the surface of the earth (Tyndall, 1861), (Tyndall, 1863). Following the findings of J.Fourier and J.Tyndall, Svante Arrhenius, in 1896, found that by reducing the atmosphere CO_2 levels by half, the temperature of Europe would also be reduced by $4-5^oC$. He also predicted that CO_2 emissions produced by human activities could possibly cause global warming in the future (Arrhenius, 1896).

All these discoveries led to the definition of the phenomenon that today is known as greenhouse effect. The first one that named the phenomenon as greenhouse effect was Nils Gustaf Ekholm in 1901 (Ekholm, 1901). In particular, greenhouse effect is a natural process that warms the Earth's surface (Australian Government, 2020). The ability of the atmospheric gases and the clouds to trap heat is what causes the greenhouse effect. More specifically, the atmospheric gases and the clouds reduce the radiation (energy) that would be sent from Earth to the space so as to keep the planet warm and at a stable temperature. The energy that is finally released to the space is approximately 30% of the incoming sun energy (The Royal Society, 2010). The two gases with the largest contribution to the greenhouse effect are water vapor and CO_2. Although water vapor is the gas with the biggest contribution (around 60% (Letcher, 2018)) to the greenhouse effect (NASA, 2008), CO_2 is the gas that actually controls the planet's temperature because it is responsible for the amount of water vapor in the atmosphere and, as a consequence, for the whole greenhouse effect (NASA, 2011).

1.2 Global Warming, Climate Change and Consequences

Global warming is the sharp rise of the Earth's temperature which started after the pre-industrial period (between 1850 and 1900) due to human activity. The main reason is the burning of fossil fuels which leads to the emission of CO_2 and other greenhouse gases which amplify the greenhouse effect (NASA, n.d.-b). As figure 1 shows, the global average surface temperature increased nearly 1^oC since 1880.

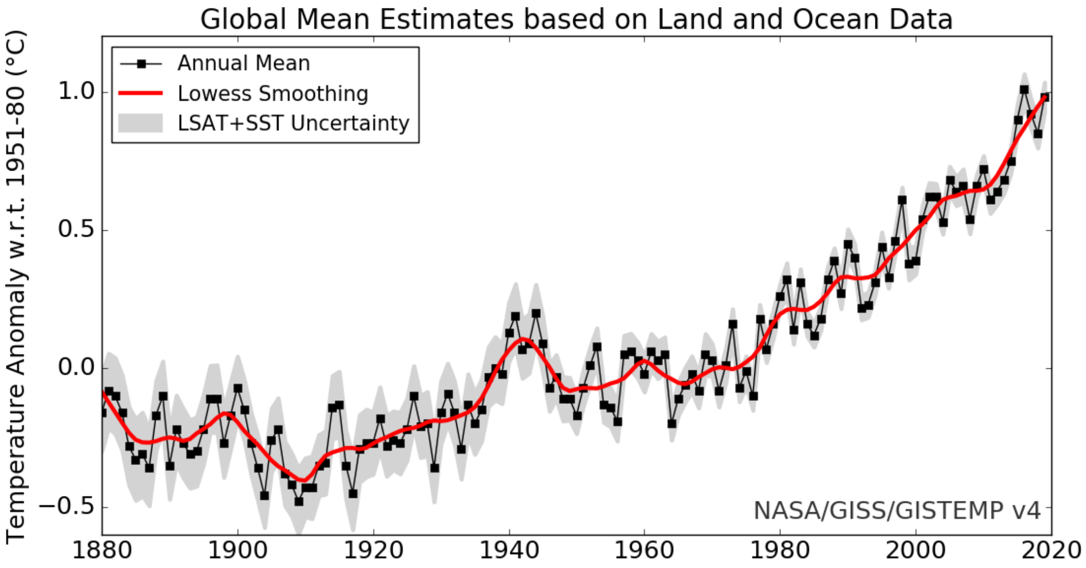

Figure 1: Land-ocean temperature index (NASA, 2020)

As mentioned before, the rise of the temperature is linked with the rise of CO_2 (and other greenhouse gases) concentration in the atmosphere. In particular, the CO_2 concentration has risen from 280ppm before the industrial revolution (T. M. L. Wigley, 1983) to 413 ppm in 2020 (CO2-Earth, 2020). The simultaneous increase of both CO_2 concentration and temperature shows their inseparable relation.

In general, climate change is a long-term shift in the weather patterns which determine the Earth's climate. Climate change has always been happening due to natural processes, such as volcanic activity, sun's energy variations and cyclical ocean patterns. However, global warming due to human activity is nowadays the biggest factor that causes changes in climate (NASA, n.d.-b).

The consequences of the climate change on the planet and humans will be much more important than just the increase of temperature in our natural habitats. The temperature rise has already led to frequent extreme natural phenomena and as it continues to increase, the impact will be worse. In particular:

- the precipitation change will cause intense heat waves, storms, floods and draughts, while the oceans temperature increase will cause intense hurricanes (NASA, n.d.-a).

- the temperature rise will cause melting of the ice and it will lead to rise of the sea levels. According to the Intergovernmental Panel on Climate Change (IPCC), sea levels will increase between 0.18 and 0.59 meters by 2099. Rise of the sea level will lead to disappearance of many coastal regions and threaten lives as about 10% of human population lives there (McGranahan, Balk, & Anderson, 2007).

- the global warming already threatens the ecosystems. The growing season has been extended and, as a result, the plants may dry out if they do not have enough water. Moreover, the smaller winters are not able to kill the sleeping insects which will be dangerous for the plants and the crops afterwards. Animals are also affected as global warming causes changes in their migration habits and lifecycles (Reid et al., 2005).

- humans will be affected too. The extreme physical phenomena, the sea levels rise and the changing ecosystems will cause either direct or indirect consequences. For example humans will be threatened by an intense hurricane but they will also be threatened by smaller food production due to failed crops.

1.3 Tackling Global Warming

The United Nations have set 17 Sustainable Development Goals (SDGs) which should be met by 2030. Three of them are related to the global warming and climate change. These are the universal access to energy (SDG 7), dealing with the health impacts of air pollution (SDG 3) and combating climate change (SDG 13) (UN, 2020b).

In order to combat climate change caused by global warming and deal with its effects, organizations dealing with the sustainable future of the human and the planet - such as the United Nations, the International Energy Agency and the International Council on Clean Transport - call for immediate action. In particular, it is necessary to almost eliminate greenhouse gas emissions by applying new policies,improving efficiency and enhancing the use of new technologies and energy carriers (United Nations, 2021).

However, because of the fact that, despite the global efforts, the energy system is expected to still be dependent on fossil fuels in the upcoming years, it is also necessary for the energy demand to be reduced (BP, 2020). Consequently, mitigating the demand of the energy system is critical in reducing greenhouse gas emissions and achieving climate goals. Transportation sector is responsible for 30% of the total greenhouse gas emissions caused by human (World Resources Institute, 2020). Consequently, it is necessary to limit the transportation energy demand in order to achieve the energy targets set by the Paris Agreement. This research aims to provide a detailed analysis regarding the global future energy demand in the transportation sector taking into account the various transportation modes, technologies and energy carriers and answer the question of **"how could the global energy demand be mitigated in the future and what role could the various technologies and energy carriers play?"**.

2 Literature Review

There are a lot of organizations dealing with future energy demand in the transportation sector. All of them aim to provide the policymakers with studies that develop pathways to limit the global temperature increase to 1.5^{o}C, decrease the transportation energy demand and bring CO_2 emissions close to net zero by 2050.

IRENA in their Global Renewables Outlook published in 2020 (IRENA, 2020) and the World Energy Transitions Outlook published in 2021 (IRENA, 2021) set their target to keep the global temperature rise under 1.5^{o}C, reduce energy demand and bring CO_2 emissions close to net zero by 2050. Regarding the transportation sector, their analysis includes light duty vehicles, heavy duty tracks, aviation and shipping and they suggest full electrification of the light duty vehicles fleet and the increase of electricity, hydrogen and biofuels shares in heavy duty tracks, aviation and shipping. They conclude that it is necessary to increase the share of renewables in the energy supply mix, achieve reduction of the projected energy demand and that it is possible to reach net zero CO2 emissions if their 1.5^{o}C scenario is followed.

REN21 in their Global Status Report published in 2021 (REN21, 2021) aim to accelerate the increase of renewable energy share in the energy supply mix and decrease energy demand. Now, biofuels account for an important share in the energy mix of the road transportation sector while new policies aim to increase the electrification of the road fleet (policies regarding rail, aviation and shipping are much less compared to road transport). However, it is highlighted that the transportation sector is far from achieving the climate goals. For the renewable energy share in the transportation sector to increase and the energy demand to decrease, REN21 calls for new strategies and policies. In their analysis, they consider road passenger and road freight vehicles, aviation and shipping and they conclude that it is necessary that new policies are applied at all the transportation modes in order, on the one hand, to increase the share of electricity, hydrogen and biofuels and, on the other hand, to decrease the energy demand.

FIA in their Renewable Energy Pathways in Road Transport report published in 2020 (REN21 & FIA Foundation, 2020) emphasize that a significant shift is necessary for road transport to achieve the climate goals set by the Paris Agreement. FIA aims to explore both the energy sector and the transportation sector and provide pathways for the penetration of renewable energy in the transportation sector. They suggest that electricity, biofuels and hydrogen could increase their share through policies, investments and research and they provide possible future shares of for each energy carrier.

BP in their Energy Outlook Report published in 2020 (BP, 2020) take into account three scenarios so as to develop strategies regarding the possible pathways that energy demand could follow in the upcoming years. In their scenarios they highlight that renewable energy will be increasingly important for meeting global energy demand, while oil and gas will be more and more doubted as society aims to become independent of oil. They also expect a mobility revolution as new technologies and needs show up. BP in their report, conclude that they expect energy demand to reach its highest point around 2030, electrification and efficiency improvements to dominate the road transport market and emphasize that hydrogen and biofuels could be a significant part of aviation and shipping energy mix.

However, after examining all the major studies regarding the future energy demand in the transportation sector, I chose to discuss ICCT's and IEA's models and scenarios in detail because these organizations, not only provide high quality research used by governments in order to transform the transportation and the energy sector (ICCT, 2021), (IEA, 2020a), but they also regularly provide a large number of reports and have their models' structure published (ICCT, 2012), (IEA, 2021a) and therefore the modelling methods can be directly compared. Consequently, a comparison of the current research with ICCT's and IEA's studies is ideal so as to highlight issues that these pioneering organizations have not studied in depth or at all and later on to stress the strengths of this research and the points that need to be improved.

2.1 ICCT's Model and Scenarios

According to "VISION 2050" report, ICCT[1] has developed two different scenarios in order to model the transportation emissions until 2050. The first scenario is the "Baseline Trajectory" scenario which assumes that no more policies than the ones already adopted by 2019 are going to be applied. The second scenario is the "Ambitious yet Feasible" which uses assumptions about improved energy efficiency, reduced costs and new policies and regulations (ICCT, 2020). Both of them are described in this chapter.

2.1.1 Model

The transportation scenarios that ICCT presented in "VISION 2050" report have been created using its own modelling tool known as ICCT's Roadmap (ICCT, 2012). The model produces results about the energy and oil demand, the greenhouse gas emissions and the amount of certain pollutants and it is built around six main categories:

1. pollutants: greenhouse gas and local air pollutants (ICCT, 2012a).

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[1] ICCT stands for International Council on Clean Transport. It is an independent non-profit organization which aims to provide high quality research to policymakers in order to transform transportation sector so as to benefit public health and mitigate climate change (ICCT, 2021).

2. modes: two and three wheel vehicles, light duty vehicles, buses, heave duty tracks, passenger and freight trains, passenger aviation and freight shipping (ICCT, 2012a).
3. regions: the ten regions with the highest annual new-vehicle sales (ICCT, 2012a).
4. time horizon: the model takes into account the years from 2000 to 2050 with a time interval equal to 5 years (ICCT, 2012a).
5. fuels: gasoline, ethanol, diesel, biodiesel, CNG, LPG, hydrogen, electricity, jet fuel and residual fuel (ICCT, 2012a).
6. vehicle technologies: internal combustion, hybrid, plug-in hybrid, battery electric and fuel cell vehicles (ICCT, 2012a).

2.1.2 ICCT's Baseline Scenario

ICCT's "Baseline Scenario" predicts that global CO_2 emissions caused by transportation are going to increase substantially and almost annually double from 12 Gt to 21 Gt by 2050. Following the assumption of no further policy adoption, the global transportation emissions map will drastically change. In particular, already adopted policies are going to offset the increase of activity in Europe and the United States, while the policies already adopted in Asia and Africa are not going to deal with the rapid rise of activity in these regions leading to significant emissions increase. Substantial increase is also expected for the global aviation and marine sectors (ICCT, 2020).

However, under the baseline scenario, the target of limiting the global temperature rise below 2^oC, and if possible below 1.5^oC, can not be achieved. As a result, further action should be taken in order to reduce the global CO_2 emissions.

2.1.3 ICCT's Ambitious yet Feasible Scenario

ICCT's "Ambitious yet Feasible" scenario is an approach which could deal with the CO_2 emissions problem and help the world achieve the temperature rise limitation goals. The transportation modes, the fuels, the policies and the assumptions that mainly affect this scenario are presented below:

2.1.3.1 Transportation Modes

Light-duty vehicles (LDVs) include passenger vehicles, light commercial vehicles and motorcycles (both two-wheeled and three-wheeled) (ICCT, 2012b). ICCT estimates that the efficiency of new LDVs can improve by 2 percent annually until

2050 (ICCT, 2020). The GFEI partners agree with this estimation. In particular, according to the GFEI, this annual improvement is necessary so that new passenger vehicles emissions reduce by 50% by 2030 and by 90% by 2050 (GFEI, 2019). Furthermore, the sales of the electric LDVs should increase by 35% by 2030 and by 86% by 2050, while the carbon intensity of the electricity grid should be decreased by 90% between 2020 and 2050 (GFEI, 2019). The most important technologies which can improve current LDVs' efficiency are hybridization, engine downsizing with turbocharging and improved aerodynamics (ICCT, 2020). Moreover, improved compliance with the applied policies could further decrease the emissions up to 0.5% annually by 2030 and 0.25% by 2050 (ICCT, 2020). However, the will of a government to apply new policies is subjected to three limitations:

- Availability of technologies
- The payback time of the implementation of new technologies
- Allowance for a phase-in period

Currently, the United States, Europe, Japan and China are the leading countries regarding global regulatory policies for light duty vehicles. Due to the expected increase of the light duty vehicles number and activity in the future, there should be a permanent and continuous effort for applying new policies and improving efficiency standards (ICCT, 2012b).

Electric Vehicles (EVs) include plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) (ICCT, 2012b). In Europe and China, ICCT assumes that 95% of the global stock of two-wheel and three-wheel vehicles will use electricity and zero-emission vehicles will make up 90% of all passenger vehicles by 2050. For the United States and the rest of the countries, ICCT assumes 66% electrification of the global vehicle stock. Wide-scale commercialization of electric vehicles combined with the decarbonization of electric grid could significantly decrease the greenhouse gases emissions after 2030 (ICCT, 2020).

Heavy-duty vehicles (HDVs) include a wide range of different vehicles used for different types of activities. Some of these are heavy-duty pick up trucks and vans, fire trucks, buses, straight trucks and long-haul tractors. Because of the big variety of vehicles and activities and the geographical diversity compared to the LDVs, it is difficult for policy makers to apply policies and regulations. However, due to the constantly increasing number of HDVs globally, there is an opportunity for globally aligned regulations implementation which would contribute to reduce both carbon emissions and HDVs production costs (ICCT, 2012b).

According to ICCT, global CO_2 emissions caused by new heavy-duty vehicles can be reduced by 2% annually (ICCT, 2020). The GFEI partners agree with this estimation (More specifically, the GFEI partners speak about 1.7% reduction) and they consider this mitigation necessary so that the target of 35% emissions reduction by 2035 and 70% emissions reduction by 2050 (compared to 2005) be achieved. Moreover, the sales of the electric HDVs should increase by 19% by 2030 and by 66% by 2050, while the carbon intensity of the electricity grid should be decreased by 90% from 2020 to 2050 (GFEI, 2019). Key technologies that could be used are improvements regarding engine efficiency and tire resistance and hybridization. Finally, improved compliance with the applied policies could further decrease the emissions up to 0.5% annually by 2030 and 0.25% by 2050 (ICCT, 2020).

The marine sector is a big contributor to the global greenhouse gas emissions. In 2010, it was responsible for about 6 percent of global oil consumption and eleven percent of global greenhouse gas emissions caused by transportation (ICCT, 2012b). Container ships (23%), bulk carriers (19%) and tankers (13%) are responsible for the fifty five percent of the global shipping industry. Improvements that can be made in order to improve efficiency and reduce the emissions include are slow streaming and application of innovative technologies such as hull air lubrication, wind-assisted propulsion, hydrogen fuel cells and batteries (ICCT, 2020).Because of the very little efficiency improvement of ships since 2000, there is space for significant reduction of greenhouse gas emissions in the marine sector (ICCT, 2012b).

Because marine sector is globally active and its operation crosses international borders, it is difficult to be regulated by individual governments. This is why there is the need for global policy frameworks with the contribution of all countries. Actions for a global policy framework in order to improve the efficiency of the ships have been driven by the International Maritime Organization (IMO) (ICCT, 2012b). The International Maritime Organization's Energy Efficiency Design Index (EEDI) requires constant efficiency improvements in the new vessels. IMO's target for 2050 is to decrease 2008's greenhouse gas emissions levels at least by fifty percent (ICCT, 2020).

The aviation sector is another major contributor to the global greenhouse emissions. In 2010, it was responsible for about nine percent of global greenhouse emissions caused by transportation and it is expected to have the highest growth among all the transportation modes (ICCT, 2012b). Some ways to reduce the aviation emissions are:

1. Technology improvement (engine efficiency increase, aerodynamics improve-

ment, lightweight materials use) (ICCT, 2012b).

2. Aircraft activity control (market-based measures (MBMs) such as CO_2 cap-and-trade systems) (ICCT, 2012b).

3. Operations management improvement (air-traffic control improvement) (ICCT, 2012b).

4. Use of low carbon fuels (ICCT, 2012b).

5. Demand Management (carbon pricing, consumer information) (ICCT, 2020).

6. Pause of of new supersonic aircrafts introduction (ICCT, 2020).

These improvements can be achieved by applying certain policies such as CO_2 emission standards, emission trading schemes (ETS) and taxes (ICCT, 2012b).

Aviation sector is also globally active with about sixty percent of fuel being consumed on international flights. As a result, there should be developed both global and local policy frameworks. Actions for a global policy framework in order to reduce aviation greenhouse gas emissions have been driven by the International Civil Aviation Organization (ICAO). The European Union has also started its own CO_2 cap-and-trade system since 2012 (ICCT, 2012b).

2.1.3.2 Fuels

In order for transportation sector to be fully decarbonized, decarbonization of the electricity grid should also be achieved. In other words, the energy sources that will be mostly used in transportation sector - electricity and liquid or gaseous fuels - should be produced by low carbon procedures. In this scenario, it is assumed that the grid will be almost fully decarbonized by 2050 (ICCT, 2020).

Electricity is expected to be one of the major transportation fuels until 2050 and especially regarding on-road vehicles and small ships and aircrafts. Electric vehicles use electricity to move. In particular, they absorb energy (electricity) from the grid by connecting to a charging station and they store the electricity into rechargeable batteries. The batteries are used as a source of electricity for the electric motor which is able to move the wheels when it is operated (edf, 2020). Electric vehicles are much more efficient than the conventional vehicles and at the same moment they are compatible with renewable energy sources which are necessary for the decarbonization of the electricity grid (ICCT, 2021).

Consequently, a combination of decarbonization of the electricity grid and an increase in the share of electric vehicles in the market would lead to the reduction of both tank-to-wheel [2] and well-to-wheel [3] (GFEI, 2019).

As figure 2 indicates there are different types of electric vehicles depending on the degree of electrification. An EV that relies on a battery which is charged from the grid and is totally powered by electricity is referred as a Battery Electric Vehicle (BEV). A Plug-in Hybrid Electric Vehicle (PHEV) combines a battery which is smaller than the battery of a BEV and can also be charged with electricity to operate and an internal combustion engine (ICE) when the battery is discharged (IRENA, 2013). A Hybrid Electric Vehicle (HEV) combines a battery and an internal combustion engine but the difference is that the battery is not able to absorb energy directly from the grid and it can only be charged through regenerative breaking system and the internal combustion engine (U.S. Department of Energy, n.d.). Until now, Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) have achieved considerable penetration into the market (IRENA, 2017). The further deployment of electric vehicles in the market depends on the implementation of four strategies:

1. The electrification of the vehicles.
2. The installation of sufficient charging stations.
3. The decarbonization of the electricity grid.
4. The connection of the EVs with decarbonized grid.

For the successful implementation of these strategies, it is necessary to apply policies so as to promote electrification of the vehicles fleet.

Hydrogen is a fuel with great potential which can be part of the future energy mix of the transportation sector (European Commission, 2021b). In general, hydrogen is an energy carrier which can be used to store and deliver energy produced from other energy sources. As a fuel, hydrogen is a zero-carbon fuel which can be produced by several processes. The most common are the reformation of fossil fuels (usually reformation of natural gas) and electrolysis (the separation of water molecules to produce hydrogen by the use of electricity) (U.S. Department of Energy, n.d.-b). However, in order to mitigate the climate change and reduce

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[2] "Tank to wheel" (TTW) emissions refer to the emissions consumed onboard a vehicle (GFEI, 2019)

[3] "Well to wheel" (WTW) emissions refer to the emissions produced both onboard a vehicle and during the fuel production process (GFEI, 2019).

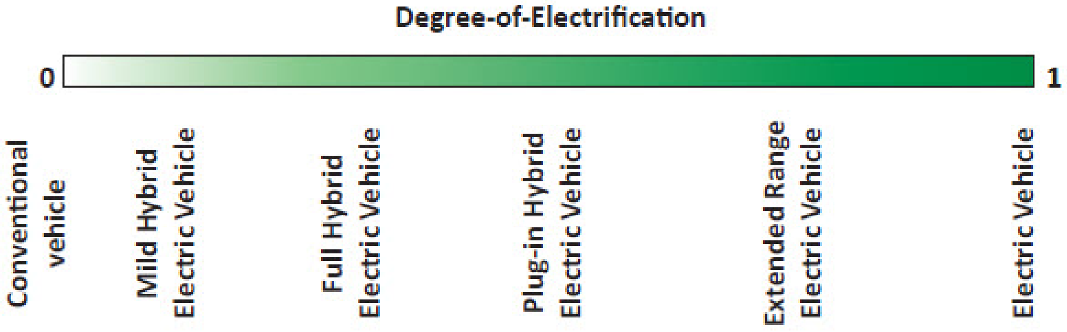

Figure 2: Degree of Electrification of an Electric Vehicle (IRENA, 2013)

greenhouse gas emissions caused by transportation, the hydrogen used for transportation purposes should be produced by the use of electrolysis and electricity used for electrolysis should be produced by renewable energy sources.

Regarding transportation, hydrogen can be used in both fuel cells and internal combustion engines but the use of hydrogen in internal combustion engines is not efficient enough compared to fuel cells (U.S. Department of Energy, n.d.-a). In particular, Fuel Cell Electric Vehicles (FCEVs) are more efficient than both hydrogen internal combustion engines and conventional internal combustion engines and they only cause water vapor emissions. A fuel cell is able to use hydrogen and oxygen molecules in order to produce electricity (and water) through an electrochemical process (U.S. Department of Energy, n.d.). As a result, a fuel cell electric vehicle uses electricity produced by hydrogen in order operate. As mentioned before, hydrogen is fuel with great potential. However, for its further penetration into the transportation sector, further investments on the infrastructure and research on production, delivery and storage as well as on the fuel cell technology and the vehicles manufacturing should be made (U.S. Department of Energy, n.d.-c).

Biofuels are an alternative type of fuels which could substitute the conventional fuels or even be blended with them (European Commission, 2021a). Biofuels have the potential to limit the use of conventional fuels. However, the biofuels that are currently most used will not decrease the carbon emissions significantly and maybe they will even increase the well to wheel emissions. Research about biofuels which have not achieved wide commercialization yet but have greater potential for carbon savings should be done so that biofuels achieve greater penetration into the market (ICCT, 2012b). IEA (IEA, 2020d) and ICCT (ICCT, 2021) include biofuels in their energy transition reports and they estimate an increase regarding their use in order to mitigate climate change and reduce greenhouse gas emissions.

2.1.3.3 Policies

In order to reduce greenhouse gas emissions and manage global energy demand in transportation sector, governments need to design policy plans. There are several policies that can be introduced by governments in order to combat climate change. The main policies that ICCT takes into account in the "Ambitious yet Feasible" scenario are:

1. Efficiency measures which aim to improve the efficiency of the new vehicles (ICCT, 2020).
2. Zero-emissions policy which aims to reach a specific percentage of zero-emission vehicles (ICCT, 2020).
3. Emission policy which aims to introduce vehicles that comply with emission restrictions for certain pollutants (ICCT, 2020).
4. Renewable fuels policy which aims to reach a specific percentage of vehicles using renewable fuels (ICCT, 2020).

2.2 IEA's Model and Scenarios

IEA's[4] World Energy Outlook and World Technology Perspectives are two reports that are published every year and they aim to provide the reader with different energy pathways depending on the choices that the world is going to make and new green technologies in order to deal with climate change. In the "World Energy Outlook 2020" and "Energy Technology Perspectives 2020", IEA has developed two main scenarios in order to model the energy system throughout the years. These scenarios are the Stated Policies Scenario and the Sustainable Development Scenario. For the first scenario, the inputs are given in the starting year of the model leading to future outcomes depending on the inputs given in the starting year, while for the second scenario, the inputs (desired results) are given in the future target year leading to conclusions on what is necessary to be done so that they can be achieved until the future target year (IEA, 2019). It is worth mentioning that, unlike ICCT, IEA creates scenarios regarding the whole energy sector and not just the transportation part. So, in this report, only the parts of IEA's scenarios that refer to transportation sector are going to be presented.

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[4] IEA stands for International Energy Agency. It is an autonomous intergovernmental organization which aims to provide the world with policy recommendations regarding energy issues (IEA, 2020a).

2.2.1 Model

All the energy transition scenarios that are presented by IEA, are produced using the IEA's World Energy Model (IEA, 2019). Regarding transportation sector, the model produces results about the energy demand of the various transportation modes and it is built around the following main categories:

1. modes: two and three wheel vehicles, light duty vehicles, light commercial vehicles, buses, medium and heavy duty tracks, rail, aviation and shipping (IEA, 2020e).
2. countries - regions: only the global transport energy demand is calculated (IEA, 2020e), (IEA, 2017), (IEA, 2019).
3. time horizon: 2000 - 2070 (IEA, 2017) in five year increments.
4. fuels: gasoline, diesel, electricity, hydrogen, biofuels, ammonia, synthetic fuels, natural gas (compressed or liquid), jet fuel, residual fuel (IEA, 2017).
5. vehicle technologies: internal combustion, hybrid, plug-in hybrid, electric and fuel cell vehicles (IEA, 2020e).

2.2.2 IEA's Stated Policies Scenario

The stated policies scenario takes into account all the already adopted policies and the policies that have been announced to be applied in the future. This scenario is not a prediction of the future but rather a detailed analysis of the energy sector transformation out to 2040 strictly based on the current policy framework. Moreover, the stated policies scenario takes into consideration the uncertainties caused by the coronavirus pandemic and the economic crisis (IEA, 2020b).

2.2.3 IEA's Sustainable Development Scenario

According to the results of the stated policies scenario, the world is not going to achieve the three energy-related sustainable development goals (SDGs). This is why IEA developed the sustainable development scenario which is based on a backcasting method so as to achieve the three energy-related sustainable development goals as set by the United Nations. According to the stated policies scenario, based exclusively on the current policy framework, the world will not be able to meet the targets of the United Nations. Consequently, IEA developed the sustainable development scenario so as to set an optimistic but feasible scenario for the successful transformation of the energy sector. Apart from the goals of the

United Nations, the sustainable development scenario is also in line with the Paris agreement aiming to achieve a temperature rise below 1.8 ^{o}C (IEA, 2020c).

The assumptions taken in the sustainable development scenario regarding the transportation sector worldwide are:

- strong focus on electric vehicles and alternative types of fuels penetration and energy efficiency improvement.
- emissions intensity of light duty vehicles to be kept under 55 g CO_2/km in advanced economies and under 70 g CO_2/km in the rest of the wrold by 2040.
- two-stroke engines of two and three-wheel vehicles to be banned.
- the emissions of diesel LDVs and HDVs to be limited.
- the efficiency of medium and heavy freight vehicles to be increased by 25% by 2040.
- the aviation fuel intensity to be decreased by 2.6% annually and.
- biofuels to be further used in the aviation sector depending on the CO_2 target (CO_2 emissions in 2050 should be 50% lower than in 2005).
- greenhouse gas emissions in shipping sector to be decreased below 50% of the 2008 levels according to the IMO strategy.

2.3 Knowledge Gap and Thesis Scope

According to the literature review presented above, the world needs to take action in order to combat climate change. ICCT and IEA are the two biggest organisations which provide studies regarding policy making in the field of transportation in order for the transportation sector to become independent of fossil fuels and contribute in the energy transition towards a green, sustainable society.

However, even though ICCT's and IEA's reports take into consideration plenty of parameters and develop various scenarios, there are still things that could be investigated further in order to provide even more accurate results which are necessary for the formulation of successful policies. To begin with, both of the above mentioned approaches do not model the global transportation energy demand on a country basis and they use five-year increments (ICCT, 2012), (IEA, 2019) which means that the inputs given regarding the countries information and the time that future policies are going to be applied are not accurate. In particular, a country by country approach allows specific country by country modelling since policies adoption is decided on a country-level rather than a region-level, while the one-year increments allow specific chronological determination of the applied policies and, consequently, better representation of their effects.

Regarding ICCT's Roadmap model, there is a strong focus on the road vehicles sector as several modes such as light duty vehicles, buses, 2-wheelers, 3-wheelers and heavy duty vehicles are taken into account, while regarding aviation and shipping sectors, only passenger aviation and freight shipping have been studied, respectively. Furthermore, only road vehicles technologies have been taken into account and there is no technology categorization in the aviation and shipping sectors (ICCT, 2012). Regarding fuels, even though a lot of different fuel options have been taken into account, ammonia is missing. Moreover, ICCT's model instead of using a diffusion model in order to study the potential penetration of new technologies in the market, it gives the future market shares as inputs (in five year increments).

Regarding IEA's World Energy Model, it is also observed that there is no technology categorization in the aviation and shipping sector (IEA, 2019), while a diffusion model for the penetration of new technologies into the market is only used for road transport.

To sum up, although it looks like IEA's model is more complete than the ICCT's one, the truth is that ICCT has developed much more clear scenarios regarding the transportation sectors with more assumptions regarding each transportation mode, fuel and policy (ICCT, 2012), (IEA, 2019). Based on the fact that ICCT makes reports regarding policy making in the transportation sector (ICCT, 2021), while IEA focuses in the whole energy sector (IEA, 2020a), it is rational that ICCT would have developed more detailed scenarios. All in all, ICCT has focused on certain regions, transportation modes, fuels and technologies in detail, while IEA has tried to cover all the types of transportation modes, fuels and technologies in all the subsectors of the energy sector such as industry sector, building sector and transport sector using less detail in its approach.

And this is where the current report is going to contribute to. This study aims to provide a detailed research regarding energy demand modelling with a strong focus on the diffusion of new technologies and alternative fuels working supplementary to the previous studies which have been conducted but they miss wide scope or detail on the study. This goal is linked with detailed modelling of the global energy demand applying theories and models that have not been applied before in order to create a tool able to deal with the weaknesses of the studies described before. In particular, the aim of this project is to study to what extent new technologies and alternative fuels could increase the share of renewable energy in the transportation sector fuel mix and how technology improvements and new policies could reduce the energy demand in the sector. For this to be achieved, the main research question that needs to be answered is:

- How could the global energy demand be limited in the future and which low carbon technologies and fuels could play a major role in the transportation sector in the following years?

For the main research question to be answered, the following sub-questions have been formulated:

1. How could future energy demand be limited by country and transportation mode in the transportation sector?
2. Which low carbon technologies and fuels could dominate in the transportation sector and what role could electricity, hydrogen, biofuels and ammonia play?
3. To what extent could low carbon fuels and new technologies increase their share in the transportation sector?
4. How could the technology improvements, the rate of diffusion of new technologies and the internal combustion engines ban affect the future energy demand?

3 Methodology

In this chapter the methods that were followed in order to answer the research questions are presented.

3.1 Conceptual Framework

The conceptual framework is based on the end-use approach for transportation energy demand forecasting analysis as it is described by Bhattacharyya and Timilsina (Bhattacharyya & Timilsina, 2009). According to this method, the calculations of the future energy demand should take into consideration the variety of transportation modes, the different kinds of vehicles, the efficiency and other characteristics of the transportation sector. Consequently, the methodology used for the transportation energy demand modelling consists of the following steps:

3.1.1 Specification of limitations, delimitations and assumptions

In any research, the researcher is called upon to overcome limitations, set boundaries and make assumptions. These are necessary in order to achieve the goal of the research. The specific limitations, delimitations and assumptions used in this thesis will be discussed in detail in a later chapter.

3.1.2 Data collection

The starting point of the modelling is the input values. The input values directly affect the outcomes of the model and this is the reason why they should be carefully selected. The data collection stage ensures that the best data are chosen in order for the results to be as accurate as possible.

3.1.3 Data treatment

After the input data have been carefully selected, they are processed so as to lead to the desired outcome. This is what the model that is developed aims to do. In this particular thesis, the model is executed by a code written in python language.

3.1.4 Correction of the model

This is a very important stage of the methodology because it allows the researcher to take a look at the model (and its results) before extracting the final results. Depending on the literature, the researcher knows what they can expect and, consequently, they are able to correct the model if some of the results do not make sense. Obviously, this stage follows the data collection and data treatment (in other words the development of the whole model) because it is important for the research to be able to have a complete image of the model.

3.1.5 Presentation of the final results and discussion

After the model has been developed and the necessary corrections have been made, the final outcomes are presented and discussed. The results show not only the data collection and the calculations accuracy but, generally, the reliability of the model. Thus, it is important that the results make sense on the literature review basis and they also support the goals of the thesis. This chapter is probably the most interesting for the reader and, as a result, the researcher should carefully demonstrate and analyze the results.

3.1.6 Discussion and Recommendations

The final stage of the methodology is where conclusions are extracted from the results. Based mostly on the current research and the literature review, the researcher is able to make suggestions regarding the research questions and the aim of this project.

3.2 Theoretical Framework

The theoretical framework aims to present and explain the theoretical background of this research so as to prepare the reader for the model explanation in the next chapter of the report. Below, all the theories used in the model are explained.

3.2.1 Diffusion of Innovations

In order to examine the factors and attitudes associated with the diffusion of new technologies in the field of transport, this research relied on the theory of the diffusion of innovations, which has been the subject of research and a useful tool in many other fields besides transport. Numerous scholars have dealt with the subject and developed interesting theories, all of which are based on that of Everett Rogers (Rogers, 2003), who in his book Diffusion of Innovation focuses on those conditions that increase or decrease the likelihood of a new idea, a new product or new practice to be adopted by members of a specific group of people or by an organization.

To begin with, Joseph Schumpeter (Schumpeter, 1955) has defined innovations as new and improved products and processes, new organizational standards, the application of existing technology in new areas, the discovery of new resources and the development of new markets. Diffusion of an innovation has traditionally been explained as the process by which the innovation "communicates" or otherwise "diffuses" over time to members of a social system through specific channels and means of communication. So, we can say that there are four key elements in a diffusion process:

1. Innovation
2. Channels of communication
3. Time
4. Social system

For Rogers (Rogers, 2003), Innovativeness is a "relative" dimension that indicates the degree to which an individual or other entity is relatively faster at adopting new ideas than other members of the social system. As it is shown in figure 3, not all the members of a social system adopt an innovation at the same time. To be precise, it has been observed that they adopt it following a gradual continuum and therefore can be categorized into groups. Rogers believes that those who adopt an innovation, or even have a predisposition, can be classified into five distinct categories based on the time of adoption and certain information features; the innovators, the early adopters, the early majority, the late majority and the laggards. The differences between the categories are in fact the forces that determine the diffusion of an innovation (Hill et al., 2017).

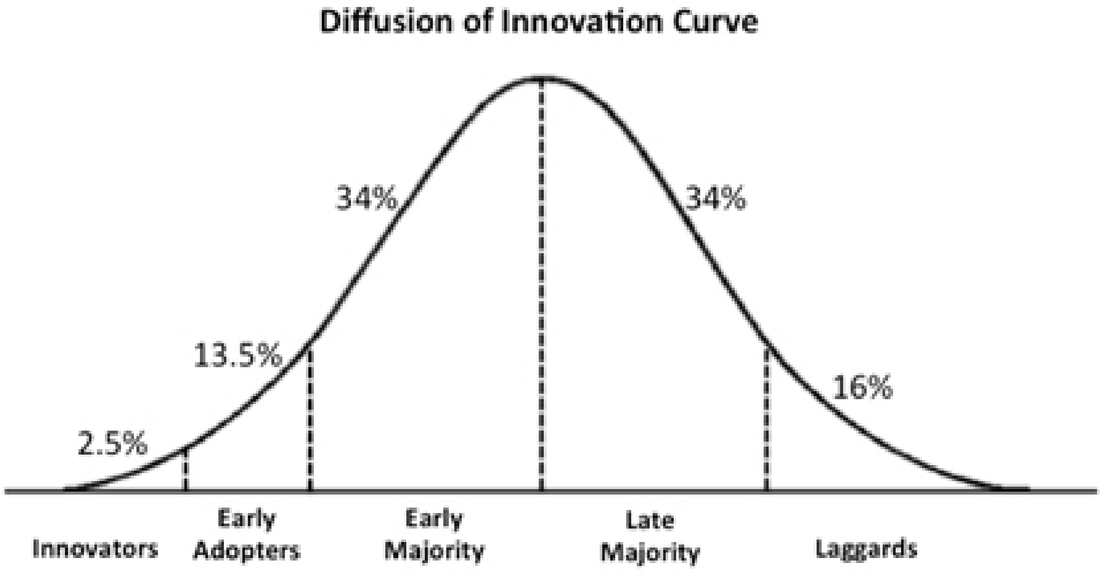


Figure 3: Adopter Classification on the Basis of Innovativeness (Rogers, 2003)

Within the Diffusion of Innovations theory, the purpose is to improve the innovation so as to satisfy the needs of all the categories of adopters. According to Rogers (Rogers, 2003), this is how the market share of the innovation will gradually reach its saturation level. This process of an innovation diffusion into the market can be seen in figure 4.

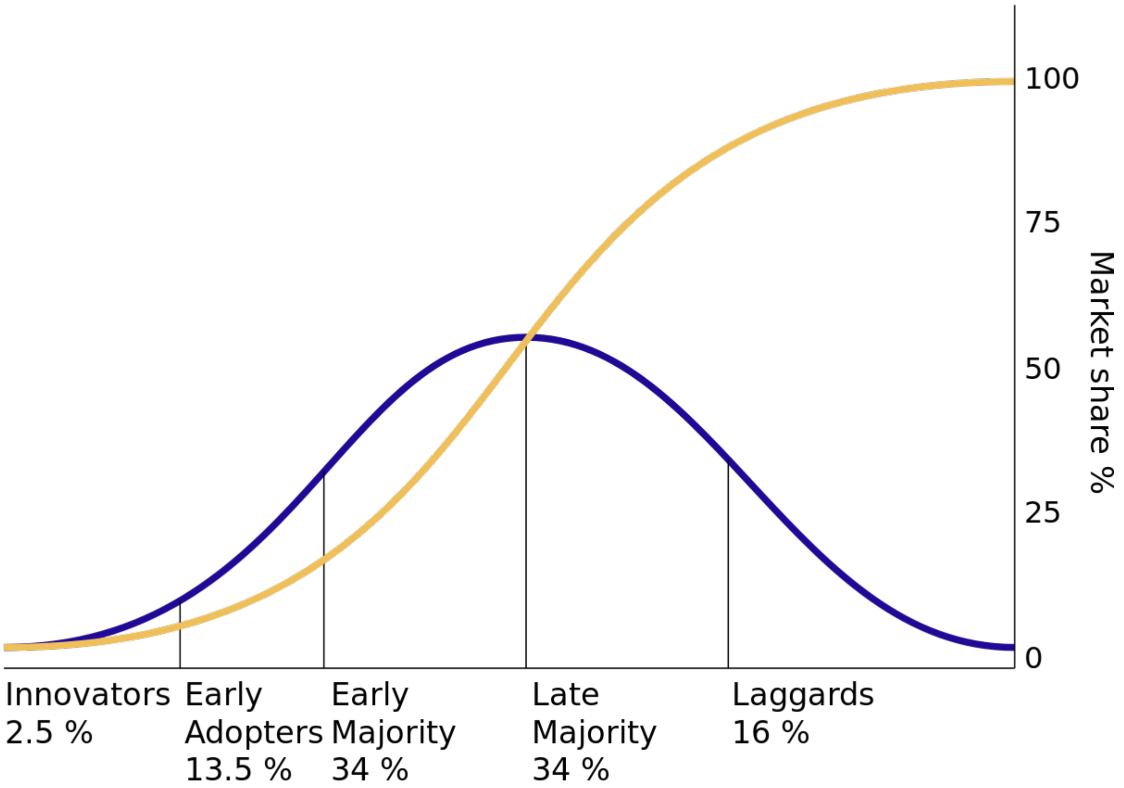


Figure 4: Typical diffusion process (Rogers, 2003)

3.2.2 Bass Diffusion model

In order to evaluate the penetration of products or services, a number of methodologies have been developed and applied, based on the mathematical and statistical background that determines the growth and penetration curves, in relation to the parameters that are the drivers for the adoption of that product at different stages of its life cycle.

The concept of "diffusion models" refers to the development of stochastic mathematical models (functions, time series or statistical processes), that evaluate the demand curve of an innovation using the historical data that exist for the innovation's penetration trajectory. The application of properly selected and fitted models leads to accurate measurements and reliable demand forecasting procedures.

The calculation of the diffusion of an innovation can be done using either qualitative or quantitative methods or a combination of them according to Martino (Martino, 1993). When quantitative methods are used, diffusion models are necessary in order to quantify the diffusion process and, particularly, to calculate the speed of adoption by applying sigmoid curves. Meade and Islam (Meade & Islam, 2006) refer to eight different diffusion models for calculating and forecasting cumulative adoption. These models are: the Bass model, the Cumulative lognormal model, the cumulative normal model, the Gompertz model, the log reciprocal model, the logistic model, the modified exponential model and the Weibull model.

In this study, the **Bass model** is used in order to reflect the deployment of new technologies into the market. It is chosen over other diffusion models because it combines simplicity, possibility for a different model for each technology as it offers the ease of use of different parameters and ability to explain most technology diffusion procedures (PricewaterhouseCoopers, 2018). If the Bass model had not been chosen and a logistic or Gompertz function had been used instead, then the model would not be able to take into account the number of previous adopters thus leading to less accurate results in the long term. According to Kanjanatarakul and Suriya, the Bass Model is proven to be superior than the logistic sigmoid curve when they are used in long term modelling (Kanjanatarakul & Suriya, 2012). Soumia and Maaroufi also compare the Gompertz, the Logistic and the Bass models in order to use the most accurate one in their model about electric cars diffusion in Morocco. They also conclude that the Bass Model is the most accurate after using the r-square and the mean absolute percentage error methods for comparing the models (Soumia & Maaroufi, 2019). Consequently, it becomes clear that the Bass model is the most suitable for this research and is expected to produce the most accurate results compared to the Gompertz and the Logistic models which are also used in similar studies. In particular, the Bass model is a diffusion model which describes the procedure by which new technologies are penetrating into the market and it differs from other similar models because it is based on the assumption that the probability of purchase at a time t is linearly connected to the number of previous buyers, as, according to Bass, there is a behavioral rationale which leads to this assumption. It was presented by Frank Bass in 1969 (Bass, 1969).

To begin with, Bass in his theory considers all four categories of early adopters, early majority, late majority and laggards as imitators. While for innovators the adoption rate does not rise with the adoption procedure increase, imitators' decisions are affected by the other groups of the society. According to Bass, the probability that a first product will be bought at time t and no other products have been bought yet is given from equation 1.

$$P(t) = p + \frac{q}{m} \cdot Y(t) \tag{1}$$

where:

Y_t is the number of adopters at time t

p is constant

$\frac{q}{m}$ is constant

Knowing that Y(0) = 0, the constant p represents the probability of a first product buy at t=0 and its value shows the significance of innovators in the adoption process. The constant $\frac{q}{m}$ indicates the influence rate of imitators as the total adopters grow.

Bass has taken into account two more assumptions in order to define his model. The first is that the market potential of the product is m. The second is that the probability for an adopter to buy a product at time t without any prior purchase to have been done is given by equation 2. Now, equation 1 has been changed in order to represent a density function of time regarding initial purchase of a product. This type of equation comes in the form of a hazard rate ($hazard\_rate = \frac{f(t)}{1-F(t)}$) which describes the conditional probability of default, or in other words, the probability of default when the default has not happened yet (PricewaterhouseCoopers, 2018).

$$P(t) = \frac{f(t)}{1 - F(t)} \tag{2}$$

where:

f(t) is the probability density function of adoption at time t

F(t) = $\int_0^T f(t)\,dt$

So, since f(t) is the probability density function of adoption at time t and m is the market potential of the product, the total number of adopters at time T is given by equation 3.

$$Y(T) = m \cdot \int_0^T f(t)dt = m \cdot F(T) \tag{3}$$

Combining equations 1, 2 and 3 results in equation 4:

$$p + q \cdot F(t) = \frac{f(t)}{1 - F(t)} \tag{4}$$

Now, knowing from equation 4 that $f(t) = (p + q \cdot F(t)) \cdot (1 - F(t)) = p + (q - p) \cdot F(t) - q(F(t))^2$, F(t) can be calculated by solving the differential equation 5.

$$\frac{dF}{dT} = (p + qF) \cdot (1 - F) \tag{5}$$

The solution is given by equation 6.

$$F(t) = \frac{1 - e^{-(p+q)\cdot t}}{1 + \frac{q}{p}e^{-(p+q)\cdot t}} \tag{6}$$

Finally, the number of adopters is given from equation 7. The only variables of this formula are the coefficient of innovation (p), the coefficient of imitation (q) and the market potential (m). The coefficient of innovation shows significance of innovators in a social system and the coefficient of imitation shows the influence of the increasing number of adopters on the imitators.

$$Y(t) = m \cdot F(t) = m \cdot \frac{1 - e^{-(p+q)\cdot t}}{1 + \frac{q}{p}e^{-(p+q)\cdot t}} \tag{7}$$

where:

- $Y(t)$ is the number of adopters at time t
- $F(t)$ is the cumulative distribution function
- p is the innovation coefficient
- q is the imitation coefficient
- m is the market potential

In order for equation 7 to be applied in the model, the parameters p, q and m should be known. The coefficient of innovation (p) and the coefficient of imitation (q) are taken from the "Driving change: technology diffusion in the transport sector" published by PricewaterhouseCoopers in 2018 (PricewaterhouseCoopers, 2018). In that report, several coefficients from different studies are presented. For our research, p and q for electric and fuel cell vehicles are chosen to be equal to p and q coefficients of new Norwegian electric cars between 2003 and 2013 as this approach about regarding electric cars is the most recent one. In particular the coefficient of innovation (p) is equal to 0.002 and the coefficient of imitation (q) is equal to 0.23. Regarding the increase of biofuel percentage used in fuel mixes, the parameters p and q are chosen to be equal to the values of the annual sales of flex-fuel (E85), compressed natural gas and hybrid vehicles in the United States between 1993 and 2002. More specifically, the coefficients p and q are equal to 0.00441 and 0.491, respectively.Finally, the market potential (m) is equal to the expected market share of a technology and it depends on the assumption of each policy maker. For the current research, the market potential assumptions are presented in the scenarios section.

The Bass model can satisfactorily be applied to most new technology diffusion processes as it is a simple and flexible model (PricewaterhouseCoopers, 2018). Moreover, there are plenty of previous researches about diffusion of new technologies using the Bass model and, as a result, there are available parameter values for the innovation coefficient and the imitation coefficient for most of the new technologies used in the transportation sector (PricewaterhouseCoopers, 2018). Consequently, the Bass model is ideal to be used as the diffusion model of this research.

3.2.3 Weibull Distribution

Weibull distribution is a probability distribution which was presented in 1939 by Waloddi Weibull. The Weibull distribution is widely used as a reliability model to describe failure versus time (Meyers, 2001). The Weibull distribution is used in this research in order to model the number of retiring vehicles and it is shown in equation 8 (ICCT, 2012a).

$$x(k) = exp(-[(\frac{k-g}{T})^b]) \tag{8}$$

where:

- k is the age of the product in years
- g is the age at which the product stops operating
- b is the failure steepness
- T is the characteristic service life
- x(k) is the probability that the lifetime is equal or greater than the age k.

3.2.4 Kumaraswamy Distribution

Kumaraswamy distribution is continuous probability distribution defined on the interval (0,1) that was presented by Poondi Kumaraswamy (Kumaraswamy, 1980). It is similar to the beta distribution, which is considered a suitable model for random behaviours of percentages and proportions (Gupta & Nadarajah, 2020), but it is much simpler. For the purposes of this research, the cumulative distribution function of the Kumaraswamy distribution is used so as to allocate the vehicles into ages. This is necessary in order to calculate the retiring vehicles using the weibull distribution. In particular, the Weibull distribution needs the age of the vehicles in years (parameter k in equation 8) so as to calculate the retiring vehicles and the Kumaraswamy distribution provides an age distribution in the base year of the model. In the following years, the model determines the age of the vehicles without the use of Kumaraswamy distribution. The cumulative distribution function of the Kumaraswamy distribution is shown in equation 9 (Jones, 2009)

$$F(x) = 1 - (1 - x^a)^b, \quad 0 < x < 1 \tag{9}$$

where:

- F(x) is the cumulative distribution function
- a,b are the parameters that control the shape of the distribution (a,b > 0)

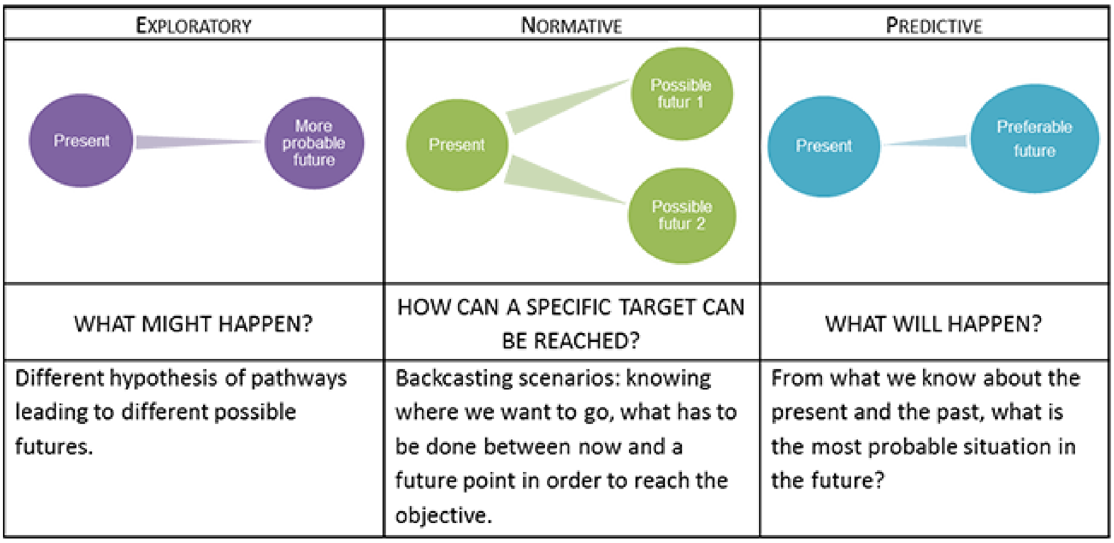
3.2.5 Scenario Planning

Scenario Planning is a strategic planning tool for policy and decision making. Scenarios are instruments used to represent possible "futures" based on present conditions, historical trends and justified assumptions. Thus the main goal of scenarios is not the accurate prediction of the future but the creation and understanding of a possible structure of it by developing a number of different scenarios (Martelli, 2001).

As it is can be seen in figure 5, scenarios can be broken down to three major categories: the exploratory scenarios, the normative scenarios and the predictive scenarios (Borjeson, Hojer, Dreborg, Ekvall, & Finnveden, 2001). In particular:

- The predictive scenarios investigate "What will happen?". In particular, what is the most possible scenario based on the current situation.
- The exploratory scenarios investigate "What might happen?" if the pathway between the present and the future changes.

- The normative scenarios investigate "How can a specific goal be achieved?" and they follow a backcasting method. In other words, what should change in the present in order for a target in the future to be achieved.



Exploratory	Normative	Predictive
WHAT MIGHT HAPPEN?	HOW CAN A SPECIFIC TARGET CAN BE REACHED?	WHAT WILL HAPPEN?
Different hypothesis of pathways leading to different possible futures.	Backcasting scenarios: knowing where we want to go, what has to be done between now and a future point in order to reach the objective.	From what we know about the present and the past, what is the most probable situation in the future?

Figure 5: The three major types of scenarios (Marine Ecosystem Services, 2021)

4 Model Structure

As mentioned earlier in the report, the main target of the thesis is to study to what extent new technologies and alternative fuels can increase the share of renewable energy in the transportation sector fuel mix and how technology improvements and new policies can reduce the energy demand in the sector. In order for this goal to be achieved, it is important to develop a model which will be able to calculate the energy demand in the transportation sector. Consequently, in this chapter the logic, the theory and the assumptions behind the model are presented.

4.0.1 Model Overview

The model consists of five different types of components. These are the external data, the fixed inputs, the input variables, the processes and the outputs. To begin with, the **external data** are big data files which have been found in literature and are given as external input in the model. Such data are the energy balances, the GDP per capita and the population of each country. Next, the **fixed inputs** are inputs that are assigned a value once and they are never going to change again. Such inputs are the current average annual distance travelled per vehicle and the current fuel consumption in each country. The **input variables** are the variables that can be changed by the model user in order to affect the outcome of a scenario. Such inputs are, internal combustion engines ban year, the biofuel mandates percentage and the efficiency improvement for each country. After the inputs have been adjusted, the **processes** stage follow. In the model processes, inputs, assumptions and mathematical formulas are put together in order to lead to the desired outcomes. The **outputs** are the last part of the model.

The model works as follows: At first, most of the variables need to be calculated in the base year of the model. Then, the calculations made for the base year are used in order to calculate the variables for the next year. This procedure operates in a loop allowing the user to insert inputs in the model for the baseyear and getting back results for the whole time period between the chosen base year and target year. In figures 6 and 7 the blocks of the model with the calculations for the base year and the next year, respectively, are shown. The model is described in detail in section 4.5.

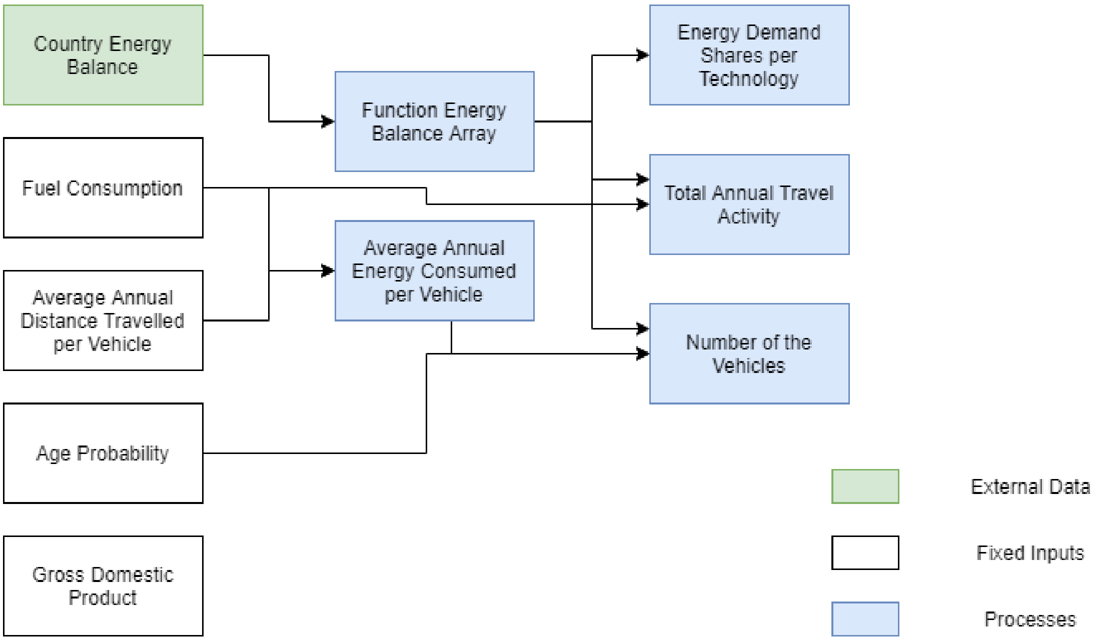


Figure 6: Overview of the Model - Base Year Data Flow Diagram

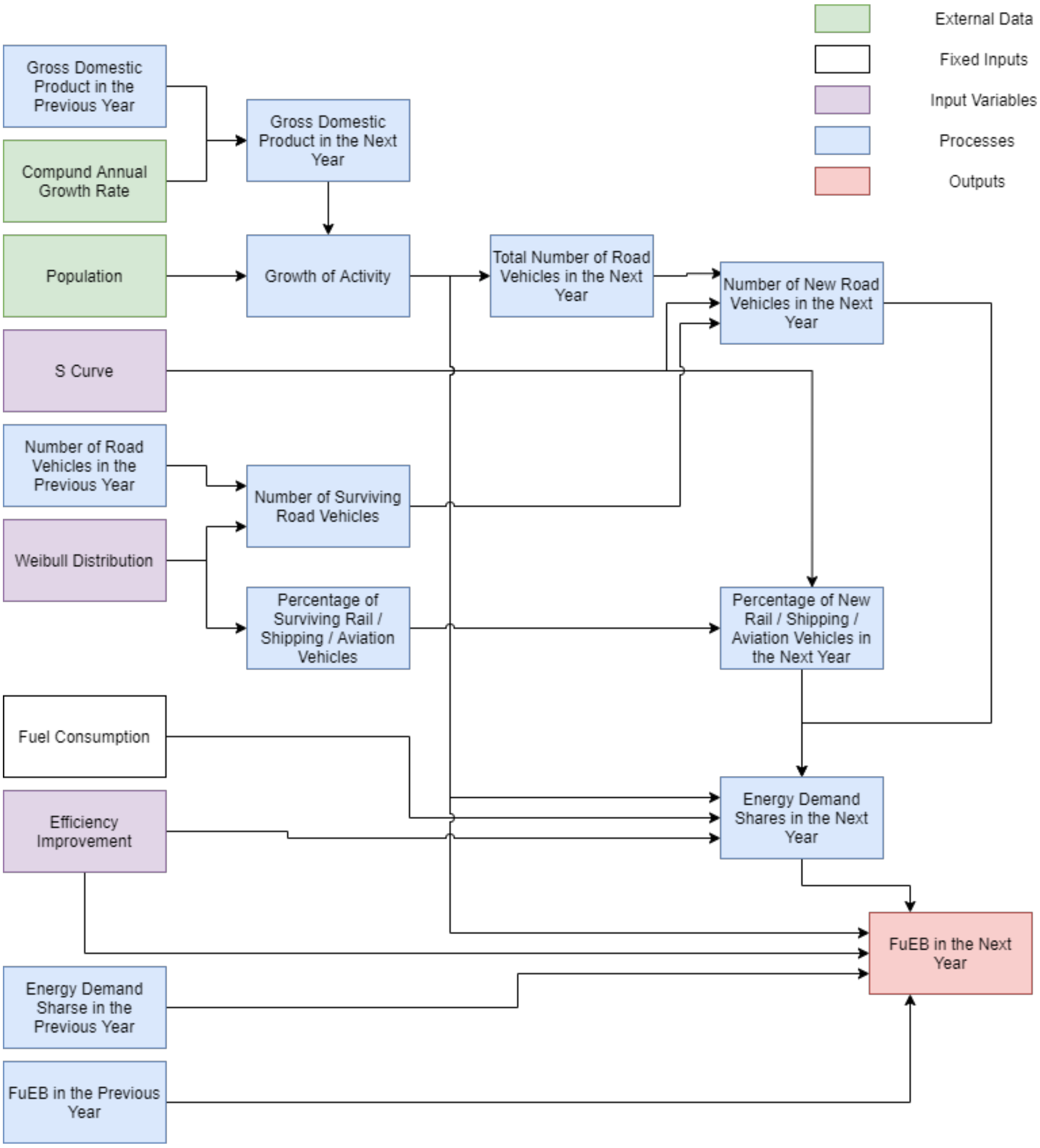


Figure 7: Overview of the Model - Next Year Data Flow Diagram

4.1 Spatial Boundaries

This research attempts to model global transportation energy demand starting from a country basis, so as to take into consideration the particular characteristics of each country separately, and as a result to provide as accurate results as possible. In order for the research to be able to reflect the world energy demand and at the same time the calculations to be made for each country separately, it was decided that the research will be made for the top thirty two energy consuming countries in the world.

According to the United States Energy Information Administration the thirty two countries with the highest energy consumption levels are: China, the United States of America, Russia, India, Japan, Canada, Germany, Brazil, South Korea, Iran, France, Saudi Arabia, the United Kingdom, Mexico, Indonesia, Italy, Turkey, Australia, Spain, Thailand, South Africa, Taiwan, the United Arab Emirates, Poland, Egypt, the Netherlands, Malaysia, Ukraine, Singapore, Pakistan, Vietnam, Argentina. (US EIA, n.d.). At country level, the inputs used for each country separately are the population, the activity of the various means of transport, the parameters of the diffusion model, the percentage of efficiency improvement and more, the year of the internal combustion engines ban, the biofuel mandates and more.

Moreover, for the needs of the model calculations, the countries are classified into nine different areas of the world as the International Energy Agency has defined them based on geographic location and economic situation in the Energy Balances report (IEA, 2020a). These areas are: Africa, OECD Europe, China, Middle East, Non-OECD Americas, Non-OECD Eurasia, OECD Americas, OECD Asia Oceania and Asia (excluding China) and they can also be seen in fugure 8. At region level, the inputs used for each region separately are mainly the fuel consumption values of the various means of transport.

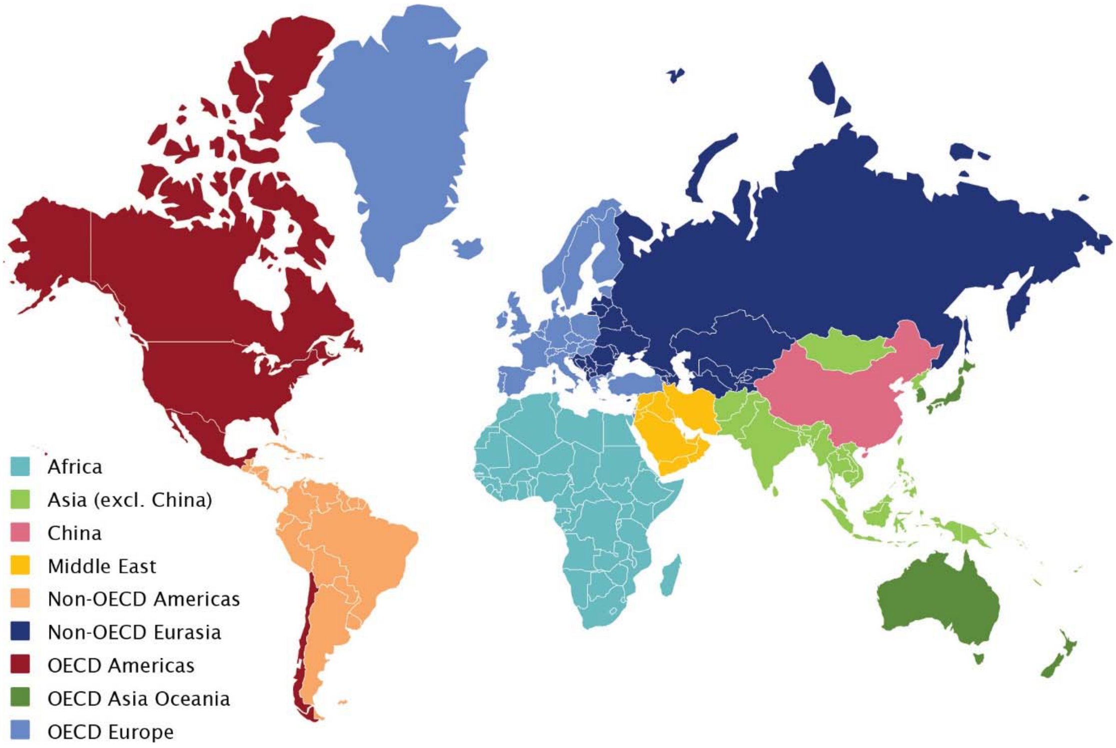


Figure 8: Regions of the world based on geographic location and economic situation (IEA, 2020a)

4.2 Time Boundaries

In this thesis project the beginning of the model (base year) is set to be in 2015 because for this year all the data that are needed for the calculations are available. The latest year that the model makes calculations for is 2050 as most organizations and research groups (such as the European Union, the ICCT and the IEA) has set 2050 as the date by which major targets should have been achieved (ICCT, 2020), (IEA, 2021b). The time interval that was chosen for the model is one year. Most models, such as ICCT's climate roadmap (ICCT, 2012a), use five-year time intervals but in this model one-year time intervals were chosen in order to achieve more accurate results and higher flexibility of the mathematical model.

4.3 Transportation Modes, Technologies and Fuels

For the needs of the energy demand modelling in the transportation sector, the transportation sector is firstly broken down to transportation modes and then the transportation modes are broken down to other subcategories. Moreover, for each mode of transportation different technologies are applied and for each technology different fuels are used. In this chapter, the various modes of transportation and the different technologies and fuels that are used are presented.

4.3.1 Transportation Modes

The transportation sector is broken down to subcategories, based mainly on the ICCT's model (ICCT, 2012a). Firstly, the sector is broken down to categories depending on the mode of transportation and, more specifically, the modes are: land, water and air. Land transportation includes both rail and road transportation. Then, the subcategories are further divided into secondary subcategories that mostly depend on whether the means of transport carry passengers or freight with the exception of water and air transportation which are distinguished into domestic and global transportation. Road transportation is also divided into 2 and 3 wheelers, light duty vehicles, buses and freight. Thus, the four main subcategories of the transportation sector are:

- Road Transportation:
  - Passengers:
    - 2 and 3 wheelers
    - Light Duty Vehicles
    - Buses
  - Freight:
- Rail Transportation:
  - Passengers
  - Freight
- Water Transportation:
  - Domestic
  - Global
- Air Transportation:
  - Domestic
  - Global

4.3.2 Technologies and Fuels

There is a number of engine technologies used in each mode of transportation. In this research, the most important technologies that are currently used and the technologies that are expected to grow in the next years are taken into consideration. In road transport, the engine technologies are divided into spark ignition gasoline engines, compression ignition diesel engines, fuel cell engines and electric engines as it can be seen in table 1. In particular, the spark ignition gasoline engines use gasoline (Tsolakis, Bogarra, & Herreros, 2017), compressed natural gas (CNG) (US Department of Energy, n.d.) and liquified petroleum gas (LPG) (IEA AMF, n.d.) as fuels, the compression ignition diesel engines use diesel and biofuels as fuels (Tsolakis et al., 2017), while the fuel cell engines use hydrogen (Tsolakis et al., 2017) (in general more fuels are used in fuel cell engines such as ammonia, but for road transport only hydrogen is expected to have significant penetration into the market) and electric engines use electricity as energy carriers (US Department of Energy, n.d.).

Table 1: Technologies and Fuels in Road Transport

Technologies and Fuels in Road Transport	
Technologies	**Fuels**
Spark Ignition Gasoline Engines	Gasoline, CNG, LPG
Compression Ignition Diesel Engines	Diesel, Biofuels
Fuel Cell Engines	Hydrogen
Electric Engines	Electricity

As it can be seen in table 2, in rail transport, the engine technologies are distinguished into steam locomotives (which are not used in most countries of the world anymore (Grabar, 2012)), internal combustion locomotives, fuel cell and electric locomotives. More specifically, the steam locomotives used to use coal as fuel (Grabar, 2012), the internal combustion locomotives use diesel, gasoline, compressed natural gas and biofuels as fuels (WWR, 2012), while the fuel cell and the electric locomotives use hydrogen and electricity respectively (WWR, 2012), (Hirschlag, 2020).

Table 2: Technologies and Fuels in Rail Transport

Technologies and Fuels in Rail Transport	
Technologies	**Fuels**
Steam Locomotive	Coal
Internal Combustion Locomotive	Diesel, Gasoline, CNG, Biofuels
Fuel Cell Locomotive	Hydrogen
Electric Locomotive	Electricity

As it can be seen in table 3, in water transport, the engine technologies are distinguished into steam engines, diesel engines, gas turbines, fuel cell engines and electric engines. In particular, steam engines use coal, diesel engines use heavy fuel oil (HFO), diesel, gasoline, liquified petroleum gas and biofuels (ShipInsight, 2019), gas turbines use compressed natural gas (ShipInsight, 2019), while fuel cell use hydrogen and ammonia and electric engines use electricity.

Table 3: Technologies and Fuels in Water Transport

Technologies and Fuels in Water Transport	
Technologies	**Fuels**
Steam Engine	Coal
Diesel Engine	HFO, Diesel, Gasoline, LPG, Biofuels
Gas Turbine	CNG
Fuel Cell Engine	Hydrogen, Ammonia
Electric Engine	Electricity

As it can be seen in table 4, in air transport the engine technologies are distinguished into turbine engines, piston engines, fuel cell engines and electric engines. More specifically, turbine engines use kerosene jet fuel (iJET, 2021), piston engines use aviation gasoline (iJET, 2021), fuel cell engines use hydrogen and ammonia and electric engines use electricity.

Table 4: Technologies and Fuels in Air Transport

Technologies and Fuels in Road Transport	
Technologies	**Fuels**
Turbine Engine	Kerosene Jet Fuel
Piston Engine	Aviation Gasoline
Fuel Cell Engine	Hydrogen
Electric Engine	Electricity

4.4 Data Collection

The starting point of the modelling is the input values. The input values directly affect the outcomes of the model and this is the reason why they should be carefully selected. The data collection stage ensures that the best data are chosen in order for the results to be as accurate as possible.

The main data that were given as inputs in the beginning of this research are the energy demand per country and per mode of transport for the baseyear, the population per country for the baseyear, the gross domestic product per capita (GDP_{PC}) per country for the baseyear, the compound annual growth rate (CAGR) per country and per year and some scores and weights for the energy efficiency per country in the baseyear. More input data are going to be presented in the next chapters of the report.

The energy demand values were taken by International Energy Agency's Energy Balances database (IEA, 2020a). In particular, the International Energy Agency annually publishes the Energy Balances report which provides detailed data about more than 180 countries worldwide. The report includes data about the energy supply and demand in a large number of different sectors and for various types of fuels.

The population values were taken from the United Nations' World Population Prospects database (United Nations, 2019). The United Nations annually publish a comprehensive report which contains projections about the population growth per country. The report is based in several indicators like fertility and mortality rates and age and sex percentages.

The gross domestic product per capita values - which instead of GDP_{PC} is going to be called as GDP in this report - and the compound annual growth rate values are taken from the International Monetary Fund's World Economic Outlook databases (International Monetary Fund, 2020b). The International Monetary Fund usually publishes the report twice a year and it contains analyses and projections about the near and medium term economy situation based on economic and policy developments in its member countries.

4.5 Mathematical Model

The mathematical model is the procedure which is followed in order to calculate the desired outcomes. This procedure uses and combines all the limitations, the assumptions and the theoretical background in order to produce results. In this chapter, the model is explained step by step.

4.5.1 Energy Balances and FuEB Array - Baseyear

As mentioned before, the International Energy Agency annually publishes the Energy Balances report which provides detailed data about more than 180 countries worldwide. The model uses the energy balances data in order to assign an energy demand value to each cell of a five-dimension array. The dimensions of the array are:

- 1st Dimension: Countries
- 2nd Dimension: Years
- 3rd Dimension: Energy Functions
- 4th Dimension: Technologies
- 5th Dimension: Fuels

The name of the five-dimension array that is created is FuEB which means Functions Energy Balance. So, in order for this array to be created, the IEA balances are given as input to the code. Then, the code uses the input data so as to produce the FuEB array. After the data are processed and the FuEB array is created, then, for all the given countries (1st Dimension), for the selected baseyear (1st element of the 2nd Dimension) (the starting year of the modelling simulation), for all the energy functions (3rd Dimension), the technologies (4th Dimension) and the fuels (5th Dimension), the cells of the array are assigned a unique energy demand value. This block of the model is shown in figure 9 .

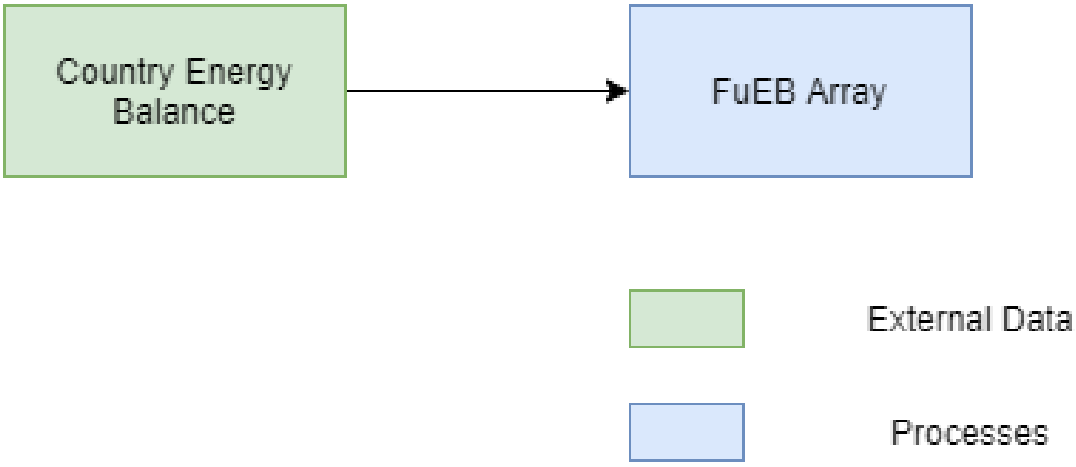


Figure 9: Energy Balances produce FuEB array

The calculation of all the values of the FuEB array is the main target of the mathematical model. In particular, the mathematical model must be able to calculate the energy demand of all the selected countries, for the whole selected time frame, for all the chosen energy functions, technologies and fuels. After the model is completed, the user should be able to change certain inputs (input variables) in order to build different scenarios.

4.5.2 Energy Demand Shares per Technology - Base Year

After the baseyear energy demand values have been inserted in the FuEB array, energy demand shares per technology are calculated for the baseyear. The energy demand share per technology is equal to the energy demand of the technology divided by the energy demand of the energy function in which the technology belongs. The energy demand of each function and the energy demand of each technology of the function are calculated from the FuEB array which is already known. Thus, the energy demand of a technology is the sum of the energy demand values of every fuel used in this technology, while the energy demand of a function is the sum of the energy demand values of every technology of the function. The energy demand shares per technology are calculated for all functions. As mentioned before, each energy function is split into technologies. For example, Light Duty Vehicles (LDV) are split into spark ignition gasoline engine vehicles, compression ignition diesel engine vehicles, fuel cell vehicles and electric vehicles. So, LDVs are the energy function while the types of the engines described before are the technologies. Consequently, the formula which calculates the energy demand shares of each technology is 10. This block of the model is shown in figure 10 .

$$TSED = \frac{TED}{FED} \tag{10}$$

where:

- TSED is the Energy Demand Share per Technology
- TED is the Energy Demand per Technology within one function
- FED is the Energy Demand of the Function

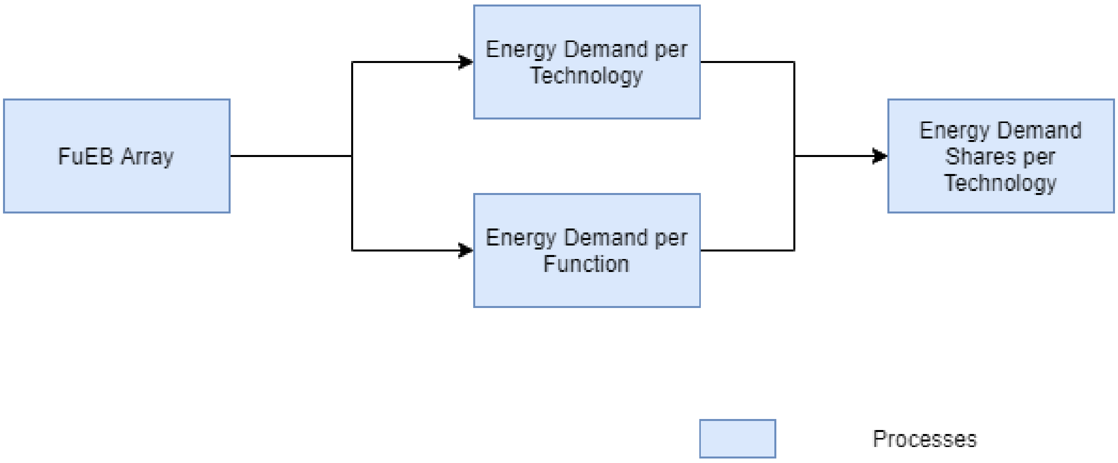


Figure 10: Energy Demand Shares per Technology - Base Year Data Flow Diagram

4.5.3 Average Annual Energy Consumed per Vehicle - Base Year

The average annual energy consumed per vehicle is a variable used for the calculation of the number of road vehicles (it is not used for rail, shipping and aviation). In the base year, it is equal to the average annual distance travelled per vehicle multiplied with its fuel consumption as it is shown in equation 11 and it is calculated per technology and per function. The average annual distance travelled per vehicle and the fuel consumption are fixed inputs (they are fixed inputs because they are data taken from literature and they are not based on scenario assumptions). In particular, the average annual distance travelled per vehicle variable depends on the country and the energy function which means that the variable's value for France's light duty vehicles is different than the value for France's buses (same country - different function) and the variable's value for China's freight vehicles is different than the value for Japan's freight vehicles (different country - same function). The fuel consumption depends on the region, the function, and the technology which means for the fuel consumption value is different if just one of those three parameters is different. The input values for the average annual distance travelled per vehicle are taken from the United Nations Economic Commission for Europe (United Nations Economic Commission for Europe, n.d.), the Organisation for Economic Co-operation and Development (Organisation for Economic Co-operation and Development, 2019) and the Global Transportation Energy and Climate Roadmap (ICCT, 2012a) and are presented in table 9 in the Appendix, while the input values for the vehicles fuel consumption are taken from the Global Transportation Energy and Climate Roadmap (ICCT, 2012a) and are presented in tables 10, 11, 12, 13, 14, 15, 16 and 17 in the Appendix. This block of the model is shown in figure 11.

$$AAECPV = AADTPV \cdot FC \tag{11}$$

where:

- AAECPV is the Average Annual Energy consumed per Vehicle
- AADTPV is the Average Annual Distance Travelled per Vehicle
- FC is the Fuel Consumption

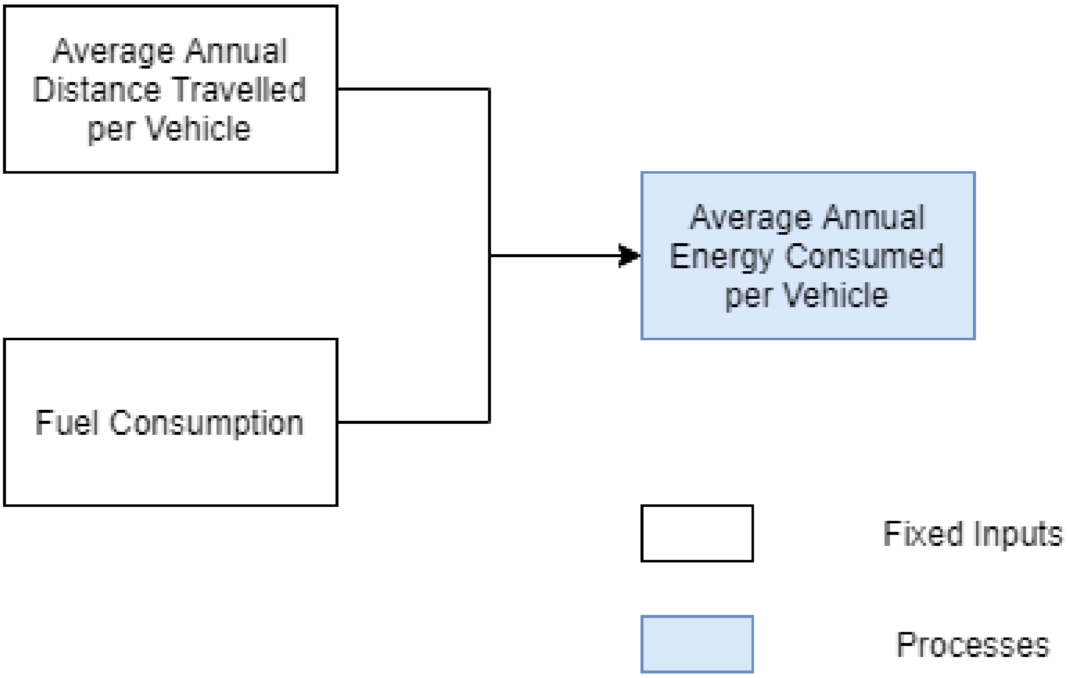


Figure 11: Average Annual Energy consumed per Vehicle - Base Year Data Flow Diagram

4.5.4 Number / Percentage of Vehicles - Base Year

At this point in the model, the number or the percentage of all kind of vehicles (road, rail, shipping and aviation) are calculated for the baseyear. They are calculated per technology, per function and per age. However, the calculation methods for road vehicles and for the rest of the vehicles are different.

Regarding road vehicles, the number of the vehicles is equal to the energy demand per technology divided by the product of average annual energy consumed per vehicle with the percentage of the vehicles of this age as it is shown in equation

12. The energy demand per technology and the average annual energy consumed per vehicle have already been calculated, while the percentage of the vehicles in each age (age probability) is taken from the Kumaraswamy distribution which is described in the Methodology chapter. This block of the model is shown in figure 12.

$$NoV = \frac{TED}{AAECPV \cdot AP} \tag{12}$$

where:

- NoV is the Number of Vehicles
- AAECPV is the Average Annual Energy consumed per Vehicle
- AP is the Age Probability (taken by the Kumaraswamy Distribution)

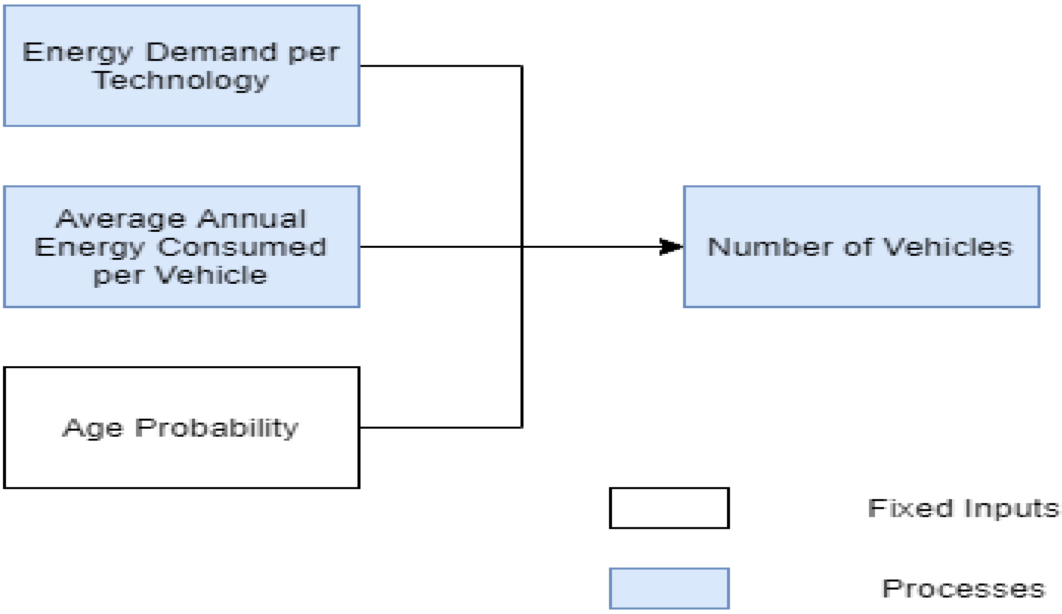


Figure 12: Number of Vehicles - Base Year Data Flow Diagram

Regarding rail, shipping and aviation "vehicles", the percentage of the vehicles is calculated and it is equal to the percentage of the vehicles of this age in the baseyear as it is shown in equation 13. This block of the model is shown in figure 13.

$$PoV = AP \tag{13}$$

where:

- PoV is the Percentage of Vehicles
- AP is the Age Probability

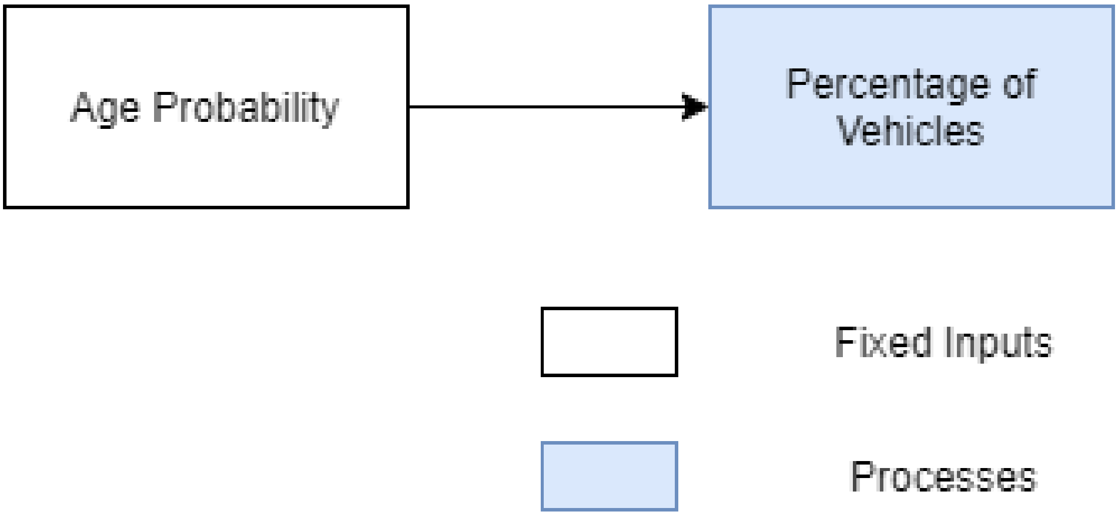


Figure 13: Percentage of Vehicles - Base Year Data Flow Diagram

4.5.5 Total Annual Travel Activity - Base Year

The total annual travel activity (TATA) is necessary for the calculation of the future energy demand. This variable is only used for the rail, shipping and aviation sectors and it is similar to the AAECPV (average annual energy consumed per vehicle) variable for the road sector. It is equal to the quotient of the energy demand per technology divided by the fuel consumption as it is shown in equation 14. TATA is calculated per technology and per function. This block of the model is shown in figure 14.

$$TATA = TED \cdot FC \qquad (14)$$

where:

- TATA stands for Total Annual Travel Activity
- FC stands for Fuel Consumption

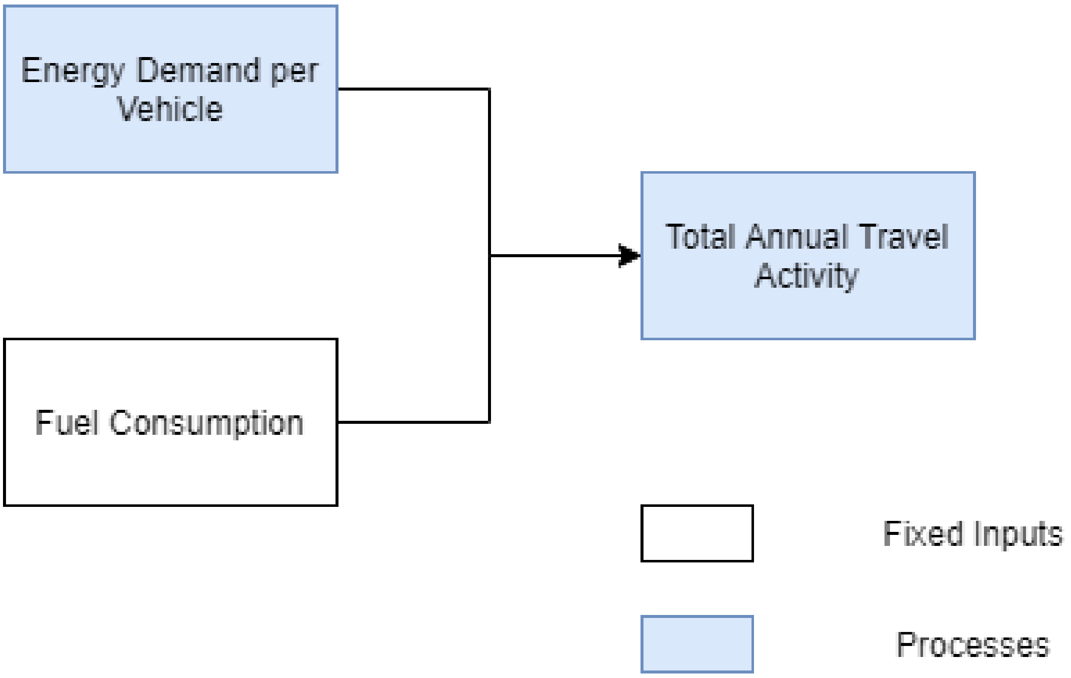


Figure 14: Total Annual Travel Activity - Base Year Data Flow Diagram

4.5.6 Gross Domestic Product - Base Year

The gross domestic product (GDP) is necessary for the calculation of the activity. It depends on the country and the year. For the baseyear, the GDP values are given as fixed inputs which are different for each country.

4.5.7 Gross Domestic Product - Next Year

The gross domestic product (GDP) for the next year is the product of the GDP of the previous year multiplied by the compound annual growth rate (CAGR) value which is taken from IMF's World Economic Outlook (International Monetary Fund, 2020a). The CAGR value depends on the geographic region and on the time period and in most cases it follows a decreasing trend over time. The regions used in this model have been described earlier in the report, while there are three different CAGR values for three different time periods (the time periods are 2000-2018, 2018-2030, 2030-2050). As a result, the GDP of the next year also depends on the country and the year and is calculated by equation 15.

$$GDP_{y+1} = GDP_y + GDP_y \cdot CAGR \tag{15}$$

where:

- GDP_{y+1} is the Gross Domestic Product of the Next Year
- GDP_y is the Gross Domestic Product of the Previous Year
- CAGR is the Compound Annual Growth Rate

4.5.8 Number of Road Vehicles - Next Year

At this point in the model, the number of road vehicles is calculated for the next year. They are calculated per technology, per function and per age. The first thing that is calculated is the total number of vehicles per function in the new year which is equal to the product of the total number of vehicles in the previous year (already calculated) multiplied with the sum of one and the growth of the total number of vehicles from the previous year to the new year as it shown in equation 16. The growth of the total number of vehicles is equal to the growth of activity as it indicated in equation 17.

$$TNoV_{y+1} = TNoV_y \cdot (1 + dTNoV) \tag{16}$$

where:

- $TNoV_{y+1}$ is the Total Number of Vehicles in the Next Year
- $TNoV_y$ is the Total Number of Vehicles in the Previous Year
- dTNoV is the Growth of the Total Number of Vehicles between the Previous Year and the Next Year

$$dTNoV = dAct \tag{17}$$

where:

- dTNoV is the Growth of the Total Number of Vehicles between the Previous Year and the Next Year
- dAct is the Growth of Activity between the Previous Year and the Next Year

In order to calculate the growth of activity, the gross domestic product and the population of the previous and the next year should be known. If the GDP and the population values are already known, then the growth of activity is calculated by the formula shown in equation 18.

$$dAct = -1 + \frac{Pop_{y+1}}{Pop_y} \cdot \frac{f(GDP)_{y+1}}{f(GDP)_y} \tag{18}$$

where:

- dAct is the Growth of Activity between the Previous Year and the Next Year
- Pop is the Population
- GDP is the Gross Domestic Product
- f is a function taken from Pieter van Exter's thesis project (van Exter, 2017), which is different for each function and is only used for the calculation of the Growth of Activity

After the calculation of the total number of vehicles per function in the next year, the calculation of the total number of surviving (not retiring) vehicles per function in the next year follows. The total number of surviving vehicles per function in the next year is equal to the sum of the products of the number of vehicles per function in the previous year with the Weibull survival curve for all ages as it is shown in equation 19. The total number of surviving vehicles in the next year is also calculated for each technology and each age in the same way. It is also worth mentioning that the parameters used in the survival curve are taken from the Global Transportation Energy and Climate Roadmap (ICCT, 2012a) and they can be seen in table 5.

$$TNoSV_{y+1} = \sum_{age=1}^{50} (NoV_{y_{age}} \cdot SurvivalCurve_{age}) \tag{19}$$

where:

- TNoSV is the Total Number of Surviving Vehicles in the Next Year
- NoV is the Number of Vehicles
- Survival Curve is a Weibull Distribution Curve used to describe failure versus time as it is described earlier in the report

Table 5: Survival Curve Parameters

Survival Curve Parameters			
Function	**b**	**T**	**g**
Road LDVs	1.9	16	4
Road Light	1.9	16	4
Road Buses	1.8	20	2
Road Freight	1.8	20	2
Rail Passenger	2.5	29	0
Rail Freight	2.5	29	0
Aviation	4.1	26	7
Shipping	6	8.5	0

Knowing the total number of vehicles (**per function**) in the new year and the total number of surviving vehicles (per function) from the previous year to the new year, it is possible to calculate the total number of new vehicles (per function) entering the fleet in the new year. The total number of new vehicles entering the fleet in the new year is simply the difference between the total number of vehicles in the new year and the total surviving vehicles from the previous year to the new year as it can be seen from equation 20.

$$TNoNV_{y+1} = TNoV_{y+1} - TNoSV_{y+1} \tag{20}$$

where:

- TNoNV is the Total Number of New Vehicles (for a certain function) entering the fleet
- TNoV is the Total Number of Vehicles
- TNoSV is the Total Number of Surviving Vehicles
- The index y represents the previous year
- The index y+1 represents the next year

After the total number of new vehicles **per function** entering the fleet in the new year has been calculated, the number of new vehicles **per technology** entering the fleet in the new year is calculated. In this point in the model, the diffusion theory, and in particular the bass model, is used in order to model the diffusion of new technologies in the market. In this research, **the electric vehicles and the fuel cell vehicles are considered as new technologies** which will have much more significant market shares in the future. The number of new vehicles

per technology entering the fleet in the new year is equal to the product of the total number of new vehicles entering the fleet in the new year multiplied with the s curve value of the technology as it is shown in equation 21.

$$TNoNV_{tech_{y+1}} = S\_Curve_{y+1} \cdot TNoNV_{y+1} \tag{21}$$

where:

- $TNoNV_{tech}$ is the Total Number of New Vehicles per technology (for a certain function) entering the fleet
- S-Curve is the diffusion curve
- TNoNV is the Total Number of New Vehicles
- The index y represents the previous year
- The index y+1 represents the next year

The value of the Bass model s-curve is given by the formula shown in equation 22. The coefficients of innovation and imitation are taken from the research of Jerome Massiani and Andreas Gohs (Massiani & Gohs, 2015) while the maximum market share is taken from the literature depending on the technology and the country.

$$S - curve = max\_market\_share \cdot \frac{1 - e^{-(p+q)\cdot t}}{1 + (\frac{q}{p}) \cdot e^{(-(p+q)\cdot t}} \tag{22}$$

where:

- max_market_share is the maximum market share that the technology is expected to reach
- p is the coefficient of innovation
- q is the coefficient of imitation
- t is the time in years that have passed since the base year

For the conventional technologies (spark ignition gasoline engine and compression ignition diesel engine), the calculation method is different. More specifically, the total number of new vehicles entering the fleet for those technologies is shown in equation 23 and 24.

$$TNoNV_{SIGE_{y+1}} = gasoline_{perc} \cdot (TNoNV_{y+1} - TNoNV_{EV_{y+1}} - TNoNV_{FC_{y+1}}) \tag{23}$$

$$TNoNV_{CIDE_{y+1}} = TNoNV_{y+1} - TNoNV_{EV_{y+1}} - TNoNV_{FC_{y+1}} - TNoNV_{SIGE_{y+1}} \tag{24}$$

where:

- $TNoNV_{tech}$ is the Total Number of New Vehicles entering the fleet
- SIGE is the Spark Ignition Gasoline Engine Technology
- CIDE is the Compression Ignition Diesel Engine Technology
- EV is the Electric Engine Technology
- FC is the Fuel Cell Engine Technology
- $gasoline_{perc}$ is the percentage of ICE vehicles using SIGE technology (this percentage is assumed to be equal to the same percentage in the base year)
- The index y represents the previous year
- The index y+1 represents the next year

Moreover, the values of the number of new vehicles per technology entering the fleet depend on the year that the use of internal combustion engine (ICE) vehicles is going to be banned in each country. After the ICE ban year, the production of new conventional technology cars is set equal to zero and only electric and fuel cell vehicles are produced. To sum up, after all the calculations that were presented in this section, the number of the vehicles per function, per technology and per age is calculated for the next year. The block of the code described in this section is shown in figure 15.

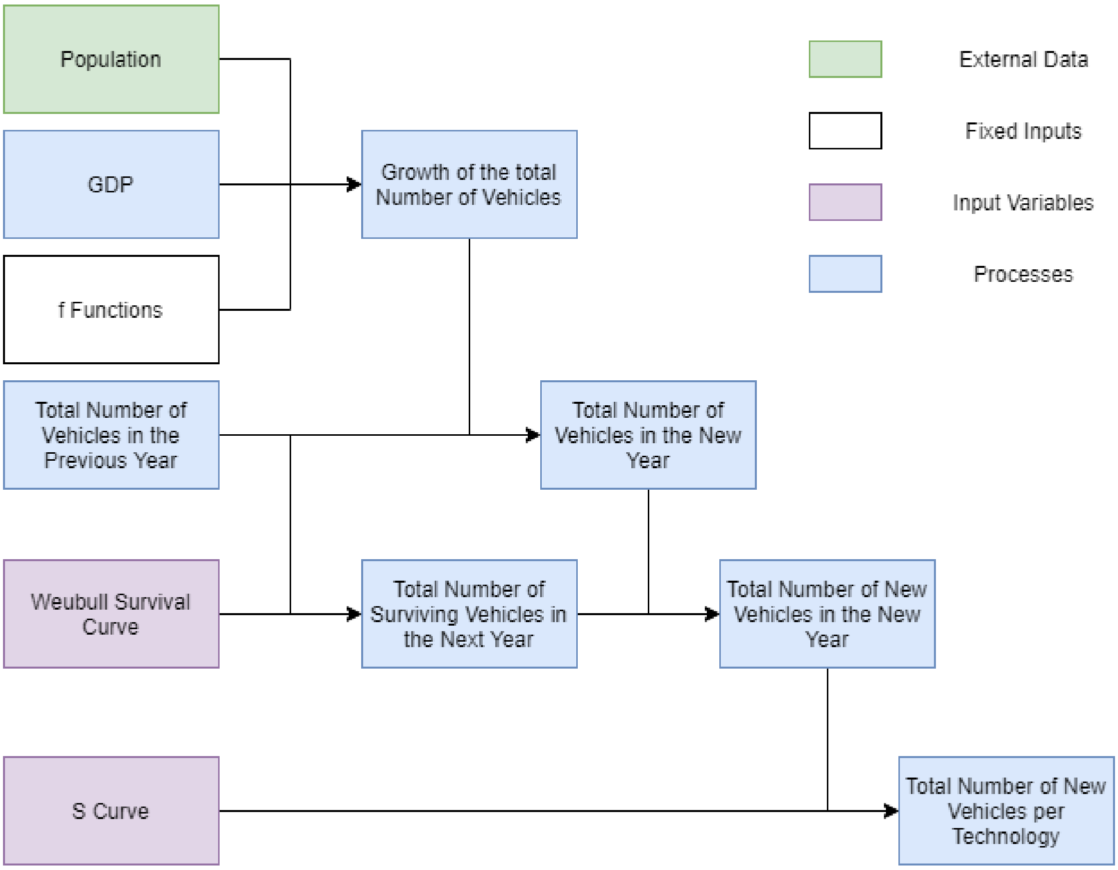


Figure 15: Number of Road Vehicles - Next Year Data Flow Diagram

4.5.9 Percentage of Rail, Shipping and Aviation Vehicles - Next Year

At this point in the model, the number of rail, shipping and aviation vehicles is calculated for the next year. They are calculated per technology, per function and per age. The first thing that is calculated is the percentage of vehicles surviving from the previous year to the next year (per function, per technology and per age) in terms of the fleet of the previous year (in terms of the fleet of the new year, it is obvious that the percentage of the vehicles surviving changes because the fleet size changes) as it is shown in equation 25.

$$PoVS_y = PoV_y \cdot Survival\_Curve \tag{25}$$

where:

- PoVS is the Percentage of the Vehicles Surviving from the previus year to the new year in terms of the fleet of the previous year

- PoV is the Percentage of the Vehicles
- Survival_Curve is the Weibull Survival Curve which has been described earlier
- The index y represents the previous year
- The index y+1 represents the next year

Then, the percentage of vehicles per technology is calculated for the next year using S curves. For the new technologies that their diffusion is described through the S curves, the percentage of vehicles is equal to the value of the S curve for the next year as it is indicated in equation 26. Then the total percentage of vehicles of all the conventional technologies is equal to the difference $1 - PoV_{Electric_{y+1}} - PoV_{FuellCell_{y+1}}$ and it is distributed among the conventional technologies based on the assumption that the analogy between conventional technologies has remained the same as it was in the base year.

$$PoV_{y+1} = S\_Curve_{y+1} \tag{26}$$

where:

- PoV is the Percentage of the Vehicles
- S_Curve is the Diffusion Curve of a New Technology which has been described earlier
- The index y represents the previous year
- The index y+1 represents the next year

Having calculated the percentage of the vehicles surviving per technology (in terms of the fleet of the previous year) and the percentage of the vehicles per technology in the new year, it is possible to calculate the percentage of the vehicles that survived per technology from the previous year to the next year (in terms of the fleet of the new year). First, the change of the percentage of vehicles per technology is calculated from equation 27 and then the percentage of the vehicles survived (in terms of the fleet of the new year) per technology is calculated from equation 28.

$$dPoV = \frac{PoV_{y+1} - PoV_y}{PoV_y} \tag{27}$$

where:

- dPoV is the change of the Percentage of the Vehicles (per technology)
- PoV is the Percentage of the Vehicles
- The index y represents the previous year
- The index y+1 represents the next year

$$PoVS_{y+1} = PoVS_y \cdot \frac{1}{dPoV} \tag{28}$$

where:

- PoVS_y+1 is the Percentage of Vehicles Survived from the previous year to the next year (in terms of the fleet of the new year)
- PoVS_y is the Percentage of Vehicles Surviving from the previous year to the next year (in terms of the fleet of the previous year)
- dPoV is the change of the Percentage of the Vehicles (per technology)
- The index y represents the previous year
- The index y+1 represents the next year

Consequently, the percentage of new vehicles per technology in the new year is given from the equation 29.

$$PoNV_{y+1} = 1 - PoVS_{y+1} \tag{29}$$

where:

- PoNV is the Percentage of New Vehicles
- $PoVS_{y+1}$ is the Percentage of Vehicles Survived from the previous year to the next year (in terms of the fleet of the next year
- The index y represents the previous year
- The index y+1 represents the next year

After all the calculations presented in this section, the percentage of vehicles per function per technology and per age for the rail, shipping and aviation sectors in the new year have been calculated. The block of the code described in this section is presented in figure 16.

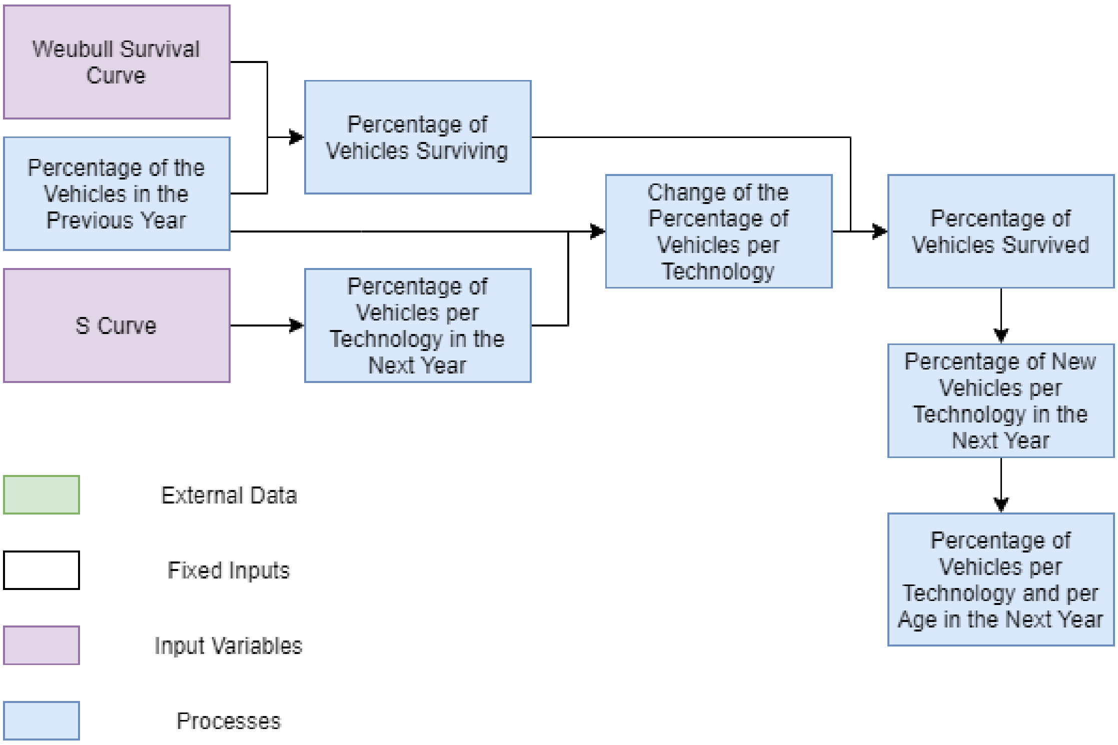


Figure 16: Percentage of Vehicles - Next Year Data Flow Diagram

4.5.10 Average Annual Energy Consumed per Vehicle - Next Year

The average annual energy consumed per vehicle in the next year is equal to the product of the average annual energy consumed per vehicle in the previous year multiplied with one minus the efficiency improvement as it can be seen in equation 30. The average annual energy consumed per vehicle in the previous year is already known while the efficiency improvement depends on the function and the technology and is an input variable given to the model. This block of the model is shown in figure 17.

$$AAECPV_{y+1} = AAECPV_y \cdot (1 - dEff) \tag{30}$$

where:

- AAECPV is the Average Annual Energy consumed per Vehicle
- dEff is the Reduction of the Specific Energy Consumption from the previous to the next year
- The index y represents the previous year

- The index y+1 represents the next year

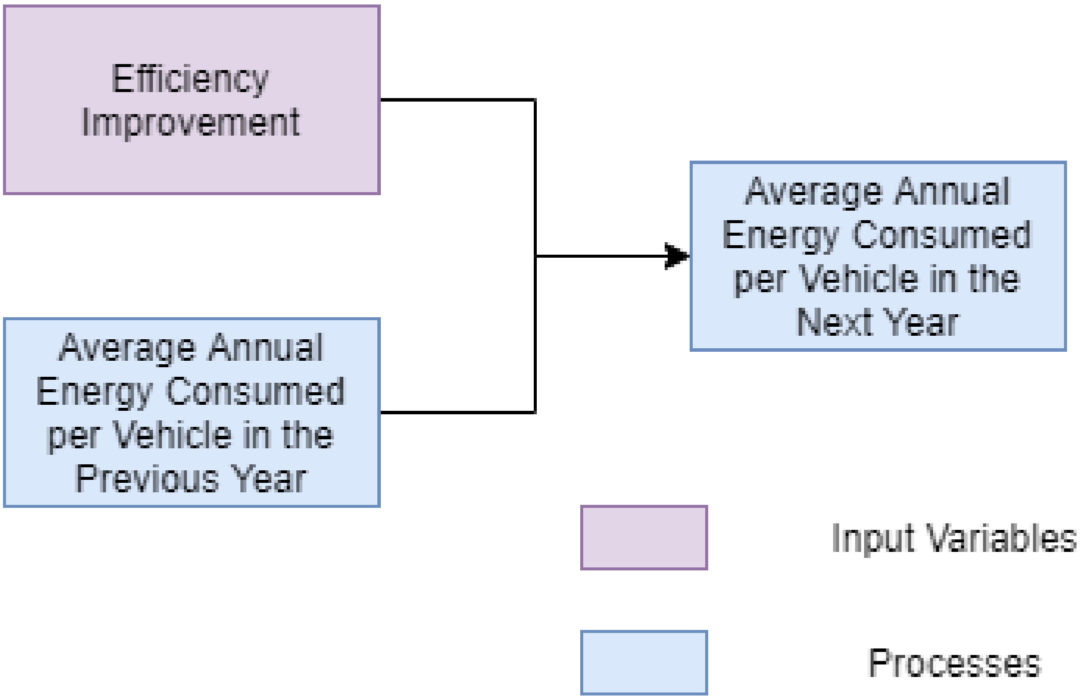


Figure 17: Average Annual Energy consumed per Vehicle - Next Year Data Flow Diagram

4.5.11 Total Annual Travel Activity - Next Year

The total annual travel activity in the next year is equal to the total annual travel activity in the baseyear multiplied with one plus the growth of activity as it is shown in equation 31. TATA is calculated per technology and per function. This block of the model is shown in figure 18.

$$TATA_{y+1} = TATA_y \cdot dAct \tag{31}$$

where:

- TATA stands for Total Annual Travel Activity
- dAct is the Growth of Activity
- The index y represents the previous year
- The index y+1 represents the next year

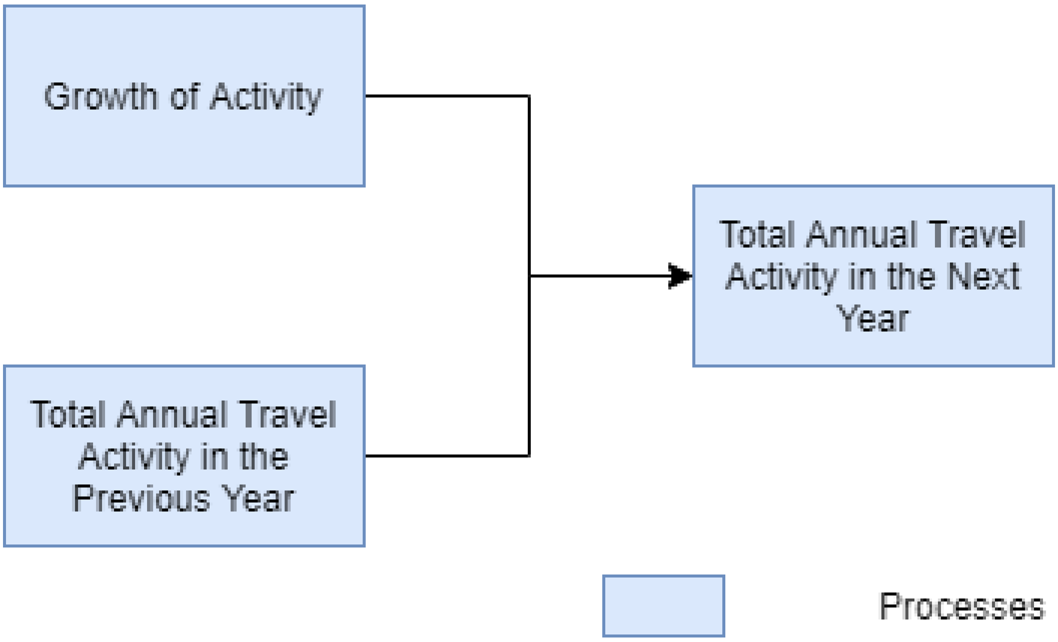


Figure 18: Total Annual Travel Activity - Base Year Data Flow Diagram

4.5.12 Energy Demand Shares per Technology - Next Year

The energy demand share per technology in the next year is equal to the energy demand of the technology in the next year divided by the energy demand of the energy function, in which the technology belongs, in the next year. Consequently, the formula which calculates the energy demand shares of each technology is 32. For road vehicles, the energy demand per technology in the next year is equal to the number of vehicles per technology in the next year multiplied with average annual energy consumed per vehicle in the next year as it is shown in equation 33, while the, for rail, shipping and aviation, the energy demand per technology in the next year is equal to the total annual travel activity per technology multiplied with the respective fuel consumption as it can be seen by equation 34. These blocks of the model are shown in figures 19 and 20.

$$TSED_{y+1} = \frac{TED_{y+1}}{FED_{y+1}} \tag{32}$$

$$TED_{y+1} = NoV_{y+1} \cdot AAECPV_{y+1} \tag{33}$$

$$TED_{y+1} = TATA_{y+1} \cdot FC \tag{34}$$

where:

- TSED is the Energy Demand Share per Technology
- TED is the Energy Demand per Technology within one function
- FED is the Energy Demand of the Function
- AAECPV is the Average Annual Energy Consumed per Vehicle
- TATA stands for Total Annual Travel Activity
- The index y represents the previous year
- The index y+1 represents the next year
- FC is the Fuel Consumption

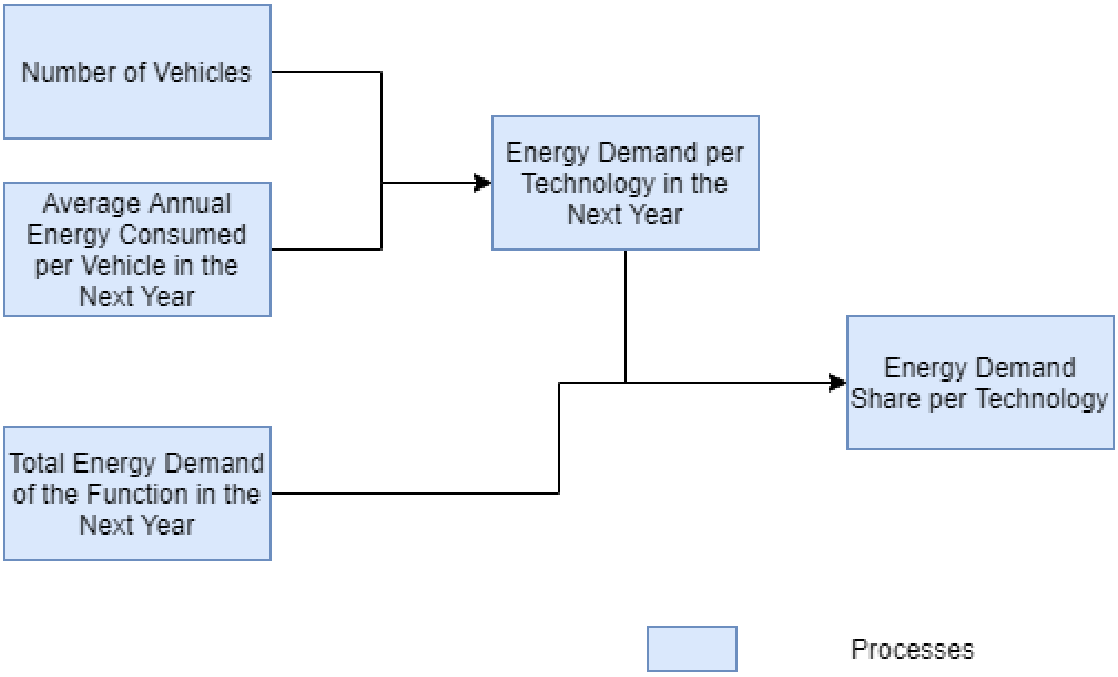


Figure 19: Energy Demand Share per Technology - Road - Next Year Data Flow Diagram

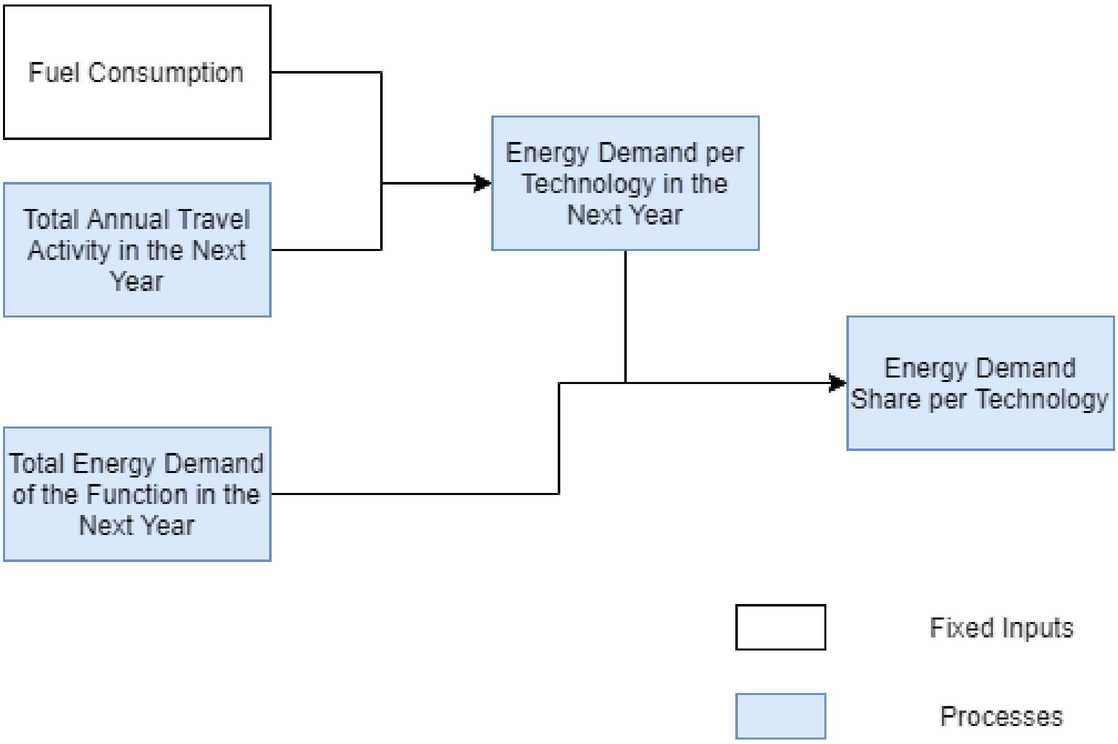


Figure 20: Energy Demand Share per Technology - Rail, Shipping, Aviation - Next Year Data Flow Diagram

4.5.13 FuEB Array - Next Year

In the last stage of the model, the FuEB array for the next year is calculated. The values of the FuEB array of the next year can now be calculated since the values of the FuEB array of the previous year, the change of activity, the efficiency improvement and the energy demand shares per technology for the previous and the next year are known. The formula which gives the values of the FuEB array for the next year is shown in equation 35. This block of the model is shown in figure 21.

$$FuEB_{y+1} = FuEB_y \cdot (1 + dAct) \cdot (1 - dEff) \cdot \frac{TSED_{y+1}}{TSED_y} \tag{35}$$

where:

- FuEB is the Function Energy Balance Array
- dAct is the Change of Activity
- dEff is the Reduction of the Specific Energy Consumption per Year

- TSED is the Energy Demand Share per Technology
- The index y represents the previous year
- The index y+1 represents the next year

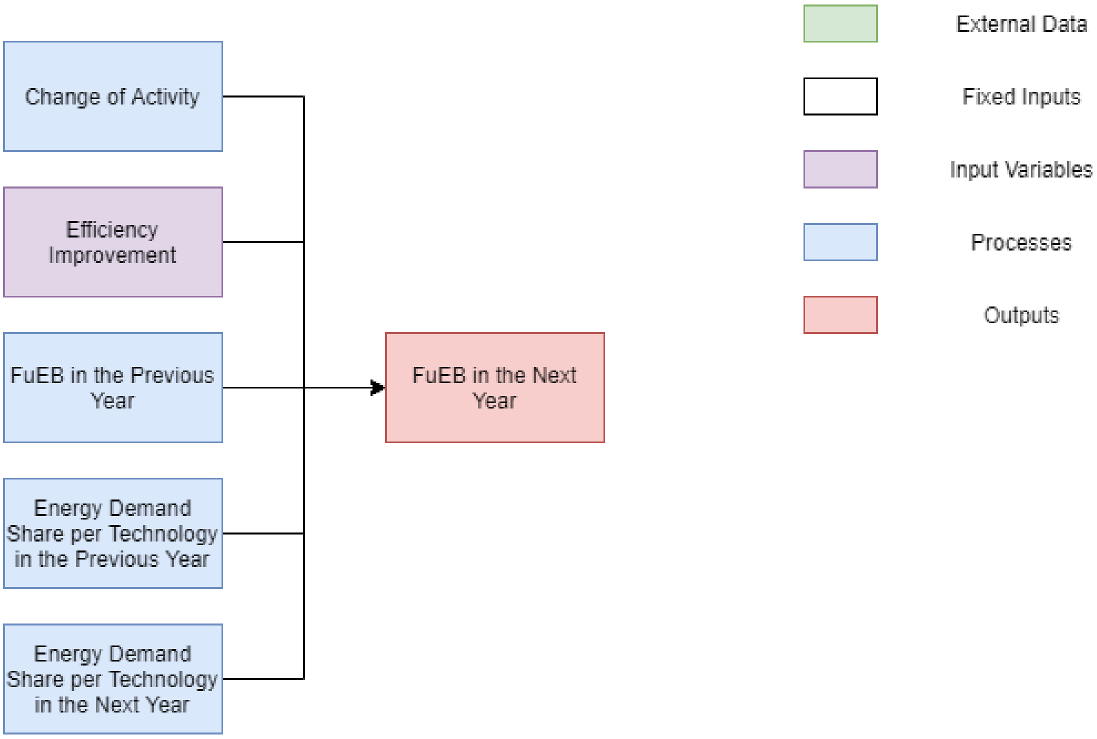


Figure 21: FuEB - Next Year Data Flow Diagram

At this point in the report, the fraction of each fuel used in each technology is implemented. Regarding all the fuels that are already used in the base year, the percentage consumption in each technology is assumed to be equal to the respective consumption in the base year. However, new percentages must be inserted for the new fuels that are going to be used after the base year of the model. Regarding biofuels, biofuel mandates are taken into account. Biofuel mandates are laws which require fuels to include certain percentages of biofuels. In this report, the biofuels are considered to be blended with diesel fuel in compression ignition diesel engines. For the development of the model, a biofuel percentage is set as a target and an s curve is used between the present and the target year to represent the growth of biofuels use until it meets the target set for each country. In case that an internal combustion engines ban takes place, the biofuels percentage continues to develop as it was planned to but the absolute value of biofuels consumption decreases as a result of the diesel fuels decrease because of the ICE ban. The biofuel mandates are presented in table 18 in the Appendix.

Regarding electricity, the percentage of electricity is equal to the percentage of electric vehicles in the fleet since electric vehicles only use electricity as an energy carrier. Regarding hydrogen, the logic is the same as for electricity since in this research hydrogen is the only energy carrier taken into account for fuel cell vehicles except for the shipping sector. In the shipping sector, fuel cell vessels are assumed to use both hydrogen and ammonia for their operation. Thus, in this case, the fractions of hydrogen and ammonia are inserted in the model as inputs and are considered constant (In particular, the hydrogen fraction is 20% and the ammonia fraction is 80% based on IEA's "Net Zero by 2050: A Roadmap for the Global Energy Sector" (IEA, 2021b)). Consequently, electricity, hydrogen and ammonia follow the growth of electric and fuel cell engines technologies.

5 Model Verification & Validation

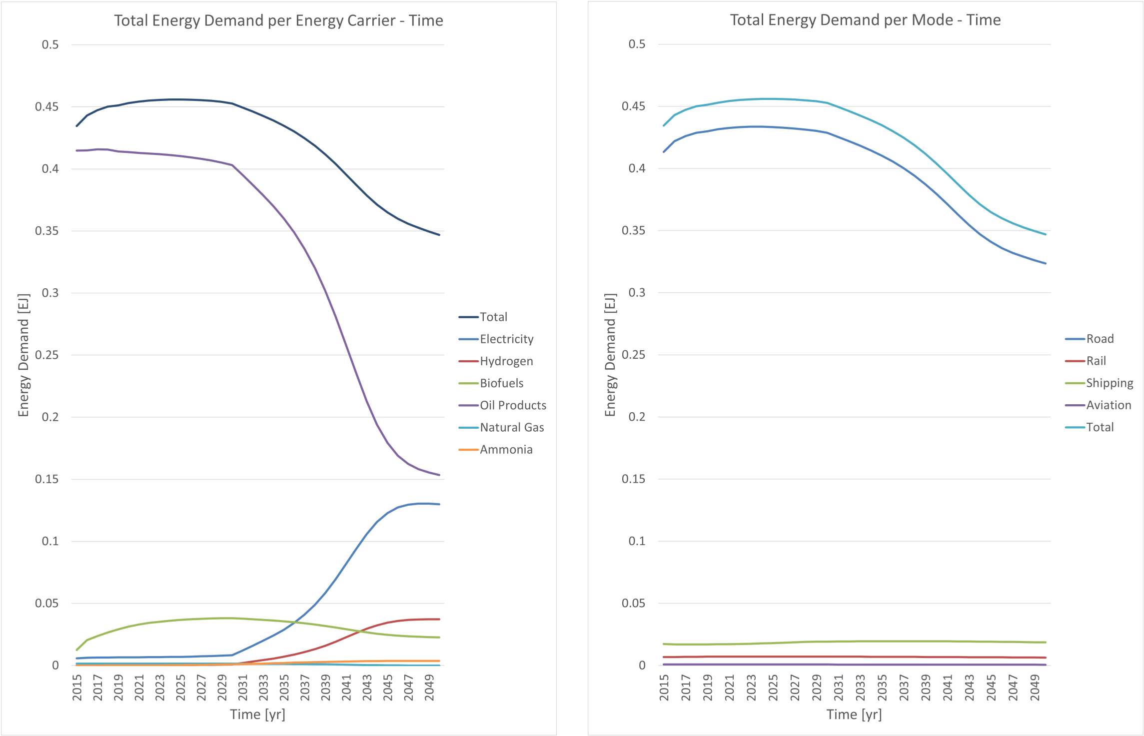
Before proceeding to the results chapter, a verification and validation of the simulation model, presented in chapter 4, should be done in order to prove that the results that will be presented in the next chapter are reliable (Law, 2014). The methods used for the verification and validation of the model are described in this chapter.

5.1 Verification

In order to verify the model, it is necessary to check if the final model accurately reflects its conceptual description (Law, 2014). According to the structure of the model, the main variables that it aims to calculate are the energy demand of the various countries, transportation modes, technologies and fuels and the energy demand shares per technology in the various countries and transportation modes from 2015 to 2050. To simplify the model verification procedure, the consistency between the final model and the model conceptual description is checked only for the Netherlands' and China cases and the current policies scenario scenario (which will be explained in detail in the next chapter) since the model operates in the same way for all the countries.

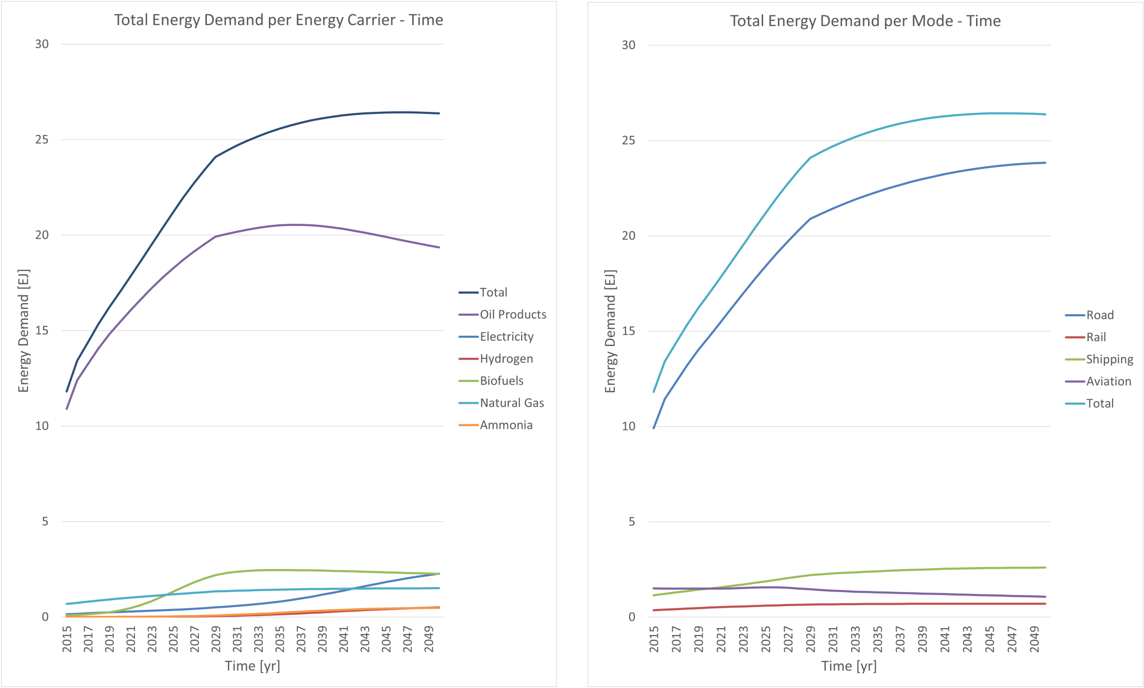
To begin with, the successful operation of the model was verified by carefully debugging and correcting the model code. After this procedure, the code was able to calculate all the results that the model aimed to produce.

Furthermore, in order to visualize the smooth operation of the model, figures that confirm the original model design are presented. In figures 22a, 22b, 23a and 23b it can be seen that the model produces results about the energy demand of the various energy carriers and transport modes for every year between 2015 and 2050. Thus, as expected, the figures present a potential pathway of the energy demand for the different energy carriers and transport modes in the upcoming years according to the current policies scenario (which is described in section 6).



(a) (b)

Figure 22: (a) Total Final Energy Use per Energy Carrier in the Netherlands - CP (b) Total Final Energy Use per Mode in the Netherlands - CP



(a) (b)

Figure 23: (a) Total Final Energy Use per Energy Carrier in China - CP (b) Total Final Energy Use per Mode in China - CP

5.2 Validation

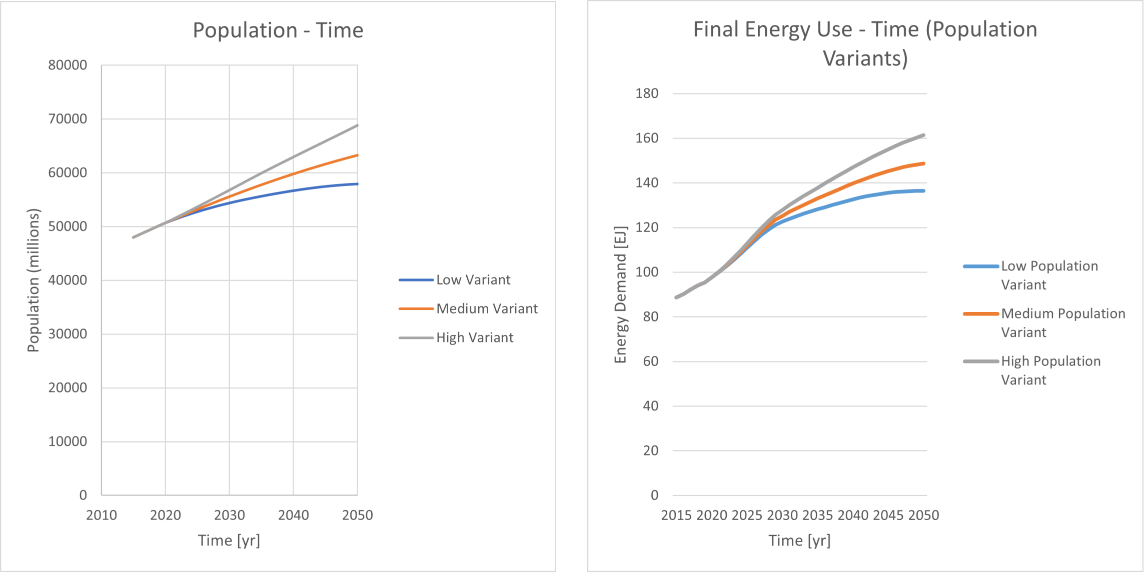
The verification of the model proves that the model has been successfully implemented and it provides the results that it was initially designed to provide. Consequently, in order to prove that the produced results are indeed a precise representation of the real world, the model needs to be validated. For the validation, also a business as usual scenario, which will be explained in the next chapter, is taken into account. This scenario is compared to similar scenarios in order to proceed to the validation. Moreover, a sensitivity analysis is conducted.

Firstly the results are compared with the results produced from other studies. IEA,in its baseline scenario, calculates the global future transportation energy demand which follows a constantly upwards trend from 2000 to 2050 and, starting from 100 EJ in 2015, reaches a value of about 170 EJ in 2050 (IEA, 2009a) showing an increase of almost 67%. In the current study, the energy demand also follows a constantly rising trend starting from 89 EJ in 2015 and reaching a value equal to 142 EJ in 2050, increasing by nearly 60%. The difference between the two absolute values can be explained by the fact that the current research takes into account only the thirty biggest energy consuming countries. However, the growth percentages are very close and the small difference between them can be explained by the different assumptions and methods used in the model.

Also, the global energy demand shares by energy carrier in the current research are compared with the BP's business as usual scenario as it was presented in their Energy Outlook (BP, 2000). BP's business as usual scenario assumes zero penetration of hydrogen in the transportation energy market and lower penetration of electricity and biofuels than the current research and as a result projects higher shares of oil products and natural gas. Also, BP does not take into account ammonia in its model. However, the difference between the shares of electricity, hydrogen and biofuels in the two studies is not higher than 5-10%. Thus, considering that the fuels in the two studies follow similar trends but differ in the degree of penetration, this difference may be due to the methods used to calculate the number of new and retiring vehicles of each technology and the assumptions according to the expected market behaviour in the next years. All in all, through the comparison with other studies, it is now confirmed that the current study follows same trends and produces similar results as other published studies.

A sensitivity analysis is also conducted so as to prove that the model reacts to changes just like a real world system. The inputs that are studied for the sensitivity analysis are the population, the gross domestic product (as a function of the compound annual growth rate), the reduction of the specific energy consumption per year, the year of the internal combustion engine ban and the coefficients of innovation (p) and imitation (q) of the bass model.

Figures 24a and 24b show the development of three different variants of population and the respective energy demand growth over time. In particular, the three different variants of population taken from the United Nations' World Population Prospects database (United Nations, 2019). The energy demand should increase or decrease when the population increases or decreases as well, as there is a direct correlation between activity and population. Indeed, the results show that as population rises, the energy demand also increases and, more specifically, for a population increase or decrease of about 11% (when compared to the medium variant) from 2015 to 2050, the energy demand also shows an increase or decrease of about 11%. Thus, as expected any projection regarding the global future energy demand is highly dependent on the population growth assumptions that are taken into account.

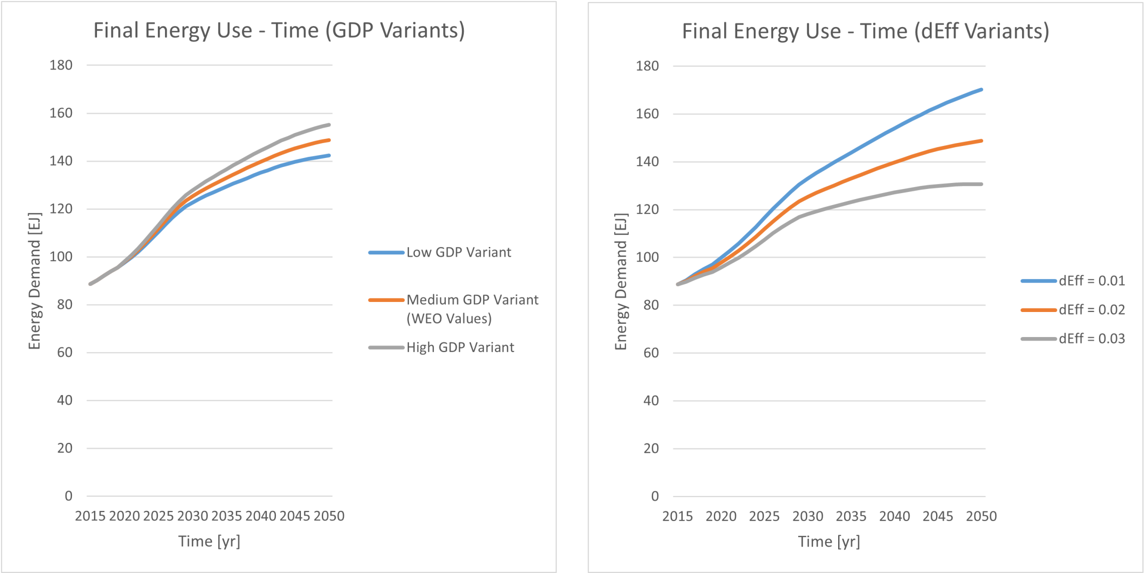


(a) (b)

Figure 24: (a) Population vs Time depending on the Population Variant (b) Final Energy Use vs Time depending on the Population

Figure 25a shows the development of energy demand over time for different Gross Domestic Product values. In particular, the GDP depends on the compound annual growth rate. So, three different variants of the compound annual growth rate based on the International Monetary Fund's World Economic Outlook databases (International Monetary Fund, 2020b) are used for the sensitivity analysis. The energy demand is expected to grow exponentially when the GDP increases, since the correlation between the activity and the GDP is exponential. The results confirm this expectation since they indicate that for a 0.5% decrease (or increase) of the CAGR values, the energy demand shows a decrease (or increase) of about 4%, which is reasonable since the correlation between the activity and the GDP is exponential and, as a result, the change of the energy demand is multiple times higher than the change of GDP.

The energy demand is expected to rise for higher values of the annual reduction of the specific energy consumption, since this means higher efficiency - due to the new technology improvements - and, as a result, lower fuel consumption. In particular, as 25b indicates, for an annual reduction of the specific energy consumption increase of 1%, the energy demand reduces by almost 12% - 14%. Indeed, the results confirm the initial expectation and they clearly show the significance of technology improvements in reducing energy demand.



(a)

(b)

Figure 25: (a) Final Energy Use vs Time depending on the Gross Domestic Product (b) Final Energy Use vs Time depending on the Annual Reduction of the Specific Energy Consumption

According to the developed model, the energy demand curve should start to decline earlier if the internal combustion engines ban is applied earlier, as a result of the lower fuel consumption of electric and fuel vehicles cars compared to conventional vehicles. More specifically, as figure 26 shows, for every five years of earlier implementation of the ICE ban, the 2050 energy demand is reduced almost 7%. This finding firstly confirms the initial expectation and, secondly, shows the importance of the time of ICE ban adoption since, even though the result of the ICE ban on the energy demand is expected to be the same in the long term, its impact on the energy demand until 2050 is considered crucial in order for the climate targets to be achieved.

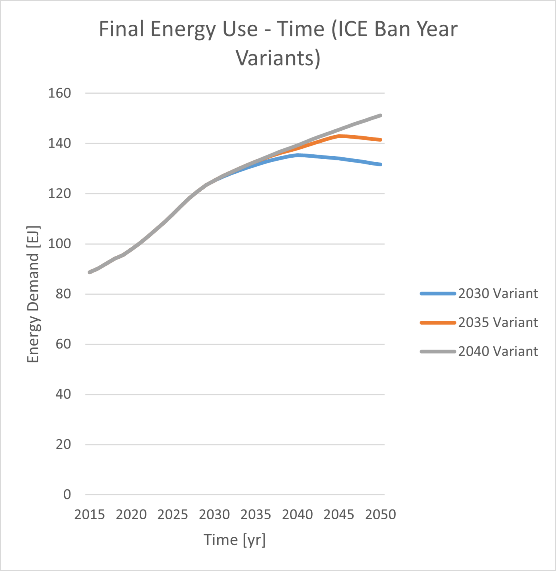
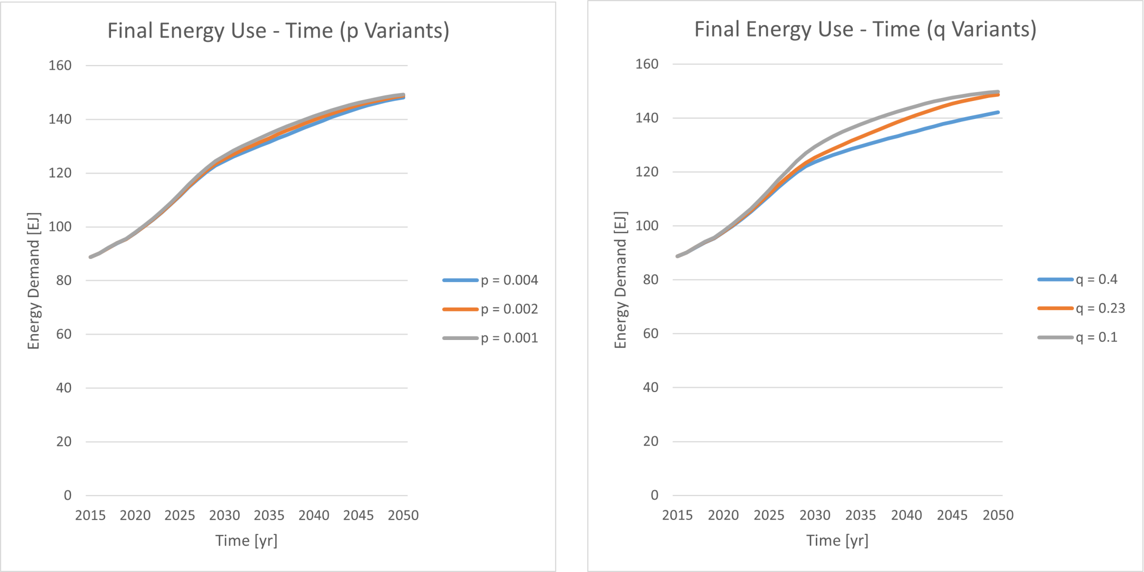


Figure 26: Final Energy Use vs Time depending Implementation Time of ICE Ban

Figure 27a demonstrates the impact of the innovation coefficient of the Bass model on the energy demand curve. In particular, for a 50% reduction of the p coefficient, the energy demand reduces by 0.4%, while for a 100% increase, the energy demand rises by 0.2%. Figure 27b shows the impact of the imitation coefficient of the Bass model on the energy demand curve. Regarding the q coefficient, for a decrease of about 65%, the energy demand falls by almost 4.5%, while for an increase of almost 75%, the energy demand grows almost by 7%. It is worth mentioning that the innovation and imitation coefficients values chosen for the sensitivity analysis are commonly used and represent a very wide range of applications (PricewaterhouseCoopers, 2018). More specifically, it seems that the effect of p coefficient on the energy demand is almost negligible, while q coefficient could significantly affect the future energy demand. In both cases it is obvious that for higher values of p and q, the energy demand decreases faster. However, as the penetration of new technologies in the market reach saturation levels, it seems that the energy demand curves of the different variants end up in the same values. This phenomenon is explained by the fact that the bass s curve differs in the development stage for different p and q values but it ends up to the same value as the final value only depends on expected final market share. Nevertheless, just like with the ICE ban policy, the innovation and imitation coefficients could play a major role regarding the new technologies penetration pace into the market and, as a result, they directly affect the level of the energy demand reduction in the short term.



(a) (b)

Figure 27: (a) Final Energy Use vs Time depending on the innovation coefficient (p) (b) Final Energy Use vs Time depending on the imitation coefficient (q)

6 Results and Discussion

In this section, two different scenarios are developed. Firstly, the different approaches and inputs are described. Then, the results are presented and explained.

6.1 Scenarios Overview

Based on the model that has been developed and explained in the previous stages of the report, two different scenarios regarding the energy demand progress in the transportation sector during the 2015 - 2050 period are considered. These scenarios are the Current Policies Scenario and the Accelerated Policies Scenario. According to the Current Policies scenario no more policies will be applied other than those already adopted by 2020, while, according to the Accelerated Policies scenario, stricter implementation of the current policies is applied and new policies are adopted. The two scenarios are distinguished by specific inputs that are different for each scenario. These are the final market share of new technologies in the long run, the annual reduction of the specific energy consumption and the ICE ban year. The differences between the two scenarios are summarized in table 6, while the guidelines for the choice of the inputs' values are presented in the corresponding subsection of each scenario.

Table 6: Scenarios Description

Scenarios Description		
Scenarios	**Current Policies**	**Accelerated Policies**
Storyline	No more policies are applied in the future other than those already adopted by 2020	New policies are adopted and a stricter implementation of the policies is applied
Policies:		
Annual Reduction of the Specific Energy Consumption	Depends on the policy implementation strictness of the different countries which is derived from the RISE database of the World Bank	3.2% (derived from IRENA's transforming energy scenario)
ICE Ban	Countries already announced an ICE Ban as presented in table 7	Universal ICE ban by 2035
LDVs	Currently announced ICE ban, Final Market Shares: 15.5% electric & 1% fuel cell	Universal ICE ban by 2035, Final Market Shares: 95% electric, 5% fuel cell
Light Duty	Currently announced ICE ban, Final Market Shares: 30% electric, 1% fuel cell	Universal ICE ban by 2035, Final Market Shares: 95% electric, 5% fuel cell
Buses	Currently announced ICE ban, Final Market Shares: 70% electric, 5% fuel cell	Universal ICE ban by 2035, Final Market Shares: 81% electric, 19% fuel cell
HDVs	Currently announced ICE ban, Final Market Shares: 8% electric, 5% fuel cell	Universal ICE ban by 2035, Final Market Shares: 26% electric, 10% fuel cell
Rail	Final Market Shares: 84% electric, 0% fuel cell	Final Market Shares: 95% electric, 2% fuel cell
Shipping	Final Market Shares: 5% electric, 20% fuel cell	Final Market Shares: 10% electric, 60% fuel cell
Aviation	Final Market Shares: 5% electric, 0% fuel cell	Final Market Shares: 10% electric, 2% fuel cell

6.1.1 Current Policies Scenario

The first scenario is the **Current Policies Scenario** and it intends to provide a potential pathway of the future global energy demand which could happen in case that no more policies are applied in the future other than those already adopted by 2020.

In the current policies scenario, electric buses and rail are assumed to reach 70% and 84%, respectively, and be the biggest part of buses and rail fleet in the future based on IEA's stated policies scenario (IEA, 2019). According to the same scenario, electric 2 and 3 wheelers and light duty vehicles are also going to account for 30% and 15.5% constituting a substantial part of the fleet. On the contrary, electric heavy duty road vehicles and marine and air vessels are not going to significantly increase in the future and are going to make up just 8%, 5% and 5% (IEA, 2019).

Regarding fuel cell technology, in the current policies scenario, fuel cell marine vessels are going to grow to 20% in the long-term and make up a substantial portion of the fleet based on Bloomberg's economic transition scenario (Bloomberg, 2020). According to IEA's stated policies scenario, fuel cell technology is not going to be significantly introduced into the rest of transportation market without further policies (IEA, 2019). Thus, based on Bloomberg's economic transition scenario, which predicts very small penetration of fuel cell passenger road vehicles (increase of 1%) and highlights that fuel cell technology will play a role in heavy duty road vehicles and buses, for the current policies scenario it is assumed that, in the long-term, fuel cell 2 and 3 wheelers and light duty vehicles are going to slightly increase to 1% of the fleet, while fuel cell buses and heavy duty vehicles are going to account for 5%. Regarding rail and aviation, it is assumed that without further policy actions, fuel cell technology is not going to be used in these sectors.

In the current policies scenario, the annual reduction of the specific energy consumption is calculated as shown in equation 36, where *autonomous_rate* is set equal to 1% and the constant is set equal to 2 showing that with the most intensive policy implementation, the rate of energy efficiency improvement is doubled.

$$dEff = autonomous\_rate \cdot constant \cdot (1 + (policy\_intensity/100)) \tag{36}$$

where:

- dEff is the Efficiency Improvement
- *autonomous_rate* is the Autonomous Energy Efficiency Improvement Rate
- The Constant is used to represent the change of the *autonomous_rate* based on the *policy_intensity*
- The *policy_intensity* is the policy implementation intensity and it is derived from the RISE database of the World Bank (Group, 2019).

The ICE ban years for each country are taken from the literature as described before and are indicated in table 7 where the countries are presented in descending order based on energy consumption. The sales market shares of electric and fuel cell vehicles that are affected by the ICE ban are equal to the assumed final market shares as they are presented in the accelerated policies scenario.

Table 7: Internal Combustion Engines Ban

Internal Combustion Engines Ban Year	
Country	**Current Policies Scenario**
Japan	2050 (IEA, 2020b)
Canada	2040 (IEA, 2020b)
Germany	2030 (IEA, 2020b)
France	2040 (IEA, 2020b)
United Kingdom	2035 (IEA, 2020b)
Mexico	2040 (Wyman, 2018)
Spain	2040 (IEA, 2020b)
Thailand	2035 (Bloomberg, 2021)
Sweden	2030 (IEA, 2020b)
Norway	2025 (IEA, 2020b)
Netherlands	2030 (IEA, 2020b)

6.1.2 Accelerated Policies Scenario

The second scenario is the **Accelerated Policies Scenario** which takes into account potential policies that could be adopted and stricter implementation of the already adopted policies in order to create an ambitious pathway where the global energy demand of the transportation sector starts to decline before mid-century.

In the accelerated policies scenario, based on ICCT's "VISION 2050"report, it is assumed that in the long-run most 2 and 3 wheelers and light duty vehicles, buses and rail are going to be electric constituting 95%, 95%, 81% and 95% of the fleet, respectively (ICCT, 2020). Also, electric heavy duty vehicles are going to substantially increase and they will account for 26%, while electric marine and air vessels are going to reach 10% each.

According to ICCT's ambitious yet feasible scenario (ICCT, 2020), road passenger vehicles are expected to be fully decarbonized in the future. Thus, in this study, it is assumed that only electric and fuel cell engines will be used in future road passenger transportation. Consequently, the potential final market shares of fuel cell light duty vehicles, 2 and 3 wheelers, buses and rail are assumed to be equal to 5%, 5%, 19% and 5%. The potential final market shares of fuel cell heavy duty vehicles and marine and air vessels are set equal to 10%, 60% and 2% based on IEA's net zero by 2050 scenario (IEA, 2021b).

In the accelerated policies scenario, the annual reduction of the specific energy consumption is set equal to 3.2% in order to represent the effect of new policies on the technology improvements and, as a result, on the efficiency of new vehicles. The magnitude of the reduction is derived from IRENA's transforming energy scenario

(IRENA, 2020). Moreover, a universal internal combustion engines ban in 2035 is assumed. The sales market shares of electric and fuel cell vehicles that are affected by the ICE ban are equal to the assumed final market shares of accelerated policies scenario as they are presented in table 6.

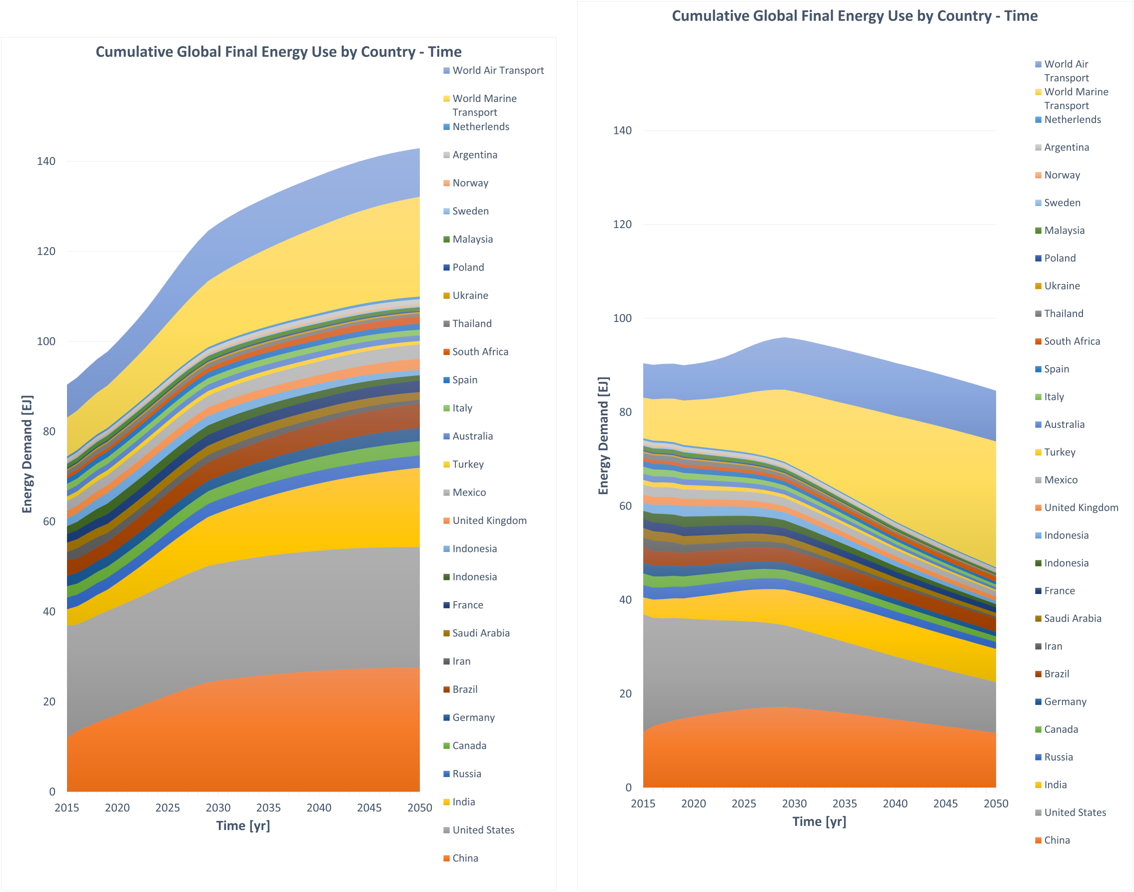
6.2 Energy Demand by Country

The results produced from the Current Policies Scenario indicate a constantly increasing trend of the global energy demand in the transportation sector despite the efficiency improvements and the policies adopted. The total global energy demand is expected to climb from about 89 EJ in 2015 to nearly 142 EJ in 2050 showing an increase of about 60%.

Unlike the current policies scenario, the accelerated policies scenario predicts that the 2050 energy demand is going to be less than the 2015 energy demand. In particular, as it is shown in figure 28, the energy demand is expected to continue growing and reach 94.269 J until 2029. However, from 2030 to 2050 it follows downward trend and it is expected to be equal to 84.835 EJ in 2050, which is almost 5% lower than the 2015 value and 10% lower than the 2029 value.

As can be seen in figure 28, the countries that contribute the most in the global energy demand growth are China, the United States and India. This observation can be easily explained since the energy demand depends on the population and the gross domestic product of each country. International marine and international air transportation sectors also play a significant role in the energy demand increase due to the increasing activity as a result of the population growth worldwide.

In the current policies scenario, the transportation energy demand in China, the United States and India increases by 132%, 7% and 385%, respectively, between 2015 and 2050. International marine and international air transportation sectors show an energy demand increase of 172% and 53%, respectively. In the accelerated policies scenario, the transportation energy demand in China and the United States decreases by almost 2% and 57%, respectively, while in India it increases by approximately 95% throughout the period 2015-2050. International marine and international air transportation sectors energy demand increase my almost 143% and 47%, respectively.



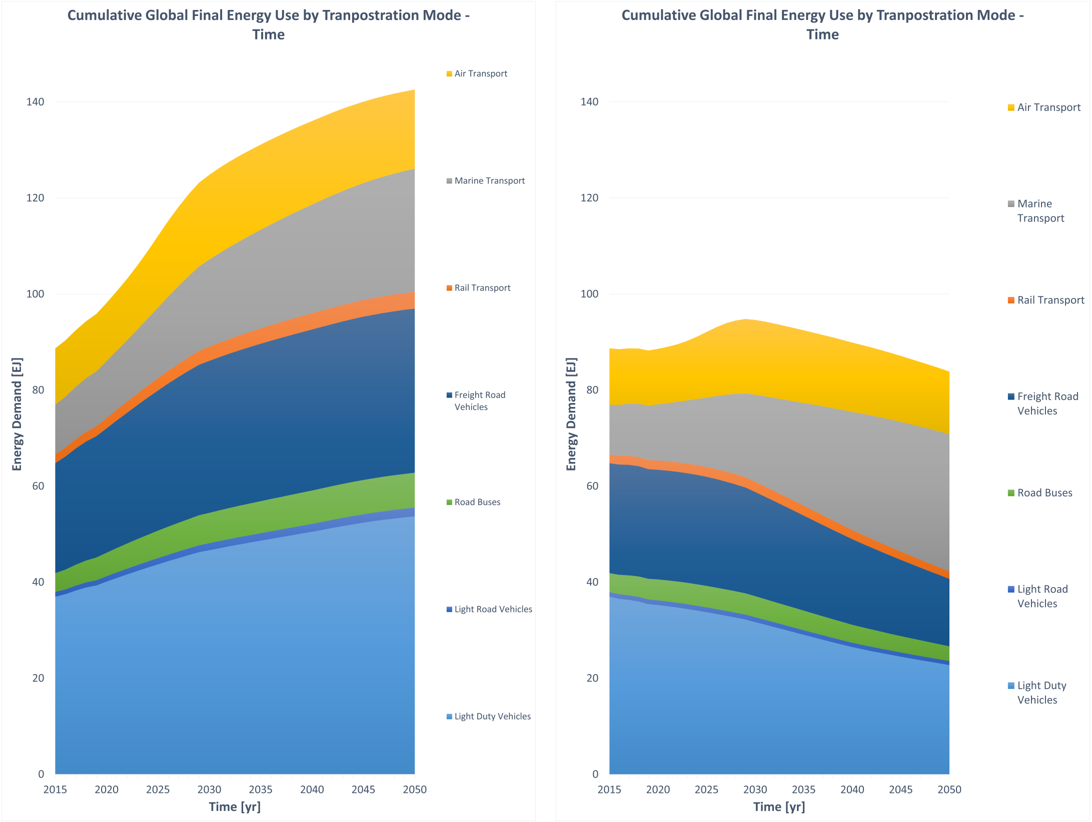
(a) (b)

Figure 28: (a) Cumulative Global Final Energy Use by Country CP (b) Cumulative Global Final Energy Use by Country AP

6.3 Energy Demand by Transportation Mode

Figure 29 shows the cumulative global energy demand by transportation mode in the current policies scenario. According to figure 29, the light duty vehicles and 2 and 3 wheelers show an energy demand increase of almost 45% and they remain the transportation mode with the most significant energy consumption followed by the road freight vehicles which show a rise of 49%. The marine and air vessels seem to have a substantial energy demand increase as well and increase by nearly 172% and 53%, respectively. Road buses also show significant increasing energy demand trends and they rise by nearly 86%.

Regarding the energy demand of the different transportation modes in the accelerated policies scenario, according to figure 29 the light duty vehicles and road freight vehicles energy demand shows the most significant reduction and decreases by 35% and 38%, respectively. 2 and 3 wheelers, buses and rail energy demand could also substantially fall by 16%, 21% and 15%, respectively. Regarding marine and air vessels, they could limit the increase of their energy demand to 143% and 47%, respectively.



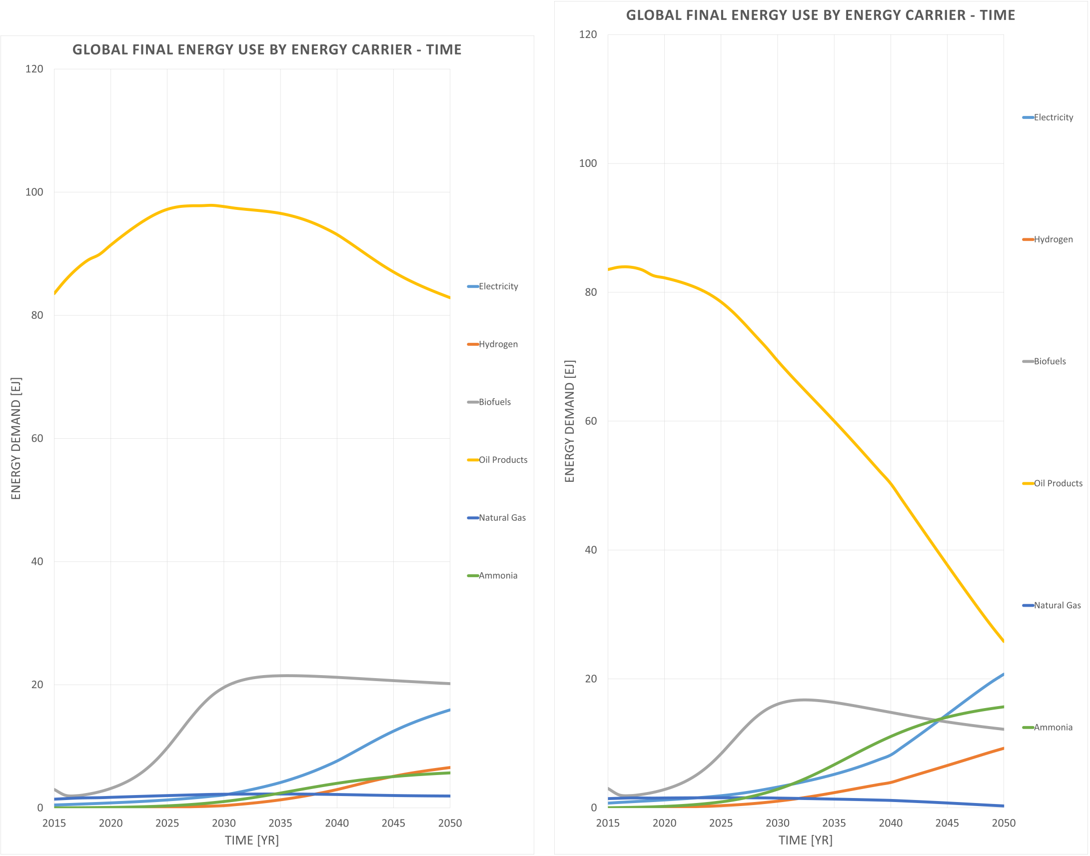
(a) (b)

Figure 29: (a) Cumulative Global Final Energy Use by Transportation Mode CP (b) Cumulative Global Final Energy Use by Transportation Mode AP

6.4 Energy Demand by Energy Carrier

Figure 30 shows the global energy demand by energy carrier in the current policies scenario. According to this scenario, in 2050, oil products will still be the most consumed energy carrier in the transportation sector worldwide. However, the oil products demand is only rising from almost 84 EJ in 2015 to just over 97 EJ in 2029 and follows a downward trend reaching approximately 82.5 EJ in 2050, which is nearly 2% lower than the 2015 levels and 15% lower than the 2027 levels. On the contrary, electricity is reasonably considered the fuel that is going to dominate in the future. As figure 30 indicates, electricity is expected to climb from almost 0.725 EJ in 2015 to almost 14 EJ in 2050 with a constantly upward trend showing a growth of aproximatelly 1800%. Biofuels also increase by 600% from about 2.995 EJ in 2015 to just above 21 EJ in 2036 and slightly decrease to almost 20000 in 2050, which is almost seven times the biofuels consumption of 2015. However, taking into consideration that the biofuels are used in mixed fuels with oil products, which have a significantly downward trend after 2027, and that biofuels show an almost steady energy demand after 2034, it is concluded that the percentage of biofuels in the mixed fuels continues to increase until 2050. Hydrogen and ammonia also show promising trends reaching almost 6.5 EJ and 5.5 EJ of energy demand in 2050, respectively. It is worth mentioning that ammonia is only expected to be used in the marine sector taking up a substantial proportion of shipping energy demand. Natural Gas does not seem to reach significant energy demand values following an almost constant value of about 2 EJ throughout the 2015-2050 time period.

In the accelerated policies scenario, the energy demand covered by electricity is expected to grow higher than the energy demand covered by oil products in 2047 according to figure 30. In particular oil products are expected to decrease by 75% and fall to 20.51 EJ in 2050 while electricity energy demand is expected to grow by 3400% and reach 25.492 EJ in the same year. Biofuels are projected to follow similar trend as in the current policies scenario and increase by 280% reaching almost 11.5 EJ in 2050. Ammonia is going to surpass the biofuels energy demand in 2044 and reach 15.674 EJ in 2050 while hydrogen is also going to reach an energy demand of 11.089 EJ in 2050.



(a) (b)

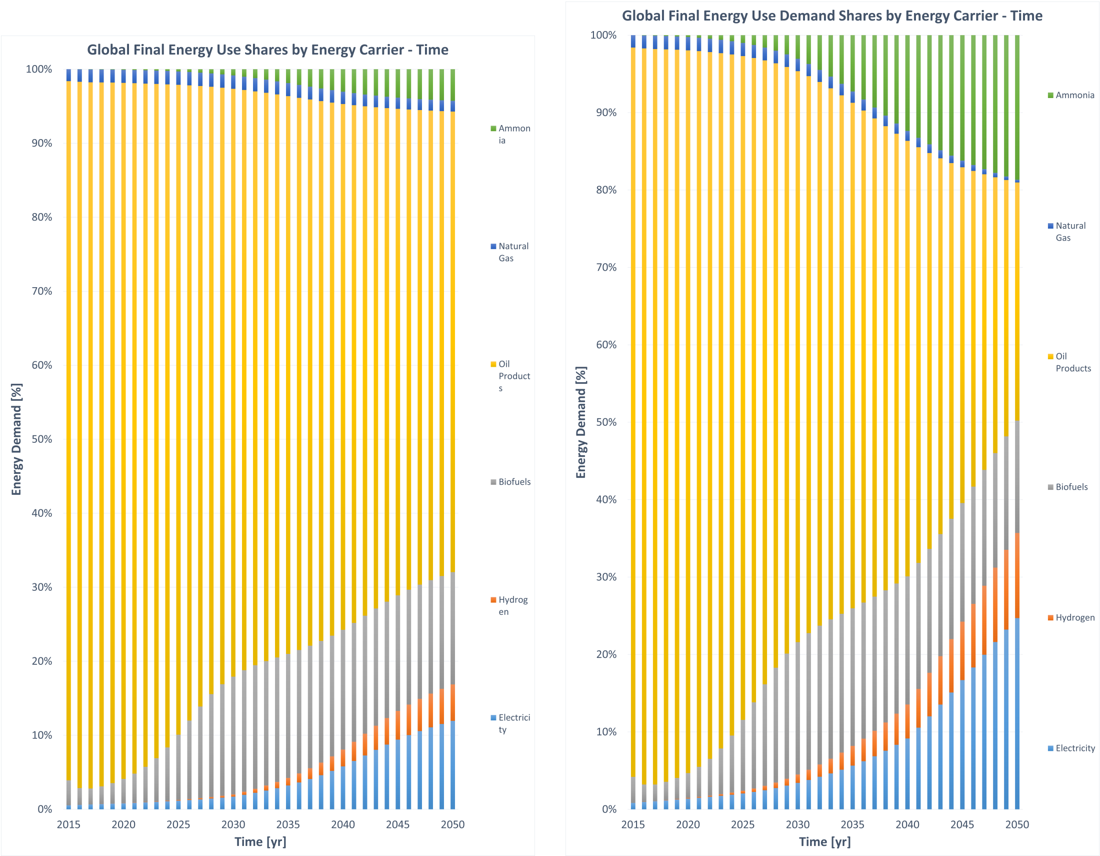
Figure 30: (a) Global Final Energy Use by Energy Carrier CP (b) Global Final Energy Use by Energy Carrier AP

6.5 Energy Demand Shares by Energy Carrier

Figure 31a shows the global energy demand shares by energy carrier in the current policies scenario. The energy demand trends that were described in the previous paragraph are now presented in the form of percentages. Thus, as can be observed in figure 31a, the oil products share shows a constantly decreasing trend starting from a percentage of almost 94% in 2015 and reaching about 62% in 2050. On the contrary, electricity which took up 0.8% in 2015 is expected to constitute about 12% in 2050. Biofuels, which made up about 2% in 2015, are expected to reach their maximum market share in 2033 with a fraction equal to 16.8% and then slightly decrease but still maintain a market share equal to about 15% until 2050. Hydrogen and ammonia show significant rising trends reaching from zero to almost 4.9% and 4.3%, respectively. Natural gas energy demand is almost constant and fluctuates between 1.3% and 1.8% during this time period.

In accelerated policies scenario, as figure 31b illustrates, oil products market share is highly decreased from about 94% in 2015 to almost 25% in 2050. Electricity and ammonia (due to its use in the marine sector) are expected to account for 30% and 18%, respectively, in 2050 and are mainly going to replace oil products followed by the significant contribution of hydrogen and biofuels which are going to make up about 13% and 14%, respectively.

In the current policies scenario, the remaining oil products consumption is mainly due to light duty vehicles, shipping and aviation activity, while, in the accelerated policies scenario it is due to shipping and aviation activity.

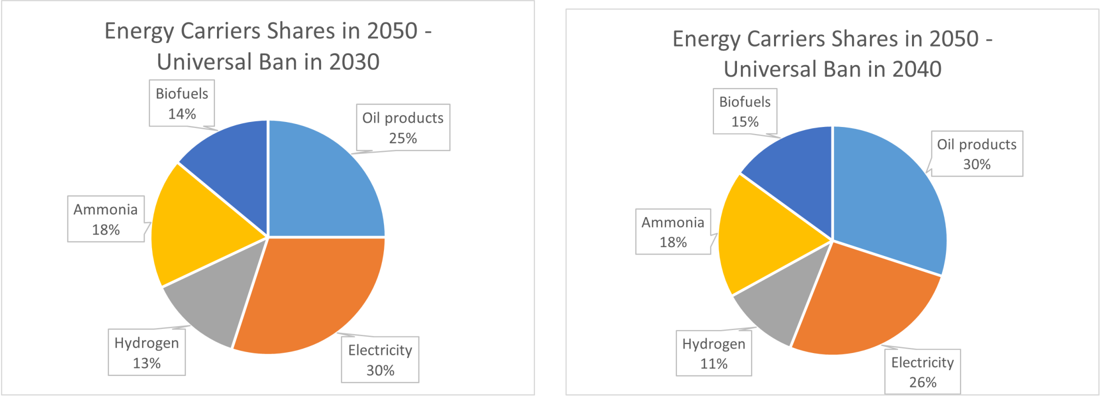


(a) (b)

Figure 31: (a) Global Final Energy Use Shares by Energy Carrier CP (b) Global Final Energy Use Shares by Energy Carrier AP

6.6 Final Energy Demand Shares Depending on the time of the ICE Ban

Figures 32a, 32b show the Global Energy Carriers Shares in 2050 with a universal ICE ban applied in 2030 and 2040, respectively. These figures show the impact of the ICE ban on the expected energy carriers shares in 2050 in the accelerated policies scenario. In particular, it seems that by extending the ICE ban adoption for 10 years, the oil products consumption in 2050 could be 20% higher, the electricity 13% lower, hydrogen 15% lower and biofuels 7& higher. Consequently, as expected, by extending the ICE ban adoption leads to lower penetration of low carbon fuels in the market.



(a) (b)

Figure 32: (a) Global Energy Carriers Shares in 2050 - Universal ICE Ban in 2030 - AP (b) Global Energy Carriers Shares in 2050 - Universal ICE Ban in 2040 - AP

6.7 Total Cumulative Energy Consumption per Energy Carrier

Table 8 shows the total cumulative energy consumption per energy carrier from 2015 to 2050 depending on the scenario and, regarding the accelerated policies scenario, on the time of the ICE ban adoption. According the accelerated policies scenario, such a strategy can significantly contribute in reducing the oil products consumption and enhancing the penetration of low carbon energy carriers. Throughout the period 2015 - 2050 it seems that oil products are by far the most consumed fuel in the transportation sector followed by electricity and biofuels, while hydrogen and ammonia also show promising trends.

Table 8: Cumulative Energy Consumption per Energy Carrier

Cumulative Energy Consumption per Energy Carrier [EJ]			
Energy Carriers	**Scenarios**		
	Current Policies	**AP - Ban 2040**	**AP - Ban 2030**
Oil Products	3320	2508 (-32%)	2043 (-62%)
Electricity	193	252 (+31%)	400 (+107%)
Hydrogen	69	100 (+45%)	156 (+126%)
Ammonia	81	225 (+178%)	225 (+178%)
Biofuels	546	402 (+36%)	397 (+38%)
Natural Gas	72	44 (-39%)	36 (-50%)

Using specific CO_2 emission factors for each energy carrier it is possible to calculate the total CO_2 emissions produced in each case. The specific CO_2 emission factors values are taken from ICCT's Global Transporation Roadmap Model (ICCT, 2012). More specifically the specific CO_2 emission factor of oil products, electricity, hydrogen, ammonia, biofuels and natural gas are 72, 0, 0, 0, 72 and 63 CO_2 tonnes per TJoule of consumed energy. Thus, the total emissions of the current policies scenario are almost 283 CO_2 Gtonnes and the total emissions of the accelerated policies scenario in the case of a universally adopted ICE ban in 2040 and in the case of an ICE ban in 2030 are approximately 212 and 178 CO_2 Gtonnes. The results show that the total CO_2 emissions produced from 2015 to 2050 are lower for sooner implementation of an ICE ban. More specifically, according to the results, the CO_2 emissions could even be reduced by 105 CO_2 Gtonnes, while a 10 year difference of a universal ICE ban adoption could cause a CO_2 emissions difference of nearly 35 CO_2 Gtonnes.

7 Discussion and Recommendations

Global Warming and Climate change are now visible and are directly affecting our everyday life. In recent years, having seen the consequences of climate change in the environment and people's lives, I realized the importance of dealing with this phenomenon. Thus, as soon as I was given the opportunity to study a subject directly related with this problem, I was more than sure that I wanted to do so. In particular, the purpose of this research was to study how the global energy demand in the transportation sector could develop in the future and which technologies and fuels could play an important role.

As was discussed in the introduction, reducing the global transportation energy demand is of crucial importance in order to cope with climate change. Before dealing with this subject, due to the contact that I had with electricity and hydrogen technologies via my academic course, I thought that the global transportation energy demand would be able to decline without further policies. However, according to the current policies scenario, this cannot happen since current policies are not able to achieve energy demand reduction and, thus, further policies implementation is needed. In particular, the results demonstrate that without further policy adoption the global energy demand will continue to increase and, according to our current policies scenario, it could grow by nearly 60% reaching almost 142 EJ in 2050. Thus, it is necessary new, stricter policies to be applied. According to the accelerated policies scenario, with the stricter implementation of the already applied policies and the adoption of new ones, the energy demand could start to decline after 2029 and fall to about 84.8 EJ in 2050, showing a decrease of almost 5% compared to 2015 levels and 10% compared to 2029 levels.

Low carbon technologies and fuels should also play a major role in order to decarbonize the transportation sector and contribute in combating climate change. What I used to believe before doing the current research, was that electric and fuel cell vehicles are going to dominate in the future. However, more policies are needed in this case as well. In both scenarios, electricity and oil products are expected to be of vital importance for the transportation sector, while biofuels, hydrogen and ammonia could also play an important role. In particular, in the current policies scenario, oil products are expected to decrease substantially and make up almost 58%, while electricity is going to grow significantly and represent almost 17% in 2050 being the second most widespread fuel after oil products. Biofuels, hydrogen and ammonia are expected to account for about 10%, 4.5% and 4%, respectively. In the accelerated policies scenario, electricity is expected to surpass oil products in 2047 and make up almost 30% of the energy consumption by 2050, while oil products are projected to account for 24%. Biofuels, hydrogen and ammonia are expected to grow to 14%, 13% and 18%, respectively. Thus, it is clear that electricity could almost double its share, while hydrogen and ammonia could climb to approximately 3 and 5 times their previous share, respectively if more policies are applied.

Overall, the results of this research demonstrate that it is possible to limit the global transportation energy demand and enhance the diffusion of low carbon technologies and fuels. In particular, in order for this to happen, according to the accelerated policies scenario, it is necessary to apply new policies in order to achieve bending of the energy demand curve and simultaneous increase of low carbon fuels - such as electricity, hydrogen, ammonia, biofuels - and technologies - such as electric and fuel cell engines. However, if no more policies than the current ones are applied, according to the current policies scenario, the global energy demand curve is expected to keep growing, while low carbon fuels and technologies will have much less impact. More specifically, electricity is still expected to account for a significant fraction of the energy demand by 2050 (though, it is almost half the percentage that is expected in the accelerated policies scenario) but hydrogen and ammonia show an even greater difference, as in the current policies scenario their penetration in the market is nearly 3-4.5 times less than in the accelerated policies scenario.

In line with the results of IEA's baseline scenario (IEA, 2009a), the global transportation energy demand as it is calculated in current policies scenarios of the current research is expected to follow a constantly upwards trend and increase by 60% by 2050. IEA's baseline scenario expects an oil products consumption of about 67.5% of the total final energy use in 2050, electricity consumption to reach almost 12% while hydrogen is not taken into account. This research's current policies scenario also expects 58% of the final energy demand to be met by oil products and 17% to be met by electricity in 2050 which agree with IEA's baseline scenario but it also expects hydrogen and ammonia to make up a substantial percentage of 4.5% and 4%, respectively. Thus, the current research agrees with IAE regarding the trends of oil products and electricity and it seems to be a little bit more ambitious regarding hydrogen and ammonia (fuel cell technology).

This study, unlike similar studies that were discussed in the literature review section and do not mainly focus on energy demand and low carbon fuels diffusion but rather on the emissions, includes in its results figures showing the final energy use in the transportation sector throughout the period 2015-2050 by country, transportation mode and energy carrier highlighting the changes in the final energy use of both oil products and low carbon energy carriers. Thus, it provides a detailed analysis of the transportation final energy demand trends under two different possible pathways (current policies scenario and accelerated policies scenario).

Moreover, the current research provides a different diffusion methodology as it uses the Bass diffusion model instead of the logistic or the Gompertz model. In particular, ICCT does not use a diffusion model, but they give the sales of new vehicles as an input in every time increment of their model (ICCT, 2012), IEA uses the Gompertz diffusion model but only for road vehicles (IEA, 2020e), while most of the reports studying the diffusion of new transport technologies mainly use either the logistic or the Gompertz model (Soumia & Maaroufi, 2019). In order to show the significance of the choice of the model in the current research, a comparison between the Bass and the logistic model is shown in figure 33. The comparison is made for the current policies scenario and it shows that the final energy use calculated with the logistic model deviates almost 2% compared to the Bass model in the long term, while in the short term the deviation reaches almost 11%. The big difference in the short term is due to the innovation coefficient which obviously plays a major role in the early development of the curve, while the imitation coefficient shapes the curve in the long term where the difference is much smaller but still significant. Based on the substantial differences of the produced results, it is concluded that the diffusion model choice is of great importance for both the short and the long term modelling as it highly affects the results during the whole 2015-2050 period.

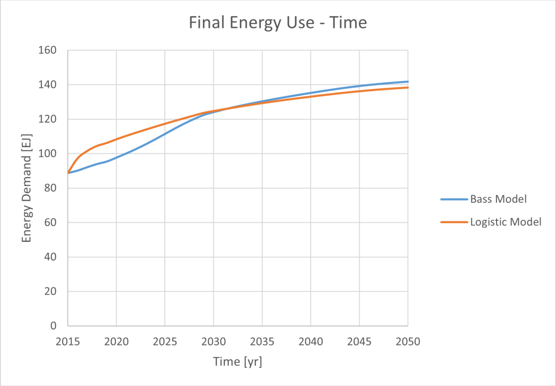


Figure 33: Global Final Energy Use vs Time depending on the chosen Diffusion Model - CP

In order for this study to deal with the lack of some information and still provide as accurate results as possible, certain assumptions and simplifications which may affect the final results were applied. The main assumptions that could be considered as "weak points" of this thesis are:

1. Due to the lack of information, the parameters used in the Weibull Distribution (Survival Curve) are universal and depend only on the transport mode, while they could be different depending on the specific characteristics of each

country, transport mode and technology. In figure 34, a sensitivity analysis is conducted regarding the impact of b, T and g parameters on LDVs energy demand in the current policies scenario. In particular, if the b parameter increases by 0.2, the T parameter increases by 2 and the g parameter increases by 1, the final energy use of LDVs grows by 0.07%, 0.14% and 0.14%. Consequently, none of the b, T and g parameters has significant impact on the final energy use and, thus, their effect on the results of the current report are considered negligible.

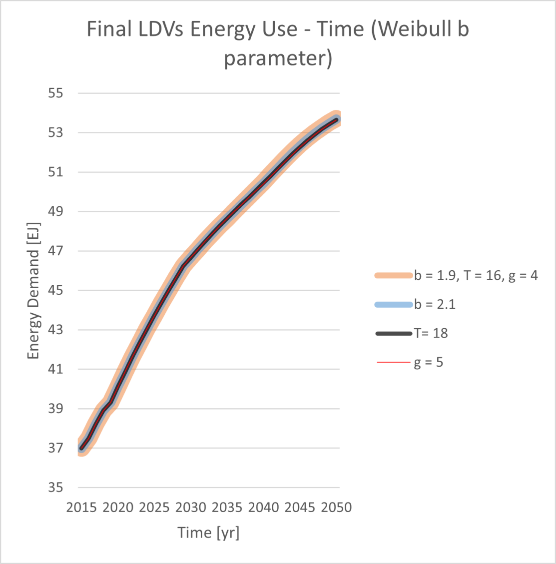
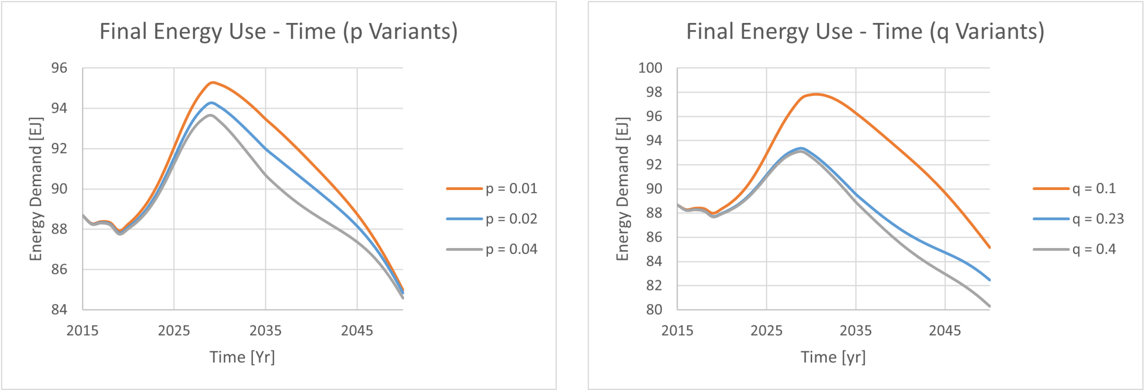


Figure 34: Final LDVs Energy Use vs Time depending on Weibull parameters - CP

2. Regarding the Bass diffusion model, universal values for the coefficient of innovation (p) and the coefficient of imitation (q) are taken from previous studies depending only on the technology (electric or fuel cell). However, there are not sufficient information in the literature so as to provide values for the p and q coefficients for all the different countries. Figures 35a, 35b indicate the impact that p and q coefficients have on final energy use in the accelerated policies scenario. According to figure 35a, for a 50%-100% change of p, the final energy use changes about 0.15% - 0.3%, while, according to figure 35b, for a 55% - 75% change of q, the final energy use changes almost 2.6% - 3.3%. Consequently, it is obvious that, in the long run, the innovation coefficient, p, does not substantially affect the final energy use but the imitation coefficient does and, consequently, it is considered a parameter of much greater importance for a long-term analysis.



(a) (b)

Figure 35: (a) Final Energy Use vs Time depending on the innovation coefficient (p) - AP (b) Final Energy Use vs Time depending on the imitation coefficient (q) - AP

3. The annual reduction of the specific energy consumption could be modelled per transport mode, technology and country. Figure 36 demonstrates the effect of this variable on the final energy use. It shows that as it increases, the energy demand decreases (due to the lower fuel consumption following the technology improvements). More specifically, for an annual reduction of the specific energy consumption growth of 1%, the final energy use falls by almost 12% - 14%. The sensitivity analysis highlights the importance of choosing accurate input values regarding the annual reduction of the specific energy consumption.

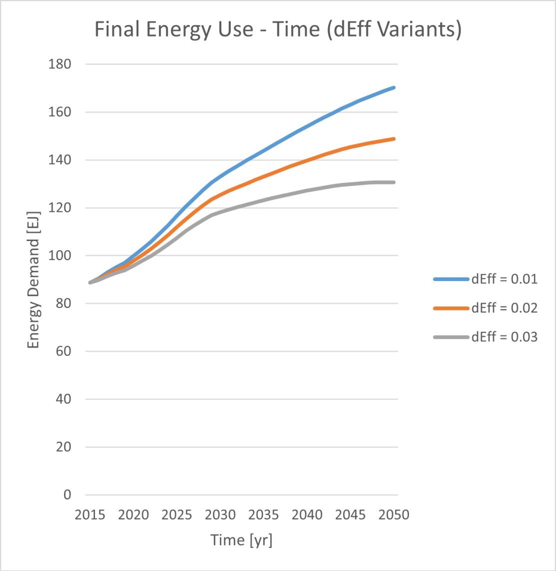


Figure 36: Final Energy Use vs Time depending on the Annual Reduction of the Specific Energy Consumption - CP

4. The expected market shares of the different technologies in the various countries by 2050 are taken from the literature. However, the literature does not provide extended information about different market shares depending on the different countries taking into consideration the specific characteristics of each country. In order to quantify the impact that a potential market share of a technology has on final oil products use, a sensitivity analysis regarding the impact that the potential market share of electric LDVs could have on the global final oil products demand of LDVs is conducted. The sensitivity analysis is conducted for the current policies scenario so as to neglect the universal ICE ban assumption. According to the sensitivity analysis, presented in figure 37, for a 15% - 20% growth of the potential market share, the oil products use increases by almost 4% - 7.5% by 2050. This is due to lower share of electric vehicles to the market leading to higher consumption of oil products and, as a result, lower consumption of electricity. Consequently, the potential market share values play an important role regarding the penetration of new technologies in the market.

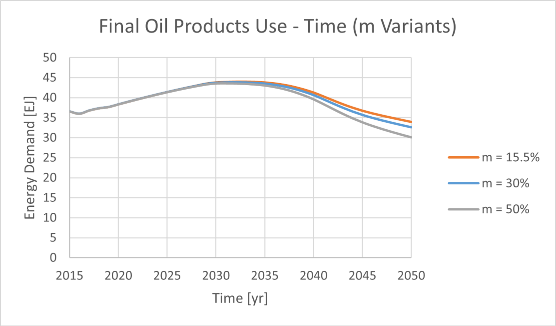


Figure 37: Final Oil Products Use vs Time depending on the Potential Market Share of Electric Vehicles - CP

This is why it is important to recommend improvements to the current study as future work. The recommendations are presented below:

- The parameters used in the Weibull Distribution (Survival Curve) are universal and depend only on the transport mode. Further research could be done in order to study the parameters for different countries and technologies. Such a research could be done by conducting a statistic analysis so as to develop real survival curves using real data and then fit b, T and g parameters against the survival curve that is developed using real data (ICCT, 2012).

- Regarding the Bass diffusion model, the coefficient of innovation (p) and the coefficient of imitation (q) are taken from previous studies for the same or similar technologies. So, a study could be done in order to provide such coefficients for each technology and each country separately. In order for this study to be successfully completed, data regarding the registrations of electric and fuel cell vehicles should be gathered in each country separately and then, by using Bass's discrete model (Bass, 1969), p and q coefficients can be calculated. The result would be, in each country and technology to have specific p and q coefficients and, consequently, more accurate results.

- The annual reduction of the specific energy consumption could be modelled per technology and per country since it largely affects the final results. However, the literature does not provide such data. In order for this to happen, further research should be done in order to calculate this parameter per transport mode, technology and country. This could be done by applying forecasting models based on historical efficiency data which would be taken per country, mode and technology.

- The expected market shares of the different technologies in the various countries by 2050 are taken from the literature. However, the literature does not provide extended information about different market shares depending on the different countries taking into consideration the specific characteristics of each country. Thus, further research could be done in each country separately so as to develop potential future market shares of the various technologies. This could happen by contacting each country's governments separately in order to gain a insight regarding their future policy plans.

8 Conclusion

This study aims to provide a pathway to limit the global transportation energy demand and enhance the use of low carbon fuels and technologies. This is approached through a detailed modelling of the global transportation energy demand from 2015 to 2050. Then two scenarios are developed in order to represent a potential pathway where no more policies are taken into account (current policies scenario) and a pathway where more policies are taken into account aiming to achieve the goals of this research (accelerated policies scenario).

In the question "How could future energy demand be limited by country and transportation mode in the transportation sector?", the results of the accelerated policies scenario indicate that new and stricter policies which could lead to efficiency improvements (and, as a result, to higher annual reduction of the specific energy consumption) and to faster and higher diffusion of low carbon technologies and fuels could achieve mitigation of the energy demand in the future. In particular, depending on the results of the policies applied in each country and transportation mode, the energy demand could start to decline after 2029 and decrease almost 5% compared to 2015 levels and 10% compared to 2029 levels, while in the current policies scenario the energy demand is expected to rise by 61% by 2050. More specifically, the countries with the biggest impact in the transportation energy demand are China, the United States and India and, according to the accelerated policies scenario, China and the United States could achieve a reduction of 2% and 57%, respectively, while India could mitigate the energy demand increase to 95%. Regarding transport modes, light duty vehicles and road freight vehicles energy demand shows the most significant reduction and decreases by 35% and 38%, respectively. 2 and 3 wheelers, buses and rail energy demand could also substantially fall by 16%, 21% and 15%, respectively. Regarding marine and air vessels, they could limit the increase of their energy demand to 143% and 47%, respectively.

The answer to the question "Which low carbon technologies and fuels could dominate in the transportation sector?", the accelerated policies scenario indicates that electricity is the energy carrier that shows the highest potential to dominate in the transportation sector, while hydrogen, ammonia and biofuels are also expected to play a major role. In particular, electricity is expected to be mainly used in road transportation, hydrogen in freight road vehicles, buses and shipping, while ammonia is only expected to be used in shipping. Consequently, the technologies that are expected to dominate in the transportation sector are electric and fuel cell engines.

Regarding the question "To what extent could low carbon fuels and new technologies increase their share in the transportation sector?", the accelerated policies scenario shows that electricity is expected to be the most significant low carbon energy carrier and could grow by 3400% and make up almost 30% of the total energy demand by 2050. Hydrogen and ammonia are also expected to penetrate into the market and constitute almost 18% and 13%, respectively. Biofuels are expected to nearly triple and make up approximately 14% in 2050. Consequently, electric and fuel cell engine technologies are expected to account for 30% and 31% of the total transportation sector by 2050.

The answer to the question "How could the technology improvements, the rate of diffusion of new technologies and the internal combustion engines ban affect the future energy demand?" is given based on the sensitivity analysis presented in chapter 5. The sensitivity analysis shows that the results are largely affected by the technology improvements (which lead to the reduction of the annual specific energy consumption), the ICE ban and the diffusion model coefficients. In particular, the sooner that an ICE ban is implemented the sooner that the energy demand curve starts to decline reaching to lower values in 2050. Regarding a universal ICE ban, the ICE ban adoption extension from 2030 to 2040 could lead to almost 14% growth in the final energy use, 20% increase of oil products consumption and 13% and 15% decrease of electricity and hydrogen consumption, respectively. Moreover, the higher that the innovation and imitation coefficients of the Bass diffusion model are, the lower that the energy demand is going to be. More specifically, according to the sensitivity analysis, the imitation coefficient has a much more significant impact on the results than the innovation coefficient as the imitation coefficient could cause a change in the final energy demand of up to 7% while the innovation coefficient could also cause a change of up to 0.4%. Regarding the annual reduction of the specific energy consumption, the sensitivity analysis results indicate that for a change of 1%, the final energy demand changes almost 12-14%. Consequently, it is clear, that all these inputs highly affect the accuracy of the result.

Consequently, regarding the main research question "How could the global energy demand be limited in the future and which low carbon technologies and fuels could play a major role in the transportation sector in the following years?", the answer is that the global transportation energy demand could only be limited if new policies are applied. Without new policies, the energy demand is expected to increase by 60% according to the current policies scenario, while, with new policies, it could start to decline after 2029 and reduce by 5% compared to 2015 levels and 10% compared to 2029 levels, according to the accelerated policies scenario. Low carbon fuels could play a major role in the future of the transportation sector if appropriate strategies are followed. In particular, as the two scenarios indicate, electricity use could almost double from 17% to 30%. Moreover, hydrogen and ammonia could substantially rise from 4.5% and 4% to 13% and 18%, respectively, showing a tremendous potential, while biofuels, could slightly increase from 10%

to 14%. Consequently, it is clear that electric and fuel cell vehicles could dominate the transport market, according to the accelerated policies scenario and, as the accelerated policies scenario indicates, it is possible for the transportation energy demand to be limited and for low carbon fuels and technologies to substantially increase their share in the market if appropriate strategies are followed.

The current research aimed to provide a model used to develop different potential pathways regarding the future situation of the transportation sector. Based on the model, the current policies scenario and the accelerated policies scenario were developed in order to demonstrate how could the global energy demand be limited and which low carbon technologies could significantly affect the transportation sector in the future. According to the results, this research shows that if strategies that favor technology improvements and low carbon fuels and technologies implementation are applied, the future energy demand could be highly reduced and at the same time technologies like electric and fuel cell engines and energy carriers like electricity, hydrogen and ammonia could dominate in the transportation sector. Moreover, it highlights that the means to reduce the future energy demand in the transportation sector and increase the share of low carbon fuels and technologies exist and, as a result, the important thing is to implement the right strategies that will cause the transportation sector to significantly change within the next 30 years. Consequently, this study has come to valuable conclusions proving that has achieved its initial target. Thus, it could be a point of reference for future studies or policy-makers that aim to develop policies regarding the transportation sector energy demand reduction and new, low carbon technologies and fuels implementation, since it provides a model different than the models that have been used until now (the Bass diffusion model, a country by country approach and greater detail in low carbon technologies and fuels have been used). So, it could be very useful if used in parallel with the other studies that demonstrate similar results but have been produced based on different approaches so as to develop policies regarding the future of the transportation sector. In particular, the current study could be mainly taken into consideration if policies regarding energy carriers such as ammonia, hydrogen, biofuels and electricity, technologies such as electric and fuel cell vehicles and internal combustion engines bans are developed or if studies regarding the transportation energy demand over the period 2015-2050 are conducted. All in all, the current research can be considered as a substantial contribution to those conducting research or developing policies regarding the future of transportation sector and, more specifically, regarding energy demand modelling and diffusion of low carbon fuels and technologies.

A Appendix

Table 9: Average Annual Distance Travelled per Vehicle

Average Annual Distance Travelled per Vehicle				
Country	**Light Duty**	**2 and 3 wheelers**	**Buses**	**Road Freight**
China	19300	5600	108500	70000
United States	19838	2702	30997	110890
India	11458	10001	89280	46000
Russia	9924	3000	38000	38358
Japan	11377	5000	28850	7046
Canada	17406	7000	39748	82863
Germany	14107	3042	43040	49581
Brazil	14017	8648	77012	88748
Iran	16482	7000	50000	45500
Saudi Arabia	16482	7000	50000	45500
France	16730	3000	37247	49581
Indonesia	18053	5661	30167	69686
United Kingdom	13178	3824	26454	49581
Mexico	10624	11000	48452	50000
Turkey	7704	11000	6315	45500
Australia	14482	4700	29100	90800
Italy	9332	5847	32234	49581
Spain	9138	498	33576	49581
South Africa	9927	5015	50000	31767
Thailand	18053	5661	30167	69686
Ukraine	11565	3000	59431	37109
Poland	8693	2881	16799	49581
Malaysia	18053	5661	30167	69686
Sweden	14103	2391	69672	49581
Norway	13193	8313	33957	49581
Argentina	14017	8648	77012	88748
Netherlands	12973	3260	66199	49581

Table 10: Fuel Consumption - Road Light Duty Vehicles

Fuel Consumption - Road Light Duty Vehicles [MJ/km]				
Region	**Technologies**			
	SIGE	**CIDE**	**Fuel Cell**	**Electric**
Africa	3.75	3.08	1.26	0.77
OECD Europe	2.24	1.83	0.74	0.45
China	2.53	2.08	0.91	0.56
Middle East	2.26	1.85	0.82	0.50
Non-OECD Americas	2.26	1.85	0.82	0.50
Non-OECD Eurasia	2.15	2.53	0.81	0.50
OECD Americas	2.66	2.18	0.96	0.59
OECD Asia-Oceania	2.66	2.18	0.96	0.59
Asia-Pacifia-40	2.66	2.18	0.96	0.59

Table 11: Fuel Consumption - 2 and 3 wheelers

Fuel Consumption - 2 and 3 wheelers [MJ/km]				
Region	**Technologies**			
	SIGE	**CIDE**	**Fuel Cell**	**Electric**
Africa	0.99	0.84	0.55	0.55
OECD Europe	1.28	1.09	0.70	0.70
China	0.86	0.73	0.47	0.47
Middle East	0.99	0.84	0.55	0.55
Non-OECD Americas	0.99	0.84	0.55	0.55
Non-OECD Eurasia	0.99	0.84	0.55	0.55
OECD Americas	1.83	1.56	1.01	1.01
OECD Asia-Oceania	0.56	0.47	0.31	0.31
Asia-Pacifia-40	0.56	0.47	0.31	0.31

Table 12: Fuel Consumption - Buses

Fuel Consumption - Buses [MJ/km]				
Region	**Technologies**			
	SIGE	**CIDE**	**Fuel Cell**	**Electric**
Africa	6.11	5.01	2.88	2.88
OECD Europe	10.17	8.34	4.67	4.67
China	9.87	8.58	5.23	5.23
Middle East	6.91	5.66	3.32	3.32
Non-OECD Americas	14.52	11.91	6.55	6.55
Non-OECD Eurasia	9.60	7.87	4.52	4.52
OECD Americas	9.91	8.01	4.62	4.62
OECD Asia-Oceania	7.54	6.18	3.63	3.63
Asia-Pacifia-40	7.54	6.18	3.63	0.31

Table 13: Fuel Consumption - Road Freight Vehicles

Fuel Consumption - Road Freight Vehicles [MJ/km]				
Region	**Technologies**			
	SIGE	**CIDE**	**Fuel Cell**	**Electric**
Africa	22.73	16.45	9.08	9.08
OECD Europe	13.21	10.83	5.96	5.96
China	19.81	16.25	8.94	8.94
Middle East	14.77	13.19	7.26	7.26
Non-OECD Americas	13.75	11.28	6.22	6.22
Non-OECD Eurasia	14.65	13.08	7.20	7.20
OECD Americas	17.43	14.29	7.88	7.88
OECD Asia-Oceania	17.64	15.74	8.67	8.67
Asia-Pacifia-40	17.64	15.74	8.67	8.67

Table 14: Fuel Consumption - Rail Passenger Vehicles

Fuel Consumption - Rail Passenger Vehicles [MJ/km]				
Region	**Technologies**			
	Steam	**ICE**	**Fuel Cell**	**Electric**
Africa	0.3			
OECD Europe	0.29			
China	0.29			
Middle East	0.29			
Non-OECD Americas	0.29			
Non-OECD Eurasia	0.29			
OECD Americas	0.29			
OECD Asia-Oceania	0.29			
Asia-Pacifia-40	0.29			

Table 15: Fuel Consumption - Rail Freight Vehicles

Fuel Consumption - Rail Freight Vehicles [MJ/km]				
Region	**Technologies**			
	Steam	**ICE**	**Fuel Cell**	**Electric**
Africa	0.24			
OECD Europe	0.15			
China	0.15			
Middle East	0.15			
Non-OECD Americas	0.15			
Non-OECD Eurasia	0.15			
OECD Americas	0.15			
OECD Asia-Oceania	0.15			
Asia-Pacifia-40	0.15			

Table 16: Fuel Consumption - Shipping

Fuel Consumption - Shipping [MJ/km]					
Region	**Technologies**				
	Steam	**Diesel**	**Gas Turbine**	**Fuel Cell**	**Electric**
Africa	0.05				
OECD Europe	0.05				
China	0.05				
Middle East	0.05				
Non-OECD Americas	0.05				
Non-OECD Eurasia	0.05				
OECD Americas	0.05				
OECD Asia-Oceania	0.05				
Asia-Pacifia-40	0.05				

Table 17: Fuel Consumption - Aviation

Fuel Consumption - Aviation [MJ/km]				
Region	**Technologies**			
	Turbine	**Piston**	**Fuel Cell**	**Electric**
Africa	2.46			
OECD Europe	1.89			
China	2.21			
Middle East	2.24			
Non-OECD Americas	2.64			
Non-OECD Eurasia	1.89			
OECD Americas	2.04			
OECD Asia-Oceania	2.23			
Asia-Pacifia-40	2.23			

Table 18: Biofuel Mandates (IATA, 2020), (The Digest, 2021), (ECAC, 2021)

Biofuel Mandates			
Country	**Road Vehicles**	**Marine Vessels**	**Aircrafts**
China	15%	20%	80%
United States	5%	20%	80%
India	20%	20%	80%
Russia	20%	20%	80%
Japan	40%	20%	80%
Canada	10%	20%	80%
Germany	12.4%	20%	80%
Brazil	27%	20%	80%
Iran	-	20%	80%
Saudi Arabia	10%	20%	80%
France	50%	20%	80%
Indonesia	20%	20%	80%
United Kingdom	12.4%	20%	80%
Mexico	10%	20%	80%
Turkey	3%	20%	80%
Australia	6%	20%	80%
Italy	10%	20%	80%
Spain	12.4%	20%	80%
South Africa	2%	20%	80%
Thailand	5%	20%	80%
Ukraine	8%	20%	80%
Poland	12.4%	20%	80%
Malaysia	10%	20%	80%
Sweden	27%	20%	80%
Norway	30%	20%	80%
Argentina	26%	20%	80%
Netherlands	12.4%	20%	80%

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