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Decarbonization of the Transportation Sector in Europe: The Impact Assessment of Mitigation Policies Within an Integrated Assessment Model

In collaboration with

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Abstract

With increasing climate change risks, the World's attention has shifted towards adaptation and mitigation planning. Climate change mitigation policies are the backbone of a future with net zero emissions. Europe has been one of the leaders in adopting clean energy technologies and intensifying decarbonization efforts. The transportation sector in Europe is one the most fossil-fuel dependent sectors, contributing to 27% of the total greenhouse gas emissions. The Fit-for-55 policy package is part of the effort that Europe has been putting to achieve carbon neutrality in the year 2050. This work aims to assess the impacts of the Fit-for-55 transportation policy of banning the sales of fossil fuel-based light duty vehicles in Europe by the year 2035. The assessment of the future impacts of the policy is done within separate scenarios each representing a World with different climate efforts. The WITCH integrated assessment model has been used as a tool to implement the scenarios and assess the policy impacts, and the transportation module within WITCH has been modified and expanded to allow a better capturing of the policy implications.

Implementing the Fit-for-55 transportation policy leads to a decrease in the total road transportation service demand because of abandoning the once cheap fossil fuel vehicles. The fleet composition shifts from being traditional vehicle dominated to electrical vehicle dominated, depending on the climate efforts and the policy implementation. The findings suggest that the decarbonization of the European transportation sector is achievable through implementing the Fit-for-55 policy along with the proposed mid-century strategies. Therefore, a combination of efforts from different sectors are necessary to achieve the future climate goals.

Keywords: Integrated Assessment Modeling, Climate Change, Mitigation Policies, Road Transport, WITCH Model.

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Executive Summary

The following research work aims to assess the of the effect of the Fit-for-55 transportation policy on the decarbonization of the European road transportation sector. The assessment of the policy was performed using the WITCH model, which is a dynamic integrated assessment model that studies the interaction between the economy, climate, and energy technologies. To enable the assessment of the transportation policy within WITCH, modifications to the passenger road transport module have been done to account for the change in total demand with respect to the fluctuations in the price of transportation services and income. The thesis work was performed during my time as a Visiting Student at RFF-CMCC EIEE under the guidance of the WITCH model team.

Introduction

Humans currently live in an era of unprecedented economic growth and technological advancement. On the way to economic and technological prosperity, the issue of climate change came into place. The greenhouse gas emissions resulting from human activities have been sharply increasing ever since the nineteenth century, as it is estimated that the most probable range of the human contribution to the warming of the Earth from the 1850-1900 until 2010-2019 is between 0.8°C and 1.3° [2]. Fossil fuels offer a cheap and fast method to achieve industrial and economic growth, but the GHG emissions that are a result of those actions induce a hidden cost that must paid by current and future generations. The effects of climate change can be observed on an environmental, economic, and social scale. To enable tackling the issues implied by climate change, decision makers have shifted towards setting climate mitigation and adaptation policies. Policies are the tools that are currently used to limit emissions, promote renewables, and ban any polluting technologies.

The transportation sector is one of the most fossil-fuel dependent sectors since oil has the major share of the total transportation fuel consumption in the world. The world passenger road vehicles contribute to around 3.6 Gt of CO2 which is 1.5 times more than the closest transportation mean which is freight road transport [29]. Over the past years, new technologies that power light duty vehicles that are more environmentally friendly, such as electric drive vehicles and fuel cell vehicles, have emerged as alternatives to traditional fossil fuel cars. However, most of the worldwide fleet still consists of traditional vehicles, and the penetration of cleaner technologies requires governments and

decision makers to set the appropriate policies that would lead consumers to switch from traditional cars to cleaner alternatives. Europe is one of the leading regions in deploying new electric drive and plug-in hybrid vehicles. However, as of the year 2021, more than 85% of the newly produced vehicles within Europe are gasoline or diesel fueled vehicles [44]. The European transport sector was responsible for 27% of the total greenhouse gas emissions in the year 2017. Those emissions are distributed between road, aviation, and maritime transport sectors and the largest share of the emissions, that is 71.7% of the total transport related emissions, is due to the road transport sector [27]. Therefore, for Europe to be able to achieve the climate goals and ambitions that it has pledged as part of the Paris Agreement, it must invest time and effort in decarbonizing the road transport sector. This led Europe to develop several plans over the past decades to regulate the road transport sector, and to plan for a carbon neutral fleet [31].

The Fit-for-55 policy package is one of the recent policy packages that has been released by the EU Commission, which is part of Europe's plans to meet the net zero goal in 2050. As the name suggests, the policy aims to reduce emissions in Europe by 55% from the 1990 levels. The package extends over several sectors such as power production and transportation, as it provides an update on the previous goals that were set for the year 2030 regarding renewable penetration. The main goal of the transportation policy update in the Fit-for-55 policy package is the ban of the sales of new fossil fuel based light duty vehicles in Europe by the year 2035 [33]. The ban of the sales of new fossil fuel-based light duty vehicles partially starts at the year 2025 until reaching the complete ban by 2035 for both, fossil fuel-based LDVs and Vans, following the trend shown in Table 1.

Table 1: Fit-for-55 Transportation Policy Ban of Sales of Fossil Fueled LDVs and Vans

	2025		2030		2035	
	Cars	Vans	Cars	Vans	Cars	Vans
Reduction of New Sales	15%	15%	60%	50%	100%	100%

The aim of the research work is to assess the Fit-for-55 transportation policy in Europe within the WITCH integrated assessment model. The policy implication on the key variables of the road transportation sector will be assessed within different scenarios.

Methodology

To enable the assessment of the Fit-for-55 transportation policy, the WITCH integrated assessment model has been utilized. WITCH is an integrated assessment model that has been built to assess climate mitigation and adaptation policies. The model has been developed initially by Fondazione Eni Enrico Mattei and the Centro Euro-Mediterraneo sui Cambiamenti Climatici and is currently maintained by RFF-CMCC EIEE [36]. The passenger road transport sector is modelled explicitly in WITCH, with the total demand for transportation services defined exogenously while the model optimizes the choice of vehicle technology through linear competition. This limited the model's capability to assess key variables in the transportation sector that are useful in the evaluation of mitigation policies.

Model Improvements

Due to the limitations that were present in modeling the road transport sector in WITCH, key improvements have been implemented into the model to enable capturing the true range of impacts of transportation policies. The static nature of total transportation service demand that has been present in the model meant that the quantity of passenger kilometers demanded each period would be the same for every scenario, even if the cost of the transportation service decreased or increased significantly. This is not the case in real-life situations since by the law of demand, as the price of a service increases, the demand should decrease.

Therefore, a new transportation total service demand has been implemented in the WITCH transportation module. The new function that is shown in Equation 1 introduces income and price elasticities that allow the total demand to vary depending on the endogenous price of transportation services that is calculated by the model.

Equation 1: New Transportation Total Service Demand Equation

$$D_{r,t} \ = \ D_{r,t-1}\left(\frac{Y_{r,t}}{Y_{r,t-1}}\right)^{\alpha}\left(\frac{P_{r,t}}{P_{r,t-1}}\right)^{\beta}\left(\frac{N_{r,t}}{N_{r,t-1}}\right)$$

Where D is the total service demand expressed in passenger-kilometers, n is the region, t refers to time. Y stands for the income, P for the price of transportation in monetary units per km, and N is the total population. α and β are income and price elasticities respectively.

The population is defined in WITCH according to the Shared Socioeconomic Pathway (SSP) that is implemented in the model. The growth or decline on population would affect the demand by a similar rate. The income is represented by GDP per capita which is defined within WITCH for different regions along the optimization period. The price of transportation is affected by the model optimization process since the prices of fuels vary according to the scenario being implemented and technology improvements. Since research and development is endogenous in WITCH, the price of transportation technologies such as electric drive and fuel cell vehicles is affected by the investment in knowledge spillovers in the respective technologies.

The price of transportation services is divided into two different components, the investment cost that is a function of the specific technology, and the fuel price which is determined on an international level according to global supply and demand. Equation 2 presents the method of calculating the aggregate cost of transportation services that is used in Equation 1.

Equation 2: Price of the Transportation Modes

$$P_{i,r,t} = \sum_{j=1}^{N} (\alpha_{j,i,r,t} \times P_{j,i,r,t}) + \frac{W_{r,t} \times V_{i,r,t}}{S_{i,r,t}}$$

Where i refers to the mode of transport that is only light duty vehicles within WITCH, j is the LDV technology, α is the share of the technology j in the sector i. The final term of the above equation includes W that is the wage rate, V the time value multiplier, and S the speed of each mode. In this research work, the second term of the equation is assumed to be zero, so the time value and speed of transportation is not considered since the only mode present is light duty vehicles.

The price of light duty vehicle technologies is calculated according to Equation 3.

Equation 3: Price of Transportation Technologies

$$P_{j,i,r,t} = \frac{P_{f,r,t} \times I_{j,i,r,t} + N_{j,i,r,t}}{L_{j,i,r,t}}$$

The term $P_{f,r,t}$ refers to the fuel price that is multiplied by the fuel intensity I. The levelized non-fuel costs of transportation is expressed as N, and the load factor for each vehicle type is L.

The levelized non-fuel cost of the transportation technology depends on the capital cost for each vehicle. The capital cost is a function of the specific parts that are present within the vehicle such as internal combustion engines or batteries. Equation 4 calculates the levelized cost of driving a vehicle that is the non-fuel cost.

Equation 4: Levelized Non-fuel Cost of Transportation Technology

$$N_{j,i,r,t} = \frac{Capital\ Cost_{j,i,r,t}\ \times CRF}{VMT_{j,i,r,t}}$$

Capital costs are defined within WITCH for each technology as endogenous variables that depend on the cost of each component of the vehicle. The VMT refers to number of kilometers traveled by each vehicle per year, and it is assumed to be constant for each region throughout the years of optimization. The term CRF refers to the Capital Recovery Factor which is calculated according to the formula in Equation 5.

Equation 5: Capital Recovery Factor

$$CRF = \frac{D \times (1 + D)^N}{(1 + D)^N - 1}$$

Where D is the discount rate that is assumed to be constant and equal to 5% [42], and the lifetime of each vehicle in the light duty vehicle fleet is 22 years.

The demand in Equation 1 is calculated according to the price calculations that have been presented, while assuming an income elasticity of 0.95 and a price elasticity of -1.18 which are in-line with the values derived from the literature [43]. The demand represents the total service demand in passenger kilometers and hence, to determine the total number of light duty vehicles, the total service demand is divided by the distance traveled by each vehicle while taking into consideration that every vehicle serves the demand of more than one individual according to the load factor parameter. The total number of light duty vehicles is calculated as shown in Equation 6.

Equation 6: Total Number of Light Duty Vehicles

$$ldv\_total_{t,n} = \frac{Total\ Service\ Demand_{t,n}}{VMT_{t,n} \times Load\ Factor_{t,n}}$$

Implementing the new transportation service demand function allows the exploration of the effects of novel scenarios on this aspect. The second issue that was tackled in the WITCH model is the linear competition between LDV technologies, which meant that each region would choose to invest in a single technology for a given year given that it is the cheapest one. To solve this issue, the Leontief function that has been used to optimize the choice of vehicle technology is replaced by a new CES function as shown in Equation 7.

Equation 7: Implemented Technology Choice Function

$$Q_{vehicle}(t,n) = \theta(n)\left[\alpha_{TRAD\_CARS}(n)Q_{TRAD\_CARS}(t,n)^{\rho} + \alpha_{HYBRID}(n)Q_{HYBRID}(t,n)^{\rho} + \alpha_{PLG\_HYBRID}(n)Q_{PLG\_HYBRID}(t,n)^{\rho} + \alpha_{EDV}(n)Q_{EDV}(t,n)^{\rho} + \alpha_{FCV}(n)Q_{FCV}(t,n)^{\rho}\right]^{\frac{1}{\rho}}$$

Where $Q_{vehicle}(t,n)$ is the total light duty vehicle demand for region n at time t. The supply of vehicles is represented by Q_j where j is the LDV technology. ρ is the substitution parameter, and α is the share parameter which is assumed to be constant and equal for all the technologies that is equal to 0.2. θ is a parameter specific for each region, and it was calibrated according to the years were historical data for light duty vehicles was available that are 2010 and 2015. The speed of which the transition of the fleet occurs depends on the value of the substitution parameter which is chosen as constant for an elasticity of 10 within this analysis. Implementing the function shown in Equation 7 prevents the instant switching between two different LDV technologies on a regional level and introduces a smoother transition within the fleet composition.

Scenario Building

After performing the required modifications in WITCH, a set of eight different scenarios have been built to assess the impact of the Fit-for-55 transportation policy. A summary of the performed scenarios is shown in Table 2. The scenarios are divided into two distinct cases that are differentiated by the implementation of the Fit-for-55 transportation policy that has been discussed above. The scenarios REF, NDC, MCS and 15DEG2020 represent different Worlds where emission mitigation efforts vary according to the climate ambitions targeted for the future. Europe commits to the pledges that it has made through each scenario without implementing the Fit-for-55 transportation ban. In the second half of the scenarios, which are characterized by the FF55 code, Europe implements only the transportation policy from the Fit-for-55 package, while the other countries commit to the same emission mitigation efforts that have been defined in the base scenarios. The REF scenario is the reference scenario where current policies are adopted, and it will serve as a basis for comparing the progress and cost of decarbonizing the transportation sector in Europe.

Table 2: Implemented Scenarios

SCENARIO CODE	DESCRIPTION
REF	Reference scenario with current policies
NDC	National determined contributions with extrapolation of carbon prices
MCS	Mid-century strategy scenario built over the NDC
15DEG2020	A 700 Gton of CO2 carbon budget scenario that aims to limit 2100 warming to 1.5°C
CURPOL+FF55	Current policy scenario with implementing the Fit-fo-55 transportation policy in Europe
NDC+FF55	NDC scenario with implementing the Fit-fo-55 transportation policy in Europe
MCS+FF55	Mid-century strategy scenario with implementing the Fit-fo-55 transportation policy in Europe
15DEG+FF55	A 700 Gton of CO2 carbon budget scenario with implementing the Fit-fo-55 transportation policy in Europe

The implemented scenarios are analyzed for the period from 2015 until 2055 to find the optimal scenario which the Fit-for-55 transportation would be most effective. The effectiveness of the policy would be evaluated based on its success in decarbonizing the road transportation sector and the cost of implementation.

Results

The implementation of the Fit-for-55 transportation policy in the different scenarios that were previously proposed has significant effects on the state of Europe's transportation sector. Figure 1 shows the total road passenger transport service demand in Europe for the scenarios that have been presented in Table 2.

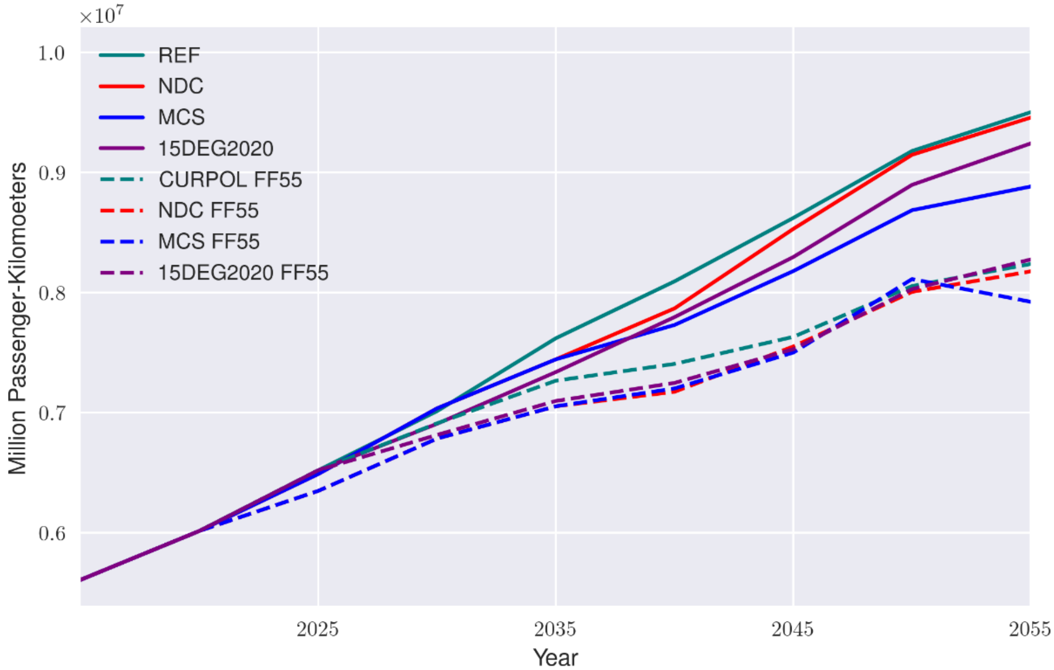


Figure 1: Total Service Demand in Europe Across All Scenarios

The total service demand varies across different scenarios that did not include the Fit-for-55 transportation policy. The REF scenario, which represents a World where the current limited climate mitigation efforts are implemented, has the highest trajectory for total service demand in Europe over the period of analysis. The demand shows a decreasing trend with the increase of climate effort, thus price of carbon, along the base scenarios. Upon the implementation of the Fit-for-55 transportation policies in the CURPOL+FF55, NDC+FF55, MCS+FF55, and 15DEG2020+FF55 scenarios, a significant decrease in the total service demand is observed relative to the respective scenarios that don't include the policy. Implementing the policy in scenarios other than the mid-century strategies would result in the convergence of the total service demand in the year 2100 to the same value as shown in Figure 1, while the increase efforts in the MCS+FF55 scenario pushes for a further reduction in demand.

To reduce the emissions that result from the transportation sector in Europe, it is necessary to increase the share of more environmentally friendly LDV technologies such as electric drive and fuel cell vehicles at the expense of the fossil fuel-based technologies. The ban that is imposed within the Fit-for-55 transportation policy leads to the reshaping of the fleet composition in Europe as presented in Figure 2.

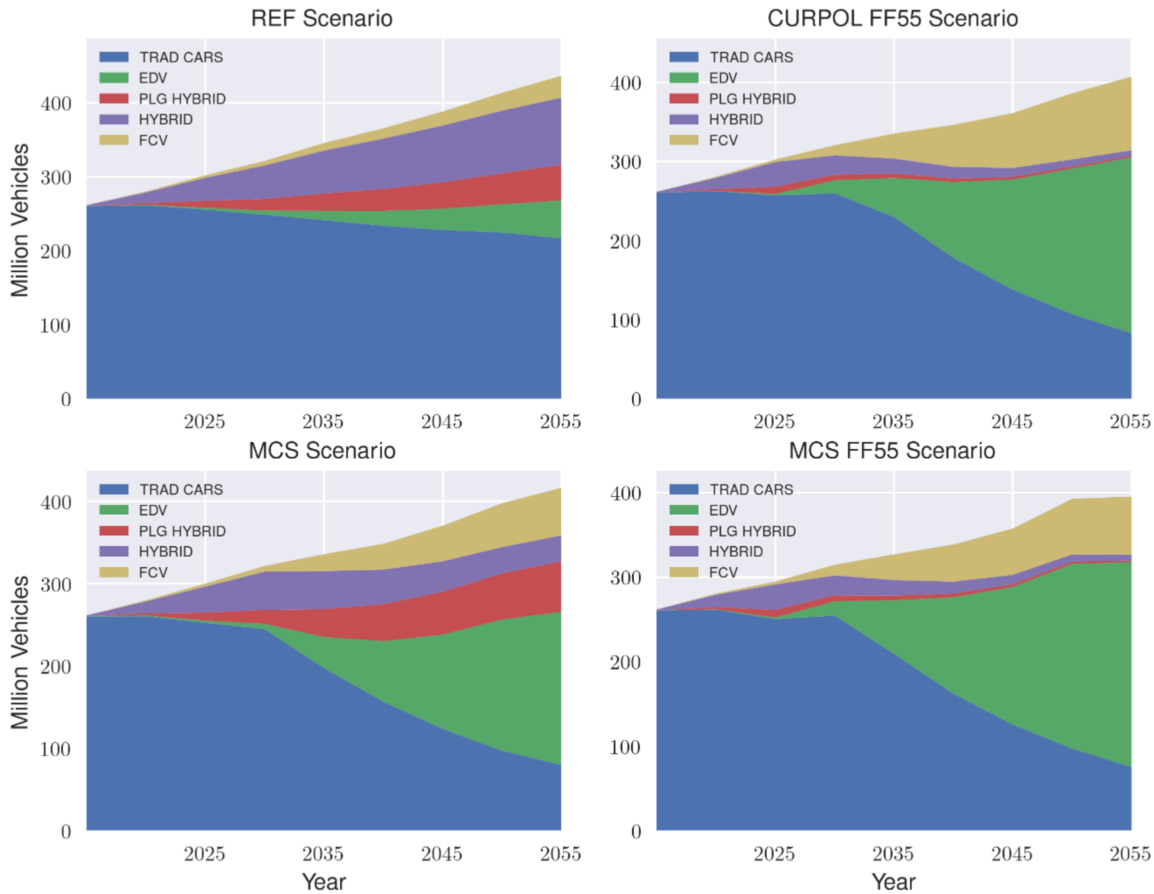


Figure 2: Europe's Fleet Composition After Implementing the Fit-for-55 Transportation Policy

Figure 2 presents a comparison between the two scenarios on both ends of the scale of climate efforts. The REF scenario, which adopts current applied policies, has the least penetration of EDVs as the fleet mostly consists of traditional and hybrid vehicles. The MCS scenario represents the highest level of commitment towards achieving lower emission targets, and this drives the penetration of electric and fuel cell vehicles by the year 2055. Implementing the Fit-for-55 transportation policy in both scenarios leads to the reduction of all fossil fuel-based vehicles' shares and the increased share of electric and fuel cell vehicles. The MCS+FF55 has a larger share of clean vehicles when compared to CURPOL+FF55 due to the increased emission mitigation efforts that start from early years.

Oil is the key driver to the current road transportation sector in Europe, and the plans that are proposed in the Fit-for-55 policy package aim to reduce the consumption of oil and to promote the deployment of renewables. The transportation policy is expected to reduce the total oil consumption in Europe for the years following the full ban in 2035 as shown in Figure 3.

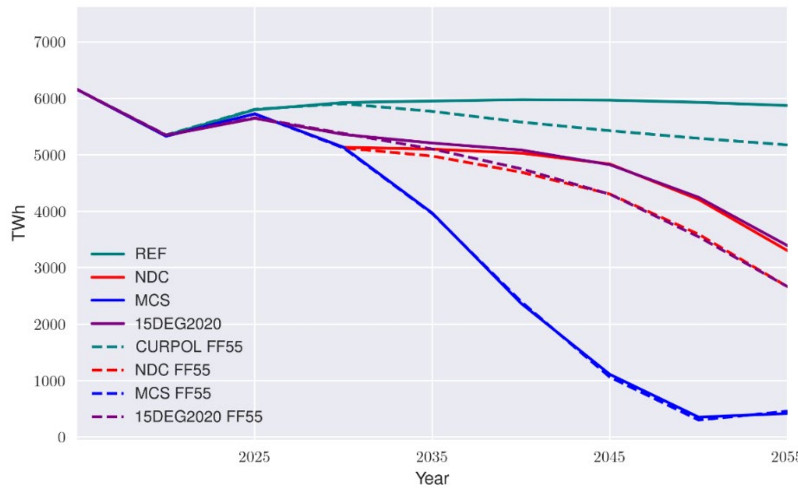


Figure 3: Oil Consumption in Europe

The oil consumption is expected to decrease significantly across REF, NDC, and 15DEG2020 scenarios after implementing the Fit-for-55 transportation policy. The reduction of fossil fuel consmption is not within the same range for the MCS scenario after implementing the ban since the fleet had been already considerably electrified. The decrease in oil consumption would lead to the reduction of CO2 emissions from the transportation sector in Europe as shown in Figure 4.

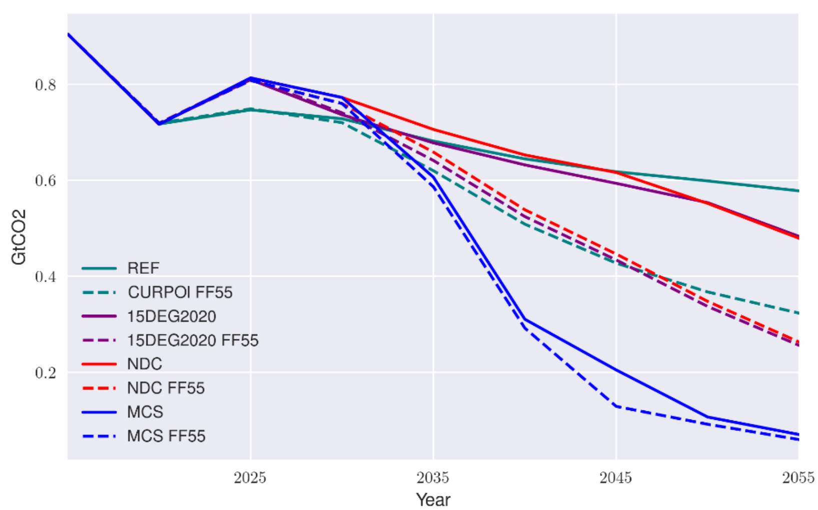


Figure 4: Transportation Sector CO2 Emissions in Europe

Implementing the Fit-for-55 transportation policy would lead to the reduction of CO2 emissions within the transportation sector in Europe for all the proposed scenarios. The policy leads to a further reduction in emissions when implemented in the MCS+FF55 scenario when compared to MCS. Even though the ban leads to the reduction in all scenarios, the true decarbonization of the transportation sector in Europe would not be possible without the increased emission mitigation efforts that are present in the mid-century strategies.

Sensitivity Analysis

The analysis that has been performed throughout this research work is based on selected values for price and technology switching elasticities. The variation of elasticities would result in a different behavior for both newly implemented demand and technology switching functions. Therefore, a sensitivity analyses on price and technology switching elasticities has been performed.

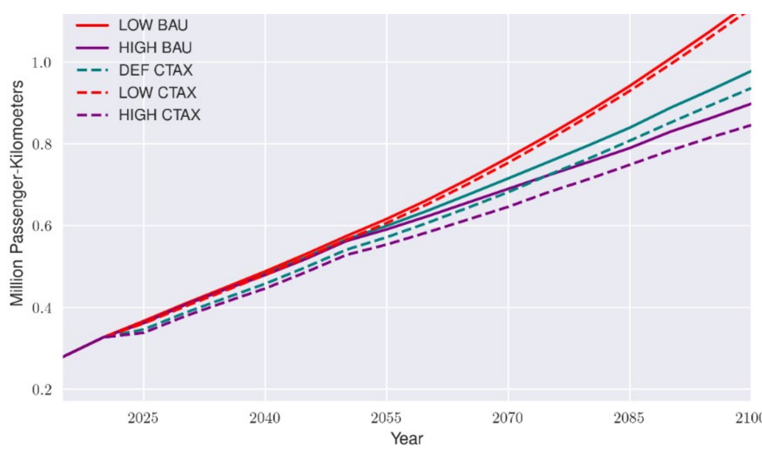
To assess different values of the price elasticity, the total service demand in compared between a BAU scenario and a carbon tax scenario with an initial tax of 50 USD/tonCO2.

Price elasticity was varied according to the values shown in Table 3.

Table 3: Price Elasticity Values

Scenario	Transportation Price Elasticity
DEF	- 1.18
LOW	- 0.4
HIGH	- 1.6

Figure 5: World Total Service Demand Sensitivity



The results of the sensitivity analysis shown in Figure 5 exhibit a decreasing trend with the increase in the absolute value of price elasticity for BAU scenarios. This is due to the increased influence of the fuel price increase, which is mainly oil in BAU scenarios, compared to the effect of the increase in income. A similar comparison may be done between BAU and CTAX scenarios with similar elasticities, where the total service demand would have a sharper decrease for the same tax for higher elasticities.

The second part of the sensitivity analysis tackles the elasticity of technology switching presented in Equation 7. The analysis is performed along similar scenarios with a starting carbon tax value of 50 USD/GtonCO2 while varying the elasticity value. The trend at which the technology switching elasticity was varied can be seen in Table 8. The elasticity values have been wide-ranging between constant and time varying in order to represent different scenarios for the ease of switching. The results shown in Figure 44 reveal that with constant higher elasticity values, electric drive vehicles' penetration would decrease in the years before 2050 and follow by a rapid increase afterwards. The time-varying elasticities insure slight EDV penetration in the early years while maintaining the increased penetration by the year 2100.

Conclusions

This thesis presents the assessment of the Fit-for-55 transportation policy in Europe using the WITCH integrated assessment model. The emission reduction that results from the policy implementation in different scenarios is assessed against the cost of executing the ban. The results suggest that the most favorable scenario that allows the decarbonization of the transportation sector in Europe is a World where mid-century strategies are coupled with the Fit-for-55 transportation policy. Implementing the ban on fossil fuel-based vehicles should be part of a greater mitigation plan that covers all sectors in order to achieve decarbonization targets.

Thesis Structure

The thesis work is organized within five chapters. Chapter one starts with a general introduction on climate change and discusses the impacts over several sectors. Then the state of the transportation sector in Europe and the World is presented to highlight the importance of emission reduction policies within this sector. The following chapter (Chapter two) presents the research methodology that has been adopted to enable the assessment of the Fit-for-55 transportation policy. At the end of the second chapter, a set of eight scenarios is built to be analyzed within WITCH. Chapter three is dedicated to the presentation and analysis of the results. Variables across the eight different scenarios are compared in order to assess the costs and benefits of the policy. A sensitivity analysis on the critical parameters that have been chosen in the methodology section is performed in chapter four. Finally, conclusions and future work possibilities are presented in the final chapter of this thesis (Chapter Five).

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Chapter One

Introduction and Literature Review

The first chapter of this thesis is dedicated to introducing the topic of climate change and discussing its impact on the European and global scale. Mitigation policies' role in tackling climate change issues are described next, and specifically the details of the Fit-for-55 policy package are introduced to choose which policies are most relevant to this work.

The role of Integrated Assessment models in mitigating climate change is discussed briefly within this chapter. A literature review of the transportation sector in Europe is presented to understand the current state of the sector.

Finally, the research questions that motivated this thesis work are presented.

1.1 Climate Change Impacts

1.1.1 Definition and General Impact

Climate Change is known to be one of the most problematic topics in the 21st century. It is defined as a change in the climate, which may be caused by human activity of not, that alters the composition of the global atmosphere, and is significantly different than the natural time variations of the climate system [1]. The influence of human actions on the global climate has been proven in several scientific studies in the past years. According to IPCC, the most probable range of the human contribution to the warming of the Earth from the 1850-1900 until 2010-2019 is between 0.8°C and 1.3°C [2]. The impacts of climate change have been evident over several sectors in the past years. The economic impact of climate change has been estimated such that a 1.3% loss in average income would result from a temperature increase of 2.5°C [3]. Inequality is expected to escalate on a global level since the distribution of the damages of climate change are projected to be more severe in certain regions of the world. Developing countries are the ones that are expected to receive the higher end of the damage. The protection cost of coastal areas in developing countries is projected to be significantly higher than that in developed countries [4]. In cases such as Africa, where coastal areas are a major economic hub, the economic damage is expected to have a great impact on the economic welfare and the communities of those nations [5].

The response towards battling climate change has been divergent between different countries. Efforts towards achieving a unified global response to tackle climate change were proposed in several conferences such as the Paris Agreement in 2015. On December 12th of 2015, 196 countries committed to acting towards confronting climate change by agreeing to a set of binding constraints that are essential towards limiting the global average temperature increase to below 2°C [6].

1.1.2 Economic Aspect of Climate Change

Economic growth is one of the main drivers of modern societies, as it serves to eliminate poverty and increase the overall welfare of the people. Energy plays an important role in driving economic growth, and this was evident in the early 1800s when humans started relying on coal as a primary source of energy. Coal went on to become one of the main pillars of the first industrial revolution in Europe [7]. This economic growth which relied on fossil-fuel based energy sources certainly did come with environmental consequences. The global average concentration of carbon dioxide in the atmosphere has risen from 280 ppm in the year 1750 to 409.8 ppm in 2019 [8]. This huge increase is mainly due to human activities that require burning fossil fuels into the atmosphere. The emissions that humans pump into the atmosphere each year are not free of any consequences. Carbon Dioxide, which accounts to around 76% of the total greenhouse gas (GHG) emissions within our atmosphere [9]. CO2 is a global externality in the sense that it has a negative cost that no matter if a nation has contributed to it or not, it will bear the consequences. This lead several economists to calculate what is known as the social cost of carbon (SCC), which aims to quantify the economic damage that is caused by the emission of a single unit of CO2 into the atmosphere [10]. Economists and climate scientist have had a long debate on what is the real SCC, since climate damages are a long-term problem, and the results of the current emission trends can only avail after several years. What complicates the issue of tackling climate change more is that fact that implementing new policies might lead to a state of injustice whether on an inter-generational of intra-generational level [11]. The economic impacts of climate change are distributed unequally between different regions, since the poor countries which are mainly located in warmer zones are more likely to take the bigger part of the damage. This fact raises political issues and increases the probability of conflict between different nations.

1.1.3 The Environmental Impact of Climate Change

Along with the economic damages that would occur due to climate change, there is a concern that also the biodiversity is at a great risk. Several models have been set-up to try to quantify the damages that would occur on animal and plant species in the coming years [12]. Forests have been subject to large damages as the areas covered by forests have been on a decline [13]. This is due to the increase in what is known as forest disturbances such as the thriving of invasive species or wildfires, that alter the biodiversity of the forests and cause large damage. The environmental damage extends to cover the ice glaciers which are melting at an accelerating pace, which in turn contributes to the rise in sea level. The sea levels have risen by around 20 cm per year from the year 1990 until 2017 [14]. This has put major coastal areas as the risk of floods would increase and the more acidic nature of the oceans would have a negative effect on the marine life. The dramatic effects of climate change that occur within the oceans' waters such as rising thermal stress and altering the pH of the ocean cause great damage to the coral reefs [15]. Coral reefs are a major source that drives marine biodiversity to thrive and grow, and their numbers have been on a sharp decline due to human made emissions. The list of damages that are due to human induced climate change extend from the deep oceans to the rainforests which have been sharply decreasing in area. The areas of rainforests have decreased by 80 million hectares since the year 1990 [16]. The forests play an important role in preserving biodiversity and absorbing excess CO2 from the atmosphere. Those are some of the harmful effects that are occurring at the moments, and without any policies that control and regulate human actions, the situation will escalate onto an irreversible state of damage.

1.1.4 The Rise of Conflict

Climate change is a global issue, and the nature of this problem requires cooperation between several nations to face and prevent the harmful consequences. Since GHG are considered as a global externality, the actions that take place in one part of the world might lead to drastic damage in another. Therefore, when two different nations or regions have opposing benefits, conflict will arise. This is relevant to climate change since energy is the main driver towards economic growth, and throughout recent history, the main source of energy has been fossil fuels. A study by Burke et al. (2015), that relied on data from 55 different studies, concluded that a 1-degree Celsius rise in temperature would increase the probability of conflict by 2.4% [17]. This is an alarming realization since humans seek economic prosperity and welfare growth, and in situations where two regions have contradicting interests it might lead to violence and conflict. Climate change is a problem that required cooperation to be solved., since even if one nation puts the required effort to reduce emissions and increase its energy efficiency, it wouldn't be enough to tackle the issue if other countries continue with increasing their emissions. To achieve cooperation between nations, several climate conferences have been done all over the world to assign responsibilities regarding controlling emissions. The most famous event in this regard was the 2015 United Nations Climate Change Conference (COP21) which was held in Paris. During that conference, a total of 196 parties agreed on what was known as the Paris Agreement, which assigns a set of responsibilities for each party to cooperate towards achieving a warming which is less than 2 Degrees Celsius [18]. Cooperation is humanity's only chance to limit the warming of the planet, and conflict prevents cooperation. Hence tackling the problem and cooperating is necessary at an early stage since it might not be possible to undo the damages in the future.

1.1.5 Human Perception of Climate Change and the Role of Mitigation Policies

A unique feature of climate change is that its effects are not instantaneous but rather accumulated in small steps that amplify by time. The human brain has developed into its current state throughout a time where the main concern was the direct environment and response towards direct danger was essential for survival [19]. Therefore, it is a natural trait that the human brain prioritizes short term danger and ignores the long-term issues such as climate change. Climate models are developed to assess the long-term effect of human actions and policies on the global climate, but those models are usually established on a timeframe which extends to 2050 and up to 2100. Those timeframes are hard to perceive by the public as a danger which will affect their future. This raises another concept in climate change which is caring about future generations. Discounting affects the future generation as the well-being of the current generation is viewed to be more valuable than the upcoming one. This concept has spurred a huge debate inside the scientific community [20].

The complexity of the concept of climate change makes it hard to deal with such an issue without the need for mitigation policies that are set by governments with the help of the scientific community. The role of mitigation policies is to reduce the emissions of the harmful greenhouse gases that are produced by human activities [21]. Climate change mitigation techniques have been proposed under three categories. The first and most traditional is deploying low carbon technologies such renewable energy production and promoting them. Another technique is capturing the already available carbon dioxide from the atmosphere, which is known as negative emissions, and storing this carbon dioxide in specific forms. The third proposed mitigation techniques are based on altering the radiation that is received by earth's surface to reduce the heating and stabilize the temperature [21]. The three mitigation techniques could be implemented by using government policies that promote certain technologies over others which could be done by incentivizing specific technologies or the taxation of the harmful emissions which result from traditional technologies. Policies are an important instrument that could limit the damage that results from human actions. It is possible to classify policies into adaptation or mitigation policies. Adaptation policies are policies that are put in place to help adapt to the environmental changes that result from climate change, while mitigation policies try to set rules that would prevent the increase in emissions and limit the damages on the climate system.

1.1.6 Climate Action in Europe

Europe is one of the most developed continents, and home to industrial giants such as Germany, Italy, and France. In recent years, the topic of climate change has become an important issue within the continent, and it has become a leading player in sustainability and climate action. The actions that have taken place in Europe prevail in abatement efforts that come in the form of policies. The extent of those policies goes from broad goals such as meeting emission targets onto more sector specific policies such as the protection of the ozone layer. The European Green Deal has set a strict target of at least a 55% reduction in GHG emissions by the year 2030 compared to the levels at the year 1990 [22]. This target is a step towards the main aim that is Europe becoming a climate neutral continent by the year 2050. Europe takes the lead in the quest of reducing the overall global emissions of GHG since it is one of the most advanced economies with extensive research in sustainable and clean energy. The effects of climate change are un-evenly distributed between different geographical regions in the world, which means Europe won't have the same dramatic consequences such as Africa and Australia. But this fact doesn't mean that Europe shouldn't care in this regard, since the damages that occur in other parts of the world would also affect Europe in in-direct ways such as increased immigration. To reinforce the importance to tackling the issue of climate change, the European Commission has set a budget of 25% of its total expenditure from the year 2021 until 2027 on climate related action [24]. Spending the resources on projects that allow transition towards climate neutrality is essential to limit the future damages. Lamontagne et al. (2019) concluded that even though the human-earth system (HES) uncertainties might disrupt the future regarding climate response, the main variables that determines earth's future is abatement efforts and climate sensitivity [24]. Climate sensitivity is a variable which is out of humans' control, and in pessimistic scenarios, it might have become a bit late to stop the harmful consequences of the damages that humans have done on the climate system. However, abatement efforts are completely within the control of current generations, and therefore Europe is concentrating its efforts to increase abatement and achieve climate neutrality.

1.2 The Transportation Sector in Europe

1.2.1 History and Current State

Ever since early human history, transportation between two different points in space was essential for the survival of humans and the building of societies. The basic form of road transport infrastructure started by marking trails that facilitate moving between different locations safely using animals such as horses or ox. From that point onwards, the transportation sector has been a great field for innovation and creativity. Modern-day transportation is a complex network of road, aviation and maritime systems that are inter-connecting the world. Road transport can be classified into two different categories, passenger, and freight. Passenger transport, which is usually estimated in passenger-km, is a representation of the movement of passengers by a single kilometer. Freight transport, which is measured by ton-kilometers, is an estimation of the amount of goods that travel between two points in space [25]. Europe has one of the most advanced road transportation systems in the world. It consists of a series of highways and railways that connect European cities in a fast and efficient manner. To ensure that Europe is well inter-connected, a policy which is called The Trans-European Transport Network (TEN-T) has been proposed by the EU commission to build a combination of road, rail, air, and maritime transport infrastructure within the continent that would connect major cities and promote economic and social activity between different members of the EU [26]. The expansion of the road transport sector in Europe highlights its importance and critical role in maintain the EU as an economic and political power.

1.2.2 Emissions and Environmental Impact

The transport sector overall contributed by 27% of the total greenhouse gas emissions in Europe in the year 2017. The emissions are distributed between road, aviation, and maritime transport methods. The largest share of the emissions that is 71.7% of the total transport related emissions is due to the road transport sector, while the remaining are divided into 13.4% and 13.9% for maritime and aviation respectively [27]. The high emissions from the transport sector have driven researchers to investigate new techniques to improve the energy efficiency the engines used for transportation whether in light duty vehicles or in aviation. Some of the more recent trends involve replacing traditional fossil fuel-based engines with electric powered engines which are more environmentally friendly. The key for decarbonizing the road transport sector being able to find an effective and reliable way to store energy, which could be done in several forms such as fuel cells or even super magnets. The most promising forms of storage for transportation are batteries and fuel cells. One of the main barriers in the face of electric drive vehicles is that lithium-ion batteries, which are the main component of the vehicle, haven't had major advancements since their introduction in the year 1990 [28]. There is a need for improvement in the materials that are used in the building of the energy storage batteries which would make those batteries more efficient and at a cheaper cost that would make it a feasible investment. Some countries in Europe such as Norway have been able to promote the penetration of electric vehicles into their fleet, but this has been done by using incentives that encourage consumers to invest their money into buying an electric vehicle. As of 2020, the total number of registered electric vehicles in Europe was 3.3 million vehicles which is second only to China [29]. However, the number of electric vehicles is still relatively low compared to the total fleet size for passenger vehicles in Europe which is composed of 242.7 million vehicles. The penetration of clean vehicles into the fleet is necessary since the world passenger road vehicles contribute to around 3.6 Gt of CO2 which is 1.5 times more than the closest transportation mean which is freight road transport [29]. The European Commission has taken several measures in recent years to try to decarbonize the transportation sector by setting standard for the new vehicle that are being sold and incentivizing clean technologies while taxing fossil fuel-based cars. In the most recent set of rules, the EU Commission has set new emission targets for the manufacturers of new road transport vehicles. The light duty vehicles have a limit of 95 g CO2/km while the vans have a limit of 147 g CO2/km [30]. This limit will be implemented on all cars that ae manufactured between the years 2020 until 2024, and the limit will be decreased by 15% for both types of vehicles by the year 2025. This forces the leading car manufactures in Europe to invest a significant amount of money in researching innovative methods to make their vehicles more fuel efficient and less polluting. To encourage manufacturers to further improve their vehicles, a scheme known as the super-credit system, where the light duty vehicles with an emission level less than 50 g CO2/km are counted more than once in the process of calculating the value of average specific emissions for the manufacturers.

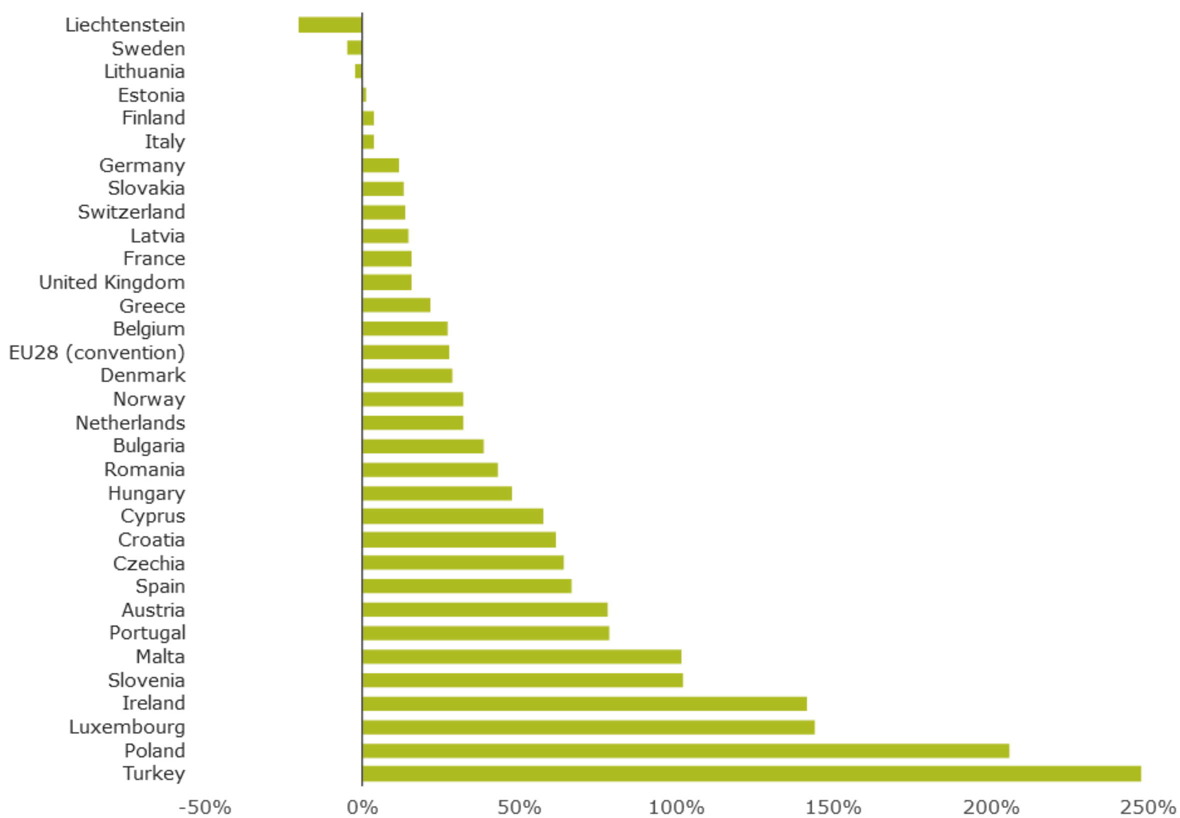

Figure 6: Percentage Change in GHG Emissions from Transport Between 1990 and 2017 in EU Countries [30].

Most of the European countries have witnessed an increase in the amount of GHG emissions from transport when compared to the levels of the year 1990 as shown in Figure 6. Countries which have had great economic growth since 1990 such as Turkey and Poland have had an increase more than

200%, which points out to the correlation between the increase personal income and the demand for transportation. This increase in the GHG emissions on most of the European countries has pushed the EU Commission into implementing several policies that would limit the damage from this huge increase for demand for transport.

1.2.3 The Role of Transportation Policies

Policies provide a guideline to take optimal decisions for a society as a whole and seek to achieve the best possible outcome. To regulate the transportation sector which has been witnessing a huge surge in the total amount of GHG emissions in the past years within Europe, a set of policies are needed. The European Commission states that the main role of the EU Transport policy is provide efficient, safe, and environmentally friendly means of transportation while generating economic growth and new job opportunities in the sector [31]. The policies that are implemented can be in several shapes and forms. Setting a limit for the maximum or average amount of emissions that are tested for new models from car manufacturers is a type of policy which aims to limit the total emissions from transport or more specific details such as limiting the amount of noise that each vehicle produces. The goal of the EU has been to have a unified and common transportation policy for all Europe, and this ambition started in Rome in 1957, where the leaders of major European countries agreed on setting a transport policy which was known as the "Treaties of Rome". This ambition is still on until today as the EU still seeks to optimize the transport policy. The management of the transportation sector must be done from the small scale of organizing electronic tolls to the maximum allowed GHG emissions from a certain vehicle. The emergence of cleaner technologies in transportation such as electric vehicles has encouraged governments to financially support the sale of those vehicles by providing incentives and easy financing schemes for citizens. The large range of variation between European countries when it comes to the introduction of new vehicles which increases emissions is clear in Figure 6, and this makes it harder for the EU Commission to set a common plan that would lead the EU to have a clean road transportation fleet. The transportation sector is one of the sectors that emits the most, and it is necessary to have huge technological and functional transformations within the sector to be able to achieve the climate neutrality goals in the future.

1.2.4 Fit-for-55 Policy Package

During the 2015 United Nations Climate Change Conference (COP21) in Paris, the main goal was to limit the emissions by the year 2050 to net zero. Europe is one of the leading continents in technology and economic development, and it has since increased its efforts to be able to achieve the net zero goal. The reduction of emissions is mainly achieved through strict policies that promote clean energy and tax technologies that emit a lot of greenhouse gases. One of the most recent policy packages that helps pave the way towards a net zero world is the Fit-for-55 policy package which was released by the EU Commission on July 14th, 2021. The policy package is part of the efforts that the EU is currently putting to keep up with the climate neutrality goal set by the green deal. The name, Fit-for-55, is inspired from the general goal which is the reduction by 55% of emissions compared the year 1990. The policy package tackles different sectors and revises several goals that have been previously put in place. One of the main points of the package is a proposal of a revised emission trading system (EU ETS) within the EU, and its extension to the shipping industry [32]. Another important aspect that the Fit-for-55 package tackles is the revision of the renewable energy directive, with the proposal of achieving up to 40% renewable energy penetration in the final energy consumption. This is a clear view on the position of the EU in the quest towards achieving net zero emissions by the year 2050. The main sector which will be studied within this research work is the transportation policy that is proposed by the Fit-for-55 policy package. The main policy in the transport sector is the banning of the new sales of any fossil fuel-based vehicles by the year 2035. Emission standards have been set since many years within Europe, but the measures that are proposed by the Fit-for-55 package are the most ambitious yet, as they propose the total ban of any fossil fuel-based cars and the transition to more environmentally friendly vehicle. The proposal which was initially given by the EU Commission had three different patterns for phasing out the sales of fossil fuel cars, each representing a different ambition regarding the intensity of phasing out the traditional fossil fuel vehicles. Table 1 shows the different proposals that were presented within the Fit-for-55 policy package. The final choice was to adopt the strictest measure which is TL_High, which leads to the total reduction for 100% compared to the year 2021 in the sales of new fossil fuel-cars.

Table 4: Fit-for-55 Transport Policy Proposals for Reduction of Fossil Fuel Cars [33].

	2025		2030		2035		2040	
	Cars	Vans	Cars	Vans	Cars	Vans	Cars	Vans
TL_Low	15%	15%	40%	35%	60%	60%	80%	80%
TL_Med	15%	15%	50%	40%	70%	70%	100%	100%
TL_High	15%	15%	60%	50%	100%	100%	100%	100%

The urgency for decarbonizing the transport sector has pushed policy makers into taking the strictest of measures, and this puts extra pressure on car manufacturers into investing in the research and development of innovative technologies that would make electric and fuel cell vehicles a more efficient and accessible vehicle options for the public.

1.3 Research Questions

Regarding what has been presented about the transport sector in Europe, there is much room for researching how would the policies be implemented and what would be the effect of those policies on the scale of the environment and the economy.

Integrated Assessment Models (IAM) are a useful tool to assess policies that have an impact on several sectors within the economy, climate, and energy sectors. The WITCH model has been used with this research work to address the research questions that have been tackled within this research work.

Based on the issues raised within the literature, the following research questions are proposed to be answered within this research work:

- What's the effect of the fit-for-55 policy package on the transport sector, in terms of fleet composition, total demand and emissions?
- How will the climate efforts done by regions in different scenarios affect the effectiveness and efficacy of the Fit-for-55 transport policy?
- What is the most cost-efficient scenario to implement the Fit-for-55 transportation policy?

The work done throughout the following research work will seek to provide answers to the presented research questions through performing a policy assessment within different scenarios that assume alternative degrees of climate commitment in Europe and the World.

Chapter Two

Research Methodology

The second chapter will be dedicated for presenting the research methodology that was adopted within this research work. A presentation of Integrated Assessment Models (IAMs) will be done before moving into WITCH model, that is the tool that was mainly used during this project.

The transportation module that was present within WITCH will be presented before introducing the necessary changes that were done to be able to monitor the change in demand along different policies.

Finally, a set of different scenarios will be presented to analyze the Fit-for-55 transportation policy within different states of the world.

2.1 Integrated Assessment Models

Integrated Assessment Modeling is a form of scientific modeling which interconnects different scientific disciplines to assist policymakers in decision making within several fields such as climate change. IAMs consider several factors within the economy, climate, and energy system at a regional and global level to study the interaction between those different systems. It is possible to classify Integrated Assessment Models into different categories that serve to analyze systems from several perspectives. In general, IAMs can be classified as computable general equilibrium, inter-temporal optimization, or simulation models [33]. The first category that is CGE models, rely on utilizing a social accounting matrix to build the model, and the economic relations between different regions and departments are modeled in a high level of detail. However, due to the lack of large amounts of data, the models that fall into the CGE category are not very common. The second category of IAMs is known as inter-temporal optimization models. This category of models does not get to the department detail level such as the CGEs, but it is more flexible inn describing processes of decision making. Such models are usually used to assist policy-makers policy optimization. The third category is simulation models such as the IMAGE model. This type of models is mainly used to simulate the future outcome of certain policies. The model is not involved in the decision-making process and the model is built in a bottom-up approach.

Integrated Assessment models have been the essential tool that researchers and scientists use to study the topic of climate change and its influence on the economy. However, there are many arguments that point out the limitations and weaknesses in integrated assessment models. The first being the lack of complexity that represents real-life situations since models are usually based on several assumptions that are left to be made by the modeler, which leaves the modeler the freedom to decide crucial parameters that alter the outcome [34]. Another argument is that typical integrated assessment models are based on macro-economic principles that assume that agents are completely rational and have perfect information, which is not a true case most of the times. However, recent models have been increasing their level of detail and incorporating more complex sectors within the model, along with modeling heterogeneity within the agents of the model such as varying transportation modal preferences between different agents [35]. Integrated Assessment Models are a suitable tool to assess the Fit-for-55 transportation policy that has been presented within this research work, and the model that has been chosen for this task is the WITCH model.

2.2 The WITCH Model

2.2.1 General Overview

The WITCH model, that is short for World Induced Technical Change Hybrid model, is an integrated assessment model that has been built to assess climate mitigation and adaptation policies. The model has been developed initially by Fondazione Eni Enrico Mattei and the Centro Euro-Mediterraneo sui Cambiamenti Climatici and is currently maintained by RFF-CMCC EIEE [36]. WITCH is written in GAMS modeling language that is used to form mathematical optimization problems. The term hybrid that is present in the model's name is since it involves both top-down and bottom-up modeling approaches. The economy is modeled within WITCH as an inter-temporal optimal growth model, where the world is divided into different regions that are 17 by default. Each region seeks to maximize its welfare through the optimization of key variables. The welfare is presented as the net present value of consumption of each individual within the economy. The energy sector within WITCH is hard-linked to the economy, and thus the investments that are done within the energy sector are chosen in an optimal way in regards to the economy [37]. The energy sector is modeled in a detailed bottom-up approach which is not a usual feature of optimal growth model, thus allowing a more detailed representation of different energy generation technologies. The world is divided into 17 different regions in WITCH model which is presented in Figure 7.

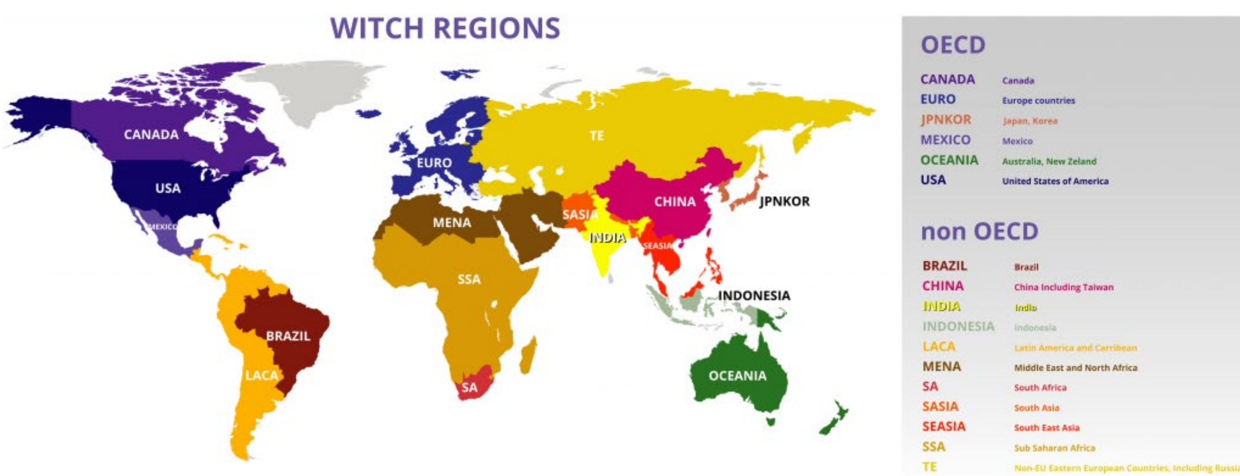

Figure 7: Regional Representation of the World within WITCH [38].

The interaction between regions in WITCH can be modelled as a non-cooperative game which is solved across an iterative algorithm to produce an open-loop Nash equilibrium. There is an option to use WITCH in cooperative mode, however for the scope of this study the non-cooperative WITCH17 model that has the world dis-aggregated into 17 different regions as shown in Figure 7 will be adopted.

The objective function in WITCH is to maximize the welfare of the regions that is the sum of the discounted utility over each region shown in Equation 8.

Equation 8: WITCH Welfare Function

$$W(n) = \sum_{t} l(t,n) \frac{\left(\frac{C(t,n)}{l(t,n)}\right)^{1-\eta} - 1}{1-\eta} \beta^{t}$$

Where C is the total consumption and l is the population of each region n at time t. η is the coefficient of the degree of relative risk aversion. Beta is the time preference discount factor, and it is calculated using the following formula.

$$\beta = (1+\rho)^{-\Delta t}$$

Rho is the discount rate, and the time step that is adopted in WITCH is 5 years.

WITCH usually runs between 2005 until 2150, and the results are analyzed between 2005 and 2100. One of the most distinct features of the WITCH model is that technical change is endogenous within the model, and it could be affected by different climate policies.

2.2.2 The Energy Sector

The energy sector in WITCH is described in a good level of details, as different generation technologies are modelled at a high level of detail to define the final use of energy and the different electricity generation methods. The energy system is represented along with the economy in a constant elasticity of substitution nested structure, which means that different technologies can be substituted such as electric and non-electric forms of energy. The electric part of the energy sector involves electricity generation from both fossil fuel-based generation methods and clean renewables. The cost of generation of electricity is an endogenous variable that is calculated by WITCH according to the policies and scenarios in place. The transportation sector is part of the energy sector, but it falls under the category of non-electric energy sector. However, the road transportation sector does not belong to the constant elasticity of substitution structure that has been previously defined for WITCH and that is shown in Figure 8.

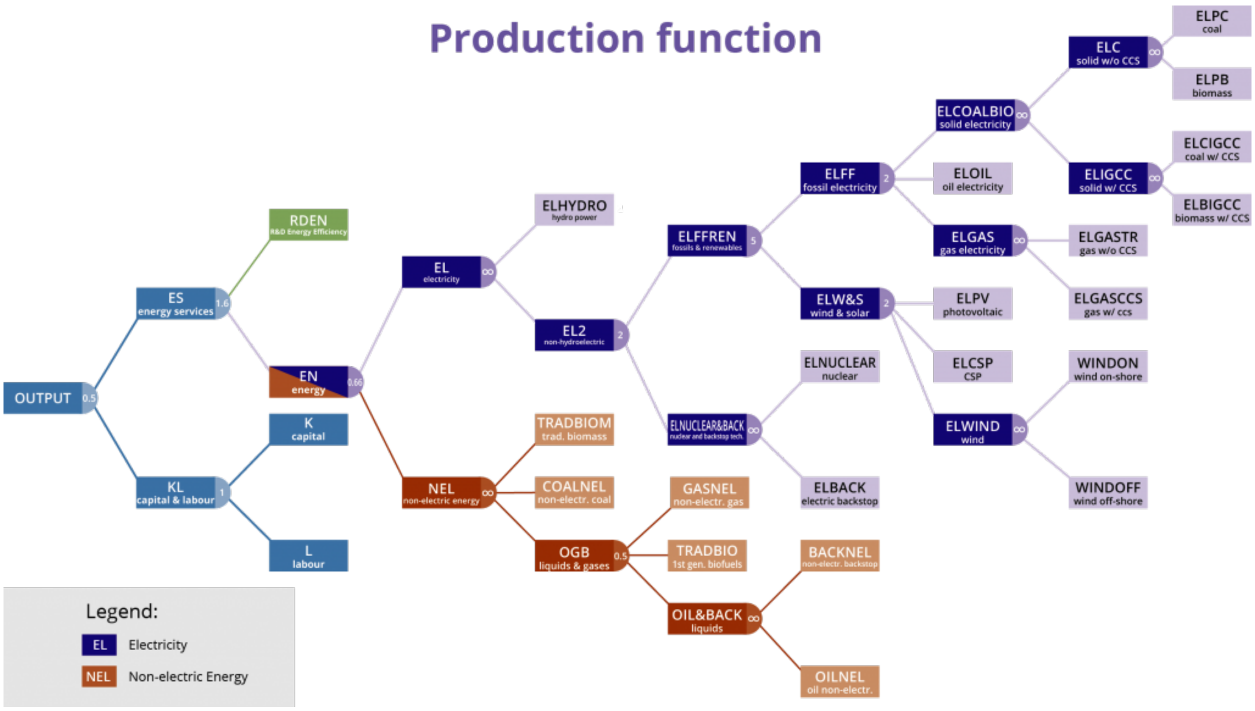

Figure 8: WITCH CES Structure for Production [38]

2.2.3 Road Transport Module

As mentioned before, the road transport part of WITCH is not part of the CES structure. The following module, which is passenger road transport, is where the main changes to the WITCH model have been done to perform this research work.

The passenger road transport in WITCH is composed of only light duty vehicles (LDVs). A light duty vehicle is a type of passenger vehicle that has a gross weight below 8,500 lbs [39]. Light Duty Vehicles can have different technologies that propagate the vehicle, each having its own type of fuel. In the WITCH model, five types of light duty vehicles are present that are presented in Table 5 below.

Table 5: Types of Vehicles in WITCH Road Transport Module

Light Duty Vehicle Type	Name code within WITCH
Traditional Fossil-Fueled Vehicles	TRAD_CARS
Hybrid Vehicles	HYBRID
Plug-in Hybrid Vehicles	PLG_HYBRID
Electric Drive Vehicles	EDV
Fuel Cell Vehicles	FCV

The total number of vehicles in the initial version of the transportation module was defined exogenously as a function of the total population and gross domestic product (GDP). That is the number of vehicles does not vary between different policies or scenarios, nor does the total service demand, which is the total amount of passenger kilometers to travel per year. The number of LDVs was calculated based on a formula by Fulton and Eads (2004), which defines the total number of vehicles per thousand capita in each region as follows [40].

Equation 9: LDV per Thousand Capita

$$ldv\_pthc(t,n) = ldv\_pthc(t-1,n) \times \left(1 + \left(\frac{gdp\_pc(t,n)}{gdp\_pc(t-1,n)} - 1\right) \times OGE\right) + AI$$

Where OGE is the ownership growth elasticity and AI is the autonomous increase, and both previous parameters depend on the maximum number of vehicles owned by thousand capita and the GDP per capita of each region. The total number of light duty vehicles in each region is then calculated by multiplying the number of light duty vehicles per thousand capita by the total number of the population as shown below.

Equation 10: Total Number of Light Duty Vehicles

$$ldv\_total(t,n) = ldv\_pthc(t,n) \times population(t,n)$$

The fleet composition is determined as an optimization problem where the choice of vehicle type is a linear competition between different vehicles, which is represented in Equation 11.

Equation 11: Linear Competition Equation for Modal Choice

$$ldv\_total(t,n) = \sum_{jveh} K_{EN}(jveh,t,n)$$

Where $jveh$ is the set of light duty vehicle technologies and K_{EN} is the number of light duty vehicles of technology type $jveh$.

Having a linear competition between different technologies has a downside of observing abnormal behavior from the model that does not represent real-life situations such selecting to invest in once technology only in a certain year if it becomes the cheapest. To try to limit having sudden switches from a single type of vehicle onto another, some constraints on the increase of a certain type of vehicle between one time-period and the other are applied in order to limit the effects of this phenomenon. Equation 12 is used to constrain the model in switching between different vehicles.

Equation 12: Constraints on the New Addition of Light Duty Vehicles

$$K_{EN}(jinv, t+1, n) - K_{EN}(jinv, t, n) < 1.124 \times (1 - \frac{K_{EN}(jinv, t, n)}{ldv\_total(t, n)}) \times K_{EN}(jinv, t, n)$$

Where the set $jinv$ is the set pf investable technologies, and the parameter 1.124 is derived by fitting a logistic function to the number of hybrid vehicles estimated by the World Energy Outlook 2010 between the years 2010 and 2035 [38].

Another important parameter that is defined exogenously in the WITCH transport module the total service demand, which is the total amount of passenger-kilometer demand per year. This parameter represents the demand for passenger travel. The travel demand depends on parameter that is known as travel intensity, that is specific and constant for each region in the case of WITCH. The travel intensity represents the amount of passenger-kilometers of travel demand for each region per unit of GDP. The values adopted by the model for travel intensity are consistent with the values provided by the IEA. Therefore, the LDV travel demand for each region would be calculated in Equation 13.

Equation 13: LDV Passenger Transport Service Demand

$$km\_d\_ldv\_tot(t, n) = travel\_intensity\_ldv(t, n) \times GDP(t, n)$$

Then, a parameter known as the load factor, which represents the number of passengers that occupy a single light duty vehicle is multiplied by the LDV travel demand calculated in Equation 13 to derive the total service demand for passenger road transport as shown below.

Equation 14: Total Service Demand

$$s\_d\_ldv(t, n) = load\_factor\_ldv(t, n) \times km\_d\_ldv(t, n)$$

The fuel consumption of each light duty vehicle, which is evaluated by the amount of energy it would require each vehicle to travel a single kilometer, is based on the value of this parameter at the year 2005, and an exponential improvement for fuel efficiency is assumed until the value of fuel consumption is cut by half by the end of the century.

The energy consumed by each type of light duty vehicle is finally calculated in Equation 15.

Equation 15: Energy Consumption of the Light Duty Vehicle

$$Q_{EN}(jveh,t,n) = km\_d\_ldv(t,n) \times fuel\_cons(jveh,t,n) \times K_{EN}(jveh,t,n)$$

The total transport service demand does not very between scenarios, but the fleet composition varies according to the cost of transport and shown above. However, the choice of vehicle technology occurs via a linear competition which causes sudden switches in investment. The results of a WITCH model Business as Usual (BAU) scenario for total service demand and fleet composition are shown in Figure 9 and Figure 10.

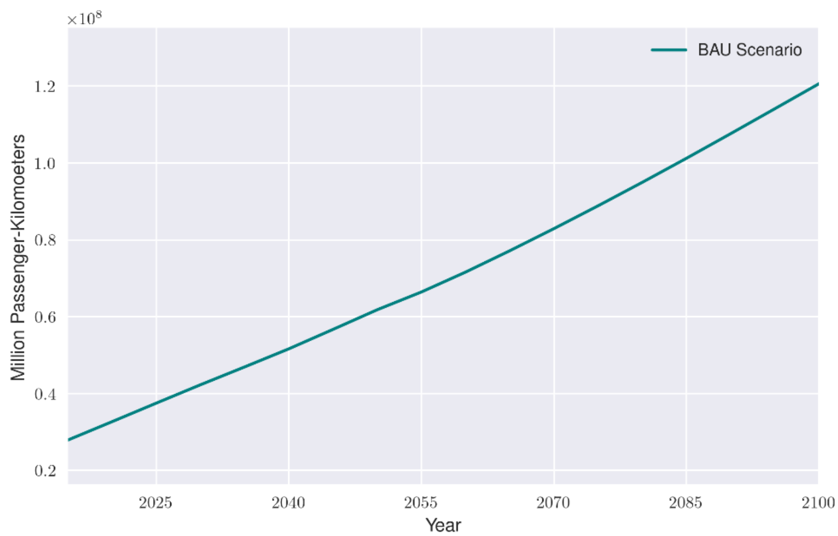

Figure 9: World Passenger Transport Total Service Demand in BAU Scenario

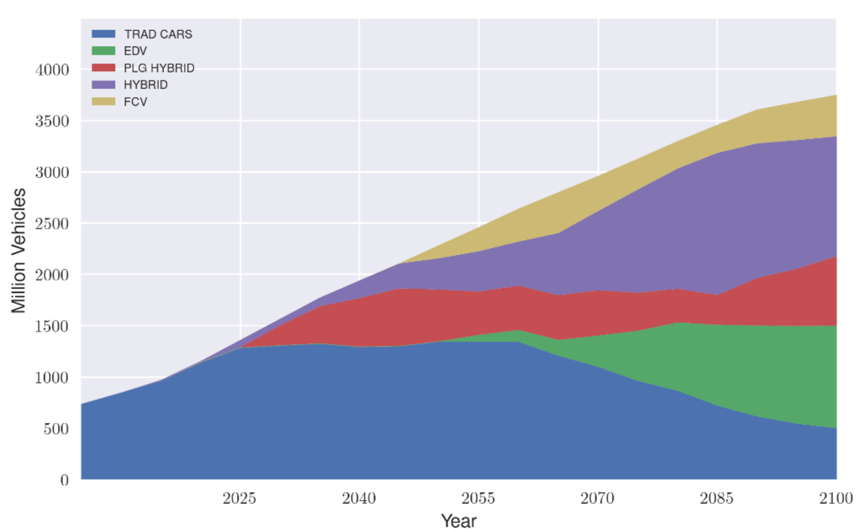

Figure 10: World LDV Fleet Composition in BAU Scenario

The working structure of the transportation module in WITCH that has been presented poses great weaknesses for evaluating different transportation or energy supply policies. The fact that the total passenger kilometer travel demand does not change throughout the model makes it impossible to check the effectiveness of transportation policy as the demand for travel won't change even if the prices of traveling become extremely high. The inelasticity of transportation demand to changes in price is not true in real life scenarios and thus there was a need for modifications in the transportation module in WITCH to make assessing the Fit-for-55 policy possible.

2.2.4 Modified WITCH Transport Module

The main goal from modifying the transportation module within WITCH was to introduce a price and income elasticity. That is if people become richer or transportation becomes cheaper, the total demand for the service is expected to increase and the opposite is also true, which is consistent with the law of demand.

A new transportation service demand has been implemented in WITCH, where the total service demand is switched from an exogenous parameter into an endogenous variable that the model would calculate based on the state of the world which has unique prices for transportation depending on the policies implemented. The function that is shown below is based upon the road transport demand function used by the GCAM transportation module [40].

Equation 16: New Transport Service Demand Function [40]

$$D_{r,t} \ = \ D_{r,t-1}\left(\frac{Y_{r,t}}{Y_{r,t-1}}\right)^{\alpha}\left(\frac{P_{r,t}}{P_{r,t-1}}\right)^{\beta}(\frac{N_{r,t}}{N_{r,t-1}})$$

Where D is the total service demand expressed in passenger-kilometers, n is the region, t refers to time. Y stands for the income, P for the price of transportation in monetary units per km, and N is the total population. α and β are income and price elasticities respectively.

Population is exogenously defined in WITCH, and it is specified according to the Shared Socioeconomic Pathway (SSP) that is SSP2 within this research work. The income is expressed by the per capita GDP which is also predefined within the model for different SSPs. The price of transportation is affected by the model optimization process since the price of fuel varies according to the policy in place. The price of transportation is divided into two different parts that are the price of fuel and the cost of investment. The cost of investment of each technology is calculated as an endogenous variable by WITCH. Equation 17 below presents the method of calculating the aggregate cost of transportation services that is used in Equation 16.

Equation 17: Price of Each Transportation Technology [40]

$$P_{i,r,t} = \sum_{j=1}^{N} (\alpha_{j,i,r,t} \times P_{j,i,r,t}) + \frac{W_{r,t} \times V_{i,r,t}}{S_{i,r,t}}$$

Where i refers to the mode of transport that is only light duty vehicles within WITCH, j is the LDV technology, α is the share of the technology j in the sector i. The final term of Equation 17 includes the term W, that is the wage rate, V the time value multiplier, and S the speed of each mode. In this research work, the second term of the equation is assumed to be zero, so the time value and speed of transportation is not considered.

The price of each technology within the light duty vehicles is calculated as follows in Equation 18.

Equation 18: Price of the LDV technology [40]

$$P_{j,i,r,t} = \frac{P_{f,r,t} \times I_{j,i,r,t} + N_{j,i,r,t}}{L_{j,i,r,t}}$$

The term $P_{f,r,t}$ refers to the fuel price that is multiplied by the fuel intensity I. The levelized non-fuel costs of transportation is expressed as N, and the load factor for each vehicle type is L. The price of fuel is calculated by the model and the load factor is defined exogenously for each region and type of vehicle. To calculate the non-fuel levelized cost of transportation, Equation 19 is used.

Equation 19: Levelized Cost of Driving [41]

$$N_{j,i,r,t} = \frac{Capital\ Cost\ \times CRF}{VMT}$$

The term $N_{j,i,r,t}$ refers to the levelized cost of driving. Capital costs are defined within WITCH for each technology as endogenous variables that depend on the cost of each component of the vehicle. The VMT refers to number of kilometers traveled by each vehicle per year, and it is assumed to be constant for each region throughout the years of optimization. The CRF is the Capital Recovery Factor which is calculated as follows.

Equation 20: Capital Recovery Factor [41]

$$CRF = \frac{D \times (1 + D)^N}{(1 + D)^N - 1}$$

Where D is the discount rate that is assumed to be constant and equal to 5% [42], and the lifetime of each vehicle in the light duty vehicle fleet is 22 years.

The total number of vehicles is then derived from the total service demand that has been calculated through the model by dividing the total service demand by the vehicle kilometers traveled multiplied by the vehicle load factor as shown in Equation 21.

Equation 21: Total Number of LDVs

$$ldv\_total_{t,n} = \frac{Total\ Service\ Demand_{t,n}}{VMT_{t,n} \times Load\ Factor_{t,n}}$$

The changes that have been implemented allow the model to respond to fluctuation in price of transportation. The degree of change of demand as the price or income varies depends on the values of price and income elasticities that are present in Equation 16. The equation was calibrated according to values of elasticity that are consistent with the literature provided by Rottoli et al. (2021) with income elasticity being 0.95 and price elasticity of -1.18 [43].

The second issue that was present in the initial version of the WITCH model transportation module is the linear competition between different light duty vehicle technologies. This method of deciding modal choice induced sudden switches between different modes in consecutive time-periods in a manner that might not be possible in real-life situations. To solve this issue, it was necessary to introduce a new function that provides a certain degree of inertia when switching between different modes, in a sense that replacing the fleet from one technology to another would take a longer period depending on the values of elasticity which resemble real-life situations more. For this part, the work was co-developed with a colleague at RFF-CMCC EIEE. To achieve a smooth transition between light duty vehicles, the modal switching between vehicles was limited via a CES production function as shown below.

Equation 22: LDV Technology Choice CES Function

$$\begin{aligned} Q_{vehicle}(t,n) = \theta(n) \big[& \alpha_{TRAD\_CARS}(n) Q_{TRAD\_CARS}(t,n)^{\rho} + \alpha_{HYBRID}(n) Q_{HYBRID}(t,n)^{\rho} \\ & + \alpha_{PLG\_HYBRID}(n) Q_{PLG\_HYBRID}(t,n)^{\rho} + \alpha_{EDV}(n) Q_{EDV}(t,n)^{\rho} \\ & + \alpha_{FCV}(n) Q_{FCV}(t,n)^{\rho} \big]^{\frac{1}{\rho}} \end{aligned}$$

Where $Q_{vehicle}(t,n)$ is the total light duty vehicle demand for region n at time t. The supply of vehicles is represented by Q_j where j is the LDV technology. ρ is the substitution parameter, and α is the share parameter which is assumed to be constant and equal for all the technologies that is equal to 0.2. θ is a parameter specific for each region, and it was calibrated according to the years were historical data for light duty vehicles was available, which are 2010 and 2015.

After performing the changes on both aspects of the transportation model that are total demand and modal switching, it is possible to investigate the response to any transportation price fluctuations that might be induced due to climate policies. The total demand and fleet composition of the new BAU scenario after performing the changes to the transportation module are shown in Figure 11 and Figure 12.

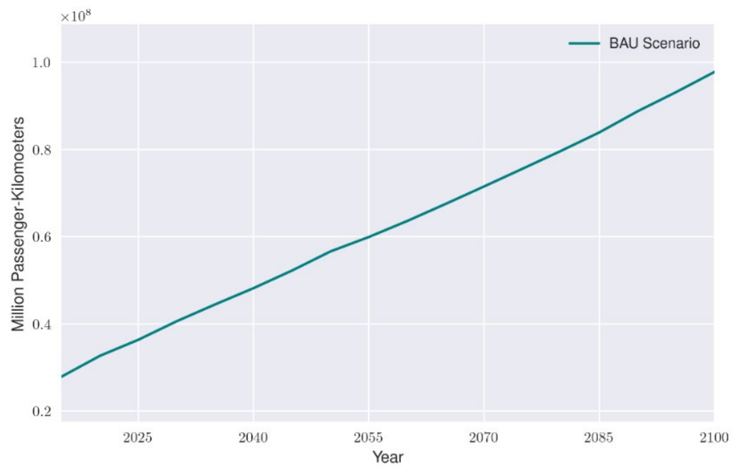

Figure 11: World Passenger Road Transport Demand in BAU Scenario

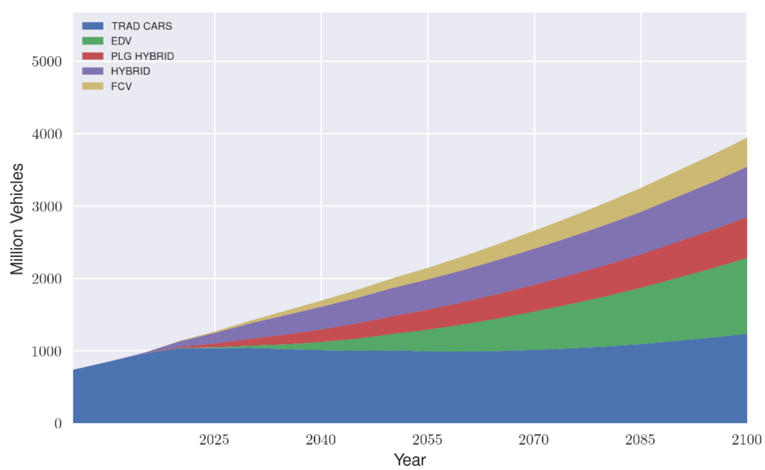

Figure 12: World LDV Fleet Composition in BAU Scenario After Implementing the CES Function

The results shown in Figure 12 show a smoother transition between vehicle types compared to the initial BAU fleet composition plot in Figure 10. The effect of introducing the technology switching function can be further seen at the regional level for Canada in Figure 13, since each region would previously invest in one technology for a given year.

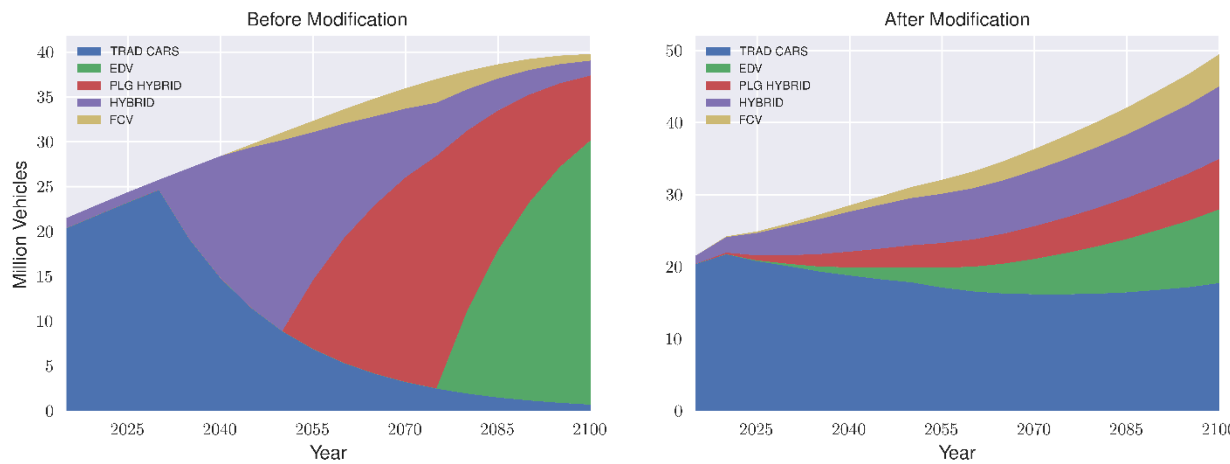

Figure 13: Fleet Composition for Canada Before and After Implementing the Technology Switching Function

The choice of vehicle technology before the improvements that have been done to the transportation module was characterized by instant switches from tradition vehicles to hybrid by the year 2030, which is as soon as the technology becomes cheaper. The same trend continues as the instant switch between technologies persists. After the implementation of the new function, the transition between technologies became smoother, and it is harder to phase out a certain technology such as traditional vehicles without implementing high carbon taxes or imposing policies that ban the sales of that technology.

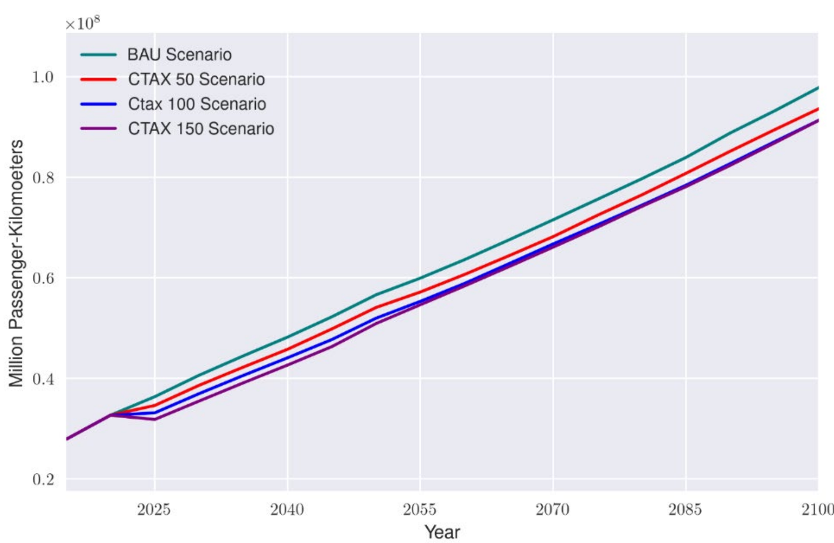

Figure 14: World Travel Demand for Different Carbon Tax Scenarios

To assess the response of travel demand with respect to the price of transportation, it is possible to run carbon tax scenarios with different starting values of the carbon tax and the carbon tax increases with time. The plot in Figure 14 presents the difference in the demand of the transportation services in passenger kilometers in four different scenarios. The first scenario is a simple BAU, while the other three are carbon tax scenarios with different initial carbon tax. The starting carbon taxes are 50, 100, and 150 $/tCO2. As the carbon tax starts at the year 2025, a slowdown of the increasing trend of the demand for transportation services is seen for the carbon tax 50 $/tCO2 and 100 $/tCO2 scenarios, and even a decrease in demand is seen for the 150 $/tCO2 scenario. This shows that the new demand function that has been implemented into WITCH has a significant effect on the total service demand, since in the previous version of the transportation module, the total demand for all the scenarios shown in Figure 14 would have been the same.

The technology choice of vehicles is influenced by the price of each technology. In a BAU scenario which does not tax the use of fossil fuels, the traditional cars are expected to be the most favored LDV technology due to the cheaper price of vehicles compared to electric or fuel cell cars. However, policies that increase the cost of fuels or even tax a certain technology would cause a great shift in the modal choice of consumers. The result of the carbon tax scenarios on the fleet composition is shown in Figure 15.

The increase in the initial carbon tax leads to the penetration of electric light duty vehicles at the expense of traditional fossil fuel-based vehicles. The pace at which the shift to EDVs occurs increases with the increase of the carbon tax, but we can observe no sudden shifts between two consecutive years. The results obtained above are for an elasticity of 10 and increasing or decreasing the chosen elasticity would affect the speed of vehicle technology shifting.

The carbon tax is one of several policies that would affect the price of transportation. Some policies add an extra cost to transportation services, while other forms of policies incentivize a certain technology or force the penetration of a certain LDV technology. The policy that will be assessed within this research work, that is the Fit-for-55 transportation policy, imposes a ban on the sales of fossil fuel-based cars by the years 2035. This type of policy does not add a direct tax to the cost of fuel, but rather forces the consumers to shift towards a different type of technology and manufacturers to invest in the research of development of cleaner light duty vehicle technologies.

Figure 15: World LDV Fleet Composition for Different Scenarios

The carbon tax is one of several policies that would affect the price of transportation. Some policies add an extra cost to transportation services, while other forms of policies incentivize a certain technology or force the penetration of a certain LDV technology.

The policy that will be assessed within this research work, that is Fit-for-55, imposes a ban on the sales of fossil fuel-based cars by the years 2035. This type of policy does not add a direct tax to the cost of fuel, but rather forces the consumers to shift towards a different type of technology and manufacturers to invest in the research of development of cleaner light duty vehicle technologies. In the case of Fit-for-55, the shift is expected to happen towards electric drive vehicles and fuel cell vehicles. The Fit-for-55 policy is part of Europe's plan for achieving climate neutrality and hence it is expected to happen in a world where several climate policies and actions are taking place on most of the emission producing sectors.

The assessment of the transportation policies would be done in several scenarios with different states of the world. The degree of which regions are taking climate action through policies affects the outcome of the policy since several parameters in WITCH such as oil prices are affected by the actions of all nations. Therefore, different scenarios have been built through the WITCH model to assess the Fit-for-55 road transportation policy.

2.3 Definition of Scenarios

2.3.1 Climate Mitigation Efforts

Since climate change has become a global issue, the leaders of the world have met on several occasions in climate conferences and pledged to commit to reducing their emissions. The degree of commitment of nations to what they pledged is still uncertain since political and economic situations change by the day in the present fast-paced world. Therefore, the assessment of climate mitigation policies is subject to an uncertain state of the world that might alter the effectiveness of the proposed policy. Due to this fact, the assessment of the Fit-for-55 transportation policy shall be done in several scenarios, where varying degree of climate mitigation efforts is present.

One of the scenarios that is not optimistic about the development of the climate mitigation efforts is one where nations continue with the current set of policies that are being implemented. The current policies vary in the level of commitment to the reduction of GHG emissions or the renewable energy penetration. In a world where only the current policies are adopted without any further actions, the goal of the Paris Agreement that is to limit the level of the warming on earth below 2 Degrees Celsius would not be possible. Implementing the transportation policy for Europe in a World adopting lenient policies would not be enough to limit the overall emissions from all sectors.

To achieve the goal of limiting the global temperature increase to below 2°C, several nations have decided to raise their level of commitment by implementing more strict climate policies and setting ambitious emission targets. Those pledges are known as the National Determined Contributions (NDCs). The NDCs extend up to the year 2030 with most nations setting different goals at various years. For example, as part of the NDCs, Europe has pledged to decrease its GHG emissions by 55% with respect to the 1990 levels by the year 2030 [18]. Europe's goal increased from 40% to 55% after the revision of the NDCs since it was deemed that more immediate climate action is required to limit the climate damages in the future. The United States has set a similar goal that is to reduce the amount of GHG emissions by 50% with respect to the values in 2005 by the year 2030. The list of contributions extends as to 185 countries, with each country having different pledges. The NDCs are updated every 5 years by the involved countries to update their part of the pledges. The Fit-for-55 policy package is part of the policies that have been proposed by Europe to achieve the 55% reduction goal, and therefore, assessing the Fit-for-55 transportation policy in a scenario where all the regions within WITCH commit to their pledged NDCs is necessary.

Apart from the NDCs, some nations have also set long term climate strategies with some of those nations pledging net zero emissions by the middle of the century. The following plans are known as the mid-century strategies. Europe, USA, Japan, and South Korea have all pledged to achieve net zero GHG emissions by the year 2050. China plans to cut the CO2 emissions to net zero by the year 2060 which is crucial goal knowing that China currently is the biggest CO2 emitter in the world. Mexico and Canada have also pledged to cut there GHG emission by 50% and 80% respectively by the year 2050. The following goals are ambitious and require a huge amount of investment in renewable energy and energy efficiency improvement.

2.3.2 Scenario Setup

Having realized that the future of the climate and the economy depends on the choices that nations make, it is necessary to assess policies within different scenarios. This is made possible in WITCH by adding extra constraints to limit the emissions and the renewable energy penetration for the regions that have pledged future action. Therefore, eight different scenarios will be analyzed within this research work, where each scenario has different constraints.

The scenarios that were performed are all based on the assumption that the world would follow a SSP2 path. The WITCH model has been used in the non-cooperative mode, and the world was divided into 17 regions as presented in Figure 7. The Scenarios that will be analyzed are:

- **REF**: The reference scenario that is used for the following research work is a current policy scenario. In this scenario, regions commit to lenient renewable energy and GHG emission goals. It will serve as a reference point for other scenarios since it gives an approximate view on the World’s future without any additional policies or commitments towards achieving net zero goals. The current policies that are implemented vary between different regions, but the overall trend of emissions worldwide does not show signs of decreasing and the global temperature is expected to rise by the end of the century.

- **NDC**: The following scenario assumes that regions commit to the National Determined Contributions until the year 2030. After that year, it is assumed that the implicit carbon price in each region at the year 2030 would converge to the carbon price values for OECD countries in the year 2050. After 2050, the price will grow at the same rate that is equal to the OECD tax rate. The following scenario is optimistic when it comes to the extrapolation of the NDC efforts, but such cooperative effort is required for regions to achieve the climate and temperature goals in the future.
- **MCS**: The mid-century strategies' scenario is built upon the NDC convergence scenario described above. This scenario assumes that specific regions that have pledged to go net zero by 2050 or other emission reduction goals such as Europe, USA, and Canada commit to their plans. China achieves net zero CO2 emissions by the year 2060. The efforts that were done in the middle of the century are then extrapolated until the year 2100 in a similar manner to that applied for the NDC scenario.
- **15DEG**: The following scenario represents a world where regions apply efforts to limit the future warming to 1.5°C by 2100. This is done by applying a carbon budget of 700 Gton of CO2 in the time-period between 2011 and 2100. The restrictions on the carbon budget would promote renewable penetration and reduce the GHG emissions. This scenario represents the long term strategy that all regions should follow in order to achieve the 1.5 Degrees target by the end of the century.
- **CURPOL+FF55, NDC+FF55, MCS+FF55, 15DEG+FF55**: The following four scenarios are based upon the above proposed scenarios. The Fit-for-55 transportation policy of banning fossil fuel light duty vehicles is applied in Europe, while the remaining regions continue with their applied policies respective to the base scenario. This allows the assessment of the policy implications in different states of Europe and the World.

Implementing the eight different scenarios with and without the Fit-for-55 transportation policy in Europe would allow the assessment of the policy while taking into account the path that Europe and the other regions are following towards emission reduction. The comparison between implementing the policy within the same type of scenario and between different mitigation paths would be done to assess the benefits and costs in each scenario.

The list of all performed scenarios is summarized in Table 6.

Table 6: Summary of Scenarios

SCENARIO CODE	DESCRIPTION
REF	Reference scenario with current policies
NDC	National determined contributions with extrapolation of carbon prices
MCS	Mid-century strategy scenario built over the NDC
15DEG2020	A 700 Gton of CO2 carbon budget scenario that aims to limit 2100 warming to 1.5°C
CURPOL+FF55	Current policy scenario with implementing the Fit-fo-55 transportation policy in Europe
NDC+FF55	NDC scenario with implementing the Fit-fo-55 transportation policy in Europe
MCS+FF55	Mid-century strategy scenario with implementing the Fit-fo-55 transportation policy in Europe
15DEG+FF55	A 700 Gton of CO2 carbon budget scenario with implementing the Fit-fo-55 transportation policy in Europe

2.3.3 Developing the Narrative

To be able to assess the effectiveness of the policy, several variables will be studied within each scenario. The degree of commitment to achieve climate neutrality goals will directly affect the emissions and energy consumption. Implementing the Fit-for-55 transportation policy within different scenarios would yield varying transportation prices and fleet compositions. The REF scenario would serve as a reference to other scenarios since it represents a world with no extra efforts apart from the current policies implemented in the transportation or other emission related sectors. The effects of the Fit-for-55 transportation policy start by the year 2025 as the reduction of the new sales of fossil fuel-based cars starts, and the policy is fully implemented by the year 2035. Therefore, the effects of this ban will be studied between the period 2015 and 2055 to check how will the policy interact with the efforts done in the NDCs and the mid-century strategies that are part of the plan to achieve climate neutrality.

Europe is one of the regions with the highest level of constraints in both the NDC and MCS scenarios, and therefore implementing those two scenarios will serve as a basis to assess the effects of the efforts encompassed within those scenarios on the future climate situation, energy mix, and the state of the passenger road transportation sector. The Fit-for-55 policy package is part of the efforts that are done to achieve climate neutrality in Europe by the year 2050, and thus implementing the transportation policy within the CURPOL+FF55, NDC+FF55, and MCS+FF55 scenarios aims specifically to assess how will implementing this extra effort in the transportation sector will contribute to the decarbonization of the transport sector.

A carbon budget scenario with carbon budget of 700 Gton of CO2 between 2011 and 2100 will be studied with and without the Fit-for-55 transportation policy to check what would be the effects in a scenario where long-term goals are present, since this scenario aims to achieve a temperature increase below 1.5°C by the year 2100.

The variables of interest in the following assessment are total transportation service demand, fleet composition, investment in transportation services, and the final energy distribution in the transportation sector. Assessing those variables between the year 2015 and 2055 will give a better understanding on how the transportation sector in affected by different policies and constraints.

Chapter Three

Results and Discussions

The third chapter aims to present the results and to perform a detailed analysis on their implications. The general final energy mix within each scenario will be presented along with the details of the state of the transportation sector in Europe and the World.

The effect of different emission mitigation efforts will be analyzed, and the effect of introducing the Fit-for-55 transportation policy in different scenarios will be studied. The scenario results are analyzed between the years 2015 and 2055, and a comparison between the benefits and the costs of implementing the transportation policy will be analyzed.

3.1 Total Transportation Service Demand

Each of the proposed scenarios has unique predictions to the future state of the world. The penetration of certain technologies over others highly depends on the adopted policies and the level of climate action. Therefore, the total demand for transportation services is expected to vary between different future scenarios. Figure 16 and Figure 17 show the variation in the World and European future service demand in passenger kilometers for the scenarios were the Fit-for-55 policy is not yet implemented.

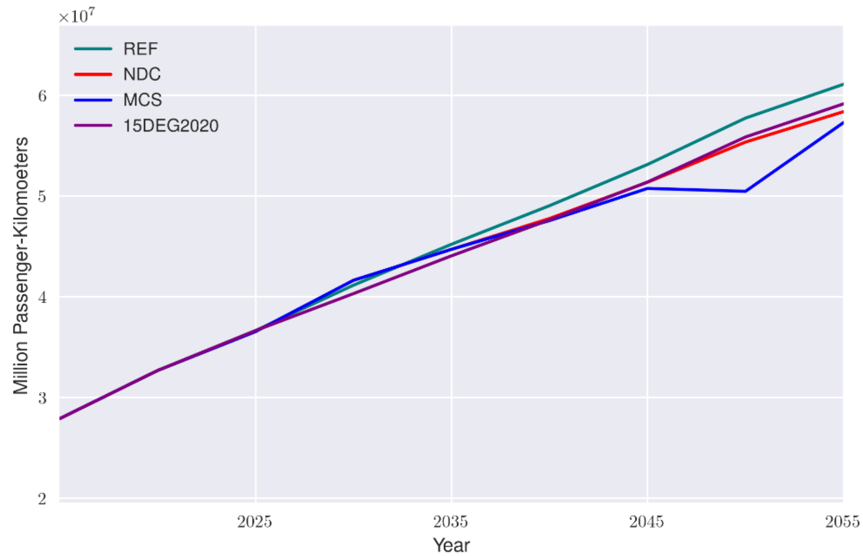

Figure 16: World Total Service Demand

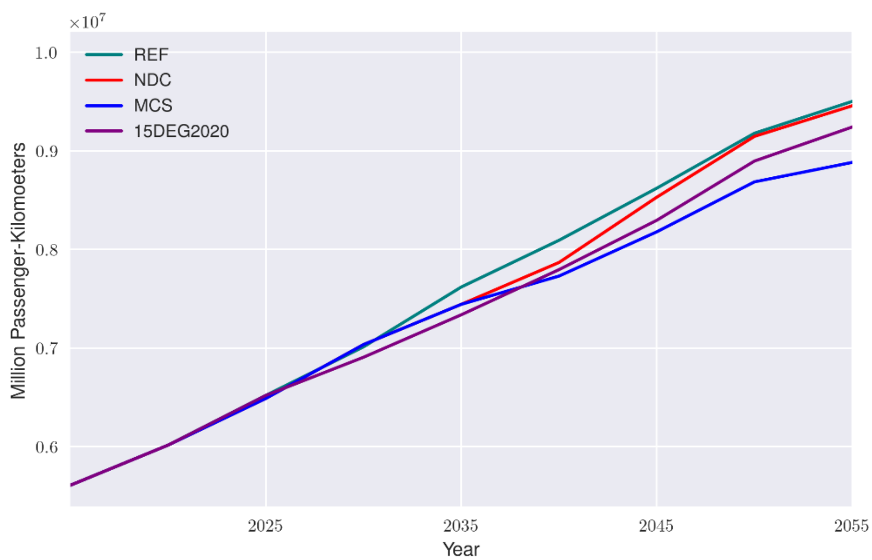

Figure 17: Europe Total Service Demand

The results of the scenarios shown in the above figures aim to present how will the demand for transportation services be affected by the policies that extend over the four scenarios that don't include the Fit-for-55 transportation policy. For both, Europe and the World, the REF scenario which is based on the current adopted policy has the highest passenger kilometer demand until the year 2055. On a Worldwide scale, the NDC and 15DEG2020 scenarios resemble a similar trend in which total demand decreases due to the increased constraints and the introduction of a carbon tax to limit emissions. The MCS scenario witnesses a significant drop in demand by the year 2045, and this is due to the increased level of ambition in the following scenario where several regions pledge to reach net zero emissions by the year 2050 which leads to cutting fossil fuel-based technologies and replacing them by renewables, as well as an increased carbon tax. In the case of Europe, the REF scenario is also the one with the highest level of demand, but the NDC scenario would recover back to a level of demand like the REF scenario by the year 2050, which could be justified by the fact that the convergence of the carbon price for Europe by the year 2050 has a lower effect on demand compared to the GDP growth, which would lead to the recovery of total demand.

The decrease in demand that has been shown previously is due to the difference in fuel prices and the introduction of carbon taxes that very between scenarios. In the case of introducing the Fit-for-55 transportation policy, new consumers after the year 2035 are forced to invest in clean technologies that are not as established as the cheaper traditional vehicles. Therefore, the price of vehicles will increase and thus causing a drop in the total demand. The Fit-for-55 policy will mainly affect the transportation sector in Europe, which can be observed in Figure 18 for the REF and CURPOL+FF55 scenarios.

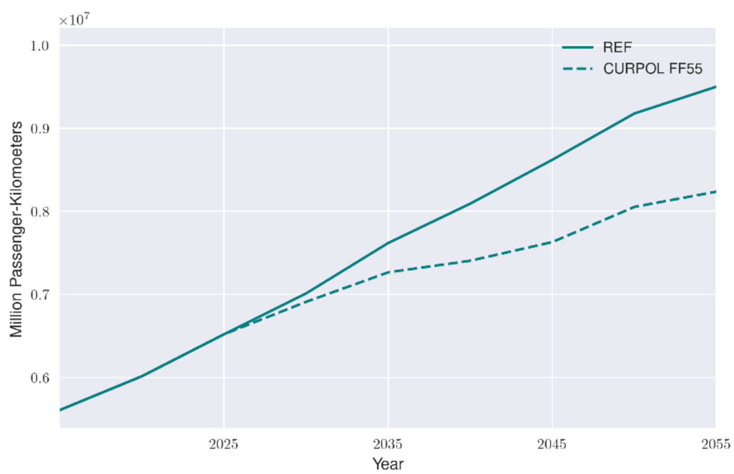

Figure 18: REF vs CURPOL+FF55 Service Demand in Europe

The comparison that has been made in Figure 18 between the REF and CURPOL+FF55 scenario in Europe shows the effect of banning fossil-fuel based LDVs, that are represented in WITCH by traditional cars, hybrid, and plug-in hybrid vehicles. The decreasing trend starts as soon as the policy begins at the year 2025 and continues at a slow rate of reduction until the year 2035 where the full ban takes place. After the year 2035, the drop in demand become steeper since at this point consumers have no choice but to buy electric drive or fuel cell vehicles which are more expensive. The shift towards more expensive LDV technologies increases the price of transportation that was presented in Equation 18, and therefore decrease the total service demand. Figure 19 presents a comparison between all the performed scenarios for the total service demand in Europe.

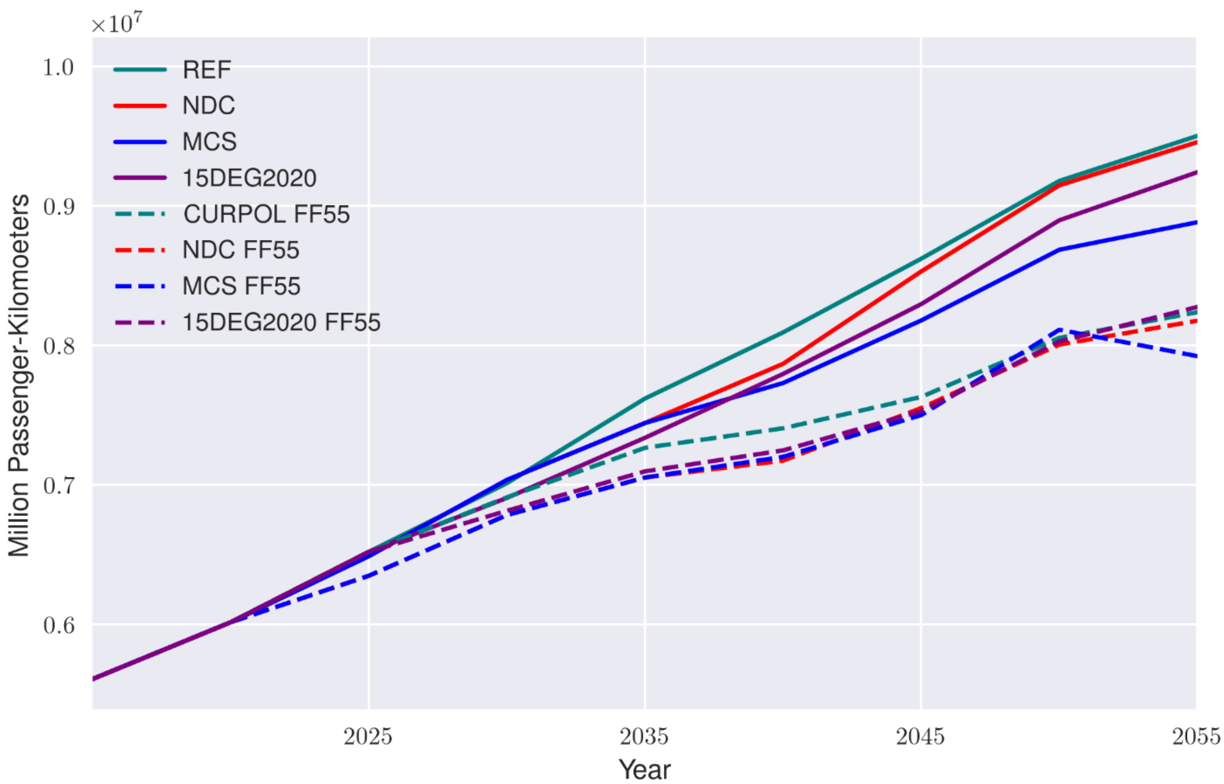

Figure 19: Total Service Demand in Europe for All Scenarios

The graph shown in Figure 19 shows the effect of implementing the Fit-for-55 on each scenario. The most significant finding is that in the three cases that are CURPOL+FF55, NDC+FF55, and 15DEG2020+FF55 the total demand will converge to a uniform value by the year 2055 even though the years between the start of the policy and the end-year witness different trends. The MCS+FF55 scenarios follows a similar trend to the NDC+FF55 scenario until the years where the mid-century strategies start effectively in Europe, which leads to an even greater decrease in the total service demand.

3.2 Travel Intensity

The variation in total service demand that has been presented reveals the impacts of the policy in an absolute sense, but different scenarios are known to have different economic outcomes since the policies that are implemented have a broader effect. Therefore, it is necessary to analyze the variable known as travel intensity, that is the amount of passenger kilometers traveled per unit of income. Travel intensity is a metric that allows the decoupling of km demand and GDP in order to measure the travel demand compared to economic growth. The travel intensities in the REF, NDC, MCS and 15DEG2020 scenarios are shown in Figure 20 and Figure 21.

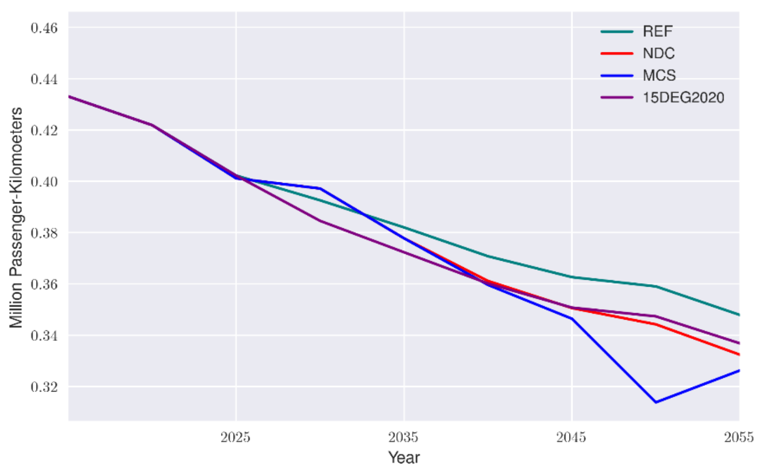

Figure 20: World Travel Intensity

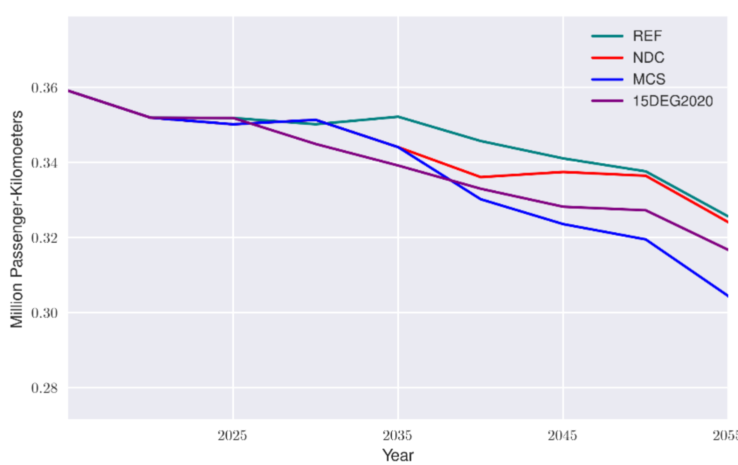

Figure 21: Europe Travel Intensity

The World travel intensity that is presented in Figure 20 shows that the travel intensity would decrease with the increased climate efforts. In the REF scenario, the decrease between the travel intensity in year 2015 and 2055 is the lowest between the other scenarios. The MCS scenario witnesses a significant decrease in the travel intensity, this is due to the penalization on total demand which would overtake the economic growth effect on the fleet expansion. On the European scale, Figure 21 shows that the travel intensity is decreasing at a lower rate where in the REF scenario the decrease in intensity between the year 2015 and 2055 is 8%, which indicates that the demand is growing in line with the GDP growth. However, the travel intensity would decrease and then recover in the NDC scenario due to the lower trend of increasing carbon tax after the NDC policy period. The MCS scenario is characterized with the lowest travel intensity, and this is due to extra effort that Europe will put into implementing the mid-century strategies which lead to the increase in prices of transportation.

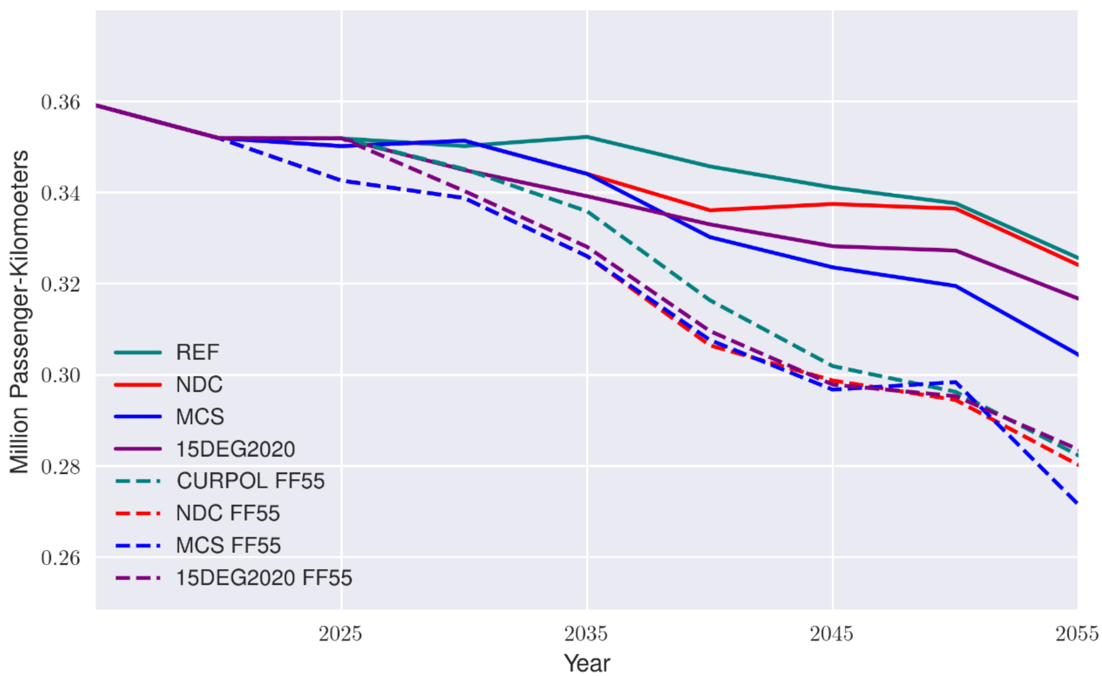

Figure 22: Travel Intensity in Europe for All Scenarios

The graph in Figure 22 shows the trend of travel intensity in Europe between 2015 and 2055 after implementing the Fit-for-55 transportation policy within the four different scenarios. The travel intensity after implementing the policy decreases for all the scenarios. It is notable that the CURPOL+FF55, NDC+FF55, and 15DEG2020+FF55 scenarios converge to the same travel intensity by the year 2055, while the MCS+FF55 scenario continues with a decreasing trend due to the extra drop in total demand compared to the GDP growth.

3.3 Fleet Composition

Developing more efficient technologies is the key to reduce emissions. The transportation sector has been a space for innovation in the past years, and alternative fuel vehicles are emerging. The fleet composition is highly affected by vehicle technology prices, as most consumers seek to have the cheapest method for traveling. The price of each technology of LDVs is effected by two factors that are the capital cost of the vehicle and the fuel price. The capital cost decreases as technologies become more established and components such as batteries and internal combustion engines become cheaper. On the other hand, fuel prices are determined by the international market in the case of oil, which is has the largest share in LDV fuels. The fleet composition on a global scale is shown in Figure 23.

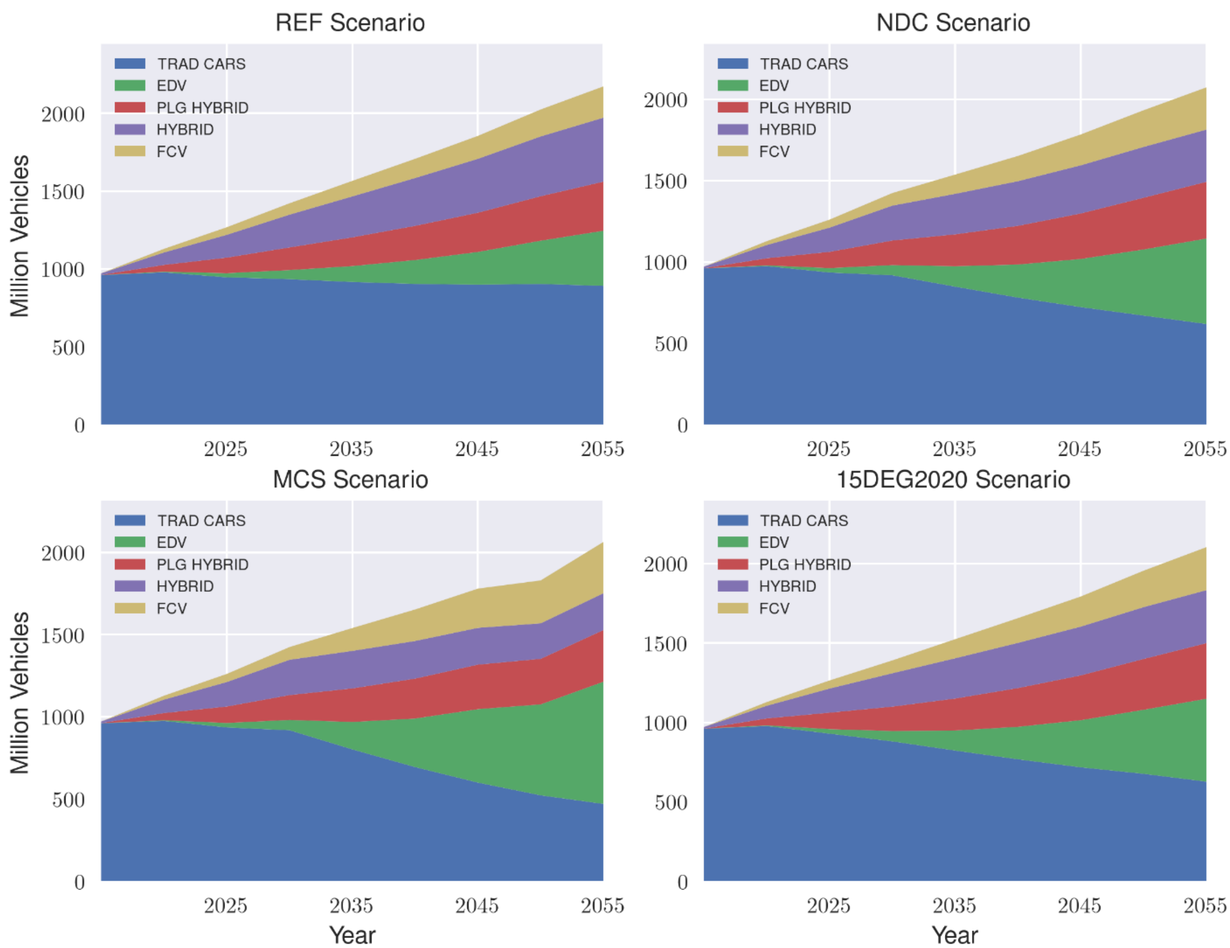

Figure 23: World LDV Fleet Composition

The fleet composition in the year 2015 is mostly dominated by traditional vehicles since it has been the cheapest and most established technology for many years. The future fleet composition varies between different scenarios according to the placed policy. The REF scenario which imposes the current policies has the highest share of traditional cars until the year 2055 which is justified since the prices of fossil fuel-based vehicles would still be the cheapest as the price of carbon is lower than other scenarios. The penetration of hybrid and plug-in hybrid technologies is limited due to the fact that fossil fuel cars would be the cheaper option. The increase in climate commitment in the NDC, MCS and 15DEG2020 scenarios leads to the decrease of the shares of traditional vehicles, and the increase of electric drive vehicles. The increase in fuel prices due to taxing emissions will increase the price of traditional vehicles to a point where electric vehicles would become the more convenient option for consumers. In the MCS scenario, the electric drive vehicles' shares would be the greatest by the year 2055 compared to the other three scenarios. The fleet composition in Europe is expected to be affected by the Fit-for-55 transportation policy, and the results of the fleet composition in Europe are shown in Figure 24 and Figure 25.

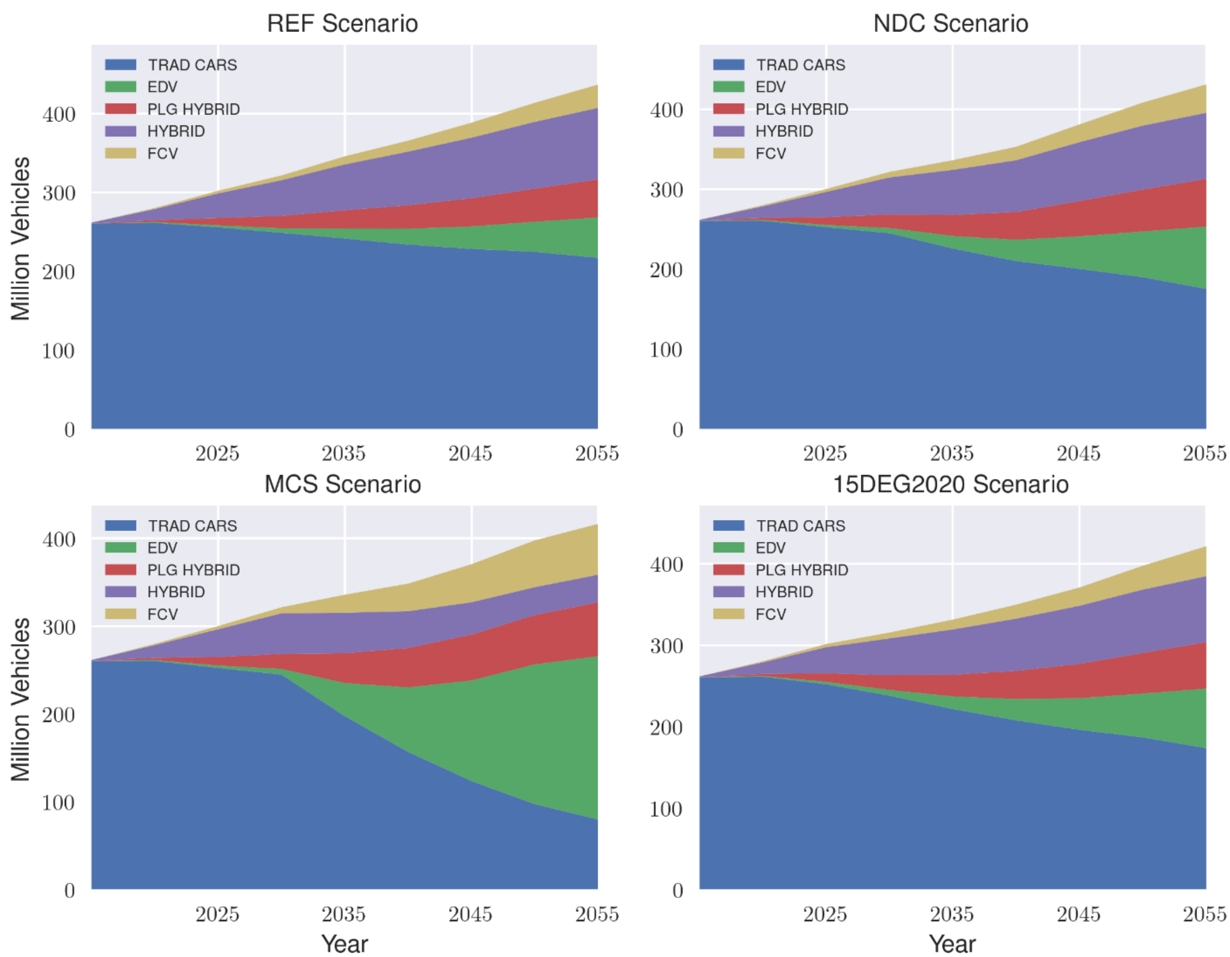

Figure 24: LDV Fleet Composition in Europe

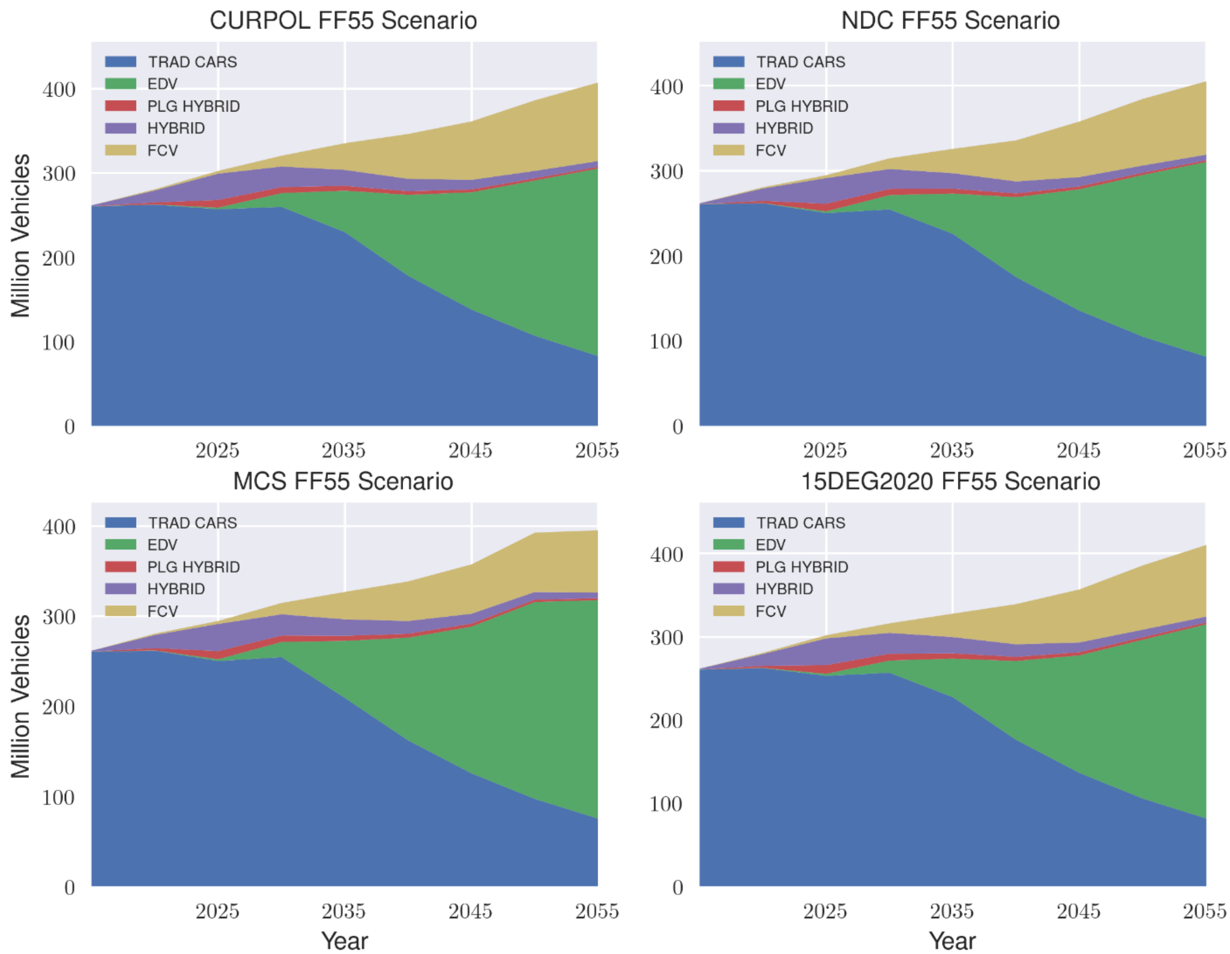

Figure 25: Europe's Fleet Composition After Implementing the Fit-for-55 Transportation Policy

Figure 24 shows the fleet composition in Europe before implementing the Fit-for-55 transportation policy. In the REF, NDC and 15DEG2020 scenarios, the price increase for the traditional LDVs is not enough to allow the effective penetration of electric drive and fuel cell vehicles. On the other hand, the MCS scenario, where Europe pledges to achieve net-zero emissions in the year 2050, causes a significant shift towards electric drive vehicles at the expense of traditional vehicles. After implementing the Fit-for-55 transportation policy, the fleet composition starts to shift from fossil fuel dominated to a fleet that mainly consists of electric drive and fuel cell vehicles. The remaining capital of traditional cars in the year 2055 is due to the accumulated fleet that follows the exponential depreciation of capital that is adopted in WITCH. The comparison of the shares of different LDV technologies from the total fleet can be better observed in Figure 26 which shows the evolution of the technology shares from the year 2020 until the year 2055 for different scenarios in Europe.

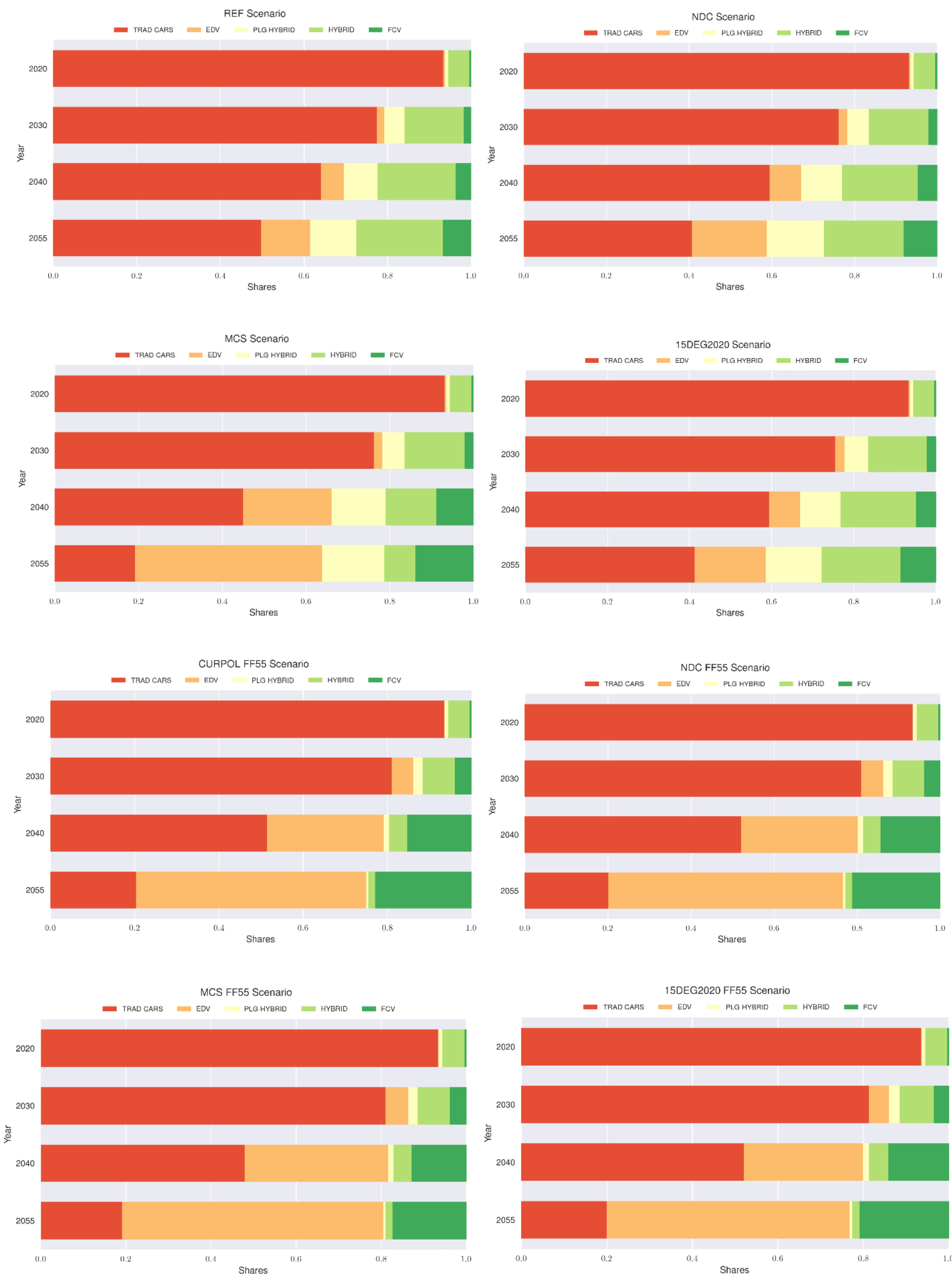

Figure 26: LDV Shares in Different Scenarios

The evolution of LDV technology shares that is presented in Figure 26 shows that even though the MCS scenario and MCS+FF55 scenario both yield a share of traditional vehicles that is less than 0.2 in the year 2055, the Fit-for-55 policy allows electric drive vehicles to take over the replaced share of traditional vehicles instead of the hybrid and plug-in hybrid vehicles that were added in the MCS scenario. In the CURPOL+FF55 scenario, the share of fuel cell vehicles was the highest between the other scenarios where the Fit-for-55 policy has been implemented as it reached more than 0.22 by the year 2055, which is because the fleet size in this scenario is the largest due to the increased demand. The share of electric vehicles in the MCS+FF55 scenario in the year 2055 is the highest of all scenarios as it reaches a level above 0.6 out of the total LDVs in Europe, which is three times more than the REF scenario where the efforts done to limit the future climate damages are at a minimum.

3.4 Share of Transportation in Final Energy Consumption

The transportation sector in Europe constitutes around 27% of the total final energy consumption, and since it is mainly based on fossil fuels, there is an urgency to reduce energy consumption in transportation and to shift to cleaner technologies. With economic and population growth, the energy demand is expected to increase specially in developing regions, and the transportation sector's energy demand is expected to follow the growth trend. Figure 27 presents the shares of different sectors in the final energy consumption on a Worldwide scale, and the share of energy consumption within each LDV technology.

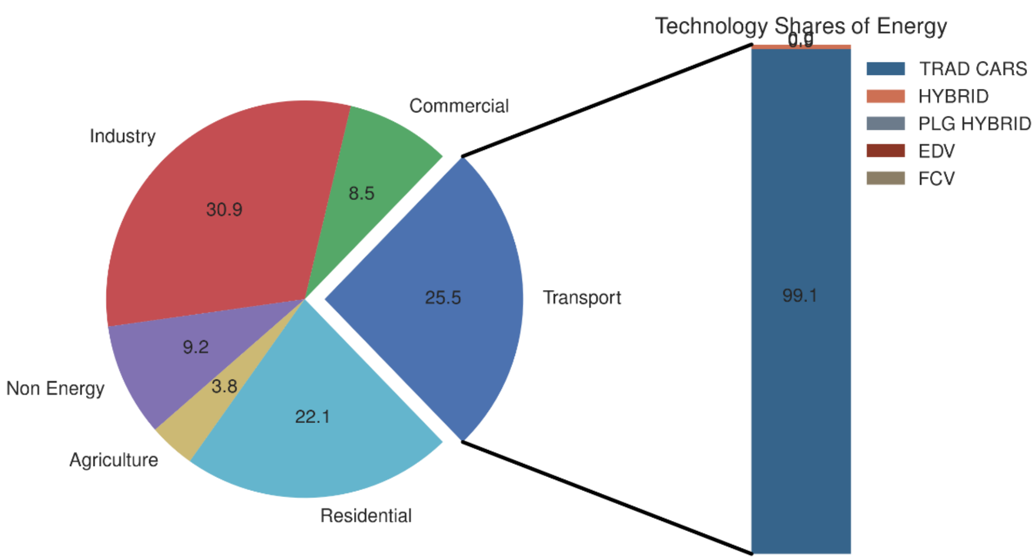

Figure 27: World Final Energy Consumption Shares Across All Scenarios by WITCH

The pie chart presented in Figure 27 shows that the transportation sector has a share of 25.5% of the World total final energy consumption that is second only to the industrial sector. The transportation sector in 2015 was dominated by traditional cars as around 99% of the energy consumption is from traditional vehicles. The share of transportation in the final energy sector is expected to vary according to the implemented policies due to the change in demand and fleet composition. Electric vehicles have a lower energy consumption per kilometer value which makes them more efficient than the traditional internal combustion engine vehicles. The shares of final energy consumption in the World in the year 2055 for the REF, NDC, MCS and 15DEG2020 scenarios are shown in Figure 28.

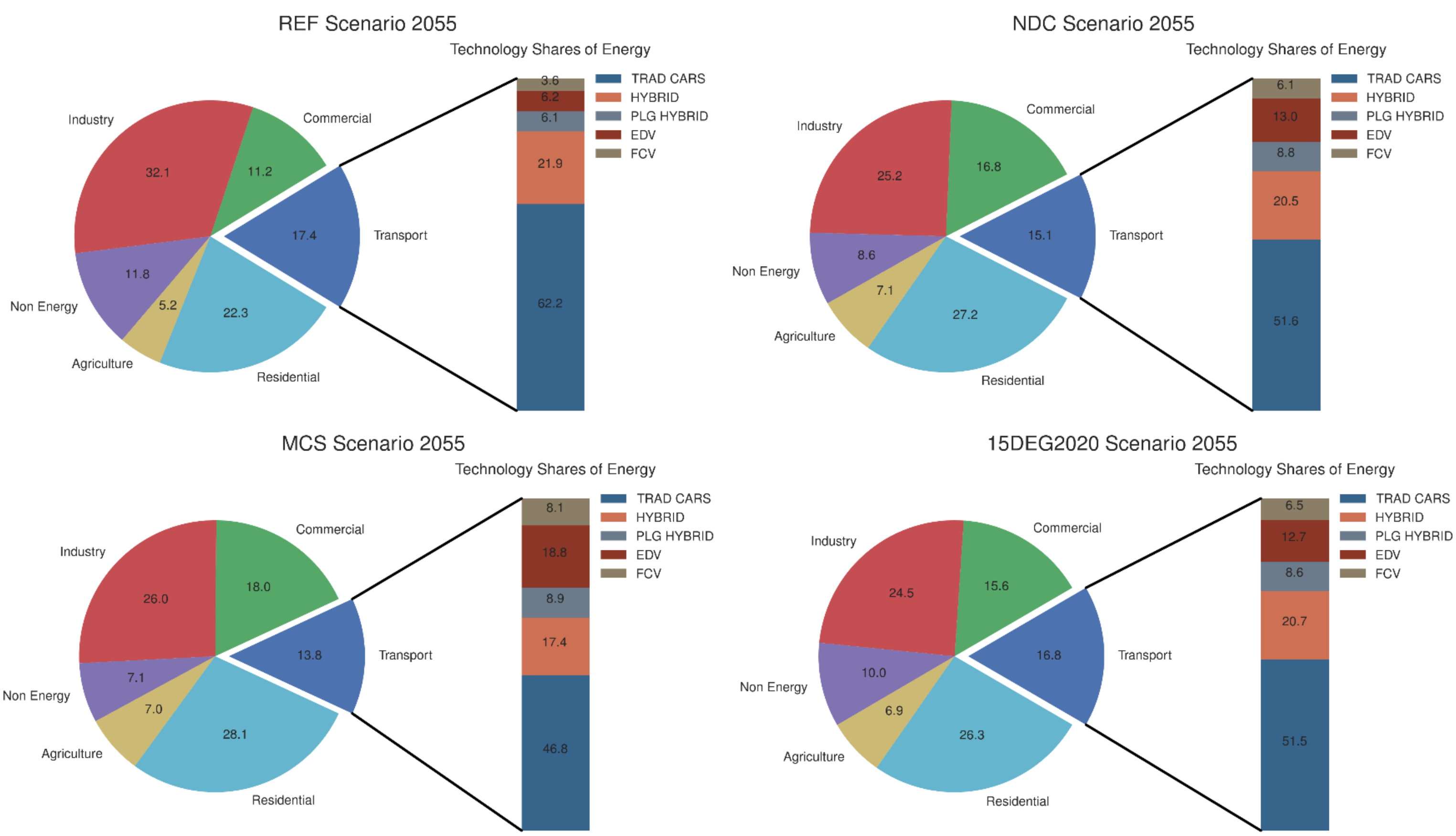

Figure 28: World Shares of Final Energy Consumption in 2055 for Different Scenarios

The results presented in Figure 28 indicate that the share of transportation in the final energy will decrease for all four scenarios on a Worldwide scale. This is due to the fact that internal combustion engines and other LDV technologies are expected to become more energy efficient in the future. The shares of transportation from total energy in the MCS scenario are the lowest due to the emergence of electric drive vehicles that are more efficient in terms of energy consumption, and due to the decrease in the total service demand in the passenger transport sector.

It may also be noticed that the shares of energy consumption by LDV technology vary between scenarios, as the share of energy for traditional vehicles deceased from 99.1% in the year 2015 to below 62.2% depending on the climate scenario. The MCS scenario has the most electric drive vehicles' share of energy consumption at 18.8% in 2055, along with an 8.1% share for fuel cell vehicles. The persistence of traditional vehicles as the most energy consuming technology in the MCS scenario even though the actual shares of traditional vehicles from the total fleet in the year 2055 is below 20% is due to the fact that fossil fuel-based cars are less efficient in terms of energy consumed per travel kilometer, which leads to a greater overall energy consumption.

The Fit-for-55 transportation policy is expected to have an impact on the final energy consumption in the transportation sector along with the energy consumption per technology. The initial shares of energy consumption in Europe in the year 2015 as calculated by WITCH are shown in Figure 29.

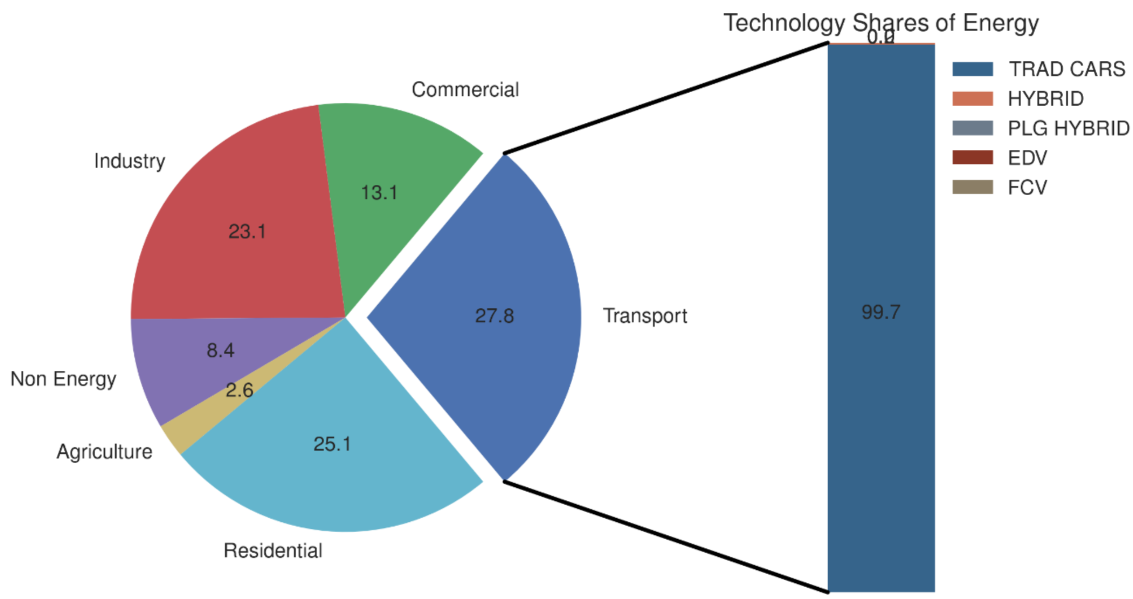

Figure 29: Sector Shares in Final Energy Consumption in Europe in 2015

The data presented in Figure 29 regarding the sector shares in final energy consumption show that the transport, residential and industrial sectors are the main sources of consumption, and they are led by the transportation sector which has a share of 27.8% of the total final energy consumption in Europe. The LDV fleet at the year 2015 in Europe mainly consisted of traditional vehicles, and thus it is expected to observe that traditional vehicles consist almost all the energy consumption from the energy consumed in the transportation sector. The results of implementing the eight different scenarios in Europe for 2055 are shown in Figure 30 and Figure 31.

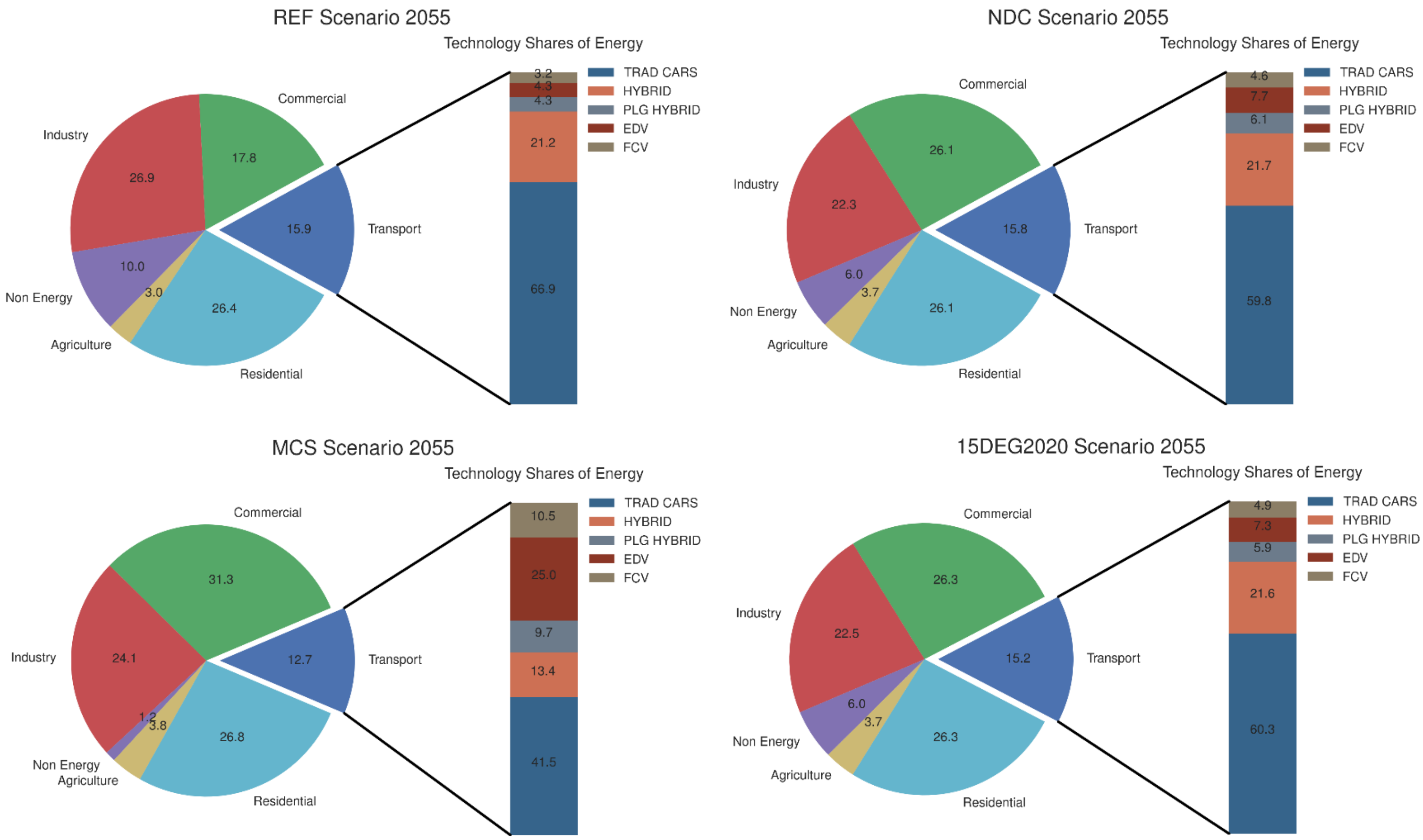

Figure 30: Sector Shares of Final Energy Consumption in Europe in 2055 Without the Fit-for-55 Policy

The case of Europe that is presented in Figure 30 shows a decrease in the share of the energy consumed in the transportation sector to the total final energy consumption for all the scenarios without implementing the Fit-for-55 transportation policy. The MCS scenario, which has high climate ambitions for Europe by 2050, reduces the share of transportation in final energy to 12.7% making it significantly less than the shares of the industrial and residential sectors. The shares of energy consumption per LDV technology would witness a drop for the traditional cars' shares within all four scenarios shown above, while having the most significant decrease in the MCS scenario where the traditional car shares reach a low of 41.5% and the electric drive vehicle shares achieve a high of 25%. However, for Europe to be able to achieve a net zero future and decarbonize the transportation sector, more effort must be put in the form of policies to further promote the penetration of clean vehicles into the fleet. Therefore, implementing the Fit-for-55 transportation policy is expected to increase the shares of electric drive vehicles' energy consumption and decrease the share of the energy consumed in the transportation sector in Europe. The final energy shares' results of implementing the Fit-for-55 transportation policy in Europe are shown in Figure 31.

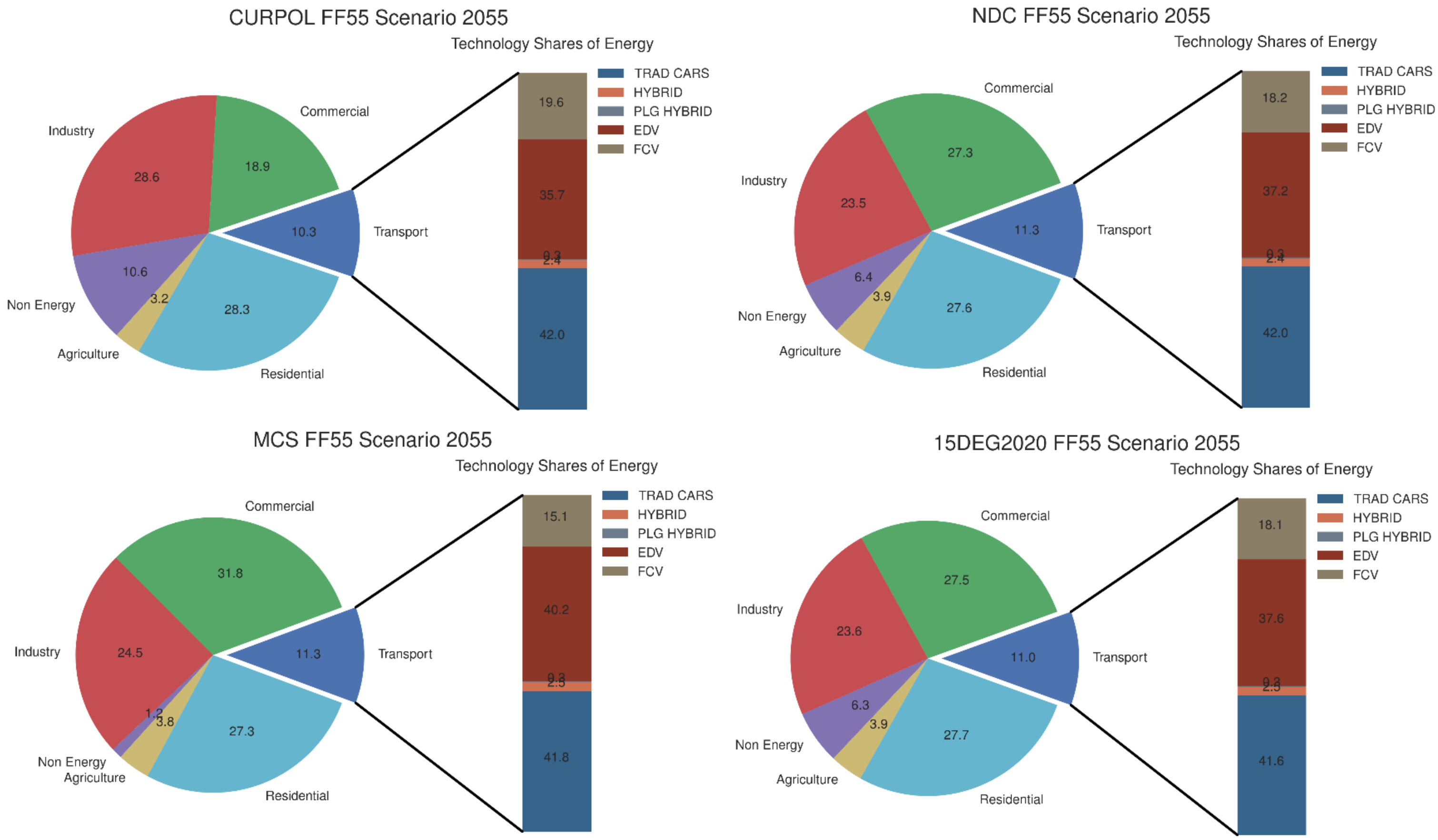

Figure 31: Sector Shares of Final Energy Consumption in Europe in 2055 With the Fit-for-55 Policy

The charts presented in Figure 31 show a considerable decrease in the share of energy consumption from the transportation sector from total energy consumption to reach around 11% for all the scenarios where the Fit-for-55 transportation policy. This decrease can be accounted to two different reasons, the first being the decrease in total transportation service demand due to the higher prices of electric drive and fuel cell vehicles, and the second is the increased energy efficiency of the two technologies that constitute most of the new fleet. The share of energy consumed per technology decreases in all scenarios for traditional cars to reach slightly above 40%, which is expected to keep decreasing with time until the remaining capital of traditional cars is fully depreciated. In all the scenarios where the transportation policy is implemented, the combined share of energy consumption of electric drive and fuel cell vehicles surpasses 50% of the total energy consumed in the transportation sector. The shares of energy consumed by hybrid and plug-in hybrid vehicles reach levels below 2.5% which is due to the ban of sales of the following vehicles at a time where they were not hugely integrated within the fleet as much as traditional cars.

3.5 Oil Consumption in Europe

The dependency of the transportation sector Worldwide and in Europe on oil as a main fuel lead to an increased level of emissions from this sector. Traditional fossil-fuel cars have been improving in efficiency with advancements in internal combustion engine technologies, but other alternatives such as electric drive or fuel cell vehicles offer a cleaner method for transportation. The implementation of the Fit-for-55 transportation policy has been found to reduce the count of traditional vehicles in the fleet in Europe, and to promote fleet electrification. Since the transportation sector highly depends on oil, the overall oil consumption in Europe has decreased in Europe after the policy implementation as shown in Figure 32.

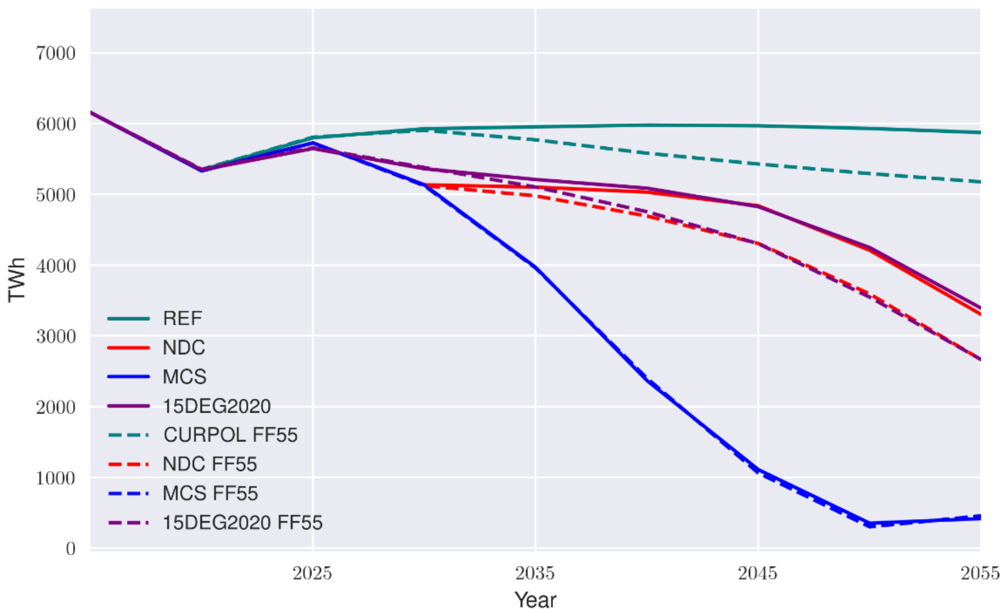

Figure 32: Oil Consumption in Europe

The scenarios REF, NDC, and 15DEG2020 result in a decrease in the total amount of consumption of oil after applying the Fit-for-55 transportation policy. The replacement of traditional vehicles by technologies that are oil-free leads to a 17% decrease in consumption between REF and CURPOL+FF55 at the year 2055. The scenario that is least affected by the policy implementation is the MCS scenario. Reducing emissions in Europe to the level of net zero by the year 2050 required the adoption of clean technology and phasing out oil, and hence there is little difference in the total oil consumption for the scenario with and without the fossil fuel car ban.

3.6 Investment Cost of Electric Vehicles

One of the important features of the WITCH model is that technology research and development is endogenous within the model. That allows technologies such as batteries or fuel cells to get cheaper according to the research and development and learning rate of technologies. This fact is of great value for the transportation sector and specially light duty vehicles. The electric drive, hybrid, and plug-in hybrid vehicles all contain batteries with different sizes, and therefore the investment cost in those technologies would be affected by the decrease in battery prices. The same applies to fuel cell vehicles that have fuel cells that vary in cost within WITCH. Therefore, the scenario that is implemented in the model has a great influence on the investment cost of each technology and thus the total service demand and fleet composition. The capital costs of transportation technologies in WITCH differ between regions depending on the research and development and spillovers within the model. The investment cost for traditional cars is assumed to be constant and equal to 21,000 USD for all regions since it is considered as a developed technology with little chance to decrease its price over the years. However, the capital cost of the remaining four technologies remains an endogenous choice of the model. The investment cost of electric vehicles is of great importance since one the main barriers for EDV penetration is the high cost of the vehicle. The evolution of the investment cost of electric drive vehicles is shown below for the performed scenarios in Europe.

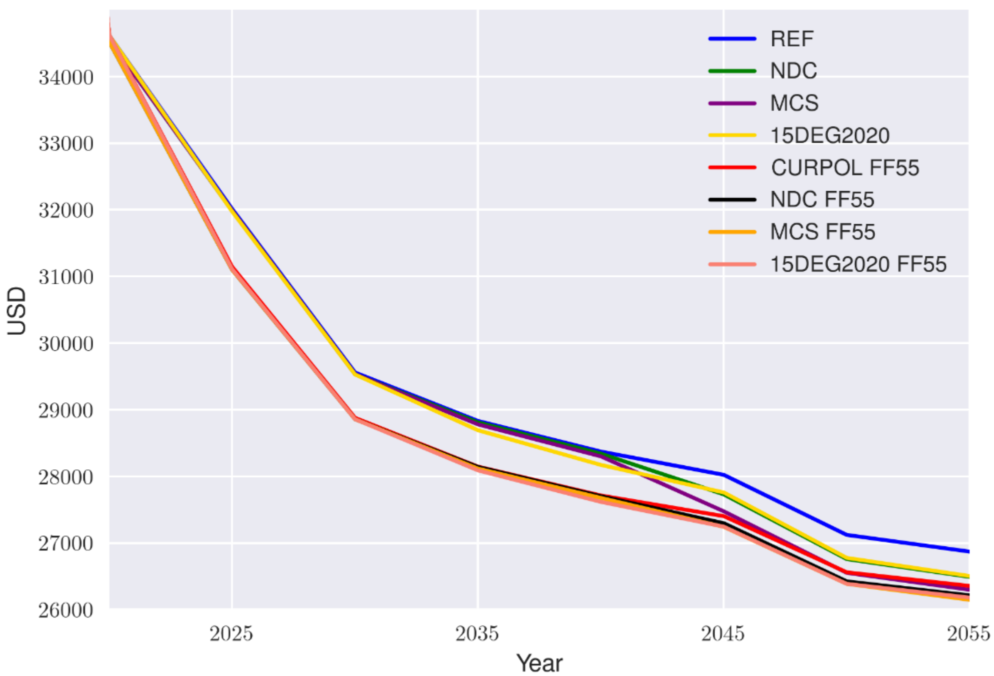

Figure 33: Capital Cost of EDVs in Europe in All Scenarios

The investment cost of electric vehicles witnesses a sharp decrease with time for all scenarios as shown in Figure 33. However, the slope of this cost drop varies across scenarios as the REF scenario maintains the highest cost per electric vehicle at around 27,000 USD per vehicle by the year 2055. This cost is around 800 USD more than the scenarios with the least cost that are MCS+FF55 and 15DEG2020+FF55. This is due to the higher volume of electric drive vehicles that has been deployed in scenarios where climate efforts are increased, which pushes cost to go down due to technology research and development. Another notable trend is the variation of cost between similar scenarios before and after imposing the Fit-for-55 transportation policy. The scenarios where the policy was implemented has a faster decrease in cost around the early years as divergence from other scenarios starts from the year 2020. For example, it is possible to observe the difference between the REF and CURPOL+FF55 scenarios that both have similar policies and constraints apart from the transportation policy. The CURPOL+FF55 scenario yields a cost of investment for electric vehicles that is 500 USD less than the REF scenario. This highlights the impact of the Fit-for-55 transportation policy on the market of electric vehicles. The key component that influences the cost of an electric vehicle is the battery, where it consists around 50% of the total cost of the vehicle [45].

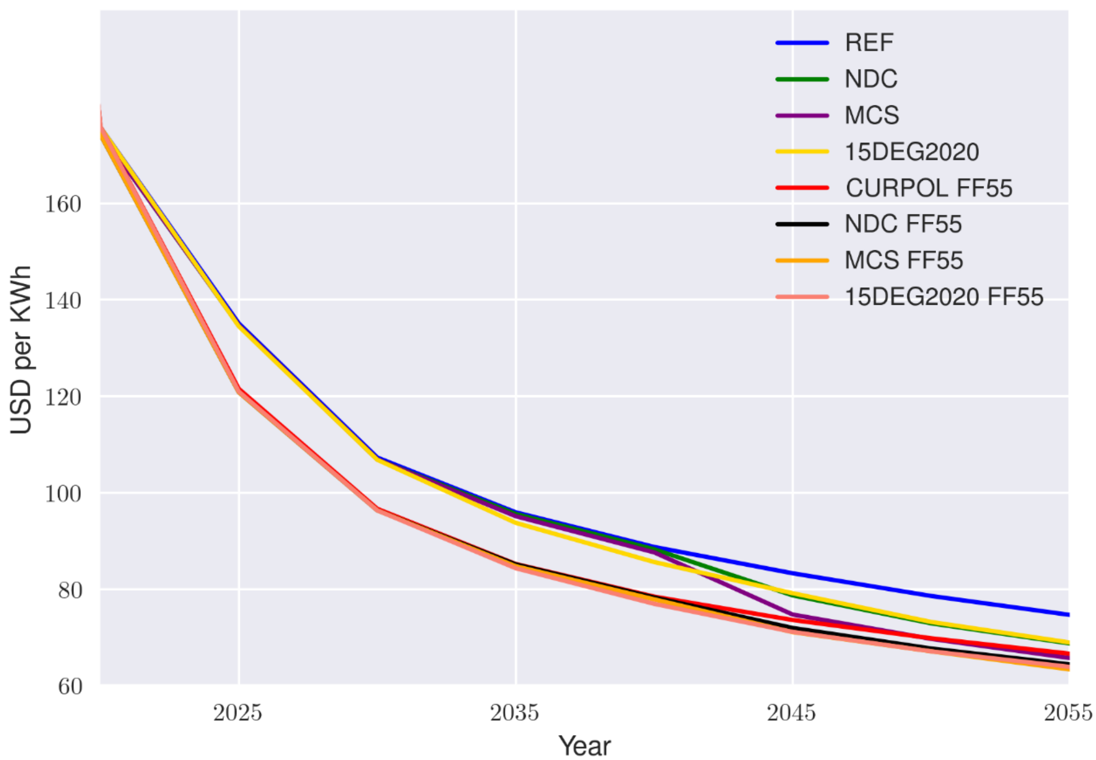

Figure 34: Cost of Batteries in Europe for All Scenarios

The graph in Figure 34 shows the trend of the cost of batteries in Europe across all the proposed scenarios. The trend of battery costs resembles the cost trend of electric vehicles that has been presented in Figure 33. This indicates the influence of the battery cost on the future of electric vehicles. Technologies such as batteries benefit from the endogenous knowledge stock which accumulates according to the amount of investments made over time and the degree of knowledge spillovers between regions. The Fit-for-55 forces the increase in investment in electric drive vehicles in Europe and thus pushing prices downwards, and it is expected that implementing similar transportation policies on a worldwide scale in technologically leading regions would lead to increased spillovers and thus a larger decrease in battery costs.

3.7 Investment in the Road Transport Sector in Europe

As the demand for transportation increases, the problem of providing the necessary supply at an affordable cost while limiting the resulting emissions becomes more difficult. The cheapest option to meet a certain demand in the road transportation sector would be to deploy traditional fossil-fueled technologies in case no carbon tax is applied. This is due to the fact that the following technologies are already established and available at a low cost. If the same demand for transportation is to be met by a supply of clean technologies such as electric or fuel cell vehicles, the price is expected to be higher. The different scenarios that have been performed in WITCH each have different policies and constraints, and thus the investments that have been made are expected to vary. The graph in Figure 35 shows the net present values for the investments in all LDV technologies in Europe between 2015 and 2055. The comparison that has been done in Figure 35 between the different scenarios is in an absolute sense as the scenarios have unequal demand for travel passenger kilometers. The net present value of the investments for REF and 15DEG2020 scenarios are lower than the scenarios where the Fit-for-55 transportation policy has been implemented even though the demand is lower in the former scenarios. The NDCs have almost the same level of investment before and after the transportation policy, while the MCS is the only scenario where the net present value of the investments is lower in the case where Fit-for-55 was not implemented. However, since the demand in different scenarios is different, it would be more useful to compare the net present value of the investments according to the demand for travel in each scenario. Therefore, it is possible to compare the net present value of investment divided by the total amount of kilometers demanded in the period of investment between scenarios. The results of the following comparison are shown in Figure 36 for the level of Europe compared to the REF scenario.

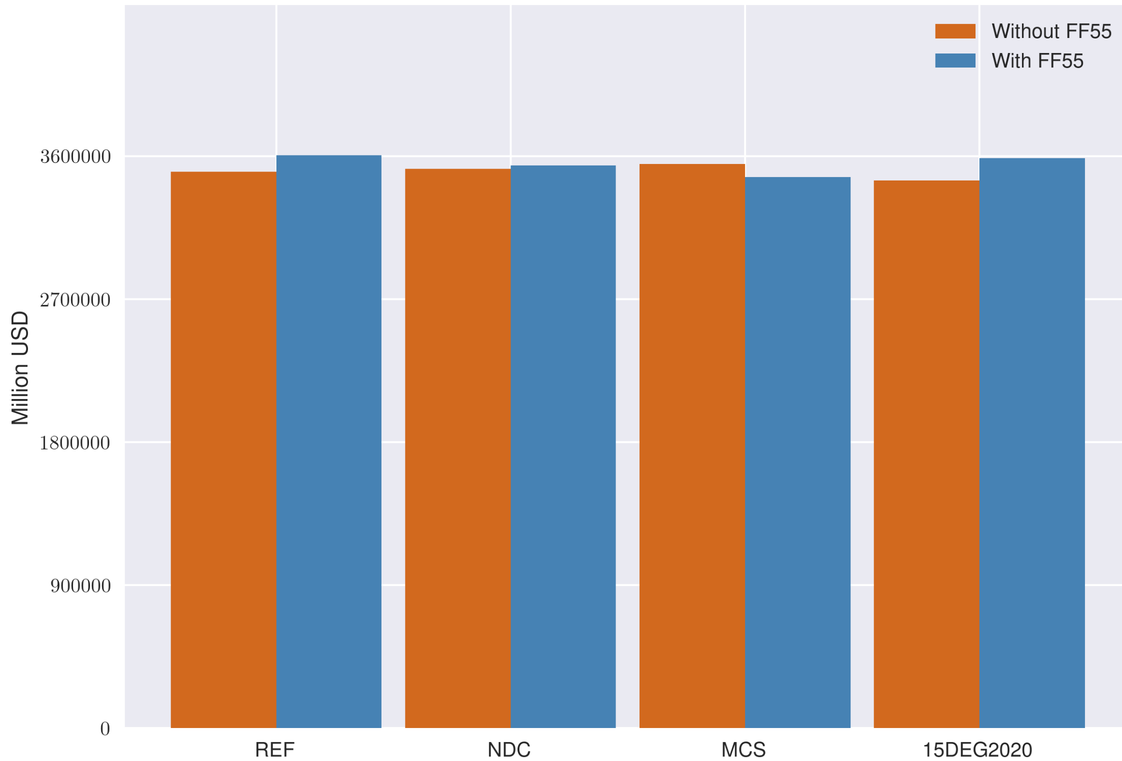

Figure 35: Net Present Value of LDV Investments in Europe Between 2015 and 2055

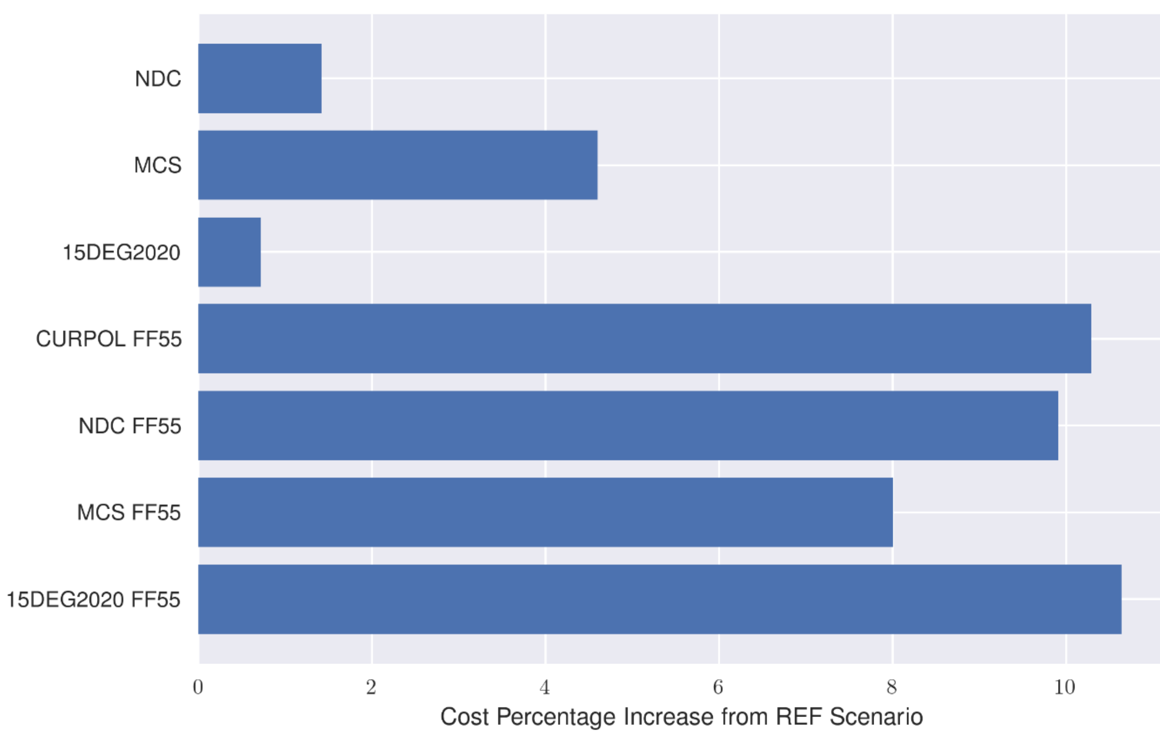

Figure 36: Percentage Different of Net Present Value of LDV Investments per Passenger Kilometer in Europe Compared to REF Scenario

The results presented in Figure 36 show that relative to REF, which is the reference scenario with the least climate effort between all the proposed scenarios, all other scenarios have an increase in the net present value of investments in LDV per passenger kilometer of demand. The observed difference relative to the REF scenario is due to the penetration of electric drive and fuel cell vehicles even while having a lower overall demand. In the case of the scenarios CURPOL+FF55 scenario, the implementation of the transportation policy is the only different constraint that has been set compared to REF scenario. The following lead to an increase of 10.2% in the investment per passenger kilometer which indicates that even with a lower demand, the investments per service are significantly higher. The 15DEG2020 scenario is the closest relative to the REF scenario with an increase of 0.7%, which is justified by the fact that the planning horizon in this scenario is longer than the NDC and MCS scenarios where the climate efforts are done in a shorter period of time and require immediate investment in clean technologies. The comparison that has been done relative to the REF scenario shows the difference between a scenario with minimum effort and other scenarios with increasing intensity of climate efforts. Another relevant method of comparison is comparing similar scenarios before and after implementing the Fit-for-55 transportation policy according to the NPV of investments per passenger kilometer between 2015 and 2055. The results of this comparison are shown in Figure 37 below.

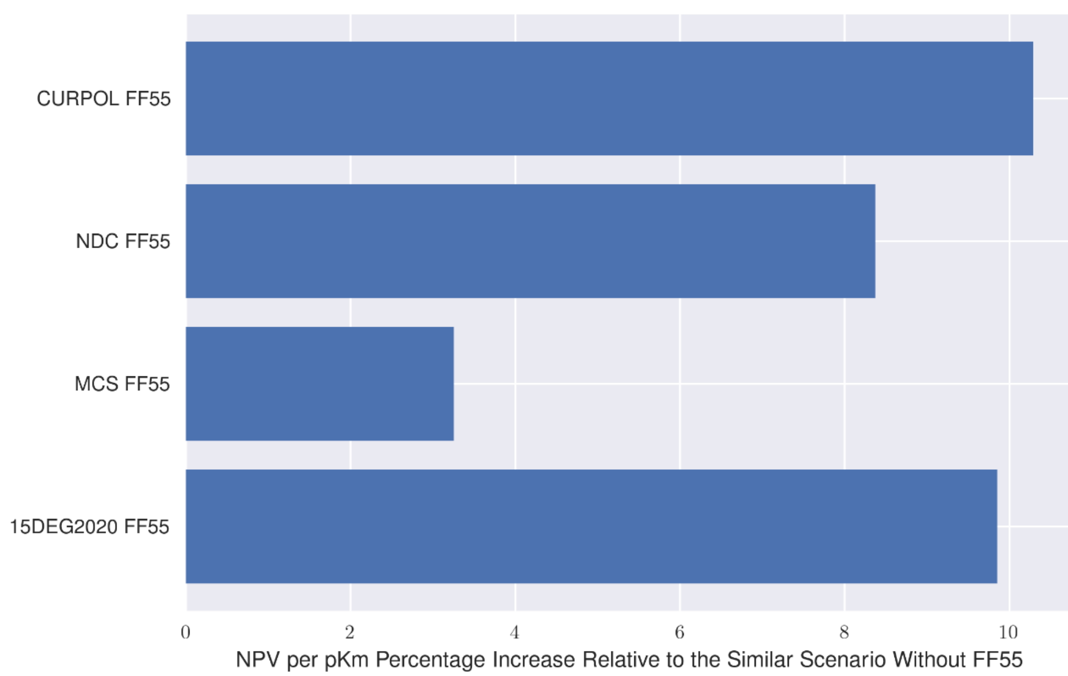

Figure 37: Relative Difference in NPV per pKm After Implementing FF55 Scenario Compared to the Same Scenario Excluding the Policy

The results presented in Figure 37 compare the net present value of the investments made in the light duty vehicles between the year 2015 and 2055 divided by the total service demand within the same period between the same scenarios before and after implementing the Fit-for-55 transportation policy in Europe. The highest increase in cost for implementing the policy is between the REF and CURPOL FF55 scenario where the relative increase is above 10%. The fleet in the REF scenario was dominated by fossil fuel-based vehicles, and the ban that would be implemented in the year 2035 would imply a high difference in investment costs since most of the fleet would be replaced by electric drive and fuel cell vehicles. The NDC scenario already has an extra penetration of clean technologies due to the efforts that have been done between 2020 and 2030, and thus applying the transportation ban in such a scenario would yield a lower increase in cost compared to the current policy scenarios. Imposing the ban in a world where the mid-century strategies are implemented as in the case of MCS+FF55 scenario yields a lower increase in NPV of investments per passenger kilometer since the electrification of the LDV fleet in the MCS scenario is already at a higher level when compared to the other scenarios.

3.8 Emissions

The main goal of implementing mitigation policies is to reduce the greenhouse gas emissions on a regional and global scale. Hence, one of the main dimensions that is taken into account when assessing the value of a policy is the decrease in emissions that results from implementing it. In the case of the Fit-for-55 transportation policy, the main sector that is tackled is the transportation sector within Europe, but the influence of the policy would have a significant impact on the overall emissions due to the large contribution of the transportation sector to the total emissions. The four scenarios that do not include the Fit-for-55 policy present different emission reduction and temperature goals, and the speed at which the emissions are reduced is proportional to the mitigation efforts of the regions. The graph shown in Figure 38 presents the trend of CO2 emissions for the REF, NDC, MCS, and 15DEG2020 scenarios on a worldwide scale. The emission trajectory of the REF scenario represents how will the CO2 emissions evolve in an increasing trend worldwide in a scenario where current policies are adopted without any increased efforts to cut emissions and promote renewable technologies. The emissions would continue with an increasing trend to reach higher levels up to 43.12 GtonCO2 in the year 2055. The NDC and MCS scenarios witness a decreasing trend of CO2 emissions until the year 2035 where the MCS scenario decrease further compared to the NDC scenario due to the additional mitigation efforts that are accompanied within the mid-century strategies from major emitters such USA, China, and Europe. The decrease in emission trends in the NDC scenario resembles the convergence extrapolation that has been explained in chapter two to represent a World where regions cooperate to achieve emission reduction targets. The 15DEG2020 scenario is accompanied with a steep decrease in emissions that is necessary to achieve the 1.5°C temperature goal at the end of the century.

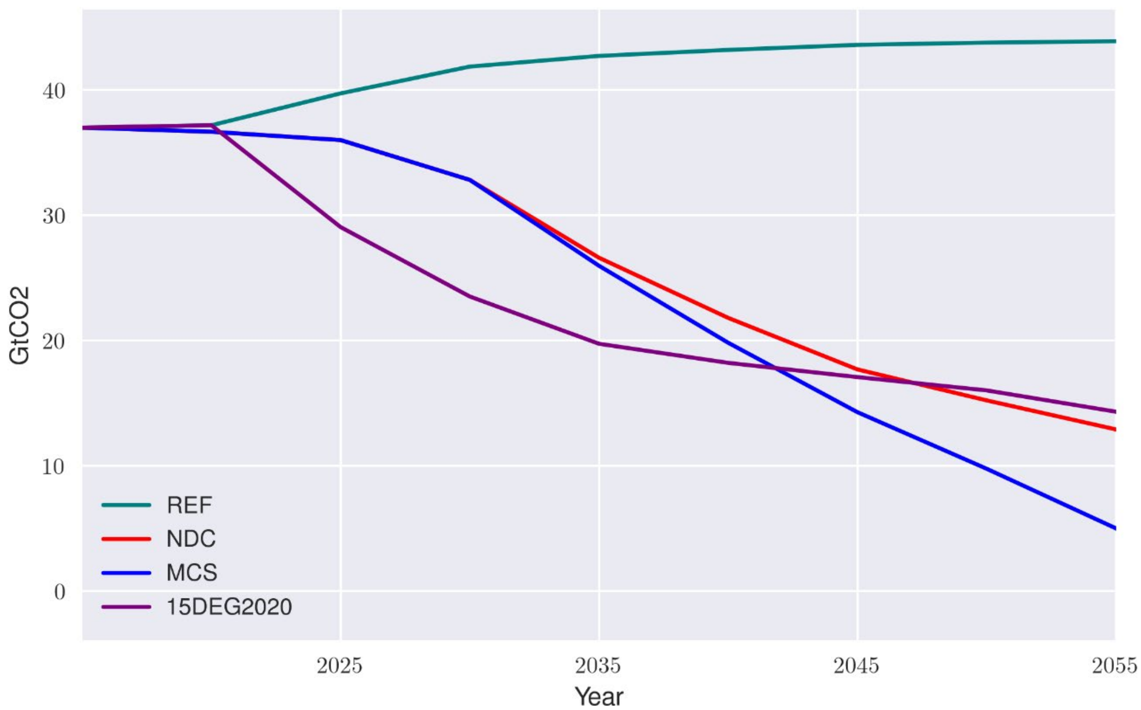

Figure 38: World CO2 Emissions

The reduction of CO2 emissions in essential to limit the harmful effects on the climate system in the future. Efforts to reduce emissions are agreed upon on a global level and regions would pledge to reduce their total emissions through implementing new policies. Europe is one of the major emitters on a global level due to its technological and economic prosperity, and therefore reducing the emissions in Europe has been a main goal in recent years. The Fit-for-55 policy package has a main target which is to reduce emissions by 55% by the year 2030, and the transportation policy that is being assessed within the following work is an essential part of this emission reduction plan. The emission trajectories from the World's transportation sector for the presented scenarios are shown in Figure 39. The trend of CO2 emissions in World is increasing for the REF and CURPOL+FF55 scenarios since the overall current policies include emission reduction targets that are not enough to decarbonize the road transport sector. The effect of the Fit-for-55 transportation policy on the reduction of total World transport emissions is more significant in the NDC+FF55 scenario since the efforts done in the NDCs are followed directly by the ban that helps in reducing the cost of batteries and electric cars caused by technology spillovers. A similar decrease is not observed in the CURPOL+FF55 and MCS+FF55 due to the high emissions from the remaining stock of vehicles in the first scenario and the already electrified fleet in the second case.

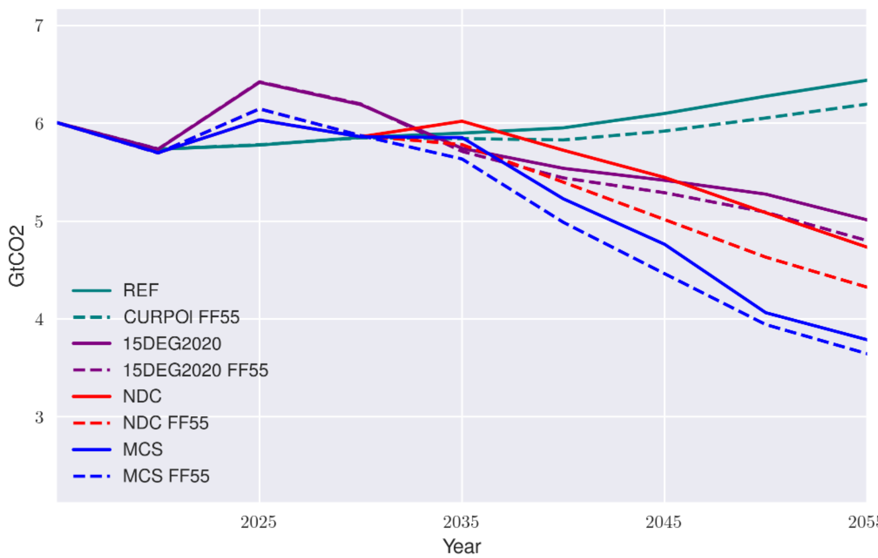

Figure 39: World Transportation Sector CO2 Emissions

The effect of the transportation policy can be seen more in depth when checking the CO2 emissions from the road transport sector. The CO2 emissions from the transport sector in Europe are shown in Figure 40.

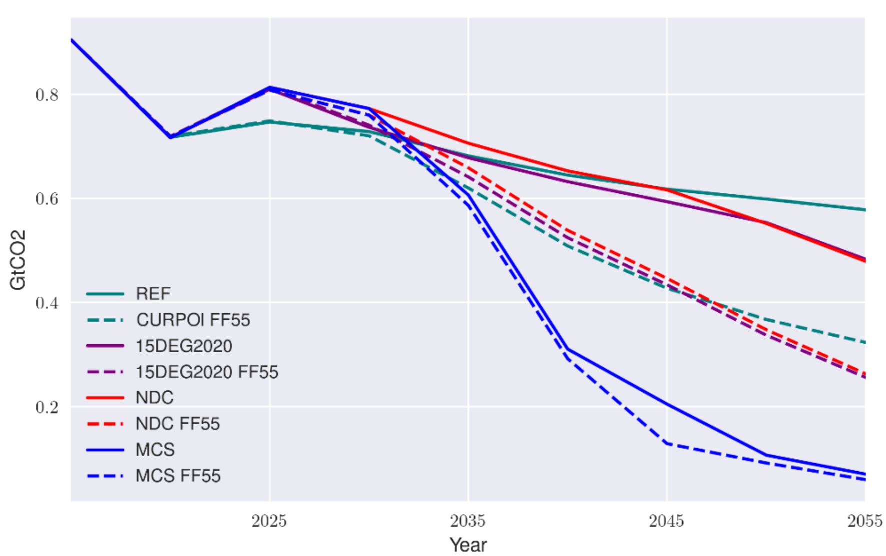

Figure 40: Transportation Sector CO2 Emissions in Europe

The effect of the Fit-for-55 transportation policy may be observed over all the scenarios where the emissions deviate starting the year 2025 to adopt a steeper decrease until the year 2055. The MCS scenario, which already has strict emission limits for Europe, is also improved by decreasing the CO2 emissions at a faster pace from 2040. The MCS+FF55 scenario achieves a level of emissions of 0.059 GtonCO2 by 2055, which represents a 93.3% from the 2015 level of CO2 emissions. To analyze the most suitable scenario to apply the Fit-for-55 transportation policy, it is useful to calculate the amount of investment made per unit of emissions saved. It is possible to calculate the ratio between the NPV of investments made in the transportation sector before and after implementing the Fit-for-55 policy within the same scenario over the difference in emissions to obtain the cost of mitigation of one ton of CO2. The results of the previous calculation are shown in Figure 41.

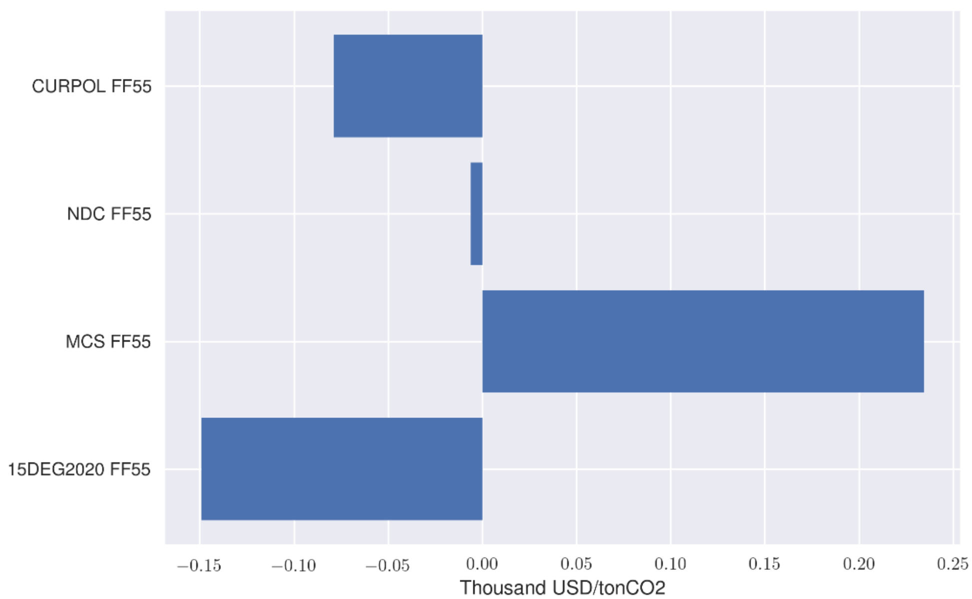

Figure 41: The Difference of NPV of the Investments in the Transportation Sector by the Difference in Emissions Before and After Applying the Fit-for-55 Transportation policy

The negative values indicate that the amount of money has been spent to reduce one ton of CO2, while a positive value represents a case where investments have been saved while reducing the total emissions. The only case where implementing the policy reduced the emissions while saving on the NPV on investments is the MCS+FF55 scenario. This can be attributed to the fact that the MCS scenario imposes strict constraints on the emissions in Europe by the year 2050, which encourages the electrification of the LDV fleet at later years, while in the MCS+FF55 scenario the electrification of the fleet starts at an earlier point in time. This leads to the rapid decrease in the cost of electric vehicles in the MCS+FF55 compared to the MCS scenario as shown in Figure 33.

The decrease in the cost of electric vehicles along with a lower demand after implementing the policy lead to lowering the total cost along with decreasing emissions. For the remaining three scenarios, the cost of reducing one ton of CO2 is the lowest in the NDC scenario at 0.01 thousand USD per ton of CO2 which is close to mitigating the emissions at no extra cost. The Fit-for-55 policy package is presented within the framework of achieving the net zero target of 2050 by Europe, and thus if the pledges are to be kept by Europe, the implementation of the transportation policy would be an added value to the overall emission mitigation plan.

The results that have been analyzed throughout this chapter highlight the impact of the Fit-for-55 transportation policy on the decrease of passenger travel demand and the fleet composition. The degree of which the policy affects demand is relative to the scenario at which the policy has been implemented under. In the MCS scenario, the intensive efforts that are already implemented make it financially more favorable to implement the policy since the net zero target already requires extensive electrification and phasing out fossil fuel technologies.

Europe's emission trajectory in the future is expected to experience a decrease even in the current applied policies. However, to limit the future damages to the climate system that would translate to economic and social losses it is crucial to reach net zero emissions by the middle of the current century. The Fit-for-55 is a complement to the mid-century strategy that Europe has set, and continuously updated, over the past years. Therefore, although implementing the Fit-for-55 transportation policy would lead to emission reduction in all of the proposed scenarios, it would be the most beneficial to implement the policy within a World where more climate mitigation efforts take place such as the MCS scenario.

Chapter Four

Sensitivity Analysis

In this chapter, a sensitivity analysis is performed on the critical parameters of the newly implemented functions that have been presented in chapter two. The implementation of the passenger travel demand and technology switch functions required assumptions for the elasticities that have been used from previous literature.

The price elasticity in the demand function is varied in this chapter to different values to assess the response of the total service demand when imposing a similar carbon tax. Another sensitivity analysis is performed for the technology switching elasticity that has an effect on the speed at which technologies penetrate the LDV fleet using constant and time-varying elasticities. This analysis has been done over scenarios with a similar carbon tax while varying the value of elasticity.

4.1 Transportation Price Elasticity

To assess the effect of the fluctuations in the price of transportation on the total travel service demand, it was required to implement a new demand function within the WITCH model's transportation module as presented in Equation 16. The demand that has been calculated is responsive to changes in the consumer's income and the price of the service. The extent to which the demand increases of decreases according to fluctuations in income of price depend on the chosen values of income and price elasticities. The price of transportation services is calculated endogenously by WITCH depending on the fuel and capital investment costs.

The analysis that has been performed in this research work adopts a price elasticity of -1.18, which translates to an inverse relationship between price and demand where an increase in price would lead to a decrease in demand. The price elasticity is assumed to be constant through the total period of optimization in WITCH.

A sensitivity analysis has been done by assuming different trends for the transportation price elasticity and analyzing the effects of this variation. To properly analyze the effect of the price increase on the demand, the comparison of total service demand has been done between a business as usual (BAU) scenario and an increasing carbon tax scenario with an initial tax of 50 USD/tonCO2. The price elasticity has been varied according to the scenarios shown in Table 7.

Table 7: Transportation Price Elasticity Values

Scenario	Transportation Price Elasticity
DEF	- 1.18
LOW	- 0.4
HIGH	- 1.6

The values presented in Table 7 represent different forms of the consumer's response to the change in price. The DEF scenario is the default case that has been used in WITCH for the analysis of this work with and elasticity of -1.17. The LOW scenario assumes that consumers would be concerned less about the price of the service as their demand for the service would not be hugely affected by its price. The HIGH scenario adopts the highest value of responsiveness to the fluctuations in price as the demand would be highly affected by the price variations.

The scenarios that have been performed for the purpose of the sensitivity analysis of the price elasticity compare the decrease in demand on a worldwide and regional level for the region of Europe between the years 2015 and 2100. The results of total service demand variation for a World scale are shown in Figure 42.

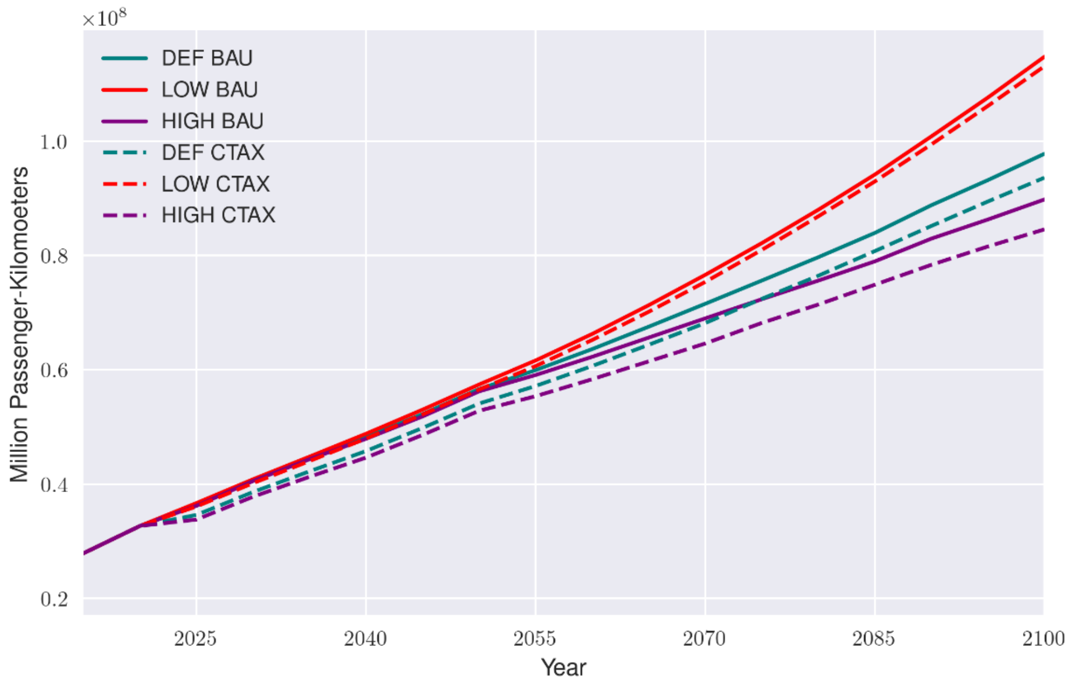

Figure 42: World Total Service Demand Sensitivity

The total service demand in the BAU scenario follows an increasing trend for the variations of the price elasticities with different slopes according to the value of the elasticity. The LOW scenario, which has an elasticity of -0.4, witnesses the highest increase in demand in the BAU scenario since the income growth is the dominant factor in driving the increase in demand since the income elasticity is 0.95. The trends in the other BAU scenarios are decreasing as the absolute value of the elasticity increases since the increase in the price of transportation would have a greater effect on the over time. The notable effect of decreasing the absolute value of the elasticity is the decrease in demand between the BAU and CTAX scenarios within the same elasticity scenarios. The total service demand in year 2100 for the LOW CTAX scenario is 1.45% less relative to the LOW BAU scenario. This gap in the case of the HIGH scenarios is extended to a 5.82% decrease between HIGH BAU and HIGH CTAX scenarios by the year 2100. The most significant drop in the total service demand occurs at the year 2025 which is the carbon tax start date. This is due to the large increase in the price of transportation services relative to the year 2020 which had no carbon tax in place.

The sensitivity analysis that has been conducted in Figure 42 shows the effect of varying the transportation service's price elasticity on the total World demand, and it is possible to observe deeper at a regional level to assess how will the total service demand respond to the variation of elasticity.

The graph shown in Figure 43 presents the difference in total service demand for a region that has been chosen as an example from WITCH, that is Eastern Europe, to observe the effect of varying the price elasticity in a manner similar to that presented in Table 7.

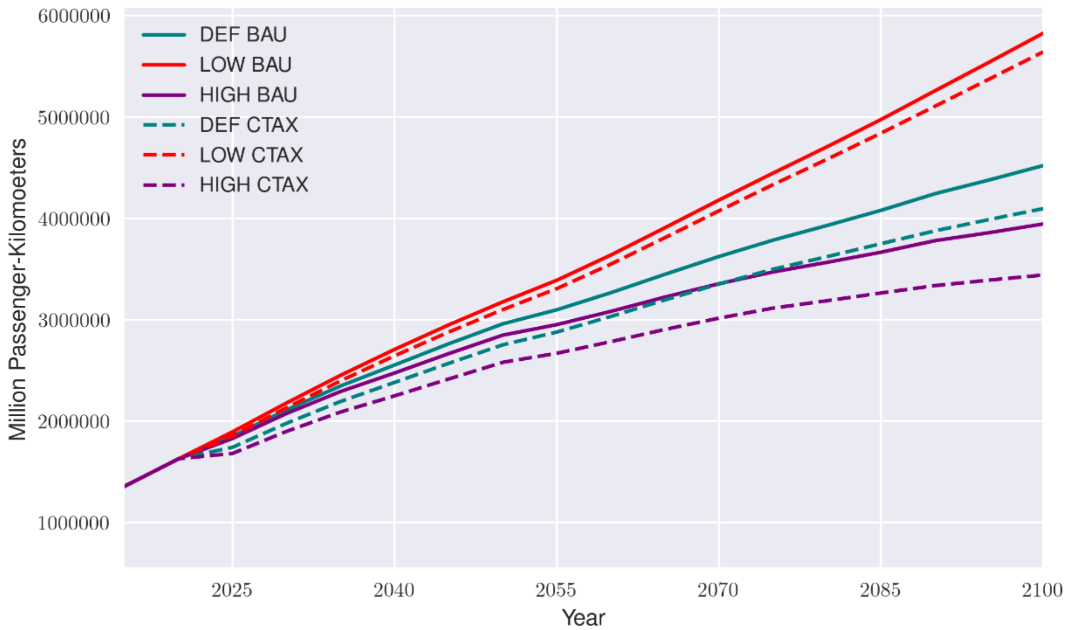

Figure 43: Eastern Europe Total Service Demand Sensitivity

The sensitivity analysis on a regional level shown in Figure 43 shows a similar behavior to that on the Worldwide level. The overall demand in the BAU scenarios strictly increases with the decrease in the absolute value of price elasticity, this due to the increase of the price of transportation over the years since in a BAU scenario the fleet is oil dependent while oil becomes mor expensive as the extraction increases over the years. The relative difference between the BAU and CTAX scenario total service demand increases with the increase of the absolute value of the price elasticity which is in-line with the overall trend that has been observed for the world in Figure 42. The price of a service is an essential factor for consumers to make their investment decision, and the elasticity value represents the importance of the service to the consumers and if they are willing to pay the additional amount of money to keep using the same service.

4.2 LDV Technology Switching Elasticity

One of the changes that has been done within the modeling of the transportation sector in WITCH is the introduction of a new function to account for the choice of vehicle technology additions. The original version of WITCH included a Leontief function that represented a linear competition between different types of LDV technologies and therefore lead to the adoption of a single type of vehicle in a certain region at a specific point in time. This phenomenon is very improbable in reality since there are several factors and preferences that alter the consumers' choice of purchasing a vehicle other than the cost of the car. The newly implemented CES function that is shown in Equation 22 helps in slowing the process of switching from one technology to another depending on the value of elasticity.

The elasticity that has been used in the analysis of this research work has a value of 10. The elasticity represents how much does the variation in price between different technologies affect the consumer's choice to switch to the cheaper one. A higher value of elasticity indicates that the consumer would switch to the cheaper option more frequently, and as the value of elasticity approaches infinity, the equation tends to behave as a linear competition. The value of this elasticity in reality depends on several factors that are linked to economic, social and behavioral sciences. Moreover, this elasticity might vary over time since the switching process between different technologies might be easier in the future than it is currently. Therefore, a sensitivity analysis has been performed by varying the elasticity values for an identical carbon tax scenario with an initial carbon tax of 50 USD/tonCO2. The elasticity has been varied to a constant value and time-varying values as shown in Table 8.

Table 8: Technology Switching Elasticity Sensitivity Values

Scenario	Technology Switching Elasticity
DEF	10
HIGH	15
LINEAR	Linear increase from 5 to 20
EXPO	Exponential decay upwards from 5 to 20

The HIGH scenario represents a world where switching between different technologies according to the price is more rapid, but it happens at a constant rate over time. The LINEAR and EXPO scenarios represent a World where the process of switching between technologies becomes easier in the future. However, the difference is that in the LINEAR scenario the increase in elasticity is uniform over time while in the EXPO scenario the switching elasticity increases rapidly in the earlier years until it slows down in the future to reach the final target value of elasticity. The impact of the performed sensitivity analysis on the World fleet composition is shown in Figure 44.

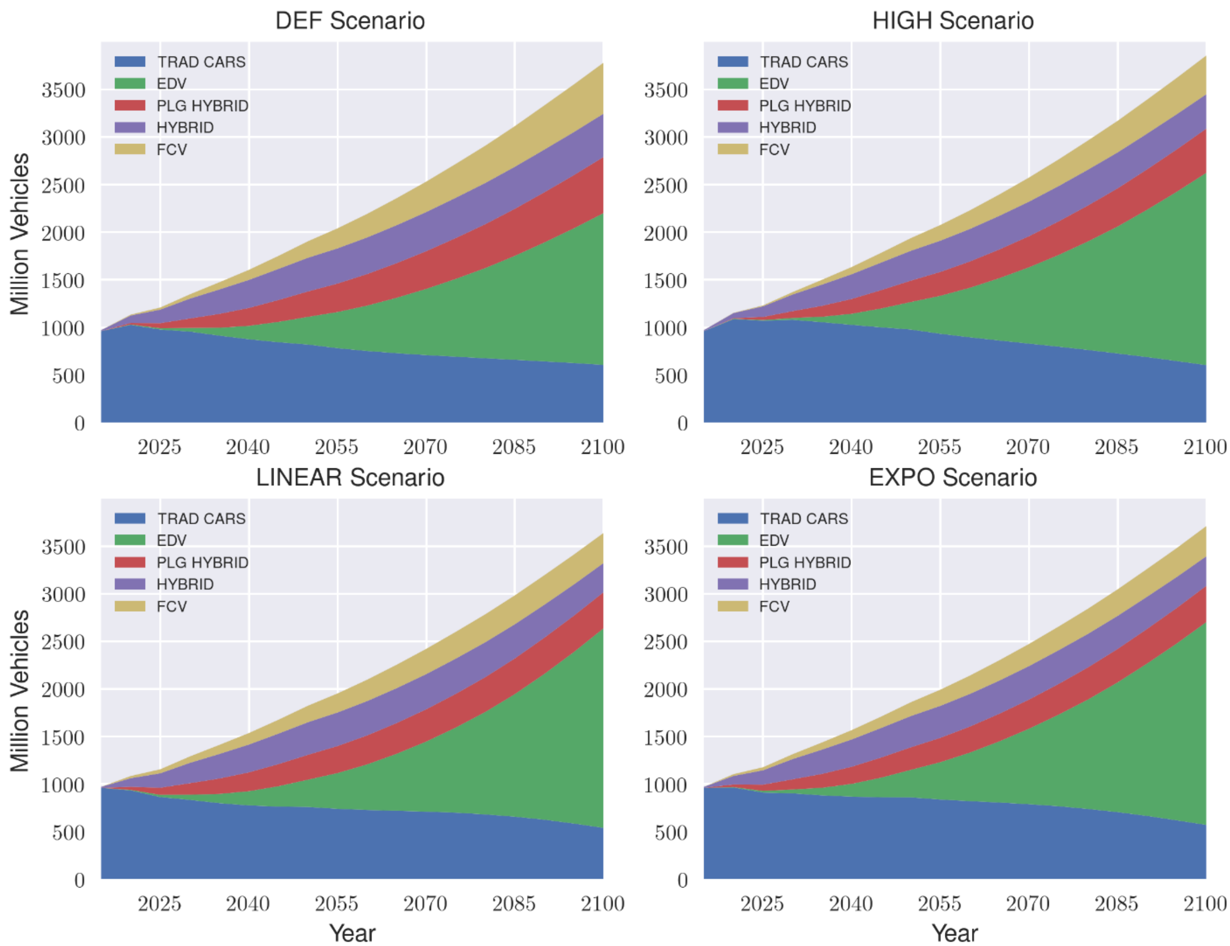

Figure 44: World Fleet Composition After the Sensitivity Analysis

The World fleet composition that has been presented in Figure 44 shows different trends of EDV penetration and TRAD CARS reduction across the four scenarios. The comparison between DEF and HIGH scenarios that both have a constant value for the elasticity reveals two main differences. The first is observed between the year 2025 and 2055 where the share of traditional cars is higher in those years for the HIGH scenario, and this is due to the higher switching elasticity which drives consumers to choose more traditional vehicles at the early years due to their cheaper price. The second trend is observed after the year 2055 where electric drive vehicles decrease in price while the tractional cars' price increases due to the increasing carbon tax to a point where it is cheaper to purchase an electric drive vehicle. After the year 2055, the electric vehicles penetrate the fleet more rapidly than the DEF scenario to achieve higher electrification by the year 2100.

The LINEAR and EXPO scenarios present a different approach to model the speed of technology switching when compared to DEF and HIGH. The LINEAR scenario has a lower elasticity in the early years, and therefore even though it is cheaper to drive a traditional vehicle, the other types of vehicles such as EDVs and HYBRIDs increase their share in the early years. As time increases, the penetration of electric drive vehicles increases since as the EDVs become cheaper, the ability to switch between technologies becomes easier. When comparing the LINEAR and EXPO scenarios to each other, the share of traditional vehicles decreases more rapidly in the early years for the LINEAR scenario since the elasticity growth is slower, but higher electrification is achieved in the year 2100 for the EXPO scenario which is due to the higher elasticity at the late years of the analysis where EDVs became cheaper. A similar analysis has been made on a regional level for Eastern Europe, and the results that were obtained are shown in Figure 45.

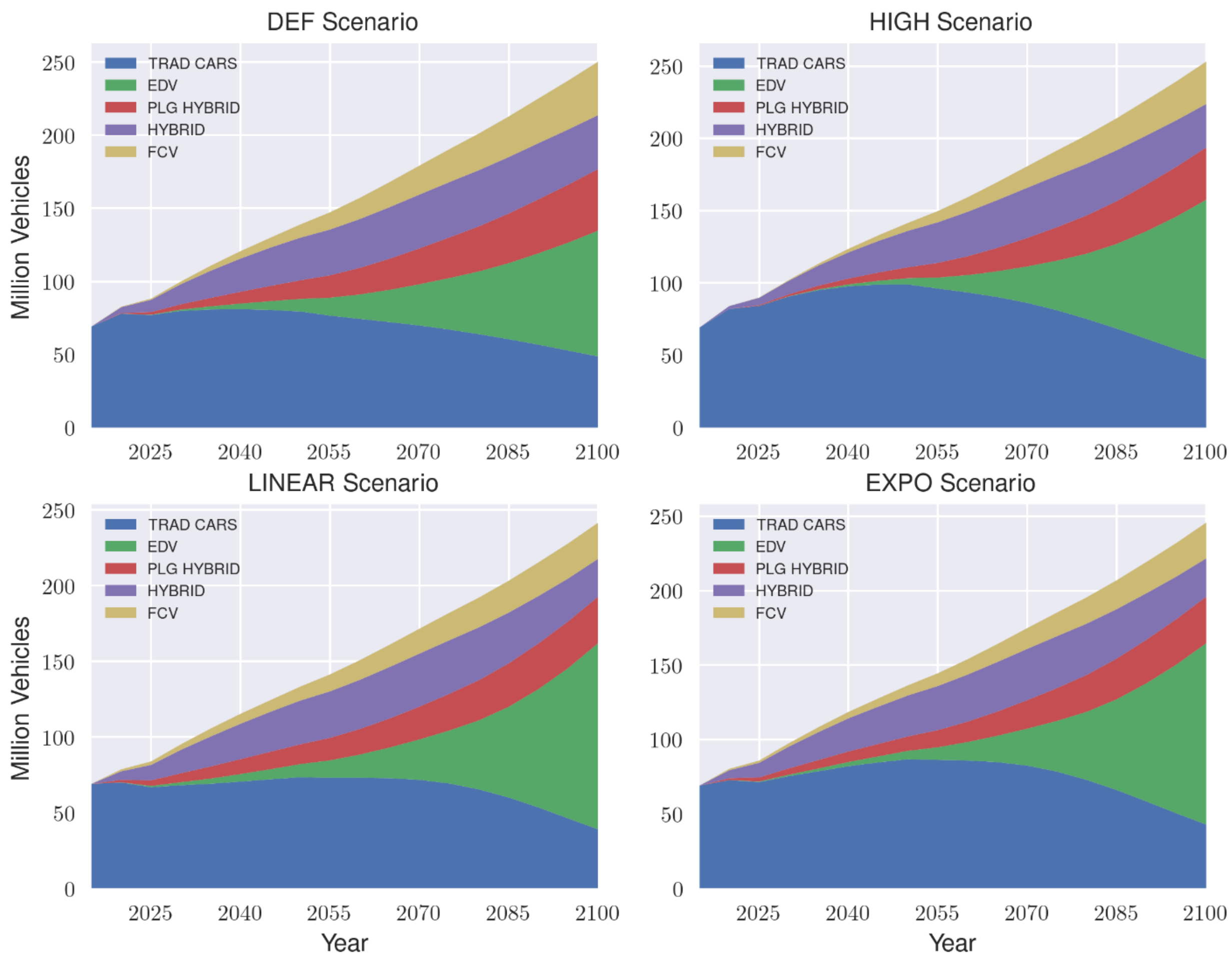

Figure 45: Easter Europe Fleet Composition After the Sensitivity Analysis

The comparison between the DEF and HIGH scenarios shown in Figure 45 shows a magnified picture of the phenomenon observed on a World scale. The traditional vehicles increase in number during the first period of tie between 2015 and 2050, which is due to the fact that traditional cars are cheaper than other technologies in this period and it is easier to switch vehicle technologies with higher elasticity. The trend is then reversed after 2050 as the electric drive vehicles increase rapidly to reach higher electrification at 2100. The LINEAR and EXPO scenarios show different degrees of increase of traditional vehicles in the early years since the elasticity increases at a faster pace in the EXPO scenario, while having a steeper decrease in traditional vehicles after the year 2050 for the EXPO scenario since electric vehicles are cheaper by that time.

The choice of elasticity has different effects in separate periods of time regarding the penetration of certain technology at the expense of another. The choice of a time varying elasticity allows a more flexible approach to modeling the switch between technologies according to future technology advancements or behavioral changes across different points in time. Another approach would be to vary the elasticity values according to the regional differences since the economic and social aspects would affect the ability to switch between one technology and another in certain cases.

Chapter Five

Conclusions

The research work that has been performed within this project served to assess the Fit-for-55 transportation policy in Europe. The policy indicates that a ban of the sales of new fossil fuel based light duty vehicles and vans would fully take place in the year 2035. Such a ban requires light duty vehicle manufacturers to adapt to the process of producing more efficient and environmentally friendly transportation technologies, that although present currently in the market, they still aren't competitive enough to replace traditional fossil fuel cars without any incentives.

The assessment of the policy took within the scope of an integrated assessment model that is the WITCH model. The transportation sector is modeled explicitly within WITCH as two separate modules that are passenger road transport and freight transportation. Passenger travel service demand is an exogenous parameter that depends on the GDP growth of each region, and thus assessing the impact of policies on the total service demand was not possible initially. The passenger road transport sector is modelled as light duty vehicle demand that is met by a supply of five different vehicle technologies that are traditional, electric, hybrid, plug-in hybrid, and fuel cell vehicles. To enable the assessment of policy impact on the total demand, changes have been implemented into the transportation module in WITCH. A new total service demand function that takes into account the impact of price fluctuations on the total passenger kilometer has been implemented in the model. The technology choice has been enhanced through implementing a CES function that replaced the previous Leontief function that modeled the technology choice as a linear competition where one type of vehicle was deployed in a certain region at every timestep as it is the cheapest option. The newly implemented technology choice function allowed limiting the total number of vehicles from the same technology that are being added each year which resembles real-life behavior.

After performing the changes that allow the assessment of the Fit-for-55 policy, eight different scenarios were implemented in WITCH each resembling a different degree of climate efforts on a worldwide scale, and for each scenario the Fit-for-55 policy has been implemented in order to compare the results against a REF scenario where current policies are the limit of climate efforts, and the Fit-for-55 policy is not implemented. Scenarios with similar climate efforts have been compared against their respective scenarios that differ only with implementing the transportation policy.

The analysis that has been implemented through this work concluded that implementing the Fit-for-55 transportation policy in a scenario that implements the mid-century strategies to achieve net zero targets by 2050 is the most efficient option. This process minimizes the cost of implementation of the policy while decreasing the total amount of CO2 emissions from the transportation period through the period of investigation that extended from 2015 until 2055.

The decarbonization of the road transport sector is essential to achieve the emission targets that would limit the future warming by the end of the century that would inflict social and economic damage on current and future generations. Discounting the importance of future generations when compared to the current living one drives an ethical debate that has been discussed within scientific and political communities, but Europe would be taking action to limit the harmful effects that future generations would suffer by implementing Fit-for-55 transportation policy which forces the ban of fossil fuel vehicles. Banning the new sale of fossil fuel-based vehicles as early as 2035 is an ambitious plan that, if implemented as planned, would reshape the passenger road transportation sector in Europe in the near future.

5.1 Limitations and Future Work

The main assessment that has been performed in this work was performed using the WITCH integrated assessment model. Although IAMs provide a reliable mathematical approach to modeling real-world problems, there still exist some limitations and a room for improvement. One of the gaps in the modeling of road transportation in WITCH is the lack of multiple modes of transportation such as busses, trains, and bikes. This limits the ability to fully represent the transportation sector in several regions that have a well-developed public transportation sector such Europe. This creates a substitutability between the two different types of road transport that are private and public transportation. The cost and impact distributions of policies would be assessed in a more detailed way as the model would represent a more realistic version of the passenger road transportation.

The choice of light duty vehicle technology in WITCH currently depends on the cost of driving the respective vehicle. Therefore, cheaper modes of transportation are more favored by the model and are selected as the consumers' choice. However, this is not always the case in real-life situations. Humans don't always have full information to take the best economically reasonable decision, and even if they do, behavioral differences and personal preferences play a role in the final choice of consumers. Consumer heterogeneity in not currently modelled in the transportation sector in WITCH, and this makes it less representative of real-life situations.

Bibliography

[1] Protocol, K. (1997). United Nations framework convention on climate change. *Kyoto Protocol, Kyoto*, *19*(8). [2] IPCC: Climate Change 2021 PDF.

[3] Tol, R. S. (2020). The economic impacts of climate change. Review of Environmental Economics and Policy.

[4] Nicholls, R. J., Wong, P. P., Burkett, V., Codignotto, J., Hay, J., McLean, R., ... & Saito, Y. (2007). Coastal systems and low-lying areas.

[5] Desanker, P. V., & Justice, C. O. (2001). Africa and global climate change: critical issues and suggestions for further research and integrated assessment modeling. Climate Research, 17(2), 93-103.

[6] The Paris Agreement. unfccc.int. (n.d.). Retrieved September 15, 2021, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[7] Deane, P. M., & Deane, P. M. (1979). The first industrial revolution. Cambridge University Press.

[8] Climate change: Atmospheric Carbon Dioxide: NOAA Climate.gov. Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov. (2020, August 14). Retrieved September 20, 2021, from https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide.

[9] *Ar5 climate change 2014: Mitigation of climate change*. IPCC. (n.d.). Retrieved November 2, 2021, from https://www.ipcc.ch/report/ar5/wg3/.

[10] https://www.feem.it/en/publications/feem-working-papers-note-di-lavoro-series/a-simple-formula-for-the-social-cost-of-carbon/

[11] Jafino, B. A., Kwakkel, J. H., & Taebi, B. (2021). Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. Wiley Interdisciplinary Reviews: Climate Change, e721.

[12] Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. Ecology letters, 15(4), 365-377.

[13] https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-forests_.html

[14] Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 333-363, doi: 10.7930/J0VM49F2.

[15] US Department of Commerce, N. O. and A. A. (2015, March 3). How does climate change affect coral reefs? NOAA's National Ocean Service. Retrieved October 11, 2021, from https://oceanservice.noaa.gov/facts/coralreef-climate.html.

[16] The state of the world's forests 2020. www.fao.org. (n.d.). Retrieved October 11, 2021, from https://www.fao.org/state-of-forests/en/.

[17] Burke, M., Hsiang, S. M., & Miguel, E. (2015). Climate and conflict. Annu. Rev. Econ., 7(1), 577-617.

[18] Paris agreement. Climate Action. (n.d.). Retrieved November 1, 2021, from https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en.

[19] Pahl, S., Sheppard, S., Boomsma, C., & Groves, C. (2014). Perceptions of time in relation to climate change. Wiley Interdisciplinary Reviews: Climate Change, 5(3), 375-388.

[20] Weisbach, D., & Sunstein, C. R. (2008). Climate change and discounting the future: a guide for the perplexed. Yale L. & Pol'y Rev., 27, 433.

[21] Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. Environmental Chemistry Letters, 1-26.

[22] European Green deal. Climate Action. (n.d.). Retrieved October 17, 2021, from https://ec.europa.eu/clima/eu-action/european-green-deal_en.

[23] Supporting climate action through the EU budget. Climate Action. (n.d.). Retrieved October 17, 2021, from https://ec.europa.eu/clima/eu-action/funding-climate-action/supporting-climate-action-through-eu-budget_en.

[24] Lamontagne, J. R., Reed, P. M., Marangoni, G., Keller, K., & Garner, G. G. (2019). Robust abatement pathways to tolerable climate futures require immediate global action. Nature Climate Change, 9(4), 290-294.

[25] Transport - Freight Transport - OECD data. theOECD. (n.d.). Retrieved October 17, 2021, from https://data.oecd.org/transport/freight-transport.htm#indicator-chart.

[26] Pereira, L. (2020, March 10). Trans-European Transport Network (TEN-T). Mobility and Transport - European Commission. Retrieved October 17, 2021, from https://ec.europa.eu/transport/themes/infrastructure/ten-t_en.

[27] Danielis, R., Scorrano, M., & Giansoldati, M. (2021). Decarbonising transport in Europe: Trends, goals, policies and passenger car scenarios. Research in Transportation Economics, 101068.

[28] Pollet, B. G., Staffell, I., & Shang, J. L. (2012). Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. Electrochimica Acta, 84, 235-249.

[29] IEA. (2021, October 28). *Transport – topics*. IEA. Retrieved November 2, 2021, from https://www.iea.org/topics/transport.

[30] Greenhouse gas emissions from transport in Europe. European Environment Agency. (2021, May 11). Retrieved October 21, 2021, from https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12.

[31] Transport. European Commission - European Commission. (2019, December 10). Retrieved October 22, 2021, from https://ec.europa.eu/info/policies/transport_en.

[32] Fit for 55. Consilium. (2021, October 11). Retrieved October 23, 2021, from https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/#.

[33] Wang, Z., Wu, J., Liu, C., & Gu, G. (2017). Integrated assessment models of climate change economics. Springer Singapore.

[34] Asefi-Najafabady, S., Villegas-Ortiz, L., & Morgan, J. (2020). The failure of Integrated Assessment Models as a response to 'climate emergency'and ecological breakdown: the Emperor has no clothes. Globalizations, 1-11.

[35] McCollum, D. L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., ... & Fujisawa, S. (2017). Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. Transportation Research Part D: Transport and Environment, 55, 322-342.

[36] Documentation. The WITCH model. (n.d.). Retrieved October 25, 2021, from https://www.witchmodel.org/documentation/.

[37] Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., & Tavoni, M. (2006). ?? WITCH: A World Induced Technical Change Hybrid Model. ? The Energy Journal, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

[38] Model. The WITCH model. (n.d.). Retrieved October 25, 2021, from https://www.witchmodel.org/model/.

[39] US: Vehicle definitions. Transport Policy. (n.d.). Retrieved October 27, 2021, from https://www.transportpolicy.net/standard/us-vehicle-definitions/.

[40] GCAM v5.4 documentation: Demand For Energy. (n.d.). Retrieved October 29, 2021, from http://jgcri.github.io/gcam-doc/demand_energy.html#transportation-service-demand.

[41] Levelized cost calculations. Levelized Cost Calculations | Transparent Cost Database. (n.d.). Retrieved October 29, 2021, from https://openei.org/apps/TCDB/levelized_cost_calculations.html.

[42] Baptista, P., Melo, S., & Rolim, C. (2014). Energy, environmental and mobility impacts of car-sharing systems. Empirical results from Lisbon, Portugal. Procedia-Social and Behavioral Sciences, 111, 28-37.

[43] Rottoli, M., Dirnaichner, A., Kyle, P., Baumstark, L., Pietzcker, R., & Luderer, G. (2021). Coupling a Detailed Transport Model to the Integrated Assessment Model REMIND. Environmental Modeling & Assessment, 1-19.

[44] Mathieu, L. (2019). Electric surge: Carmakers' electric car plans across Europe 2019–2025. *European Federation for Transport and Environment AISBL.*

[45] *Electric vehicles*. IRENA International Renewable Energy Agency. (n.d.). Retrieved November 12, 2021, from https://www.irena.org/costs/Charts/Electric-vehicles.