Scenario based lifecycle analysis of greenhouse gas emissions from petroleum-derived transportation fuels in 2050

By

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Abstract

Petroleum-derived fuels made up 93% of the energy demand for the transportation sector in 2013, and are projected to remain a significant source in the future (65% to 90% in the year 2040) [1]. These fuels contribute significantly to global green house gas (GHG) emissions, both from their production and combustion emissions. Production emissions make up one fifth of the emissions associated with the entire petroleum fuel lifecycle. Although the current non-combustion production lifecycle emissions of these fuels are well understood, their future lifecycle emissions have yet to be quantified.

In this thesis, a global, scenario-based analysis of petroleum-derived transportation fuels is carried out to estimate lifecycle emissions in the year 2050. The 2050 scenarios differ by the stringency of environmental policies, including no new additional policies, "moderate" new policies, and "strong" new policies. Data from existing projections for the energy sector in 2050 is used to create lifecycle inventories for the three 2050 scenarios. The production lifecycle emissions for the year 2050 are calculated to be 14.3 – 19.2 g CO_2e/MJ for jet fuel, 17.2 – 24.9 g CO_2e/MJ for diesel, and 21.1 – 26.8 g CO_2e/MJ for gasoline. The production emissions in 2050 could deviate from 2020 values by as much as +20% to -21%, depending on future policy choices. If these production emissions are applied to global fuel demand, the range of emissions reductions from these policy scenarios spans 8.5% of all GHG emissions in 2013.

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1 Introduction

1.1 Background: petroleum-derived transportation fuels

Liquid petroleum-derived fuels accounted for 31% of the world's primary energy demand in 2013 [1]. These petroleum-derived products are widely used throughout the world in applications such as transportation, industry, and power generation (see Figure 1.1 for sectorial breakdown). The transportation sector consumes more than half of the world's fossil fuel oil (56%), where it powers road, aviation, and marine modes of transport [1,2]. Oil made up 93% of the energy demand by the transportation sector in 2013 [1], with the remainder being met by bioenergy, electricity, or natural gas [1,3].

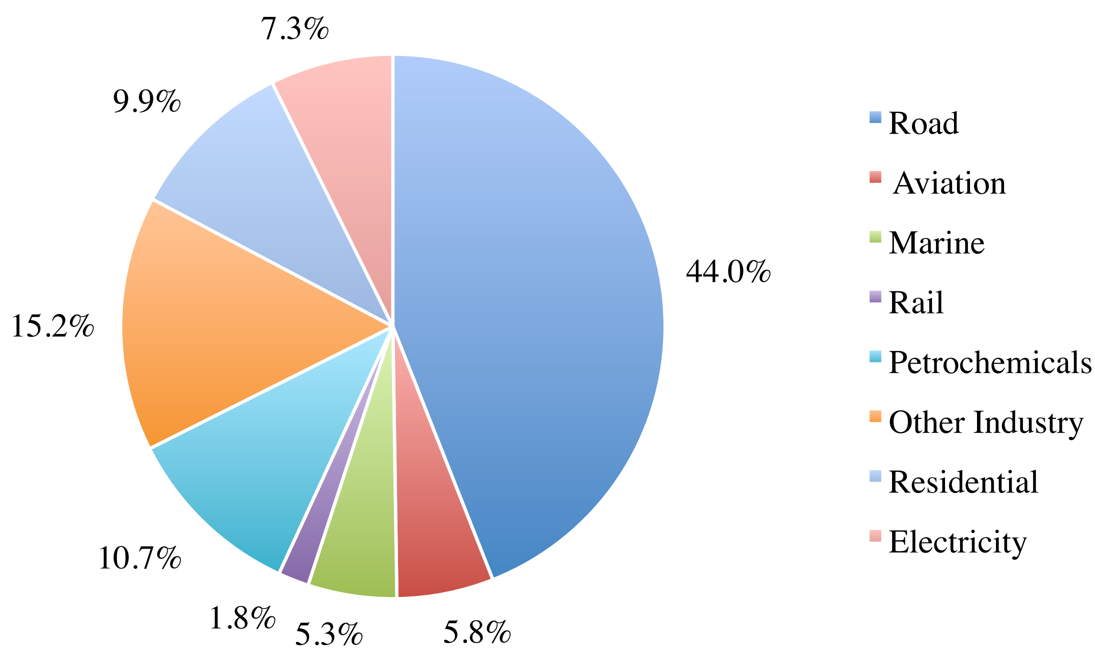

Figure 1.1: Global use of petroleum-derived fuels by sector in 2013 [2]

The combustion of all liquid petroleum-derived fuels was responsible for 34% of global greenhouse gas (GHG) emissions in 2013 [1]. The oil used for transportation was responsible for

22% of those total global emissions, or two thirds of the total oil emissions [1]. However, considering combustion emissions alone does not account for the emissions associated with the production of these fuels. On average, production emissions are equal to one quarter of the combustion emissions [4,5].

In the year 2040, the International Energy Agency (IEA) projects that petroleum will still account for 22-27% of global primary energy demand [1]. The GHG emissions from the combustion of these fuels are expected to account for 31-40% of total GHG emissions in 2040 [1]. The IEA also projects that oil will continue to dominate the transportation sector's energy demand, making up 65-90% in the year 2040 [1].

Despite forecasts for continued use of petroleum-derived fuels in the future, production emissions of petroleum fuels have yet to be quantified past the year 2020 [4]. The production emissions for petroleum fuels have changed in the past and are expected to change in the future. These changes are due to factors such as the types of crude oil resources extracted, improved process efficiencies, and uptake of new technologies [4]. For example, Azadi et al estimated an average 3.8% increase from 2005 to 2012 and a 6.6% increase from 2012 to 2020 for production emissions of petroleum-derived transportation fuels (diesel, gasoline, jet fuel) [4]. Such changes to production emissions are likely continue to occur between now and 2050, however the extent of these changes are largely unknown.

1.2 Motivation: quantifying fuel production emissions in the future

A lifecycle perspective on environmental impact includes emissions from the production, operation, and end-of-life [6]. In order to make robust emissions management plans or goals, one must have a comprehensive understanding of emissions sources [7]. Quantifying the production emissions of petroleum-derived transportation fuels aids in understanding a major emission source (5.5% of global emissions in 2013 [1]).

One might question why it is worth quantifying future production emissions, rather than just using present values in their stead. To ensure accurate analysis, the data used in calculations should all come from the same time period. Using future data, rather than present values, is more appropriate and consistent when analyzing or planning for the future activities.

However, real-world policies do not always use data that comes from the same time periods. One such example is the US Renewable Fuel Standard (RFS) [8]. Under the RFS, production target volumes are set for various types of alternative fuels [8]. These targets can be met through producing the specific type of alternative fuel, or by applying a credit acquired from a different type of alternative fuel [8]. Credits are awarded based on the reduction in fuel production emissions achieved by alternative fuels with respect to the baseline set by conventional fuels [8]. Under the RFS, the baseline production emissions values for petroleum-derived transportation fuels are taken from the year 2005 [8]. Thus, alternative fuels being produced presently (2017) are compared to a benchmark that is out of date (2005).

Temporal inconsistency is problematic, because it means that the logic within policy and reality are not aligned. The reductions measured in the policy are inconsistent with the reductions measured in reality. In reality, fuel producers compare their fuels to current market competition. However, in the policy, present alternative fuels are being compared to conventional fuels from years past. Similarly, when fuel producers are planning for the future, they draw comparisons to future technology. Competing technologies are compared within the same timeframe. Actors within the fuels space plan for the future considering that policies are predictable and remain in effect. Thus, this issue of temporal consistency is important to technology innovators or investors, as well as regulators.

In addition to RFS, other alternative fuel policies use petroleum emissions as a baseline, since petroleum is the conventional fuel technology. The International Civil Aviation Organization (ICAO) is creating a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [9]. CORSIA sets an emissions cap for the airline industry at 2020 emissions levels, and enacts a carbon market around this cap [9]. Airlines may use various mechanisms to reduce their emissions, such as improved airport operations, more efficient aircraft, tradable offset credits, and alternative fuels [9]. Like the RFS, alternative fuels within CORSIA will receive credits based on their reduction in production emissions from the convectional baseline [9].

Understanding the future emissions of petroleum-derived transportation fuels is also important for activities aimed at reducing the emissions intensity of this industry. Combustion emissions constitute 80% of the entire fuel lifecycle emissions [4]. However, combustion emissions of CO_2 are stoichiometrically tied a fuel's composition, and are therefore inherently difficult to change [10]. Although production only makes up 20% of lifecycle emissions, these emissions represent a subset that could be reduced independent of fuel consumption. By calculating the production emissions in the year 2050, one will also gain an understanding of the sensitivity of production emissions to different values. This knowledge can be used to design emission reduction strategies.

Overall, quantifying the production emissions of petroleum-derived transportation fuels has several uses. These future values can enhance future planning by providing temporally relevant values. Policies that can use these values include the US RFS and ICAO's CORSIA.

Additionally, creating these projections will foster an understanding of the fuel production pathway, which can facilitate the identification of opportunities for emissions reduction. Understanding how petroleum fuels will contribute to GHG emissions in the long-term future helps to realize a complete picture of emissions sources, which will impact innovation, research, and investments associated with all fuels [11,12].

1.3 Research questions

The main question that this research aims to answer is as follows:

> *Given future policy changes, what will the production emissions of petroleum-derived transportation fuels be in the year 2050?*

Thus, this research will quantify the potential emissions in 2050. This will establish how much the emissions change from present values to future ones, given future changes to environmental policies. Additionally, through exploring these emissions, this research will be able to answer a second question:

> *To what extent can the production emissions of petroleum-derived transportation fuels be reduced?*

Understanding how and why emissions change will inform the ways in which one could control the emissions associated with petroleum production processes. This research will quantify the opportunity space of emissions associated with petroleum production, including growth and reduction. By answering these two questions, a third policy question can be answered:

> *How can decision-makers use these future forecasts?*

Those working in policy or business around transportation or fuels are actors impacted by these changes. Assessing how these decision-makers can use the quantitative forecasts made in this thesis clarifies the practical applications of this work.

1.4 Research approach

To answer the research questions posed, two methods are combined in this thesis.

1.4.1 Lifecycle analysis

To quantify the production emissions of petroleum-derived fuels, a lifecycle analysis (LCA) will be used in this thesis. LCA examines the entire lifecycle of a product, process, or system, and quantifies the environmental impact per unit utility delivered [6]. For this research, LCA will capture the GHG emissions across the production lifespan per unit of fuel energy produced.

LCAs originated in the 1960s, and have progressed from quantifying environmental burdens to economic and social impacts [13]. LCAs have broadened their scope from products to economy wide impacts [13]. The main steps include: goal and scope definition, lifecycle inventory analysis, impact assessment, and interpretation [14,15].

A large body of literature on the lifecycle emissions of petroleum fuels already exists. LCA tools such as GHGenius, GHOST, GREET, OPEM, OPGEE, and PRELIM [16] have been used to compare various types of crude oil [17]. These studies are limited in geographic scope, as they only assess one resource at a time. Recent studies have focused on unconventional crude resources, such as oil sands [18,19,20,21] and tight oil or shale formations [22,23,24,25]. Although the use of these sources and their associated methods are newer, these resources represent less than 10% of current global oil supply [1].

Other work has studied the cumulative impact of various crude resources so as to quantify the average lifecycle emissions for fuels produced from those different resources. Crudes from both conventional and unconventional resources have been modeled, and their impacts have been aggregated to a regional level. Regional studies include those of the US [5], North America [26], Europe [27], Korea [28], and the world [4]. This body of work demonstrates that the production emissions for transportation fuels are quantifiable at a global level.

Moving the temporal focus of an LCA from the past or present to the future has been studied to a lesser extent. Outside of the petroleum fuels area, some previous work has projected future emissions. First, LCA applied to the near-term future is reviewed, followed by emissions projections for the long-term future.

Azadi et al performed a well-to-pump lifecycle analysis of petroleum-derived transportation fuels for the present and near-term future of year 2020 [4]. A new LCA model was developed to assess the impacts of petroleum extraction and refining on a global scale [4]. Near-term projections were used to extend lifecycle inventory data from 2005 and 2012 to 2020 [4].

Argonne National Laboratory (ANL) has performed a cradle-to-grave lifecycle analysis of various light-duty vehicles for the present and the near-term future of year 2025 [29]. The fuel-vehicle pathways considered were selected based on techno-economic readiness levels, for which data was then fed into the GREET LCA model [29].

Ou et al conducted a scenario-based analysis of road transportation in China for the long-term future of year 2050 [30]. They projected factors such as energy demand, vehicle population, and operational emissions based on historical data for six scenarios [30]. Vehicle and fuel lifecycle emissions were not calculated.

Vaillancourt et al projected the integrated energy system for Canada in the year 2050 [31]. This was based on five scenarios derived from the TIMES optimization model, and included energy demand, operational emissions, and technology selection [31]. A similar study using the TIMES model was done by Yang et al for California in 2050 [32]. Electricity grid lifecycle emissions were not calcualted.

Recently (2017), Cooney et al projected the production lifecycle emissions for petroleum-derived transpiration fuels for the year 2040 in the US [33]. Their analysis utilized the OPGEE and PRELIM lifecycle analysis tools. The main factors of focus in their forecast were the variation in crude supply to the US, and how that impacts extraction emissions [33]. However, this work does not consider changes to refinery emissions, and is limited in geographic scope.

In these studies reviewed, the LCA method was rarely extended to the long-term future. For the studies on emissions from transportation or energy stems, the fuel emissions values used in these future-oriented studies were taken from current datasets, which raises the issue of temporal consistency. Thus, to the best of the authors' knowledge, the lifecycle emissions of petroleum fuels have yet to be quantified beyond the year 2020 on a global level [4].

There are many challenges associated with conducting an LCA on the long-term future of petroleum fuels. LCAs require high-granularity input data, collected from many countries and data sources [4]. Often, data may not be available due to measurement, reporting, or industry confidentiality [34]. To fill these gaps, interpolation or estimation are used, introducing uncertainty into the analysis.

In addition to the input data, there are challenges associated with the LCA models themselves. Real-world factors or processes may not be fully understood, which may lead to discrepancies between model theory and real-world practices [34,35]. Fundamental LCA assumptions about system boundaries or allocation methods may lead to difficulties in comparing results [36]. Modelers could hide assumptions within LCA in order to alter or skew the results to achieve preferred outcomes [37]. Reap et al systematically discuss other challenges and limitations of the LCA method [38,39].

Despite these limitations, LCA is a leading tool for evaluating environmental impacts. Few alternative methods exist which can analyze the environmental impact so thoroughly. Many countries have included or recommended LCA within their environmental policies, such as Australia, Canada, Japan, Korea, and the US [13].

1.4.2 Scenario-based analysis

The future is inherently uncertain. As well, there are limits to the extent to which one can validate future-oriented models [35]. Despite the uncertainty, future projections provide valuable information [40]. Projections of the future can help to connect potential actions or choices with their resulting implications [7]. Projections can help think through decisions by communicating the bounds, limits, or range of possible outcomes [41]. Future projections can be obtained through various methods, such as regressions of trends, systems dynamics models, or scenario-based analyses [41].

In this thesis, a scenario-based approach is used to tackle the challenge of forecasting the future. Scenario-based approaches provide a helpful framework for conceptualizing the future by grouping coherent assumptions about potential future realities [12]. This approach demonstrates how choices or actions impact an outcome. Scenarios act as exploratory narratives, which "facilitate organizational learning and generate critical insights into strategic decision-marking [7]." Scenarios better capture uncertainties or surprises, factors that predictive forecasts often miss [41]. Unlike predictions, scenarios do not claim to identify the most likely or probable future outcomes [7].

Scenarios-based methods originated in the 1960s, and were first used by oil industry experts [7,41]. Since then, scenarios have been used for future emissions and climate change modeling [42,43,44,45,46], future energy consumption [7,41], and oil prices [1,2,3]. The main steps include: issue selection, identification of relevant drivers, scenario design via a consistent logic, and interpretation [7,47].

In this research, the scenarios consider how potential environmental policies with varying levels of stringency would impact fuel production emissions in the year 2050. These potential policies capture future changes relevant to socioeconomic factors (e.g. oil demand) as well as technical practices (e.g. emissions intensity).

This thesis combines two robust methods. Scenario-based analysis is used to organize assumptions associated with potential realities for the year 2050. The environmental consequences for these potential policy actions are quantified using an LCA model, which assesses the production emissions for petroleum-derived transportation fuels. The scenario-based approach enables the application of LCA to a future temporal state by extending the lifecycle inventory data accordingly [48]. This approach combines the illustrative abilities of stories with the numerical rigor of models [7].

1.5 Thesis structure

In this first chapter, the demand for and emissions from petroleum-derived transportation fuels have been surveyed. Production emissions for these fuels have yet to be quantified past the year 2020, despite the many uses for this data. The approach to answering the research questions posed was briefly introduced, including the use of LCA and scenario-based analysis.

In Chapter 2, the policy context of transportation fuel emissions is presented. The motivation behind regulating fuel emissions is established, and the challenges associated with regulation are explained. Current policies are compared to identify regulatory gaps.

In Chapter 3, the approach presented in the introduction will be expanded upon in greater detail. First, the LCA model used to represent the petroleum production process will be presented. Next, the design of the 2050 scenarios will be explained. Afterwards, the collection of data will be detailed. This data informs the 2050 scenarios and is used as in the lifecycle inventory data, an input to the LCA model.

In Chapter 4, the resulting lifecycle emissions for the year 2050 will be presented and discussed. A sensitivity analysis on these results will also be presented and discussed.

In Chapter 5, the implications of these results will be expanded upon. From a technical perspective, the opportunity space associated with these emissions will be quantified. From a policy perspective, the use of these 2050 forecasts will be examined.

Lastly, in Chapter 6, the conclusions from this research will be summarized, and areas for future work will be noted.

2 Policy

This thesis focuses on the production GHG emissions from transportation fuels, namely: gasoline, diesel, and jet fuel. In this chapter, the issue of transportation GHG emission will be discussed from a policy perspective. First, the reasons behind regulating transportation emissions are presented. Then, the issue of regulating these emissions is examined through a political economy lens. Following this, real policies for regulating these emissions are surveyed. Finally, this chapter wraps up by discussing some challenges unique to regulating transportation emissions. This chapter highlights the regulatory gap surrounding fuel production emissions, which helps to frame the calculation of future lifecycle emissions of petroleum-derived fuels.

2.1 Why regulate?

The emissions from road and air transportation come from many decentralized sources. Road transportation includes personal vehicles, public transit, and cargo trucking. Air transportation includes personal, commercial, and military aviation. These industries provide local and global transportation services for people and goods. They contribute to the economy through employment and trade, as well as socially, through tourism, disaster relief, and connectivity [49].

The benefits of transportation come at a cost to society through polluting the earth's atmosphere. The combustion of petroleum fuel in air creates pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and soot, as well as other chemical species and noise [10]. CO_2 is notable since it contributes to the greenhouse effect. Although this effect is necessary at a certain level to create livable surface temperatures, changes in concentrations of GHGs in the atmosphere can disturb this radiative balance and affect the earth's climate system [45]. This interference is causing climate change and increasing global average surface temperatures.

The Intergovernmental Panel on Climate Change (IPCC) states that it is extremely likely (at least 95% probability) that anthropogenic GHG emissions have been the cause of observed warming and climate change since the mid 20th century [50]. Overall, there is an academic consensus of about 97% that the cause of climate change is anthropogenic in nature [51,52]. Despite this scientific evidence, 69% of Americans surveyed in 2015 believe that climate change is caused by anthropogenic means [53]. 71% of the American public is convinced that climate change is happening [53]. These statistics highlight the disconnect between the scientific community and the general public regarding opinions on scientific issues.

Climate change is an environmental issue of global concern with a likelihood of irreversible consequences [54]. The impacts of climate change include increases in temperatures, sea levels, and frequency of extreme weather events such as storms, floods, droughts and fires [55]. If air pollution is defined as a commodity, it is clear that there are few well-defined markets for this good [56]. For example, there two cap-and-trade markets in the US (the California Cap-and-Trade Program [57] and New England's Regional Greenhouse Gas Initiative [58]), but they are limited to emissions from power plants and factories [59]. The lack of pollution markets results in an inefficient allocation of goods or resources known as a market failure [60].

This market failure is exacerbated by the fact that these emissions are also an economic externality to the transaction of transportation. This means that transportation carries with it a cost that affects a party who did not choose to incur it [61]. When an airplane flies or a car drives, those near the vehicle do not consent to the increased emissions in their vicinity. Without a market for pollution (e.g. an emissions pricing system), neither the vehicle owner, nor the passengers onboard, account for this external cost.

Political economist Viscusi notes that without regulation of a negative externality, it is likely that the externality generating activity will be overly pursued [62]. In this case, without sufficient environmental regulations, transportation may be pursued in excess, despite the pollution it generates. Thus, there is motivation behind regulating the GHG emissions of the transportation industry.

2.2 Political economy considerations

Political economy includes the use of economic theories to understand political systems [62]. Viewing pollution as an externality through a political economy lens motivates regulatory intervention. By applying other political economy concepts – property rights, common goods, bargaining costs – the challenging nature of regulating pollution can be further understood.

Accounting for environmental externalities is further complicated due to the fact that property rights, both for the atmosphere and the pollution, are unclear and ill defined. Unstable property rights impede transactions, thus creating inefficiency. Without title to a resource, it is difficult for actors to utilize the resource in markets for trade or sale [62]. For pollution, this hindrance is seen through difficulties establishing emissions pricing systems; for the environment, this obstruction is observed through the atmosphere becoming a common good. In both cases, the ambiguous property rights create weak incentives to invest in the resource, as securing a return on the investment is challenging without ownership of the property [62]. Without investments, the creation of an emissions trading system or atmospheric restoration project is challenging. In addition, ambiguous ownership can lead to parties treating the atmosphere like a common resource, which can be problematic. Shared resources that lack regulation can often be misused or overused, as individuals utilize their resource for their own interests, rather than the interests of the group. Thus, unstable property rights limit market development and enable misuse of the common atmosphere.

The number of stakeholders affected by environmental pollution is high, which results in a collective action problem. With an increasing number of parties, the likelihood that a member will take action on a group interest decreases [63]. This results in inaction towards a benefit that would be reaped by many, since rationally, no individual is willing to bear the cost alone. Environmental protection or restoration is costly, and although such a project would have widespread benefits, the large number of people affected complicates coordination of their collective action on the problem. Olson hypothesizes that without selective incentives, collective action is difficult to achieve [63]. If action is taken, it is likely that free riders will secure unearned benefits due to the contributions of others. Thus, accounting for environmental externalities is hindered due to the large number of people affected creating a collective action and free rider problem.

The many actors involved in the collective action problem also contribute to bargaining costs associated with finding a solution to the environmental externality. Transportation spans multiple geographic boundaries, with stakeholders coming from multiple counties or countries, sometimes holding disparate interests. Creating a policy that these parties all agree upon involves significant bargaining costs, due to difficulties associated with coordinating negotiations, collecting information, and settling upon a mutually acceptable contract. [64]. These bargaining costs delay problem-solving associated with addressing environmental externalities.

Finding a solution to transportation's environmental externalities must take into account the unstable property rights of the environment and pollution, as well as the complications associated with the number of parties impacted by the problem. These realities confound a classical economics approach to externalities. Coase's theorem states that an economically efficient solution to an externality can be found if property rights are complete, and if parties can negotiate without cost. Coasean theory would also call attention to the fact that the allocation of property rights determines who pays the cost of the externality [62]. Transportation's environmental externalities violate both assumptions for Coase's theorem. Property rights for the atmosphere and pollution are ambiguous, and the negotiations over solving the externality are not cost-free. These political economy concepts help to explain why classical economics alone cannot perfectly the problem of transportation emissions.

2.3 Current regulation

Regulating GHG emissions is an essential step in mitigating climate change. For transportation, this would involve promoting or incentivizing transportation technology options with low GHG emissions. If actors were economically rational, they would choose between technologies so that they could optimize the cost per unit GHG emissions abated [65]. Political economy shows that the problem of transportation emissions could not be solved from a rational economic perspective alone. In light of these idealizations, real world policies are presented and compared in the following section. These include regulations that manage the environmental impact of road and air transportation through reducing fuel consumption per unit transportation activity, and through reducing emissions associated with each unit of fuel consumed.

Air travel is more international than road travel. Although both modes can be regulated at a domestic level, a harmonized regulatory standard between countries is more straightforward for an international industry like aviation [66]. Harmonization of regulatory standards eliminates redundancies in existing regulation by combining multiple domestic standards into one international standard. This simplifies the process of meeting regulatory requirements and reduces regulatory compliance costs [66]. Such harmonization of technical standards in some ways motivated the creation of ICAO [67]. This internationality was also why the 1992 Kyoto Protocol tasked ICAO with managing aviation emissions, rather than individual member states within the UNFCCC [68]. The differing geographical scales of road and air transport have resulted in different policy approaches.

The ICAO CO_2 standard sets a minimum fuel economy required for new aircraft models from 2020 onwards [69]. These fuel economies differ based on the aircraft's areal footprint and range, and by the type of aircraft (e.g. commercial or business) [70]. This pushes aircraft fleets to become more fuel-efficient. However, it is worth noting that the turnover time for aircraft (~30 year) is longer than road vehicles (~11 years) [71,72].

In addition to the CO_2 standard, ICAO is also managing aviation emissions through CORSIA. CORSIA sets an emissions cap for the aviation industry, as discussed in Chapter 1 [9]. Actors within the airline industry can choose between various emission reduction mechanisms to comply with the emissions cap. Alternative jet fuels included within CORSIA will take lifecycle emissions into account. Neither of ICAO's polices target the lifecycle production emission of petroleum-derived jet fuels.

In the US, road transportation emissions are managed through the Corporate Average Fuel Economy (CAFE) standard. This standard sets a minimum fuel economy required for a new road vehicle in a given year [73]. These fuel economies differ depending on the vehicle's areal footprint, and the type of vehicle (e.g. car or truck). Vehicles that do not meet the CAFE standard are taxed. Vehicles using biofuels (or electricity vehicles) receive credits that boost their fuel economy [74]. CAFE pushes new fleets of road vehicles to be increasingly fuel-efficient.

There is also the Renewable Fuel Standard (RFS) in the US, discussed previously in Chapter 1. The RFS targets fuel producers, while the CAFE standard targets vehicle manufacturers. However, neither policy incentivizes consumers to choose low emissions vehicles. The CAFE standard does not consider fuels from a lifecycle perspective. RFS recognizes differences between alternative fuels, but not conventional fuels. Neither of these polices aim to reduce the lifecycle production emission of petroleum-derived fuels.

Fuel specifications dictate the chemical makeup of transportation fuels, including hydrocarbon content (e.g. benzenes, aromatics, olefins) and toxin levels (e.g. sulfur, sediment, copper) [75]. These standards specify what the fuel can contain to ensure consistent combustion. However, these standards do not specify how the fuel is produced or the emissions associated with that process.

Real-world policies regulating the environmental impact of GHGs from transportation focus more on vehicle operation (e.g. fuel economy and fuel type) than fuel production. Fuel production specifications also focus on operational combustion, rather than production. Although both air and road policies differentiate between the production emissions of alternative fuels to some degree, they do not distinguish between the production emissions of different conventional fuels. This regulatory gap is a potential area where emission reductions could be achieved.

2.4 Challenges

Transportation emissions have several unique factors that impact policy-making. These include: the production synergies amongst petroleum products, the treatment of fuel products as homogenous, and the sectorialized view of emissions by policy-makers.

Although the production emissions of petroleum-derived fuels are not currently being targeted through policies, there are some considerations to make if they were to be regulated.

Crude oil is made up of a mixture of hydrocarbons of varying molecular size and structure [76]. Thus, when refineries process crude, they produce a mix of products. Although the product mix can be varied (e.g. through lengthening or shortening the hydrocarbon chain length), there are limits to these processes. Thus, there are important fuel synergies and co-product interactions for which policies must account.

One should also consider the inconsistency between the treatment of conventional and alternative fuels. Numerous policies differentiate between alternative fuels based on their production emissions. Conversely, conventional fuels are treated homogenously and assigned one value for production emissions. In reality, conventional fuels can be produced from crude of varying quality, extracted by various methods, and refined in different ways. The Carnegie Endowment's Oil Climate Index shows that production emissions from petroleum fuels can vary by as much as 53 g CO_2e/MJ, depending on the production processes [77]. This raises the question as to why conventional fuels are treated differently than alternative fuels, despite their heterogeneity. If such difference were reflected by policies, actors would be able to better choose between technologies based on cost per emissions abated.

The UNFCCC manages emissions through individual member states, which group emissions sectorially [78]. For road transportation, operational transportation emissions would be separate from industry emissions, which capture the production of fuels and vehicles. For air transportation, ICAO would cover the operational emissions, while the production emissions would still be covered within industry under the UNFCCC. Segregating emissions based on sector separates operation and production emissions. This risks missing synergies between the aspects of the transportation lifecycle that transcend sectorial boundaries.

For example, unless advancements in petroleum-derived fuels impact the combustion emissions, these emissions would only be captured in industrial sectors, not in transportation. If advancements in alternative fuels were made, impacts would be reflected by increases to the industrial and agricultural sector, and decreases to transportation. However, this sectorialized view does not capture the transfer of emissions between sectors or their net impact to global emissions.

The existence or lack of human-made distinctions between physical processes complicates regulations. This is made evident by distinctions between geographic regions and sector emissions, and lack of distinctions between fuel synergies and types. These challenges must not be overlooked when regulating transportation emissions.

Other policy challenges exist which are not unique to transportation emissions. One is the temporal tradeoff between policy changes: adaptive approaches can take more new information into account, but lack the predictability of consistent policies [79,80,81]. Enforcing emissions regulations can be challenging, as made evident by the VW scandal [82,83]. Lastly, one must be aware that regulating emissions – an externality – may bring about externalities of it's own. For example, biofuels may have lower production emissions than petroleum fuels, but may impact emissions through land use change and compete for arable land.

2.5 Summary

Transportation GHG emissions contribute to climate change, yet are often not directly regulated. Various social, economic, and technical factors influence regulation. The property rights of emissions and the atmosphere are not well defined. Many stakeholders are vying for use of the transportation service while also incurring its environmental burden. The emissions disregard geographic and sectorial boundaries, while the boundaries between petroleum products are blurred and artificial. These issues all complicate the policy-making process.

These challenges have limited the scope of current policies. Most policies regulate GHG emissions indirectly through reducing vehicle fuel demand, such as the US CAFE standard for road vehicles, and the CO_2 standards for international aviation. To the best of the author's knowledge, no policies focus on reducing the fuel production emissions of conventional fuels. The rest of this thesis will focus on these fuel production emissions. By projecting how fuel production emissions could change by the year 2050, this work will quantify the opportunity space for emission reductions between various potential future scenarios.

3 Methods

This Chapter details the methods used to project the production emissions of petroleum-derived transportation fuels to 2050. First, details on the petroleum LCA model are presented. Next, the logic behind the design of the scenarios used to depict the year 2050 is explained. Afterwards, the collection of projection data used to inform the 2050 scenarios is discussed.

3.1 Approach

The research problem of projecting the future emissions of transportation fuels can be cast as a "wicked problem". Wicked problems involve stakeholders who have different values [84]. In this work, stakeholders could include those from conventional and alternative fuel communities. The solutions of wicked problems are intertwined with how the problem itself is defined [84]. Kwakkel et al define decision-making under deep uncertainty – such as the future – as a wicked problem [85]. One must be cognizant of the complex nature of the problem at hand in order to apply appropriate analysis methods [86].

3.1.1 LCA model

The lifecycle model used to conduct this analysis was first described in Azadi et al (further details can be found in the paper) [4]. The petroleum products analyzed are gasoline, jet fuel, and diesel. The functional unit used is equivalent mass of carbon dioxide per lower heating value of fuel produced (g CO_2e/MJ_{fuel}), where CO_2, CH_4, and N_2O species are included within CO_2e. Factors for global warming potential were taken from the IPCC on a 100-year basis [87]. The system boundary in this analysis extends from well to pump (WTP), which can be separated into four main stages: extraction of crude from the ground, crude transportation to a refinery site, refining the crude into a fuel product, and product transportation to the end user. Emissions are allocated to different refinery products on an energy basis. The total lifecycle extends from well-to wake or well to wheel (WTW). However, the pump to wake (PTW) or combustion emissions have been excluded from this analysis. Overall, 139 distinct GHG emission points are calculated in the LCA model [4]. The model calculates global values through a bottom-up approach, based on processes modeled for 91 extraction countries and 113 refining countries [4].

The 2050 analysis builds on this model, using the 2020 results from Azadi et al as a reference case [4]. Figure 3.1 illustrates the main factors added to the LCA model to complete the 2050 analysis.

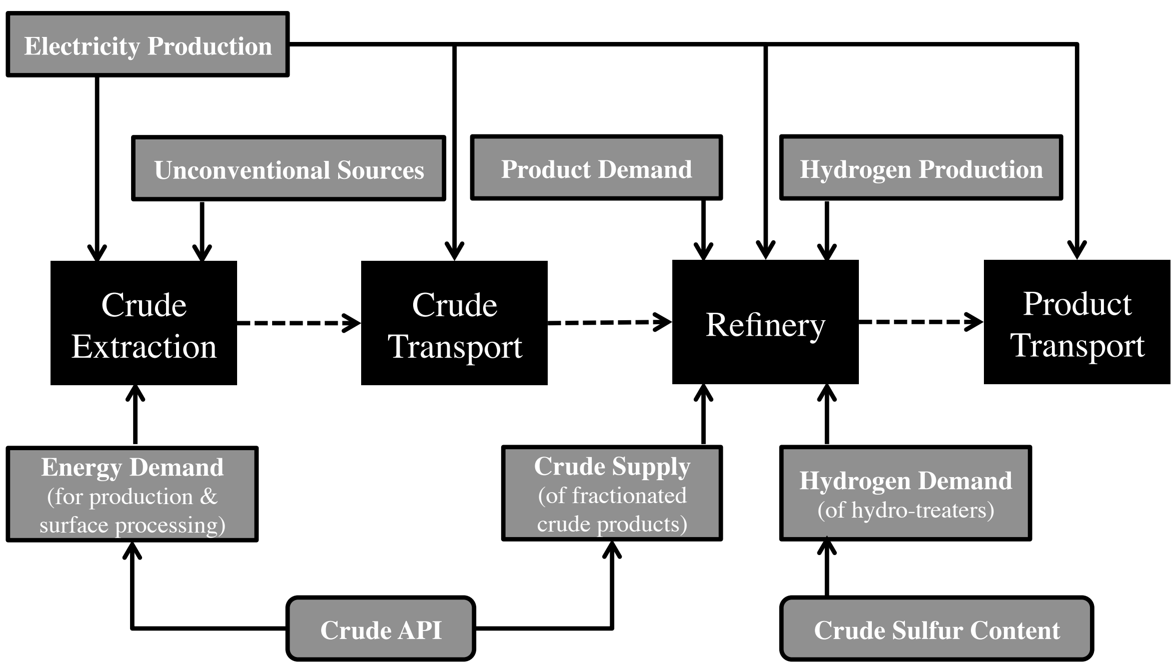

Figure 3.1: Incorporation of 2050 parameters into petroleum LCA model.

The black boxes show the original LCA model, and the grey boxes show the extensions for the 2050 study. The dotted lines represent mass flows of crude and refined products between the main lifecycle stages; the solid lines represent flows of data into various stages of the LCA model. The rounded boxes represent 2050 factors that are scenario agnostic, whereas the sharp boxes represent 2050 factors that are specific to a given scenario.

3.1.2 Scenario design

The possibility space associated with petroleum industry operations in the year 2050 is captured through a scenario-based approach. Scenarios describe how the future may unfold and serve to bound predictions by representing extremes. In this study, the scenarios represent different levels of stringency for environmental polices that may exist in the year 2050. The Current Policies (CP) scenario is made up of the policies that are present today, and does not include any changes, whereas the Moderate New Polices (MP) and Strong New Policies (SP) scenarios consist of additional policies.

These scenarios differ with respect to three main themes: resource extraction, carbonization of utilities, and product demands. The assumptions associated with these themes are described subsequently, and quantified in Table 3.1. For extraction, CP leaves the production of unconventional petroleum resources unrestricted, whereas access to unconventional sources of crude becomes somewhat restricted under MP and heavily restricted under SP. For utilities, CP maintains present practices for the production of hydrogen and electricity. These utilities are decarbonized to varying levels under MP and SP. For product demands, CP sees a growth in demand for all petroleum products. Under MP, the demand for petroleum-derived road fuels is reduced at a faster pace than that of petroleum-derived aviation fuels. Under SP, the demand for both petroleum-derived road and aviation fuels abates simultaneously.

Together, these three scenarios represent a range of stringency associated with various environmental polices. These policies and assumptions impact the operations and subsequent emissions of the petroleum industry and its products. Details about the data used to inform these scenarios follow, with further supporting information listed in the Appendix.

Table 3.1: Relevant model parameters informing policy scenarios

Policy Scenario	Reference (2020)	Current (2050)	Moderate New (2050)	Strong New (2050)
Emission Index for Electricity Generation [$g\ CO_2\ /\ MJ$]	114.0 [4]	114.0 [4]	113.3 [88]	68.3 [88]
Emission Index for Hydrogen Production [$g\ CO_2\ /\ MJ$]	99.0 [4]	99.0 [4]	68.3 [89] [90]	28.0 [89] [90]
Tight Oil Production Rate [*mmbbl / day*]	5.2 [4]	12.2 [91]	5.9 [1]	3.5 [92]
Tight Oil Emissions Index [$g\ CO_2\ /\ MJ$]	6.3 [4]	6.3 [4]	6.3 [4]	1.8 [22]
Oil Sands Production Rate [*mmbbl / day*]	4.25 [4]	9.6 [91]	8.0 [1]	4.9 [92]
Oil Sands Emissions Index [$g\ CO_2\ /\ MJ$]	High* [4]	High* [4]	High* [4]	Low* [16]
Gasoline Demand [*mmbbl / day*]	22.5 [4]	28.2 [2]	21.4 [88]	11.7 [88]
Jet Fuel Demand [*mmbbl / day*]	12.0 [4]	19.5 [93]	17.0 [88]	10.3 [88]
Diesel Demand [*mmbbl / day*]	27.1 [4]	38.5 [2]	27.5 [88]	22.7 [88]
Total Petroleum Demand [*mmbbl / day*]	85.2 [4]	126.2 [2] [93]	81.5 [88]	56.8 [88]
Naphtha Supply [*mmbbl / day*]	18.5	29.1	18.3	13.1
Middle Distillate Supply [*mmbbl / day*]	23.0	34.7	22.4	15.6

* *See Table A4.1 of the Appendix for specific values.*

3.2 Crude quality

One global change that is scenario-agnostic is the future crude quality. As crude resources continue to be consumed, easily accessible and high quality resources will be utilized first. This will leave a greater portion of low quality crude resources in the future, which are both harder to access and process. Sources such as the Organization of Petroleum Exporting Countries (OPEC) [2,94] and the US Energy Information Agency [95] predict a shift towards crudes consisting of heavier hydrocarbons and having higher sulfur content (details in A1 of the Appendix). For this analysis, OPEC's 2040 prediction of average crude quality is extended to 2050, yielding a decrease of 0.57 degrees API and an increase of 0.24% sulfur content. OPEC's predictions are used because they are global in scope. These changes are visualized in Figure 3.2. This new API and sulfur content are incorporated into the extraction and refinery stages, as explained in Section 3.4 and 3.5.

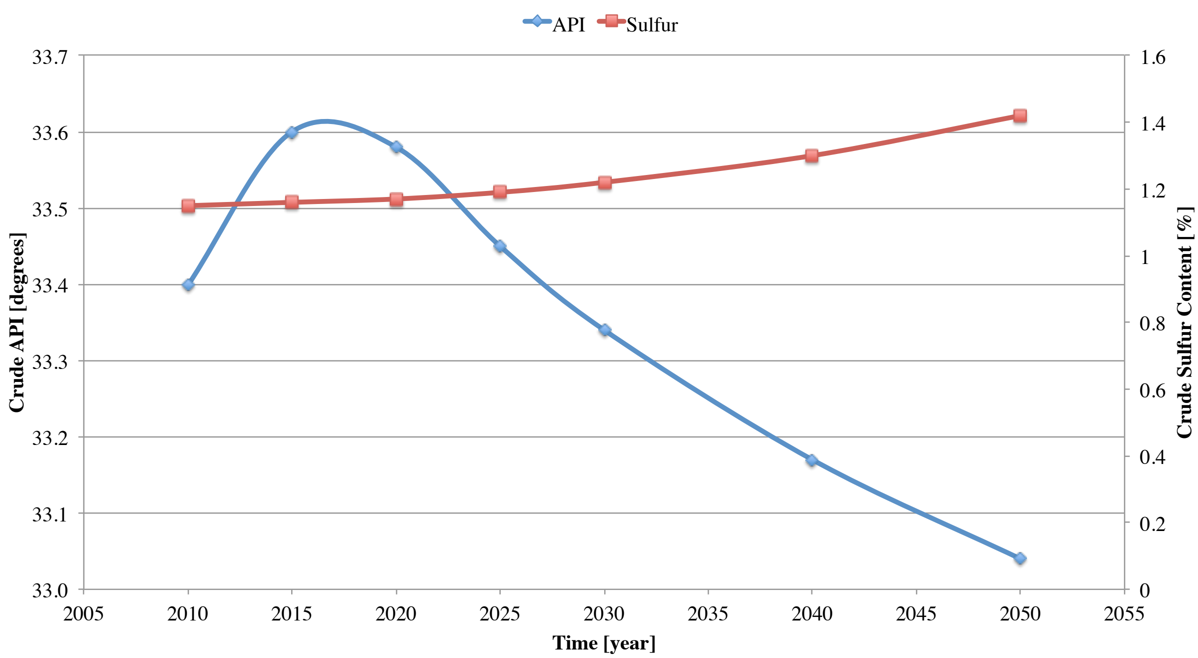

Figure 3.2: Changes in global average crude quality from 2010 to 2050

3.3 Utilities

Various utility inputs are needed within the petroleum production process. Electricity and hydrogen are two major inputs for which the emissions associated with their production are expected to change greatly by the year 2050.

3.3.1 Electricity

Electricity is used during each lifecycle stage. Depending on how energy policies evolve in the future, the electricity grid may become more decarbonized through the adoption of lower emissions or renewable technologies. The World Energy Council (WEC) outlines two future scenarios in their 2013 report World Energy Scenarios: a Jazz Scenario, representing market-driven and individualistic development choices; and a Symphony Scenario, representing regulation-driven and globally united policy choices [88]. The electricity supply portion of Jazz and Symphony are used in this analysis for MP and SP, respectively. CP uses the same grid makeup as the 2020 reference case [4,96]. The capacity of these different technologies on the electric grid is used to calculate the emissions intensity of electricity generation in different regions via the Greenhouse Gases Regulated Emissions and Energy use in Transportation (GREET) model [97]. Global emissions intensity factors are listed in Table 3.1, with emissions intensity presented for each country in A2 of the Appendix.

3.3.2 Hydrogen

Hydrogen is a major input to petroleum refineries, consumed by hydrocracking, hydro-treating, and isomerization units. Currently, hydrogen is primarily produced through steam reforming of natural gas [4], which remains the case in CP. However, less emissions-intensive methods of hydrogen production may be adopted in the future if more stringent environmental policies arise. For example, electrolysis using renewable electricity could be prevalent, as assumed under SP [89,90]. As a mid-point, an Argonne National Laboratory (ANL) projection for a hydrogen production technology mix is combined with ANL and EU estimates for the emissions intensity of hydrogen production to define a value for MP [89,90]. The resulting emission indices for hydrogen production are listed in Table 3.1, with further details in A3 of the Appendix.

3.4 Extraction

No changes are made to the conventional extraction processes within the LCA model. Updates to unconventional extraction processes, such as tight oil and oil sands, include their production rates and emissions indices, shown in Table 3.1. The emissions intensity of these unconventional practices varies between 9.4 and 24.5 g CO_2/MJ, as shown in the A4 of the Appendix. No decrease from the 2020 reference is expected unless stringent environmental practices are mandated in SP.

For tight oil resources, such as fracking and horizontal drilling, the IEA expects production beyond 2020 to expand outside of the US, into Algeria, Argentina, Australia, Canada, China, Iran, Mexico, Poland, Qatar, Russia, and Turkey [1]. Total global production from tight oil in 2020 is estimated to be 5200 kbbl/day [4], and is predicted to change to 3500 – 12200 kbbl/day by 2050 [91,92].

Oil sands resources can be extracted by mining or in situ techniques, which differ depending on whether there is crude or bitumen in the ground. Total production from oil sands in 2020 is estimated to be 4250 kbbl/day [4], and could increase to 4900 – 9600 kbbl/day by 2050 [91,92] due to Brazil joining Canada in development of these resources [1].

The future decrease in crude quality is incorporated within the extraction stage through decreasing the crude API at each extraction site by the projected factor (0.57 API). The heavier crude increases the energy required for production and surface processing activities, which results in an increased demand for electricity and fossil fuel energy inputs.

3.5 Refinery

Refineries take crude oil, a mixture of molecules, as an input. Various physical and chemical refinery processes produce uniform end products, such as gasoline, jet fuel, and diesel. The quality of the crude input, as well as the mix of desired end products, impact how refineries operate, and thus the emissions associated with them.

3.5.1 Sulfur and hydro-treaters

The future increased sulfur content of the crude results in a "quality gap" between the crude supply and product demand [98]. This is incorporated in the refinery model through additional desulfurization. For each additional percentage point of sulfur removal demanded, hydro-treating units require hydrogen at a rate of 150 standard cubic feed (scf) of hydrogen per barrel of feed processed [99]. Hydrogen consumption rates for different units under the increased sulfur levels are listed in the A5 of the Appendix.

3.5.2 End product demands

Relative product demands are also expected to change from 2020 levels in the future. For CP, road fuel demand increases by 34% per OPEC's projection [2] and air fuel demand increases by 63% per the Freeway Scenario in WEC Global Transport Scenarios [93]. Like electricity, WEC's Jazz and Symphony demand projections informed MP and SP, respectively [88]. Under MP, road fuel demand decreases by 1% while air fuel demand increases by 42%. Under SP, road and air fuel demands both decrease, by 31% and 14%, respectively. Overall, the total crude demand changes by +60%, -18%, and -41% for CP, MP, and SP. These product demand profiles are listed in Table 3.1 and A6 of the Appendix. Figure 3.3 visualizes these demand profiles as percentages of total crude oil demand.

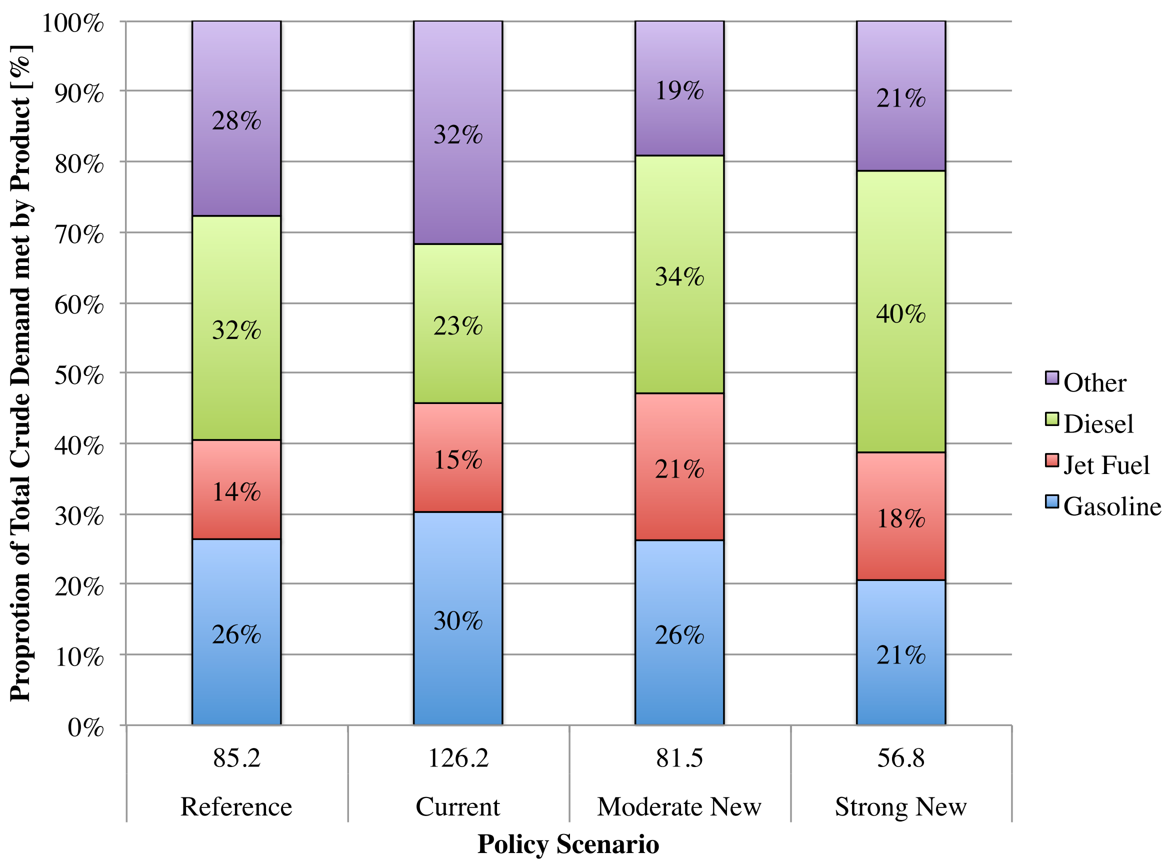

Figure 3.3: Breakdown of total petroleum products as a portion of total crude demand

The different crude products make up fractions of the total crude demand in the y-axis. The total crude demand (in millions of barrels per day) and the policy scenario are listed in the x-axis.

3.5.3 API and crude supply

In the petroleum industry, density is measured through API (American Petroleum Institute) gravity, which is inversely proportional to density. The natural availability of different hydrocarbon molecules within unprocessed crude is dependent upon the crude's API. These unprocessed hydrocarbons make up a supply of intermediary crude cuts. Assays of hydrocarbons from AspenTech's Process Industry Modeling System (PIMS) show that naphtha and middle distillate cuts typically make up 23.6% and 27.6% of the total distillation unit output, respectively [100]. However, when this distribution is adjusted by the future decreased crude API (0.57 API), the yields for these cuts decrease to 23.0% and 27.5%, respectively (details in A7 of the Appendix). These yield changes are visualized in Figure 3.4. Larger impacts are seen in the lighter end than the heavy end due to crude fractionation dependence on density. The resulting supply of relevant refined crude products is listed in Table 3.1.

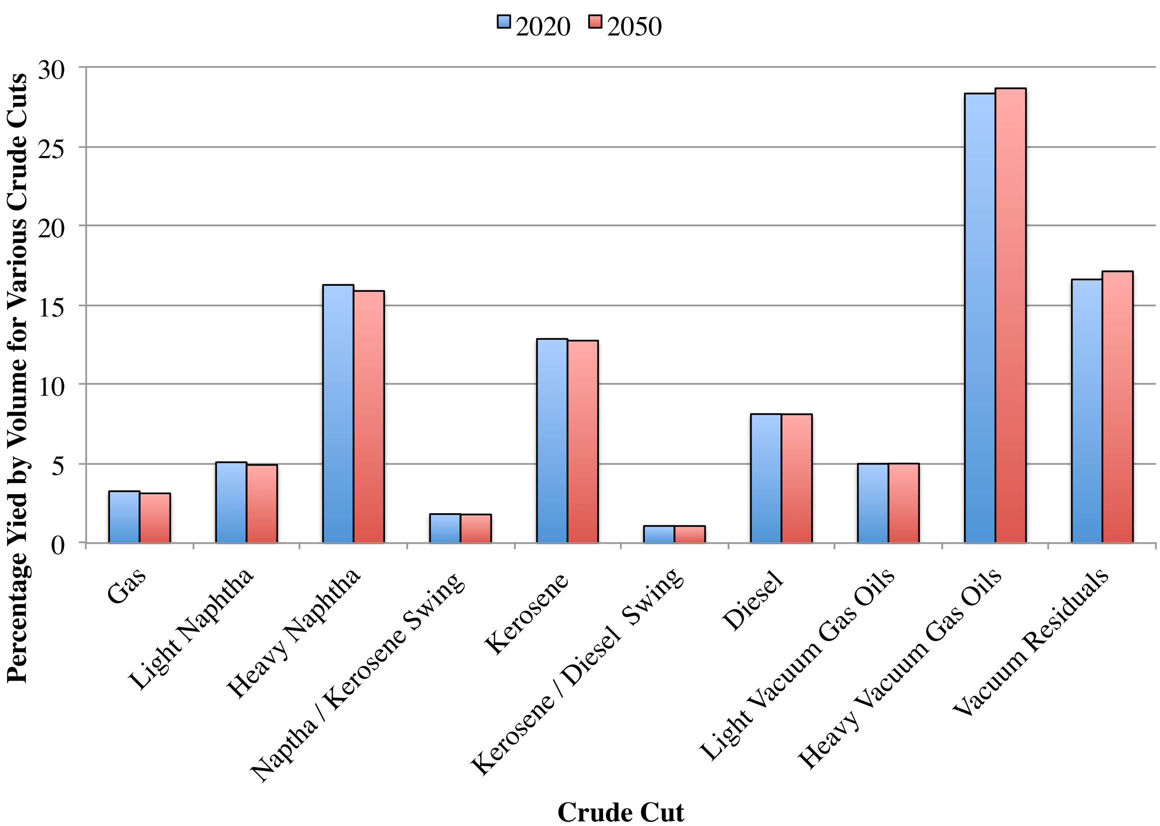

Figure 3.4: Typical yields of various crude cuts from unprocessed petroleum crude

3.5.4 Operation

Together, API and product demand change refinery operations, as additional secondary processing may be required to meet the new product demands given the new product slate. These changes can be captured on a global level through representing the refinery emissions, *RE*, for each product, *i,* as follows:

$$RE_i = k_{i,1} \cdot E_{i,1} + k_{i,2} \cdot E_{i,2} \quad (1)$$

where the refinery emissions, for a given scenario and product are made up of two aggregated processing components: primary and secondary. Each component is made up of emissions, *E*, for that process, and the proportion, k, of the final product that is produced via that pathway. The initial proportions, k_1 and k_2, are listed in Table 3.2, and are derived from 2020 values for refinery product outputs and their respective processes (details in A.8 of the Appendix).

Figure 3.5 shows a generic refinery schematic, where primary and secondary processes are distinguished from one another. Primary processes mainly include distillation, hydro-treating, and reforming units, while secondary processes include additional cracking or coking units.

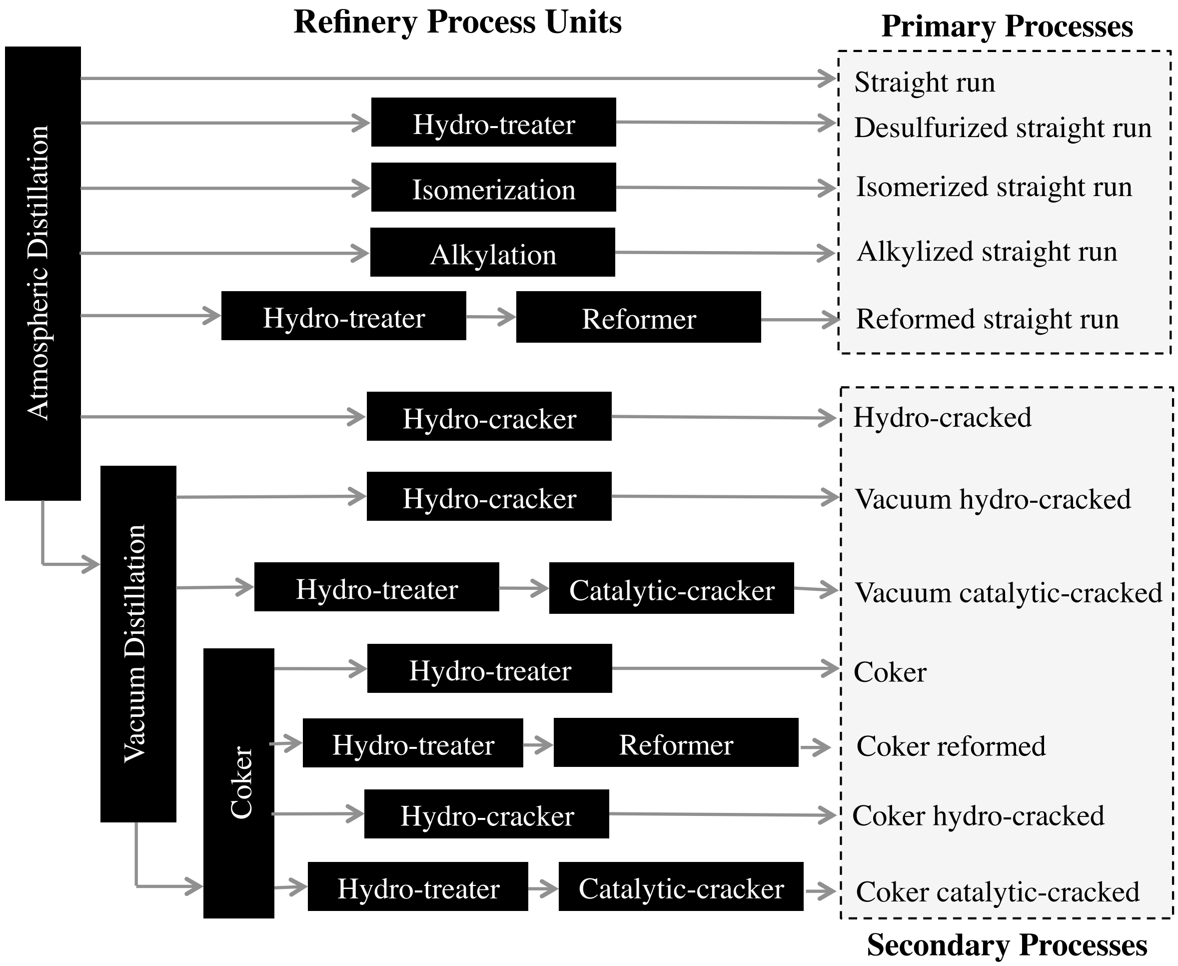

Figure 3.5 Schematic illustrating selected refinery processing units and production pathways

Black boxes represent various refinery processing units. The grey arrows represent material flows between units. Grey boxes on the left list the refinery units that processed the crude within the refinery, sorting these pathways into "primary" and "secondary" processes.

The emissions for primary processing are calculated by examining refinery emissions when secondary processing units are removed from operation in the model. The breakdown of primary and secondary units for each fuel product is provided in the A8 of the Appendix. The resulting primary emissions, E_1, vary by product and scenario, shown in Table 3.2.

The initial refinery emissions, *RE*, are determined from a base LCA run for each scenario-product pair, shown in Table 3.2. Then, the emissions for secondary processing, E_2, can be solved for using Equation 1, shown in Table 3.2.

Table 3.2: Refinery information for 2050 scenario-product permutations

Pair (Fuel – Scenario)	k_1	k_2	*RE*	E_1	E_2	k_1'	k_2'	*RE'*
Jet Fuel – Current	87.6	12.4	5.47	3.77	17.72	82.0	18.9	6.29
Jet Fuel – Moderate New			4.35	3.12	13.21	60.7	39.3	7.08
Jet Fuel – Strong New			3.27	2.52	8.70	69.8	30.2	4.38
Diesel – Current	37.5	62.5	11.17	6.62	13.90	24.9	75.1	12.01
Diesel – Moderate New			8.81	5.21	10.95	28.9	71.3	9.30
Diesel – Strong New			6.44	3.87	7.97	18.8	81.2	7.20
Gasoline – Current	42.7	57.3	13.23	3.57	20.49	41.6	58.4	13.46
Gasoline – Moderate New			12.00	4.32	17.81	41.6	58.4	12.20
Gasoline – Strong New			10.62	5.09	14.84	41.6	58.4	10.79

Based on the future crude availability and product demand in 2050, the division between primary and secondary processing is adjusted for each scenario-product pair. This is shown in Table 3.2 as k_1'and k_2' for 2050, updated from k_1 and k_2 from 2020. Using the component emission and updated proportions, updated refinery emission, *RE'* can be calculated as follows (listed in Table 3.2):

$$RE'_i = k'_{i,1} \cdot E_{i,1} + k'_{i,2} \cdot E_{i,2} \qquad (2)$$

This represents refinery operations changing to adjust for future crude quality, supply, and product demand slates. Note that the adjustment, *RE'*, is calculated on a global level, whereas the initial value, *RE*, is an aggregate of refinery-specific values.

3.6 Summary

In this Chapter, the modifications the petroleum LCA model for use in analyzing the long-term future were listed. The higher-level logic and data details of the 2050 scenario were explained. The data used to inform the 2050 lifecycle inventory was detailed, including the crude quality, electricity and hydrogen emission factors, crude extraction practices, and petroleum refining operations. The results of this scenario-based LCA are presented next.

4 Results

In this Chapter, the well-to-pump (WTP) production emissions from the LCA are presented for gasoline, jet fuel, and diesel. A sensitivity analysis of the refinery and WTP emissions are performed with respect to several key model parameters.

4.1 Lifecycle emissions

The LCA results are visualized in Figure 4.1 and provided in tabular form in Table 4.1, with details in A9 of the Appendix).

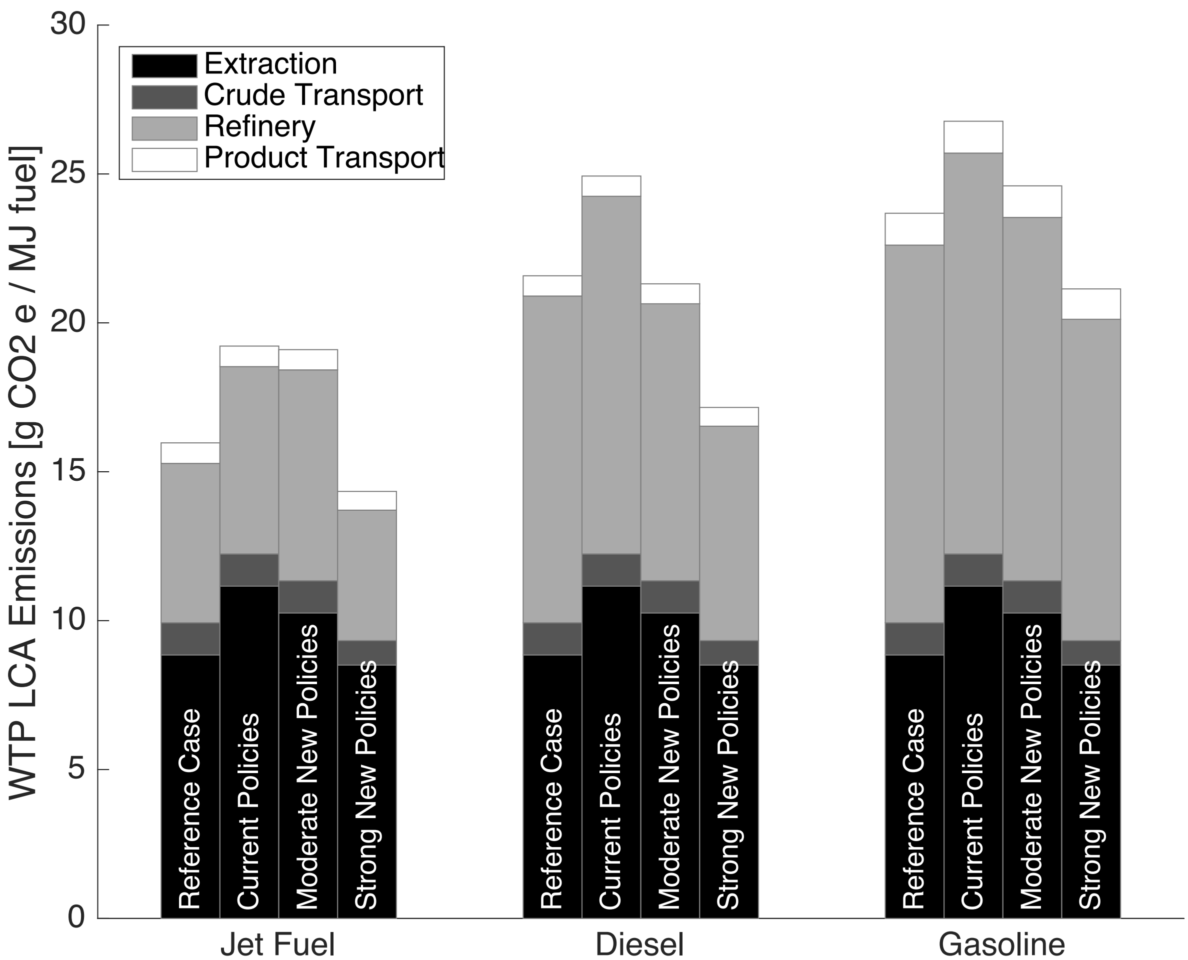

Figure 4.1: WTP emissions broken down by fuel, scenario, and lifecycle stage

Table 4.1: Lifecycle emissions by fuel and scenario [g CO_2e/MJ]

Fuel	Scenario	Extraction	Crude Transport	Refinery	Product Transport	WTP
Gasoline	Reference	8.85	1.08	12.68	1.07	23.68
	Current	11.16	1.08	13.46	1.07	26.78
	Moderate New	10.26	1.08	12.20	1.06	24.60
	Strong New	8.51	0.82	10.79	1.02	21.14
Jet Fuel	Reference	8.85	1.08	5.35	0.69	15.97
	Current	11.16	1.08	6.29	0.69	19.22
	Moderate New	10.26	1.08	7.08	0.68	19.09
	Strong New	8.51	0.82	4.38	0.63	14.34
Diesel	Reference	8.85	1.08	10.97	0.68	21.58
	Current	11.16	1.08	12.01	0.68	24.94
	Moderate New	10.26	1.08	9.30	0.67	21.31
	Strong New	8.51	0.82	7.20	0.63	17.16

The emissions in the crude extraction stage are the same for all fuel types, as the crude has not yet been fractionated into different product cuts. In CP and MP (11.16 and 10.26 g CO_2e/MJ), extraction emissions increase from the 2020 reference (8.85 g CO_2e/MJ) due to the increased production from tight oil and oil sands resources. Extraction emissions for SP (8.51 g CO_2e/MJ) are lower than the reference because of the decreased use of unconventional resources, as well as the reduced emissions intensity of these activities.

The emissions in the crude transportation stage are also the same across all fuel types, as the crude has still not yet been fractionated. The CP and MP emissions are the same as those for the reference case (1.08 g CO_2e/MJ), but decrease slightly in SP (0.82 g CO_2e/MJ). Tankers and pipelines are the main modes of transportation at this stage, and pipeline emissions are reduced by the decreasing emission intensity of electricity.

Refinery emissions vary by scenario and fuel type. Of the three fuels considered, jet fuel has the lowest refinery emissions (4.38 – 7.08 g CO_2e/MJ), while gasoline has the highest (10.79 – 13.46 g CO_2e/MJ). Overall, gasoline and diesel exhibit a net trend of decreasing refinery emissions with increasing scenario stringency. This decrease in refinery emissions is due to the decreasing emissions indices for electricity and hydrogen production. These emission reductions are mainly associated with the hydro-treating and cracking units (rather than upgrading, distillation, and thermal operations).

Jet fuel refinery emissions are not monotonically decreasing with scenario stringency. The majority of jet fuel comes from primary processes, for which primary process emissions are the lowest of the three fuels considered (see Table 3.2). Although absolute jet fuel demand decreases with increasing scenario stringency, jet fuel demand as a fraction of total crude demand is not monotonically decreasing (see Table 3.1 and Figure 3.3). This fraction is largest in MP (21%), followed by SP (18%), CP (15%) and reference (14%). The changing primary and secondary proportions of jet fuel reflect this non-monotonicity, which show the refinery operations adjusting for the changing demand slate. As a consequence, jet fuel refinery emissions follow this non-monotonic trend.

Gasoline has very high secondary emissions (see Table 3.2), and uses these processing pathways for most of its fuel production (58.4%). Both absolute gasoline demand and its demand as a fraction of total crude demand decrease with increasing scenario stringency (from 30% to 21%). The gasoline demand keeps pace with the decrease in straight run naphtha supply from the crude. Because of this, the split between primary and secondary processes remains the same for gasoline across the scenarios.

Interestingly, primary-pathway emissions for gasoline follow a counterintuitive trend and increase with increasing scenario stringency. This is due to the fact that gasoline receives an emissions credit for the hydrogen production in the catalytic reforming units. However, this credit decreases in absolute size as the hydrogen being displaced becomes cleaner with increasing scenario stringency. Thus, a net increase in primary refinery emissions is observed.

Diesel fuels mostly come from secondary processes, and have the lowest secondary emissions of the three fuels (see Table 3.2). While absolute diesel demand decreases with increasing scenario stringency, diesel demand as a fraction of total crude demand increases from 23% to 40% with increasing scenario stringency. This change in product slate gives rise to an additional of 18.7% of diesel being processed by secondary means.

The emissions in the product transportation stage are slightly higher for gasoline (1.02 – 1.07 gCO_2e/MJ) than the other fuels (0.63 – 0.69 gCO_2e/MJ). This is due to the fact that gasoline accounts for indirect VOC emissions (during loading, transit, and unloading) in addition to direct emissions. Multiple modes of transportation are used, including: tankers, pipelines, trucks, and rail. Gasoline also has emissions associated with storage, filling, and refueling processes. Like the crude transport, pipeline emissions are reduced with increasing scenario stringency due to the decreasing emission intensity of electricity.

The WTP emissions in 2050 may change drastically from the 2020 reference point: by +20% to -10% for jet fuel, +16% to -21% for diesel, or +13% to -11% for gasoline. For all three fuels, the CP 2050 scenario is greater than the 2020 reference by 13 – 20%, and SP is less than the reference by 10 – 21%. MP is greater than the 2020 reference for gasoline and jet fuel by 4% and 20% respectively, but less for diesel by 1%. WTP jet fuel emissions are very similar for CP and MP (19.2 and 19.1 g CO_2e/MJ), due to the high refinery emissions within the MP scenario.

4.2 Sensitivity analysis

As previously stated, variations in demand for different petroleum products impact the product slate and subsequent refinery emissions. The 2050 scenarios in this thesis assume that diesel makes up a greater share of road fuels than gasoline with increasing scenario stringency. However, demands may evolve differently than the future scenarios considered in this study. The sensitivity analysis in Figure 4.2 examines how refinery emissions vary when the total road fuel demand is kept constant, but the proportion of road fuels varies from mostly gasoline to mostly diesel (tabular form in A10 of the SI).

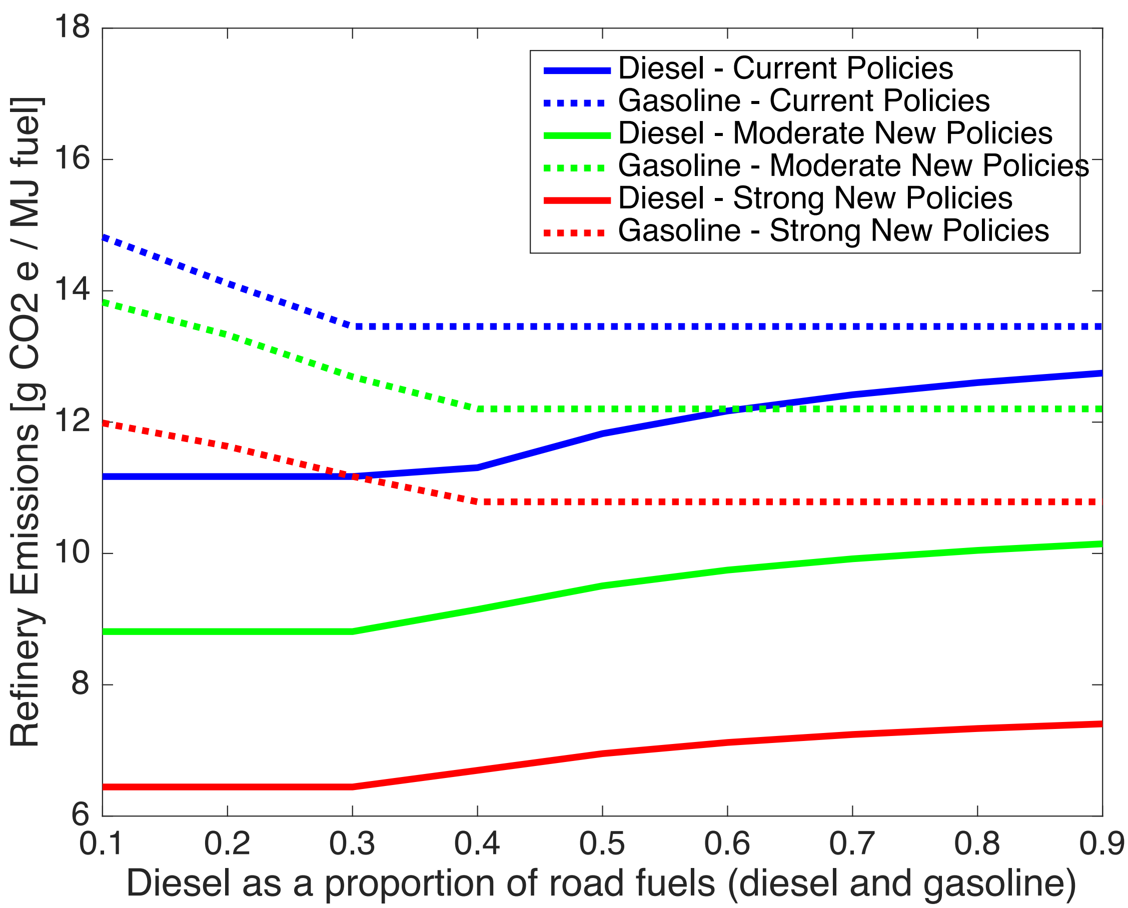

Figure 4.2: Impact of road product demand on refinery emissions

The results of Figure 4.2 are built upon, so that sensitivity can be measured as the increase in refinery emission (g CO_2e/MJ) per change in proportion of fuel demand from gasoline to diesel (mmbbl / day). Diesel refinery emissions are less sensitive to changes in demand proportion from gasoline to diesel (ranging from +0.042 g CO_2e/MJ per mmbbl / day change in demand for CP, to +0.046 g CO_2e/MJ per mmbbl / day change in demand for SP), while gasoline refinery emissions are more sensitive to changes in demand proportion from gasoline to diesel (ranging from -0.102 g CO_2e/MJ per mmbbl / day change in demand for CP, to -0.118 g CO_2e/MJ per mmbbl / day change in demand for SP). Sensitivity of refinery emission to demand split increases with increasing policy scenario stringency for both gasoline and diesel. Thus, the refinery and subsequent WTP emissions are sensitive to the absolute product demand, but more so for some fuels than others. However, due to synergies amongst the different fuels and their impact on the ultimate product slate, choice of dominant fuel amongst the mix impacts emissions as well.

The sensitivities of WTP emissions with respect to the use of unconventional resources and the emission intensity of transportation and utilities are quantified in Figure 4.3 (tabular form in A11 of the SI). The 2020 WTP emissions are used as the baseline.

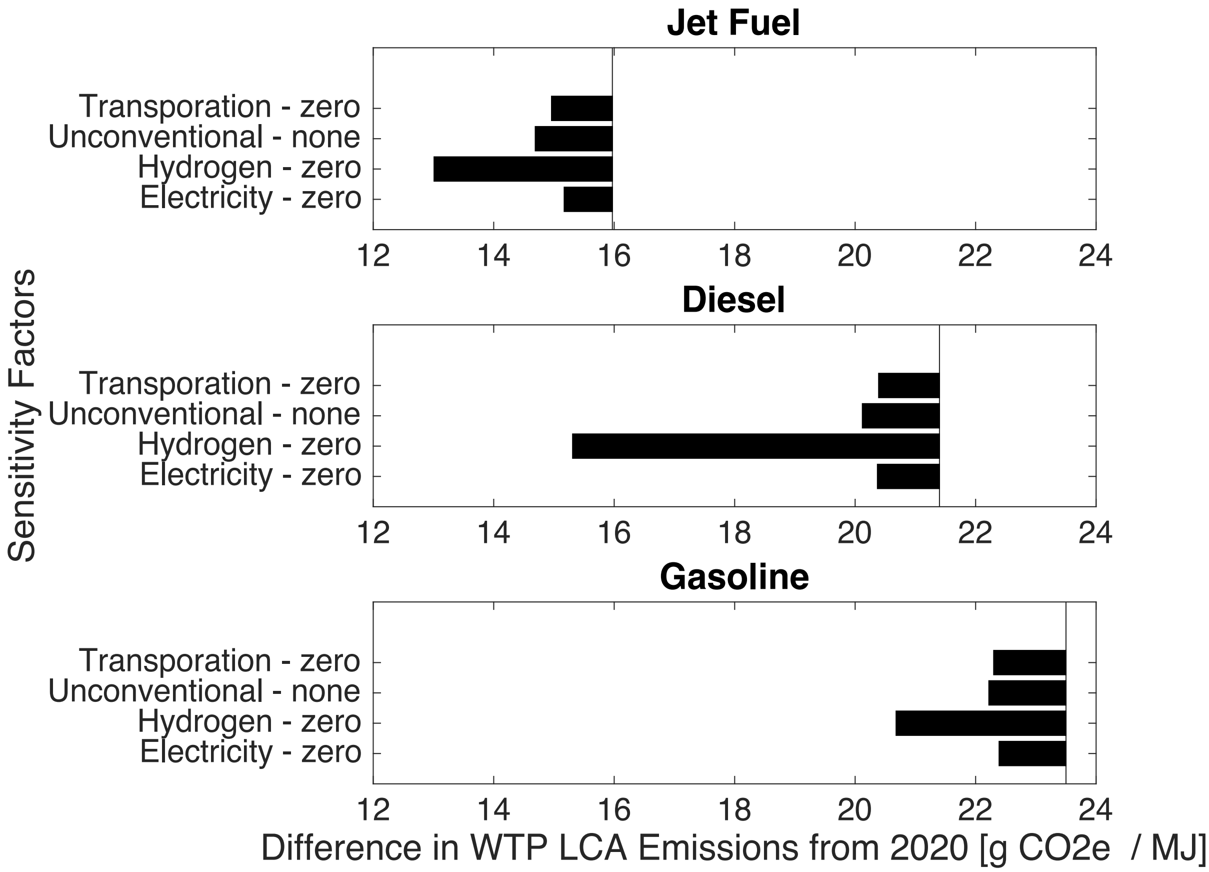

Figure 4.3: Impact of extraction, transportation, and utilities on WTP emissions

If unconventional sources of crude oil, such as oils sands and tight oil, are not used to produce transportation fuels, WTP emissions could be reduced by 1.28 g CO_2e/MJ for all fuel types. If crude oil and finished fuel transportation transitions to GHG emissions-free methods, WTP emissions could be reduced by 1.01 – 1.20 g CO_2e/MJ. If electricity generation becomes GHG-emissions neutral, WTP emissions could decrease by 0.80 – 1.11 g CO_2e/MJ. Lastly, if hydrogen production becomes GHG emissions-free, WTP emissions could decrease by 2.82 – 6.09 g CO_2e/MJ.

The use of transportation, electricity, and hydrogen varies amongst the different fuels, which is reflected in their WTP sensitivity to these factors. Most notably, hydrogen has the largest impact on emissions reductions and varies considerably between fuel types. The variation is due to refinery processes. Although diesel and gasoline use 80% of the hydrogen in the refinery, gasoline receives a credit for hydrogen production in the reformer, which lowers its sensitivity. The magnitude of reduction potential from clean hydrogen production suggests that this could be a worthwhile area of focus for achieving WTP emissions reduction.

4.3 Summary

The WTP production emissions of gasoline, jet fuel, and diesel were presented in this section for the three 2050 scenarios. The differences between these WTP emissions were discussed in terms of the four stages of the lifecycle. In addition, a sensitivity of these results with respect to key model parameters revealed that the emissions intensity of hydrogen is a very sensitive factor, but that this sensitivity varies between fuel types.

5 Discussion

In this Chapter, the results presented in Chapter 4 will be discussed in relation to the research questions posed in Chapter 1. First, the lifecycle production emissions for transportation fuels will be compared temporally from 2005 to 2050. Next, the impact of production emissions on a global scale for total fuel demand will be assessed to understand their emissions reduction potential. Afterwards, the applications of these projections to policy will be discussed.

5.1 Production emissions in 2050

Figure 5.1 shows the 2050 WTP production lifecycle emissions established in this thesis alongside prior values for the years 2005, 2012, and 2020 by Azadi et al [4], and the years 2005, 2014, 2020, and 2040 by Cooney et al [33] (tabular form in A12 of the Appendix). Recall that values from Cooney et al [33] are for the US, while values from Azadi et al [4] and this thesis are for the world. In Azadi et al [4], the WTP emissions increase from 2005 to 2020 due to the expanding use of unconventional crude resources in the extraction stage. For all three fuels, production emissions are seen to increase at varying rates between 2005 and 2020.

Cooney et al present revised 2005 numbers in their 2017 paper, alongside values for the years 2014 – 2040 [33]. The revised 2005 values are higher than the original values presented by NETL due to changes in modeling software [5,33]. Thus, production emissions decrease or stagnate from 2005 to 2020.

The 2050 scenarios developed in this thesis diverge from Azadi et al's 2020 results. The CP scenario shows how emissions could increase from 2020 to 2050, with growing WTP emissions attributed to increased use of unconventional crude resources and additional refinery emission due to the future quality gap in crude oil feedstock. Conversely, the SP scenario shows how emissions could decrease from 2020 to 2050 because of factors such as de-carbonization of utilities, reduced product demands, and reduced use of unconventional crude. Comparing the 2050 MP scenario to the 2020 estimates yields different results for each fuel type.

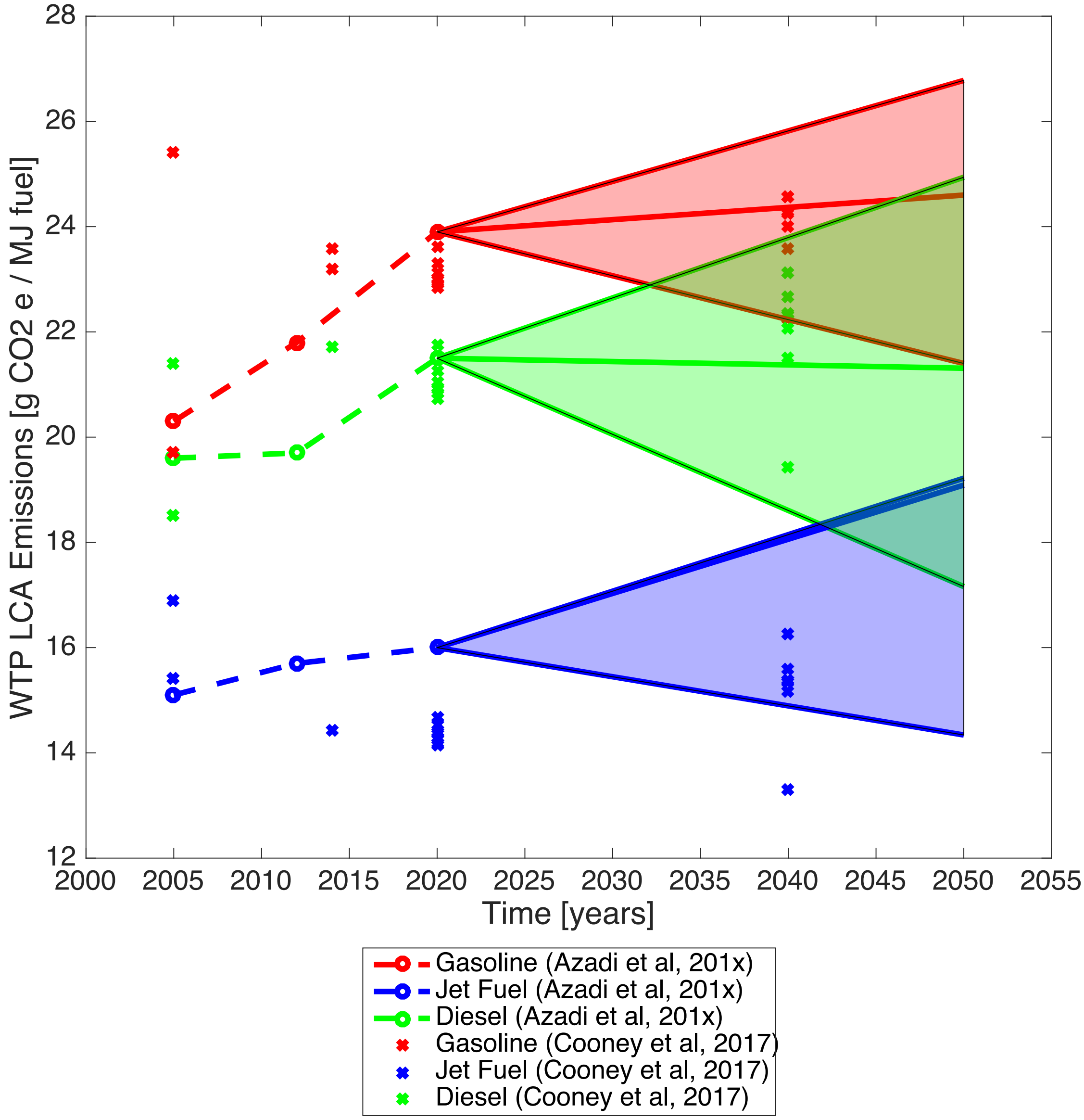

Figure 5.1: WTP emissions for petroleum-derived transportation fuels over time

The 2040 projections developed by Cooney et al diverge from 2020 estimates. These 2040 values mostly fall within the range of 2050 values developed here. Differences in results can be attributed different models and assumptions. While Cooney et al [33] focused mainly on differences in future crude supply to the US, this thesis considered changes to extraction, refinery, and utility inputs across the production lifecycle. In addition, Cooney et al [33] used a hydrogen based allocation for their refinery models, while this thesis used energy based allocation. Furthermore, the values for 2005 to 2020 vary between Azadi et al [4] and Cooney et al [33], which impacts future projections. Lastly, the different geographic scope can account for some differences as well.

The percentage changes in WTP emissions from 2020 to 2050 for each policy scenario and transportation fuel type are listed in Table 5.1.

Table 5.1: Percentage change in WTP emissions from 2020 reference to 2050 scenarios

Policy Scenario	Jet Fuel	Diesel	Gasoline
Current	20.4%	15.5%	13.1%
Moderate New	19.6%	-1.3%	3.9%
Strong New	-10.2%	-20.5%	-10.7%

These three scenarios for 2050 are connected through a consistent logic, where the stringency of relevant environmental policies differs. Together, they illustrate what production emissions could be if the actions outlined in the scenarios are taken.

The CP scenario shows a “business as usual case.” If the environmental stringency of current policies remains unchanged, one can expect the production emissions of fuels to increase in the future (13.1 – 20.4%).

In the MP scenario, some actions are taken through additional environmental policies of moderate stringency. Diesel emissions decrease by 1.3%, while gasoline emissions increase by 3.9%, and jet fuel emissions increase 19.6%. This shows that moderate policies might be insufficient to yield significant reductions to WTP emissions. However, these environmental polices may have impacts beyond the WTP emissions of fuels. For example, total fuel demand in

2050 stays at 2020 levels in the MP scenario. Thus, the effectiveness of a policy differs depending on the goals or metrics being considered. The MP case also shows that the impact of policies on WTP emissions varies amongst fuel types.

The SP scenario goes a step further than MP, and shows what would happen to emissions if additional environmental policies of a strong stringency were adopted. By comparing MP to SP, one can see that strong policy actions need to be taken in order to decrease emissions (10.2 – 20.5%).

The range of potential scenarios for 2050 helps to capture the inherent uncertainty associated with the future by exploring how WTP emissions could vary if different choices are made [85]. These scenarios extend the temporal bounds and the breadth of possibilities associated with understanding the future [101]. The scenario-based approach offers a range of values for potential production emissions in the year 2050, rather than a distinct prediction of what is most likely to occur.

5.2 Opportunities for emission reduction

The WTP emissions from petroleum-derived fuels (g CO_2e/MJ) can be considered on the scale of global fuel demand (mmbbl / day). This metric yields the total impact of production emissions on a global scale (M tonnes CO_2e / year). It is calculated by converting fuel demand from barrels to joules using energy content, and then applying the WTP emissions to this demand (details in A13 of the Appendix). Table 5.2 lists the total GHG emissions associated with producing fuels to meet global demand.

Table 5.2: Lifecycle emissions from global production of transportation fuels

[M tonnes CO_2e / year]

Policy Scenario	Gasoline	Jet Fuel	Diesel	Total
Reference (2020)	1,057.4	415.9	1,215.3	2,688.6
Current (2050)	1,498.7	813.5	1,994.7	4,306.9
Moderate New (2050)	1,044.9	704.5	1,217.6	2,967.0
Strong New (2050)	490.9	320.6	809.2	1,620.7

These figures can be compared to the total global GHG emissions from all sources in 2013, (31,646 M tonnes CO_2e) [102]. Diesel contributes the most to emissions, followed closely by gasoline, and then jet fuel. The production emissions of major transportation fuels are on the order of magnitude of one tenth of global emissions, representing a significant and non-negligible source.

The three 2050 scenarios can be compared to the 2020 reference point in terms of change in total emissions. Table 5.3 lists the absolute difference in emissions between the 2020 and 2050 results. This difference is also shown as a percentage of total GHG emissions in 2013 (31,646 M tonnes CO_2e).

Table 5.3: Change in production emissions from 2020 reference to 2050 scenarios

2050 Policy Scenario	Absolute Difference [M tonnes CO_2e / yr]	Difference as a percentage of 2013 emissions
Current	1,618.3	5.1%
Moderate New	278.3	0.9%
Strong New	-1,067.9	-3.4%

The range of emissions between CP and SP is 2,686 M tonnes CO_2e, which is equivalent to 8.5% of 2013 global emissions. This range conveys the potential opportunity space for emissions reductions. In practical terms, it represents the emission reductions that could be achieved if today's environmental policies (CP) are adapted to be more stringent (SP). A cost-benefit analysis (CBA) is one way to evaluate the potential effectiveness of adopting SP as a means of reducing global GHG emissions.

A CBA would involve costing the benefits of reduced GHG emissions, possibly through calculating the economic cost of avoided climate damages through an integrated assessment model. One would also need to calculate the economic cost associated with the technology changes to the production process. When doing this CBA, it is also worth noting that the benefits (global emissions reductions) are proportional to the size of petroleum demand, while the costs may not be (e.g. made up of fixed costs for new technology installation and variable operating costs). As well, some of the technological changes required by such a policy may be fully within the petroleum industry (e.g. extraction methods), while others may be outside of it (e.g. electricity grid). This could complicate the allocation of both costs and benefits of the potential policy, as there may be ripple effects outside of the petroleum industry.

5.3 Use of forecasts

Craig et al discuss the many uses of long-range forecasts [41]. Forecast can aid bookkeeping, sell an idea, educate, and more [41]. By highlighting the consequences of actions, scenarios can help inform behaviors [41]. Craig et al deem a forecast to be successful if it: helps planners, influences the perception of an issue, clarifies understanding of physical or economic principles, or highlights emerging trends [41]. Note that the success of a long-range forecast is not whether it correctly predicts the future, but whether the information communicated in the forecast influences the behaviors of relevant actors.

Future forecasts can aid in thinking through future possibilities [41]. Scenarios require analysts to design data sets with fundamentally different assumptions and observe their subsequent results. This illustrates the consequences of a given set of actions, enhancing understanding of the dynamics of a complex system. For example, the 2050 scenarios in this thesis highlighted the interdependences of product demands within the petroleum supply chain. Abating the demand of one fuel class may have unintended consequences on the emission from another fuel class, as is the case for road and air fuels in MP. Highlighting these complexities can enhance how planners think about the future.

Future forecasts can help identify the bounds or limits of the range of possible outcomes [41]. By understanding the range of outcomes and the choices that lead to these outcomes, the decision-making process becomes more informed. Ranges can help limit technology or policy options to consider, and converge on ones to pursue. In this thesis, the CP scenario represents one extreme of inaction, while the SP scenario represents another extreme of positive action. Decision-makers may use this information differently depending on their objectives, but the forecasts will ultimately help frame the scope of the discussion.

Despite being a technical artifact, the narrative nature of scenarios makes them easier to understand. Scenarios increase the accessibility of technical concepts to non-technical actors, which can facilitate discussions between technical analysts and policy-makers or business decision-makers. These discussions can enhance communication and understanding between stakeholder groups, and can also serve an educational purpose [41]. In this thesis, the scenarios help transform technical details of oil extraction and refining into policy objectives and discrete outcomes. Making this technical information more accessible can help diversify the stakeholders partaking in decision-making.

Thus, forecasts can enhance understanding of complex systems, bound the range of potential future outcomes, and facilitate communication between stakeholder groups. These uses show how scenarios provide tangible conceptualizations of the future around which discussions can be had, despite the unavoidable uncertainty of the future. Forecasts ground speculative discussions of the future in rigorous models containing logic and evidence.

5.4 Policy implications

Although presenting the fuel production emissions in 2050 as a range of values is technically accurate, it may be challenging to integrate within a policy. Using a range of values as a baseline for comparison is confusing. In this thesis, the 2050 emissions differ by 6.1 g CO_2e/MJ on average, which is about 29% of the average WTP emissions or about 6.6% of average WTW. This may span too large a range to be a clear baseline. For example, within the US RFS, alternative fuels are differentiated by emission reductions equivalent to 20, 50, and 60% of the conventional petroleum-derived baseline WTW baseline [8].

Ultimately, policy-makers will have to choose how to incorporate this future range into their policies. Accurately predicting the future is a question that transcends science, or a question “which can be asked of science, and yet cannot be answered by science [103].” Such "trans-science” questions come down to value judgments as well as scientific assessments. Thus, scientific knowledge alone cannot inform decisions about the future [103]. For the work done in this thesis, policymakers will have to judge which scenario is most likely to happen, and use forecasted values associated with those choices.

When choosing between values and scenarios within this 2050 range, one must be cautious of the consequences of over- or under-estimating the conventional baseline of fuel production. If estimates of the conventional baseline are under-estimated (too low), those planning for climate change may not implement as much mitigation as needed. Under-estimates would de-incentive alternative fuels, as they would have a harder baseline to compete against.

Some may not compete, which would lead to a missed opportunity. Others may compete, but may end up over-investing to compete against an under-estimated conventional baseline, which would be wasteful.

Conversely, if the conventional baseline is over-estimated (too high), alternative fuels may be over-incentivized. This could be problematic, as alternative fuel producers might under-invest in emission reductions, and then not be able to compete against the over-estimated conventional baseline. This would be a poor return on investment, both economically for alternative fuel producers, and societally for the lack of sustainable technology options. These hypotheticals show how conventional baselines impact alternative fuels and climate change planning. This would have ripple effects within research, industry, and government [11,12].

5.5 Summary

Calculating the production emissions of petroleum-derived transportation fuels for certain 2050 scenarios quantifies what emissions could be in the year 2050, not what they will be. Extending the temporal view of emissions to 2050 addresses Research Question 1. Depending on the policies pursued, WTP emissions of petroleum-derived transportation fuels could increase by up to 20.4% or decrease by as much as 20.5%. The opportunity space associated with reducing global emissions in 2050 through changing the petroleum production process answers Research Question 2. The SP scenario could decrease emissions in 2050 from the CP scenario by an amount equivalent to 8.5% of 2013 global GHG emissions. Discussing the uses of these forecasts helps answer Research Question 3. The dynamics that scenarios illustrate help to inform policy-makers about how their actions would impact future outcomes, and thus help guide decision-making.

6 Conclusions

This thesis establishes a range of production emissions for petroleum-derived transportation fuels (gasoline, diesel, jet fuel) in the year 2050. These values are calculated using a lifecycle emissions model of the petroleum production process, which is combined with scenarios that describe the environmental policy stringency in the year 2050. These scenarios allow the LCA approach to be extended to the future by creating lifecycle inventory that are representative of the future, which are each consistent with the respective scenario assumptions.

The 2050 WTP production emissions are found to be as follows: 14.3 – 19.2 g CO_2e/MJ for jet fuel, 17.2 – 24.9 g CO_2e/MJ for diesel, and 21.1 – 26.8 g CO_2e/MJ for gasoline. These values capture the environmental consequences of future policies, which range from not modifying current policies (CP), to greatly increasing the environmental stringency of current policies (SP). On a global scale, the possibility space associated with these scenarios spans 8.5% of all GHG emissions in 2013.

This work shows that significant global emissions reductions can be achieved if efforts are made towards reducing the production emissions of petroleum-derived fuels. This is an under-regulated area of transportation emissions, and thus one from which benefits still remain to be reaped. Of all the factors considered in the 2050 scenario-analysis, the production emissions for the hydrogen being consumed by the refinery are of particular interest, as the WTP emissions are particularly sensitive to it.

This thesis does not predict what the production emission of petroleum-derived fuels will be in the year 2050, as the future cannot be predicted. By describing the consequences that various policy actions would have on future production emissions, this thesis enhances current understanding of the dynamics of the petroleum production process. These emissions forecasts highlight synergies that exist between fuel types, and help to bound potential future environmental outcomes. This information can facilitate discussions about the future between diverse stakeholders so that decisions can be made in a collaborative and well-informed manner. There are clear applications of this work to the US RFS and ICAO's CORSIA, as well as other studies, policies, or plans dealing with future petroleum fuel use.

6.1 Future Work

Scenario-based analysis is an exploratory strategy for demonstrating the potential outcomes of a given set of choices. The three 2050 scenarios chosen in this study do not capture the full solution space of potential futures that may unfold by 2050. Furthermore, the lifecycle model is temporally static, with time being represented completely by its input data. This model may fail to incorporate some future changes because of this.

This work could be built upon by focusing on several areas. Firstly, the method of estimating refinery adjustments to the future quality gap could be improved upon. For example, geography could be considered on a finer level, or refinery processes could be subdivided further. Adding an additional scenario to examine a more negative worldview, such as one where existing environmental policies are repealed, could add new insights. Lastly, the costs associated with emission reduction opportunities discussed in the sensitivity analysis could be quantified. A cost benefit analysis of the emissions benefits realized through implementing these practices would be interesting for future work on this topic.

Appendix

A1: Future crude quality

Future crude quality impacts the energy demand in the extraction stage, and the refinery processes. An average of the two global OPEC predictions was used in the model. Projections on how the average crude density (API) changes over time were collected for various regions, as shown in Table A1.1:

Table A1.1: Average crude API in various regions over time [degrees API]

Region		NA (OPEC WOO2014) [94]	Global (OPEC WOO 2014) [94]	Global (OPEC WOO 2015) [2]	USA (EIA 2014) [104]
Year	2010	31.57	33.44	33.40	*35.14*
	2015	32.89	33.56	33.60	38.68
	2020	32.40	33.34	33.58	38.47
	2025	31.31	33.19	33.45	38.18
	2030	30.52	33.06	33.34	38.41
	2040	29.84	32.86	33.17	38.44
	2050	29.70	32.74	33.04	38.48
Change (2020 to 2050)		-2.70	-0.60	-0.54	0.01

Projections on how the average crude sulfur content changes over time were also collected, as shown in Table A1.2:

Table A1.2: Global average crude sulfur content over time [% sulfur]

Region		Global (OPEC WOO 2014) [94]	Global (OPEC WOO 2015) [2]
Year	2010	1.16	1.15
	2015	1.15	1.16
	2020	1.16	1.17
	2025	1.17	1.19
	2030	1.19	1.22
	2040	1.27	1.3
	2050	1.39	1.42
Change (2020 to 2050)		+0.23	+0.25

A2: Emission indices for electricity generation

Electricity is used as an input throughout the petroleum production process. Various projections of the technology mix used to generate electricity in the year 2050 were collected, and assigned to the three policy scenarios. The CP scenario used the same emission index for electricity generation as the 2020 reference case, with data from the Paul Scherrer Institut (PSI) [96]. The MP and SP scenario utilize the technology mix projections for the electricity grid in 2050 from the "World Energy Scenarios" report from the World Energy Council (WEC) [88]. The WEC projects the proportion that technologies will make up the grid (in percentage). The MP scenario in this study uses the Jazz scenario, with data shown in Table A2.1. The SP scenario in this study uses the Symphony scenario, with data shown below in Table A2.2.

Table A2.1: MP electricity grid technology and associated emission index for electricity generation

Technology	*Percentage [%]*									*[g CO_2e/ MJ]*
	Coal	Oil	Gas	Nuc-lear	Hydro-power	Bio-mass	Wind	Solar	Geo-thermal	Emissions Index
South & Central Asia	80.5	0	5.6	1.5	6.2	1.45	2.25	1.25	1.25	209.7
East Asia	47.6	0	22.1	8.9	10.9	1	3.6	4.9	1	145.1
Europe	25.2	0	20.8	13.76	12.99	8.9	16.35	1.2	0.8	107.3
Latin America & Caribbean	9.95	0	16.9	1.42	31.83	16.75	8	12.45	2.7	45.9
Middle East & North Africa	4.3	0	76.8	4.57	1.43	5.9	0.7	5.3	1	97.1
North America	23.6	0	33.5	6.9	11.3	0.7	20.4	1.5	2.1	97.5
Southeast Asia & Pacific	38.7	0	20.7	0	6.1	4	7	16.2	7.3	122.9
Sub-Saharan Africa	15.9	0	35.6	1.2	7.3	8.8	3.2	24.7	3.3	81.3
World	37.6	0	25.4	6	10.8	4.7	8.3	5.7	1.5	113.4

Table A2.2: SP electricity grid technology and associated emission index for electricity generation

Technology	*Percentage [%]*									*[g CO_2e/ MJ]*
	Coal	Oil	Gas	Nuc-lear	Hydro-power	Bio-mass	Wind	Solar	Geo-thermal	Emissions Index
South & Central Asia	32.4	0	13.6	6.6	14.5	4.9	11.8	15	1.2	97.7
East Asia	16.9	0	20.1	21.7	15.2	2.3	3.8	20	0	65.6
Europe	16.9	0	14.1	21.3	16.2	8.5	15.6	7.4	0	59.4
Latin America & Caribbean	3.8	0	11.2	3.3	46.35	18.75	4.4	12.2	0	43.2
Middle East & North Africa	6.4	0	46.4	9.5	1	8.4	0	27.3	1	69.0
North America	18.5	0	19.5	17.4	14	1.8	13.8	11.2	3.8	66.8
Southeast Asia & Pacific	20.8	0	24.3	6	13.2	3.8	3.2	24.2	4.5	81.0
Sub-Saharan Africa	14.1	0	23.8	2.6	19.1	9.7	3.9	22.6	4.2	63.9
World	17.4	0	19.8	14.85	16.1	5.75	8.05	16.25	1.8	68.3

The emissions index for electricity production (last column of Tables A2.1 and A2.2) was calculated using the GREET model and informed by the technology mix within these table [97]. These regional emission indices were used to represent the various individual countries within the LCA model, as shown in Table A2.3:

Table A2.3: Emission indices for electricity generation by country or region and policy scenario

Country	Policy Scenario [g CO_2e/MJ electricity produced]			
	Reference	Current	Moderate New	Strong New
South Africa	157.0	157.0	81.3	63.9
Tanzania	56.0	56.0	81.3	63.9
Tunisia	112.0	112.0	97.1	69.0
Argentina	81.0	81.0	45.9	43.2
Bolivia	110.0	110.0	45.9	43.2
Brazil	28.0	28.0	45.9	43.2
Canada	45.0	45.0	97.5	66.8
Chile	82.0	82.0	45.9	43.2
Colombia	23.0	23.0	45.9	43.2
Cuba	193.0	193.0	45.9	43.2
Ecuador	56.0	56.0	45.9	43.2
Mexico	110.0	110.0	97.5	66.8
Peru	50.0	50.0	45.9	43.2
Trinidad	158.0	158.0	45.9	43.2
United States of America	112.0	112.0	97.5	66.8
Venezuela	128.0	128.0	45.9	43.2
Australia	160.0	160.0	122.9	81.0
China	171.0	171.0	145.1	65.6
Chinese Taipei	139.0	139.0	145.1	65.6
India	177.0	177.0	209.7	97.7
Indonesia	142.0	142.0	122.9	81.0
Iran	123.0	123.0	97.1	69.0
Japan	94.0	94.0	145.1	65.6
Malaysia	105.0	105.0	122.9	81.0
Saudi Arabia	125.0	125.0	97.1	69.0
South Korea	98.0	98.0	145.1	65.6
Thailand	109.0	109.0	122.9	81.0
Austria	53.0	53.0	107.3	59.4
Azerbaijan	81.0	81.0	209.7	97.7
Belgium	48.0	48.0	107.3	59.4
Bosnia and Herzegovina	154.0	154.0	107.3	59.4
Bulgaria	107.0	107.0	107.3	59.4

Croatia	88.0	88.0	107.3	59.4
Czech Republic	120.0	120.0	107.3	59.4
Denmark	72.0	72.0	107.3	59.4
Estonia	178.0	178.0	107.3	59.4
Finland	51.0	51.0	107.3	59.4
France	15.0	15.0	107.3	59.4
Germany	93.0	93.0	107.3	59.4
Greece	147.0	147.0	107.3	59.4
Hungary	83.0	83.0	107.3	59.4
Iceland	4.0	4.0	107.3	59.4
Ireland	110.0	110.0	107.3	59.4
Italy	86.0	86.0	107.3	59.4
Latvia	75.0	75.0	107.3	59.4
Lithuania	47.0	47.0	107.3	59.4
Luxembourg	92.0	92.0	107.3	59.4
Macedonia	183.0	183.0	107.3	59.4
Netherlands	95.0	95.0	107.3	59.4
Norway	5.0	5.0	107.3	59.4
Poland	168.0	168.0	107.3	59.4
Portugal	82.0	82.0	107.3	59.4
Romania	96.0	96.0	107.3	59.4
Russia	101.0	101.0	107.3	59.4
Serbia and Montenegro	159.0	159.0	107.3	59.4
Slovakia	66.0	66.0	107.3	59.4
Slovenia	67.0	67.0	107.3	59.4
Spain	69.0	69.0	107.3	59.4
Sweden	8.0	8.0	107.3	59.4
Switzerland	19.0	19.0	107.3	59.4
Turkey	154.0	154.0	107.3	59.4
Ukraine	86.0	86.0	107.3	59.4
United Kingdom	95.0	95.0	107.3	59.4
World	114.0	114.0	113.4	68.3

A3: Emission indices for hydrogen production

Various units within petroleum refineries consume hydrogen. To determine the average emission intensity for hydrogen production, one needs to know which technologies are being used to produce hydrogen, and the emissions intensity associated with those technologies. This data can then be combined to create a weighted average that represents the emissions intensity for global hydrogen production, which is used within the LCA model. These factors are shown in Table A3.1:

Table A3.1: Emission indices for various methods of hydrogen production

Technology		Emission Index *[g CO_2e/MJ]*		Policy Scenario *[%]*			
		Min	Max	Reference [4]	Current [4]	Moderate New [89]	Strong New
Reforming	Natural Gas [90]	3.0	150.0	100	100	0	0
	Coal [90]	49.4	264.2	0	0	26.5	0
Electrolysis	Electricity [90]	0.0	240.0	0	0	24.9	0
	Biomass [89]	201.7	267.5	0	0	23.9	25
	Wind	28.0	28.0	0	0	9.4	25
	Solar	28.0	28.0	0	0	1.1	25
	Nuclear	28.5	28.5	0	0	14.3	25
Emission Index *[g CO_2e/MJ]*				99.0	99.0	68.3	28.0

The CP scenario utilized the 2020 emission indices. The MP scenario utilized an ANL projection for technology mix. The SP scenario assumed that all hydrogen was produced through the cleanest electrolysis methods.

A4: Emission indices and production rates for unconventional extraction methods

The emission indices of extraction methods can vary due to type of technology used. These emission indices can change because of factors such as improvements in efficiency or movement towards emissions free power sources (e.g. eliminating diesel as a fuel for prime movers).

The emissions associated with oil sands extraction vary depending on the specific extraction technique. The LCA model for this study captures four methods, shown in Table A4.1.

Table A4.1: Emission indices for oil sands extraction methods [g CO_2 / MJ]

Extraction Technique	Surface Bitumen	In Situ Bitumen	Surface Mining	In Situ Mining
High [4]	24.5	29.0	9.4	18.3
Low [16]	15.9	19.1	9.4	10.3

Tight oil is another unconventional resource, for which the hydraulic fracturing (fracking) extraction technique is used. The emissions for this technique are shown in Table A4.2.

Table A4.2: Emission indices for tight oil extraction methods [g CO_2 / MJ]

Extraction Technique	Fracking
High [4]	6.32
Low [22]	1.80

The "low" emissions from Tables A4.1 and A4.2 are used within the SP scenario, and the "high" emissions are used within the other three scenarios (reference, CP, and MP).

The production rates for crude from oil sands resources are shown in Table A4.3. The use of oil sands resources expands in geography based on IEA's WEO [1], and by quantity based on Exxon's forecast [91]. The MP and SP scenarios have quantities based on other scenarios from the IEA's WEO [1].

Table A4.3: Production rates for oil sands extraction methods [kbbl / day]

Country	Policy Scenario			
	Reference [4]	Current [91] [1]	Moderate New [1]	Strong New [1]
Canada	4250	5672	4747	2895
Venezuela	0	3928	3288	2005
World	4250	9600	8035	4900

The production rates of crude from tight oil resources are shown in Table A4.4. The use of tight oil resources expands in geography based on IEA's WEO [1], and by quantity based on Exxon's forecast [91]. The MP and SP scenarios have quantities based on other scenarios from the IEA's WEO [1]. The division between the four extraction techniques is constant through all four scenarios.

Table A4.4: Production rates for tight oil extraction methods [kbbl / day]

Country	Policy Scenario			
	Reference [4]	Current [91] [1]	Moderate New [1]	Strong New [1]
Algeria	0	302	146	087
Argentina	0	1722	833	494
Australia	0	234	113	67
Canada	0	1684	814	483
China	0	620	300	178
Iran	0	1251	605	359
Mexico	0	824	398	236
Poland	0	342	166	98
Qatar	0	611	295	175
Russia	0	1781	861	511
Turkey	0	234	113	67
USA	5200	2596	1255	745
World	5200	12200	5898	3500

These two unconventional crude resources make up a significant portion of total crude supply for the 2050 scenarios, as shown in Table A4.5:

Table A4.5: Production rates of total conventional and unconventional crude [kbbl / day]

Country	Policy Scenario			
	Reference	Current	Moderate New	Strong New
Oil Sands	4250	9600	8035	4900
Tight Oil	5200	12200	5898	3500
Total Crude	85200	126200	81500	56800

A5: Hydrogen consumption of hydro-treating units

Hydro-treating units utilize hydrogen to remove sulfur from crude. If there is more sulfur in the crude being processed (increased severity), the hydro-treating units demand more hydrogen to perform the sulfur removal. Several hydrogen consumption rates for the hydro-treating units were considered, listed in Table A5.1:

Table A5.1: Hydrogen demand of hydro-treating units

[scf H_2 per bbl feed processed per percentage of sulfur reduction desired]

Data Source	Relationship	Value
Petroleum Refining: Tech. & Econ. [76]	Linear	70
Colorado School of Mines [105]	Linear	160
Oil and Gas Journal [99]	Logarithmic	20 - 150
Handbook of Petroleum Processing [106]	Linear	100 - 150
Catalysis Reviews [107]	Experimental	200

The logarithmic relationship was used, and then combined with the projected sulfur increase of 0.24% to determine the hydrogen demand of the hydro-treating units given the new sulfur content of the crude. These consumption rates were used within the LCA model, and are shown in Table A5.2:

Table A5.2: Hydrogen demand of hydro-treating units [scf H_2 / bbl feed processed]

Scenario Year	Sulfur Content of Feed	Hydro-treating Unit				
		Naphtha	Gasoline	Kerosene	Diesel	Vacuum Gas Oils
2020 [4]	Reference	186	419	466	559	745
2050 [99]	+ 0.24%	250	483	530	623	809

A6: Crude product demands

The crude product demands are listed within Table 3.1 of Chapter 3, and listed again in Table A6.1:

Table A6.1: Global product demand [mmbbl / day]

Policy Scenario	Reference	Current	Moderate New	Strong New
Gasoline	22.5 [4]	28.2 [2]	21.4 [88]	11.7 [88]
Jet Fuel	12.0 [4]	19.5 [93]	17.0 [88]	10.3 [88]
Diesel	27.1 [4]	38.5 [2]	27.5 [88]	22.7 [88]
Other	23.6 [4]	40.0 [2] [93]	15.6 [88]	12.1 [88]
Total Crude	85.2 [4]	126.2 [2] [93]	81.5 [88]	56.8 [88]

The proportion that these contribute to total crude demand is shown in Table A6.2:

Table A6.2: Product demand as a proportion of total crude demand

Policy Scenario	Reference [4]	Current [2] [93]	Moderate New [88]	Strong New [88]
Gasoline	26%	30%	26%	21%
Jet Fuel	14%	15%	21%	18%
Diesel	32%	23%	34%	40%

The percentage change in demand for the 2050 scenarios from the 2020 reference case is shown in Table S6.3:

Table A6.3: Percentage change in product demand from 2020 to 2050

Policy Scenario	Current [2] [93]	Moderate New [88]	Strong New [88]
Gasoline	70%	-5%	-48%
Jet Fuel	63%	42%	-14%
Diesel	5%	1%	-16%
Other	69%	-34%	-49%
Total Crude	48%	-4%	-33%

A7: Crude product supply

The supply of various crude products through straight run distillation is dependent on the density of the crude. Global crude density is projected to decrease by 0.57 API by the year 2050, changing average global crude API from 32.89 to 32.32 [2]. Linear relationships can be found between the various cuts of crude and the total crude density [100]. With these relationships, the yields for the various crude cuts can be found, as shown in Table A7.1:

Table A7.1: Percentage yield by volume for various crude cuts [100]

Supply	Reference (2020)	Future (2050)
Gas	3.27	3.14
Light Naphtha	5.10	4.93
Heavy Naphtha	16.29	15.91
Naphtha / Kerosene Swing	1.83	1.81
Kerosene	12.88	12.78
Kerosene / Diesel Swing	1.08	1.08
Diesel	8.14	8.13
Atmospheric Residuals	50.01	50.87
Light Vacuum Gas Oils	5.00	5.02
Heavy Vacuum Gas Oils	28.37	28.70
Vacuum Residuals	16.64	17.15

Two main intermediary product groups are important to refinery calculations. These are naphtha (made up of light naphtha and heavy naphtha) and middle distillates (made up of naphtha / kerosene swing, kerosene, kerosene / diesel swing, and diesel). Naphtha makes up 23.6% of the crude in 2020, and this decreases by 2.6% due to increased API, resulting in naphtha making up 23.0% of the crude in 2050. Middle distillates make up 27.6% of the crude in 2020, and this decreases by 0.6% due to increased API, resulting in diesel making up 27.5% of the crude in 2050.

A8: Additional refinery calculations

The many refinery processing pathways by which a crude product can be produced are grouped into two categories: primary and secondary. The refinery emissions associated with primary processes categories by removing certain secondary units from the model. The division of units between primary and secondary, as well as the proportion that each product uses said unit, are listed in Table A8.1. The changes to refinery unit utilization by product between the primary processing pathways to secondary processing pathways are shaded in grey.

Table A8.1: Proportion of use for refinery units by various crude products

Refinery Units	Gasoline		Jet Fuel		Diesel	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
Desalter	0.24	0.24	0.09	0.09	0.32	0.32
Atmospheric distillation	0.24	0.24	0.09	0.09	0.32	0.32
Vacuum distillation	0.25	0.25	0.09	0.09	0.33	0.33
Coker	0.00	0.12	0.00	0.05	0.00	0.50
Catalytic Cracker	0.00	0.71	0.00	0.02	0.00	0.27
Hydro Cracker	0.00	0.58	0.00	0.11	0.00	0.31
Reformer	1.00	1.00	0.00	0.00	0.00	0.00
Hydro-treater (naphtha)	1.00	1.00	0.00	0.00	0.00	0.00
Hydro-treater (gasoline)	1.00	1.00	0.00	0.00	0.00	0.00
Hydro-treater (kerosene)	0.00	0.00	1.00	1.00	0.00	0.00
Hydro-treater (diesel)	0.00	0.00	0.00	0.00	1.00	1.00
Hydro-treater (vacuum gas oils)	0.00	0.71	0.00	0.02	0.00	0.27
Hydro-treater (unknown)	0.00	0.53	0.00	0.11	0.00	0.36
Alkylation	1.00	1.00	0.00	0.00	0.00	0.00
Isomerization	1.00	1.00	0.00	0.00	0.00	0.00
Vis-Breaker	0.00	0.06	0.00	0.00	0.00	0.14
Aromatic fractionation (BTX)	0.00	0.00	0.00	0.00	0.00	0.00
Asphalt	0.00	0.00	0.00	0.00	0.00	0.00

Additional calculations are needed to incorporate the future changes to crude API into the refinery operations and emissions. A baseline for the proportion of crude products produced from primary or secondary refinery processing pathways (k_1 and k_2) was determined from 2020 data within the model. The relevant refinery data is listed in Table A8.2:

Table A8.2: Modeled proportion of product from primary and secondary processes in 2020

Product	*[mmbbl / day]*				k_1	k_2
	Intermediary Demand	Total Demand	Primary Processed	Secondary Processed		
Jet Fuel	12.0	12.1	10.6	1.5	0.876	0.124
Diesel	27.1	16.8	6.3	10.5	0.375	0.625
Gasoline	22.5	30.0	12.8	17.2	0.427	0.573

These proportions are also combined with a ratio of end product to intermediary product. The intermediary product represents the portion of crude that the end product is produced from. This ratio acts as a cutoff point to determine whether the new proportions should be utilized, or whether the old proportions are sufficient. These ratios are listed in Table A8.3:

Table A8.3: Ratios of end product to intermediary product

End Product *[mmbbl / day]*		Intermediary Product *[mmbbl / day]*		Ratio
Jet Fuel	12.0	Middle Distillate	23.0	0.52
Diesel	27.1	Middle Distillate	23.0	1.18
Gasoline	22.5	Naphtha	18.5	1.22

A9: 2050 lifecycle emissions

The resulting lifecycle emissions shown in Figure 4.1 are broken down by fuel type, policy scenario, and lifecycle stage, shown in Table A9.1:

Table A9.1: Lifecycle emissions by scenario and fuel [g CO_2e/MJ]

Scenario	Fuel	Extraction	Crude Transport	Refinery	Product Transport	WTP
Reference	Gasoline	8.85	1.08	12.68	1.07	23.68
	Jet Fuel	8.85	1.08	5.35	0.69	15.97
	Diesel	8.85	1.08	10.97	0.68	21.58
Current	Gasoline	11.16	1.08	13.46	1.07	26.78
	Jet Fuel	11.16	1.08	6.29	0.69	19.22
	Diesel	11.16	1.08	12.01	0.68	24.94
Moderate New	Gasoline	10.26	1.08	12.20	1.06	24.60
	Jet Fuel	10.26	1.08	7.08	0.68	19.09
	Diesel	10.26	1.08	9.30	0.67	21.31
Strong New	Gasoline	8.51	0.82	10.79	1.02	21.14
	Jet Fuel	8.51	0.82	4.38	0.63	14.34
	Diesel	8.51	0.82	7.20	0.63	17.16

If calculation of the WTW emissions is desired, the combustion (PTW) emission can be added to the WTP emissions. Combustion emission are listed in Table A9.2:

Table A9.2: Combustion emissions for transportation fuels [4]

Fuel	Gasoline	Jet Fuel	Diesel
PTW	69.3	72.9	74.1

A10: Fuel sensitivity analysis

Figure 4.2 is shown in tabular form in Table A10.1. The emissions are in units of g CO_2e/MJ, and represent refinery emissions for that fuel-scenario pair. Demand is in millions of barrels per day (mmbbl / day), and represents product demand for that fuel-scenario pair.

Table A10.1: Impact of road product demand on refinery emissions

Scenario	Fuel	Data Type	Data Point									
			Ref	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Current	Diesel	Demand	27.1	6.7	13.3	20.0	26.7	33.4	40.0	46.7	53.4	60.0
		Emissions	11.2	11.2	11.2	11.2	11.3	11.8	12.2	12.4	12.6	12.7
	Gasoline	Demand	22.5	60.0	53.4	46.7	40.0	33.4	26.7	20.0	13.3	6.7
		Emissions	13.2	14.8	14.1	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Moderate New	Diesel	Demand	27.1	4.9	9.8	14.7	19.6	24.5	29.3	34.2	39.1	44.0
		Emissions	8.8	8.8	8.8	8.8	9.1	9.5	9.7	9.9	10.0	10.1
	Gasoline	Demand	22.5	44.0	39.1	34.2	29.3	24.5	19.6	14.7	9.8	4.9
		Emissions	12.0	13.8	13.3	12.7	12.2	12.2	12.2	12.2	12.2	12.2
Strong New	Diesel	Demand	27.1	3.4	6.9	10.3	13.8	17.2	20.6	24.1	27.5	31.0
		Emissions	6.4	6.4	6.4	6.4	6.7	7.0	7.1	7.2	7.3	7.4
	Gasoline	Demand	22.5	31.0	27.5	24.1	20.6	17.2	13.8	10.3	6.9	3.4
		Emissions	10.6	12.0	11.6	11.2	10.8	10.8	10.8	10.8	10.8	10.8

A11: Factor sensitivity analysis

The change in WTP emissions (g CO_2e/MJ) from the 2020 baseline for due to the sensitivity analysis performed in Figure 4.3 is shown in tabular form in Table A11.1.

Table A11.1: Impact of extraction, transportation, and utilities on WTP emissions [g CO_2e/MJ]

Fuel	Jet Fuel	Diesel	Gasoline
Electricity	-0.80	-1.03	-1.11
Hydrogen	-2.96	-6.09	-2.82
Unconventional	-1.28	-1.28	-1.28
Transportation	-1.01	-1.01	-1.20

The electricity sensitivity assumes an emission index of 0 g CO_2e/MJ electricity generated. The hydrogen sensitivity assumes an emission index of 0 g CO_2e/MJ hydrogen produced. The unconventional sensitivity assumes that none of the crude is acquired from unconventional resources or practices, or that the production rate from unconventional sources (oil sands and tight oil) is 0 kbbl / day. The transportation sensitivity assumes an emission index of 0 g CO_2e / distance travelled for all transportation methods considered within the LCA model.

A12: Fuel WTP emissions in different years

Values illustrated in Figure 5.1 from this thesis, Azadi et al [4], and Cooney et al [33] are shown in tabular form in Table A12.1. Note that values from Cooney et al are for the US [33], while values from Azadi et al [4] and this thesis are for the world.

Table A12.1: WTP emissions [g CO_2e/MJ]

Year or Scenario	Jet Fuel	Diesel	Gasoline
2005 [4]	15.1	19.6	20.3
2005 [33]	15.4 – 16.9	18.5 – 21.4	19.7 – 25.4
2012 [4]	15.7	19.7	21.8
2014 [33]	14.4	21.1	23.2 – 23.6.6
2020 [4]	16.0	21.5	23.9
2020 [33]	14.4 – 14.7	20.7 – 21.8	22.8 – 23.6
2040 [33]	13.3 – 16.3	19.4 – 23.1	22.3 – 25.0
2050 – Current Policies	19.2	24.9	26.8
2050 – Moderate New Policies	19.1	21.3	24.6
2050 - Strong New Policies	14.3	17.2	21.1

A13: Global quantification

In order to quantify the WTP emissions (g CO_2e/MJ) on the scale of global fuel demand (mmbbl / day) one must first know the volumetric energy contents of the fuels, listed in Table A13.1 (where there are 159 liters per barrel):

Table A13.1: Energy content of transportation fuels

Energy Content	Gasoline	Jet Fuel	Diesel
[MJ / L]	34.2	37.4	35.8
[MJ / bbl]	5437.8	5946.6	5692.2

Next, one must convert fuel demands from units of millions of barrels per day (in in Table A6.1) into mega joules per year, listed in Table A13.2.

Table A13.2 Global demand of transportation fuels in 2050 [MJ / year]

Scenario	Gasoline	Jet Fuel	Diesel
Reference	4.47E+13	2.60E+13	5.63E+13
Current	5.60E+13	4.23E+13	8.00E+13
Moderate New	4.25E+13	3.69E+13	5.71E+13
Strong New	2.32E+13	2.24E+13	4.72E+13

Then, one can multiply the annual fuel demand (Table A13.1, in MJ / year) by the WTP emissions (Table A12.1, in g CO_2e/MJ) to determine the annual production emissions for each fuel-scenario pair. For convenience, this is listed in millions of tonnes of CO_2e/year in Table A13.3 (where there are one million grams in a tonne):

Table A13.3: Global production emissions of transportation fuels [M tonnes CO_2e / year]

Scenario	Gasoline	Jet Fuel	Diesel
Reference	1,057.4	415.9	1,215.3
Current	1,498.7	813.5	1,994.7
Moderate New	1,044.9	704.5	1,217.6
Strong New	490.9	320.6	809.2

Thus, the total annual WTP emissions associated with each scenario can be found by adding the emissions from the three fuels together, shown in the first column of Table A13.4 (M tonnes CO_2e / year). The difference in emissions between the 2020 reference case and the 2050 scenarios is in the second column of Table A13.4 (M tonnes CO_2e / year). Lastly, in the third column of Table A13.4, difference in emissions (column 2) is shown as percentage of total global GHG emissions in 2013 (31,646 M tonne CO_2e) [1].

Table A13.4: Change in production emissions from 2020 to 2050

Scenario	Total Emissions	Difference	Percentage
Reference	2,688.6		
Current	4,306.9	1,618.3	5.1%
Moderate New	2,967.0	278.3	0.9%
Strong New	1,620.7	-1,067.9	-3.4%

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