**POLITECNICO DI MILANO**
**Master of Science in Energy Engineering**
**Department of Energy**
**School of Industrial and Information Engineering**

# Modeling Hydrogen & Fuel cell in Transportation & Energy Sectors through Different Climate Change Policies

in collaboration with
RFF-CMCC European Institute on Economics & the Environment

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# Abstract

The major challenge facing the energy and transport system is the reduction of its fossil fuel consumption and carbon footprint.The share of electricity in all of the energy consumed by end users worldwide would need to increase to 40 % in 2050 (from about half that amount in 2015) to achieve the decarbonised energy world envisaged by the Paris agreement. This requires a shift in the way we produce and consume energy. In recent years, hydrogen was considered as a silver bullet to help tackling these issue, however, it needs a plethora of projections,analyses and discussions. The main focus of the present work is to model hydrogen and fuel cell to be used in fuel cell vehicles and energy storage systems. This modeling includes costs related to production, transmission and distribution as well as refueling station costs for hydrogen along with modeling transportation sector and different types of vehicles and freights as competitors. WITCH is used as the core Integrated Assessment Model (IAM) for the mentioned modeling process & Codes are written in GAMS.

Fuel cell vehicles show an exciting future and solution for a sustainable transportation sector and hydrogen itself seems to play a vital role in decent pathways for decarbonization the energy system. However, there are numerous obstacles and barriers which has to be considered as well. The deployment of new energy and transport technologies will be hampered by their higher cost and technical shortcomings (eg range for battery cars, temperature sensitivity for fuel cell cars, volatility of the electricity produced by renewable energy sources). Therefore, future cost reductions and developments are of paramount importance.

**Keywords**: Integrated Assessment Models(IAM);WITCH, Hydrogen Economy, Fuel Cell, Storage, Transportation, Energy Sector, Energy Modeling, Renewable Energy Sources

# Executive Summary

**Framework** Today's energy and transport system, which is based mainly on fossil energy carriers, can in no way be evaluated as sustainable. Given the continued growth in the world's population as well as the progressive industrialisation of developing nations, particularly in Asia but also in South America, the global demand for energy is expected to continue to escalate in the coming decades – by more than 50% until 2030, according to the International Energy Agency (IEA) – with fossil fuels continuing to dominate global energy use. At the same time, there is a growing global consensus that greenhouse gas (GHG) emissions, which keep rising, need to be managed. Hence, security of supply and climate change represent two major concerns about the future of the energy sector which give rise to the challenge of finding the best way to rein in emissions while also providing the energy required to sustain economies. Concerns over energy supply security, climate change as well as local air pollution and the increasing prices of energy services are having a growing impact on policy making throughout the world. The transport sector today accounts for some 18% of primary energy use and some 17% of global CO2 emissions, with the vast majority of emissions coming from road transport. Transport is also responsible for 20% of the projected increase in both global energy demand and greenhouse gas emissions until 2030. At present, oil is still the largest primary fuel with a share of more than one third in the global primary energy mix and more than 95% of transport energy demand. Any oil supply disruptions would therefore hit the transport sector hardest since, worldwide, it is almost entirely dependent on oil. Moreover, there is a high geographical concentration of oil as well as a growing import dependency on a few, often politically unstable countries (at least from the Western world's point of view). Mounting anxiety about the economic and geopolitical implications of possible shortages in the supply of oil as a pillar of our globalised world based on transportation and the need to reduce greenhouse gas emissions in the transport sector are triggering the search for alternative fuels. In this project the opportunities as well as shortcomings of hydrogen as an alternative fuel is discussed.

**Methodology** The tool we used in our research is the World Induced Technical Change Hybrid(WITCH) model, which is a dynamic optimization Integrated Assessment Model (IAM) designed to investigate climate change mitigation and adaptation policies and developed by Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC). IAMs power lies in their ability to schematize complex dynamics, such as the relationship between climate, energy and economy, allowing to derive a simple interpretation of multiple interdependent phenomena. WITCH, in particular, is a regionally dis-aggregated hybrid global model with top-down, simplified representation of the global economy and a bottom-up, detailed energy input component. The energy sector is particularly developed and hard-linked with economy, so energy investments and resources are chosen optimally considering trends of macroeconomic variables and policy-induced economical stimuli. One of the major challenges encountered during our work concerned the lack of data in literature about key aspects of our formulation. In particular, we found considerable difficulties in assessing the projected future cost decrease of technologies and their overall potential in the different regions of the world. During the research, we retrieved the most recent data, focusing on the latest technical publications, and when data were missing we made our own assumptions, always verifying their technical consistence and coherence. Another difficult task, frequent in Integrated Assessment modeling, consisted in determining an acceptable trade-off between technical details and simplified representations fitting to the aggregated structure of the model. Literature review, designing the equations, translation of equations into GAMS language, finding relevant data and assumptions, running the model over different scenarios as well as sensitivity analysis are respectively the main steps in doing the project.

**Structure** Considering the chapters division, the work is structured as follows. In **Chapter 1**, the general framework, motivation behind the project, methodology and main questions are discussed. **Chapter 2**, summarizes a quick review on the IAMs and especially WITCH model which is the core tool. Main attributes of hydrogen as well as its applications, production methods and transmission means are explained in the **Chapter 3**. **Chapter 4** is related to changes and improvements in the modules. Curtailment, hydrogen and transportation (both light vehicles and freight trucks) modules are the main modules which introduced or modified in the project. **Chapter 5** starts with defining different scenarios, and continues with the results obtained in various parts of model under already defined scenarios. Robustness analyses on different uncertain assumptions and values is an essential part of the project. Sensitivities on costs of production, fuel cells, and hydrogen infrastructure as well as fuel efficiency, growth constraint, regional discount and switching on/off the hydrogen are argued in **Chapter 6**. The last part, **Chapter 7** is dedicated to the conclusion of outcomes of project and more futures possible improvements.

#### Main results

- **Existing momentum of traditional fleet.** In all scenarios, no matter what is the policy, still traditional vehicles and trucks will be leading the near-future.
- **Regulations currently limit the development of a clean hydrogen industry.** Government and industry must work together to ensure existing regulations are not an unnecessary barrier to investment. No carbon tax means no room for justifying fuel cell vehicles.
- **Fuel cell vehicles do not require insane carbon tax.** There is no chance for hydrogen technology in transportation to grow without climate change policies, however, putting some rational taxation on carbon is enough for hydrogen-using vehicles to grow. The more strict and harsh policies favors electric-drive vehicles way more than fuel cell vehicles.
- **Hydrogen helps regions which are harder to de-carbonize.** Results show hydrogen as a favorable technology and solution for some regions which are less likely to shift toward a green sustainable transportation fleet such as China, Mena, Russia and India.
- **Producing hydrogen from low-carbon energy is costly at the moment.** Producing hydrogen by electrolysers are expensive right now. Main method of today's hydrogen production is by using natural gas. In that case carbon capture is vital. In both cases, investments in R& D is necessary to decrease the cost of production.

- **The development of hydrogen infrastructure is slow and holding back widespread adoption.** Hydrogen prices for consumers are highly dependent on how many refueling stations there are, how often they are used and how much hydrogen is delivered per day. Tackling this is likely to require planning and coordination that brings together national and local governments, industry and investors.

- **Regional price index benefits fuel cell vehicles.** The main disadvantage of green-fuel vehicles is the higher cost than traditional cars. By considering lower car price index for different regions, average difference between the costs of different technologies declines and this fact benefits green-fuel vehicles such as hydrogen vehicles.

Figure 1 shows the improvement and different results on number of light vehicles in the transportation fleet step by step. Starting from the default results obtained before the project, continuing with outcomes after the modifications with switching off and on the hydrogen and lastly, by enabling regional discount for regions.

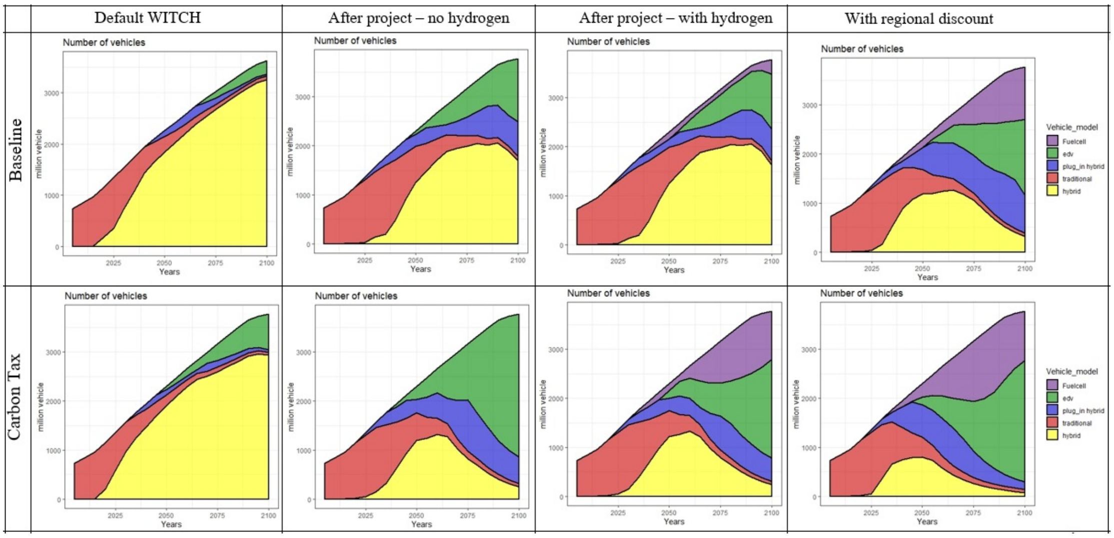

Figure (1) Summary of improvement evolution- results on fuel cell vehicles

Figure 2 shows fuel cell vehicles, fuel cell trucks and total hydrogen demand/production (respectively from left to right) for year 2100. Without any carbon tax, there is no room for fuel cell vehicles, so their total number and share stays low. Also for freight trucks, as we put more strict policies on carbon tax total number of fuel cell trucks grows. However, in both cases, there is an optimal initial carbon tax value for implementing hydrogen. For FCVs ctax50 and for FCV_stfr ctax30 shows the maximum usage of hydrogen, and all in all ctax30 indicates the highest amount of hydrogen demand/production.

Figure (2) Hydrogen usage over different climate policies

Figure 3 directly indicates the amount of hydrogen production which is needed to meet climate change goals at end of the century. By using stringent policies amount of total emissions and therefore, temperature increment would be lower. Graph on the left shows that more hydrogen is needed as we want to reach climate goals ranging from $3.7°C$ to around $2°C$. To achieve more ambitious goals below $2°C$ in 2100, hydrogen demand will not keep rising and fluctuates over different scenarios.

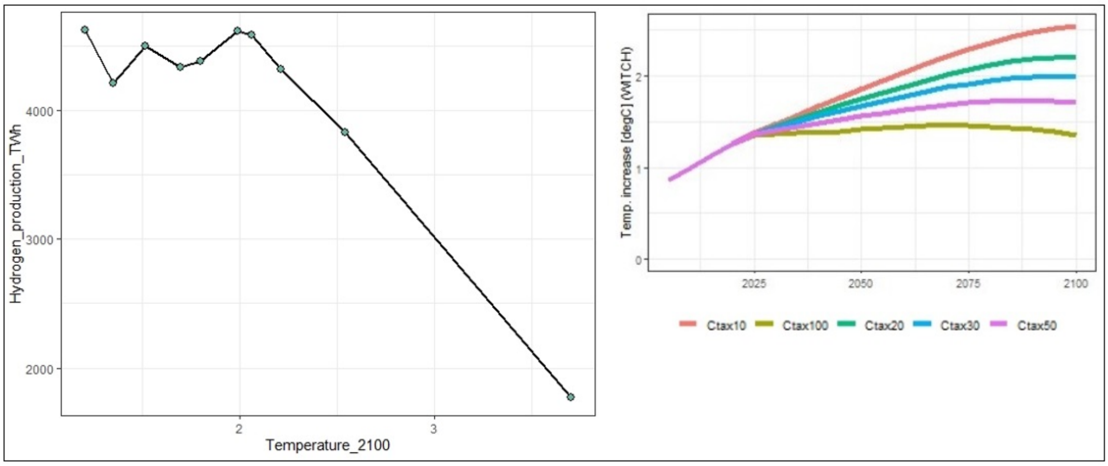

Figure (3) Temperature increase and hydrogen production

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# Acronyms

**BAU** Business As Usual

**BEV** Battery Electric Vehicle

**CCS** Carbon Capture and Storage

**CTax** Carbon Tax

**DRI** Direct Reduced Iron

**EDV** Electric Drive Vehicle

**Elecz** Electrolyzer

**FCV** Fuel Cell Vehicle

**GAMS** General Algebraic Modeling System

**GDP** Gross Domestic Product

**HBD** Hybrid

**IAM** Integrated Assessment Model

**ICE** Internal Combustion Engine

**LbD** Learning-by-doing

**LbR** Learning-by-research

**LiB** Lithium Battery

**OM** Operation and Maintenance

**PC** Per Capita

**PHES** Pumped Hydroelectric Energy Storage

**PHEV** Plug-in Hybrid Electric Vehicle

**RD** Research and development

**RES** Renewable Energy Source

**SGR** Steam Gas Reform

**STFR** Standard Truck Freight

**WITCH** World Induced Technical Change Hybrid

# Chapter 1

# Introduction & Motivation

## 1.1 Climate Change Framework

There has been a marked acceleration in global warming since the mid-20th century with an average temperature increase of 1C between 1961 and 2016 (measures against the pre-industrial period which serves as a reference). The effects are clearly visible, one of the most remarkable being the sea level rise as the thermal expansion of water due to this increased warming causes this water to take up more and more of the ocean's surface. The melting of the ice caps also contributes to this sea level rise, and the gradual retreat of the summer Arctic sea ice is a further indication of global warming.

Our energy system is based on solar energy. The Earth absorbs heat and emits thermal radiation into the atmosphere. Half of solar radiation is captured by the surface of the Earth. Surface temperature therefore increases and produces heat radiation, of which 90% is absorbed into the atmosphere.

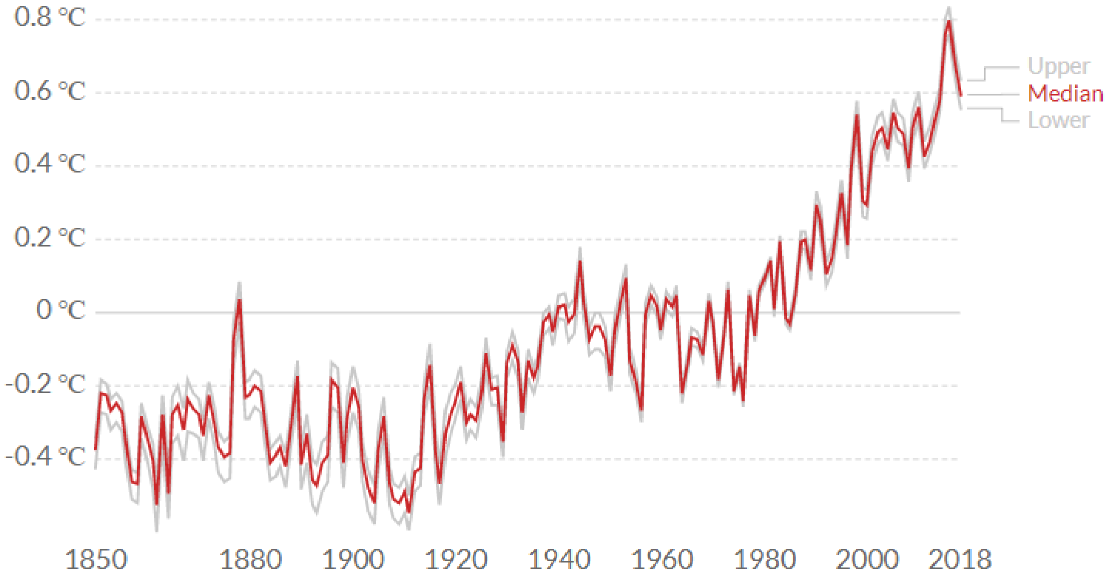


Figure (1.1) Average global temperature anomaly

The Intergovernmental Panel on Climate Change (IPCC) reports that an increasing temperatures may cause irreversible damages in terms of rising sea level, extreme weather events, loss of biodiversity and ocean acidification. These will affect the entire Earth ecosystem and all people around the globe to different extent, being likely to trigger migration movements and conflicts for water and land use in the future, with negative impacts on national economies. In order to avoid the adverse impacts due to anthropogenic emissions, there are two approaches: mitigation and adaptation. The former one refers to actions that decrease the scale of climate changes, either reducing GHG emissions or enhancing the climate system's capacity to absorb such gases, while the latter one requires modifying habits to minimize impact on people and economies.

### 1.1.1 The challenge for road transport

The transport sector today accounts for some 18% of primary energy use and some 17% of global CO2 emissions, with the vast majority of emissions coming from road transport. Transport is also responsible for 20% of the projected increase in both global energy demand and greenhouse gas emissions until 2030. At present, oil is still the largest primary fuel with a share of more than one third in the global primary energy mix and more than 95% of transport energy demand. Any oil supply disruptions would therefore hit the transport sector hardest since, worldwide, it is almost entirely dependent on oil. Moreover, there is a high geographical concentration of oil as well as a growing import dependency on a few, often politically unstable countries (at least from the Western world's point of view). Mounting anxiety about the economic and geopolitical implications of possible shortages in the supply of oil as a pillar of our globalised world based on transportation and the need to reduce greenhouse gas emissions in the transport sector are triggering the search for alternative fuels.

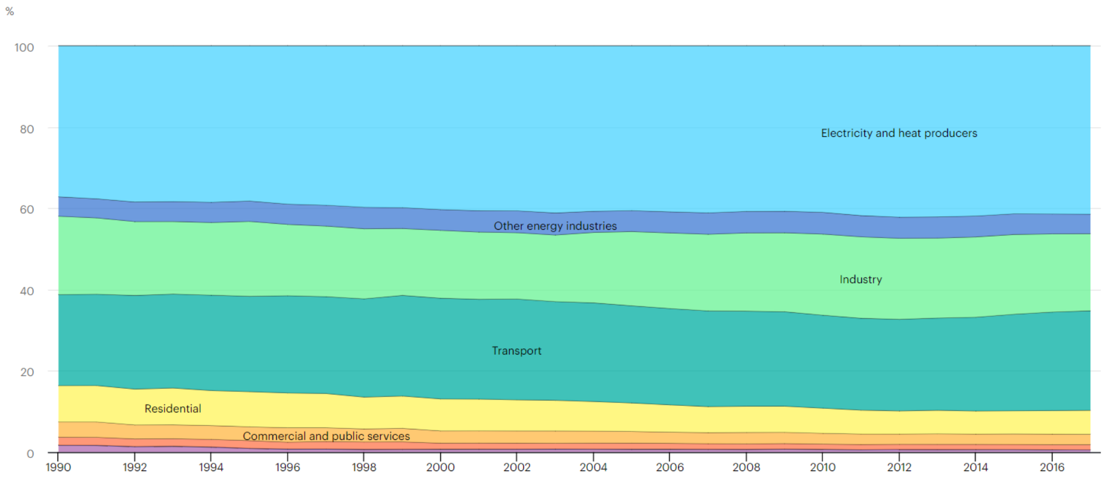


Figure (1.2) CO2 emissions by sector, World 1990-2017

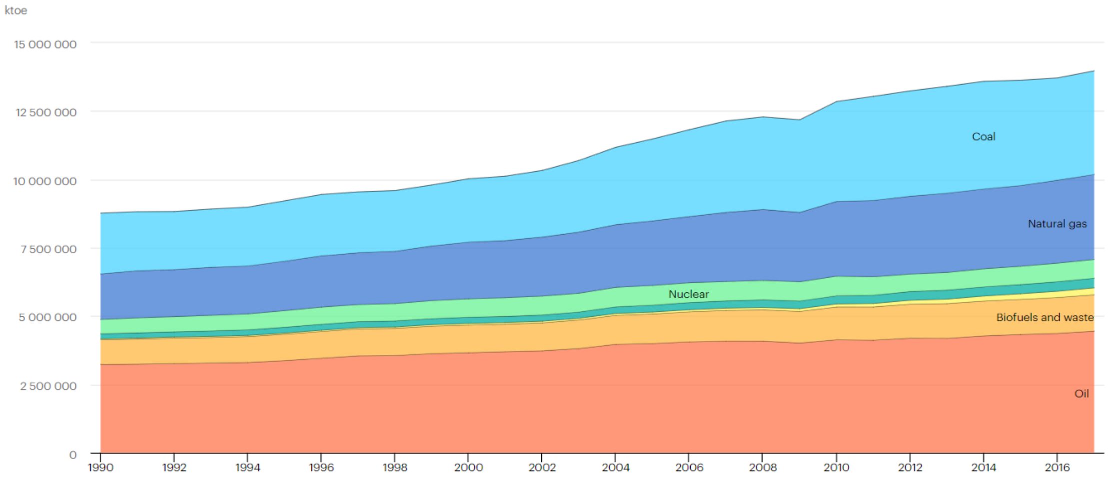


Figure (1.3) Total primary energy supply (TPES) by source, World 1990-2017

Transport systems perform vital societal functions, but in their present state cannot be considered 'sustainable'. Particular concerns in this respect include local air pollution (particulate matter, ozone), climate change, congestion, land use, accidents, and noise. Local air pollution, especially from road transport, is quickly becoming a major issue for urban air quality, particularly in the world's growing megacities. At a global level, greenhouse gas emissions from the transport sector and from fuel production represent another major problem and are increasingly subject to regulation around the world. Since the 1970s, GHG emissions from the transport sector have grown by more than 120% worldwide, and most scenarios predict that this trend will continue in the future. The increasing global demand for fuel is one of the main reasons for the rise in greenhouse gas emissions. Emissions of CO2, the main greenhouse gas from human activities, are the subject of a worldwide debate about energy sustainability and the stability of the global climate. Evidence that human activities are causing the planet to warm up is now unequivocal according to the Intergovernmental Panel on Climate Change (IPCC). To meet stringent climate change targets, such as stabilising CO2 concentrations below 550 ppm, or limiting the global temperature rise to 2 C above pre-industrial levels requires drastic CO2 reductions of 60–80% in 2050 compared to 1990 emissions, which is a daunting challenge. This will require a portfolio of technologies and mitigation activities across all sectors such as improving energy efficiency, carbon capture and storage (CCS) and the use of renewable energies or nuclear power. Deep emissions' cuts will also be required in the transport sector. Implementing CO2 emissions reduction measures in the transport sector is often accompanied by the co-benefits of reducing traffic congestion and/or improving air quality. [12]

## 1.2 Research Questions & Methodology

### 1.2.1 Main Questions

The focal point of this project is on hydrogen and fuel cell, their inevitable expenses, advantages & disadvantages. the research questions that are going to be addressed with this work are the following ones:

- What is the role of Hydrogen in future transportation and storage of energy systems?
- What are the opportunities as well as shortcomings of implementing and developing Hydrogen, fuel cell & electrolyzers?
- Which pathways should be paved by transportation sector and how is the share of vehicles in order to achieve climate change goals?
- What is the influence of technological improvements on using hydrogen deployment over time?

- What are the options for production & distribution of Hydrogen? Observing the effects of these infrastructural costs on future of Hydrogen economy.

### 1.2.2 Methodology

The tool that is used in this research is the World Induced Technical Change Hybrid(WITCH) model, which is an optimization Integrated Assessment Model (IAM) designed to investigate climate change mitigation and adaptation policies and developed by Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC). IAMs power relies on their ability to capture complex dynamics, such as the relationship between climate, energy and economy, allowing to derive a simple interpretation of multiple interdependent phenomena. To achieve this, a high grade of simplification and aggregation is needed.

One of the biggest issues was finding reliable data. Uncertainty is an inextricable part of any integrated assessment model, so even the most precise modelings and projections demand a certain amount of assumptions for future.

Here is the steps & structure of carrying this project out:

1. Literature Review. collecting information on both technical and economic specifications for Transportation,Hydrogen,Storage,etc. so to provide the background for an accurate modeling.
2. Designing model equations. raw data and concepts from literature are translated into a mathematical structure. The modeling choices about the characterizing costs and performance parameters have been performed.
3. Implementation in numerical form of the equations and translation in General Algebraic Modeling System (GAMS) language, the programming language of WITCH. This phase required particular attention, as our final implementation of the electric storage and grid sections, after the supervision of other researchers, are going to be used in the official version of the WITCH model.
4. Performing different Runs through different cases & scenarios as well as doing sensitivity analyses to understand better the results and cause/effect between inputs/outputs.

5. Analysis and Discussion of Results, coming both from the main runs as well as sensitivity analyses.

### 1.2.3 Thesis Structure

Considering the chapters division, the work is structured as follows. In **Chapter 1**, the general framework, motivation behind the project, methodology and main questions are discussed. **Chapter 2**, summarizes a quick review on the IAMs and especially WITCH model which is the core tool. Main attributes of hydrogen as well as its applications, production methods and transmission means are explained in the **Chapter 3**. **Chapter 4** is related to changes and improvements in the modules. Curtailment, hydrogen and transportation modules are the main modules which introduced or modified in the project. **Chapter 5** starts with defining different scenarios, and continues with the results obtained in various parts of model under already defined scenarios. Robustness analyses on different uncertain assumptions and values is an essential part of the project. Sensitivities on costs of production, fuel cells, and hydrogen infrastructure as well as fuel efficiency, growth constraint, regional discount and switching on/off the hydrogen are argued in **Chapter 6**. The last part, **Chapter 7** is dedicated to the conclusion of outcomes of project and more futures possible improvements.

# Chapter 2

# Model Description

## 2.1 Integrated Assessment Models

Integrated Assessment is the process of using pieces of information from different branches of human knowledge and combining them to get meaningful insights on a certain topic. When applied to climate change, the main branches involved are political science, economics, climate science, biochemistry and engineering, combined to understand how human activities (production of goods, consumption of energy, transportation, investment choices etc.) affect GHG emissions and, ultimately, temperature increase. The dynamics governing all the described phenomena and their interactions are described in a mathematical form and are synthesized in a numerical model, typically computer-based. Given their capability to synthesize and provide a considerable amount of information about the problem as a whole, without focusing just on a narrow field of expertise, IAMs are particularly suitable for policy design and assessment. They provide insights about the effects of policy measures on the entire economic system, reporting also the detailed consequences on the modeled sectors. In evaluating the link between economic activity and GHG emissions, IAMs can follow two different approaches: a top-down or aggregated approach, that represents reality starting from a low number of variables summarizing the relationships between sectors in a very condensed way, typical of macroeconomics and econometric studies (e.g. using a damage function to quantify the impact of climate change on economy with only one parameter); a bottom-up or dis-aggregated approach, that describes in detail the relevant sectors of the economy, such as energy, agriculture, transportation and, given their configuration, builds up the effects on both economy and environment. Despite being regarded as the main tool to analyze the investment efforts required to

meet climate change mitigation targets.
However, IAMs present a number of limitations in predicting the exact influence of human activities on climate change, hereby summarized:

- Model uncertainty: there is a level of uncertainty associated to the response of temperature increase to growing concentrations of GHG in the atmosphere, represented by confidence intervals around the climate module estimations.
- Parameter uncertainty: it is not possible to predict parameters such as the exact prices of energy technologies in the long term, especially if the technology is not commercially mature or it is just at an early stage of development. Some assumptions must be introduced.
- Future as past: Another issue is that IAMs are, in general, biased towards "future-as-past", where existing societal trends, habits and relationships persist.
- Political constraints: the limited knowledge of future emissions pathways and forcing trajectories impacts on the reliability of models predictions.

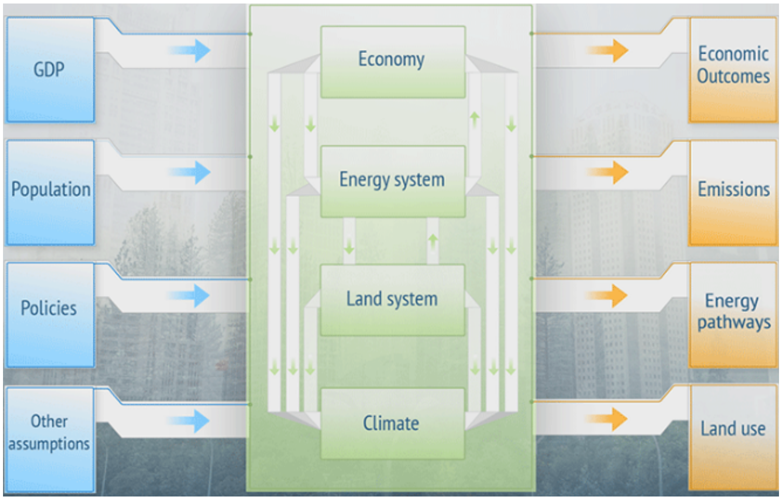


Figure (2.1) IAMs general structure [source:Carbonbrief.org]

## 2.2 WITCH

WITCH represents the world in a set of representative native of 17 regions (or coalitions of regions); for each it generates optimal mitigation and adaptation strategies for the long term (from 2005 to 2100) as a response to either climate damage or some external constrain on emissions, concentrations or temperature. These strategies consist of investment profiles resulting from a maximization process in which the welfare of each region (or coalition of regions) is chosen strategically and simultaneously accordingly to other regions. This makes it possible to capture regional free-riding behaviors and strategic interaction induced by the presence of global externalities. The non-cooperative, simultaneous, open membership game with full information, is implemented through an iterative algorithm which yields the open-loop Nash equilibrium. In this gametheoretic set-up, regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of oil and carbon permits, and technological R&D spillovers. The endogenous representation of R&D diffusion and innovation processes constitute a distinguishing feature of WITCH, allowing to describe how R&D investments in energy efficiency and carbon free technologies integrate the currently available mitigation options. The model features multiple externalities, both on the climate and the innovation side. The technology externalities are modeled via international spillovers of knowledge and experience across countries and time. In each country, the productivity of low carbon mitigation technologies and of energy depend on the region stock of energy R&D and by the global cumulative installed capacity, two proxies for knowledge and experience respectively. The R&D stock depends on domestic investments, domestic knowledge stock, and foreign knowledge stock through international spillovers. The spillover term depends on the interaction between the countries' absorptive capacity, and the distance of each region from the technology frontier. This formulation of technical change affects both decarbonization as well as energy savings.

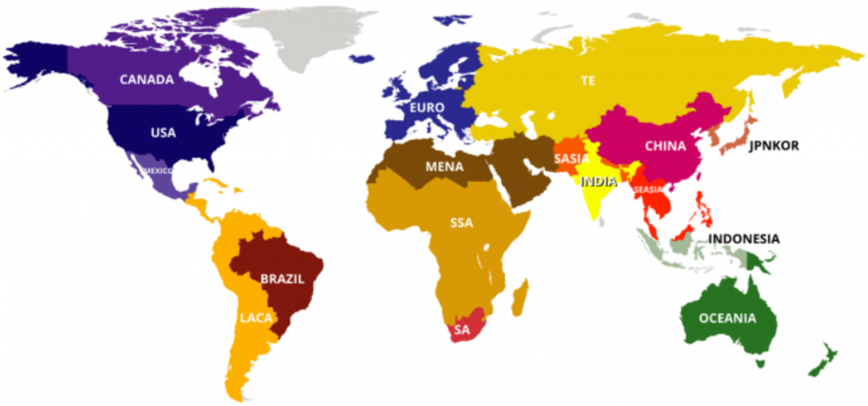


Figure (2.2) WITCH regions

| **Region symbol in WITCH** | **Actual regions** |
|---|---|
| CANADA | Canada |
| EURO | European countries |
| JPNKOR | Japan, Korea |
| MEXICO | Mexico |
| OCEANIA | Australia, New Zeland |
| USA | United States of America |
| Brazil | Brazil |
| CHINA | China & Taiwan |
| INDIA | India |
| INDONESIA | Indonesia |
| LACA | Latin America & Carribean |
| MENA | Middle East & North Africa |
| SA | South Africa |
| SASIA | South Asia |
| SEASIA | South East Asia |
| SSA | Sub-Saharan Africa |
| TE | Eastern European Countries including Russia |

Table (2.1) Specification of regions in WITCH

### 2.2.1 Economy

In the model, a social planner (with perfect foresight) maximizes a utility function the sum of regional discounted utility of each coalition. The regional utility function at any point in time and each region is based on Constant Relative Risk Aversion (CRRA) utility function derived from consumption per capita (and log-shaped). If no coalitions are present, the model optimizes considering each region as a coalition. Consumption, the argument of the utility function, is given by the budget constraint as the output of a single region, to which investments (in final good, energy and extraction sector, R&D, grid and adaptation), operation and maintenance costs (O&M) are subtracted, as they represent competing claims of the economy.The economic output of each region is represented by a nested production function combining labour, capital (these two aggregated in a Cobb-Douglas function) and energy services in a Constant Elasticity of Substitution (CES) framework, plus the influence of a climate damage function, cost of fossil fuels and GHG emissions mitigation, reducing the ouput. All economic quantities are defined in 2005 United States Dollars.

### 2.2.2 The CES Framework

The Constant Elasticity of Substitution production function is a macroeconomic functional form that sees the output as a function of a number of inputs. The peculiarity of this function is that it accounts for the extent to which one input (e.g. labour) can be substituted by another one (e.g. capital) to produce the final output, through the concept of elasticity of substitution. Equation 2.1 represents a general two-variable CES production function.

$$Y = A[aX_1^{\rho} + (1-a)X_2^{\rho})]^{\frac{1}{\rho}} \tag{2.1}$$

The output Y depends on the productivity A, on the two inputs $X_1$ and $X_2$, on a, determining the optimal distribution of inputs, and on $\rho$, which is in turn a function of $\sigma$ (the elasticity of substitution between the two outputs), as:

$$\sigma = \frac{1}{1-\rho} \tag{2.2}$$

Therefore, if $\sigma$ approaches infinity the CES function becomes linear and the two output become perfect substitutes (the two inputs can be used equivalently to generate the same output). The more $\sigma$ approaches zero, the more the two outputs become complements, so a certain amount of both should always be provided to obtain the output, and the margin to substitute one source of input with another decreases.

### 2.2.3 Energy

WITCH includes a comprehensive range of technology options to describe the final use of energy and the generation of electricity. The energy sector is described by a production function that aggregates different factors at various levels and with associated elasticities of substitution $\rho$. The main distinction is among electric generation and non-electric consumption of energy. The key technological-economic features represented are: yearly utilization factors, fuel efficiency, investment, and operation and maintenance costs, capital depreciation. Both the electric and the non-electric sector (comprising transportation, industry, residential and commercial energy use) are accounted into energy demand and supply. As the energy sector is hard-linked with the economic sector, the optimal solution pursued by the model involves management of energy investments and choices of technology adoptions. This sector has a bottom-up design, with a detailed description of the different technologies performances, primary fuel requirements and pollutant emissions. Electric sector includes both fossil-based plants, such as gas, coal and oil, and low carbon options such as wind, solar, biomass, Carbon Capture and Storage (CCS) and hydro, plus an electric backstop technology (representing a basket of promising technological options, far from commercialization). Non-electric demand regards transportation, industrial, commercial and residential sectors. Cost of production includes investments, O&M and fuel costs.
Investment costs in energy technologies are subject to two different types of learning, allowing for cost improvements in the future:

- Learning by doing: investment costs decrease proportionally to cumulative installed capacity, therefore endogenously. Before our work, the technologies benefiting from this type of learning were solar, wind and advanced biofuels. This project also added batteries for more precise projections.

- Learning by researching: similarly to what is done for general energy intensity of the economy, it is possible to invest money and accumulate an R&D capital stock, whose growth determines a technology cost decrease. This is done for the two backstop technologies (electric and non-electric) and for energy efficiency improvements, that decrease the total energy demand at same output level.

The existing capital of generation technologies and grid undergoes depreciation, meaning that capital shrinks in time if no further investments are done. WITCH uses a standard exponential depreciation rule: the depreciation rate is calibrated based on a finite useful life of each technology, with a linear depreciation rate of 1% per year until the end of the lifetime and full depreciation thereafter. Based on realistic plant lifetimes, the exponential depreciation rate is found equalizing the integral of both depreciation schedules.

### 2.2.4 Climate & Emission

GHG emissions are responsible for climate change, and can be generated by energy sector (power production, residential heating, transportation and industry) and land use. Emissions include Carbon Dioxide (CO2), NitrousOxide (N2O), Methane (CH4) and Fluorinated gases (targets of Kyoto Protocol). The estimates of agriculture, forestry and bioenergy emissions are provided in input from Global Biosphere Management Model (GLOBIOM), a land-use model soft-linked with WITCH. As regards the relation between GHG concentration in the atmoshpere and temperature increase, WITCH can internally convert regional emissions or can alternatively be soft linked with a climate model (as done in our work): Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC).

### 2.2.5 Endogenous Learning Curves

**Two-Factor Learning Curve**

In two-factor learning curves, investment costs decrease as a result of the accumulation of knowledge (learning-by-researching) or experience (learning-by-doing). The accumulation of knowledge is produced by investments in research and development, as discussed above, while the stock of experience is proxied with global cumulative installed capacity, wcum (full global technology spillover is assumed). Cost of batteries is one of the technologies which is using this approach after the project. The two-factor learning curve takes the following form:

$$\frac{SC_j(t,n)}{SC_j(0,n)} = (\frac{RD_j(t,n)}{RD_j(0,n)})^{-lbr\_factor}.(\frac{wcum_j(t,n)}{wcum_j(0,n)})^{-lbd\_factor} \quad (2.3)$$

where *wcum* is Cumulated Installed Capacity and *lbr_factor* and *lbd_ factor* measure the strength of the learning effect. They relate to the corresponding learning rates, lbr_ rate and lbd_ rate, which measure the rate at which unit costs decrease for each doubling of the knowledge or capacity stock, through the following relationships:

$$lbd\_rate = 1 - 2^{-lbd\_factor} \tag{2.4}$$

$$lbr\_rate = 1 - 2^{-lbr\_factor} \tag{2.5}$$

**One-Factor Learning Curve**

For some technologies only one factor is considered, Either learning-by-doing or learning-by-research. The cost evolution of wind (onshore and offshore) and solar (PV and CSP) technologies follows a technical change framework as well, but in this case only learning-by-doing is taken into account. Thus, investment costs decrease according to the progressive technology deployment (global cumulative capacity), while no dedicated R&D investments are considered. On the contrary, the cost evolution of fuel cells follows a one-factor learning curve based on learning-by-researching. The relevant cost equation can easily be derived, Eq(2.6) for lbr & Eq(2.7) for lbd:

$$\frac{SC_j(t,n)}{SC_j(0,n)} = (\frac{RD_j(t,n)}{RD_j(0,n)})^{-lbr\_factor} \tag{2.6}$$

$$\frac{SC_j(t,n)}{SC_j(0,n)} = (\frac{wcum_j(t,n)}{wcum_j(0,n)})^{-lbd\_factor} \tag{2.7}$$

### 2.2.6 Others

**Population** forecasts are taken from the common scenarios that have been developed at IIASA(International Institute for Applied System Analysis) and the OECD based on individual country forecasts. In the standard version of the model, SSP2 "middle of the road" scenario is aggregated over WITCH regions.

**GDP** baseline projections have been developed at the OECD and are common over different models. These GDP baseline forecasts are done for individual countries using Purchasing Power Parities(PPP). The data into USD through market exchange rates is converted using the conversion factor of 2005. The data series from the OECD are given until the year 2100. In order to obtain the data until the time horizon of WITCH, the GDP is extrapolated continuing with the growth rate in 2100 but decreasing it linearly to zero growth at the end of the time horizon. All baseline data can be accessed at the SSP database. The total number of countries available from the database is 184 and thus covering over 95% of the world population. [9] [13] [7] [8]

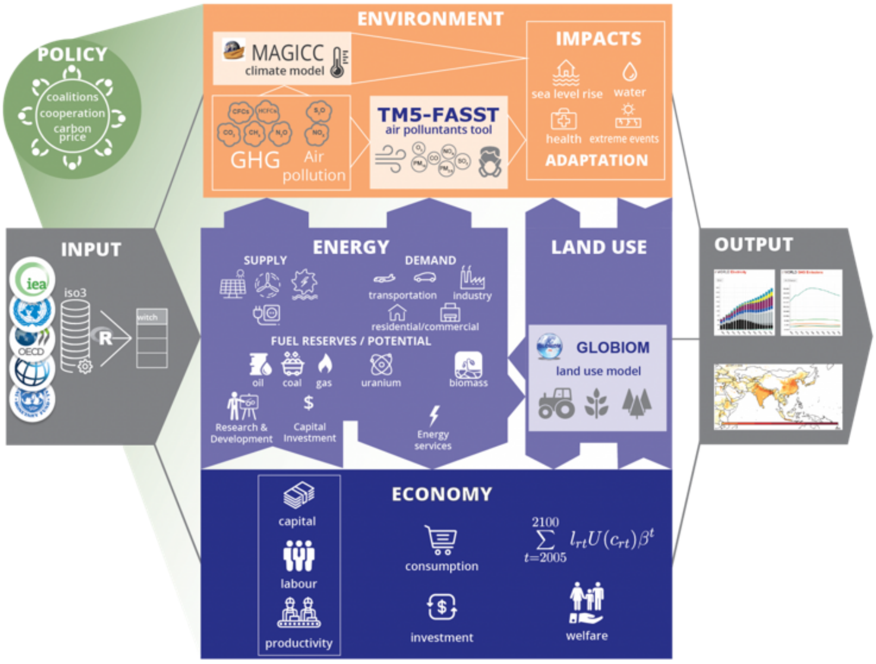


Figure (2.3) WITCH structure

# Chapter 3

# Hydrogen

## 3.1 History & Features

Hydrogen has seen several waves of interest in recent history, none of which fully translated into rising, sustainable investment. A brief summary of these earlier periods indicates that this may have been because hydrogen scale-up was highly dependent on high and rising prices for oil and gas, and was focused to a considerable extent on a single end-use sector: transport.

Hydrogen and energy have a long shared history. The first demonstrations of water electrolysis and fuel cells captured the imagination of engineers in the 1800s. Hydrogen was used to fuel the first internal combustion engines over 200 years ago. Hydrogen provided lift to balloons and airships in the 18th and 19th centuries, and propelled humanity to the moon in the 1960s. Hydrogen in ammonia fertilizer (from fossil fuels and, earlier, from electricity and water) has helped feed a growing global population. And hydrogen has been an integral part of the energy industry since the mid-20th century, when its use became commonplace in oil refining. Supplying hydrogen to industrial users is now a major business globally. Demand for hydrogen, which has grown more than threefold since 1975, continues to rise. Demand for hydrogen in its pure form is around 70 million tonnes per year (MtH2/yr). This hydrogen is almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production.1 As a consequence, production of hydrogen is responsible for carbon dioxide (CO2) emissions of around 830 million tonnes of carbon dioxide per year(MtCO2/yr), equivalent to the CO2 emissions of Indonesia and the United Kingdom combined. In energy terms, total annual hydrogen demand worldwide is around 330 million tonnes of oil equivalent (Mtoe), larger than the primary energy supply of Germany.

**Why hydrogen?** Existing markets for hydrogen build on its attributes: it is light, storable, reactive, has high energy content per unit mass, and can be readily produced at industrial scale. Today's growing interest in the widespread use of hydrogen for clean energy systems rests largely on some additional attributes:

- Hydrogen is the most abundant and lightest of the elements. It is odorless and nontoxic. It has the highest energy content of common fuels by weight -nearly three times that of gasoline. Hydrogen is not found free in nature and must be "extracted" from diverse sources: fossil energy, renewable energy, nuclear energy and the electrolysis of water. Lowcarbon production from fossil fuels is possible, if combined with carbon capture, use and storage (CCS) and emissions during fossil fuel extraction and supply are mitigated.

- Hydrogen can be converted to electricity by a fuel cell, an electrochemical device. Unlike batteries, fuel cells operate continuously in the presence of hydrogen and oxygen (in ambient air). Fuel cells are "scalable" and may be used in very small to very large sizes. The only byproducts of fuel cells are heat and water.

- Hydrogen's relationship to renewables cannot be overemphasized. The 2015 IEA Technology Roadmap for Hydrogen and Fuel Cells recognizes that hydrogen with a low-carbon footprint has the potential to facilitate significant reductions in energy-related CO2 emissions. Thus, use of renewable feedstocks for hydrogen production is very attractive from the environmental perspective.

- Like electricity, hydrogen is an "energy carrier." It can be used in a full range of applications in all sectors of the economy: transportation, power, industry, and buildings.

- Hydrogen can be used for decentralized power production in a future energy system that is increasingly inclined to consider distributed generation as an option to exclusively centralized power production. "H2 investment risk is reduced if H2 production takes place in decentralized electrolyzers, especially with low cost renewables.

| **Property** | **Hydrogen** | **Comparison** |
|---|---|---|
| Density(g) | 0.089 kg/m3 (0C, 1bar) | 1/10 of NG |
| Density(l) | 70.79 kg/m3 (-253C, 1bar) | 1/6 of NG |
| Boiling point | -252.76C (1bar) | 90C below LNG |
| Energy per unit of mass (LHV) | 120.1 MJ/kg | 3x that of gasoline |
| Energy density (ambient cond, LHV) | 0.01 MJ/L | 1/3 of NG |
| Flame velocity | 346 cm/s | 8x methane |
| Autoignition Temperature | 585C | 220 for gasoline |
| Ignition energy | 0.02 MJ | 1/10 of methane |

Table (3.1) Hydrogen properties

- Since fuel cell electric vehicles (FCEVs) are emission-free at the tailpipe, use of hydrogen in the transport sector positively impacts urban air quality, whether or not the hydrogen feedstock is produced from a renewable source.

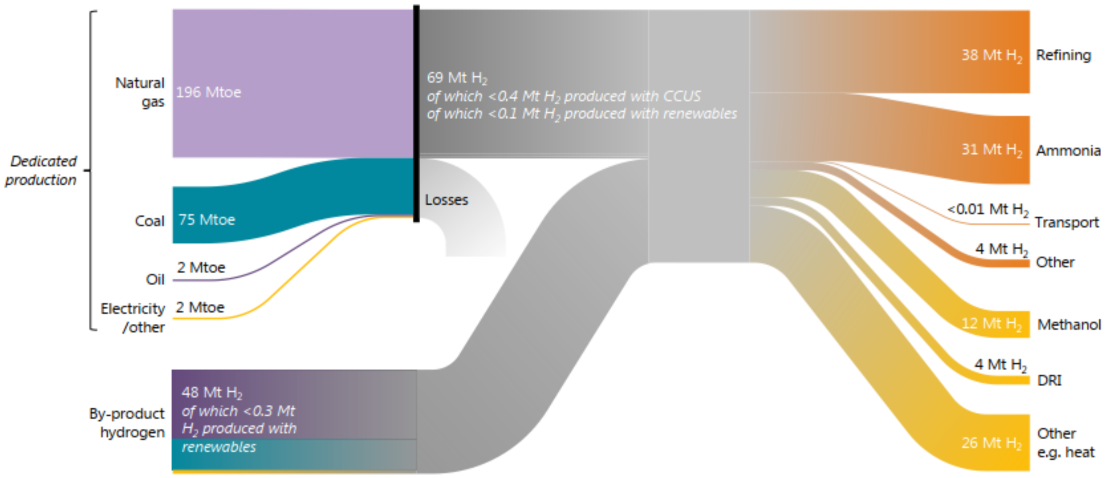


Figure (3.1) Today's hydrogen value chain

**What are hydrogen Challenges?** While the factors in favor of a sustained upswing in investment in hydrogen are much stronger and better aligned than in any prior period, significant challenges still need to be addressed. Overcoming these challenges will be central to launching the virtuous cycle for hydrogen;

1. **Policy and technology uncertainty:**Climate change ambition remains the single most important driver for widespread use of clean hydrogen. The speed with which governments will push the transition to low-carbon energy sources in different countries and sectors remains a major uncertainty. In the absence of clear, and ideally binding, commitments to sustainable and resilient energy systems

in the long term, major financial commitments to hydrogen technologies and infrastructure are much less attractive.

2. **Value chain complexity and infrastructure needs:** Hydrogen value chains can follow many different paths. Demand for low-carbon hydrogen can come from a variety of sectors, and there are many permutations of hydrogen supply and handling that could meet it. The most cost-competitive outcome will, moreover, be different in various regions and applications. Infrastructure such as pipeline and delivery networks is of particular importance for a new energy carrier such as hydrogen. While hydrogen can be produced locally, its storage and distribution benefit from economies of scale.

3. **Regulations, standards and acceptance:** Around the world, the state of existing regulations and standards currently limits hydrogen uptake. Certain regulations are unclear or not written with new uses of hydrogen in mind and do not allow exploitation of the full benefits hydrogen can provide. Some important standards have yet to be agreed, including standards dealing with hydrogen vehicle refueling, gas composition for cross-border sales, safety measures, permitting, materials and how to measure life cycle environmental impacts.

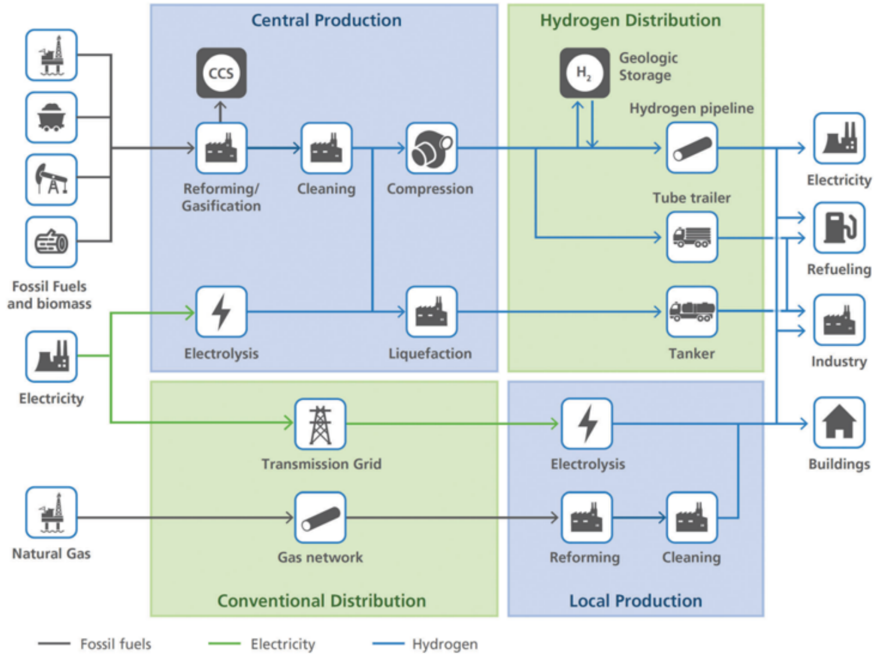


Figure (3.2) Hydrogen pathway [51]

## 3.2 Applications

### 3.2.1 Hydrogen in Transport

Hydrogen gas has long been heralded as a potential transport fuel. It is seen as offering a lowcarbon alternative to refined oil products and natural gas, and complementing other alternatives like electricity and advanced biofuels. Hydrogen fuel cell electric vehicles (FCEVs) would reduce local air pollution because – like battery electric vehicles (BEVs) – they have zero tailpipe emissions. As discussed in Chapter 2, hydrogen can be converted to hydrogen-based fuels, including synthetic methane, methanol and ammonia, and synthetic liquid fuels, which have a range of potential transport uses. Synthetic liquid fuels produced from electrolytic hydrogen are often referred to as “power-to-liquid”. The suitability of hydrogen and these hydrogen-based fuels in different transport modes is presented in Table 5, which sets out some of their main advantages and disadvantages.40 In general, hydrogen-based fuels could take advantage of existing infrastructure with limited changes in the value chain, but at the expense of efficiency losses. Hydrogen-based fuels offer particular advantages for aviation (in the form of synthetic jet fuel) and for shipping (as ammonia), sectors where it is more difficult to use either hydrogen or electricity.

| | **Current role** | **Demand perspectives** |
|---|---|---|
| **Light-duty vehicles** | Around 15000 vehicles in operation mostly in US, EU and Japan | The global car stock is expected to continue to grow |
| **Heavy-duty vehicles** | ∼25 000 forklifts<br>∼500 buses<br>∼400 trucks<br>∼100 vans. | Strong growth segment; long-haul and heavy-duty applications are attractive for hydrogen |
| **Maritime** | Limited to demonstration projects for small ships and on board power supply in larger vessels | Maritime freight activity set to grow by around 45% to 2030. |
| **Rail** | Two hydrogen trains in Germany | Rail is a mainstay of transport in many countries |
| **Aviation** | Limited to small demonstration projects and feasibility studies | Large storage volume and redesign would be needed for pure hydrogen |

Table (3.2) Hydrogen in transportation

### 3.2.2 Oil Refinery

Hydro-treatment and hydro-cracking are the main hydrogen-consuming processes in the refinery. Hydro-treatment is used to remove impurities, especially sulphur (it is often simply referred to as desulphurisation and accounts for a large share of refinery hydrogen use globally. Today refineries remove around 70% of naturally incurring sulphur from crude oils. With concerns about air quality increasing, there is growing regulatory pressure to further lower the sulphur content in final products. Hydro-cracking is a process that uses hydrogen to upgrade heavy residual oils into higher-value oil products. Demand for light and middle distillate products is growing and demand for heavy residual oil is declining, leading to an increase in the use of hydro-cracking. In addition to hydro-treatment and hydro-cracking, some hydrogen that is used or produced by refineries cannot be economically recovered and is burned as fuel as part of a mixture of waste gases. The United States, China and Europe are the largest consumers of hydrogen in refineries. The three regions represent around half of total refinery hydrogen consumption, reflecting the volume of crude oil they process and the stringency of their product quality standards.

### 3.2.3 Chemical Sector

The chemical sector produces a complex array of outputs, from plastics and fertilisers to solvents and explosives. Hydrogen is part of the molecular structure of almost all industrial chemicals, but only some primary chemicals require large quantities of dedicated hydrogen production for use as ammonia and methanol. More than 31 MtH2/year of hydrogen are used as feedstock to produce ammonia, and more than 12 MtH2/year to produce methanol. A further 2 MtH2/year are consumed in comparatively small-volume processes (for example in hydrogen peroxide and cyclohexane production), but most of this is supplied from by-product hydrogen generated within the sector.

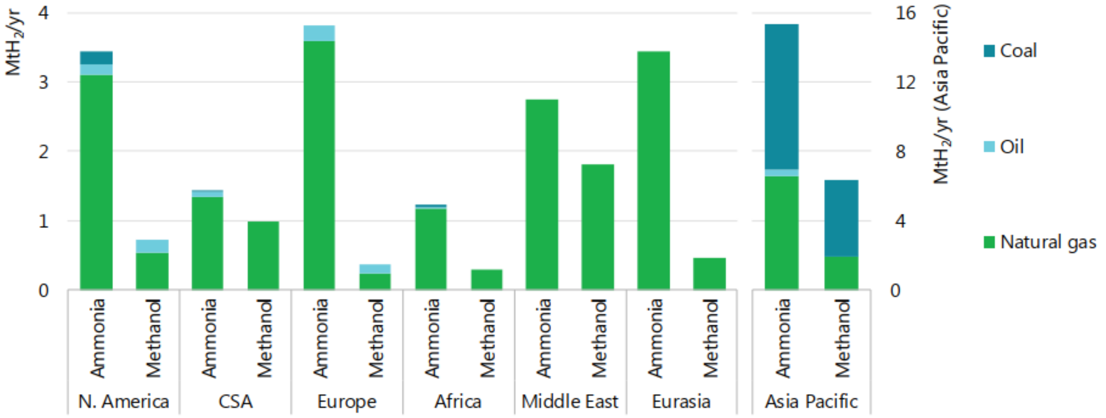


Figure (3.3) Hydrogen demand for ammonia and methanol production in 2018[IEA]

Demand for hydrogen for primary chemical production is set to increase from 44 Mt/yr today to 57 Mt/yr by 2030 as demand for ammonia and methanol grows (Figure 39).28 Demand for ammonia for existing applications is set to increase by 1.7% per year between 2018 and 2030 and to continue to rise thereafter. The share represented by demand for industrial applications grows more quickly during this period; that for nitrogen-based fertilisers is likely to start to plateau or even decline in many regions after 2030.

### 3.2.4 Steel and Iron Production

Direct reduced iron(DRI) is a method for producing steel from iron ore. This process constitutes the fourth-largest single source of hydrogen demand today (4 MtH2/yr, or around 3% of total hydrogen used in both pure and mixed forms), after oil refining, ammonia and methanol. Based on current trends, global steel demand is set to increase by around 6% by 2030, with demand for infrastructure and a growing population in developing regions compensating for declines elsewhere. Like the chemical sector, the iron and steel sector produces a large quantity of hydrogen mixed with other gases as a by-product (e.g. coke oven gas), some of which is consumed within the sector and some of which is distributed for use elsewhere. Virtually all of this hydrogen is generated from coal and other fossil fuels. To reduce emissions, efforts are underway to test steel production using hydrogen as the key reduction agent (as opposed to carbon monoxide derived from fossil fuels), with the first commercial-scale designs expected in the 2030s. In the meantime, low-carbon hydrogen could be blended into existing processes that are currently based on natural gas and coal to lower their overall CO2 intensity.

### 3.2.5 Heating

Heat and hot water accounts for 60–80% of final energy consumption in residential and commercial buildings across Europe.[12] Emissions from heating need to be reduced rapidly and largely eliminated by 2050.

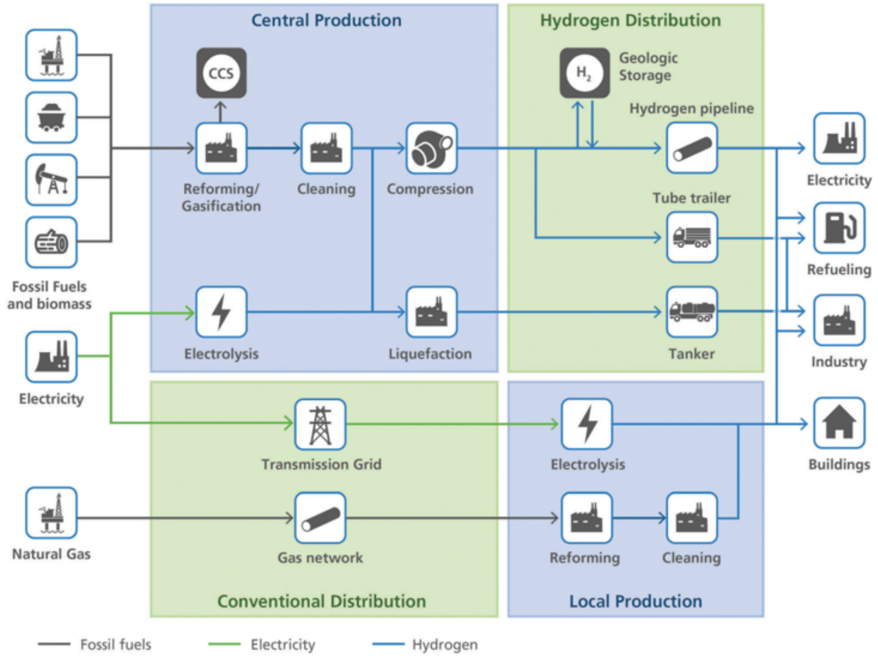


Figure (3.4) The share of fuels used for domestic heating in ten countries [12]

There are some options for low-carbon heating, such as electrification, heat networks, on-site renewables and green gas. Each of these options has their own advantages and disadvantages. But, here some solutions regarding hydrogen will be discussed:

- **Blending hydrogen into natural gas**: In major heating markets like Canada, the United States and Western Europe, blending low shares of hydrogen – 3–5% hydrogen by volume – into supplied natural gas would have little impact on end-use equipment such as boilers and gas cookstoves. In some cases 20% blend found no problems with leakage, flame stability, back firing or ignition, nor were there problems with pipes or heating equipment at 30Other projects around the world have tested specific pieces of equipment, with similar conclusions.

- **100% hydrogen use**: From the perspective of costs, 100% hydrogen use in buildings (e.g. via a fuel cell or hydrogen boiler) appears most attractive for relatively large commercial buildings or building complexes, and for district energy networks. Fuel cells, co-generation units or other hybrid systems could be used in such cases with energy storage capacity (provided by thermal storage or via a district energy network) to meet heating, cooling and electricity demand, taking advantage of on-site renewables or low electricity prices. Fuel cell and co-generation technologies could equally be used in district energy networks, which when paired with storage (either thermal or hydrogen) could improve power system balancing across the year, avoiding large seasonal peaks and enabling greater flexibility in the grid. Paired with large-scale heat pumps, those district energy solutions could also dramatically increase the overall efficiency of heat production for buildings.

### 3.2.6 Power Generation and Electricity Storage

Hydrogen plays a negligible role in the power sector today: it accounts for less than 0.2% of electricity generation. This is linked mostly to the use of gases from the steel industry, petrochemical plants and refineries. But there is potential for this to change in the future. Co-firing of ammonia could reduce the carbon intensity of existing conventional coal power plants, and hydrogen-fired gas turbines and combined-cycle gas turbines could be a source of flexibility in electricity systems with increasing shares of variable renewables. In the form of compressed gas, ammonia or synthetic methane, hydrogen could also become a long-term storage option to balance seasonal variations in electricity demand or generation from renewables. [3] [30]

#### Co-firing of ammonia in coal power plants

In 2017 the Japanese Chugoku Electric Power Corporation successfully demonstrated the co-firing of ammonia and coal, with a 1% share of ammonia (in terms of total energy content) at one of their commercial coal power stations (120 MW) (Muraki, 2018). Using ammonia as fuel raises concerns about an increase in NOx emissions, but the demonstration managed to keep them within the usual limits and to avoid any ammonia slip into exhaust gas.

#### Flexible power generation

**Hydrogen** can be used as a fuel in gas turbines and Combined Cycle Gas Turbines(CCGT). Most existing gas turbine designs can already handle a hydrogen share of 3–5% and some can handle shares of 30% or higher. The industry is confident that it will be able to provide standard turbines that are able to run entirely on hydrogen by 2030.

**Ammonia** is another potential fuel for gas turbines. The direct use of ammonia has been successfully demonstrated in micro gas turbines with a power capacity of up to 300 kW(Shiozawa, 2019).

**Fuel cells** can also be used as a flexible power generation technology. With electric efficiencies of 50–60% (lower range today, upper future potential) being in a similar range to those of CCGTs, the choice between fuel cells and CCGTs in economic terms largely depends on their capital costs.

#### Large-scale and long-term storage

The integration of increasing shares of variable renewable energy(VRE) sources in the electricity system requires a more flexible electricity system. High shares of renewables can create a need for long-term and seasonal storage, for example to provide electricity during periods of several days with very little wind and or sunshine. Hydrogen and hydrogen-based fuels from electricity via electrolysis) are potential options for long-term and large-scale storage of energy. **Salt caverns** are the best choice for the underground storage of pure hydrogen because of their tightness and low risk of contamination. Alternative underground hydrogen storage options such as pore storage and storage in depleted oil and gas fields are also being investigated. Converting electricity into methane via power-to-gas is a further long-term storage option, and one which could take advantage of the existing transport and storage infrastructure for natural gas. Around 70 power-to-gas projects to produce methane are in operation today, most of them in Europe. [36] [35] [1] [38] [5]

## 3.3 Production Methods

One of the advantages of using hydrogen as energy carrier is that all primary resources such as fossil fuels, renewable energy sources (solar, wind, hydro, geothermic, biomass) and nuclear power could be used for its production.

| Material | Technology | % |
|---|---|---|
| **Natural Gas** | Steam Gas Reforming (SGR) | 48 |
| **Oil** | Partial Oxidation | 30 |
| **Coal** | Gasification | 18 |
| **Water** | Electrolysis | 4 |
| Others | | 0.1 |

Table (3.3) Hydrogen production share today

### 3.3.1 Steam Gas Reforming

Natural Gas feedstock is mainly constituted by methane molecule (CH4), which represents the hydrocarbon with the highest H/C ratio. The composition of the NG could slightly change in dependence of the geographic region where it is extracted, but generally the mixture contains mainly small amounts of light hydrocarbons(C2–C4). At high temperatures (700 – 1100 C) and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen as following reaction:

$$CH_4 + H_2O \leftrightharpoons CO + 3H_2 \qquad \Delta H = +206\,kJ/mol \tag{3.1}$$

Which is a strongly endothermic reaction. Additional hydrogen can be obtained by reacting the CO with water via the water-gas shift reaction (exothermic):

$$CO + H_2O \leftrightharpoons CO_2 + H_2 \qquad \Delta H = -41\,kJ/mol \tag{3.2}$$

The production cost of hydrogen from natural gas is influenced by various technical and economic factors, with gas prices and capital expenditure (CAPEX) being the two most important. Fuel costs are the largest cost component in all regions and account for between 45% and 75% of production costs. Low gas prices in the Middle East, the Russian Federation, and North America give rise to some of the lowest hydrogen production costs. Gas importers such as Japan, Korea, China and India have to contend with higher gas import prices, and that makes for higher hydrogen production costs. In figure(3.5) we can see the cost of hydrogen produced by steam gas reforming process over different regions with two options; 1. No carbon capture, 2. With carbon capture.

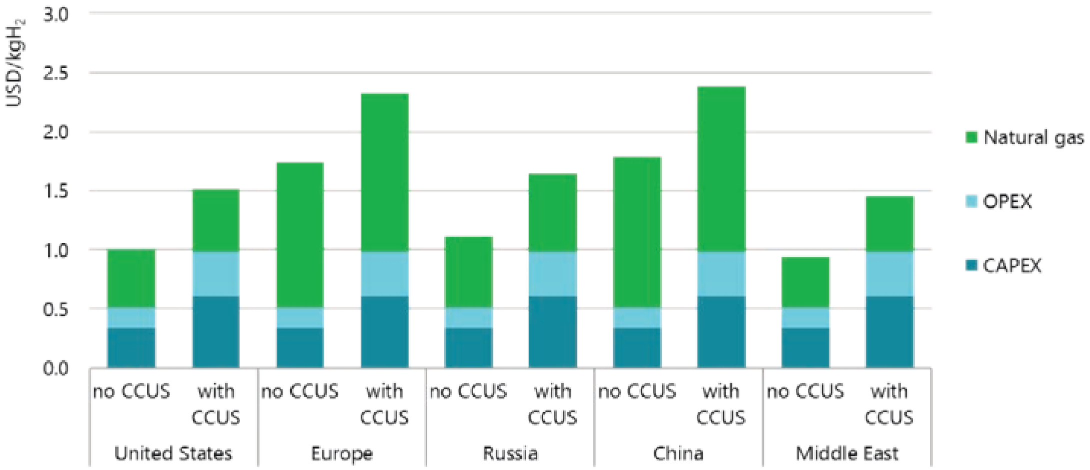


Figure (3.5) cost of steam gas reforming [9]

### 3.3.2 Partial Oxidation

An alternative route to produce synthesis gas starting from hydrocarbon feedstock is the partial oxidation reaction (POX). This reaction utilizes the oxygen in the air as oxidant and results moderately exothermic. Partial oxidation is a technically mature process in which natural gas or a heavy hydrocarbon fuel (heating oil) is mixed with a limited amount of oxygen in an exothermic process. General reaction is:

$$C_nH_m + \frac{n}{2}O_2 \rightarrow nCO + \frac{m}{2}H_2 \tag{3.3}$$

A non-catalytic partial oxidation process based on the above reactions has been largely used for the past five decades for a wide variety of feedstocks, in particular heavy fractions of refinery, such as naphtha, vacuum fuel oil, asphalt residual fuel oil, or even whole crude oil. The absence of catalysts implies that the operation of the production unit is simpler (decreased desulfurization requirement) but the working temperatures results higher than 1200C.

### 3.3.3 Coal Gasification

Another important thermal method is based on the gasification process, currently used on industrial scale essentially to generate electricity. This technology is also the oldest method for hydrogen production and could convert any type of organic material, such as coal and other petroleum or biomassderived mixtures. The interest towards this approach comes from the practical possibility of using coal as fuel that is the most world-wide available and relative cheap fossil fuel.

$$C + 2H_2O \leftrightharpoons CO_2 + 2H_2 \qquad \Delta H = +90\,kJ/mol \tag{3.4}$$

Gasification process could be inserted in a Integrated Gasification Combined Cycle plant (IGCC)to improve the overall process efficiency. The syngas produced in the gasifier is used as fuel in the gas turbine generator of the integrated combined-cycle technology, which consists also of a heat recovery steam generator and a steam turbine/generator. A simplified scheme of a proposed gasification overall plant for generation of both electricity and hydrogen is reported below.

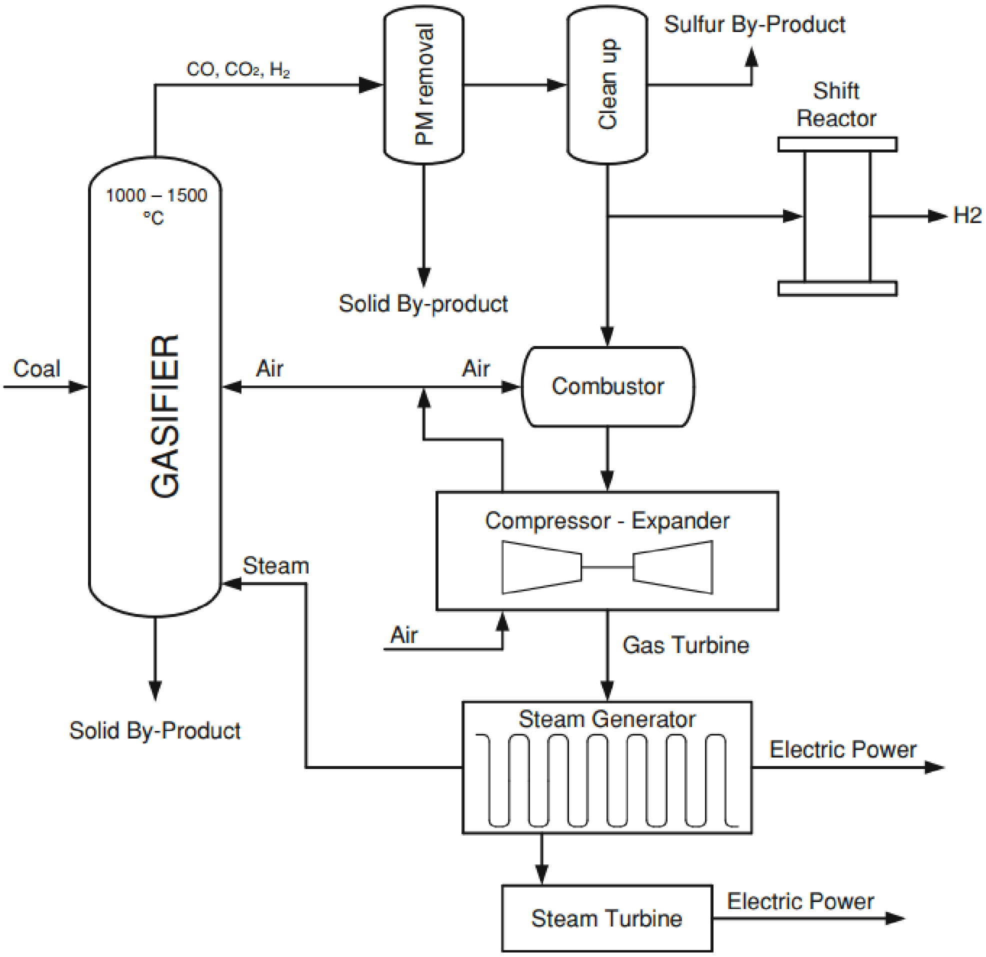


Figure (3.6) Scheme of an integrated gasification plant

### 3.3.4 Water Electrolysis

Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen. In pure water at the negatively charged cathode, a reduction reaction takes place, with electrons from the cathode being given to hydrogen cations to form hydrogen gas.

**Electrolyzer types**

1. **Alkaline electrolysis** is a mature and commercial technology. It has been used since the 1920s, in particular for hydrogen production in the fertiliser and chlorine industries. The operating range of alkaline electrolysers goes from a minimum load of 10% to full design capacity. Several alkaline electrolysers with a capacity of up to 165 megawatts electrical (MWe) were built in the last century in countries with large hydropower resources (Canada, Egypt, India, Norway and Zimbabwe), although almost all of them were decommissioned when natural gas and steam methane reforming for hydrogen production took off in the 1970s. Alkaline electrolysis is characterised by relatively low capital costs compared to other electrolyser technologies due to the avoidance of precious materials.
2. **Proton exchange membrane (PEM) electrolyser** systems were first introduced in the 1960s by General Electric to overcome some of the operational drawbacks of alkaline electrolysers. They use pure water as an electrolyte solution, and so avoid the recovery and recycling of the potassium hydroxide electrolyte solution that is necessary with alkaline electrolysers. They are relatively small, making them potentially more attractive than alkaline electrolysers in dense urban areas.
3. **Solid oxide electrolysis cells (SOEC)** are the least developed electrolysis technology. They have not yet been commercialised, although individual companies are now aiming to bring them to market. SOECs use ceramics as the electrolyte and have low material costs. They operate at high temperatures and with a high degree of electrical efficiency. Because they use steam for electrolysis, they need a heat source

The production costs of hydrogen from water electrolysis are influenced by various technical and economic factors, with CAPEX requirements, conversion efficiency, electricity costs and annual operating hours being the most important. CAPEX requirements are today in the range of USD 500–1400/kWe for alkaline electrolysers and USD 1100–1800/kWe for PEM electrolysers, while estimates for SOEC electrolysers range across USD 2800–5600/kWe. The electrolyser stack is responsible for 50% and 60% of the CAPEX costs of alkaline and PEM electrolysers respectively. The power electronics, gas-conditioning and plant components account for most of the rest of the costs. Future cost reductions will be influenced by innovations in the technologies themselves, (for example the development of less costly materials for electrodes and membranes), and by economies of scale in the manufacturing processes (for example by the development of larger electrolysers). Figure (3.7) illustrates the potential for cost reduction in current alkaline and PEM electrolysers from switching to larger multi-stack systems. [21] [14] [16] [22] [11]

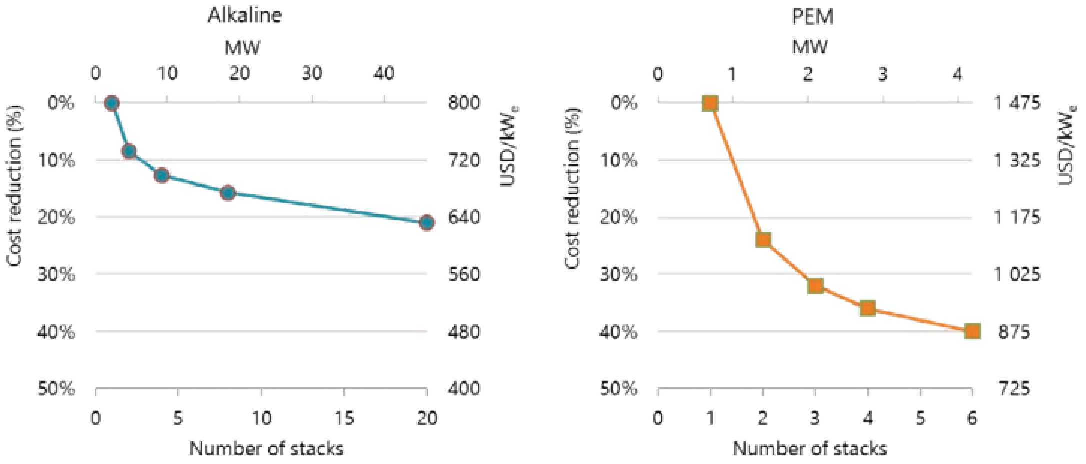


Figure (3.7) Alkaline & PEM electrolysers CAPEX economies of scale [9]

## 3.4 Transmission & Distribution

If hydrogen is to play a meaningful role in clean, flexible energy systems, it will be largely because it can be used to store energy in large quantities for long periods and to move it over very long distances. Delivery infrastructure choices and costs are thus critically important.

### 3.4.1 Blending hydrogen in existing natural gas grids

Blending hydrogen into the natural gas infrastructure that already exists would, however, avoid the significant capital costs involved in developing new transmission and distribution infrastructure. Further, if blending were to be carried out at low levels, while it might increase the cost of natural gas delivery to consumers, it would also provide reductions in CO2 emissions. Blending would be considerably easier to implement if steps were taken to clarify existing national regulations on hydrogen in natural gas and to harmonie regulations across borders. However, blending faces a number of challenges:

- The energy density of hydrogen is around a third of that of natural gas and so a blend reduces the energy content of the delivered gas: a 3% hydrogen blend in a natural gas transmission pipeline would reduce the energy that the pipeline transports by around 2%
- Hydrogen burns much faster than methane. This increases the risk of flames spreading. A hydrogen flame is also not very bright when burning. New flame detectors would probably be needed for high-blending ratios.
- Variability in the volume of hydrogen blended into the natural gas stream would have an adverse impact on the operation of equipment designed to accommodate only a narrow range of gas mixtures.

### 3.4.2 Pure hydrogen pipelines

There are close to 5000 km of hydrogen pipelines around the world today, compared with around 3 million km of natural gas transmission pipelines. These existing hydrogen pipelines are operated by industrial hydrogen producers and are mainly used to deliver hydrogen to chemical and refinery facilities. The United States has 2 600 km, Belgium 600 km and Germany just under 400 km (Shell, 2017). Pipelines have low operational costs and lifetimes of between 40 and 80 years. Their two main drawbacks are the high capital costs entailed and the need to acquire rights of way. These mean that certainty of future hydrogen demand and government support are essential if new pipelines are to be built.

Existing high-pressure natural gas transmission pipes could be converted to deliver pure hydrogen in the future if they are no longer used for natural gas, but their suitability must be assessed on a case-by-case basis and will depend on the type of steel used in the pipeline and the purity of hydrogen being transported (NREL, 2013).20 Recent studies in the Netherlands have suggested that the existing natural gas network could be used to transmit hydrogen with small modifications (Netbeheer Nederland, 2018; DNV GL, 2017). *The main challenge* is that three times more volume is needed to supply the same amount of energy as natural gas. Additional transmission and storage capacity across the network might therefore be required, depending on the extent of the growth of hydrogen.

### 3.4.3 Shipping

There are currently no ships that can transport pure hydrogen. Such ships would be broadly similar to LNG ships and would require the hydrogen to be liquefied prior to transport. While both the ships and the liquefaction process would entail significant cost, a number of projects are actively looking to develop suitable ships. The expectation is that these ships will be powered by hydrogen that boils off during the journey (around 0.2% of the cargo would likely be consumed per day, similar to the amount of natural gas consumed in LNG carriers). Unless a high-value liquid can be transported in the opposite direction in the same vessel, ships would need to return empty.

### 3.4.4 Trucks

Today hydrogen distribution mostly depends on compressed gas trailer trucks for distances less than 300 km. Liquid hydrogen tanker trucks are often used instead where there is reliable demand and the liquefaction costs can be offset by the lower unit costs of hydrogen transport. In fact a single trailer transporting compressed hydrogen gas can hold up to 1100 kgH2 in lightweight composite cylinders (at 500 bar). This weight is rarely achieved in practice, however, as regulations around the world limit the allowable pressure, height, width and weight of tubes that can be transported. In the United States, for example, the pressure limit for steel tubes means that a trailer has a maximum load of 280 kgH2 (although the US Department of Transport recently approved the manufacture and use of higher-pressure composite storage vessels). [34] [43] [26] [43] [2] [15] [19]

# Chapter 4

# Model Development & Implementation

In this chapter formulations as well as logistics behind them will be explained. Three main modules had be introduced or modified to the model; **Curtailment/Storage module, Hydrogen module, Transportation module**. In the following sections all of the modules will be discussed explicitly. However, following figure helps us to understand better the modifications.

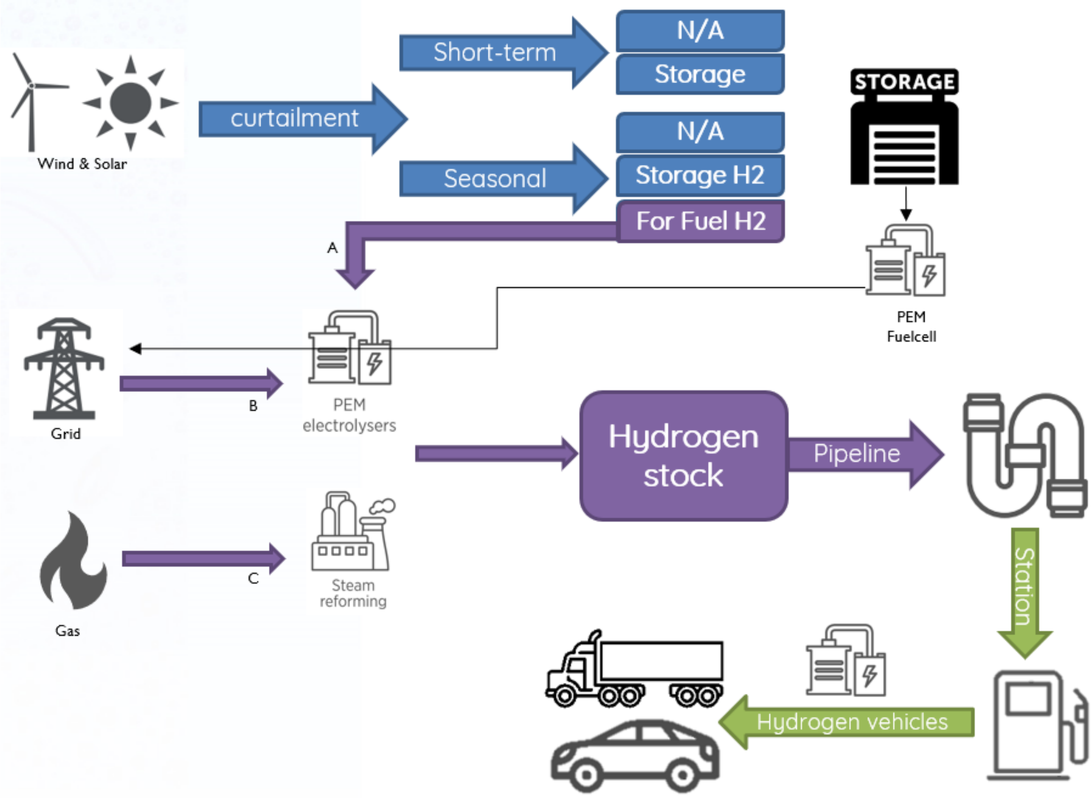


Figure (4.1) Brief structure of developments to model

There is production and transmission part of hydrogen in one side. On the other hand, transportation module is linked and it uses produced hydrogen for yearly demand of fuel cell vehicles (FCVs) and/or fuel cell freight trucks.

## 4.1 Curtailment/Storage Module

This module's main task is to calculate curtailment electricity produced from solar or wind sources. Curtailed electricity means the production which exceeds demand requirement. There are two types of curtailed electricity in module.

**Short-term curtailment:** it represents daily shifting of electricity generation to meet peak load, that does not happen in coincidence with high Variable renewable energy(VRE) production, or to exploit daily differences in electricity prices.

**Seasonal curtailment:** it stands for the set of technologies used to implement a shifting of generation between different seasons. It could be exploited particularly in regions where high electricity demand is strongly decoupled from high VRE generation among different seasons. In the modeling, it can receive input from one source only, i.e. VRE seasonal curtailment.

Curtailment is being calculated based on the share of renewable source. The higher share, the higher curtailed electricity. Following function is used to estimate both "short-term" as well as "seasonal" curtailment.

| **Index** | **Showing** |
|---|---|
| curt-type | Seasonal/Short-term |
| j-vre | offshore wind/<br>onshore wind/<br>CSP solar/<br>PV solar |
| t | Time step |
| n | Region |

Table (4.1) Indices guideline for curtailment/storage module

$$Q_{curt}(j-vre, curt-type, t, n) = Q_{BC}(j-vre, t, n) \times curt\_coefficient(curt-type, n) \times Share^{2}_{el-VRE} \quad (4.1)$$

Where, $Q_{curt}$is amount of curtailed electricity[TWh], $Q_{BC}$ is amount of electricity before computing curtailment[TWh], curt-coefficient is the main coefficient to calculate amount of short-term and seasonal curtailment based on the region.

### 4.1.1 Short-term Storage

Short-term extra production has 2 options. It can be stored or wasted.(mainly to costs of storage technologies in specific time periods and regions) The technologies chosen to be considered in modeling short-term electric storage in WITCH are:

1. **Pumped Hydro Energy Storage (PHES):** it is the only commercially-proven largescale storage technology, with more than 300 plants and almost 100 GW of installed capacity worldwide; the working principle of this technology is very simple, as it stores electrical energy in the form of hydraulic potential energy, pumping water from lower to higher reservoirs, thus increasing its geodetic height.
2. **Compressed Air Energy Storage (CAES):** it is a mechanical storage technology that works converting electricity into air high pressure through a compressor, storing the air in a reservoir (most commonly an underground cavern) and then heating up the air and expanding it in a turbine to generate electricity when needed.
3. **Lithium-ion batteries (LiB):** it is a relatively old technology that has widespread applications in electronics (laptops, tablets, smart phones), Plug-In Hybrid and Full-Electric Vehicles and power grid applications.

| Technology | Lifetime [year] | Depreciation rate | Cost [$/W] | Cost reduction rate |
|---|---|---|---|---|
| **PHES** | 45 | 0.0286 | 0.5346 | 0 |
| **CAES** | 35 | 0.0346 | 0.8536 | -0.17 |
| **LiB** | 20 | 0.0555 | 0.4618 | -0.28 |

Table (4.2) Short-term storage technologies

Deprecation rate is calculated through formulation below:

$$\delta_i = \frac{1}{Lifetime_i - \frac{0.01}{2} Lifetime_i^2} \tag{4.2}$$

Also, cost reduction is exogenous by:

$$Cost_t = Cost_0(tperiod_t^{reduction\_rate}) \tag{4.3}$$

For each technology a variable showing installed capacity $K_{short.storage}(j-stor,t,n)$ and another variable showing investment costs $I_{short.storage}(j-stor,t,n)$ is defined. Following equation connects I,K and $\delta$ :

$$K_{short.storage(j-store,t+1,n)[W]} = K_{short.storage(t,n)}(1-\delta^{\Delta t}_{(j-store)})_{[W]}+ \Delta t \frac{I_{short.storage(j-store,t+1,n)}[\$]}{Cost(j-store,t+1,n)[\frac{\$}{W}]} \quad (4.4)$$

Two other equations also needed for this part:

$$K_{short.storage(j-store,t,n)} \times Operating.hours[h] \geqslant \sum_{j-vre} Q_{short.storage(j-vre,j-store,t,n)} \quad (4.5)$$

$$\sum_{j-stor} Q_{short.storage}(j-stor, j-vre, t, n) \leq Q_{curt}(j-vre, 'short-term', t, n) \quad (4.6)$$

Equation (4.5) forces installing capacities based on amount of desired storage. Equation (4.6) limits desired storage value by all technologies to be lower than the available short-term curtailment.

### 4.1.2 Seasonal Storage

Seasonal storage can receive electricity input from one source only: seasonal curtailment of VRE generation. Seasonal storage has been modeled with the production and subsequent consumption of hydrogen. Produced hydrogen is by electrolyzing (in hydrogen module will be discussed completely), and it can be used for fuel cell vehicles or getting back into grid after going through fuel cells. Therefore, three ultimate options are considered for seasonal curtailment; 1. Hydrogen storage, 2. Hydrogen for transportation, 3. Wasted.

$$K_{seasonal.storage(t+1,n)[W]} = K_{seasonal.storage(t,n)}(1-\delta^{\Delta t}_{(fuelcell)})_{[W]}+ \Delta t \frac{I_{fuelcell.storage(t+1,n)}[\$]}{Inv.Cost.FC(t+1,n)[\frac{\$}{W}]} \quad (4.7)$$

$$K_{seasonal.storage(t,n)} \times Operating.hours[h] \geqslant \sum_{j-vre} Q_{seasonal.storage(j-vre,t,n)} \quad (4.8)$$

$$Q_{EN}(j-vre,t,n) = Q_{BC}(j-vre,t,n) - \sum_{curt-type} Q_{curt}(j-vre,curt-type,t,n) + Q_{seasonal.storage} + Q_{short.storage} \quad (4.9)$$

In Eq(4.7) installed capacity of fuel cells needed for seasonal storage, their depreciation & investment cost is calculated. Eq(4.8) forces capital installation with respect to amount of storage. While, Eq(4.9) calculates new available electricity after deduction of curtailments and addition saved electricity by storage.

$$Cost_{storage}(t,n) = Q_{seasonal.storage} \times H_2.storage.cost[\frac{\$}{Wh}] + I_{short.storage} + I_{fuelcell.storage} \quad (4.10)$$

Eq(4.10) computes costs related to all types of storage for regions, in which $H_2.storage.cost$ is specific cost of storing hydrogen equal to $25[\frac{\$}{MWh}]$. [10] [17] [20]

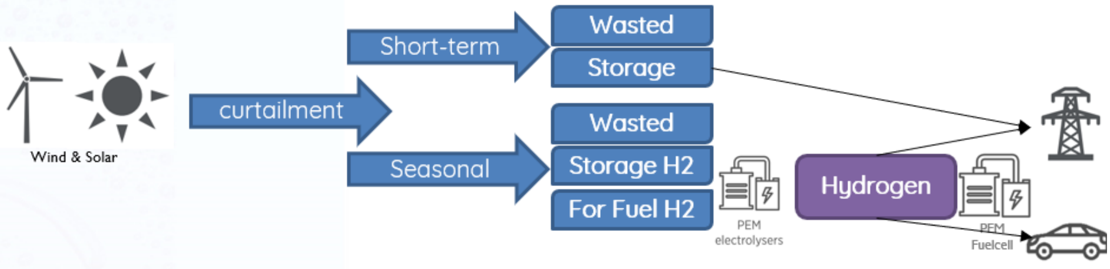


Figure (4.2) Brief structure of storage/curtailment

## 4.2 Hydrogen Module

### 4.2.1 Production of Hydrogen

For producing hydrogen in WITCH two methods chose. Steam gas reforming using natural gas with two options; With carbon capture, or without carbon capture, as well as electrolyzing electricity.

Energy efficiencies of plants is improving over time exogenously. 5% energy efficiency reduction is assumed due to presence of carbon capture, and electrolyzers assumed to enhance more because of more investments in R& D and its role in decarbonization targets.

| Production plant | Lifetime | Operating hours | O&M |
|---|---|---|---|
| **Steam Gas Reform (SGR)** | 25 | 5000 | 4% |
| **Electrolyzer** | 25 | 5000 | 3% |

Table (4.3) Hydrogen Production methods in WITCH

| Efficiency | <2025 | 2025-2050 | 2050< |
|---|---|---|---|
| **SGR** | 75% | 80% | 80% |
| **SGR + CCS** | 70% | 75% | 75% |
| **Electrolyzer** | 75% | 85% | 90% |

Table (4.4) Production efficiency

Capital investment costs can be seen in table(4.5). A constant CAPEX for SGR is assumed. On the other hand, for electrolyzer plants, an exogenous reduction of cost is considered suggested by [].

| Plant CAPEX [$/W] | <2030 | 2030-2050 | 2050< |
|---|---|---|---|
| **SGR** | 0.5 | 0.5 | 0.5 |
| **Electrolyzer** | 1.6 | 0.9 | 0.6 |

Table (4.5) CAPEX of production plants

For each type of production an installed capacity (K) and an invested capital (I) is defined. Depreciation rate is calculated as the same method as in previous section based on lifetime ($\delta$).

**Amount of needed natural gas calculation**

$$CH_4 + 2H_2O \leftrightharpoons CO_2 + 4H_2 \qquad \Delta H = +165\, kJ/mol \tag{4.11}$$

Based on main reaction of steam reforming, 1 mole of methane gives 4 moles of hydrogen. Giving molar of methane=$16\frac{Kg}{Kmol}$ and that of hydrogen=$2\frac{Kg}{Kmol}$, Heating value of methane=$48\frac{MJ}{Kg}$ and that of hydrogen=$120\frac{MJ}{Kg}$, we have following calculations:

$$48\frac{MJ}{kg} \times 16\frac{kg}{kmol} \times 1kmol_{CH4} \Rightarrow 120\frac{MJ}{kg} \times 2\frac{kg}{kmol} \times 4kmol_{H2} \tag{4.12}$$

$$768MJ_{CH_4} \rightarrow 960MJ_{H_2} \Rightarrow 0.8MJ_{CH_4} \rightarrow 1MJ_{H_2} \tag{4.13}$$

So for 1 unit of energy hydrogen we need 0.8 unit of energy methane from feedstock. We name it as "SGR-coefficient". In following equations amount of natural gas is linked between production sector and feedstock.

$$H_2.production(SGR,t,n) \times \eta(t) \times SGR.coefficient = Q_{NG.sgr} \tag{4.14}$$

$$H_2.production(SGRCCS,t,n) \times \eta(t) \times SGR.coefficient = Q_{NG.sgrccs} \quad (4.15)$$

**Connecting grid to electrolyzer plants**

Electricity is coming from grid ($Q_{grid}$) as well as seasonal curtailment as already discussed($Q_{curt.transport}$) to produce hydrogen by electrolyzing(elecz). Grid is connected to all electricity generations i.e. coal, gas, nuclear, wind, PV and CSP.

$$H_2.production(elecz,t,n) \times \eta(t) = Q_{grid} + Q_{curt.transport} \quad (4.16)$$

One more constraint is needed for total usage of seasonal curtailment in this part. It should be noted that difference between right-hand and left-hand of following equation in the wasted part of seasonal curtailment.

$$(Q_{seasonal.storage} + Q_{curt.transport}) \times \frac{1}{\eta_{elecz}} \leq Q_{curt.seasonal} \quad (4.17)$$

**Equations for investment, installed capacity and depreciation**

For each one the plants there is an equation as below.()

$$K_{prod.type(t+1,n)[W]} = K_{prod.type(t,n)}(1 - \delta^{\Delta t}_{(plant)})_{[W]} + \Delta t \frac{I_{plant(t+1,n)}[\$]}{CAPEX(prod.type,t+1,n)[\frac{\$}{W}]} \quad (4.18)$$

What is more, an equation is needed to connect all produced hydrogen to total hydrogen demand in transportation sector.()

$$\sum_{prod.type} H_2.production(prod.type) \times \eta(prod.type) = H_2.demand \quad (4.19)$$

Last equations of this part is dedicated to compel more capacity installation as a function of growing demand of production for each technology.

$$H_2.production(SGR\pm CCS,t,n) \leq K_{SGR\pm CCS(t,n)} \times Operating.hours[h] \quad (4.20)$$

There is a minor difference between the formulation of SGRs and elecz. That is because electricity used for storage needs electrolyzers too, so it is allocated here.

$$H_2.production(elecz,t,n) + Q_{seasonal.storage} \leq K_{elecz(t,n)} \times Operating.hours[h] \quad (4.21)$$

**Growth rate constraint** To be more realistic an equation is implemented for production plants which does not allow them to grow and expand faster than a certain percentage over a time step:

$$K(prod.type,t+1,n) \leq K(prod.type,t,n) \times (1+growth.rate)^{\Delta t} \quad (4.22)$$

Market growth rate is set to 15%, and it can be changed to analyze the difference in results.

**Equations for total costs of production**

total cost in each time step is summation of CAPEX for new installations as well as OPEX based on operation & maintenance which is a percentage of CAPEX.

$$Cost.prod(t,n) = \sum_{prod.type} I(prod.type,t,n) + \sum_{prod.type} O\&M(prod.type) \quad (4.23)$$

Also, for SGR+CCS amount of stored carbon is linked to carbon capture module of model. Its cost is being calculated based on different types of CCS technologies and stoichiometric coefficients. 89% of emissions will be stored in this scope. [31] [33]

### 4.2.2 Infrastructure

Two main infrastructural costs are taken into account. Regarding, transmission and distribution of hydrogen is modeled by pipelines. Also, some costs are related to construct new refueling stations to deliver hydrogen to final users.

**Pipelines**

Pipelines are one of the most difficult delivery technology to represent in energy system models because the capital investment costs and energy efficiencies depend on the pipeline length (and hence the spatial characteristics of the region), the diameter and the chosen throughput. To calculate the cost of pipelines two main factors are important.

- Cost of hydrogen delivery pipelines per length with is a function of its diameter[$ /L]
- Length of pipes demand which is function of hydrogen demand itself.

To calculate first parameter, following equation is implemented. [39] [23]

$$I\frac{\$}{m} = I_A \times D^2 + I_B \times D + I_C \tag{4.24}$$

| **Pressure[bar]** | 70-100 | $I_A$ **[$/mm2]** | 0.0022 |
|---|---|---|---|
| **Lifetime[y]** | 40 | $I_B$ **[$/mm]** | 0.86 |
| **O&M[1/year]** | 4% | $I_C$ **[$]** | 247.5 |
| **Density[kg/m^3]** | 5.7 | **Speed[m/s]** | 15 |

Table (4.6) Pipeline techno-economic parameters

It is assumed that 18% of total length is for transmission and delivering hydrogen from plants to borders of cities which requires more diameter i.e. 1m, while 82% is for distribution and delivering hydrogen from border of cities to refueling stations and has a diameter of 0.3m[]. Hence, we have following calculations:

$$D_{mean} = 18\%(D_{1000}) + 82\%(D_{300}) \tag{4.25}$$

And then with $D_{mean}$ we use equation 4.23 to calculate investment cost [$ /m].

Estimation of length demand is more tricky. There is no direct source or data, so in this project the ratio of existing natural gas pipelines over natural gas consumption in a region is used as a proxy to determine the length needed for a unit of hydrogen energy.

$$\frac{NG.network.length}{NG.consumption} = \frac{H_2.pipeline.length}{Hydrogen.demand} \tag{4.26}$$

Now to use the proxy we used a number of countries data. After comput-

| Country | NG consumption [PJ/year] | NG pipeline[km] | km/(Twh/year) |
|---|---|---|---|
| USA | 70000 | 1600000 | 282.81 |
| Germany | 2500 | 26000 | 128.67 |
| Brazil | 570 | 17000 | 369.01 |
| Japan | 1300 | 4456 | 42.41 |
| Indonesia | 600 | 11700 | 241.27 |
| Russia | 7600 | 163000 | 265.37 |
| Nigeria | 160 | 4000 | 309.59 |
| China | 4900 | 104000 | 262.61 |
| **Average = 237.25 km/(Twh/year)** | | | |

Table (4.7) Pipeline length proxy

ing necessary values, following equations is used for constructing new pipelines[Million meter], its depreciation over lifetime and investment cost.

$$L_{pipe(t+1,n)[Mm]} = L_{pipe(t,n)}(1-\delta^{\Delta t}_{(pipe)})_{[Mm]} + \Delta t \frac{I_{pipe(t+1,n)}[T\$]}{Inv.cost(pipe,t+1,n)[\frac{T\$}{Mm}]} \quad (4.27)$$

$$H_2.demand(t,n) \times TWh2Mm \leq L_{pipe}(t+1,n) \quad (4.28)$$

In which TWh2Mm coefficient is that of determined from table(4.7).

**Location factor & pipeline cost modeling** It is obvious that specific construction cost of pipelines could be different in each region due to the specific economical factors, labor cost and spatial features of region. Hence, to be more precise a location factor is considered as a multiplier to final costing for each region.

$$Cost.pipe(t,n) = Location.factor(n) \times (I_{pipe}(t,n) + O\&M_{pipe}) \quad (4.29)$$

**Refueling Stations**

Representing fueling stations in energy system models poses similar difficulties to pipeline simulation. It is necessary to define the fueling station design(s) and to assume an appropriate utilization factor which minimizes the investment costs while taking into account consumer behavior

| Region | Location factor |
|---|---|
| JPNKOR | 0.8 |
| MEXICO | |
| BRAZIL | |
| LACA | |
| SASIA | |
| SEASIA | |
| CHINA | 0.7 |
| INDIA | |
| INDONESIA | |
| SA | |
| SSA | |
| TE | |
| MENA | 0.9 |
| Others | 1 |

Table (4.8) Pipeline location factor

(consumers are not generally willing to organize their fueling station visits so that the maximum utilization rate is achieved throughout each day). However, considering all those complexities may be redundant and make the solving process harder. [28] [42] [41]

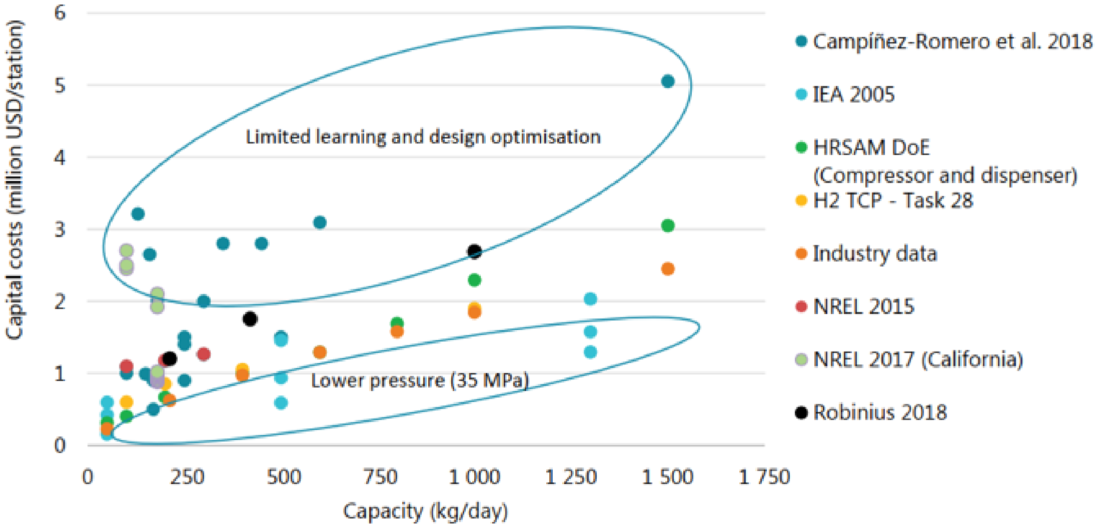


Figure (4.3) Literature review on refueling station cost

As it can be observed from the most of reports and literature estimations on refueling station cost are various, ranging a huge spectrum of values. In this project only 1 type of station is taken into account. **250kg/day≒ 1million $**
1kg of hydrogen gives roughly 33.6 kWh energy. Therefore, a coefficient of **TWh2Mton=0.0297** can be driven. Specific cost of refueling stations

can be computed as below:

$$\frac{1}{250}\frac{M\$}{kg/day} \times \frac{1\Delta t}{(365\times 5)days} \times 1000\frac{T\$.kg}{M\$.Mton} \approx 0.002192\frac{T\$}{Mton} \tag{4.30}$$

Now the main equations of stations:

$$K_{rf(t+1,n)[Mton]} = K_{rf(t,n)}(1-\delta^{\Delta t}_{(rf)})_{[Mton]} + \Delta t \frac{I_{rf(t+1,n)}[T\$]}{Inv.cost(rf,t+1,n)[\frac{T\$}{Mton}]} \tag{4.31}$$

$$H_2.demand(t,n)\times TWh2Mton \leq K_{rf}(t+1,n)[Mton] \tag{4.32}$$

$$Cost.rf(t,n) = I_{rf}(t,n) \tag{4.33}$$

## 4.3 Transportation Module

Road transport is explicitly modeled in WITCH, in two modules representing the passenger (in particular Light Duty Vehicles, LDVs) and the freight sectors. The rest of the transport sector is indirectly modeled in the aggregated non-electric sector in the CES structure.

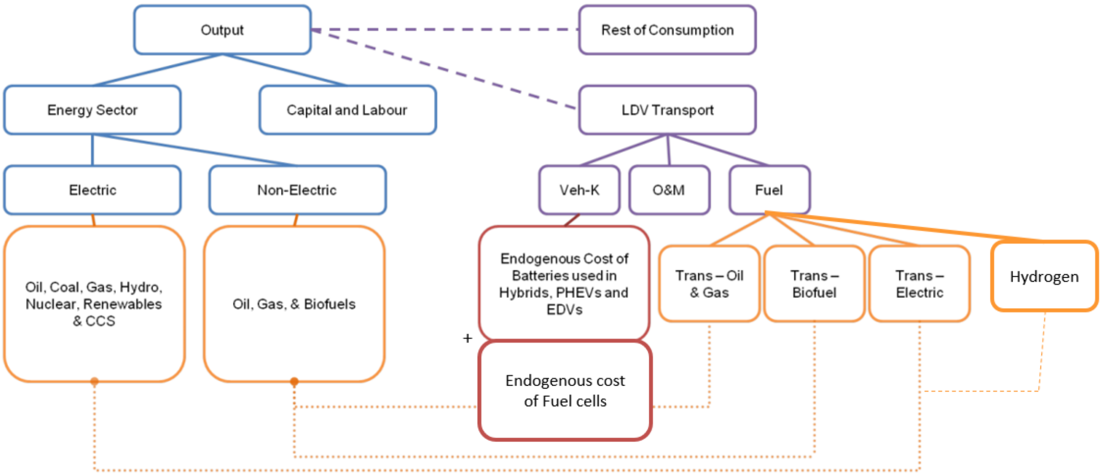


Figure (4.4) Transport Sector Structure

The LDV types (jveh) represented in the model are:

- Traditional combustion cars [trad_ cars]
- Hybrid cars [hybrid]
- Plug-in hybrid cars [plg_ hybrid]
- Electric drive cars [edv]
- Fuel cell cars [fcv]

The same vehicle classification is applied to trucks too, jfrt: i.e. trad_ stfr, hbd_ stfr, plg_ hbd_ stfr, edv_ stfr, fcv_ stfr.
The figure (4.4) shows how the structure of the road transport sector fits within WITCH. The composition of vehicle types (denoted in the figure as Veh-K) is determined by a Leontief function of a range of different costs. Modifications on cost of different vehicles will be explained later.

#### Quick information on different types of vehicles

- A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle whose battery can be recharged by plugging it into an external source of electric power, as well as by its on-board engine and generator. Most PHEVs are passenger cars, but there are also PHEV versions of commercial vehicles and vans, utility trucks, buses, trains, motorcycles, scooters, and military vehicles.
- A hybrid vehicle uses two or more distinct types of power, such as internal combustion engine to drive an electric generator that powers an electric motor, e.g. in diesel-electric trains using diesel engines to drive an electric generator that powers an electric motor, and submarines that use diesels when surfaced and batteries when submerged. Other means to store energy include pressurized fluid in hydraulic hybrids.
- A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is a type of electric vehicle which uses a fuel cell, instead of a battery, or in combination with a battery or supercapacitor, to power its on-board electric motor. Fuel cells in vehicles generate electricity to power the motor, generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat.

- An electric vehicle, also called an EV, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery, solar panels or an electric generator to convert fuel to electricity.
- Traditional vehicles means vehicles that work with internal combustion engine (ICE). An internal combustion engine (ICE) is a heat engine in which the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is applied typically to pistons, turbine blades, rotor or a nozzle. This force moves the component over a distance, transforming chemical energy into useful work.

[40]

### 4.3.1 Total Number of Transportation Fleet

The number of vehicles (both LDV and freight) is set equal to a projection depending on GDP and population growth. This projection is not part of the optimization process (i.e. given GDP and population, demand is given). Concerning LDVs, the calculation of the number of vehicles per thousand capita ldv_ pthc(t, n) is based on the IEA/SMP model (Fulton and Eads 2004) which is in turn based on the work of (Dargay and Gately 1999). The following equation has been implemented with parameters set to those in the table below. In particular, the Autonomous Increase (AI) and the Ownership Growth Elasticity (OGE) values depend on the GDP per capita and on the relevant ownership level.

| GDP_pc | Max Ownership Level | Ownership Elascticity | (AI) |
|---|---|---|---|
| $\leq$ 5000 $ | no maximum | 0.30 | 3 |
| >5000 $ | 300 vehicles per thousand capita | 1.30 | 3 |
| >5000 $ | 500 vehicles per thousand capita | 0.60 | 3 |
| >5000 $ | 600 vehicles per thousand capita | 0.25 | 4 |
| >5000 $ | n/a | 0.10 | 4 |

Table (4.9) Ownership level data

$$ldv_{pthc}(t,n) = ldv_{pthc}(t-1,n) \times (1 + (\frac{gdp_{pc}(t,n)}{gdp_{pc}(t-1,n)} - 1) \times OGE) + AI \tag{4.34}$$

The total number of vehicles is obtained by multiplying this value by the population.

$$ldv_{tot}(t,n) = ldv_{pthc}(t,n) \times population(t,n) \tag{4.35}$$

Concerning trucks, the total number of vehicles, strf_ total, grows over time according to the GDP per capita growth (again, following the IEA/SMP modeling assumption, Fulton and Eads (2004)).

$$stfr_{tot}(t,n) = stfr_{tot}(t-1,n) \times \frac{gpd_{pc}(t,n)}{gpd_{pc}(t-1,n)} \tag{4.36}$$

Initial number of cars and trucks are among inputs of model. After that, the composition of the vehicle fleet, for both LDVs and freight, is determined by the optimization model, where a linear competition among the vehicle types takes place (mitigated by the presence of additional restrictions and constraints, see below).

$$ldv_{tot}(t,n) = \sum_{jveh} K_{EN}(jveh,t,n) \tag{4.37}$$

$$stfr_{tot}(t,n) = \sum_{jfrt} K_{EN}(jfrt,t,n) \tag{4.38}$$

In which, $K_{EN}$ is the number of each type of vehicle and trucks [million cars]. [24] [29]

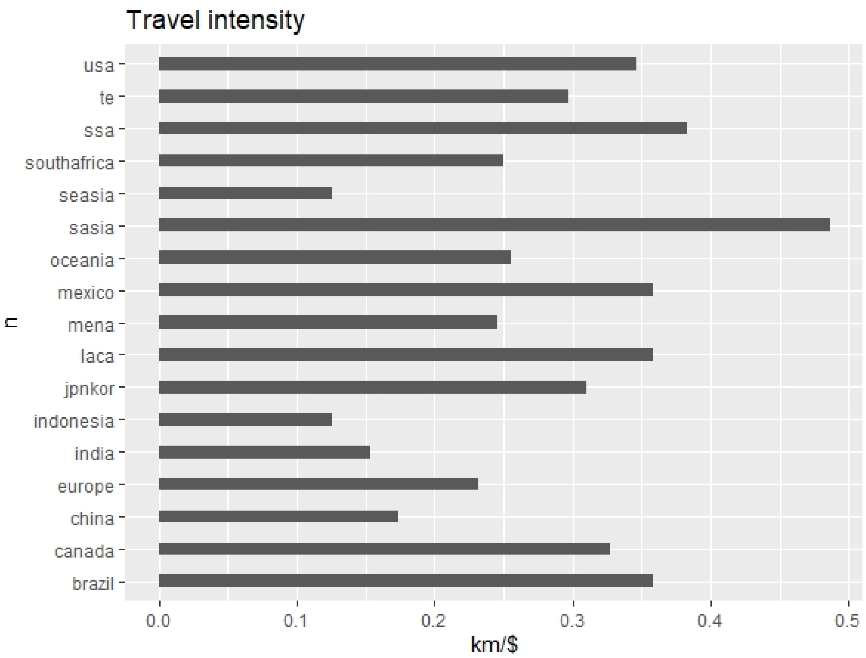


Figure (4.5) Travel intensity of different regions in WITCH

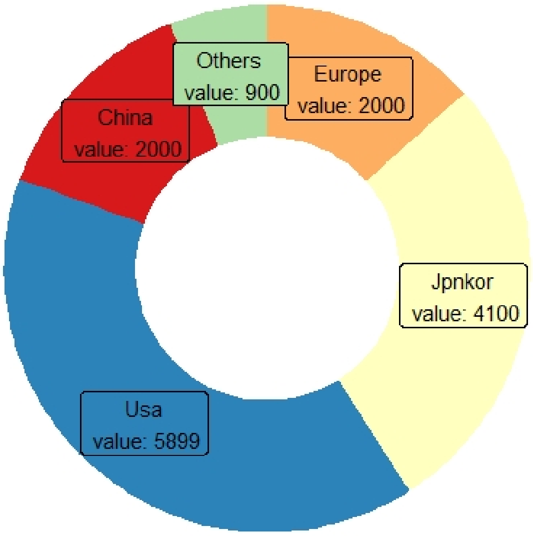


Figure (4.6) Initial number of fuel cell vehicles inputted into model

Figure 4.6 shows the already existing number of fuel cell vehicles which it is implemented and inputted as initial condition. [25]

### 4.3.2 Kilometer Demand & Fuel Consumption

Energy consumption associated to the different vehicle types is given by the product of the number of vehicles, the kilometer demand per vehicle (km_ d) and the specific fuel consumption (fuel_ cons):

$$Q_{EN}(jveh,t,n) = km_d.ldv(t,n) \times fuel.cons(jveh,t,n) \times K_{EN}(jveh,t,n) \tag{4.39}$$

The equation is written for LDVs (jveh), but the same applies to freight (jfrt).

Fuel consumption is the energy consumed by each vehicle for covering one kilometer. It exponentially decreases over time in order to simulate advancements in vehicle efficiency, approximately halving by the end of the century.

$$fuel.cons(jveh,t,n) = fuel.cons_{2005}(jveh,n) \times t^{eff.rate(t,n)} \tag{4.40}$$

eff.rate for LDVs is equal to -25% and for STFRs is equal to -22% [in code frt].

Concerning LDVs, the kilometer demand is calculated starting from the travel intensity, derived from IEA/SMP and considered constant over time in the different regions, according to the following scheme:

$$km_d.ldv_{tot}(t,n) = travel.intensity(t,n) \times GDP(t,n) \tag{4.41}$$

$$km_d.ldv(t,n) = \frac{km_d.ldv_{tot}(t,n)}{ldv_{tot}(t,n)} \tag{4.42}$$

More details regarding the LDV modeling can be found in (Bosetti and Longden 2013), while the freight sector modeling is described in Carrara and Longden (forthcoming, 2016).

### 4.3.3 Cost of Vehicles

While the cost of traditional combustion vehicles is held constant at 2005 levels, cost of other type of vehicles are a function of their key components.

| Vehicle | Electric Motor[kW] | Battery[kWh] | Fuelcell[kW] | ICE[kW] |
|---|---|---|---|---|
| hybrid | 20 | 2.4 | 0 | 58 |
| plg-hybrud | 47 | 8 | 0 | 58 |
| edv | 75 | 55 | 0 | 0 |
| fcv | 75 | 1.3 | 70 | 0 |

Table (4.10) Size of key components

| | Manufacturing | Elec. Motor | Fuelcell | Battery | ICE | Tank | Charger |
|---|---|---|---|---|---|---|---|
| trad-cars | $\chi$ | | | | $\chi$ | $\chi$ | |
| hybrid | $\chi$ | $\chi$ | | $\chi$ | $\chi$ | $\chi$ | |
| plg-hybrid | $\chi$ | $\chi$ | | $\chi$ | $\chi$ | $\chi$ | $\chi$ |
| edv | $\chi$ | $\chi$ | | $\chi$ | | | $\chi$ |
| fcv | $\chi$ | $\chi$ | $\chi$ | $\chi$ | | $\chi$ | |

Table (4.11) Cost component in different type of vehicles

General formulation is as below:

$$\begin{aligned}
&\textbf{Vehicle}\quad \textbf{cost} = Manufacturing\ cost + \\
&Internal\ combustion\ engine(ICE)\ cost \times size + \\
&Electric\ motor\ and\ transmission\ cost \times size + \\
&Battery\ cost \times size + \\
&Fuel\ cell\ cost \times size + \\
&\qquad\qquad\qquad\qquad\qquad Petrol\ tank/Charger
\end{aligned} \tag{4.43}$$

Regarding electric drive vehicles an additional term is added to total cost of ownership related to the cost of recharging stations. That is mainly because of more coherency between edvs and their main competitors (fcvs).

### 4.3.4 Key Components

The characteristics of future technologies are inevitably changing over the next decades due to technological learning: generally learning curves are applied both to energy requirements and costs, resulting a function of time, cumulative capacity, and R&D investment. Significant cost reduction may result from R&D before a technology enters the market, as well as further rebates can take place after market introduction, through learning-by-doing, economies of scale, continued research and maturing supply chains.

Given that it is not possible to foresee exactly the evolution of costs, three different approaches may be used when working with IAMs:

1. Assume no technological change to examine whether, with stock turnovers, current technology characteristics are sufficient to meet energy system goals.

2. Use Exogenous Technical Learning, that is an exogenous forecasts of how technologies' costs may develop in the future. Cost reduction depends only on the time elapsed and may thus be specified

outside the model. It is possible to forecast such changes as a function of time according to historical comparison with similar technologies.

3. Use Endogenous Technical Learning (ETL), meaning that the future cost parameters are no longer a function of time alone, but depend on the experience acquired and the knowledge stock accumulated around that technology. It is mentioned that two types of ETL is possible; one-factor curve & two-factor curve.

| | Constant | Exogenous Change | Endogenous Change | |
|---|---|---|---|---|
| Manufacturing | $\chi$ | | LBD | LBR |
| Electric Motor | | $\chi$ | | |
| Fuelcell | | | | $\chi$ |
| Battery | | | $\chi$ | $\chi$ |
| ICE | $\chi$ | | | |

Table (4.12) Technology change modes

#### Knowledge stock and R& D Coefficients

At each point in time, new ideas are produced using a Cobb-Douglas combination between domestic investments in innovation, $I_{RD}$, the existing stock of knowledge, $RD_{rd}$ and the knowledge of other countries, SPILL. The contribution of foreign knowledge to the production of new domestic ideas depends on the interaction between two terms: the first describes the absorptive capacity whereas the second captures the distance from the technology frontier, which is represented by the stock of knowledge in leader countries. i.e. USA, JPNKOR, EURO, CANADA, CHINA.

$$RD(n,t+1) = RD(n,t)(1-\delta_{rd})^{\Delta t} + \Delta t . I_{rd}^{b} \times SPILL_{rd}(t,n)^{d} \tag{4.44}$$

#### Costs of Key Components

Figure 4.7 shows the coherence between calculated battery cost in WITCH and predictions. [4] [27] [32] [44] [18]

| **R&D factors** | **Battery** | **Fuelcell** |
|---|---|---|
| a | 1 | 1 |
| b | 0.85 | 0.9 |
| c | 0 | 0 |
| d | 0.15 | 0.15 |
| lbr | -0.193 | -0.277 |
| lbd | -0.160 | 0 |
| $\delta$ | 5% | 5% |
| Start[year] | 2020 | 2030 |
| Gap[years] | 10 | 10 |

Table (4.13) R&D factors of battery and fuelcell

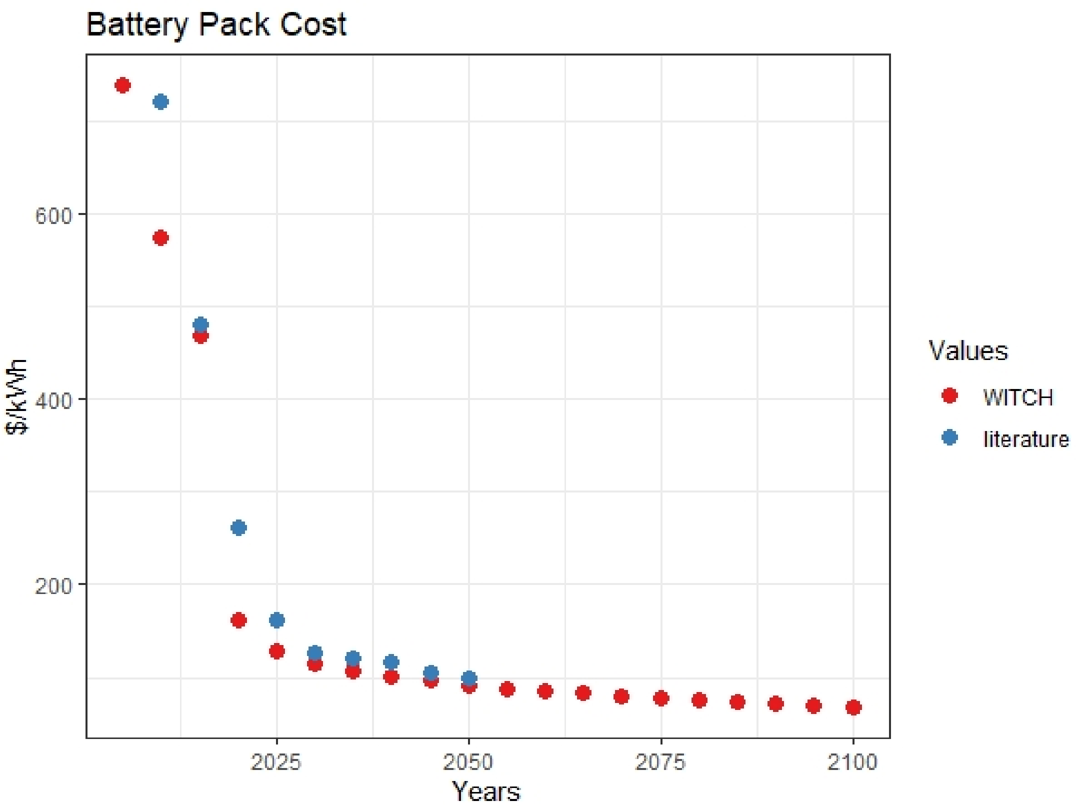


Figure (4.7) Battery pack cost in WITCH

And also costs of fuel cell through R& D determines at below.

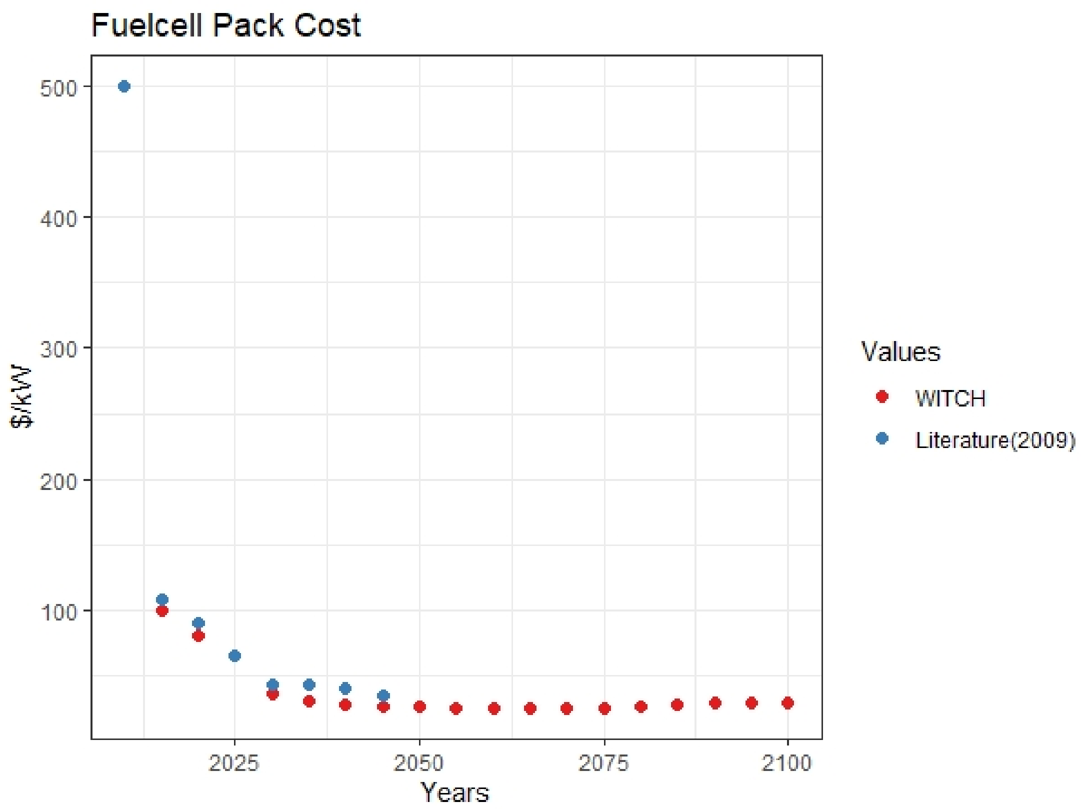


Figure (4.8) Fuelcell pack cost in WITCH

| Year | <2010 | 2010-2030 | 2030-2050 | >2050 |
|---|---|---|---|---|
| Electric motor cost [$/kW] | 243 | 40 | 31 | 23 |

Table (4.14) Electric motor cost

### 4.3.5 Freight

Concerning number of trucks, the total number of vehicles, strf_ total, grows over time according to the GDP per capita growth (again, following the IEA/SMP modelling assumption, Fulton and Eads (2004)).

$$stfr_{pthc}(t,n) = stfr_{pthc}(t-1,n)(\frac{gdp_{pc}(t,n)}{gdp_{pc}(t-1,n)}) \tag{4.45}$$

To compute the costs of trucks, a value for traditional truck is fixed and assumed as reference cost. Then, cost of other types calculated accordingly:

$$\begin{aligned}&\textbf{Truck}\quad\textbf{cost} = \alpha\,(cost_{reference}) + \\ &disutility\ cost + \\ &Battery\ cost \times size + \\ &\qquad Fuel\ cell\ cost \times size\end{aligned} \tag{4.46}$$

Disutility cost acounts for Additional costs to investment cost of freight. and $\alpha$ is a coefficient which related to the manufacturing cost after reducing a portion of that due to absence of internal combustion engines for edv_ stfr and fcv_ stfr. [6] [45]

| **Truck type** | **Battery size [kWh]** |
|---|---|
| Hybrid | 8.75 |
| Plug-in hybrid | 110 |
| Electric drive | 310 |
| Fuel cell | 120 |

Table (4.15) Battery size of freight trucks

# Chapter 5

# Scenarios and Results

## 5.1 Scenario Definition

In this context two main attributes distinguishes different scenarios defined to analyze the results. **Carbon Tax** & **Carbon Budget**.
Carbon tax is a form of pollution tax. It levies a fee on the production, distribution or use of fossil fuels based on how much carbon their combustion emits. The government sets a price per ton on carbon, then translates it into a tax on electricity, natural gas or oil.
A carbon budget can be defined as a tolerable quantity of greenhouse gas emissions that can be emitted in total over a specified time. The budget needs to be in line with what is scientifically required to keep global warming and thus climate change "tolerable." Carbon budgeting should not be confused with the use of targets, thresholds or caps to set emissions reduction goals.
All being said, 3 main scenarios are considered listed below:

1. **Scenario A:** Baseline scenario without imposing any carbon tax or carbon budget.

2. **Scenario B:** Imposing initial carbon tax equal to 30 $[\$/tCo2]$ at 2020 which results in 2C temperature at 2100.

3. **Scenario C:** Implementing carbon budget, Total CO2, 2019-2100 equal to 800 Gton.

**Time horizon** As discussed earlier default time horizon in WITCH is 2005-2150 with 30 time steps of 5 years. To avoid overshooting it is decided to mainly limit the ending year to 2100. Data are calibrated in 2005 or/and 2020 data.

**Shared Socioeconomic Pathways** Over the past few years, an international team of climate scientists, economists and energy systems modellers have built a range of new "pathways" that examine how global society, demographics and economics might change over the next century. They are collectively known as the "Shared Socioeconomic Pathways" (SSPs).These SSPs are now being used as important inputs for the latest climate models and in this context SSP2 is used as the baseline (Middle of the road).

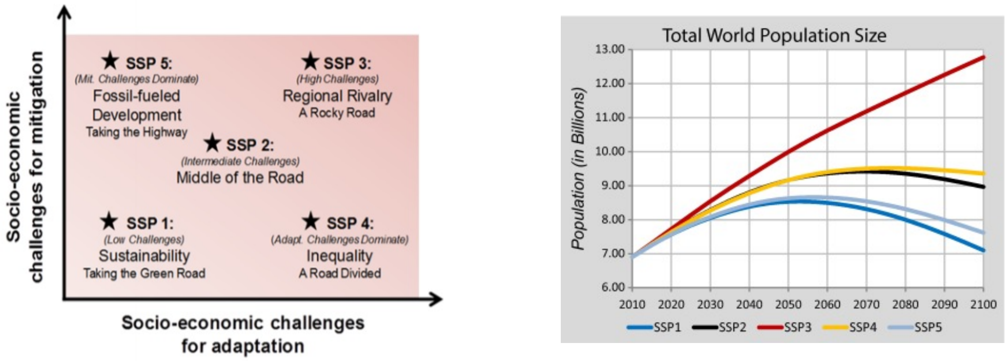
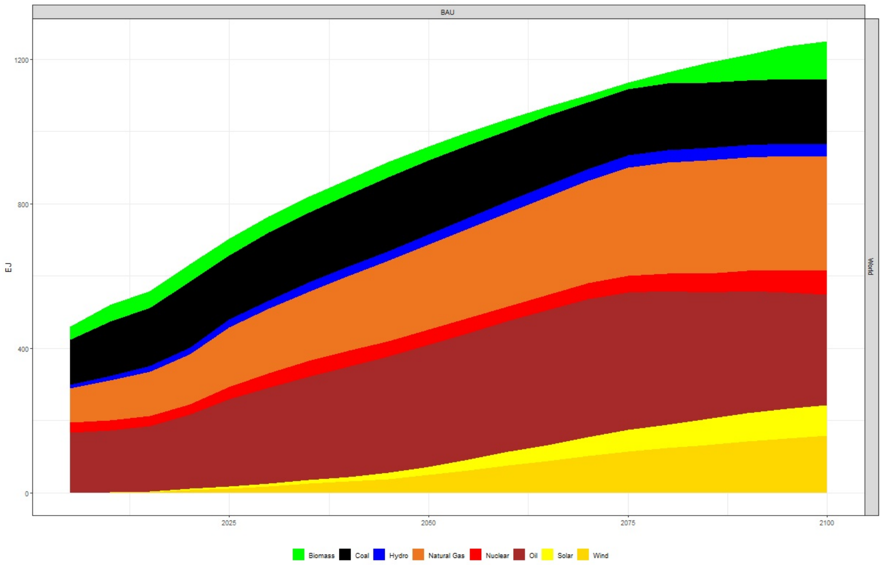


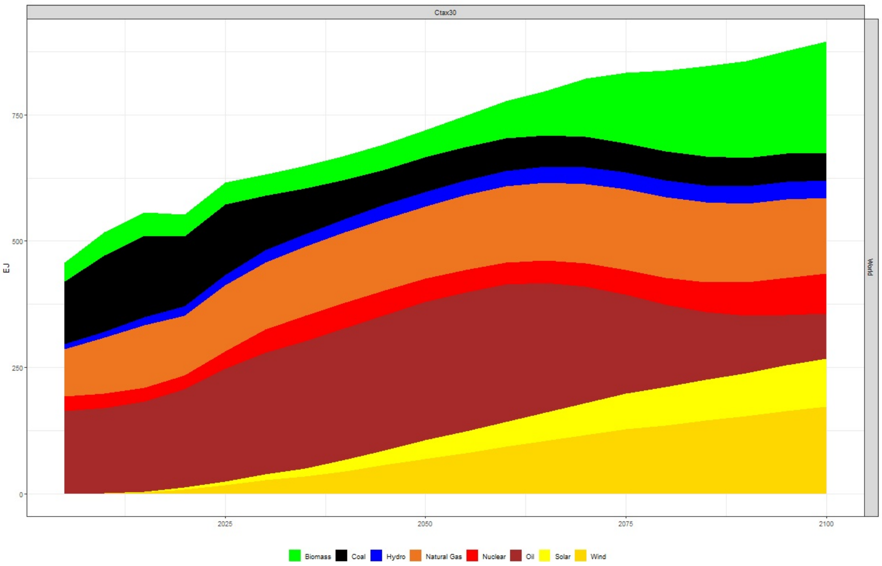
Figure (5.1) Different SSPs defined by IIASA

### 5.1.1 Energy mix

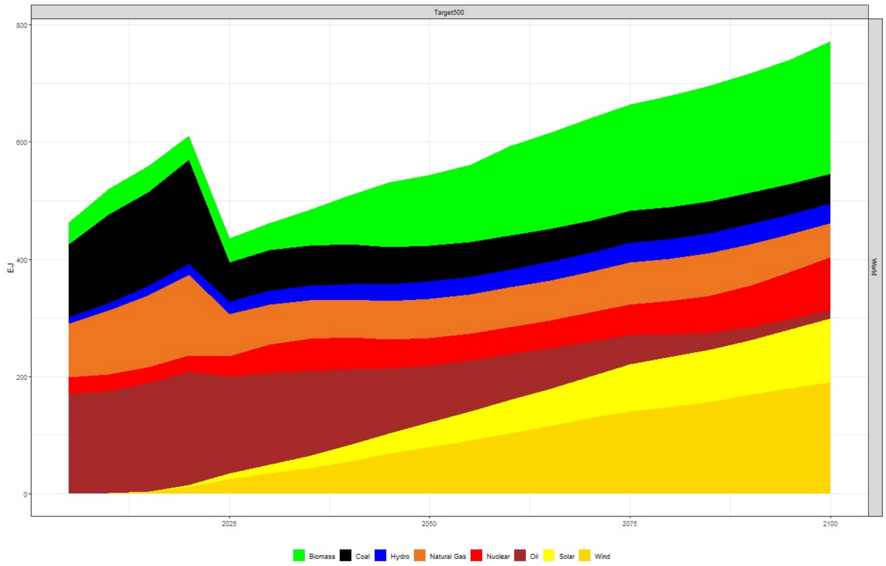
By implementing different scenarios energy mix of world would be diverse. By putting more severe constraints and carbon policies there are more renewables available such as biomass, wind and solar, while the amount of energy produced by fossil fuel sources such as coal, oil and gas decline. It is imperative to understand this behavior to perceive further results and changes due to various policies.



(a) Scenario A



(b) Scenario B



(c) Scenario C

Figure (5.2) Energy mix for different scenarios

### 5.1.2 Climate related outcomes

This is part is dedicated to monitor some general outcomes by already defined scenarios in order to know better the situation imposed by each scenario.

**Carbon tax** In scenarios based on an initial carbon tax, starting carbon tax is an input, however, over time model chooses the next values of carbon tax based on a numerous of other parameters. Here we can see the evolution of carbon taxation over time based on different scenarios

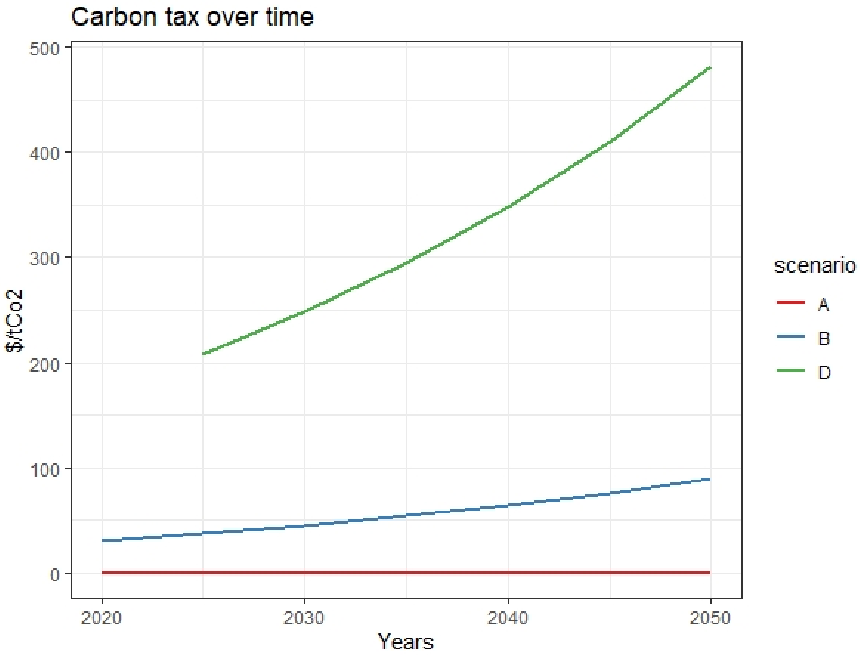


Figure (5.3) Carbon tax of different scenarios over time

**Emission** Global stock of Co2 is the cumulative quantity of carbon dioxide which is in atmosphere. We can observe an immense difference between different scenarios. Scenario A will continue to accumulate more and more carbon while other scenarios change their slop over time and even become negative in some cases.

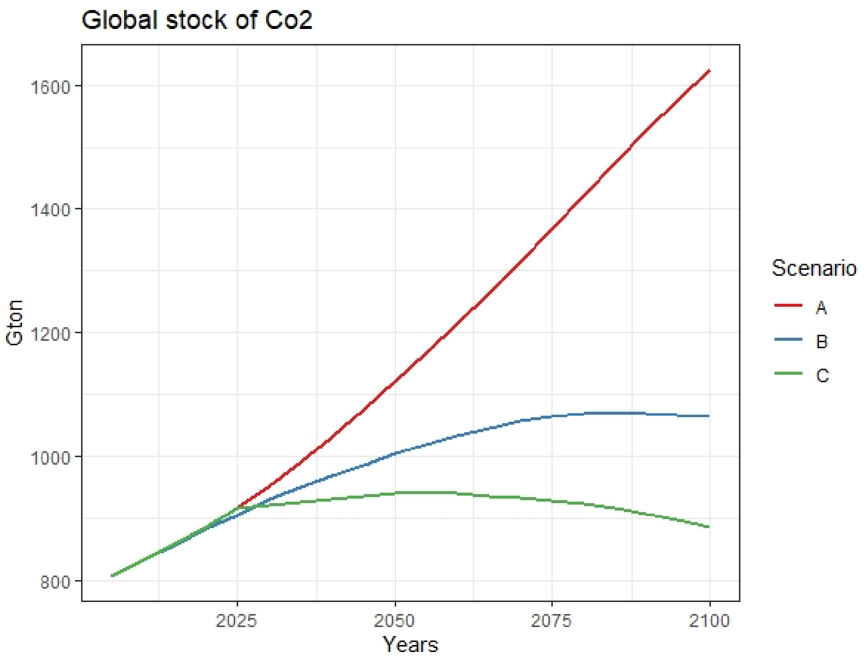


Figure (5.4) Cumulative Co2 stock

In the following figure we can see Co2 emission per year produced.

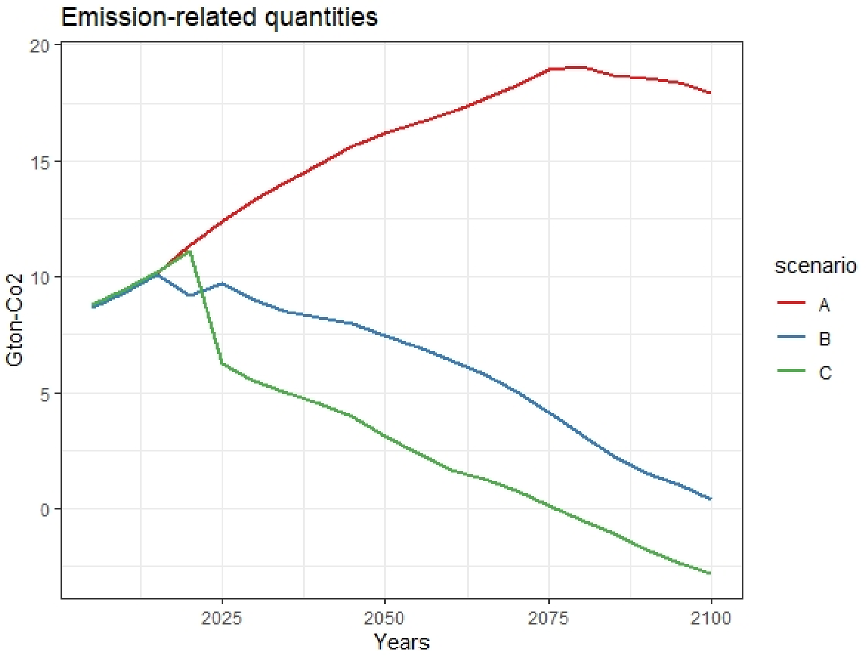


Figure (5.5) Carbon dioxide quantity

In scenario B it decreases to reach 0 at the end of century. Scenario C and D lead to a condition that cause negative carbon emission. The turning point is around 2075.

**Temperature** Finally, we can observe the change in temperature difference between present and pre-industries (1900) for each scenario.

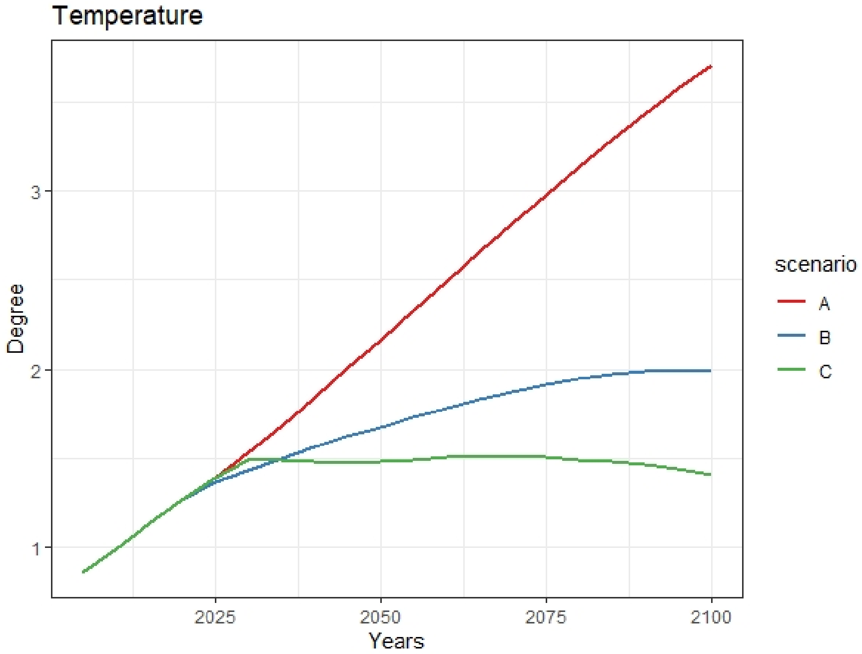


Figure (5.6) Temperature

Scenario A just raises the temperature to around 4°$C$ at 2100 while scenario B gives rise to 2°$C$ which is compatible with goals in Paris agreement in 2015. Scenario C shows a more ambitious goal which is reaching lower than 2°$C$ (around 1.5°$C$).

**Carbon intensity** Energy intensity is a measure of the energy inefficiency of an economy. It is calculated as units of energy per unit of GDP. High energy intensities indicate a high price or cost of converting energy into GDP.

An emission intensity (also carbon intensity) is the emission rate of a given pollutant relative to the intensity of a specific activity, or an industrial production process; for example grams of carbon dioxide released per megajoule of energy produced, or the ratio of greenhouse gas emissions produced to GDP.

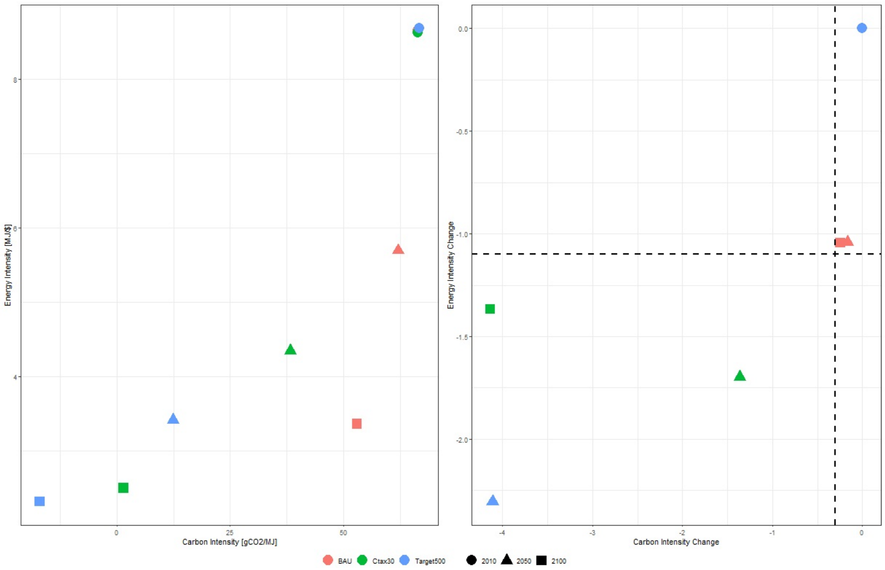


Figure (5.7) Carbon intensity

On the figure above Y-axis shows energy intensity $[MJ/\$]$ and X-axis shows carbon intensity$[gCo2/\$]$. By observing the figure we can understand the better energy efficiency of scenario B and C with respect to A over different time horizons.

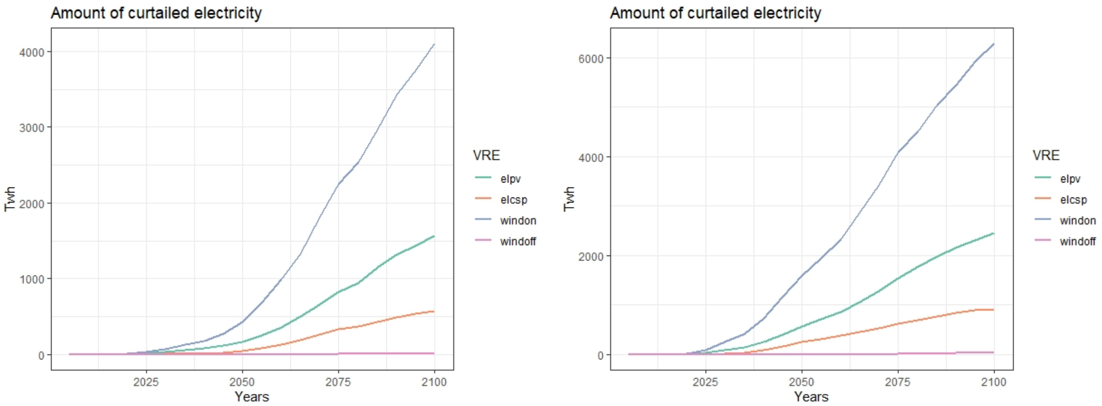
## 5.2 Results

### 5.2.1 Storage and curtailment

First, let see some results on the curtailment and storage added module. Figure below shows the amount of total worldwide curtailed electricity distinguished by the type of VRE. Scenario A and B are compared in a frame and it can be understood that in scenario B as we impose carbon tax, so the share of renewables is higher than that of scenario A. Curtailment was defined as a function of share of VRE, so the higher VRE, the higher curtailment.

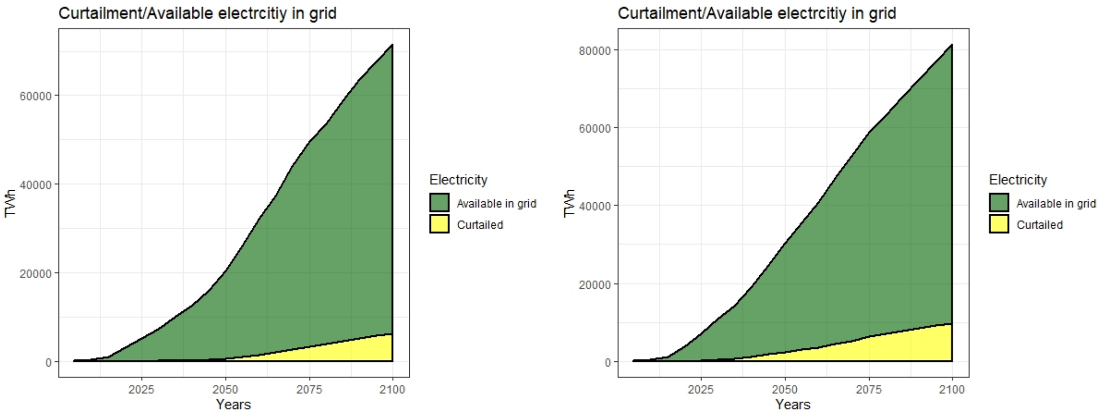
Now, let see the share of these amount of extra electricity in proportion to total electricity generation. In scenario A which is high carbon, the ratio of $\frac{Curtailment}{Total-electricity}$ is around $7\%$ while in scenario B this value is around $12.5\%$. So, one of the biggest problems of decarbonization in energy and electricity sector can be seen here. One major aim of this project is to make this problem into an advantage by giving the possibility to use extra generation.

As it is mentioned before, curtailed electricity is divided into two categories; short-term and seasonal. short-term has two main options, either



(a) Scenario A (b) Scenario B

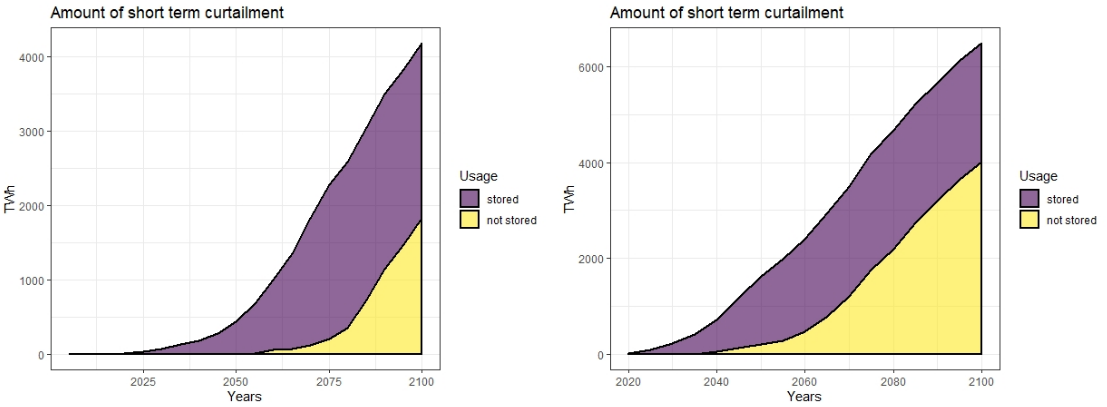
Figure (5.8) Curtailment amount over time



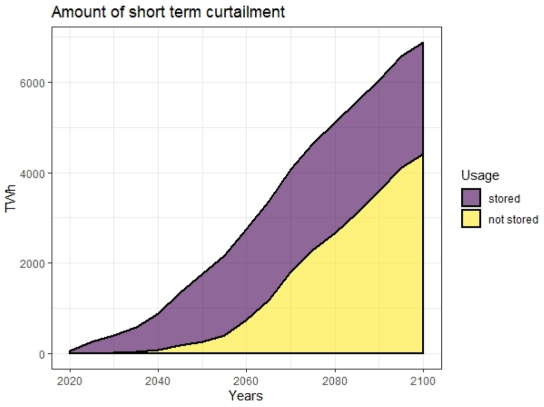
(a) Scenario A (b) Scenario B

Figure (5.9) Curtailment percentage in comparison to total generation

to be stored or not be stored due to presumably high cost of storage technologies.



(a) Scenario A (b) Scenario B



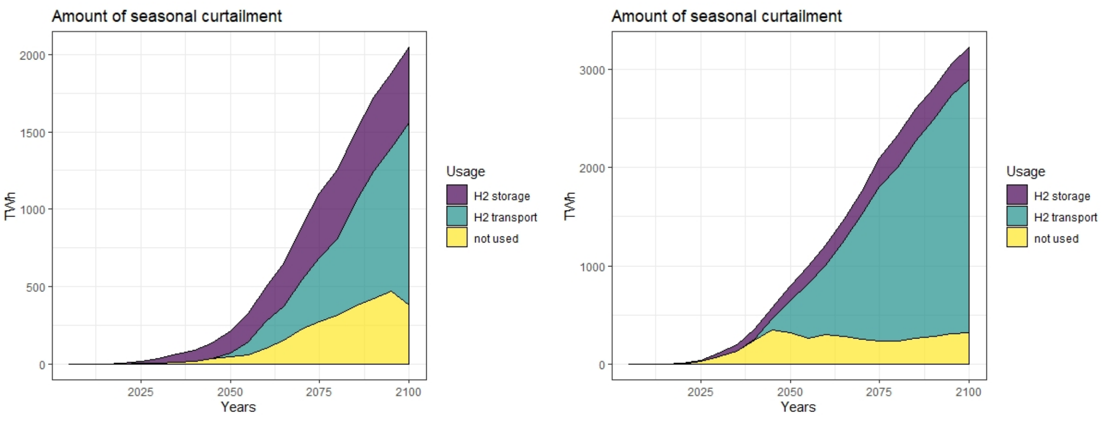
(c) Scenario C

Figure (5.10) Stored short-term curtailment vs not stored

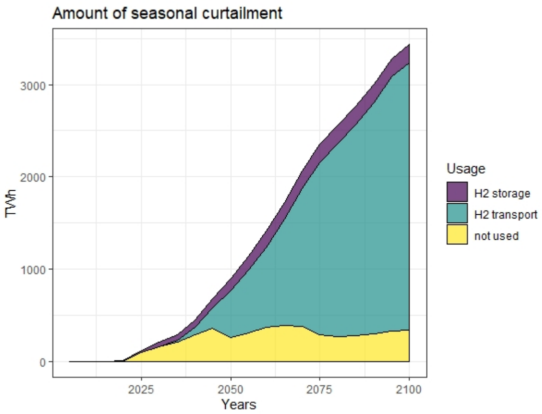
Optimization process is linear in this part, so considering the costs of storage by different technologies i.e. CAES, Hydro pump and Li-ion batteries, regions choose same amount of short-term storage regardless of scenario and price of carbon. However, the share of storage decreases over higher carbon tax and that's mainly because of constant storage and higher total curtailment.

On the other hand, seasonal extra electricity has three options; 1.converted into hydrogen to be used in transportation sector as fuel, 2.converted into hydrogen to be stored and goes back to grid when needed, 3.not used and be wasted due to high costs. If option 1 or 2 is chosen, it means that we need electrolyzers proportional to the amount of converted hydrogen. After that to use this hydrogen from hydrogen feedstock, in option 2 external fuel cells are needed to turn the hydrogen back to electricity which implies more investment costs. For option 1, fuel cells are in vehicles and their cost is accounted into vehicles' ownership cost.

Almost in all scenarios the major part is allocated to option 1 which



(a) Scenario A (b) Scenario B



(c) Scenario C

Figure (5.11) Different usage of seasonal curtailment in different scenarios

is using extra electricity as converted hydrogen fuels. in scenario B and C there are more usage of fuel cell vehicles so the amount of needed hydrogen is higher than that of scenario A. Ratio of storage in Scenario A and D is higher than others which implies that costs of storage plus extra electrolyzers and fuel cells are still low enough to store electricity as hydrogen and use it in grid.

### 5.2.2 Transportation

#### Number of Vehicles

In this part results for transportation module will be said. First and most important result is about total share of vehicles in world by implementing different scenarios of climate change.

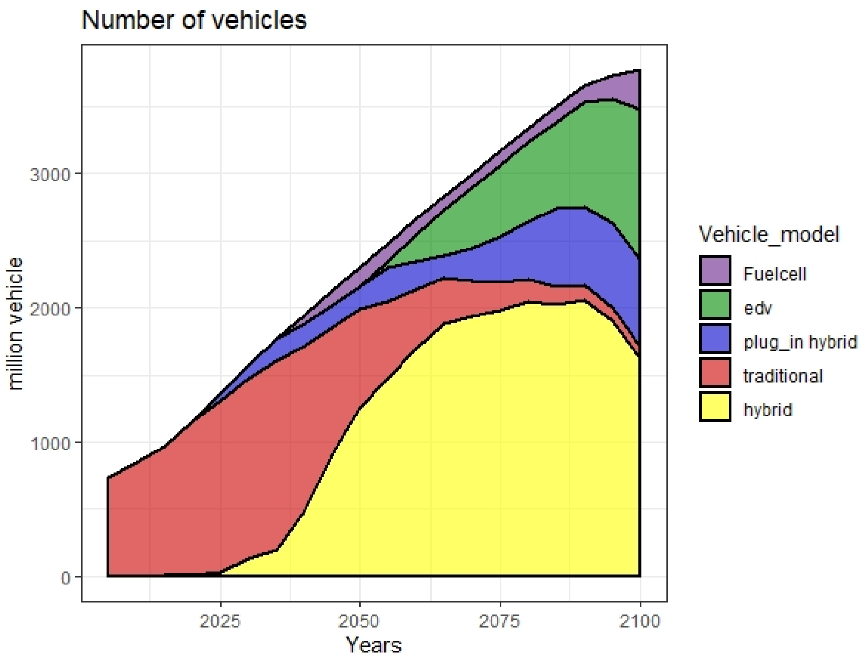


Figure (5.12) Share of worldwide vehicle fleet scenario A

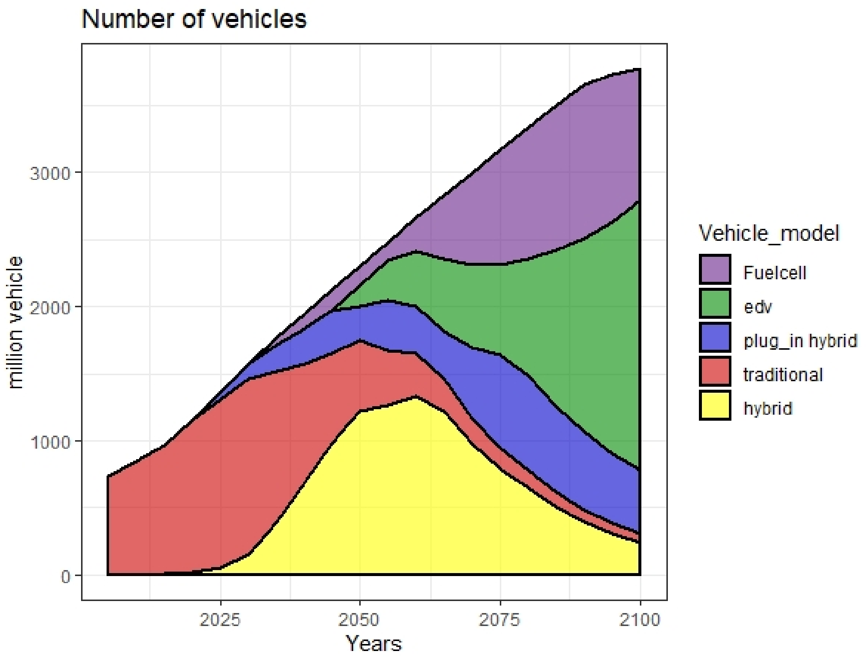


Figure (5.13) Share of worldwide vehicle fleet scenario B

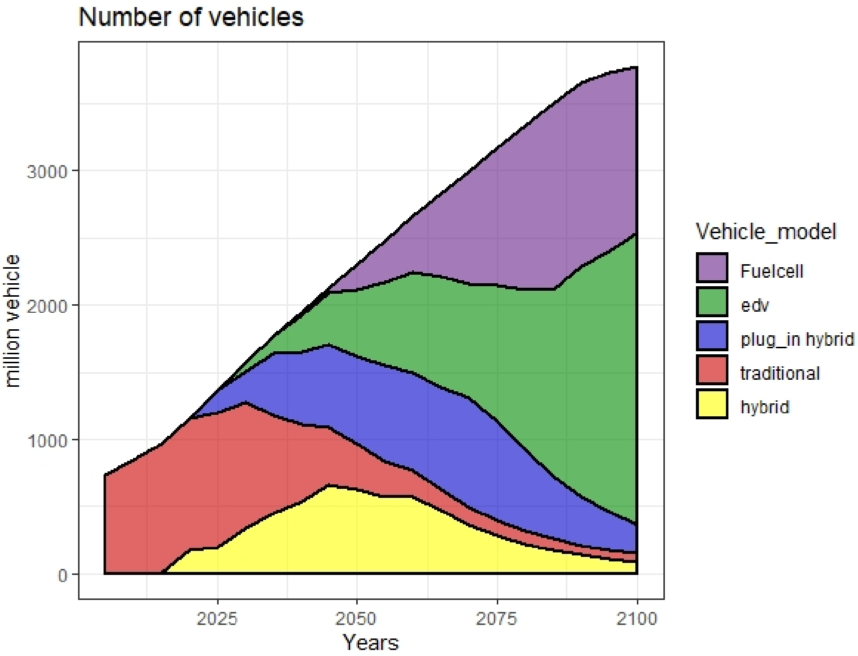


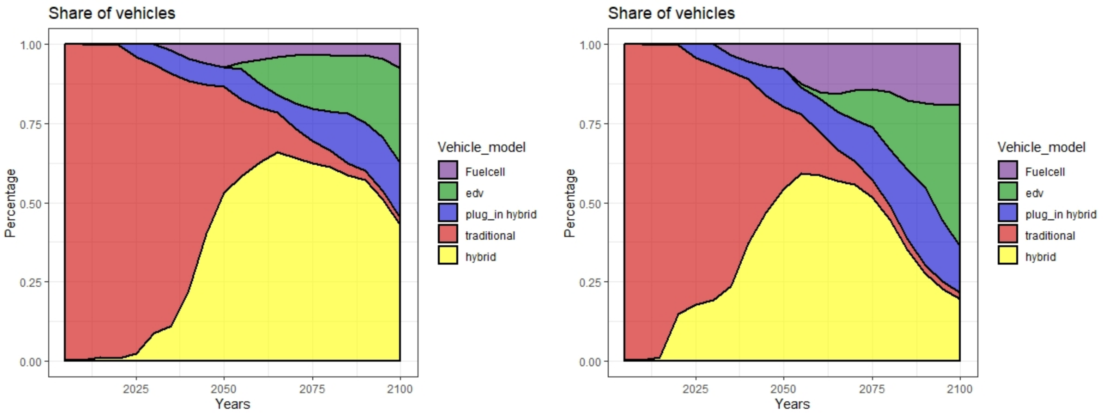
Figure (5.14) Share of worldwide vehicle fleet scenario C

In scenario A (no carbon tax) dominant type is still going to be traditional diesel vehicles until 2025. After that, hybrid vehicles and plug-in hybrid vehicles starts to grow. After 2060 fuel cell and electric drive vehicles start to showing up in the world fleet, however, the numbers are not huge and they cannot expand efficiently due to higher costs of manufacturing and infrastructure and no taxing on carbons emitted by traditional and hybrid vehicles. At the end of century hybrid and plug-in hybrid will be the dominant part of transportation light duty vehicles.

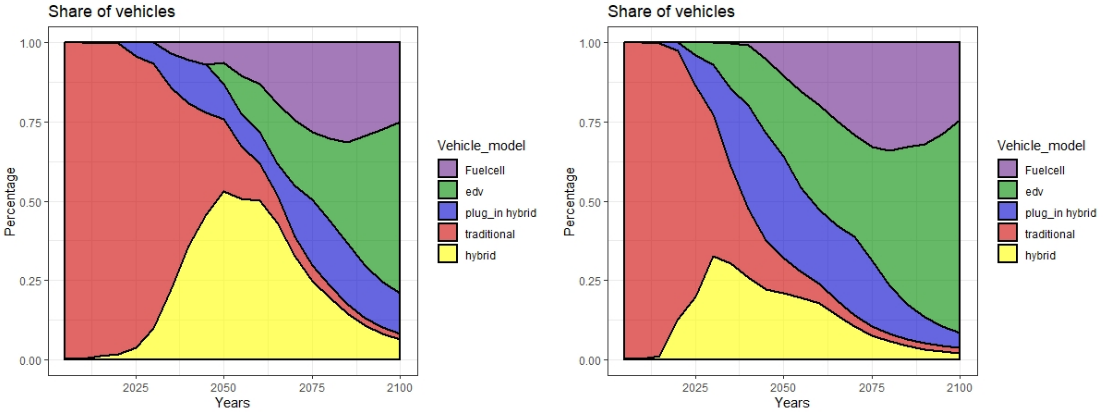
Scenario B is with initial carbon tax of $30\frac{\$}{tCo2}$, so in the first period of time (up to 2025) still traditional vehicles are dominant but hybrid vehicles are present more than previous scenario. This early dominance of diesel cars are due to their momentum and strong presence in today's world. Consequently, after around 2050 fuel cell, electric and plug-in hybrid vehicles start to expand rapidly. Figure 5.13 shows the importance of all of these three types in a future green transportation. It is a matter of region based on their own unique socio-economic, utility and resources to use which one of vehicles. At the end of century, hybrid and traditional cars are almost removed from the fleet.

Scenario C is a more extreme case of scenario B, consequently, plug-in hybrids start to grow sooner than before. Another interesting founding is that electric vehicles start their presence sooner than fuel cell cars (unlike scenario B). It stands to reason that a normal carbon tax is in favor of hydrogen cars while imposing an extreme tax is in favor of electric cars. In

fact, at 2100 number of hybrids are less than before and there are more electric vehicles instead of hybrid and diesel cars. Number of hydrogen vehicles are almost as much as previous case.
All in all, by comparing these figures, one can conclude that in order to transition to a more environmental-friendly vehicle fleet it is imperative to impose restricting policies such as carbon tax or carbon budget. Another point is that fuel cell vehicles does not need an extremely high carbon tax to be presence in the future of transportation. On the other hand, by increasing carbon tax, electric vehicles will become more and more dominant. In the next parts we will go more detail into regions.



(a) BAU (b) Carbon tax 10



(c) Carbon tax 30 (d) Carbon budget

Figure (5.15) Percentage share of vehicle fleet

**Detailed regional usage of FCV**

In this section we will go through the usage of fuel cell vehicles in different regions and different time steps to understand how can hydrogen be a part of future transportation.

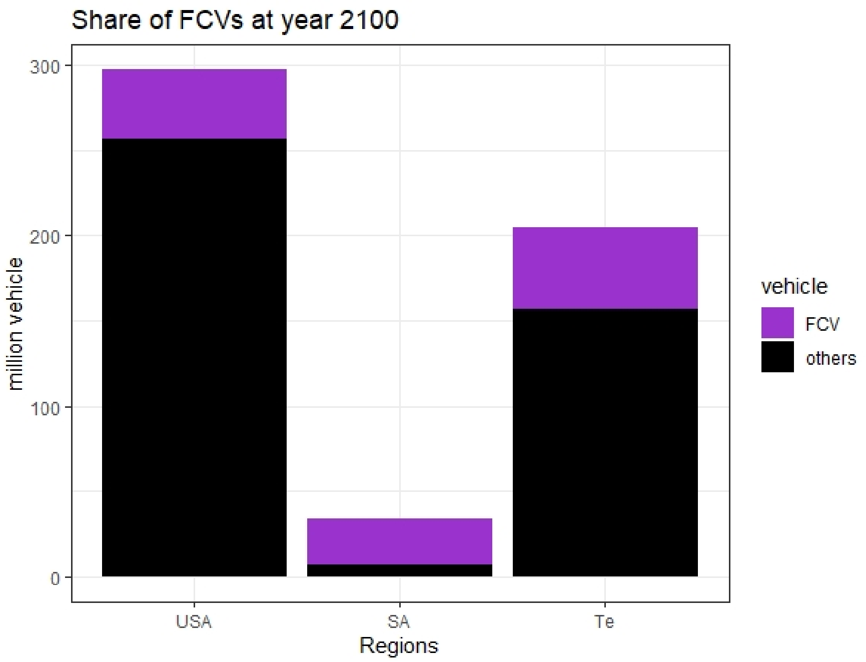


Figure (5.16) Region/s using fuel cell vehicles in 2100 [scenario A]

As we saw before, share of fuel cell vehicles are very low in scenario A, now we can observe that in fact, USA, SA and TE are the only regions which partly uses them. In case of USA, This could be due to high share of renewable sources used even in business as usual scenario at 2100. So they could use free extra curtailment for transportation. However, in other regions we see zero participation of hydrogen in transportation.

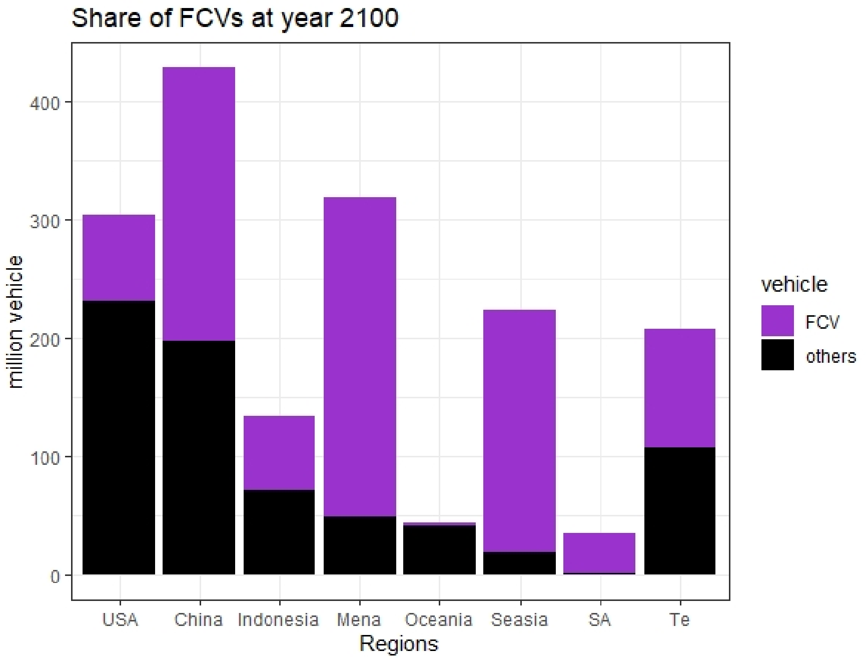


Figure (5.17) Region/s using fuel cell vehicles in 2100 [scenario B]

In scenario B, more regions are using fuel cell cars. i.e. China, Indonesia, Mena, Oceania, Seasia, South africa and TE. This result is interesting due to the fact that we can see a lot of regions in which there are no movement toward a green transportation or energy future. So, hydrogen could be a silver bullet to help de-carbonizing hard-to-decarbonize regions such as Mena or China. What is more is the fact that actually share of usage is in a wide range. Starting from Oceania share of fcvs are around 5%, the percentage boosts in Indonesia to 9%, and other regions such as China or Mena and Seasia expand the share to more than a half. The most ratio is related to South africa in which they will transform all of their fleet into hydrogen fuel cell vehicles.

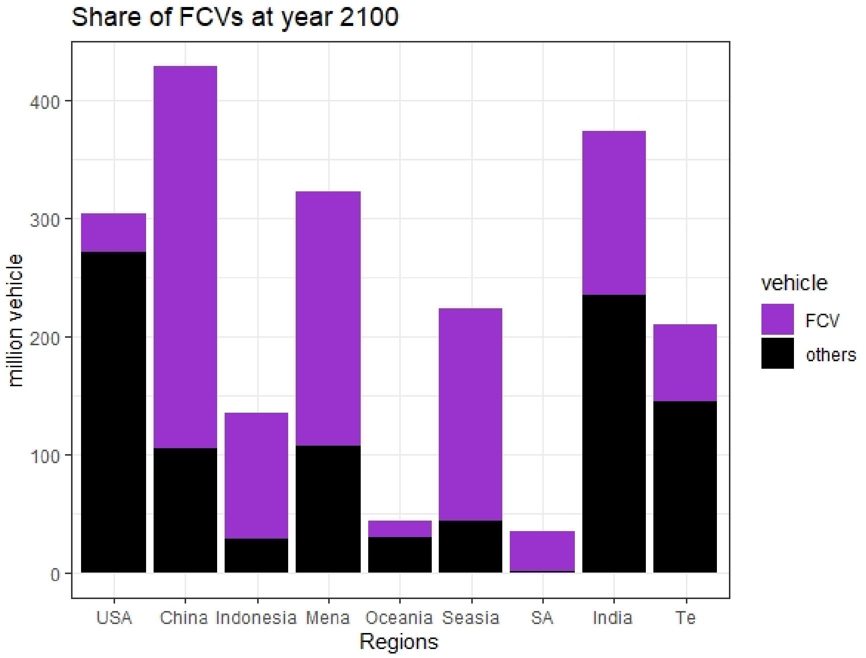


Figure (5.18) Region/s using fuel cell vehicles in 2100 [scenario C]

By surging more carbon tax, some of the aforementioned regions prolong their penetration into hydrogen cars such as China and Oceania. Remarkable is that we can monitor a decline in the share for certain regions like Seasia. (they choose more electric vehicles by more carbon taxing). Last part of changes is related to India. It was no India in even scenario B, although, here we can see the share of around 70% in India which is fascinating. India is another region which is hard to de-carbonize and hydrogen shows a solution, but in collaboration with a high taxation on carbon.

### Evolution of FCV usage over regions

It is fruitful to have a look on regions over different time steps in an identical scenario (in this case scenario B). We can see that Some regions such as US and Oceania start to use fuel cell vehicles at 2050, while others need more time and at 2075 we can see their share of hydrogen. Furthermore, at 2100 regions develop their usage completely and more deeply if needed. Another point here is that number of total vehicles is increasing over time as it is defined to the model exogenously. So, we may see a declination in the share but an increment in the absolute number of vehicles simultaneously.

### Share of fuels in ICE vehicles

For internal combustion vehicles, three main fuels are used. In this context, oil, traditional biofuel and advanced biofuel are the available fuels. Share of usage of these fuels will be shown in figures below.

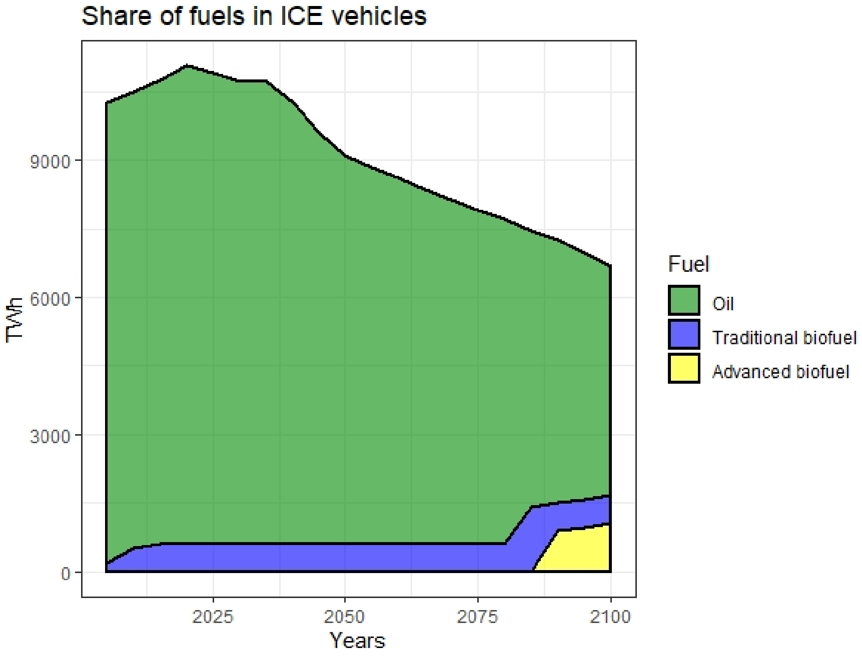
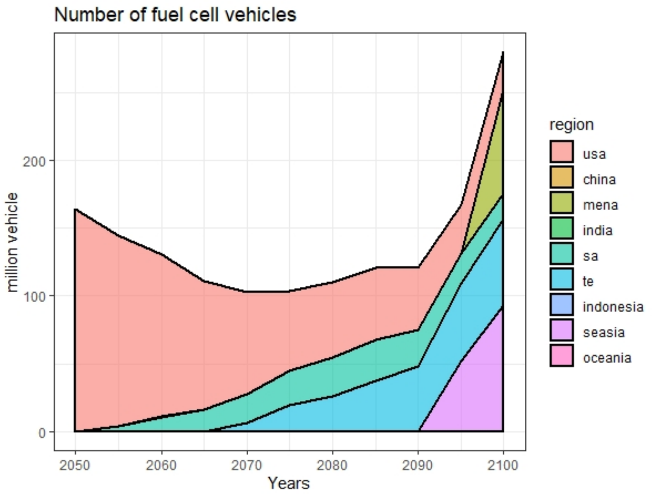
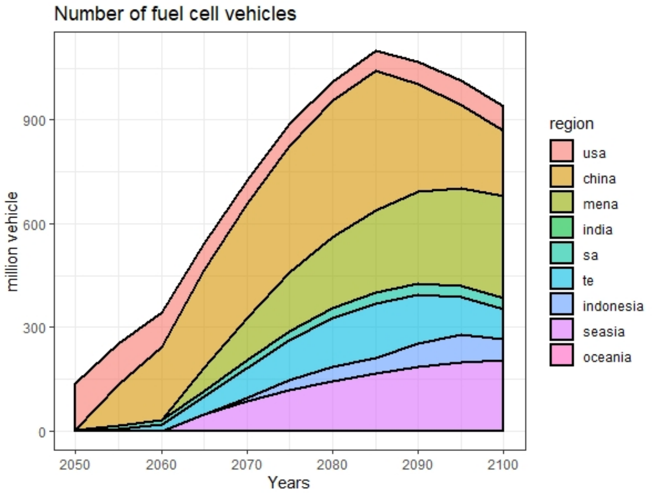


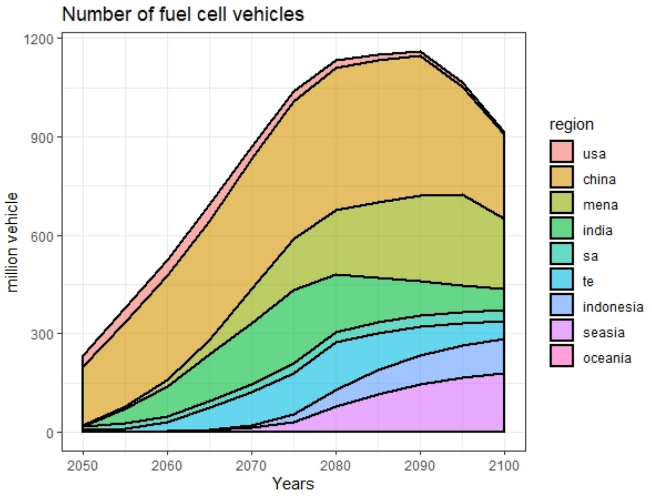
Figure (5.20) Share of usage of ICE fuels [scenario A]



(a) Scenario A



(b) Scenario B



(c) Scenario C

Figure (5.19) Evolution of hydrogen vehicles for regions

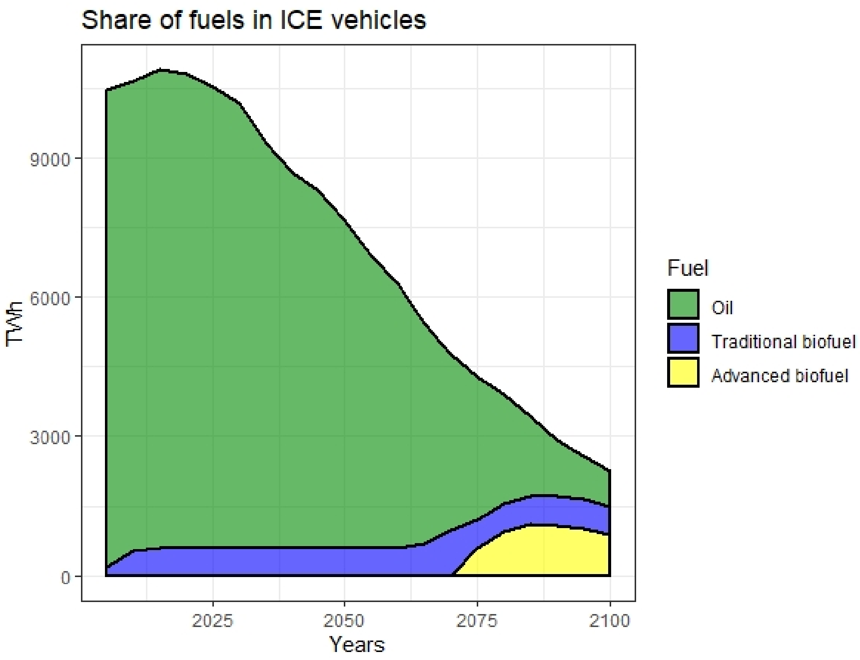


Figure (5.21) Share of usage of ICE fuels [scenario B]

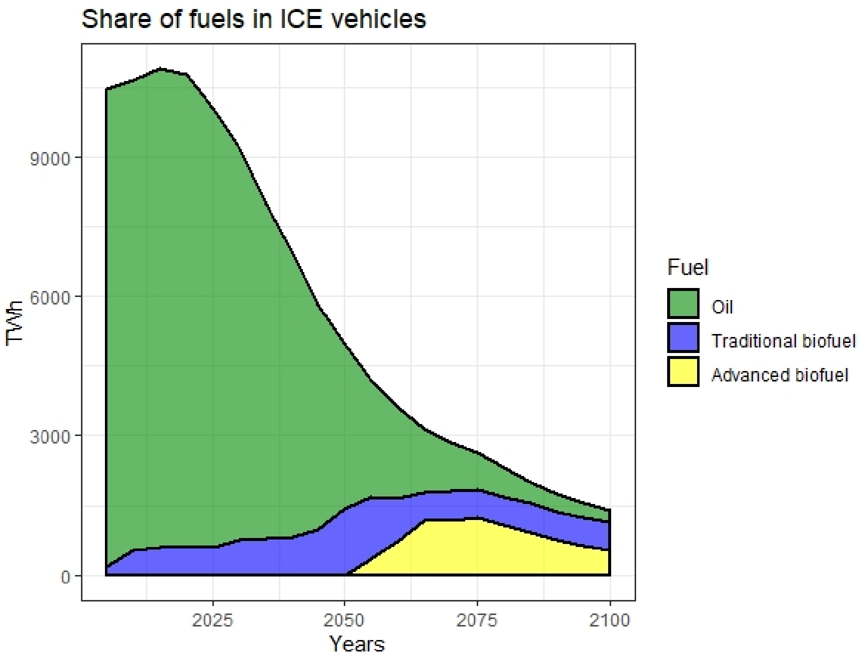


Figure (5.22) Share of usage of ICE fuels [scenario C]

First point that comes to mind by observing figures is that total fuel consumption of internal combustion vehicles is going down in all scenarios due to lower usage of traditional cars as well as increasing in fuel efficiency. This decrements' slopes are sharper in scenario B and C. This findings are compatible with the results given in Figure 5.13 and Figure 5.14. Now by considering scenario A we can see that at the end of century still the leading fuel will be oil which is not favorable. However, in scenario B by putting carbon tax in that specific time step, share of three available fuels are almost same. Consequently, as it is expected by increasing even more taxation on carbon, oil will possess the minor share among others.

Biofuels can be produced from plants (i.e. energy crops), or from agricultural, commercial, domestic, and/or industrial wastes (if the waste has a biological origin).[2] Renewable biofuels generally involve contemporary carbon fixation, such as those that occur in plants or micro-algae through the process of photosynthesis. While, Advanced bioenergy is produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues, e.g. wheat straw/corn stover/bagasse, wood based biomass), non-food crops (i.e. grasses, miscanthus, algae), or industrial waste and residue streams, has low CO2 emission or high GHG reduction, and reaches zero or low indirect land use change impact.

### Energy consumption of vehicles

It is been said that each type of vehicle uses different fuels as input. But, all of them can be converted into energy terms in TWh. Now, by considering initial energy consumption and rate of improvement in consumption, specific energy spending of different cars can be achieved.

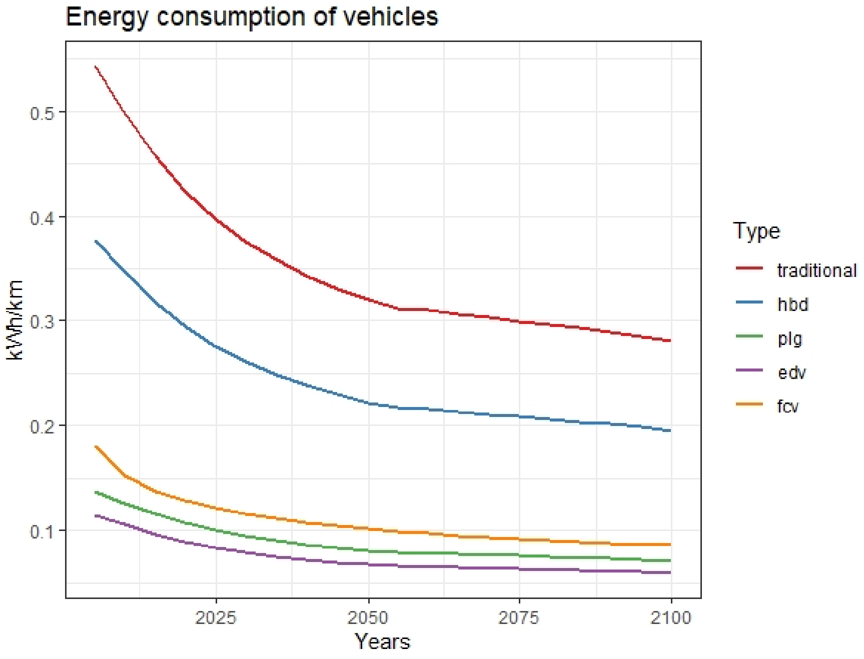


Figure (5.23) Specific energy consumption of vehicles

On the Y-axis we have $\frac{kWh}{km}$ and X-axis shows years. Most energy expenditures are belong to traditional and hybrid cars, while, lowest expenditure are respectively related to electric vehicles, plug-in hybrid and fuel cell vehicles. Due to the fact that energy consumption is decreasing exogenously it is not a function of the scenario. Hence, there is no difference in different scenarios and energy consumption of vehicles is identical for all cases. Some could argue that this values could be different across regions which is true, but for the sake of simplicity it is assumed that all regions have access to same quality of cars.

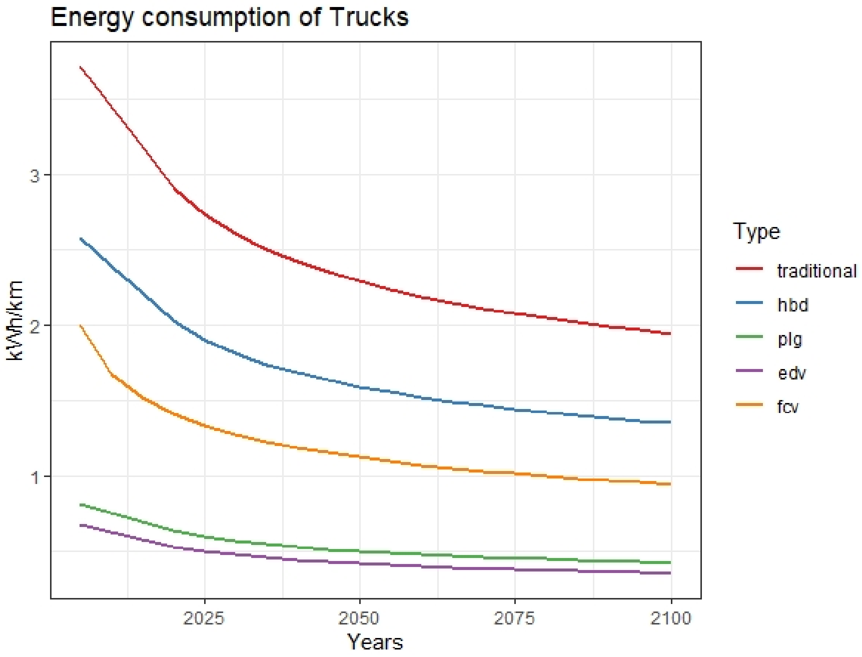


Figure (5.24) Specific energy consumption of trucks

Samely as vehicles, figure above shows the fuel consumption of freight trucks of different types.

### Final cost of vehicles

The functions of computing final cost of vehicles are defined earlier in page 52. Here we show the results of total ownership costs of cars based on initial specific cost of each key component and their endogenous or exogenous rate of cost decrements. Scenario B is chosen to compare the costs due to rational value of carbon tax which is more practical and realistic in real world. In other scenarios only fuel cell and electric drive vehicles costs may vary due to utilization of fuel cell and big size batteries.

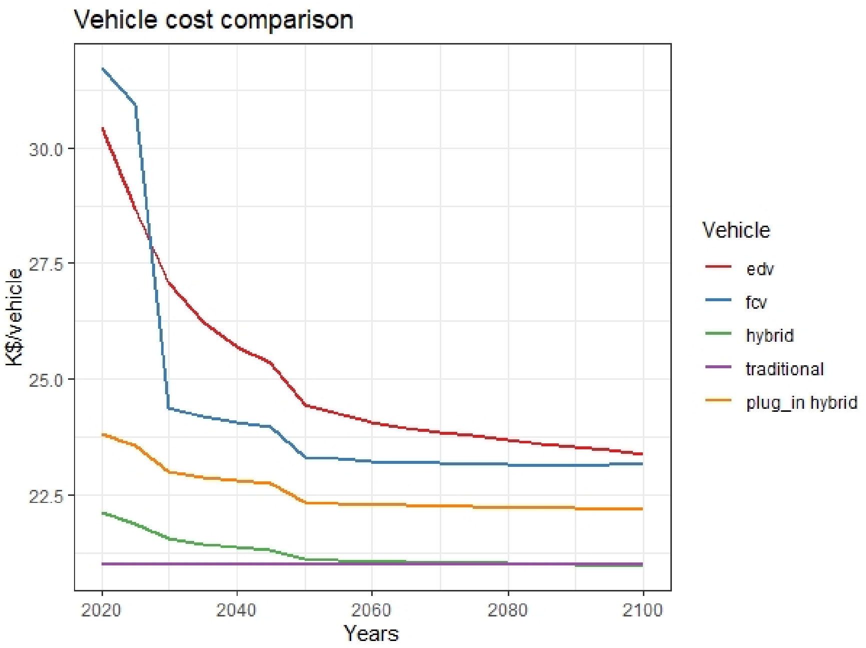


Figure (5.25) Cost of vehicles over whole time horizon

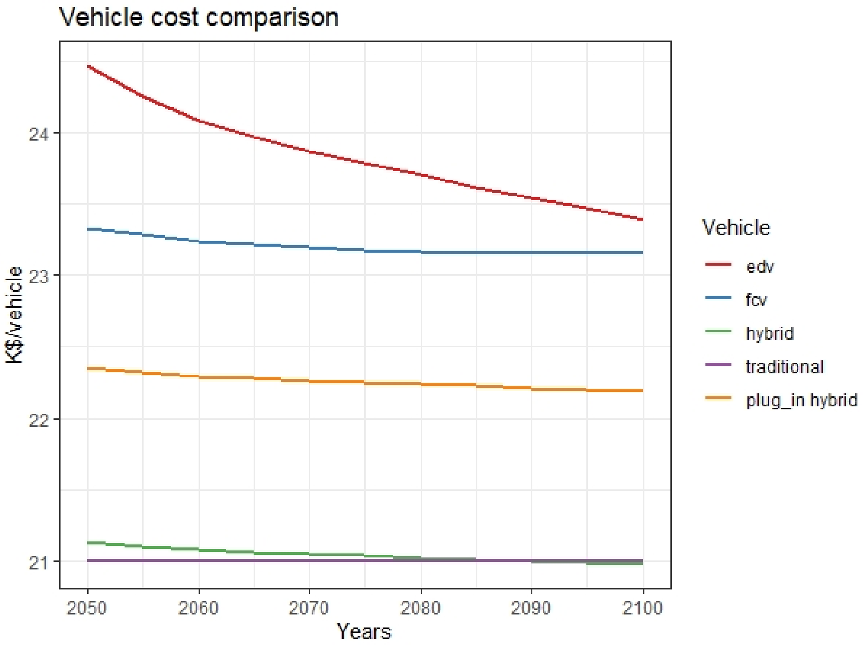


Figure (5.26) Cost of vehicles 2050-2100

Traditional vehicle's cost is assumed constant, while that of others are declining over time. Up until around 2030 fuel cell vehicles will the most expensive one because of high cost of fuel cells. But, fuel cell specific cost is and will be declining tremendously with an unexpected growing rate. 20 years ago it costed around 1000-1500 $\frac{\$}{Kw}$ and today it costs below 100 $\frac{\$}{Kw}$. Therefor, after 2030 it is expected that electric drive vehicles be the most expensive one. By observing the values at 2100 it can be

seen that by more improvement in batteries, edv and fcv costs converge to a certain point. Plug-in hybrid is always in the middle and hybrid vehicles are cheapest after traditional cars. At the end, hybrids will converge to traditional cars too. all of these costs are an average over all regions, while different regions may show various costs with a small marginal difference.
These trends in results are compatible with other IAMs such as Time IAM (TIAM).

Here we can see the minor difference in cost of batteries in different regions and scenarios as mentioned before. This is mainly because of being endogenous.

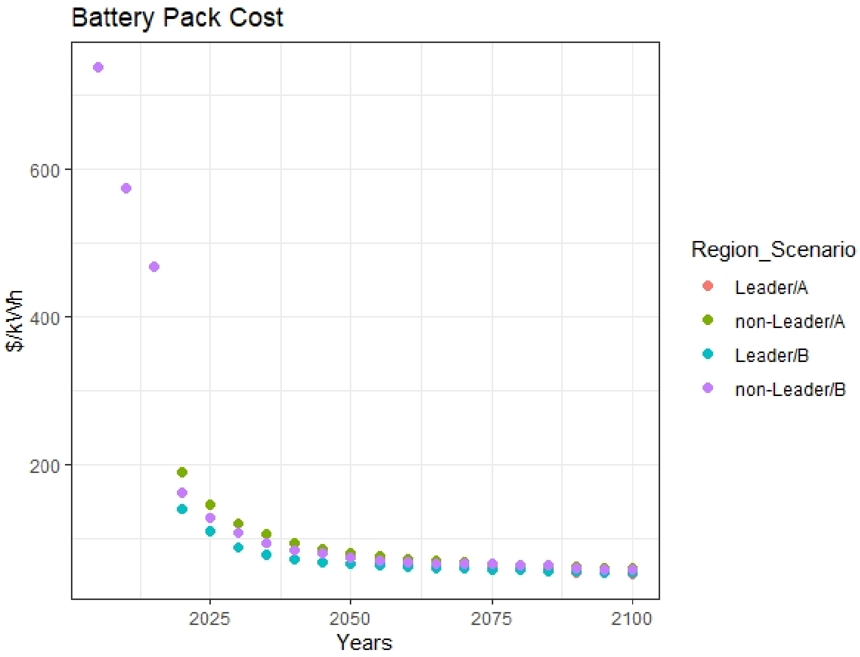


Figure (5.27) Cost of batteries in different regions/scenarios

**Number of Freight trucks**

Another important output of transportation module is related to number of freight trucks. Again, these results will be shown for our three main scenarios.

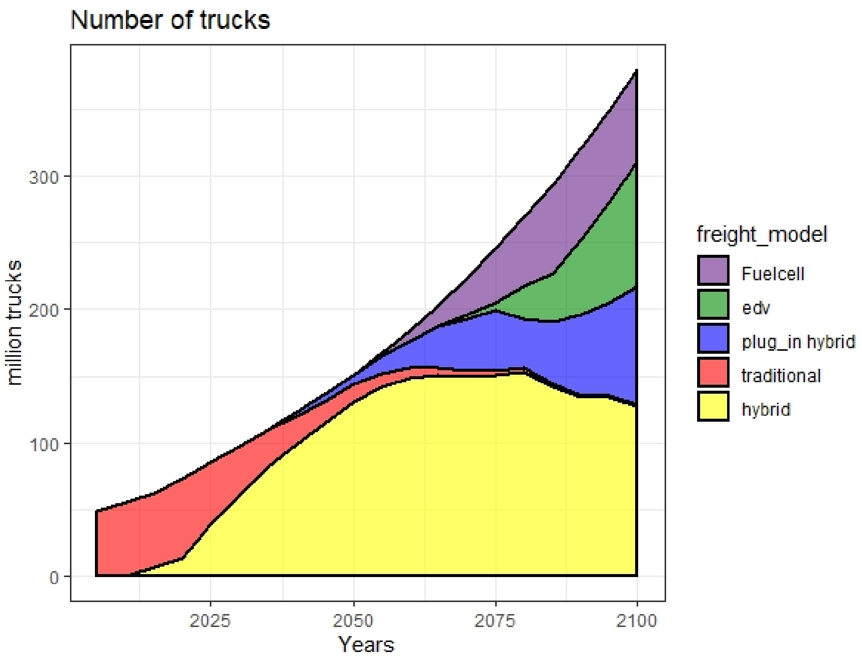


Figure (5.28) Share of worldwide freight fleet scenario A

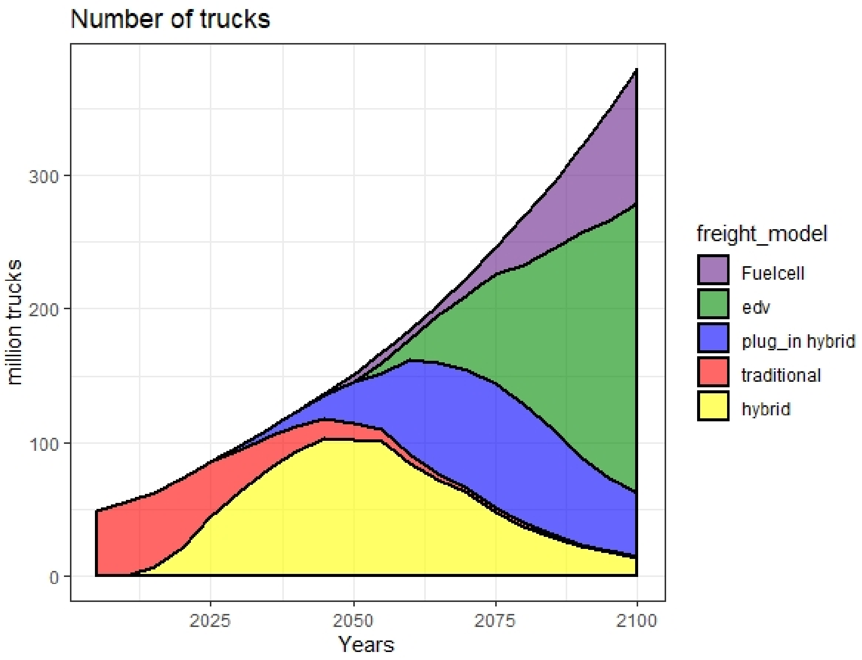


Figure (5.29) Share of worldwide freight fleet scenario B

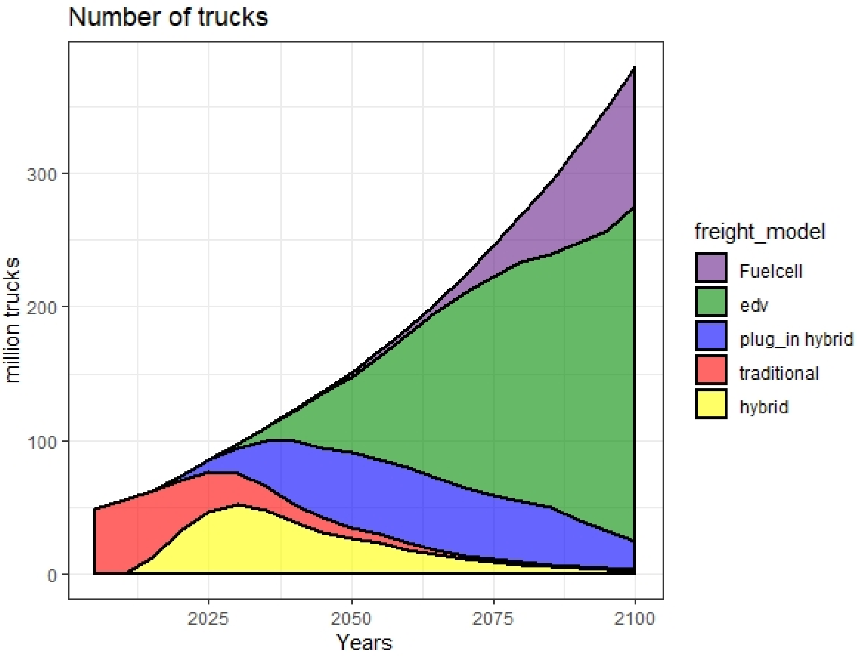
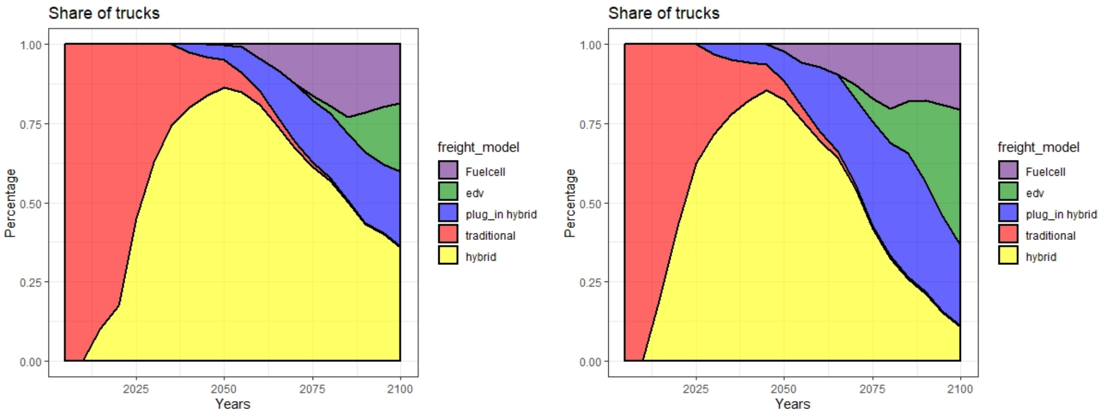
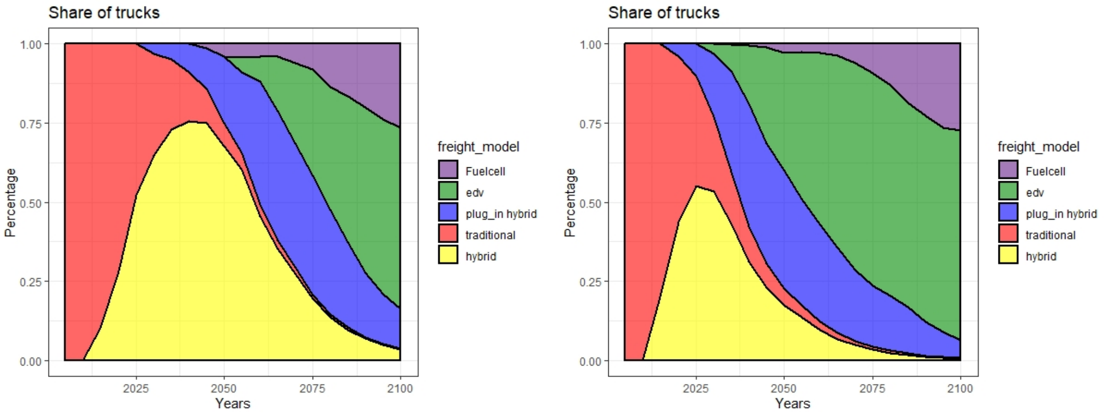


Figure (5.30) Share of worldwide freight fleet scenario C

In scenario A which has no specific policy hybrid trucks will be dominant at the end of century. Among three types of green-fuel trucks, we can expect almost equal share. Plug-in hybrids showing a faster start in comparison to other two types. Scenario B with carbon tax allows green-fuel trucks to expand and grow sooner and faster. Number of fuel cell trucks will be higher than that of previous case, however not much. On the other hand, electric-drives will be the leading technology at 2100. Plug-ins again start sooner but as time goes on they are replaced by more efficient fuel cell and electric-drive trucks. Scenario C, with a more strict policy for de-carbonization, follows the same trend as scenario B, but with a faster expansion. Traditional and hybrid trucks start to vanish starting around year 2025. Electric-drive trucks gain more benefit from the mitigation policies, so they prevail the total fleet.
In all scenarios, even scenario A, traditional trucks have no chance to stay and expand. While, number of others are strongly affected by the policy chosen. It is of paramount importance to have a limiting policy in order to have a green fleet of freight trucks.



(a) BAU (b) Carbon tax 10



(c) Carbon tax 30 (d) Carbon budget

Figure (5.31) Percentage share of freight truck fleet

**Detailed regional usage of FC trucks**

In this section we will go through the usage of fuel cell trucks in different regions and different time steps to understand how can hydrogen be a part of future freight transportation.

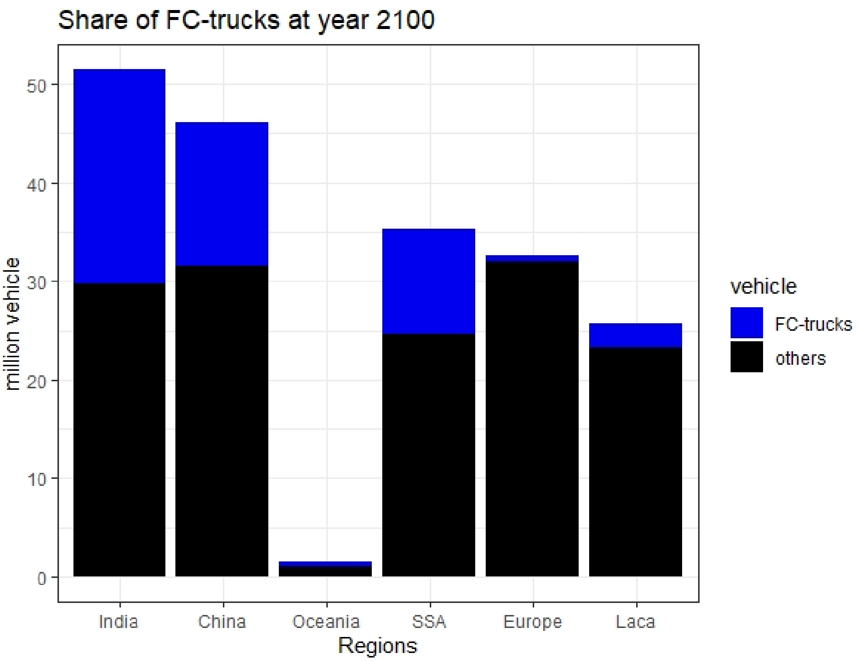


Figure (5.32) Region/s using fuel cell trucks in 2100 [scenario A]

As scenario A suggests, even with no carbon policy and baseline scenario India, China, Oceania, SSA, Europe and Laca regions use hydrogen trucks in 2100. Although the share for Europe is not huge, but it is expected to be more by putting policies.

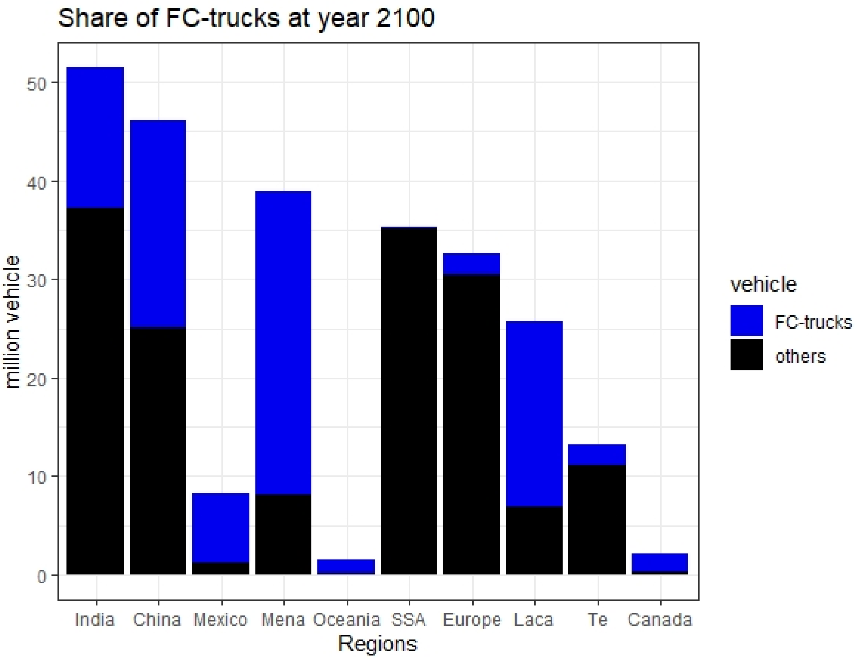


Figure (5.33) Region/s using fuel cell trucks in 2100 [scenario B]

With a carbon tax policy, 4 more regions join the cluster. Some regions such as India almost keep the same amount of trucks in both cases, while some others like China will benefit from policies to choose more fuel cell trucks. The impact of carbon policy is more visible for some other regions such as Mena, Mexico, Canada and Laca.

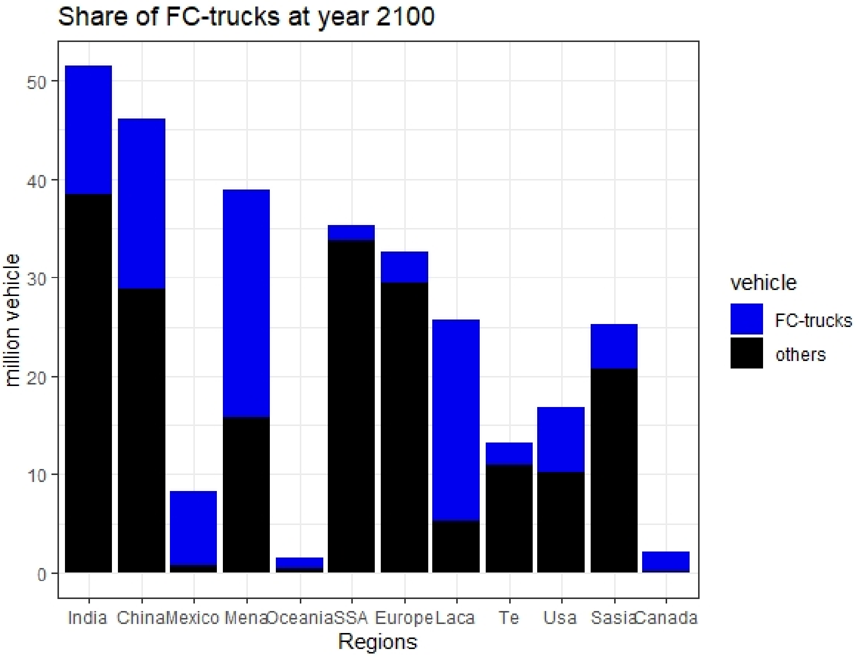
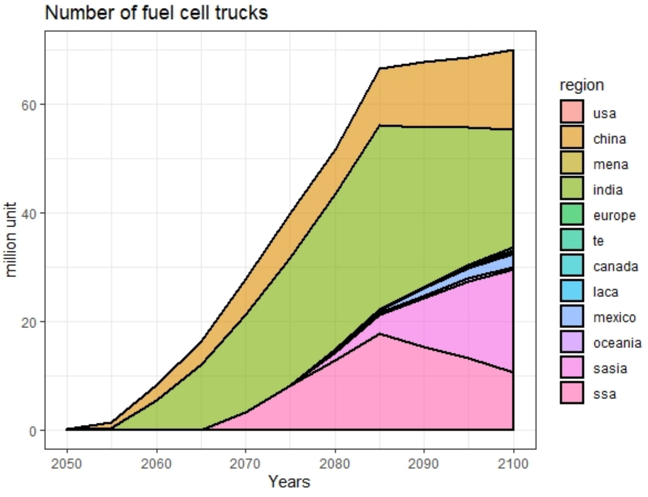


Figure (5.34) Region/s using fuel cell trucks in 2100 [scenario C]

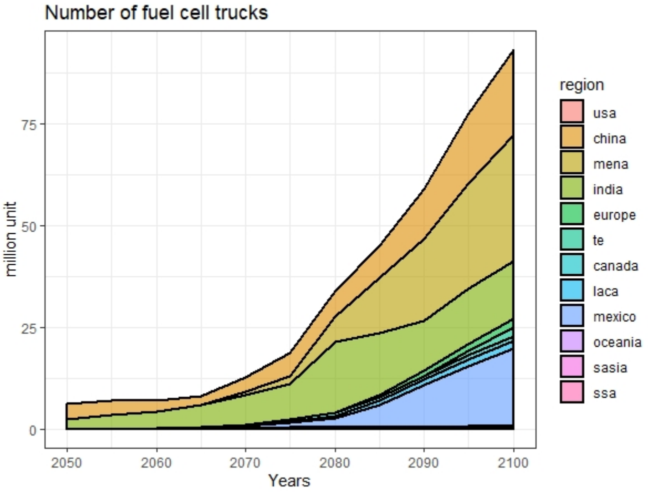
By having a more strict policy, in this case with a narrow carbon budget, all the present regions in case B are present here as well, but usually with a more share of hydrogen. In addition, two more regions joined the group i.e. USA and Sasia. It stands to reason that, for USA it is viable to use hydrogen trucks only if there is a severe policy on carbon. However, we saw that it is not the case for vehicles in USA. Maximum share of FC-trucks are correspond to Mexico, Canada, Laca and Oceania while the highest gross number is for Mena and Laca.

### Evolution of FC trucks usage over regions

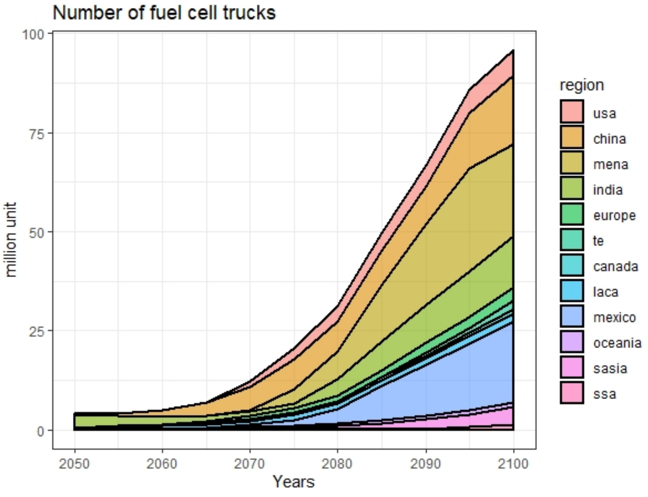
Same as that of fuel cell vehicles, we analyze the evolution of fuel cell trucks over time here (for scenario B). In year 2050 only India and China start using hydrogen freight. In the next time step other using regions initiate to build infrastructures and implementing fuel cell trucks. Also, India will go more deeper into the share. By the end of century, a huge evolution may happen -between 2075 and 2100-, so all in all 10 regions use fuel cell trucks. Mena, Mexico, Canada and Laca experience the most growth in comparison to other regions leading to a huge share of fuel cell hydrogen freight fleet. China continues its path to possess more hydrogen trucks.



(a) Scenario A



(b) Scenario B



(c) Scenario C

Figure (5.35) Evolution of hydrogen trucks in regions

**Share of fuels in ICE vehicles**

Also for internal combustion trucks, three main fuels are used. In this context, oil, traditional biofuel and advanced biofuel are the available fuels. Share of usage of these fuels will be shown in figures below.

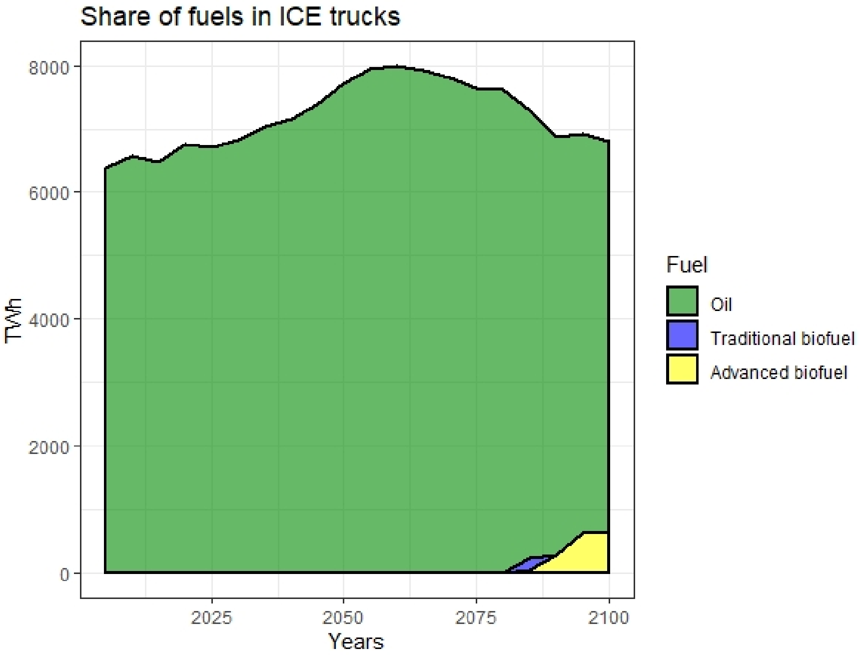


Figure (5.36) Share of usage of ICE Trucks' fuels [scenario A]

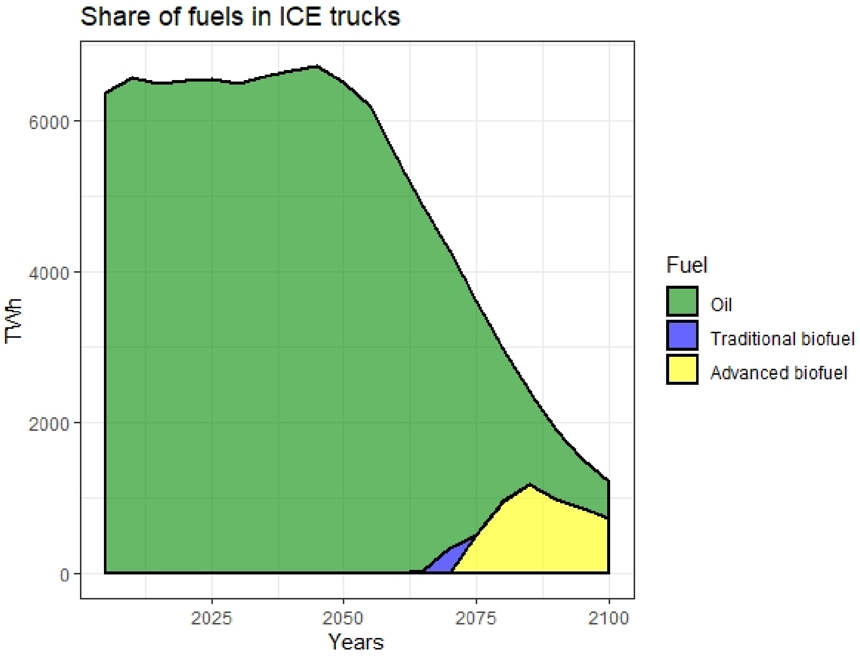


Figure (5.37) Share of usage of ICE Trucks' fuels [scenario B]

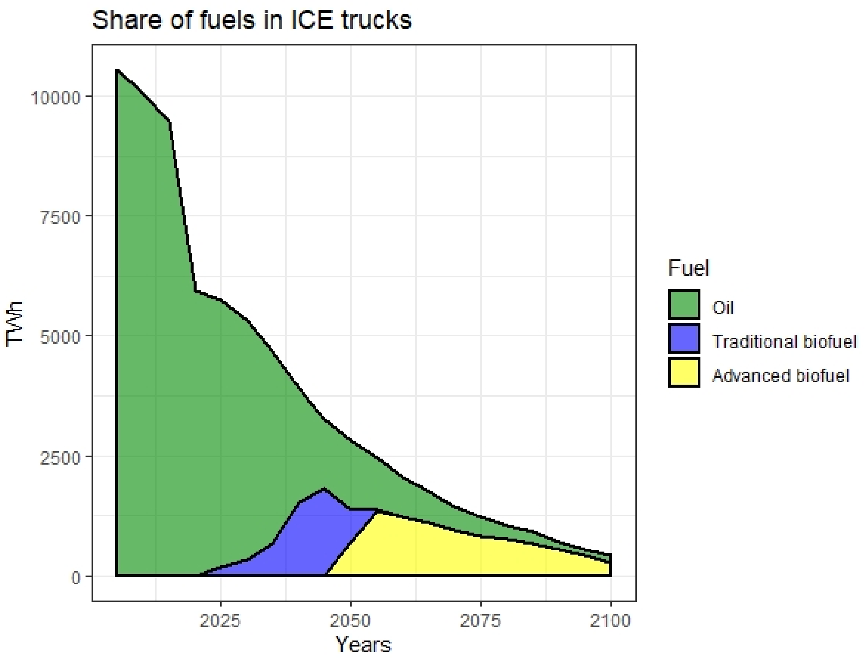


Figure (5.38) Share of usage of ICE Trucks' fuels [scenario C]

Without any policy, oil is the main part of internal combustion fuels even up to 2100. There is only a negligible amount of traditional and advanced biofuels at the end. By putting carbon tax and carbon budget policies, not only does total demand of internal combustion fuels decrease, but also oil demand drop dramatically giving more opportunity to biofuels to participate.

### Co2 in transportation

Burning fossil fuels like gasoline and diesel releases carbon dioxide, a greenhouse gas, into the atmosphere. Greenhouse gas (GHG) emissions from transportation account for about 29% of total USA greenhouse gas emissions, making it the largest contributor of USA GHG emissions. Between 1990 and 2017, GHG emissions in the transportation sector increased more in absolute terms than any other sector. The main indicator to analyze the results in de-carbonization of transportation sector is the amount of Co2 emitted by this sector.

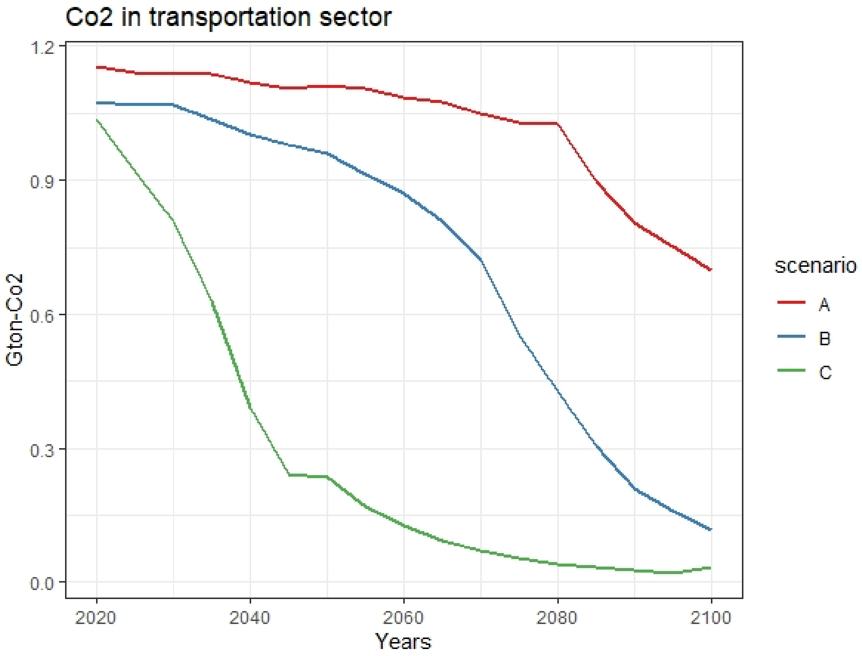


Figure (5.39) Co2 emission from transportation sector

As it is expected scenario A without any carbon tax shows highest emission even after a huge time horizon. Other scenarios suggest lower emissions. Respectively C and B offer lowest ones. Both scenarios C and B reach to almost zero emission at the end of century.

### 5.2.3 Hydrogen

**Hydrogen demand**

To have a comprehensive view on total hydrogen demand on the global scale figure below is useful. It shows the summation of hydrogen demand by all regions in different time steps in different scenarios.

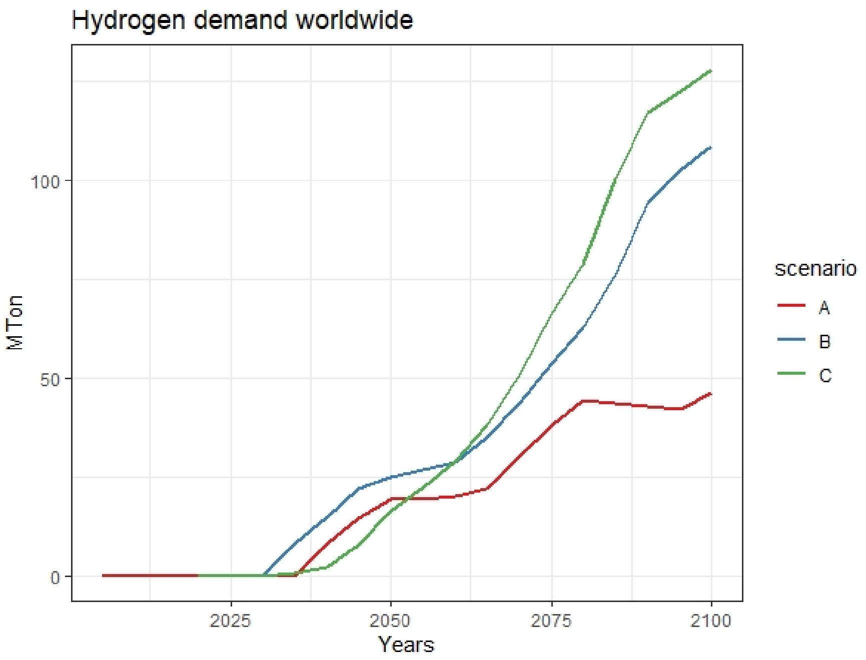
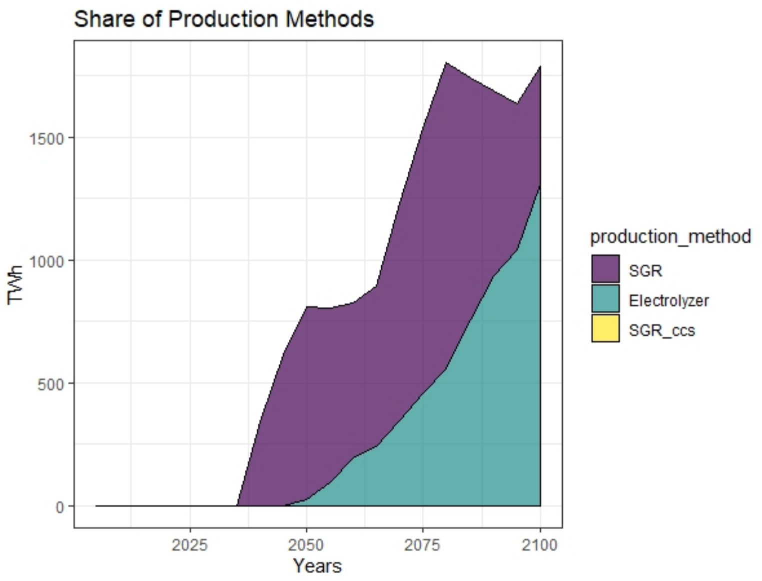


Figure (5.40) Hydrogen demand on global scale

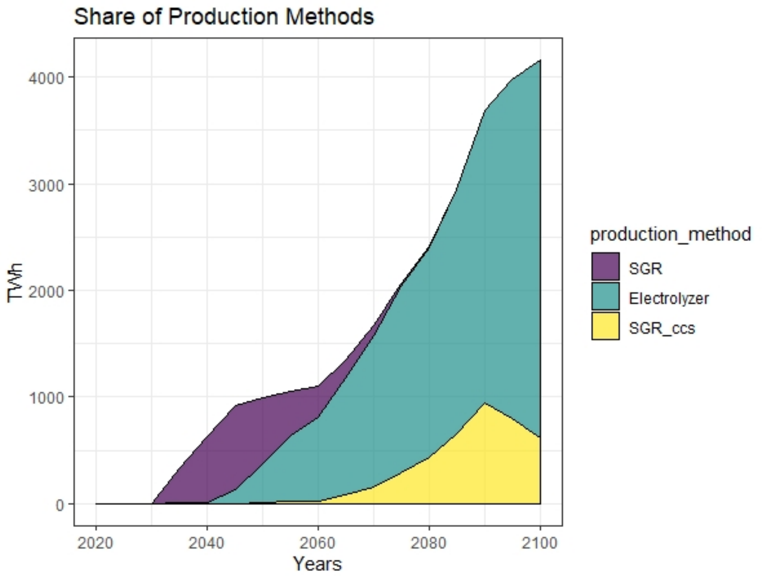
For now, and for this project hydrogen demand is only linked and consumed in transportation sector. It is doable to connect hydrogen to other applications and sectors such as heating or oil refinery in next projects and steps. This being said, Amount of hydrogen demand is directly related to number of hydrogen vehicles and trucks. The main break point is at 2075, After that time climate friendly scenarios will continue to use hydrogen while in scenario A we observe a declination in demand. Also, scenario B is the only scenario that starts to demand hydrogen after around 2030. This is merely a summation over all regions, so, it has to bear in mind that different regions demand various amount of hydrogen with respect to their number of vehicles and trucks.

**Share of production**

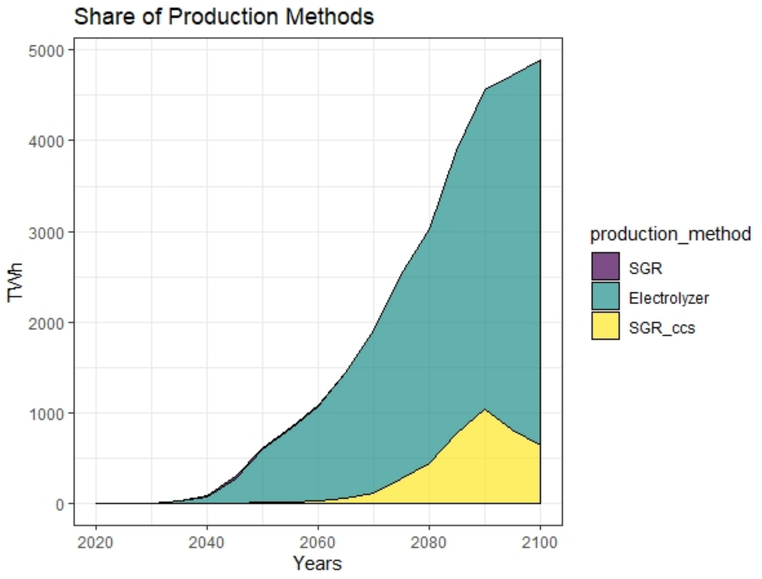
Now it is fruitful to investigate the share of each production method. As it is already mentioned, there are three options available to produce hydrogen. i.e. Electrozying(elecz), Steam gas reforming(SGR) and Steam gas reforming with carbon capture(SGR+CCS).



(a) Scenario A



(b) Scenario B



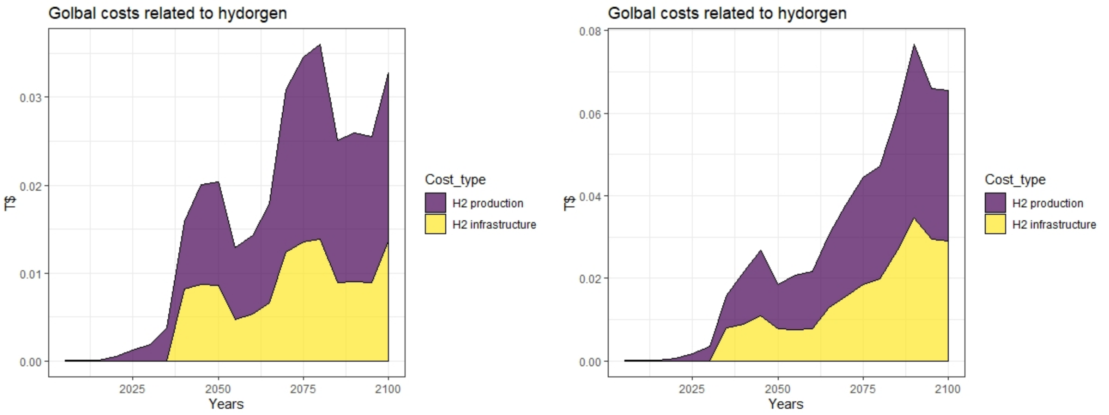
(c) Scenario C

Figure (5.41) Share of worldwide production across different methods of production

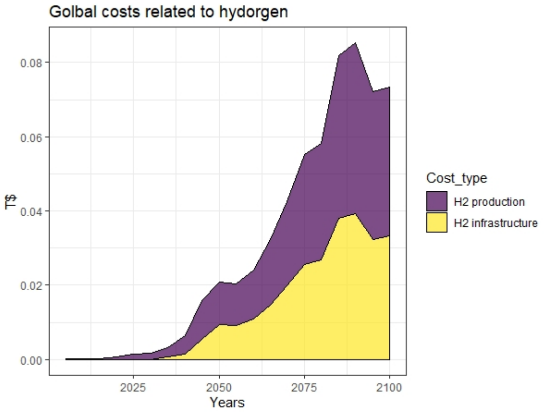
Starting from scenario A, it is obvious that no CCS is used. At the beginning dominant method is SGR. That is mainly because, in the early years still electrozying is a more expensive option and also natural gas is more available. Meanwhile, Electrolyzers become cheaper, more curtailment and more renewable energy is available across countries, so share of electrolyzing is going to increase.
In scenario B, Again same as previous case starting demand is going to answered by natural gas reforming. However, here the rate of electrolyzers' expansion is much higher than before due to the fact that in this scenario there are a lot more renewables which can be used to produce a more clean hydrogen. SGR+CCS starts to have a role at around 2080, but still the dominant part stays with electrolyzing. Limited SGR+CCS is because of the extra costs of carbon capturing and also the fact that it is not going to capture 100% of the produced carbon.
Finally, in scenario C carbon tax is much higher and every tons of carbon matters a lot. In those cases, we can see that SGR is almost obliterated and always electrolyzing is the major part of hydrogen production with a minor part for SGR+CCS. All in all, usually regions with higher share of renewables and accessible extra electricity will mostly use electrolyzing method, while regions who possess high amounts of natural gas use SGR+CCS.
For now investment cost of SGR is assumed constant and that of electrolyzing plants are reducing exogenously over time. A more precise approach could be to endogenize cost reduction in different regions. However, in sensitivity analysis effect of different costs of plants will be discussed.

### Cost of production vs infrastructure

Here we can see cost configuration related to hydrogen. Both costs related to pipelines as transmission and distribution lines as well as refueling station costs are accounted into infrastructure costs. Production cost is summation of costs related to all types of production used in a time step.



(a) Scenario A (b) Scenario B



(c) Scenario C

Figure (5.42) Hydrogen production and infrastructure cost

Without any carbon tax we have less demand of hydrogen (as discussed before), hence, after a peak in 2075 hydrogen demand decreases, so as hydrogen expenses. In all other scenarios total expenses are on a positive trend. This expenses are including new investments for new plants (any technology) or O& M of existing plants. Also for infrastructural cost, there are installation of new refueling stations and pipelines with respect to the demand of a specific region as well as O& M and depreciation of structures considered.

Most important point here is that infrastructural costs are almost half of the total expenses which is huge. In fact, one of the major obstacles to make hydrogen fuel cell vehicles common is the problem of lacking infrastructures. So, if hydrogen wants to be considered as a fuel of future, a big push is needed to go toward creating and installing necessary bases and backgrounds needed. It does not depend on the case, and even in scenario C with highest severity of carbon price, still inevitable infrastructural expenses are present.

**Average hydrogen price**

To calculate levelized cost of hydrogen (LCOH) following equation is considered.

$$LCOH(t,n,ptype) = \frac{\sum_{t=0}^{n} \frac{Investment+(Gas/Electricity)cost+O\&M}{(1+r)^t}}{\sum_{t=0}^{n} \frac{P_{H2}}{(1+r)^t}} \tag{5.1}$$

In which, investment costs of plants, cost of electricity or natural gas used as well as maintenance cost is taken into account for each region in each time step. r is discount rate and n is lifetime of each plant. The equation is being used for every region and every type of production method. After that, a weighted average is used to reach to a specific value for LCOH by each production method globally.

$$\overline{LCOH(t,ptype)} = \frac{\sum_n LCOH(t,n,ptype) \times H_2.production(t,n,ptype)}{\sum_n H_2.production(t,n,ptype)} \tag{5.2}$$

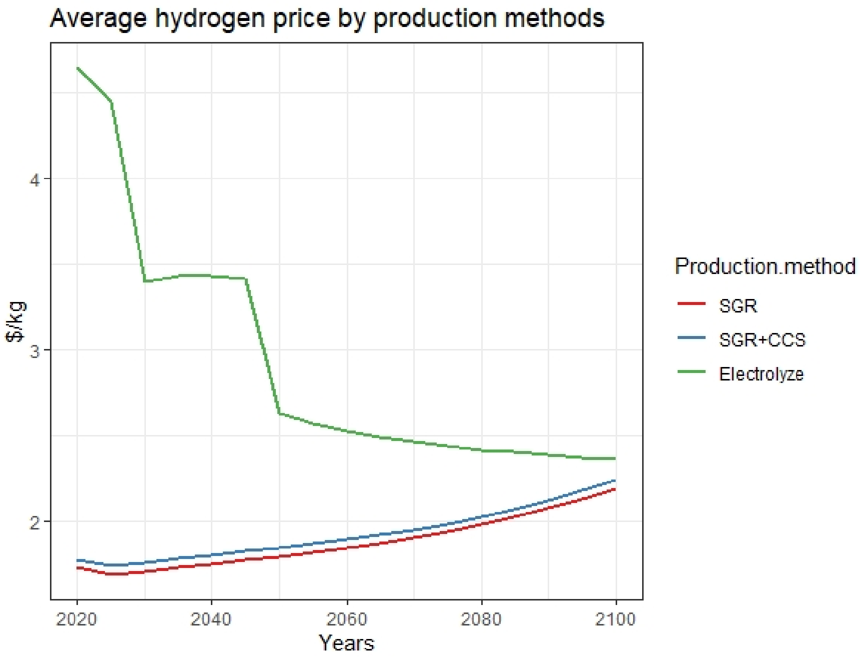


Figure (5.43) Average final price of hydrogen

Figure 5.43 shows the modifications of LCOH over time by different production methods. If steam gas reforming is used price is much lower at the beginning, but over time it increases with a gentle slope due to

the natural gas price and added O& M expenses. There is a difference between SGR and SGR+CCS which is because of added costs related to carbon storage, That is the only part that differs these two type of production. On the other hand, as far as electrolyzing concerns, the price using this method decreases dramatically. Main fraction points(2030 and 2050) are the points in which investment cost of electrolyzers are going to decrease and even after that due to lower cost of electricity or presence of more renewables and free curtailments it reduces more and more. At the end, they converge to around 2.2 $\frac{\$}{kg}$.
As long as investment cost of electrolyzers is exogenous, it strongly depends on the assumptions and assumed rate of improvements. In sensitivity analyses effect of various investment costs will be discussed.

### Global emission related to hydrogen production

It is of paramount importance to see the emission related to hydrogen production, while, it is not accounted into emissions of fuel cell vehicles.

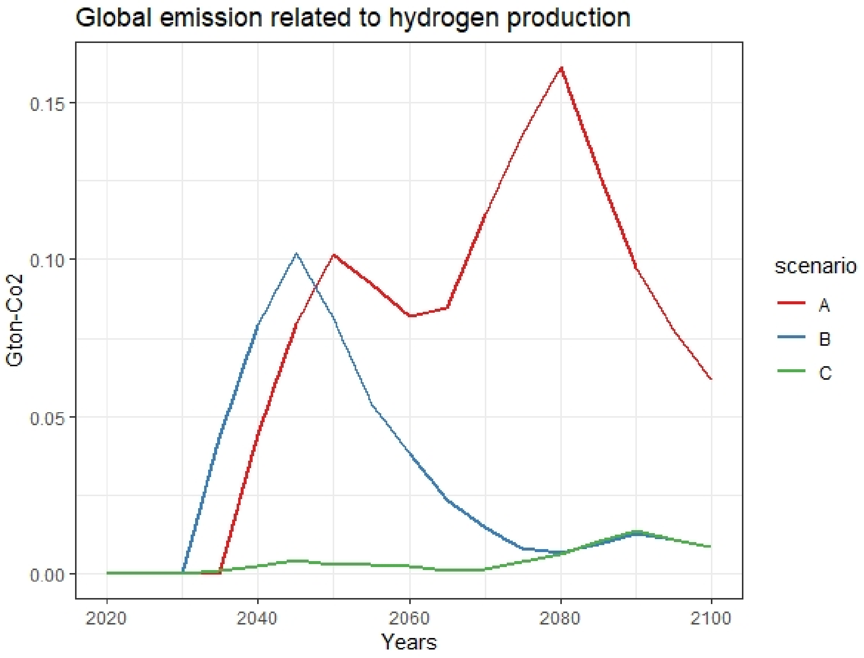


Figure (5.44) Hydrogen production emission

As far as production by electrolyzing emits no or low carbon, so emissions here are almost directly linked to usage of SGR method. It is proved by matching Figure 5.44 with Figure 5.41. So, in scenario A the peak of Co2 emission is at around 2090 and that of scenario B is around 2050. These time steps are the peak of SGR usage by related scenarios. As it is expected in scenario C emission is so low, and hydrogen production is almost 100% green. The minor part of emissions in latter scenarios are because of little emission from SGR+CCS, considering this fact that CCS remains 10% or carbon emitted.

## 5.3 Investment

One of the main features of the WITCH model is the characterization of endogenous technical change. Albeit difficult to model, technological innovation is key to the decoupling of economic activity from environmental degradation. The returns to R& D investment depend on the stock of previously accumulated knowledge. Higher knowledge stock facilitates generation of new, energy saving innovations. In addition, international spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries.

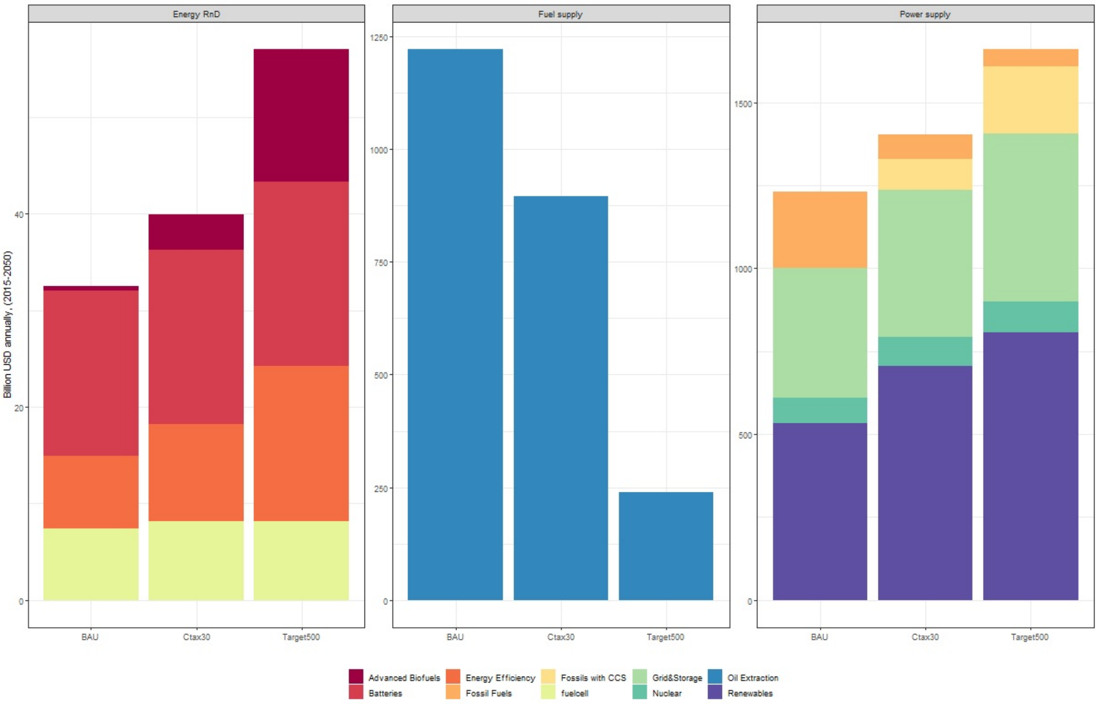


Figure (5.45) Investment in different scenarios

The most-left graph shows yearly total investment on research and development for scenario A(BAU), B(Ctax) and C(Carbon target). As we move further into higher carbon taxation, we expect more investment in energy efficiency. Also, there is a feedback loop between amount of fuel cell usage, its cost and required invested capital. All in all, the summation of all four R& D investments of batteries, fuel cell, energy efficiency and advanced biofuels is going to increase.

The graph in the middle gives us information about the amount of money invested in fuel supply by oil extraction. As we have seen in the results on transportation section, in scenario B and C oil consumption and oil fuels are no longer as essential as before due to presence of FCVs and EDVs. Consequently, fuel supply needs less oil extraction which is a fruitful result.

The most-right graph indicates financial expenditure in power supply sector. The most obvious changes are related to fossil fuels and renewables. Regarding fossil fuel sources, there is a shift to using carbon capture technology. Carbon capture (CCS) employs additional costs to system which is not competitive without carbon tax. What is more, is the higher amount of investment in using renewable sources to make them cheaper and more affordable in the future. It can be realized that renewables and CCS need supportive policies without a doubt.

### 5.3.1 Investment in different vehicles

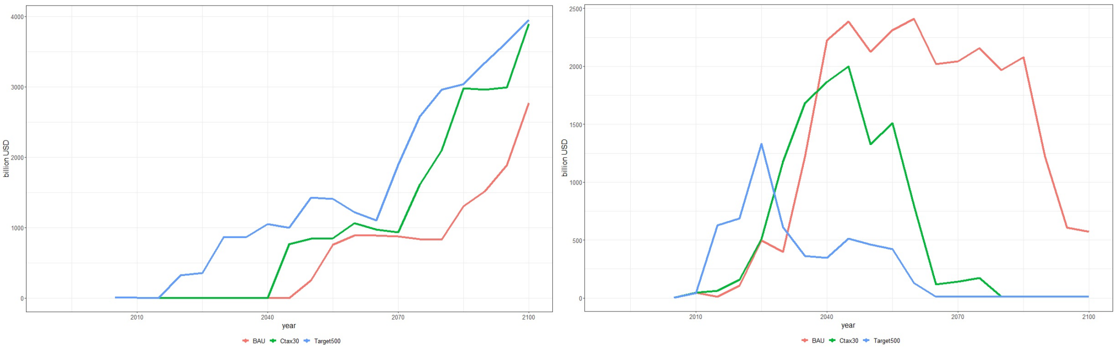
Now let's see the total investment in different type of vehicles over time in different scenarios. Electric drive vehicles are going to attract more investment over time for all three scenarios with a simple attitude. However, respectively carbon target and carbon tax scenarios start sooner. There is a small declination around year 2060 which is mainly due to penetration of fuel cell vehicles.

Hybrid vehicles in BAU scenario demand a lot of investments with a roughly constant peak in years between 2040 and 2080. By reinforcing carbon policies, this peak will be lessened, shifting to early years. As the time goes on, by introducing edv and fcv, there would be less duty for hybrid vehicles, and therefore less financing.

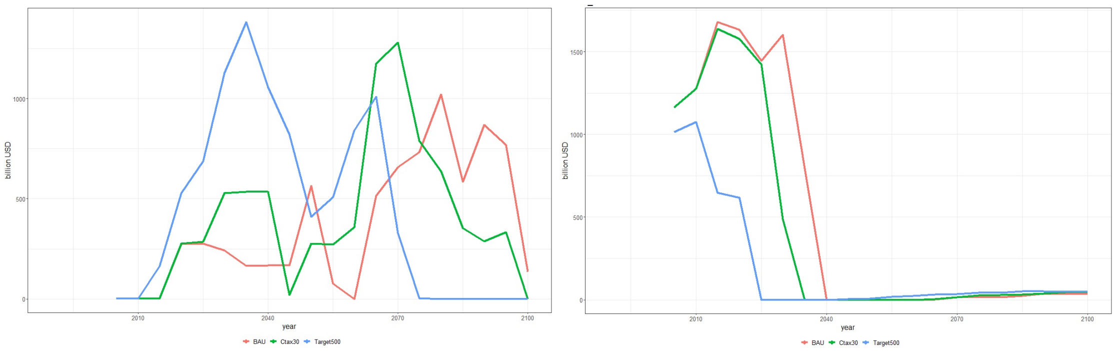
Plug-in hybrid vehicles experience a lot of fluctuations. There are two peaks with various amounts and during different times with respect to the scenario. First peak is due to initial investment needed to initiate usage of plug-in hybrids and the second one is necessary to catch up with other green fuel vehicles.

Traditional diesel vehicles show identical trend in all scenarios. In all cases they absorb some investment in early years as the momentum of their usage stays. But, after a short time this amount starts to diminish dramatically to a value of around 0 around year 2040-50. Carbon budget and tax enhances this declination with an even faster change.

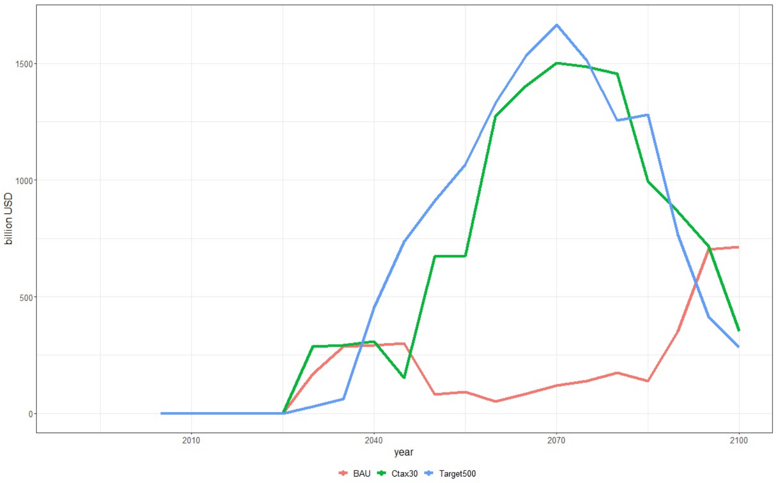
Lastly, for fuel cell vehicles the trend is two fold. Without any particular policy fuel cell vehicles do not attract much attention and expenditure up until 2100. On the other hand, by putting carbon policies the behavior utterly transforms. in both B and C cases investment on fuel cell vehicles rockets up starting in around 2040, reaching to its peak in 2070. After the climax, there is no more need to this amount of huge investment. Also, in this period edvs are strong competitions which do not allow fuel cells to rule over all the market. There is almost a 10-year gap between starting the investment and usage of hydrogen vehicles.



(a) Electric drive (b) Hybrid



(c) Hybrid plug-in (d) Traditional diesel



(e) Fuel cell

Figure (5.46) Worldwide investment in different type of vehicles

# Chapter 6

# Sensitivity Analyses

Mathematical model can be highly complex, and as a result, its relationships between inputs and outputs may be poorly understood.

As mentioned before, this model inputs are subject to sources of uncertainty, including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This uncertainty imposes a limit on our confidence in the response or output of the model. Further, models may have to cope with the natural intrinsic variability of the system, such as the occurrence of stochastic events.

Good modeling practice requires that the modeler provide an evaluation of the confidence in the model. This requires an evaluation of how much each input is contributing to the output uncertainty. Sensitivity analysis addresses this issue performing the role of ordering by importance the strength and relevance of the inputs in determining the variation in the output.

## 6.1 Cost of Production

First sensitivity analysis is on cost of production both on SGR as well as electrolyzing. Also, for SGR plants default value is 0.5 [$/W]. For the high cost scenario it is fixed to 0.7 and for the low cost scenario it is 0.3. Figures below show the difference in results for number of vehicles, freight trucks as well as total hydrogen demand.

| Year | <2030 | 2030-2050 | >2050 |
|---|---|---|---|
| Normal capex[$/W] | 1.6 | 0.9 | 0.5 |
| High capex[$/W] | 1.8 | 1.1 | 0.7 |
| Low capex[$/W] | 1.4 | 0.7 | 0.3 |

Table (6.1) Electrolyzer plants capex scenarios

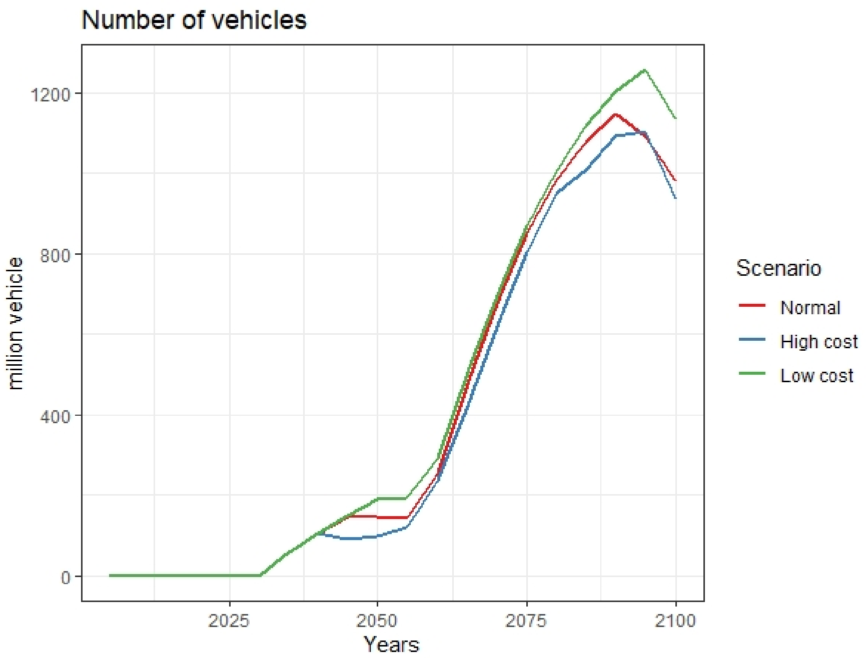


Figure (6.1) Sensitivity on production cost- vehicles

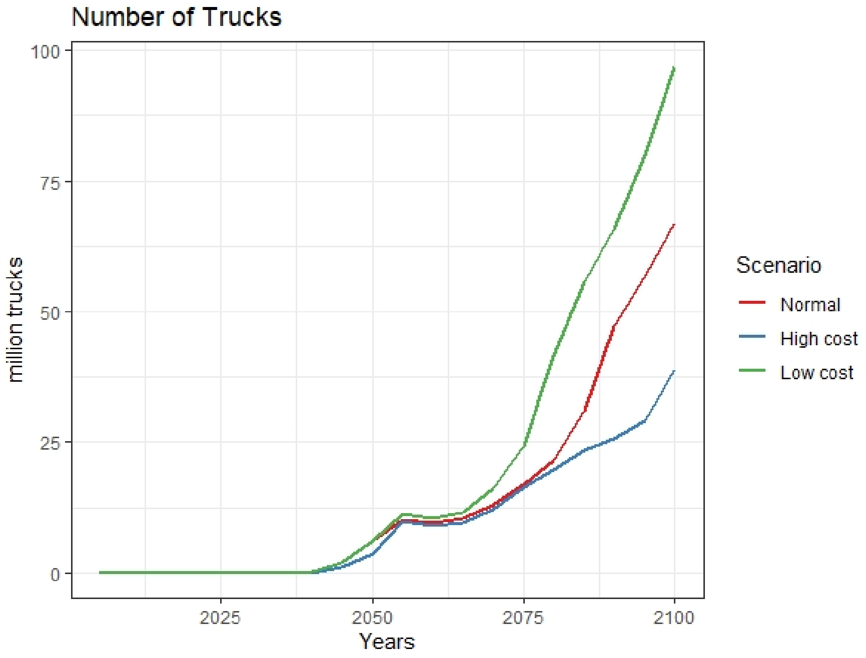


Figure (6.2) Sensitivity on production cost- freight

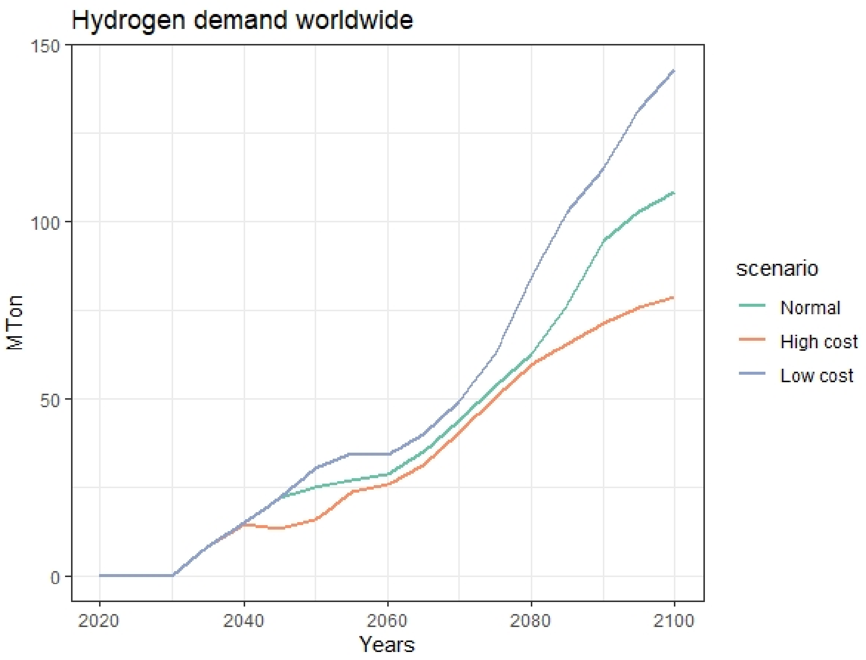


Figure (6.3) Sensitivity on production cost- hydrogen demand

Difference in the number of trucks is more observable than that of passenger vehicles. This could be due to the fact that each freight truck has a higher fuel consumption. So, the higher costing on supplying its fuel would affect the number more.

## 6.2 Cost of Fuelcell

Now fixing all other variables, we are differing the learning-by-research coefficient of fuel cell component which gives rise to different cost of fuel cell, and consequently the vehicles itself.

| Year | LBR coefficient of fuel cell |
|---|---|
| Normal | 0.277 |
| High cost | 0.243 |
| Low cost | 0.3 |

Table (6.2) LBR coefficient of fuel cell

It is obvious that, the higher the coefficient, the lower the final cost of component.

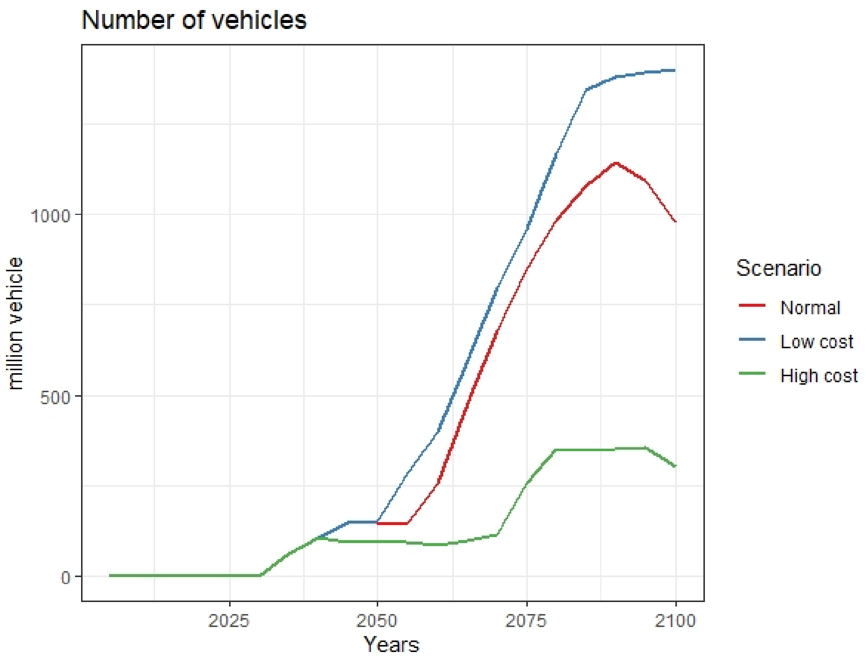


Figure (6.4) Sensitivity on production cost- vehicles

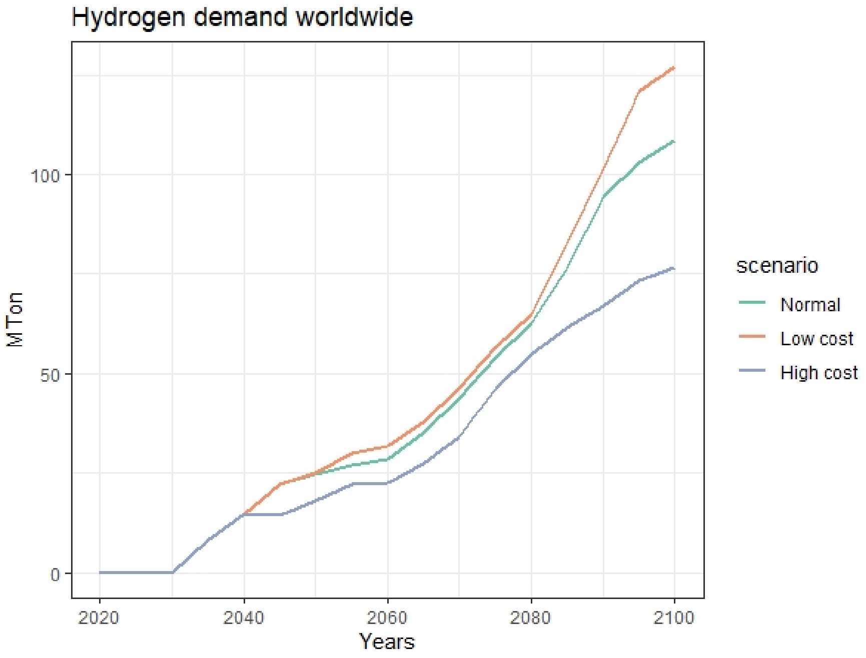


Figure (6.5) Sensitivity on production cost- hydrogen demand

This variation in the final cost of fuel cell component has an immense impact on the final number of vehicles in the fleet share.

## 6.3 Fuel Efficiency

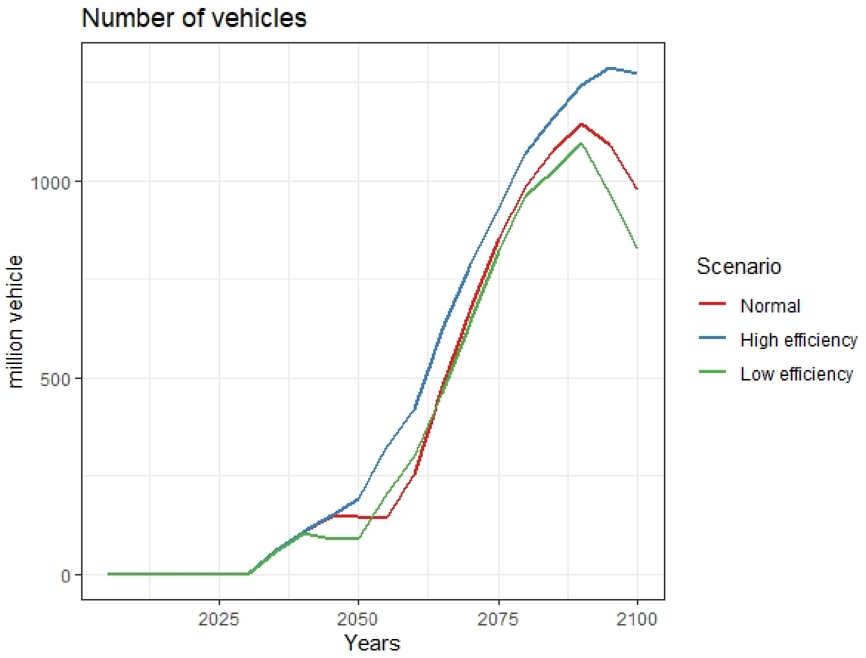


Figure (6.6) Sensitivity on fuel efficiency- vehicle

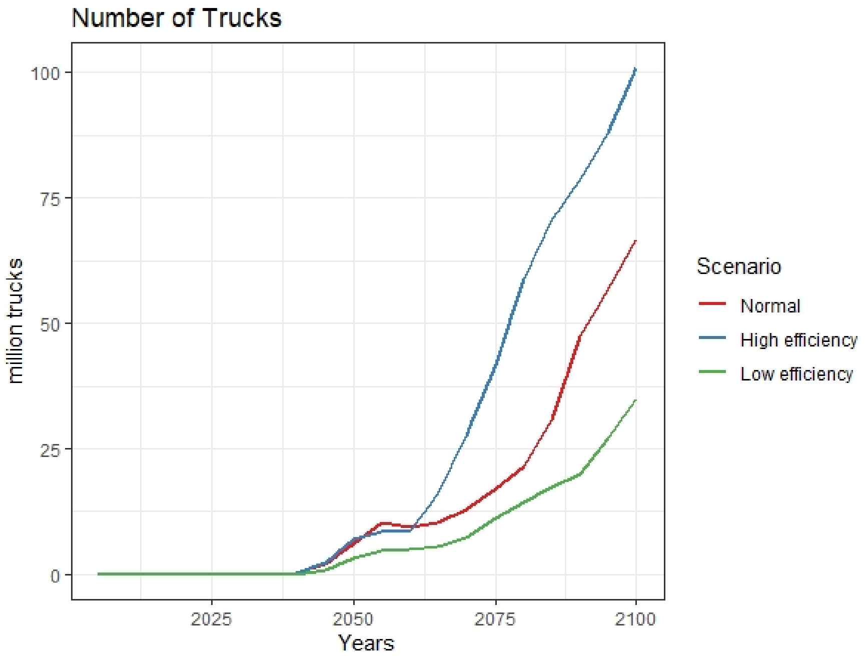


Figure (6.7) Sensitivity on fuel efficiency- freight

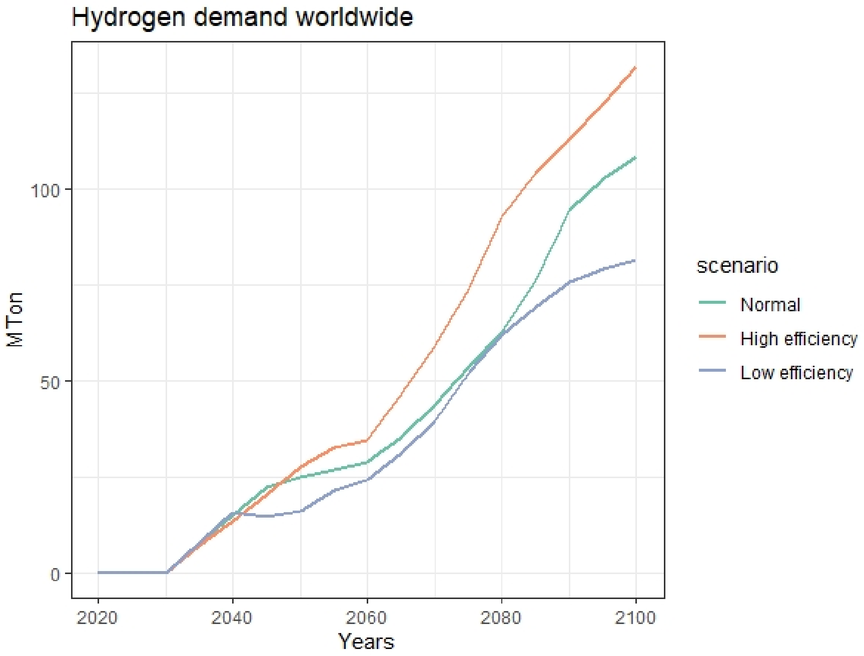


Figure (6.8) Sensitivity on fuel efficiency- hydrogen demand

## 6.4 Infrastructural Costs

Infrastructural costs of hydrogen technology in transportation are one of the main obstacles in their path. By doing some sensitivity analysis on these costs, we can evaluate and confirm the impact. Infrastructure here consists of pipelines and refueling stations. Two cases are present. A high-cost scenario with increasing pipeline and refueling station installation cost by 20% as well as a low-cost scenario with decreasing mentioned values by 20%.

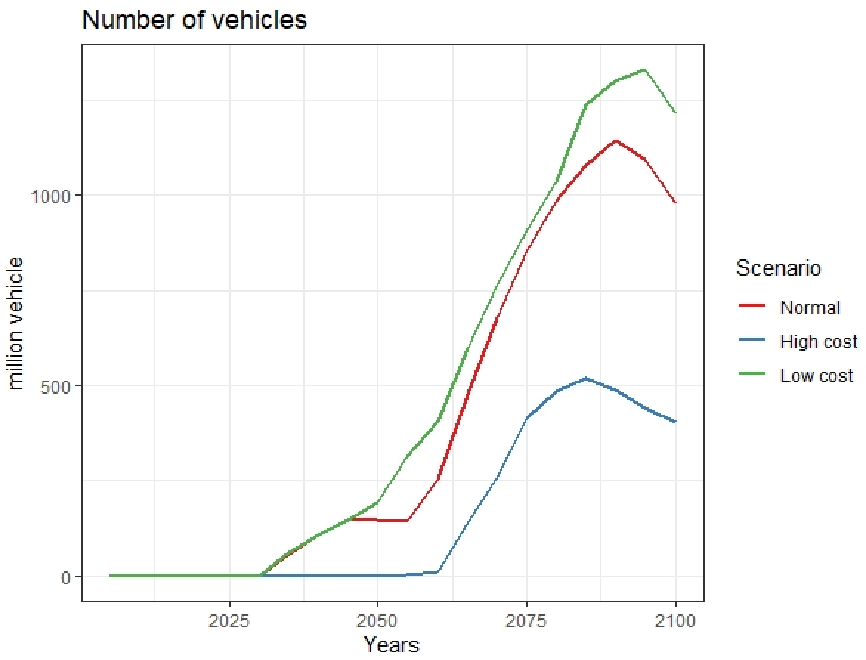


Figure (6.9) Sensitivity on infrastructural cost- vehicle

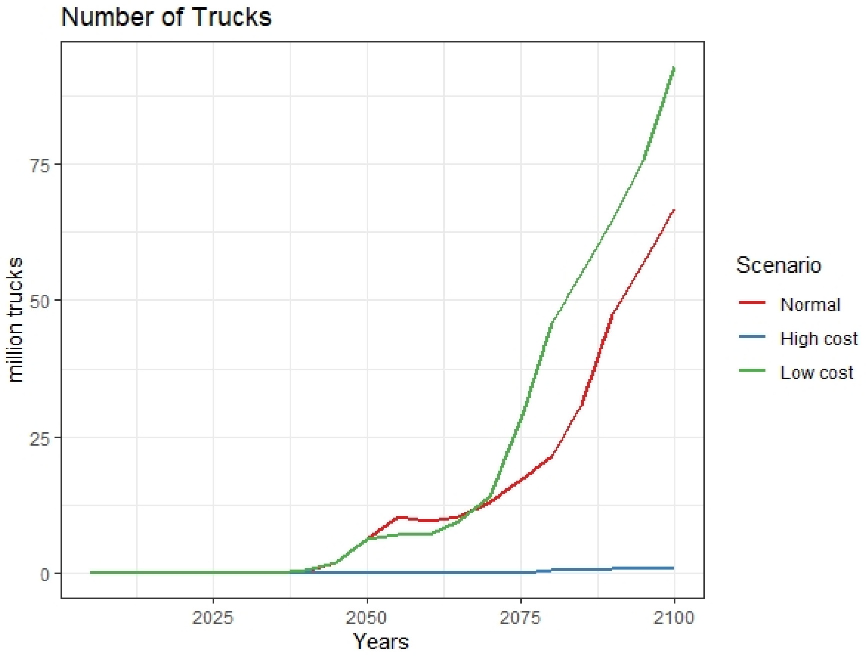


Figure (6.10) Sensitivity on infrastructural cost- freight

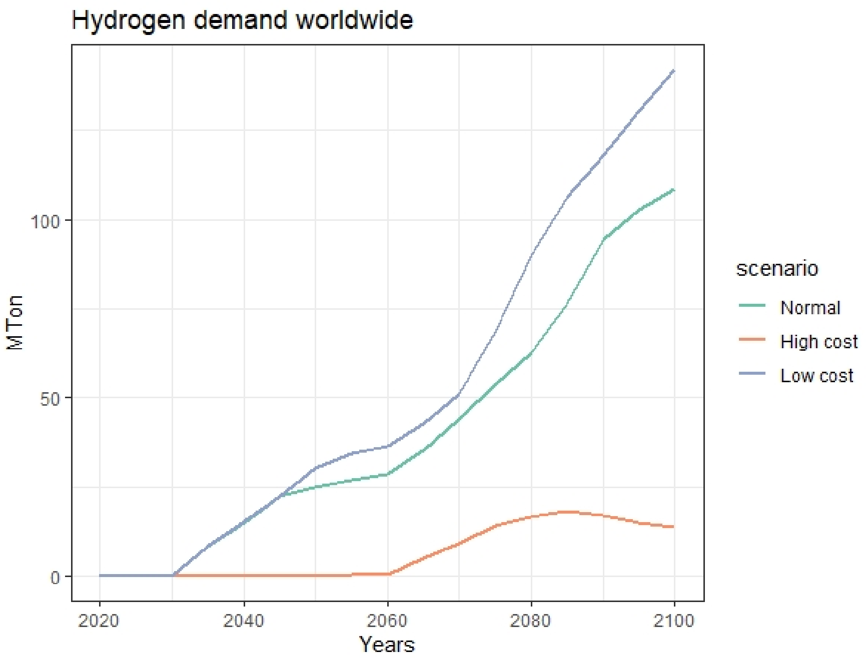
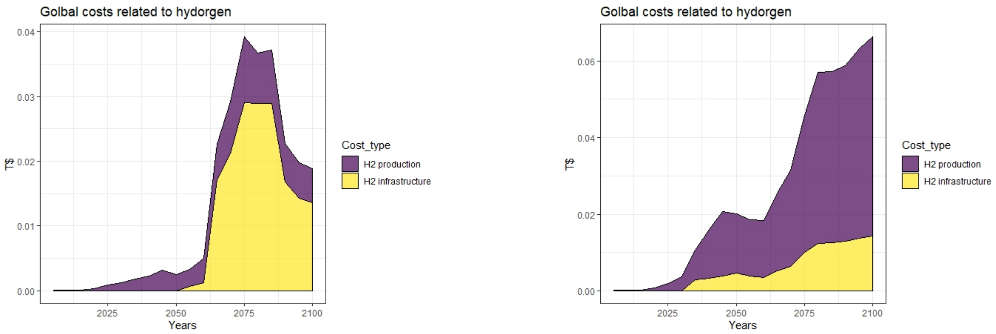


Figure (6.11) Sensitivity on infrastructural cost- hydrogen demand



(a) High-infra-cost (b) Low-infra-cost

Figure (6.12) New share of costs with new infrastructural costs

## 6.5 Growth Constraint on Production Plants

As discussed in previous chapters, there is a growth limit per each time step for hydrogen production plants. Installed capacities cannot exceed more than a certain percentage which is growth constraint. Here, four different constraints are considered. 20% is the default growth constraint, and it is compared with 10, 15 and 30% possible growth.

Results show that this maximum cap for growth is actually limiting the usage of hydrogen. So, if it is allowed that plants install higher, we would see higher number of hydrogen vehicles and freight, and consequently, total hydrogen production and demand. On the other hand, if constraint is fixed to 10%, usage of hydrogen and fuel cells drop dramatically.

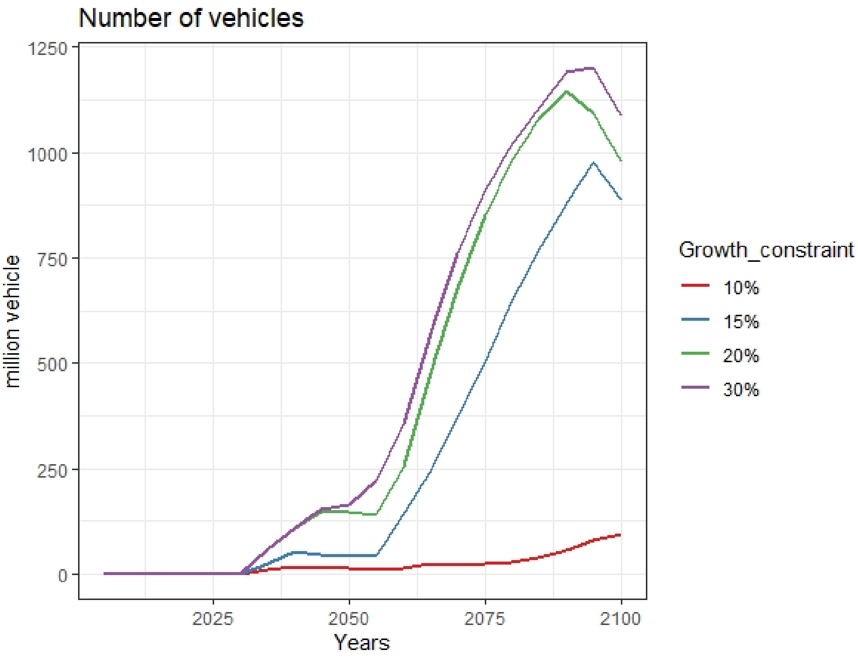


Figure (6.13) Sensitivity on growth limit- hvehicle

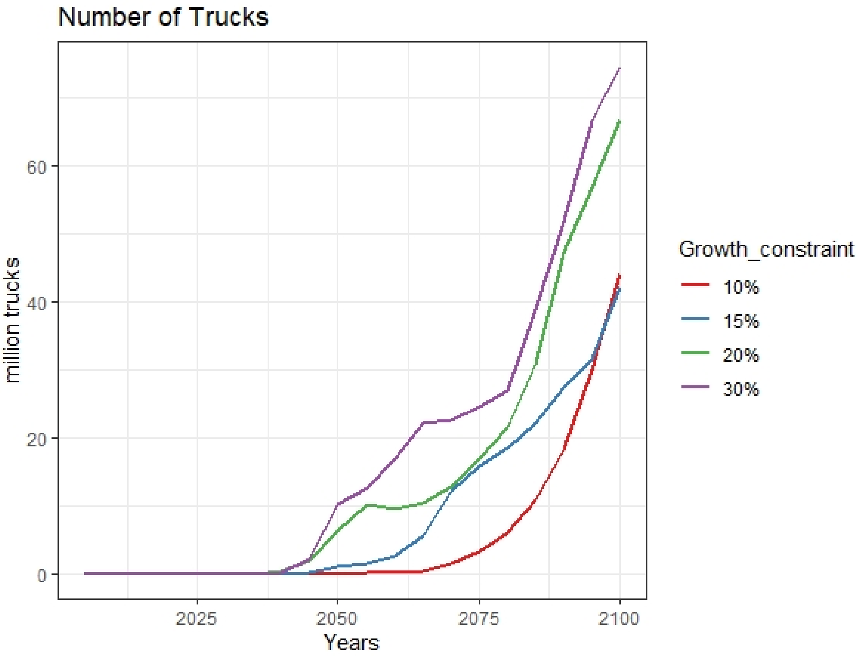


Figure (6.14) Sensitivity on growth limit- freight

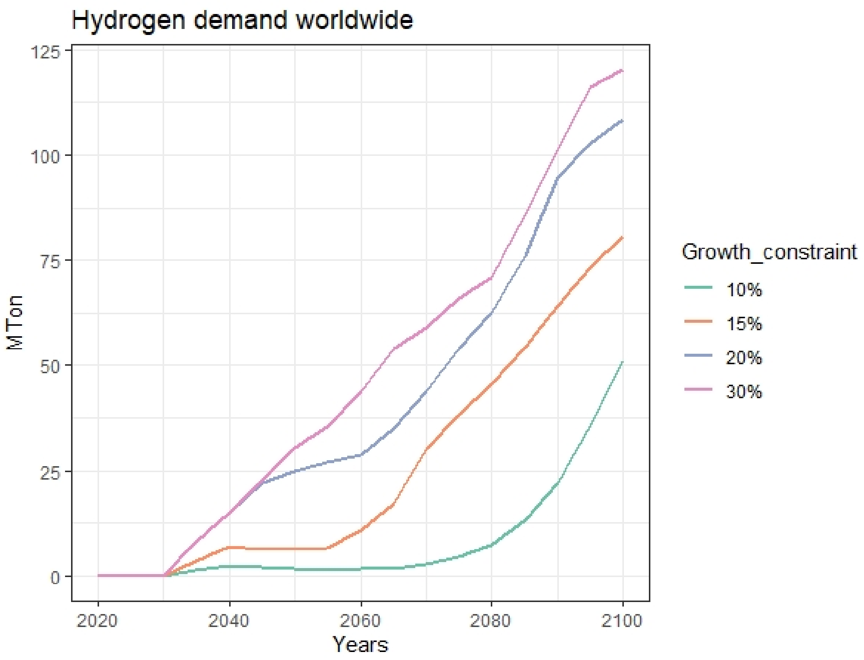


Figure (6.15) Sensitivity on growth limit- hydrogen demand

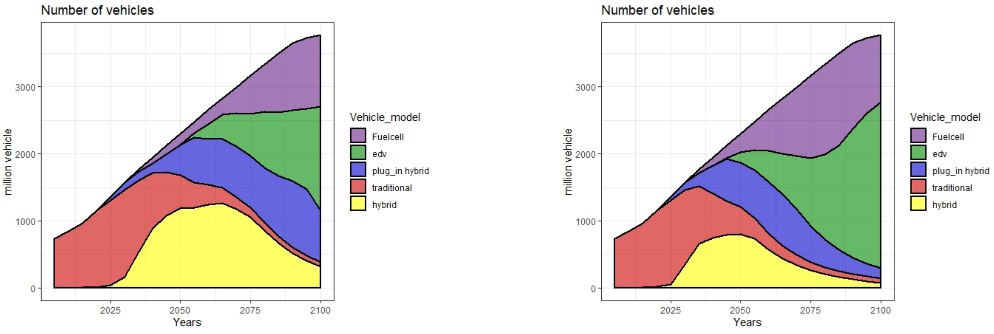
## 6.6 Regional Discount

In this part the role of regional discounting on vehicles are being analysed. This is mainly due to the fact that cost of some same vehicles are not same in different regions. For example, vehicle price index in India is less than that of EU or US. Regional discount refers to a coefficient, and final investment cost of vehicles is divided by that number.

| Region | Regional discount coefficient | Region | Regional discount coefficient |
|---|---|---|---|
| Brazil | 1.5 | Mena | 1.5 |
| Canada, US | 1 | Mexico | 1.5 |
| China | 2 | Oceania | 1.198 |
| Europe | 1.05 | Sasia | 2.2 |
| India | 2.5 | Seasia | 1.5 |
| Indonesia | 1.5 | SA | 1.1 |
| Jpnkor | 1.027 | SSA | 1.5 |
| Laca | 1.5 | TE | 1.5 |

Table (6.3) Regional discount coefficient

This coefficients are applied to all type of vehicles. However, it is possible to enable only some regions and some type of vehicles take benefit of this factor to observe the impact of a plethora of scenarios and incentives related to specific countries for specific type of cars.



(a) BAU (b) Carbon tax

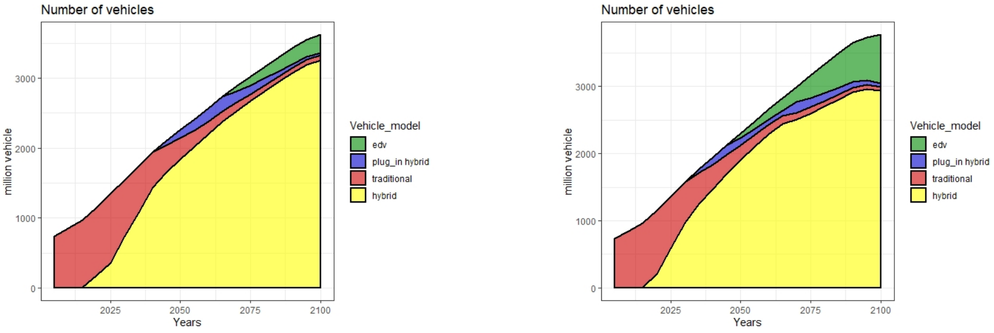
Figure (6.16) Vehicle fleet share with regional discount

Obvious impact of adding regional discount to the model is more usage of green-fuel energy vehicles such as FCVs and EDVs. The reason lies behind the investment cost of vehicles itself. Main obstacle of using FCV and EDV cars are their higher cost in comparison to others. So, by dividing all costs by a fixed coefficient, average difference between high-cost cars and low-cost cars will decline which suggests more green-fuel vehicles.

## 6.7 Without Hydrogen

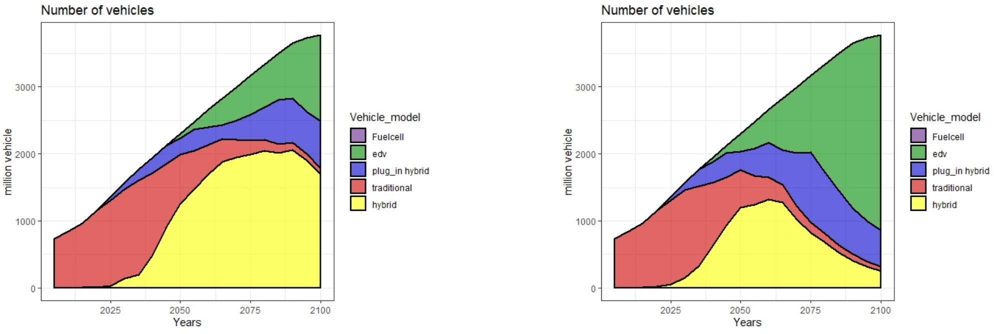
It is of paramount importance to see what happens if hydrogen is not present in the model. In this part two different comparison will be done. Final achieved results will be compared, firstly, to a scenario in which hydrogen is not allowed to expand at all and is switched off. And, secondly, to the default version of WITCH before doing current changes and project.

### 6.7.1 Vehicle fleet



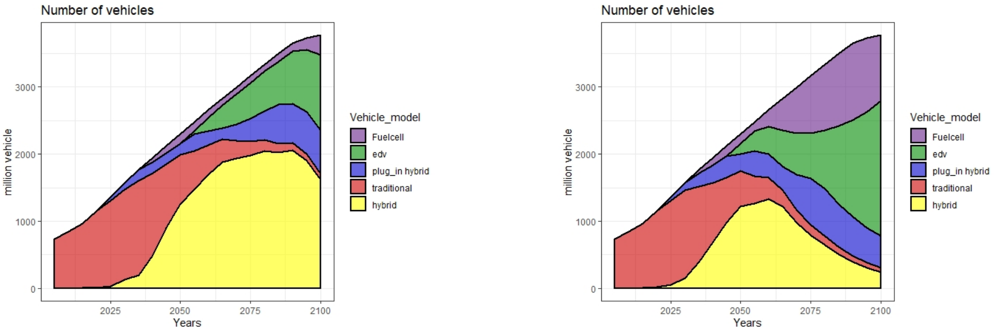
(a) BAU (b) Carbon tax

Figure (6.17) Vehicle fleet share in defualt WITCH



(a) BAU (b) Carbon tax

Figure (6.18) Vehicle fleet share without hydrogen



(a) BAU (b) Carbon tax

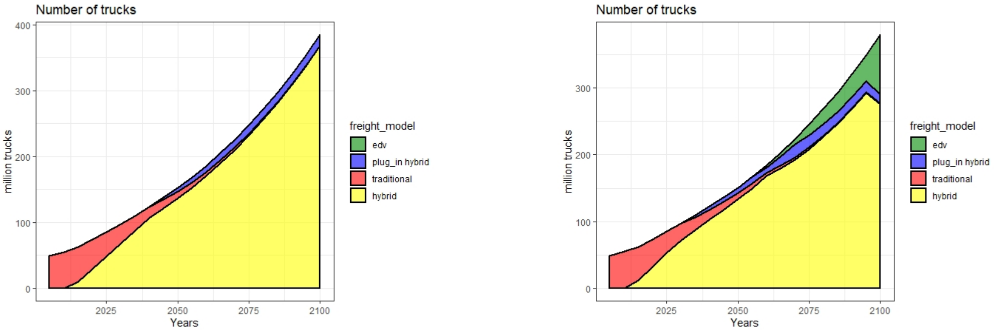
Figure (6.19) Vehicle fleet share of normal results

Comparing 6 figures above gives a decent insight to the changes in transportation sector done in this project. Figure 6.17 shows the results of default results in transportation module in WITCH. There was no fuel cell, so only 4 type of vehicles are present. With default equations on cost configuration of vehicles and previous modules hybrid vehicles were the dominant part of fleet in both baseline and carbon tax scenarios. Edvs and plug-in hybrids had a limited share even with carbon policies which is not realistic with respect to recent momentum and observations.

Figure 6.18 indicates the share and number of vehicles by switching off hydrogen, but with new cost configuration and changes. Now, there is more room for electric drive and plug-in vehicles even in baseline scenario. One of the main reasons behind is related to modifications in battery costs to be more realistic. In carbon tax scenario edv would the major part of transportation.

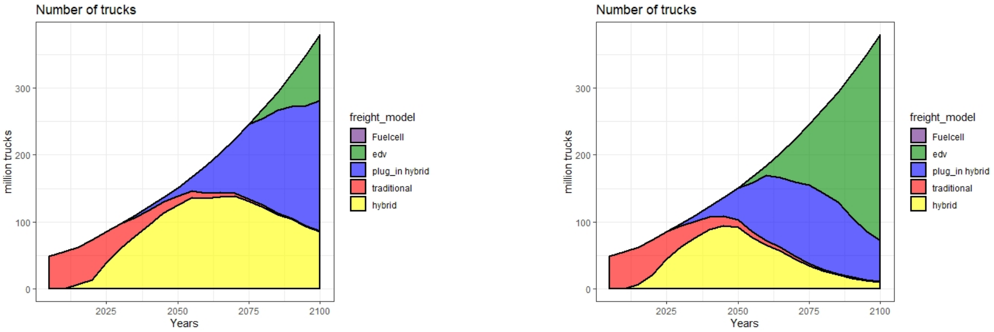
Now, Figure 6.19 presents current and final results achieved with hydrogen switch on. By comparing the figures, one can perceive that electric drive and fuel cells are the main competitors to each other. In other words, the summation of edvs and fcvs is mostly a function of carbon policy. While, in a constant policy, the differentiation of share between these two relates to other factors such as cost of components, fuel efficiency, infrastructural costs and so on.

### 6.7.2 Freight truck fleet



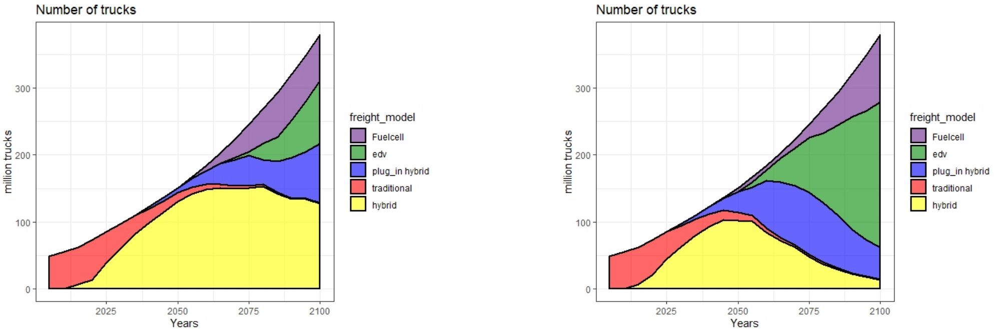
(a) BAU (b) Carbon tax

Figure (6.20) Freight truck fleet share in defualt WITCH



(a) BAU (b) Carbon tax

Figure (6.21) Freight truck fleet share without hydrogen



(a) BAU (b) Carbon tax

Figure (6.22) Freight truck fleet share of normal results

Figure 6.20, Figure 6.21 and Figure 6.22 display the same results of previous section but for that of freight trucks. Again, in default WITCH version hybrid trucks were the main part of fleet with a negligible role for other type of trucks. As the changes made in freight transportation module now there is more room for plug-in hybrids and electric drive trucks to participate in the truck fleet. In baseline scenario there are more plug-ins which is mainly because of their lower cost with respect to electric drives. However, in ctax scenario the additional cost of electric trucks would be justified. By switching on the hydrogen trucks, in BAU the share occupied by electric and plug-ins now are divided between three type including electric, plug-in and fuel cell trucks.

### 6.7.3 Natural gas integrity

In this part, it will be a good idea to look at the natural gas demand and production in the model to see its integrity with hydrogen production. Figure 6.23 shows amount of natural gas in ctax (B) scenario with and without hydrogen. In the case with hydrogen (orange curve) the demand of natural gas would be higher due to hydrogen production by SGR which discussed before.

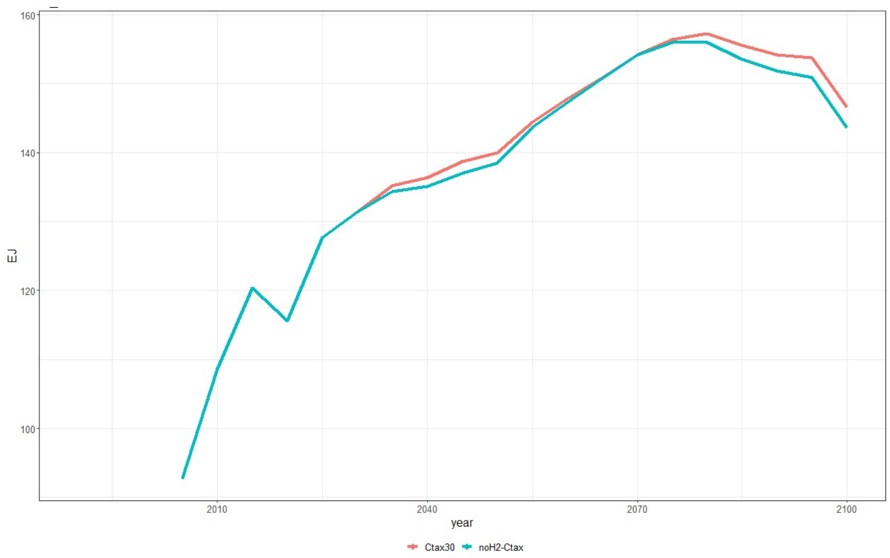


Figure (6.23) Natural gas production with and without hydrogen

## 6.8 More Policies

In this section more and different policies based on the main policies will be compared. For now we had baseline, carbon tax with initial value of $30\$/tCo2$, and carbon budget target 2019-2100 equal to 500Gton scenarios.

### 6.8.1 More Carbon tax cases

Regarding different carbon taxes, initial carbon taxes of 10, 20, 30, 50 and 100 $\$/tCo2$ are considered as different cases.

Figure 6.27 shows the amount of carbon tax over time in the model based the initial value introduced.

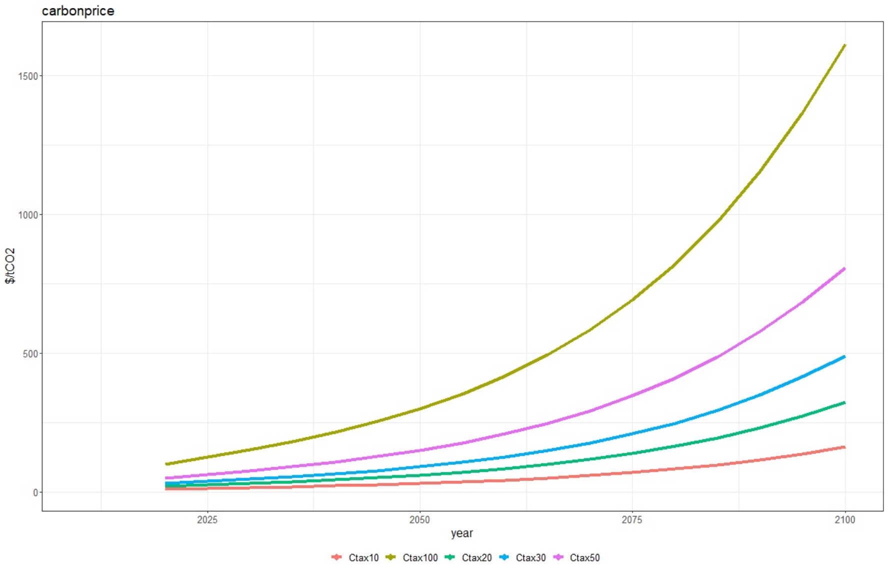


Figure (6.24) Carbon tax of different sensitivity cases over time

Aforementioned cases give rise to different climate outcomes. Figure 6.25 indicates respectively, Co2 emissions, total radiative forcing and temperature increase with respect to pre-industrial level for all five cases. Without any doubts, the higher carbon price, the lower emissions and therefore temperature.

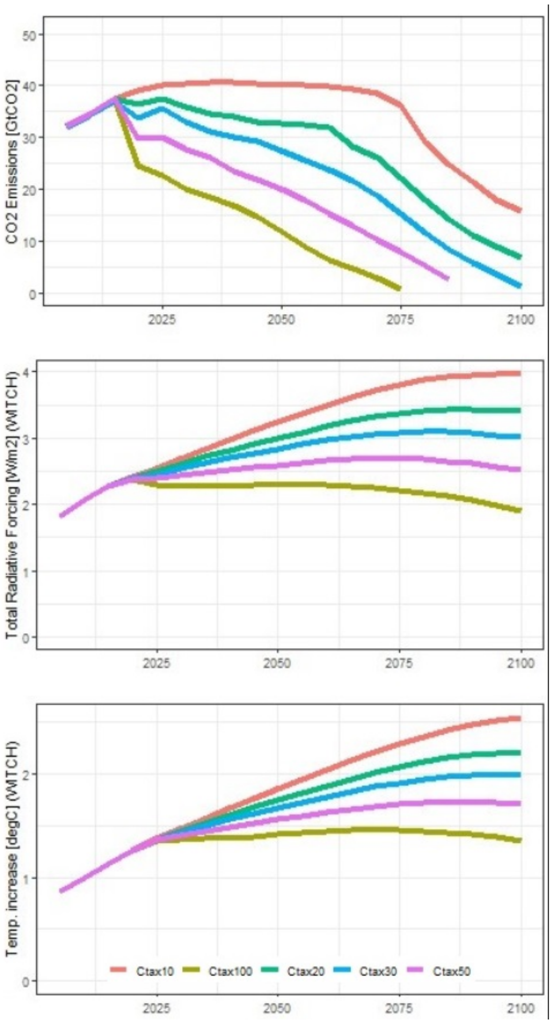
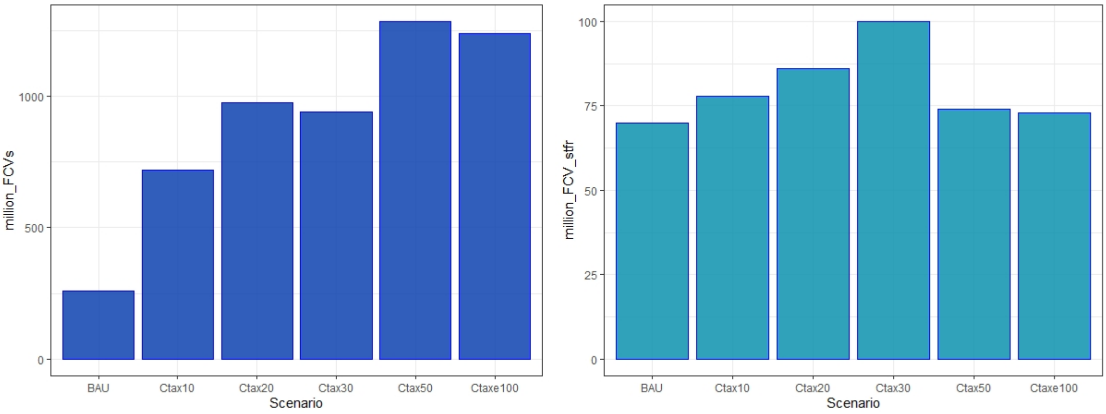
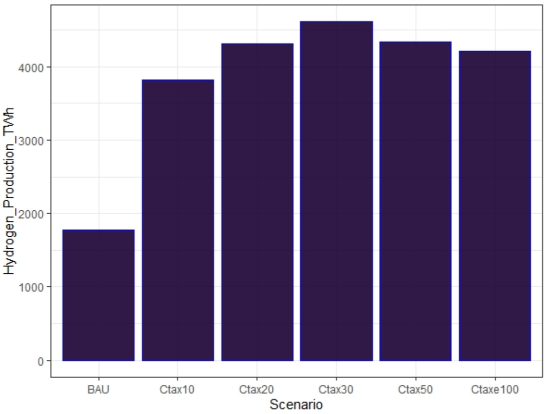


Figure (6.25) Climate related outcomes of sensitivity cases over time

To conclude the results in this part three main parameters is chosen; number of fuel cell vehicles, number of fuel cell trucks and total amount of hydrogen production/demand. Without any carbon tax, there is no room for fuel cell vehicles, so their total number and share stays low. Also for freight trucks, as we put more strict policies on carbon tax total number of fuel cell trucks grows. However, in both cases, there is an optimal initial carbon tax value for implementing hydrogen. In fact, in some cases even increasing the carbon price gives rise to less hydrogen demand. This is due to the fact that other types of green-fuel vehicles and trucks get benefit from carbon policies as well. For FCVs ctax50 and for FCV_stfr ctax30 shows the maximum usage of hydrogen, and all in all ctax30 indicates the highest amount of hydrogen demand/production. One can conclude that implementing hydrogen does not need crazy high and impossible carbon tax values.



(a) Scenarios vs number of FCVs (b) Scenarios vs number of FCV_stfr



(c) Scenarios vs amount of hydrogen production

Figure (6.26) Carbon tax scenarios sensitivity

Figure 6.26 directly indicates the amount of hydrogen production which is needed to meet climate change goals at end of the century. By using stringent policies amount of total emissions and therefore, temperature increment would be lower. Graph on the left shows that more hydrogen is needed as we want to reach climate goals ranging from 3.7°$C$ to around 2°$C$. To achieve more ambitious goals below 2°$C$ in 2100, hydrogen demand will not keep rising and fluctuates over different scenarios. Hence, to reach 2°$C$ target hydrogen production/demand can be in a linear proportion with the target, while after that other options seem more interesting.

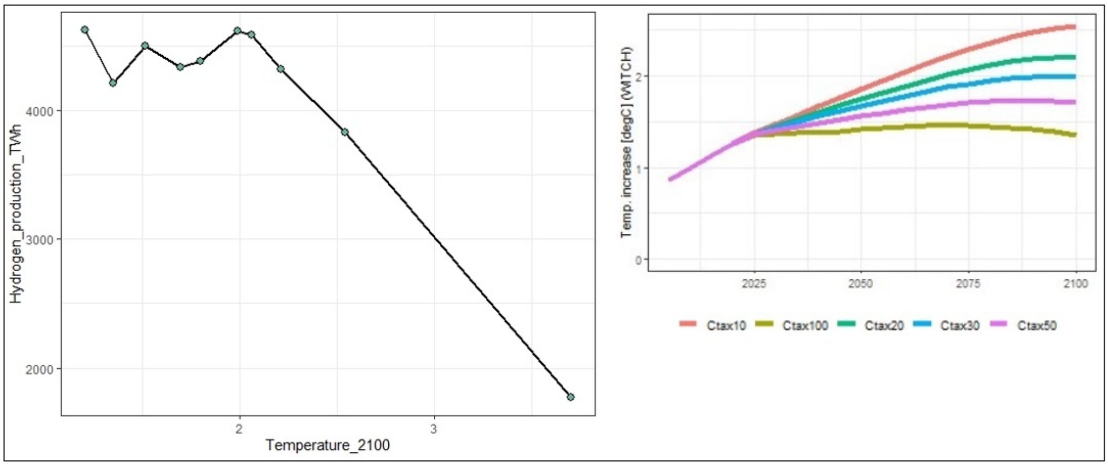


Figure (6.27) Hydrogen amount vs temperature target in 2100

# Chapter 7

# Conclusion and Future Work

## 7.1 Conclusion

In this chapter, we summarize the main results achieved in our work and the main conclusions we can draw from them, answering to the questions that motivated our research. The questions are reported in the following:

- What is the role of Hydrogen in future transportation and storage of energy systems?
- What are the opportunities as well as shortcomings of implementing and developing Hydrogen, fuel cell & electrolyzers?
- Which pathways should be paved by transportation sector and how is the share of vehicles in order to achieve climate change goals?
- What is the influence of technological improvements on using hydrogen? deployment over time?
- What are the options for production & distribution of Hydrogen? Observing the effects of these infrastructural costs on future of Hydrogen economy.

**Main questions discussion** The main objective of this project was to model hydrogen production options and plants, transmission and distribution and refueling stations. Also, modeling fuel cells, electrolyzers and fuel cell vehicles and trucks was another critical part of thesis. Hydrogen could be use either in transportation or storage sector. Also, amount of extra electricity produced by renewable sources was introduced as curtailment. This amount is divided into a short-term and seasonal curtailment. After modeling all the equations, inputting data and calibration three main scenarios were defined to analyze the results; Baseline scenario(A), Carbon tax scenario(B), Carbon budget and target(C) in which respectively we have more strict and limiting policies on carbon. The more strict policies, the lower temperature and emissions at the end of century. All scenarios use SSP2 as the population and production functions. Time horizon is 2005-2100.

To see the role of hydrogen as storage we have to observe results on curtailment module. Short-term extra electricity has two options, be stored or be wasted. On the other hand, seasonal curtailed electricity has three options, be stored by converting into hydrogen, be used as hydrogen fuel or be wasted. In Scenario(A) a huge amount of extra electricity would be wasted due to high costs of storage and low demand of hydrogen. By putting carbon tax in (B) & (C) share of wasted electricity decreases while most of the curtailment will be used as fuel. Storage still has a limited part due to high costs of storage. If storage by hydrogen wants to become affordable a lot of research and developments are still needed.

Conversely, hydrogen plays a crucial role in transportation sector. Transportation accounts for around 17% of total worldwide emission, meaning it has to be mitigated by implementing new policies and pathways. Hydrogen offers an exciting solution. It is the most abundant and lightest element. Non-toxicity, high energy content, diverse sources of production are among other encouraging attributes. Hydrogen is an "energy career" which can be transported almost easy. Converting hydrogen into electricity or vice versa is easily achievable by using fuel cells and electrolyzers. If renewable sources are used, hydrogen production can be a green product which helps to decarbonize, however, if fossil fuels are being used, carbon capture and storage is essential. This fact is utterly achieved by the results in this project. In (A) Steam gas reforming using natural gas has a huge part in production, while by increasing carbon tax, low-carbon strategies are imperative, so we saw a huge shift from SGR to SGR+CCS and electrozying from renewables' extra electricity. Although, hydrogen seems attracting, there are some obstacles which needs to be tackled. Lack of infrastructure, current high costs of hydrogen production and fuel cells are some of the most important ones. When green methods of production wants to be used the cost of production becomes even more challenging.

As the results in **vehicle** transportation section suggests, in all scenarios traditional vehicles would be still dominant in early years. By decreasing the number of traditional cars, hybrids start to grow regardless of the policy taken. This is mainly because of the lag between impulsing the policy and actions taking place as well as the present momentum of traditional diesel fuels. In scenario(A) only 3 regions use hydrogen and the total demand is very low in comparison to other types. EDVs, PHEVs and hybrids will be the dominant part of fleet. Now, by putting carbon taxes, hydrogen has incentives to become a participant. Some regions invest money in R& D of fuel cell and costs become more affordable. 2035-2040 is the era of FCVs initiation. Both FCVs and EDVs experience a booming growth leading to be the main actors of fleet at the end of century. A key finding is the result that shows by increasing even more carbon tax after a certain value, electric vehicles benefit more than fuel cell vehicles.*Hence, putting carbon taxes and instrumenting policies are vital for hydrogen vehicles, while more harsh and almost unrealistic policies is not favorable and necessary to them.* In these cases 8-9 regions use fuel cell vehicles out of total 17 present regions.

Another decisive part of transportation is related to **freight trucks**. In this case number of fuel cell trucks are less dependent on the policy. Initiation era would be a bit later, around 2050. Even in BAU scenario (A) results suggest using fuel cell trucks for 6 regions. By putting carbon policies, total number of hydrogen trucks will be higher but not as high as electric trucks. As we go deeper into harsh policies, diminishing trend of traditional and hybrid trucks will be sharper, giving more and more room to plug-in and electric trucks. One of the most distinguishable difference of freight fleet compare to vehicle fleet is that despite the lower share of fuel cell in this case, total number of regions using fuel cell trucks is higher -12 regions out of 17.

Sensitivity analyses on cost of hydrogen production and infrastructural costs proves the obstacles discussed earlier. By enlarging the investment cost of production plants optimal number of hydrogen using vehicles and trucks would decrease, with a higher impact on trucks. Furthermore, cost of infrastructure affects both vehicles and trucks immensely. This shows the importance of lack of infrastructures such as transmission pipelines and refueling stations as an obstacle. Another robustness analysis on fuel cell learning coefficient indicates the relevance of learning growth and investment on the final cost of fuel cells and consequently the FCV itself. It is worthy to mention that difference made by increasing cost has more impact than decreasing. Growth constraint is another limiting factor which not allows hydrogen plants to grow as much as possible. If growth limit goes down from 20% to 10% hydrogen production reduced dramatically.

Regional discount refers to any regional difference in the price index for vehicles. It is practically useful when we want to observe the effects of any particular incentives on some kind of vehicles or all of them. In our case only car price index for different regions has been considered, meaning that now the mean cost of vehicles in some regions such as India or China is lower than that of Europe or USA. The result is higher FCVs and EDVs and PHEVs. This can be explained by the lower difference between green-fuel vehicles and traditional, hybrid ones, which mitigates the high cost of green vehicles.

## 7.2 Future work

Future work and available room to continue the project divides into two main parts:

**Further tasks on hydrogen itself to make it more precise** To have a better and more thorough evaluation on hydrogen part many other steps could be done in future. Firstly, as mentioned before, there are plenty methods for producing hydrogen such as partial oxidation, coal gasification, biomass gasification and many more. In this project only electrolyzing and steam gas reforming are considered as the main means to produce amount of necessary hydrogen. So, by adding more competitor plants and technologies share of production and average price of hydrogen could vary. The same holds true for delivery options of hydrogen. For now the only available choice is by using pipelines. However, it is possible to add delivery and transmission by trucks and already installed natural gas pipelines. The next improvement could be on endogenizing production costs. As it concerns now, steam gas reforming costs are fixed to a constant value and electrolyzing costs are decreasing, yet exogenously. By introducing investment costs of these production plants to learning-by-doing and learning-by-research algorithm to predict future costs, results could improve.

Apart from enhancing possible improvements that already mentioned, there are other bigger desirable advancements. Allowing the trade of hydrogen could be a big change. For now, each region at each specific time step has to produce its own hydrogen based on its own demand. By adding trade to the model, this fact could change. Maybe producing hydrogen would be cheaper in some regions due to their specific natural resources and infrastructures. So, some regions would act like exporters of hydrogen, some others are importers, while the rest could act as a combination of a local producer and importer. Second big advancement is to connect hydrogen to other sectors as well. Heating sector, oil refinery and chemical sector are the main targets to be included.

**Further developments on transportation sector** Transportation module modification was a major part of this project as we seen the improvement by comparing the results with those of default WITCH. In fact there are more capacities to improve transportation sector even more. Greenhouse gas emissions from commercial aviation are rapidly increasing. If the global aviation sector were treated as a nation, it would have been the sixth-largest source of carbon dioxide (CO2) emissions from energy consumption in 2015, emitting more than Germany. [37]. For now there is no aviation sector in WITCH model. However, it could be a fruitful idea to make it happen in order to have a more correct observation. Public transportation holds true same as aviation.

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