An investigation into the required investment to transition the heavy-duty vehicle sector of New Zealand to hydrogen

by

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Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Engineering Management) in the Faculty of Engineering at Stellenbosch University

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March 2021

Declaration

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Date: 22 October 2020

Abstract

Reducing greenhouse gas emissions in the transport sector is known to be an important contribution to climate change mitigation. With looming climate commitments, it is becoming increasingly important for New Zealand to develop a plan for addressing these emissions. Some parts of the transport sector are particularly difficult to decarbonise. This includes the heavy-duty vehicle sector, which is considered one of the "*hard-to-abate*" sectors of the economy. Heavy-duty vehicles are difficult to decarbonise because they are sensitive to weight, range, and refuelling duration. Current batteries cannot compete with the high energy density of diesel as they are too heavy and take too long to recharge. Transitioning from diesel trucks to hydrogen fuel cell trucks has been identified as a potential way to decarbonise the sector. If the hydrogen is produced with electrolysers powered by renewably generated electricity, then the vehicles would have negligible carbon emissions. Hydrogen produced in this way is known as "*green*" hydrogen. The current and future costs and efficiencies of the technologies enabling a transition to green hydrogen remain unclear. In light of these uncertainties, the primary aim of this study is to investigate the investments required to decarbonise New Zealand's heavy-duty vehicle sector with hydrogen; by applying systems thinking.

The transition from diesel trucks to hydrogen fuel cell trucks forms part of the energy- and sustainability-transition literature. To better understand the potential transition to hydrogen, a "*systems thinking*" approach is applied, and simulation modelling is identified as an appropriate tool with which to investigate the transition. Of the three simulation modelling techniques assessed, system dynamics modelling (SDM) is found to be the most appropriate technique for this study. As an SDM methodology designed specifically for modelling hydrogen transitions could not be found, one was created. This was done by combining aspects of the SDM literature with the hydrogen transition modelling literature. The resulting modelling process ensured that aspects of particular importance to hydrogen transitions were not neglected. Using this synthesized modelling process a system dynamics model was constructed. The model was tested to develop a high degree of confidence in the model and to ensure that the model limitations were well understood. The modelling period was set from 2020 to 2050, which is when New Zealand hopes to achieve carbon neutrality. Subsequently, five scenarios were designed and modelled in a manner that explores the wide range of potential outcomes.

The results of the scenarios are analysed in order to draw insights from the study and to make recommendations for policymakers. The total investment requirements are assessed by considering the hydrogen production capacity investments, and the investments required to supply marginal electricity to the hydrogen production systems. Production capacity investments are found to range between 1.37 and 2.02 billion New Zealand Dollars, and marginal electricity investments are found to range between 4.33 and 7.65 billion New Zealand Dollars. These investments represent scenarios in which 71% to 90% of the heavy-duty vehicle fleet are decarbonised with fuel cell trucks by the end of the modelling period. The wide range of these findings reflects the large uncertainties in estimates of how hydrogen technologies will develop over the course of the next thirty years. Numerous policy recommendations are drawn from the results of the scenarios. Most notable is the finding that even pessimistic assumptions of progress in hydrogen technology indicate that fuel cell

trucks will become competitive with diesel trucks well before 2050. The importance of having a regulatory authority that facilitates and oversees the hydrogen transition is also recognized. Finally, clear opportunities for future work are outlined. These opportunities include data collection, model expansion, and a comparison of the model results to alternative studies that research the investments required to decarbonise the heavy-duty vehicle sector with alternative technologies such as battery-electric trucks, biodiesel, and catenary systems.

Opsomming

Die vermindering van kweekhuisgasvrystellings in die vervoersektor lewer ‘n belangrike bydrae tot die stryd teen klimaatsverandering. Met die naderende klimaatsverpligtinge word dit vir Nieu-Seeland al hoe belangriker om 'n plan te ontwikkel om hierdie vrystellings aan te spreek. Sommige dele van die vervoersektor is besonder moeilik om koolstofvry te maak. Dit sluit die swaarvoertuigsektor in, wat beskou word as een van die "moeilik afnemende" sektore van die ekonomie. Swaar voertuie is moeilik om koolstofvry te maak, omdat hulle sensitief is vir gewig, afstandsangs, en die tydsduur van brandstof hervulling. Huidige batterye kan nie meeding met die hoë energiedigtheid van diesel nie, want batterye is te swaar en neem lank om te herlaai. Die oorgang van dieselvragmotors na waterstofbrandstofselvragmotors is geïdentifiseer as 'n moontlike manier om die sektor koolstofvry te maak. As die waterstof vervaardig word met elektroliseerders wat aangedryf word deur hernubare opgewekte elektrisiteit, sal die voertuie se vrystellings onbeduidend wees. Waterstof wat op hierdie manier geproduseer word, staan bekend as 'groen' waterstof. Die huidige en toekomstige koste en doeltreffendheid van die tegnologieë wat die oorgang na groen waterstof moontlik maak, bly onseker. As gevolg van hierdie onsekerhede ondersoek hierdie studie die beleggings wat nodig is om Nieu-Seeland se swaarvoertuigsektor met waterstof koolstofvry te maak.

Die oorgang van dieselvragmotors na brandstofselvragmotors vorm deel van die energie- en volhoubaarheid-oorgangsliteratuur. Om die potensiële oorgang na waterstof beter te verstaan, word 'n "stelsel denkwyse" benadering toegepas en simulasie-modellering word geïdentifiseer as 'n gepaste hulpmiddel om die oorgang mee te ondersoek. Van die drie simulasiemodelleringstegnieke wat beoordeel is, word daar gevind dat stelseldinamika-modellering (SDM) die mees geskikte tegniek vir hierdie studie is. Aangesien 'n SDM-metodologie wat spesifiek ontwerp is vir die modellering van waterstofoorgange, nie gevind kon word nie, is een geskep. Dit is gedoen deur aspekte van die SDM-literatuur te kombineer met aspekte van die waterstofoorgangsmodellering-literatuur. Die gevolglike modelleringsproses het verseker dat aspekte wat veral belangrik is vir waterstofoorgange nie verwaarloos word nie. Met hulp van die gevolglike modelleringsproses is 'n stelsel-dinamika-model opgestel. Die model is getoets om 'n hoë mate van vertroue in die model te ontwikkel en om te verseker dat die modelbeperkings goed verstaan word. Die modelleringsperiode is vasgestel van 2020 tot 2050. 2050 is wanneer Nieu-Seeland hoop om koolstofneutraliteit te bereik. Daarna is vyf verskillende gevalle ondersoek op ‘n manier wat die wye verskeidenheid van potensiële uitkomste verken.

Die resultate van die verskillende gevalle word geanaliseer om insigte uit die studie te put en aanbevelings vir beleidsmakers voor te stel. Die totale beleggingsvereistes word beoordeel deur beide die beleggings wat nodig is om die nodige waterstof te produseer, asook die beleggings wat nodig is om marginale elektrisiteit aan die waterstofproduksiestelsels te lewer, in ag te neem. Daar word gevind dat beleggings in produksiekapasiteit tussen 1.37 en 2.02 miljard Nieu-Seelandse dollar wissel, en dat marginale beleggings tussen 4.33 en 7.65 miljard Nieu-Seelandse dollar wissel. Hierdie beleggings verteenwoordig gevalle waarin 71% tot 90% van die swaarvoertuigvloot aan die einde van die modelleringsperiode met brandstofselvragmotors koolstofvry gemaak word. Die wye verskeidenheid van hierdie bevindings weerspieël die groot onsekerheid in ramings van hoe

waterstoftegnologieë in die loop van die volgende dertig jaar sal ontwikkel. Uit die resultate van die gemodelleerde gevalle word talle beleidsaanbevelings getrek. Die opvallendste is die bevinding dat selfs pessimistiese aannames van vordering met waterstoftegnologie daarop dui dat brandstofselvragmotors nog lank voor 2050 met dieselvragmotors sal kan meeding. Die belangrikheid daarvan om 'n regulerende owerheid te hê wat die waterstofoorgang kan vergemaklik, word ook herken. Ten slotte word duidelike geleenthede vir toekomstige werk uiteengesit. Hierdie geleenthede sluit in data-insameling, uitbreiding van die model en 'n vergelyking van die modelresultate met alternatiewe studies wat ondersoek instel na die beleggings wat nodig is om die swaarvoertuigsektor koolstofvry te maak met alternatiewe tegnologieë soos battery-elektriese vragmotors, biodiesel en aansluitstelsels.

Acknowledgements

As far back as I can remember I have been privileged to enjoy the support, love, and attention of countless teachers, mentors, friends, and family members. This thesis is primarily the result of the investments those people made in me over the course of the past 30 years. They often did not receive adequate thanks or appreciation in return. I fully acknowledge the debt I owe to them and would like to thank them from the bottom of my heart.

The most recent set of mentors deserve a special mention for their contribution to this work:

- Prof Alan Brent for taking a chance on me, leading the study, and always being able and willing to provide guidance and advice. I could not have asked for a better thesis supervisor.
- Josephine Musango and Imke De Kock, for their support and assistance in this endeavour.
- Len Malczynski, without whom I would have learned much less, been even more frustrated, and certainly missed my self-imposed deadlines.
- The peers that made class worth attending, made studying fun, and kept academic loneliness at bay.
- Tannie Karina – who proved to be as kind and supportive as my memories of her from undergrad.

Lastly, I want to thank Craig and Margaret Morrell for welcoming me into their home at short notice and enabling me to maximize my academic outputs while having loads of fun and new experiences.

Dedication

To love is one thing,
To be loved is another,
But, to be loved by the one you love… is everything.

~Anonymous

To Lauren, my wife, who has shown me the truth in these words.

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Chapter 1 Introduction

In this chapter, the study is introduced by providing essential background information and developing a rationale for the study. Subsequently, the problem statement is articulated along with the aim and objectives of the research. The research design is presented, and the scope of the research is discussed. Finally, an outline of each chapter in the document is presented.

1.1. Background

Since the start of the 20th century, the world has seen unprecedented population growth and socio-economic development. These phenomena were made possible in large part by developments in technology that allowed people to exploit natural systems for economic benefit. Although many benefits have resulted from these technologies, they have also placed many essential natural systems under severe pressure (Steffen *et al.*, 2015). This has resulted in what Edgar Morin calls the global "*polycrisis*" - a set of interlocked ecological and socio-economic crises (Swilling, 2012). The best-known among these crises must be that of climate change. Scientists now unanimously agree that anthropogenic climate change is taking place and that climate change is only one of many potentially deleterious repercussions of human activity (Cook *et al.*, 2016).

In order to mitigate these repercussions, it is necessary to decouple[1] economic growth from its historic attachment to environmental degradation, and particularly from the emission of greenhouse gasses that drive climate change. Such decoupling is no mean feat and will require a multifaceted approach, as well as collaboration between governments, industries, and societies. Some sectors of the economy are expected to be particularly difficult to decarbonise and are often referred to as the hard-to-abate sectors. One of the technology-oriented concepts that have recently garnered international attention for its potential to play a key role in decoupling, is the hydrogen economy. The hydrogen economy is a suite of technologies working together to enable widespread use of hydrogen as a fuel as well as an energy vector (Crabtree *et al.*, 2004). By producing hydrogen with electrolysis powered by renewable energy, the resultant "*green hydrogen*" would have a negligible carbon footprint. Green hydrogen could then be traded internationally and used in myriad applications to generate heat and/or electricity and thereby facilitate a just-transition to a thriving low-carbon economy (Marbán and Valdés-Solís, 2007).

Like many countries around the world, New Zealand has made numerous commitments and goals to becoming a more sustainable society. Among these are ambitious goals to achieve 100% renewable electricity by 2035, and to become a net-zero emissions economy by 2050 (MBIE, 2019a; MFE, 2019). In support of these goals, New Zealand has shown significant interest in being part of the envisioned international hydrogen economy. The government has signed a memorandum of cooperation with Japan, indicating both countries' commitment to "*endeavour to encourage and facilitate as appropriate the advancement of linkages and cooperation*" concerning hydrogen technology and infrastructure development (MBIE, 2018, p. 1). Furthermore, the New Zealand

[1] According to UNEP (2011) "*Decoupling at its simplest is reducing the amount of resources such as water or fossil fuels used to produce economic growth and delinking economic development from environmental deterioration.*"

government has commissioned several documents consulting stakeholders and outlining the government's vision to become a world leader in the development of a hydrogen economy (MBIE, 2019b). New Zealand and Japan are not the only countries considering the potential of a hydrogen economy. In recent years multiple governments such as Australia, Japan, and South Korea made commitments to, or expressed an interest in, the hydrogen economy as a national strategy towards renewable and sustainable energy (CSIRO, 2018; WEC, 2020). This is a promising development as the full potential of a hydrogen economy can only be realised if multiple countries are committed to being a part of it (Hydrogen Council, 2020).

In addition to the interest shown by academics and governments, private industry has also indicated much support for the future of hydrogen technologies. KPMG (2019) reports that in both 2018 and 2019 a strong majority of automotive executives believed fuel cell electric mobility to be the number one key trend in their industry. This conviction is supported by a report co-authored by Deloitte and Ballard (2020), which indicates that within less than 10 years fuel cell electric vehicles (FCEV) will become cheaper to run than battery or diesel alternatives in various applications. The automotive industry is not alone in its support for a hydrogen future. German multinational conglomerate ThyssenKrupp has shown significant interest in positioning itself as a leader in hydrogen technology, specifically targeting hydrogen for use in energy storage and green ammonia production (Brown, 2018). More broadly, a report by the Hydrogen Council, co-authored by McKinsey & Company, identified three market segments in which hydrogen was deemed to exhibit significant opportunities: Transportation, Heat and Power, and Industry Feedstocks (Hydrogen Council, 2020). With so much interest and support across public and private sectors, hydrogen's prevalence across multiple industries may rise significantly in the coming decade as technologies mature, infrastructure develops, and pressure to decarbonise the economy mounts.

It is tempting to assume that with so much support for hydrogen the case for its future proliferation would by now be uncontested and clearly planned. This is not so. Not only are there critics of the envisioned hydrogen future, but even among proponents, it is agreed that there remain significant challenges that need to be navigated for the vision to be realized (Hydrogen Council, 2020). Energy transitions are fraught with myriad complexities that hamper their progress, and the hydrogen transition is no exception. Around the world, various stakeholders are operating in different geographical and policy contexts. These stakeholders need to make sense of the opportunities that a hydrogen transition might offer in their specific context. Key drivers and challenges need to be identified, and various scenarios need to be considered. This type of analysis requires many assumptions to be made and involves much estimation. Attempting to gain insight into what the future might hold is never easy, especially not in a world with high levels of interconnectivity and feedback.

Given the above complexities, a polarity of opinion has emerged in the literature regarding a hydrogen-powered future. On one side of the discussion, proponents are asserting that even in a free market economy green hydrogen will find areas of application (Hydrogen Council, 2020). The proponents argue that this is already happening, and that the speed and extent of the transition to hydrogen are the only aspects that are up for debate. On the other side of the discussion, critics assert that the theorized hydrogen future will never work in practice, and that resources can be allocated much more effectively than in the pursuit of a hydrogen future. This opposition is typically based on a conviction that hydrogen technologies are not able to compete with battery technology, and that even if it were capable of doing so, the capital requirements of transitioning to hydrogen would be insurmountable (Concept Consulting, 2019a). It is in this context of complexity, uncertainty, and polarity of opinion, that this study finds its focal problem and research objectives. As sustainability transitions require change at a systemic level, systems thinking has been identified as an appropriate lens through which to examine the potential transition to hydrogen in New Zealand.

1.2. Problem statement

To meet decarbonisation commitments, New Zealand needs to reduce emissions in all sectors of the economy. The so-called "*hard-to-abate*" sectors are particularly difficult to decarbonise as they are ill-suited to direct electrification, batteries, and efficiency improvements. "*Green*" hydrogen - generated via electrolysis and powered by renewable energy - has been identified as a potential route to reducing emissions in a number of these hard-to-abate sectors. Heavy-duty vehicles (HDVs) are one of the hard-to-abate sectors that are particularly well suited to decarbonisation with hydrogen. However, there are significant uncertainties in the data required to assess the investments needed to transition New Zealand's HDV sector to hydrogen. These uncertainties result in a wide spectrum of findings within the literature[2] with regards to the competitiveness of hydrogen as a decarbonisation strategy. Without accurate estimates of the investment requirements, a transition to green hydrogen cannot be compared to alternative decarbonisation strategies. Therefore, a need to investigate these investment requirements further is identified, and particularly how changes in the sector system affect the required investment.

1.3. Research aim and objectives

The aim of the study is to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. To support the attainment of the research aim, the following research objectives (RO) are defined:

i. RO1: Contextualize hydrogen transitions in New Zealand and identify the main factors influencing a hydrogen transition in the sectors of the economy that are best suited to hydrogen;
ii. RO2: Develop a set of requirement specifications to determine an appropriate method for investigating a transition to hydrogen in New Zealand's heavy-duty vehicle sector;
iii. RO3: Evaluate various modelling approaches and identify an appropriate approach that satisfies the developed requirement specifications;
iv. RO4: Utilize the modelling approach identified and selected in RO3 to develop, verify and validate a model that captures the dynamics of the heavy-duty vehicle sector;
v. RO5: Identify and develop scenarios to explore how various policies and technological developments influence the hydrogen transition in the heavy-duty vehicle sector; and
vi. RO6: Provide recommendations and insights for transitioning the heavy-duty vehicle sector of New Zealand to hydrogen.

[2] The work of proponents, such as the Hydrogen Council (2020) and Leaver *et al.* (2012), stand in contrast to sceptics, such as Concept Consulting (2019a). Furthermore, much of the literature is outdated considering the speed of technological innovation (IRENA, 2020).

1.4. Research design

This research undertook a deductive reasoning approach, by considering the research problem from a systems perspective. Through deductive progression, the type of research changed from exploratory to descriptive. Initially, exploratory questions were asked about the use of hydrogen in New Zealand, and the factors influencing a transition to hydrogen (Van Wyk, 2015). Subsequently, the type of research became more descriptive, with evaluative, and predictive aspects (Mouton, 2001; Van Wyk, 2015). Questions such as the following were asked: "*how might various policies and technological developments combine to influence the hydrogen transition in the heavy-duty sector?*" and *"what investments are required to decarbonize the heavy-duty vehicle sector?*". The deductive progression and the various phases of the research are depicted in Figure 1, which is adapted from the work of Van Wyk (2015).

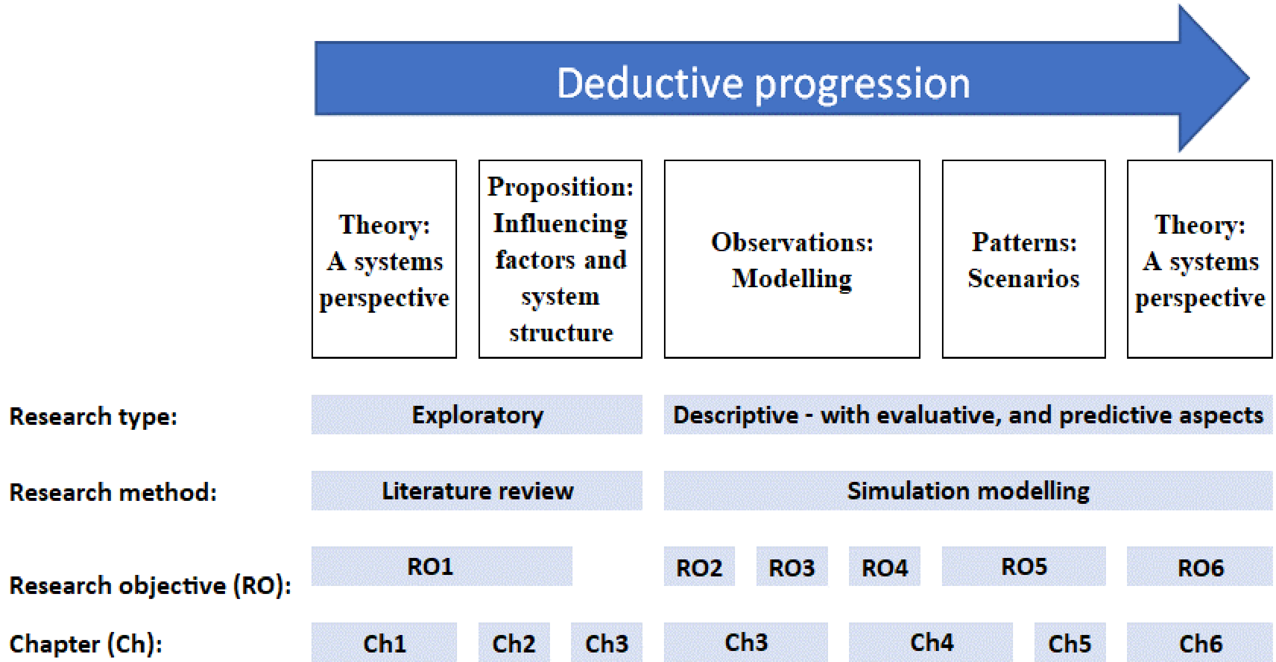


Figure 1: Deductive progression of this study

Mouton (2001) classifies research designs according to four dimensions, namely: empirical versus non-empirical studies, primary versus secondary data, numerical versus textual data, and the degree of control or structure in the design. As is typical of simulation studies, this study followed an empirical approach, used secondary data of a numerical nature, and had a medium-to-high degree of control (Mouton, 2001).

The research approach that was adopted to guide the attainment of the stated research objectives is informed by previous studies of a similar nature (Van Niekerk, 2015; Oosthuizen, 2016; Thomas, 2019). Based on these studies the following steps were taken:

i. **Step 1:** Survey literature pertaining to: energy transitions; the hydrogen economy; the hydrogen economy in New Zealand (with a focus on the heavy-duty vehicle sector); and simulation modelling approaches appropriate to simulating hydrogen transitions in the heavy-duty vehicle sector of the New Zealand economy;
ii. **Step 2:** Analyse literature pertaining to hydrogen economy transitions in New Zealand, to determine whether there is a need for further research on this topic; and to identify the sectors

and associated factors that are most influential in the potential transition to a hydrogen economy in New Zealand;

iii. **Step 3:** Based on the analysis carried out in Step 2, develop a set of requirement specifications that can guide the selection of an appropriate method to investigate the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen;

iv. **Step 4:** Evaluate various modelling approaches and identify an appropriate approach that best meets the requirement specifications developed in Step 3. Gain the necessary skills and experience to become adept at the selected modelling approach.;

v. **Step 5:** Iteratively develop a model of appropriate scope. The model must capture the dynamics of the heavy-duty vehicle sector and the associated factors that were identified in Step 2;

vi. **Step 6:** Validate and verify the performance and execution of the model with each new addition to the model, with appropriate techniques;

vii. **Step 7:** Develop scenarios that explore how various policies and technological developments influence the hydrogen transition in the heavy-duty vehicle sector; and

viii. **Step 8:** Prioritise interventions for transitioning the heavy-duty vehicle sector of New Zealand to green hydrogen.

1.5. Research scope

The overarching objective of this study is to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. Although hydrogen can be used to decarbonise several sectors of the New Zealand economy, the focus of this study is on the heavy-duty vehicle sector alone. The inter-sectoral synergies that are expected to arise if other sectors were to transition to hydrogen are, therefore, not considered in this study. Additionally, the study is defined, geographically, around the North and South islands of New Zealand. Therefore, the influence that a global transition towards hydrogen may have on New Zealand is not considered.

1.6. Document outline

This document is intended to be a presentation of how the main aim, as well as the research objectives, were achieved. In this section, an outline of each chapter in the report is presented along with an overview of how the chapter contributes to the study.

The first chapter starts by providing a brief background to the study and identifying a gap in the literature that informs the problem statement. After articulating the problem statement, the research objectives that address the problem statement are set out, and an approach for achieving the research objectives is outlined. The research methodology used to guide the literature review and data collection process is also presented in this chapter. The purpose of the first chapter is to introduce the reader to the study that was carried out, as well as the document reporting the study.

In chapter two the concept of a hydrogen economy is placed within the context of energy transitions in New Zealand. To achieve this, the relevant energy transitions and hydrogen economy literature is reviewed. Potential applications for hydrogen in various sectors of the New Zealand economy are presented, and the key factors influencing these opportunities are reviewed. The purpose of this chapter is to present findings from the literature that support the decision to undertake this study and to showcase the potential applications of hydrogen in New Zealand.

In the third chapter the systems thinking literature is reviewed and it is found that the systems of interest to this study can be classified as Complex Adaptive Systems. Simulation modelling is identified to be an effective way of analysing Complex Adaptive Systems, and therefore a set of requirement specifications are drawn up to help identify the most appropriate simulation modelling option. Discrete Event Modelling, Agent-Based Modelling, and System Dynamics Modelling (SDM) are reviewed according to the requirement specification, and it is found that SDM is the most appropriate option for this study. The well-established literature on SDM is combined with recent literature proposing a guideline for effectively modelling hydrogen transitions. This synthesis results in a methodology specifically designed for modelling hydrogen transitions with SDM. Finally, the tools, mathematics, and testing methods of SDM are presented. The purpose of this chapter is to describe why SDM was chosen for this study and to document how a methodology for using SDM to model hydrogen transitions was created.

In chapter four the application of the first three steps of the methodology developed in the previous chapter is documented. The processes addressed in this chapter include study conceptualization, causal loop modelling, dynamic modelling, model testing, scenario planning, and the statement of assumptions and limitations. The purpose of this chapter is to demonstrate that the designed methodology was followed and that it led to a functioning model that is useful to the purpose of the problem under investigation. The presentation of the final step of the synthesized methodology – the discussion of results – is divided into two parts and presented in the last two chapters. This is done in an attempt to improve the readability of the report.

In chapter five the key results of the modelled scenarios are presented. The most important results are then discussed in detail, with regular reference being made to the applicable assumptions and limitations of the study. The purpose of this chapter is to present the outputs from the model and to develop an understanding of those outputs. Based on this discussion of the results, the final chapter is able to draw conclusions and recommendations.

In the final chapter of the report, chapter six, the learnings, recommendations, and conclusions of the study are presented. First, recommendations and insights for policymakers are drawn from the results of the model as well as the modelling process. Subsequently, recommendations for future research are presented. Finally, the research objectives are reviewed to ensure that all stated objectives were achieved. The purpose of this chapter is to ensure that as much as possible is learned from the study.

1.7. Chapter 1 conclusion

This chapter started by providing background information that introduced the rationale for the study. The background information emphasised that even though the New Zealand government, as well as private industry, are interested in using hydrogen to decarbonise the economy; there is a gap in the literature regarding what roll hydrogen might play, and how much it would cost to transition towards being a "*hydrogen economy*". The problem statement was articulated, and the scope of the study was focused on the heavy-duty vehicle sector of the New Zealand economy. Subsequently, it was noted that the main aim of the study is to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. Six research objectives were defined in support of this aim, and a research design to achieve the objectives was developed. Finally, the research presented in this report was outlined, presenting an overview of what is achieved in each of the chapters.

In the next chapter, the hydrogen economy is framed within the greater energy transition, and the literature on hydrogen transitions in New Zealand is reviewed. To place this research in perspective, an analysis of the economic sectors that lend themselves to hydrogen is presented, along with the key factors influencing the potential for a hydrogen transition in each sector.

Chapter 2
Contextualizing hydrogen economy transitions in New Zealand

In this chapter, a better understanding of hydrogen's place in the sustainability- and energy- transition is developed by reviewing the relevant literature. In the first section of the chapter, the literature analysis methodology is presented. Subsequently, the history of the sustainability movement is reviewed, and ways of understanding sustainability transitions are explored. The energy sector is identified as a backbone sector that is essential to decarbonise; thereby introducing the concept of energy transitions. In the third section of the chapter the hydrogen economy literature is reviewed, and it is found that there exists a significant polarity of opinion regarding the possibilities of using hydrogen to decarbonise the economy. In the fourth section of the chapter, the prospects of a hydrogen economy in New Zealand are assessed by identifying the sectors of the economy that lend themselves to hydrogen. Finally, the key factors affecting the proliferation of hydrogen in each sector are identified. Therefore, this chapter contextualizes hydrogen transitions in New Zealand and addresses the first research objective.

2.1. Literature analysis methodology

To develop a comprehensive understanding of the latest knowledge in the fields of research that are relevant to this study, a traditional literature review (also known as a narrative literature review) is carried out. According to Cronin *et al*. (2008, p. 38), a traditional literature review *"critiques and summarizes a body of literature and draws conclusions about the topic in question"*. Traditional literature reviews have the benefit of enabling a broader set of literature to be assessed but are limited in that they are not as rigorous as systematic literature reviews, and are therefore susceptible to the author's biases (Bettany-Saltikov, 2012). Cronin *et al*. (2008) suggest a process for conducting a traditional literature review that minimizes the potential for such bias to creep into the review. Their process, as presented in Figure 2, is used to guide the literature review in this study.

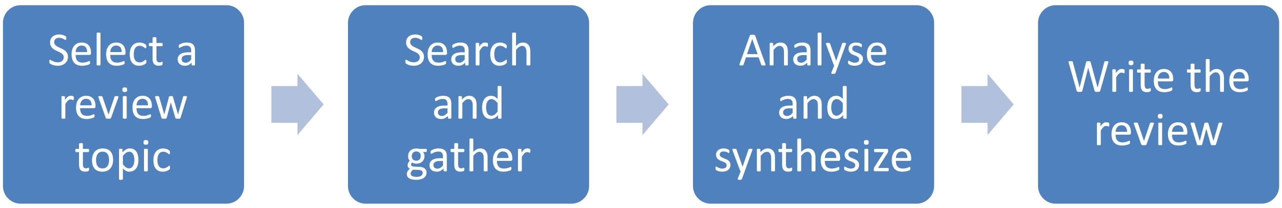


Figure 2: The traditional literature review process (Cronin *et al.*, 2008)

The first step in the literature review process is to select a topic for review. The topic of this study is presented in the title of the report. In the second step, literature relevant to the review topic must first be found, and then a decision must be made whether to include a given document in the body of literature that will be examined. Computers and the internet give a researcher access to an overwhelming amount of information, including academic databases that contain studies from all around the world. SUNScholar and Google Scholar are the databases most frequently used in this study. These databases are perused utilizing keywords derived from the various topics that together comprise the review topic. Examples of the derivative topics and associated keywords that were used to review the literature are presented in Table 1. Journal articles, technical reports, and books are all considered in this review. When determining whether to accept a document for review, an opinion of the document is acquired by reading the abstract, executive summary, or table of content. Based on this reading, a few factors are assessed according to the criteria suggested by Engle (2020), who proposes that an information source can be evaluated based on various aspects relating to the author, the date of publication, the publisher or journal, the intended audience, and the objectivity and quality of the writing. Only documents written in English are considered. A strong preference for recent publications is applied when considering information that is known to change rapidly (such as the cost of electricity), while more lenience is shown towards literature relating to fundamental theories, and seminal works with many citations. If the work is accepted into the body of literature it is categorized according to the four main categories suggested by Cronin *et al*. (2008), namely: primary, secondary, conceptual/theoretical, or anecdotal/opinion. Mendeley Reference Management Software is used to store documents that are accepted into the body of literature (Mendeley, 2020). Mendeley also facilitates referencing, note-taking, underlining, summarizing, and document management.

Table 1: Examples of keywords used to search databases

Topic	Key words
Transitions	Sustainability transition, energy transition, hydrogen transition, New Zealand hydrogen transition, New Zealand decarbonisation, etc.
Hydrogen Economy	Hydrogen economy, fuel cell trucks, green hydrogen, levelized cost of green hydrogen, electrolyser hype cycle, New Zealand hydrogen economy, New Zealand green hydrogen, etc.
Systems	Complex Systems, systems thinking, systems, complex adaptive systems, system dynamics, etc.
Modelling	Hydrogen economy modelling, modelling fuel cell trucks, modelling complex systems, system dynamics modelling, discrete event simulation, agent-based modelling, etc.

The third step in the literature review process is to analyse and synthesize the literature that was gathered in the second step. Initially, the document is skimmed through. During the skimming process, potentially useful information is marked for future reference in a manner that enables comparison with other sources. Subsequently, the main points in the document are summarized. As this study utilizes secondary data sources it is necessary to collect and organize these data in a sensible manner (Mouton, 2001). If a document contains relevant quantitative data, these data are noted on the document itself in a way that differentiates it from qualitative data. The data are also noted in a document that matches the data requirements of the study with the literature addressing those requirements. Where applicable, the data is converted into consistent units for ease of comparison; all financial values are converted into New Zealand dollars. This process facilitates data collection by logically ordering the quantitative data that have been found and enabling quick reference to be made to an appropriate data source when necessary. Additionally, if insufficient data have been collected for a given data requirement, this will be clear to see from the lack of sources matched to that requirement. While sorting the data in this manner, the potential limitations of using secondary data are considered, and an effort is made to ensure that the data are not used inappropriately.

Specifically, the data are assessed for geographical and technological relevance, as well as for potential inaccuracies that may result from applying a technology in a manner that is not relevant to this study (Bell and Bryman, 2016). If, at this stage, the document looks particularly promising it is read in full.

The final step is to write a literature review. During the writing process, the views of the various literature sources are compiled to create an overview of the surveyed literature. Any noteworthy patterns or discrepancies in the literature are also noted. The literature review is presented in chapters two and three of this report. The literature review is also of fundamental importance to the simulation modelling process presented in the fourth chapter of the report. The structure of the model, as well as the mathematics that inform model behaviour are constructed around the literature review and the collected data. Data sources used in the model are referenced in the model under the "*comments*" section of the appropriate variable. The referencing in the model is done according to the method suggested by Martinez-Moyano (2012), which enables an automated assessment of whether a variable has source information associated with it. This method ensures that the model reflects the data, and significantly improves the transparency of the model assumptions.

2.2. Energy transitions

The concept of sustainable development, as we understand it today, is often traced back to the 1987 Report of the World Commission on Environment and Development: Our Common Future, also known as the Brundtland Report (Brundtland *et al.*, 1987). This report was the first to use the phrase "*sustainable development*", and proposed the following definition, which has since been the source of much debate: "*Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland *et al.*, 1987, p. 1). Before the Brundtland report, there were several noteworthy works that brought attention to the concept without naming it. Most notably, the 1972 UN Conference on Human Environment in Stockholm emphasized the need for environmental management, and a group known as The Club of Rome published a report called The Limits to Growth (Meadows *et al.*, 1972), which declared that the world was on course to exceed ecological limits within the near future if the then-current rate of environmental degradation was not significantly reduced (Mebratu, 1998). The concepts introduced by these parties – now more than 40 years ago – have become globally accepted, and are the focus of much attention in academia, politics, and the media. The challenge of changing our ways significantly enough and fast enough to avoid the disastrous effects of environmental collapse is often described as the ultimate challenge facing humanity at this time. To live within planetary boundaries and move towards more socially just societies, we need almost all economic sectors to transition towards more sustainable practices (EEA, 2018). These transitions towards a more sustainable future have come to be known as sustainability transitions (Markard *et al.*, 2012). According to Turnheim *et al.* (2020, p. 116), "*the key question for policy makers is no longer whether or why transitions are needed, but how to make them happen*".

There is a relatively young, but flourishing, body of knowledge researching sustainability transitions with the hopes of understanding how they can be expedited. To this end, five main approaches to sustainability transitions have been identified within the literature. According to the EEA (2018) three approaches, namely: *socio-ecological, socio-technical,* and *socio-economic* approaches to sustainability transitions, "*provide conceptual frameworks for understanding and informing systemic* *change*". These three approaches stand in contrast to the fourth and fifth approaches - namely *action-oriented approaches*, and *Integrated Assessment Modelling* (IAM) - which are analytical in nature. The EEA (2019) report concludes that although the first four perspectives have their own method for understanding and analysing sustainability transitions, they all come to the conclusion that co-evolution, lock-in (of existing systems), complexity, uncertainties, trade-offs, and non-linearities are fundamental to understanding the nature and characteristics of systemic change. In contrast to this, the "*mainstream*" approach to understanding systemic change - as represented by IAM - takes the approach of neo-classical economics and focuses on incentives, market forces, and state interventions to influence rational actors into making decisions that will lead to long term improvements in the sustainability of the given system (EEA, 2019) .

Markard (2018) – who follows a socio-technical approach to understanding sustainability transitions – proposes that sustainability transitions have five key characteristics that need to be considered in order to realize a successful transition:

i. Public policies: policies that support and enable the transition are essential;
ii. High-level complexity and uncertainty: sustainability transitions are "*wicked problems*". This complexity is irreducible;
iii. Transitions are value-laden: therefore, targets are subjective;
iv. Transitions are highly contested: There is no clear way forward that suits all parties; and
v. Context dependency: Variations can be expected. A one-size-fits-all approach is not appropriate.

By considering these key characteristics, stakeholders can better analyse and plan the sustainability transitions that are required in various sectors of the economy. For more information regarding sustainability transitions, the reader is directed towards one of the more popular approaches known as Multi-Level Perspectives (Markard and Truffer, 2008).

There is much debate about which parts of the economy are in greatest need of sustainability transitions, and even more debate about what these transitions should look like. The EEA (2019, p. 17) has identified the food, energy, mobility, and shelter sectors as "*backbone systems*" – systems which are not only essential to human livelihoods but also lead to significant environmental degradation. Therefore, within sustainability transitions, we find the concept of energy transitions, which can be defined as a "*long-term change towards a more sustainable energy system*" (EEA, 2016, p. 4). Many countries have set in place programs for their energy transitions - for examples of this, see the case studies presented in *Sustainability transitions: policy and practice* (EEA, 2019). Many countries have included hydrogen in their energy strategy or developed a separate hydrogen strategy (IEA, 2019; WEC, 2020). Hydrogen is potentially able to facilitate progress in the energy transition as well as the transition of the other backbone systems (Hydrogen Council, 2020).

Markard (2018, p. 628) has proposed that energy transitions have entered into a second phase, which is not simply an acceleration of the first phase, but contains "*qualitatively new phenomena*". Where the first phase was primarily concerned with establishing the technical and economic feasibility of renewables, the second phase is characterized by the "*complex interaction of multiple technologies, the decline of established business models and technologies, intensified economic and political struggles of key actors such as utility companies and industry associations, and major challenges for* *the overall functioning and performance of the electricity sector*" (Markard, 2018, p. 628). It is within this second phase of energy transitions that the hydrogen economy is vying for its place as an enabling technology that can facilitate transitions to a more sustainable future.

2.3. The hydrogen economy

The first mention of a hydrogen economy can be traced back to a paper published in the early 1970s (Bockris and Appleby, 1972; Bockris, 2013)**.** According to Moliner *et al.* (2016), the idea sprang from a need to innovate during the first oil crisis. Since then, the topic has seen much attention from academic, political, and private entities alike. Although the fundamental ideas behind a hydrogen economy have remained largely unchanged, much has been done to refine the concept and keep it up to date with technological advances. This section will begin with an overview of what the hydrogen economy is, and then move on to present the state of current hydrogen technology, and the prevailing sentiment from academics and politicians regarding the potential futures facing hydrogen.

To prevent the socio-ecological disasters associated with the burning of fossil fuels, the hydrogen economy proposes that renewable energy be used to produce hydrogen gas from water electrolysis. The resulting hydrogen gas, known as green hydrogen, can be used as an energy vector to fuel various economic processes by providing heat and/or electricity. Green hydrogen can also be used as an industrial feedstock, thereby displacing hydrogen produced from hydrocarbons - known as brown hydrogen (Crabtree *et al.*, 2004)**.**

At its full extent, the hydrogen economy utilizes cheap and mostly decentralized renewable energy technology to generate green hydrogen close to the consumer. This decentralized approach reduces the need for significant infrastructure investments. Where the decentralized approach is not feasible a network of largely dedicated hydrogen pipelines, ships, and trucks would distribute centrally produced hydrogen to the desired location, potentially in the form of a Liquid Organic Hydrogen Carrier (LOHC), which would ease the challenges associated with the storage and transportation of elemental hydrogen (Ozin, 2017; Preuster *et al.*, 2017). The green hydrogen would then be used in one of three main applications, namely: in a fuel cell to generate electricity; in a combustion reaction to generate heat; or as an industrial feedstock. In this way, hydrogen could be used for the decarbonisation of various industrial processes including electricity grid balancing, transportation, industrial and domestic heat generation, petrochemical cracking, steel production, and ammonia production (Concept Consulting, 2019b). There also exists the opportunity for an international commodity market to develop around the import/export of green hydrogen from areas with excess renewable energy - like Australia and New Zealand - to areas lacking adequate renewable energy resources - like Japan and South Korea (Hydrogen Council, 2020).

This vision is of course much easier to imagine than to realize in practice. Much research has aimed to develop a better understanding of the feasibility of the concept described above. As discussed in the previous section, sustainability transitions are fraught with irreducible complexity, resulting in transition pathways being difficult to understand and manage. The feasibility of a hydrogen transition is in large part determined by the maturity and affordability of the underlying technologies. To date, these technologies have struggled to prove commercially feasible. 2019 marked the first year that global fuel cell shipments exceeded the MW mark, and roughly two-thirds of the demand came from two companies - Toyota and Hyundai (E4Tech, 2019). The 2019 demand represents a 40% increase on 2018 figures but remains a minuscule fraction of the global energy mix. Similarly, the IEA (2019) reports that in 2018 there were less than 11 200 fuel cell electric vehicles on the road globally, with sales in 2018 almost doubling those of 2017. According to the Hydrogen Council (2020), there were less than 500 hydrogen filling stations in operation in 2019, with 200 additional stations expected to come online in 2020, and an expectation of more than 10 000 stations by 2030. These examples indicate that although the share of hydrogen in these markets is currently very small, it is growing at a significant rate.

It is worth noting that there is already a large and growing market for elemental hydrogen, with 2018 demand coming in above 70 million tonnes (IEA, 2019). The market is comprised mainly of oil refining and the production of ammonia, methanol, and steel (IEA, 2019). This demand is currently being met by carbon-emitting production processes that produce hydrogen from fossil fuels. The IEA (2019) reports that 6% of global natural gas, and 2% of coal are used to produce hydrogen for these industries. The Hydrogen Council (2020) notes that in 2018 less than 5% of global hydrogen demand was met with low carbon sources. This is due, in large part, to the costs of green hydrogen remaining prohibitively high, with current production costs around 6 USD per kg, and costs at the pump amounting to roughly double that due to underdeveloped distribution and storage infrastructure (Hydrogen Council, 2020). There are however optimistic estimates that by 2030 production costs could be below 2 USD per kg, and below 5 USD per kg at the pump (Hydrogen Council, 2020; Taylor, 2020).

The world is still far from operating as a hydrogen economy. However, hydrogen has recently enjoyed significant interest from various actors. Several local and national governments have indicated their intention to assess the potential of hydrogen in various industries, and the number of countries with policies that support hydrogen investment is increasing (IEA, 2019; WEC, 2020). There are several significant players like the IEA, IRENA, and the Hydrogen Council who believe that there is a clear future for green hydrogen and that the only thing to debate is the extent to which it will manifest, and how to expedite the transition. These proponents of a hydrogen future typically share the view that hydrogen technology is emerging from "*the trough of disillusionment*" and steadily climbing the "*slope of enlightenment*" as defined by the Gartner hype cycle (Moliner *et al.*, 2016, p. 19501). The Hydrogen Council (2020) states that various factors have recently come together in a way that enables green hydrogen to break into several lucrative commercial markets. IRENA (2020) suggests that COVID-19 relief funds should be put towards green hydrogen (amongst others), and their *Global Renewables Outlook* report dedicates an entire section to exploring the role of hydrogen in getting the world to net-zero emissions. The IEA (2019, p. 18) succinctly labelled 2019 as "*a moment of unprecedented momentum for hydrogen*". With all this excitement surrounding hydrogen, it is interesting to observe polarity of opinion regarding the prospects of a hydrogen future. In contrast to the abovementioned organizations, several voices in the sustainability transitions literature are convinced of the folly of a hydrogen transition. These detractors express confidence that the shortcomings of the hydrogen economy will never be overcome.

Sovacool & Brossman (2010, p. 2000) contend that a hydrogen economy would face "*a host of socio-technical challenges*" as well as "*immense (and potentially intractable) obstacles*". They suggest that the hydrogen economy only attracts interest due to its ability to be turned into a "*fantasy*" that satisfies cultural, psychological, and economic needs based on "*a future world where energy is abundant, cheap, and pollution-free, [and] society can continue to operate without limits imposed by population* *growth and the destruction of the environment*". This strong language is not limited to Sovacool & Brossman (2010). Eames *et al.* (2006, p. 361) suggest that the amount of attention directed at the hydrogen economy is due in large part to the "*interpretive flexibility*" of the concept, and the lack of a clear definition. Amid the polarized opinions, Ball & Weeda (2015, p. 7918) offer a tempered perspective, suggesting that energy transitions typically require many decades and that it would be non-sensical to suggest a "*definitive answer*" at this time either in favour of or against, the hydrogen economy. The authors also indicate that hydrogen will most certainly act in tandem with various other technologies and that the term "*hydrogen economy"* might be misleading as it creates inflated expectations of hydrogen. Sovacool & Brossman (2010, p. 2008) echo this sentiment in the conclusion of their paper, suggesting that "*extreme fantasies*" undermine more realistic ambitions.

Lastly, it is worth noting that the literature which actively opposes a hydrogen future seems to be outdated compared to the literature in support of it. Sovacool and Brossman (2010, p. 2008) suggested that the bias in the number of articles supporting the hydrogen economy, as compared to those that oppose it, can be ascribed to the fact that "*scholars tend to write in favour of their own projects but not to position themselves against others*". However, their sentiment is now more than a decade old and might need to be reconsidered in light of recent developments in technology and policy (IRENA, 2020). The World Energy Council (2019, p. 5) has indicated that cost reductions in renewable energy and fuel cells, in combination with the pressure of climate change requirements and the involvement of China have led to a "*realistic potential*" for hydrogen to play a role in the energy transition.

A possible deduction from these insights is that the focal question when it comes to hydrogen should not be "*what can we do to make the hydrogen economy a reality?",* but rather "*how might the sustainability transition benefit from the use of green hydrogen?"*. Building on these insights, the following section will consider opportunities for hydrogen in New Zealand.

2.4. The hydrogen economy in New Zealand

Just as in the global context, there are significantly divergent opinions regarding the potential for a hydrogen economy in New Zealand. This section will begin with a review of the literature focusing on the role of green hydrogen in New Zealand. Documents published by academic institutions, private entities, as well as governmental organizations will be reviewed. This review is followed by an analysis of the opportunities and barriers faced by green hydrogen in various sectors of the New Zealand economy. Finally, key factors influencing the utility of hydrogen in the identified sectors are discussed. By discussing how hydrogen can be used to decarbonise various sectors of the economy, this section contextualizes the hydrogen economy in New Zealand. Subsequent chapters will focus on the sector of interest to this study, namely the heavy-duty vehicle sector.

2.4.1. Literature review of hydrogen in New Zealand

In the past two years, the New Zealand government has demonstrated an active interest in hydrogen's potential to stimulate and decarbonise the economy. In March of 2020, the government invested almost 20 million dollars in a green hydrogen production facility in South Taranaki, which will supply an agri-nutrients manufacturing plant. This investment was made through the Provincial Growth Fund, which - to date - has funded four hydrogen projects in Taranaki. According to the deputy prime minister, there is potential for further funding available, and it is hoped that the initiative will catalyse a green hydrogen market (Peters, 2020).

The potential for hydrogen in Tarakani was outlined In September of 2019 when the government released a report titled: *A Vision for hydrogen in New Zealand* (MBIE, 2019b). The report aimed to "*signal the opportunities that hydrogen can bring to New Zealand and frame discussions for a national strategy"* (MBIE, 2019b, p. 7). Furthermore, the report called for the public (both individuals and companies) to submit their responses to key questions regarding the role of government in a hydrogen transition. These submissions were published online, along with an analysis of the responses that were received before the submission deadline. Although the analysis states that most respondents support the vision for hydrogen as outlined by the government green paper, the report goes on to indicate that a wide distribution of sentiments were voiced on all topics (MBIE, 2020).

Earlier in 2019, a regional development agency published a document outlining how hydrogen technologies might be utilized in the near future (Venture Taranaki, 2019). The report included a roadmap and various business cases that illustrate a desire for the region to act as a catalyst that will expedite a hydrogen transition in New Zealand. Although this report outlines a promising path for the future of hydrogen in New Zealand, the report has been criticized for being too vague to be useful, especially in comparison to the Australian equivalent which presented much more detail (Ballance Agri-Nutrients Limited, 2019; CSIRO, 2018).

In the years preceding these reports, the government commissioned several studies to assess the value of hydrogen to the economy. In 2008 CRL Energy (now Verum Group) published a report, which used System Dynamics Modelling to investigate pathways to a hydrogen economy (Leaver *et al.*, 2012). A separate report analysed the results of the simulation study, and suggests a focus on a "*challenging but achievable*" scenario in which hydrogen demand grows steadily by a factor of 10 between 2008 and 2050, and costs $6 per kg by 2050 (CRL Energy Ltd, 2008, p. 4). The year before these reports were published, the same organization released a document titled "*Cost and Impacts of a Transition to Hydrogen Fuel in New Zealand"* which placed international literature in the New Zealand context, and reviewed five different hydrogen supply options, finding that each scenario had unique challenges and opportunities (Smit and Campbell, 2007).

As can be seen from the amount of work that has been done to understand hydrogen's potential in New Zealand, there has been a consistent interest in the topic for more than a decade. However, the literature is as divided in the New Zealand context as it is in the rest of the world. A recent set of papers published by Concept Consulting presents an analysis that makes a hydrogen future look much less likely (Concept Consulting, 2019c). The report compares hydrogen to other decarbonisation strategies and focuses on analysing transport, industrial heat, space and water heating, and power generation. The findings are that most hydrogen technologies are mature, but that costs remain high and will only reduce if manufacturing quantities can exploit significant economies of scale. The report goes on to state that - except for certain niche environments - hydrogen will not be a cost-competitive decarbonisation strategy unless large carbon taxes are implemented, and even then, it will face significant competition. The report estimates that utilizing hydrogen rather than more direct electric options would result in 50% more generation capacity being required. The report is based on estimates and assumptions that are contested by other stakeholders. Mohseni & Brent (2019) have calculated significantly lower levelized costs for hydrogen generation than those used by Concept Consulting, and the Australian National Hydrogen Roadmap assumes significantly lower cost estimates than the Concept Consulting study (CSIRO, 2018).

Lastly, it is worth noting that a paper entitled *"Low-emissions economy"*, published by the New Zealand Productivity Commission (2018), does not focus on hydrogen to the extent that "*A vision for Hydrogen in New Zealand"* does (MBIE, 2019b). The paper addresses the potential for hydrogen to decarbonise certain industrial sectors, but in general, the view of the report is that although hydrogen presents opportunities, there is a lot of work to be done to make it viable, and it will face competition from various other technologies.

To better understand how hydrogen might present economic opportunities and decarbonise the economy, the literature typically focuses on a few core sectors of the economy. These sectors will now be discussed individually to present both the opportunities and barriers to implementing hydrogen in New Zealand.

2.4.2. Sectoral analysis

To better understand the opportunities and barriers to a hydrogen future in New Zealand, several economic sectors that lend themselves to hydrogen will be discussed. These sectors appear frequently in the literature, although studies do not necessarily consider all sectors (Hydrogen Council, 2017). The analysis of certain sectors, especially as they apply to the New Zealand context, requires a degree of estimation and assumption. This is because many of the technologies have not been deployed at scale, and one can only guess what dynamics might emerge if they are assembled into value chains that interact with society and the economy (Hydrogen Council, 2020).

The electricity sector

The ability of a country to produce green hydrogen is dependent on the country's ability to generate electricity from renewable sources. In this regard, New Zealand is very well placed, with 84% of electricity generated in 2018 coming from renewable sources (MBIE, 2019c). Additionally, the government estimates that the potential new wind generation capacity is 45% of current hydro capacity – this is significant given that hydro is by far the leading contributor to the electricity mix. Figure 3 presents sources of electricity generation in New Zealand by fuel type over the past few decades. Because hydropower represents such a large fraction of electricity generation, the country is particularly susceptible to seasonal variations in rainfall, as well as droughts. This can undermine the availability of renewably generated electricity, but also presents an opportunity for hydrogen to be used as a vector for energy storage. Excess hydrogen can be generated and stored at times when there is excess renewable electricity available. This gas would then be used to generate electricity at times when renewable energy sources are not available. This strategy is often known as Power-to-Gas (Stevenson *et al.*, 2018). It is typically accepted that most natural gas turbines can burn a gas mixture that contains up to 20% hydrogen (European Commission, 2020a). This 20% capacity represents a significant opportunity for the early adoption of green hydrogen. In order to move beyond 20% hydrogen, infrastructure investments would need to be made.

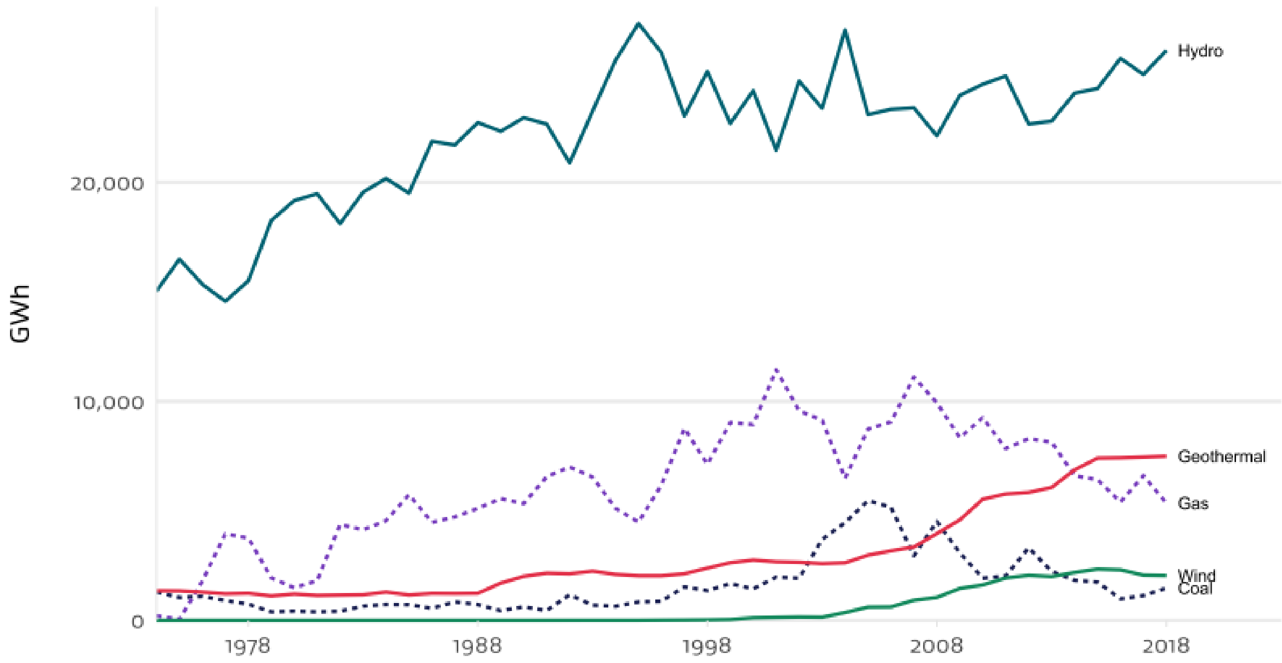


Figure 3: Electricity generation by fuel type in New Zealand (MBIE, 2019c).

The transport sector

The various parts of the transport sector offer different opportunities and barriers to the adoption of hydrogen. In road transport, hydrogen is best suited to heavy-duty vehicles, forklifts, and vehicle fleets that require extended periods of operation - such as taxis (Energy Transition Commission, 2018; Hydrogen Council, 2020). Hydrogen is often seen to be competing *against* battery technology, but well-considered scenarios see potential for the technologies to flourish in parallel, each playing to its strengths. Typically such scenarios find that batteries outperform hydrogen in the light and medium-duty vehicle categories, but in heavy-duty and long-range applications the low weight of the fuel, and the quick refuelling times give hydrogen a distinct advantage (Deloitte and Ballard, 2020; Hydrogen Council, 2020). This is because the gravimetric energy density of batteries is currently much too low to compete with diesel (Gross, 2020). In April 2020 New Zealand had more than 20 000 registered battery- and hybrid- electric vehicles (Ministry of Transport, 2020a). The only fuel cell electric vehicles in New Zealand at the time were for display and promotion purposes (Maetzig, 2019). Fuel cell trains also show much promise in the short to medium term, with shipping and aeronautics currently showing the least viability (Hydrogen Council, 2020).

Green hydrogen generation and export

Currently, no commercial-scale operations are producing green hydrogen in New Zealand. The first such project received $19.9m of funding from the government in March 2020, with the potential for significant additions in the future (Peters, 2020). This commitment by the government indicates that there is potential for New Zealand to produce green hydrogen. This, along with the proximity of countries like Japan and South Korea who have indicated an interest in importing green hydrogen, could result in the development of an international market (MBIE, 2018). Australia finds itself in a similar situation and has signalled a strong commitment to rapidly exploring the potential of green hydrogen exports (COAG, 2019). Although there exists a very real potential for a global export market to develop around green hydrogen, there is much work that needs to be done to establish such a market. Trade routes would need to be established, renewable energy capacity increased, electrolysers commissioned, and long-distance transport options explored (Concept Consulting, 2019a). Additionally, such a market could inflate domestic prices for both hydrogen and electricity (Concept Consulting, 2019a). The proximity of Australia will be a significant factor in considering New Zealand's export options, but it seems likely that demand will outstrip supply, leaving room for both New Zealand and Australia in the export market (Concept Consulting, 2019a). Potential international shipping routes, with estimated costs, are presented in Figure 4.

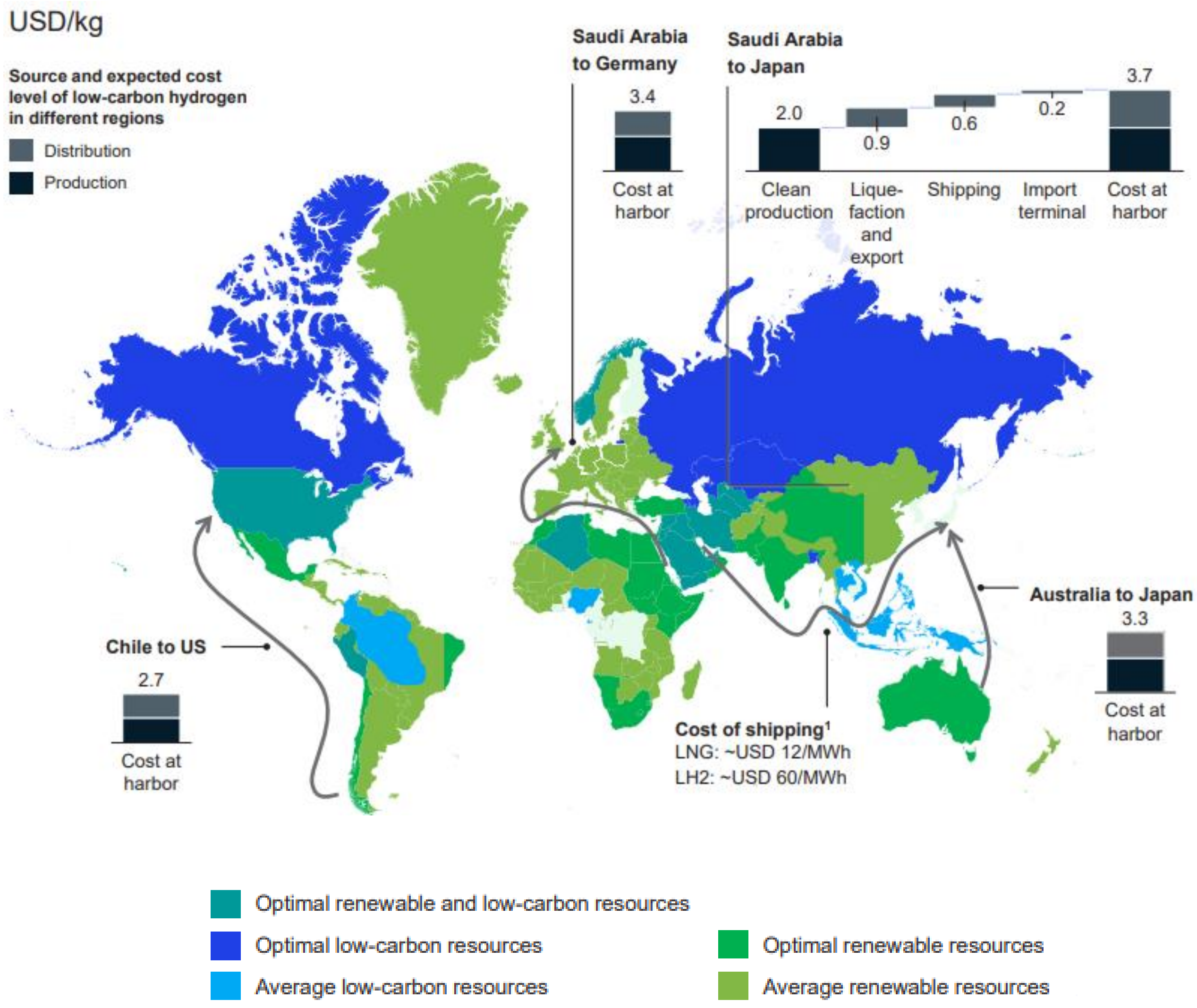


Figure 4: Potential hydrogen shipping routes, and costs estimates for 2030 (Hydrogen Council, 2020)

Heating (domestic and industrial)

Hydrogen could potentially replace natural gas and thereby a host of domestic and industrial heating applications. Hydrogen could be produced on-site or delivered via pipeline. Low concentrations of hydrogen can be mixed with natural gas in existing pipelines (MBIE, 2019b). If high concentrations are to be transported then existing pipelines will need to be modified to prevent embrittlement, and end-user infrastructure would need to be adapted (MBIE, 2019b). A potential barrier to using hydrogen for heat is the high efficiency of heat pumps (Concept Consulting, 2019a). The appeal of heat pumps is somewhat decreased by the inconvenience and investments that would be required to switch to heat pumps, as opposed to delivering hydrogen via the existing natural gas infrastructure (Venture Taranaki, 2019). It is expected that as heat pump and hydrogen technologies mature they will develop unique strengths that lead to the development of niche applications for each technology. It is expected that hydrogen will be best suited to addressing the needs of high-temperature applications, such as industrial heat, and applications in which existing gas infrastructure is more easily converted to hydrogen than replaced with heat pumps (European Commission, 2020a).

Industrial feedstocks

Industrial feedstocks represent a significant opportunity for green hydrogen, as it can easily replace the brown hydrogen that is currently in use. The first green hydrogen production facility in New Zealand will feed an Agri-nutrients plant in the Taranaki region (Hiringa Energy, 2020a). Similar opportunities are presented in various industries including:

i. The production of methane (CH_4) - the country's largest methane producer, Methanex, is mentioned in the *H2 Taranaki Roadmap* report for both its convenient location next to a port, as well as the potential to use green hydrogen in the production process (Venture Taranaki, 2019);
ii. Glenbrook steel mill – a major emitter of CO_2 is currently exploring the possibility of replacing coke with hydrogen in the reduction process (NERI, 2019); and
iii. Marsden Point Oil Refinery - the country's only oil refinery, can use green hydrogen to offset brown hydrogen in the hydrocracking process (MBIE, 2019c).

2.4.3. Identification of key factors

Each of the sectors identified in the previous section presents unique challenges and opportunities for a hydrogen future. The extent of these challenges and opportunities is determined by key factors that influence the viability of a hydrogen future in the given sector. Certain factors, such as standardization and regulation, are more important in one sector than another. The transport sector, for example, might not be able to import vehicles from the USA due to those vehicles being built to different standards. Other technologies, such as electrolysers and fuel cells, are expected to face less resistance due to variations in standards and regulation. Although some factors are more important in one sector than another, other factors play an important role in all sectors. The factors that are universally important include:

i. The cost of electricity;
ii. The cost, efficiency, and lifetime of hydrogen production and storage technologies such as electrolysers and storage tanks;
iii. The cost, efficiency, and lifetime of hydrogen utilization technologies such as fuel cells and gas turbines;
iv. Policy factors such as carbon taxes that influence the economics of decarbonisation projects;
v. The competition presented by fossil fuel alternatives;
vi. The competition presented by alternative decarbonisation technologies; and
vii. How the abovementioned factors will change over time – i.e. the learning rates associated with these factors.

The remainder of this section will discuss the key factors influencing the viability of a hydrogen transition in each of the identified sectors.

Key factors affecting electricity generation and the gas grid

The role of hydrogen in electricity generation, especially in the initial stages of the transition, is likely to be centred around the use of hydrogen in gas peaker plants (Venture Taranaki, 2019). The hydrogen would be blended into the natural gas to offset the carbon footprint of the generated electricity. From this perspective, it can be seen that hydrogen's main role in both the gas grid and in the electricity sector is for heating. Hydrogen might be combusted to drive a turbine for electricity generation, or to heat a kiln in a factory, or to warm the water in a home – in all of these applications, the ability of hydrogen to produce heat is the factor of central interest. More specifically, the difference in the heat generated from the combustion of a given volume of hydrogen compared to the heat generated from the combustion of the same volume of natural gas will be an important factor in the use of hydrogen for these applications.

Another important consideration when blending hydrogen into existing gas infrastructure is the cost of blending, and the acceptable blend percentage (European Commission, 2020a). There is much research looking at this, and most of the reviewed studies indicate that a blend of up to 20% hydrogen would not require any existing infrastructure to be adapted. Blends higher than 20% would require various investments to prevent hydrogen embrittlement and ensure that the experience of the end-user is not negatively affected (MBIE, 2019b).

Key factors affecting industrial feedstocks

Hydrogen is already a feedstock in various industrial processes. Most of this "*brown*" hydrogen is produced by Steam Methane Reformation (SMR) – which is to say from carbon-emitting fossil fuels. In the majority of applications, green hydrogen can simply replace this brown hydrogen. Therefore, the most important factor by far when considering green hydrogen as an industrial feedstock is the difference in cost between green hydrogen and brown hydrogen. The cost of brown hydrogen is dependent on the cost of natural gas, the SMR process, and the carbon tax imposed on the emissions from the SMR process. The cost of green hydrogen is dependent on the cost of renewable electricity along with the costs associated with the production, storage, and utilization technologies – specifically the capital cost, maintenance cost, efficiency, and lifetime of these technologies. Additionally, the learning curves of these factors are of great interest. It is expected that as these technologies are produced at a greater scale, steep learning curves will be achieved (Hydrogen Council, 2017).

Key factors affecting green hydrogen export

The existence of an export market for green hydrogen seems imminent based on commitments made by Japan and South Korea (MBIE, 2019b). As with any commodity market, the price upon delivery will be the main factor to consider. There is significant work to be done in establishing trade routes and transportation technologies – both of which will factor into the price of the delivered product. The export of hydrogen will be assisted by existing methanol exports from New Zealand to Asia, and potentially also by the use of a Liquid Organic Hydrogen Carrier (LOHC) (MBIE, 2019b). LOHC are organic compounds that enable hydrogen to be stored and transported in states that are more manageable than elemental hydrogen. Australia has voiced strong interest in exporting green hydrogen, and exported its first shipment in April of 2019 – yet it is unlikely that Australia will saturate the market (MBIE, 2019b). New Zealand is likely to only export green hydrogen once domestic demand for the gas has been met, but there is concern that an export market could drive up the local cost of both hydrogen and electricity (MBIE, 2019b).

Key factors affecting the transport sector

As previously mentioned, the uptake of hydrogen in the transport sector is particularly sensitive to policies and regulations. The sector already has a host of standards and regulations to which hydrogen technologies would need to comply. In addition to these existing standards, the sector will require the development of standards and regulations specific to hydrogen technologies if these technologies are to become commonplace (Hydrogen Council, 2017). Although enabling policies and standards are essential to the acceptance of hydrogen in the transport sector, overly restrictive policies, regulations, and standards can prevent or slow the development of hydrogen in the sector (Hydrogen Council, 2020). This becomes particularly apparent when considering hydrogen on an international level, as there is a need for policies and regulations that enable international collaboration as well as confidence in the consumer.

Although various forms of transport could be converted to hydrogen, particular promise is shown by heavy-duty vehicles (Hydrogen Council, 2020). However, the large-scale adoption of hydrogen vehicles of any kind would require the development of a sufficiently expansive hydrogen refuelling network. The development of such a network represents a significant infrastructure investment and poses a potential barrier to the adoption of hydrogen vehicles. Case studies from around the world – such as South Korea and Japan (Hydrogen Council, 2017) – show that there are various ways of overcoming this barrier. Additionally, Hiringa Energy has recently announced plans for implementing an extensive hydrogen refuelling network in the coming years (Hiringa Energy, 2020b).

2.5. Chapter 2 conclusion

Efforts to transition towards a more sustainable future are known as sustainability transitions. Although most economic sectors need to transition towards more sustainable practices, there are a few "*backbone sectors*" that have been identified as the main sectors in need of decarbonisation (EEA, 2019). These sectors are food, energy, mobility, and shelter (EEA, 2019). Hydrogen generated by low-carbon production processes offers potential decarbonisation strategies for all these sectors. The vision of using hydrogen extensively for this purpose is known as the hydrogen economy. A review of the literature expanded upon the polarity of opinion regarding the feasibility of using hydrogen for decarbonisation efforts at both a national and international scale. Proponents seem convinced that hydrogen has a clear and promising future that will provide economic opportunities while enabling decarbonisation of the economy. Detractors believe that hydrogen technologies face a host of challenges that will never be overcome. Considering this discrepancy, a sectoral analysis was presented to clarify the challenges and opportunities that a hydrogen transition will face in New Zealand. Finally, the key factors that influence the viability of a hydrogen future in each sector were presented.

By considering the application of hydrogen in various sectors of the economy, the potential hydrogen economy in New Zealand was contextualized. The rest of this report will focus on the heavy-duty vehicle sector of the transport sector of the New Zealand economy. The transport sector is considered one of the sectors of the economy that are well suited to decarbonisation with hydrogen, and heavy-duty transport is understood to be particularly well suited (Energy Transition Commission, 2018). The main factors influencing the use of hydrogen in this sector include the cost and efficiency of hydrogen technologies, the cost of electricity, as well as a need for additional policy and regulation. In the next chapter, strategies that enable hydrogen transitions to be studied effectively will be investigated. Specifically, the next chapter will review systems thinking and consider various simulation modelling approaches to determine which approach is best suited to this study.

Chapter 3
Modelling hydrogen transitions in New Zealand

In this chapter, the literature analysis methodology presented in Section 2.1 is used to review systems, systems thinking, and simulation modelling. In the first section of this chapter, an overview of systems thinking is presented, and the differences between complicated and complex systems are explored. It is found that the systems of interest to this study can be classified as Complex Adaptive Systems, and that Simulation modelling is an appropriate approach to investigating such systems. A set of requirement specifications is developed and used to identify that System Dynamics Modelling (SDM) is an appropriate modelling technique for this study. Subsequently, the SDM literature is combined with recent literature proposing a guideline for effectively modelling hydrogen transitions. The steps of the resulting modelling methodology are presented, followed by a review of the mathematics, tools, and testing methods associated with SDM. Therefore, the second and third research objectives are addressed in this chapter.

3.1. Systems thinking

It would go against the tenets of systems thinking to provide an overly specific definition of what systems thinking, or indeed a system, is (Midgley, 2007). As such, a host of broad definitions is found in the literature for both concepts. This section will start by referring to various definitions in the literature to illustrate what is meant by the word *system* and the concept *systems thinking*. Subsequently, the difference between complicated and complex systems will be discussed, and the concept of Complex Adaptive Systems (CAS's) will be introduced.

Systems

Donella Meadows (2008, p. 2), in her seminal book Thinking in Systems, defines a system as "*a set of things – people, cells, molecules, or whatever – interconnected in such a way that they produce their own pattern of behaviour over time*". Maani and Cavana (2007, p. 7) suggest a system is "*something that is a collection of other things that form a group or entity… a collection of parts that interact with one another to function as a whole*". Lastly, and somewhat more specifically, Jackson (2003, p. 3) offers that "*a system is a complex whole, the functioning of which depends on its parts and the interactions between those parts*". In an attempt to synthesize these definitions I have previously suggested that a system be thought of as "*a set of things (not necessarily physical) interacting with, and influencing, each other, their environment, and the set itself*" (Kotze, 2015, p. 2). One of the aspects that are agreed upon is that a system has a boundary that determines what is part of it and what is not. Furthermore, a system is comprised of smaller pieces, typically called subsystems or entities, that necessarily interact with each other in some way that results in the characteristics of the system (Maani and Cavana, 2007). Building on this understanding of a system, an attempt can be made to understand what systems thinking is. Figure 5 adapted from Van Niekerk (2015) is useful when considering a system or systems thinking.

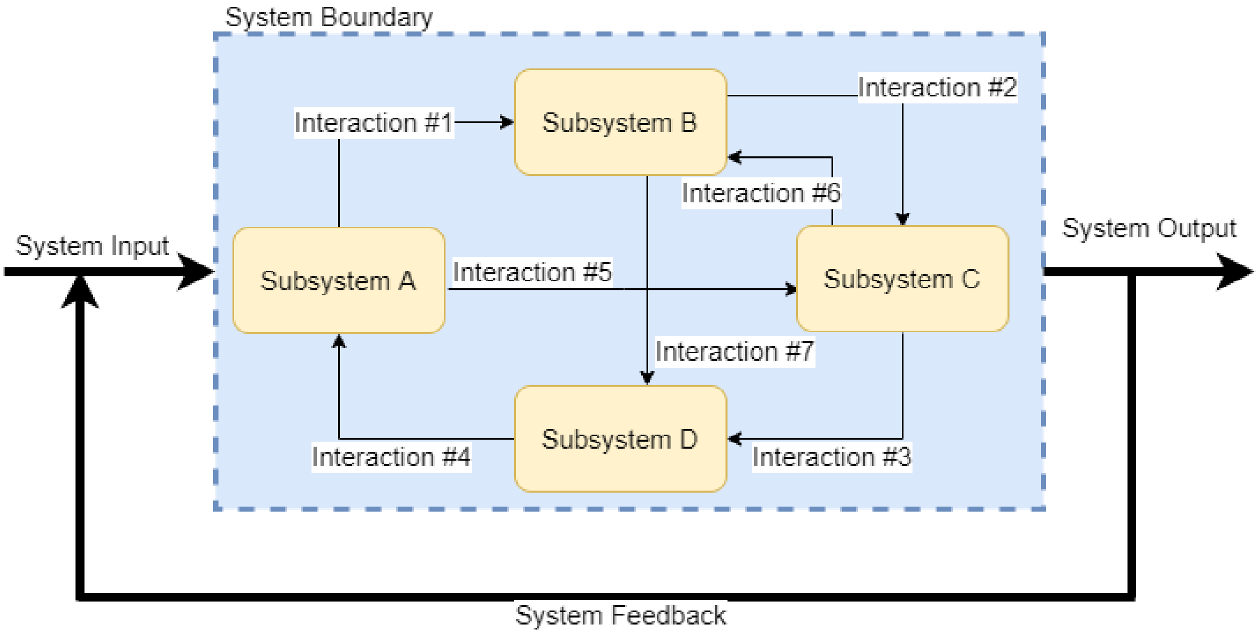


Figure 5: Structure of a system

Systems thinking

Midgley (2007, p. 11) suggests that systems thinking is an "*umbrella term [for] approaches that seek to be more holistic*". A relatable conception of systems thinking can be found in the tenet that a system is not the sum of its parts, but rather "*the product of their interactions*" (Maani and Cavana, 2007, p. 7). Meadows (2008) states that a central insight of systems theory is that behaviour is latent within the structure of the system, and that an appreciation of this relationship between behaviour and structure enables us to gain insights regarding the function and performance of a system. Furthermore, and of great interest to this paper, Meadows suggests that systems thinking allows us to develop an understanding of how systems can transition to more desirable states. Maani and Cavana (2007, p. 7) support this notion, stating that systems thinking pursues an understanding of "*change and complexity through the system of dynamic cause and effect over time*". Maani and Cavana (2007) go on to identify four ways of thinking that together explain the systems thinking approach to understanding systems and relationships. The four types of thinking are:

i. **Forrest thinking** – the ability to see the bigger picture (the forest) as well as the components (the trees) and interactions between the components;
ii. **Dynamic Thinking** – the ability to see that the world is constantly changing;
iii. **Operational thinking** – thinking in first principles to understand how subsystems work and interact with each other; and
iv. **Closed-loop thinking** – understanding that cause and effect can be nonlinear, and that often the effect influences the cause, resulting in feedback.

These ways of thinking can be compared to the "*skills*" and "*abilities*" that Sweeny and Sterman (2000, p. 250) suggest are required to think in systems. Sweeny and Sterman's (2000) list of skills and abilities include the basic mathematical skills which are typically taught in high school, as well as more advanced concepts such as:

i. Understanding how the interactions between the subsystems lead to the behaviour of the system;
ii. Identify feedback loops that are expected or understood to occur;
iii. Recognize stocks (or accumulations) and the flows that increase or decrease the level of the stock;
iv. Identify delays and appreciate their impact;
v. Identify non-linear behaviour; and
vi. Recognize (and challenge) the boundaries of modelled systems.

In systems thinking, it is important to differentiate between complicated and complex systems, as well as between the related concepts of reductionism and holism. Complicated systems are systems that can be fully and permanently understood by a thorough analysis of the constituent parts (Cilliers, 2002). Such systems have linear inputs and outputs, and perfectly defined boundaries. The extent to which the system is understood is simply a function of how well it has been analysed. As such, accurate models can be created of complicated systems if the constituent parts are modelled accurately. In short, complicated systems amount to exactly the sum of their parts. This means that an effective way of studying complicated systems is to reduce them into their sub-systems. Once each of the subsystems is understood, the system will be understood. This method of analysis is appropriately called reductionism (Østreng, 2006; Poli, 2013). Figure 6 presents Acaroglu's (2017) comparison of reductionism and systems thinking.

Poli (2013) notes that the difference between complicated and complex systems is a difference of type and not degree. Although different levels of complexity exist, it would be wrong to think of a continuum that ranges from complicated on the one side to complex on the other side, on which we can rate a system (Kim *et al.*, 2015). A very complicated system remains a complicated system, and there is no such thing as a complex system which is of sufficiently little complexity that we can think of it as complicated. Complex systems are not at all like complicated systems. Instead, they are characterised by the non-linear interactions of their constituent parts and numerous feedback loops. They cannot be understood by reductionistic thinking, and they are open to environmental influences. The history of the system is important, and a full understanding of the current state of the system does not equate to full knowledge of the system. Problems in complex systems require management as they cannot be fully solved, and often such management leads to unexpected results (Maani and Cavana, 2007). In short, complex systems are the systems that we speak of when we say that a system amounts to more than the sum of its parts. Systems thinking, and specifically, a holistic approach to analysis, are essential to understanding the behaviour of such systems (Østreng, 2006; Poli, 2013).

Within complex systems, we find Complex Adaptive Systems (CAS) – a special case of complex systems (Rotmans and Loorbach, 2009). According to Chan (2001, p. 1) CAS's are characterized by "*nonlinear spatio-temporal interactions among a large number of component systems". S*uch systems can "*adapt in and evolve with a changing environment*" (Chan, 2001, p. 2). Chan (2001) suggests seven attributes[3] of CAS's, but Rotmans and Loorbach (2009, p. 186) reduce these to three unique features: *coevolution, self-organization,* and *emergence*. Coevolution is when two systems interact in

[3] The seven attributes according to Chan (2001) are: Distributed control, connectivity, co-evolution, sensitive dependence on initial conditions, emerging order, far from equilibrium, and state of paradox.

a way that changes the dynamics of each individual system. Coevolution can also take place between a system and its environment. Self-organization indicates a system's ability to restructure in response to a stimulus without external intervention, but rather as a result of internal system structures. Emergence is defined as "*the arising of novel and coherent structures, patterns, and properties during the process of self-organization*" (Rotmans and Loorbach, 2009, p. 186). If a system is identified as a CAS then certain tools and guidelines can be utilized to gain insights into the *"opportunities, limitations, and conditions under which it is possible to influence such systems*" (Rotmans and Loorbach, 2009, p. 194). These tools and guidelines are of great interest to this study as the systems that will be investigated can all be identified as CAS's based on their characteristics and behaviour. For a CAS perspective on the environment, society, economy, and technology, see Lenton and van Oijen (2002), Buckley (1998), Gintis (2006), and Fleming and Sorenson (2001), respectively**.**

One of the most powerful tools available to better understand complex systems is simulation modelling (Banks, 1999; Borshchev, 2013). Simulation modelling allows the modeller to develop a representation of a real-world system on the computer (known as a model). This model can then be used to run experiments that provide insights into the real-world system. Simulation modelling overcomes many difficulties associated with experimenting directly on the system that is being investigated, and – if done properly – reduces the cost, time, and risk required to gain insights from experiments (Banks, 1999; Borshchev, 2013). Furthermore, simulation modelling allows us to investigate systems which do not yet exist – this is particularly useful in the case of a hydrogen transition. Hofkes (1996) has suggested that the interconnectivity of environmental and economic systems need to be modelled in order to understand how they might interact with technology in a sustainable manner. There are various types of modelling, and various software packages that can be used, each with its own strengths and weaknesses. The following section will assess a few of these options to determine which is best suited to the modelling of a hydrogen transition in New Zealand.

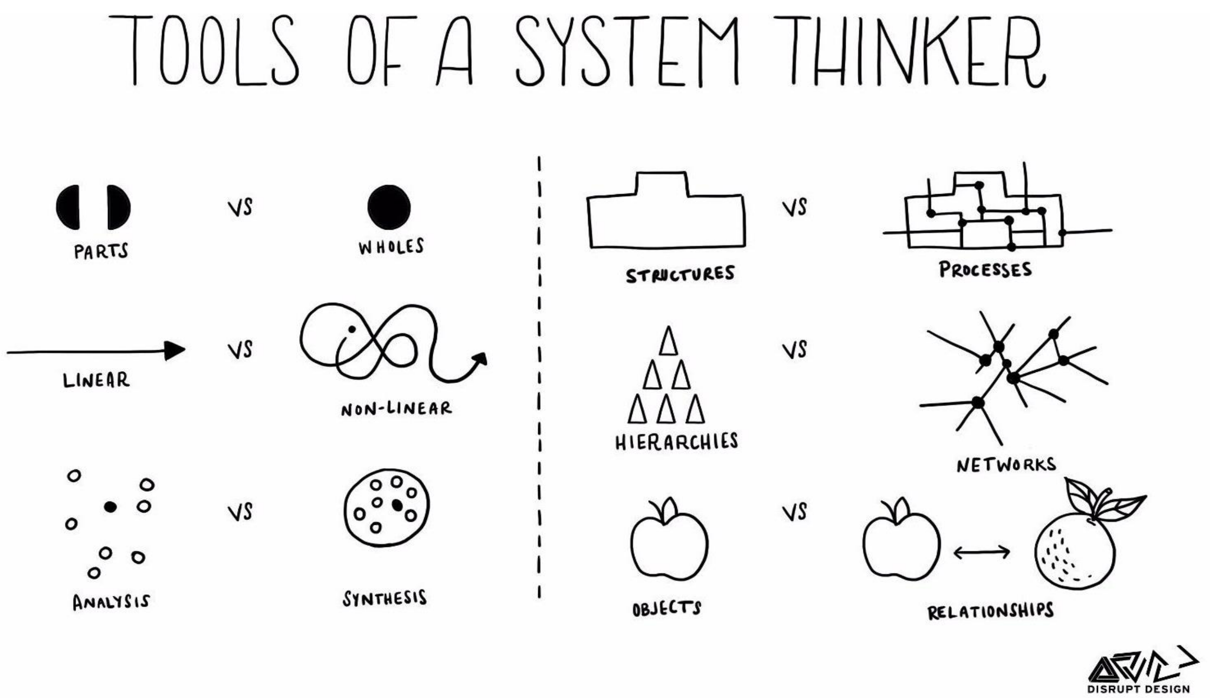


Figure 6: Tools of a System Thinker (Acaroglu, 2017)

3.2. Assessing modelling options

The previous section introduced systems thinking and established that the systems of interest to this paper are complex adaptive systems. Simulation modelling was determined to be a powerful tool that can be used to understand such systems better. There are various simulation methodologies available. This section will determine which option is most suitable for investigating a hydrogen transition in the heavy-duty vehicle (HDV) sector of the New Zealand economy. First, a set of requirement specifications will be developed to assess the various modelling approaches. Subsequently, three simulation modelling methods will be briefly presented, namely: System Dynamics Modelling (SDM), Discrete Event Modelling (DEM), and Agent-Based Modelling (ABM). These methods were selected based on their prevalence, as noted by Banks (1999) and Balestrini-Robinson *et al.* (2009). A preliminary study has indicated that System Dynamics Modelling is well suited to the requirements of this study. The modelling approaches will be assessed on their ability to meet the established criteria, and the most appropriate option will be selected. In the next section, the chosen modelling option will be presented in greater detail.

3.2.1. Criteria for assessing modelling options

To assess a modelling options ability to investigate a hydrogen transition in the HDV sector of the New Zealand economy, a set of requirements specifications will now be developed. These requirements are largely based on the work of Quarton *et al.* (2020). Their work articulates what is required to model with accuracy the role of hydrogen in an energy transition. Furthermore, the paper goes on to "*suggest some best practices for energy scenarios so that they can provide the best insight, and correctly quantify the potential of energy technologies such as hydrogen*" (Quarton *et al.*, 2020, p. 81). Their work, in conjunction with work done by Probst & Bassi (2017), Bellu & Pansini (2009), and Balestrini-Robinson *et al.* (2009) led to the following list of requirements specifications:

i. **Problem identification** – The modelling approach facilitates the process of discerning which aspects of the system are significant, and which are not;
ii. **Ease of creation** – The analyst can complete the modelling process within the allotted time;
iii. **Non-linearity** – The modelling approach accommodates non-linear responses and relationships between interconnected entities;
iv. **Dynamic behaviour and interactions** – The modelling approach appropriately represents interconnectivity and consumer behaviour; and
v. **Temporal consideration** – The modelling approach provides the ability to model scenarios over a time period consisting of sufficient duration and resolution.

3.2.2. System Dynamics Modelling

Borshchev & Filippov (2004, p. 4) note that SDM was developed by Jay W. Forrester who defined SDM as "*the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise*". More recently, Erik Pruyt, a prominent author in the SDM field, has suggested that SDM is "*a method to describe, model, simulate and analyse dynamically complex issues and/or systems in terms of processes, information, organizational boundaries and strategies*" (Pruyt, 2013, p. 1).

SDM is based on the insight that system structure determines system behaviour (Pruyt, 2013). Sterman (2002a) suggests that SDM facilitates a better understanding of the structure and dynamics of complex systems, thereby catalysing successful interventions. He also notes that by modelling feedback, stocks, flows, and time delays, SDM enables a better understanding of *dynamic complexity* – "*the often counterintuitive behaviour of complex systems that emerges from the interactions of the agents over time*" (Sterman, 2002a, p. 5). The importance of feedback is derived from the insight that real-world systems react to interventions, and if the system's reaction is not considered, then incorrect assumptions will be made about the outcome of the intervention (Sterman, 2002a). The significance of this is often amplified by the presence of various feedback loops within a given system. *Stocks* represent stores, collections, or accumulations of a certain items, and *flows* define how these items move between the stocks and into or out of the system boundary (Maidstone, 2012). *Time Delays* are of great import to SDM because they often create instability in a system and prevent actors from accessing information about the current state of the system.

In SDM models are built through an intuitive graphical interface, which enables rapid model development while accommodating nonlinearities between system entities. SDM works at a high level of abstraction, typically considering aggregates rather than individuals. This makes SDM well suited to problems in a very wide range of applications ranging from astronomy to psychology and economics. The shortcomings of SDM include difficulty in determining what should be included in the model, and a necessity for understanding the system from an aggregate perspective (Balestrini-Robinson *et al.*, 2009). Figure 7 depicts the behaviour of various feedback loops in an SDM model.

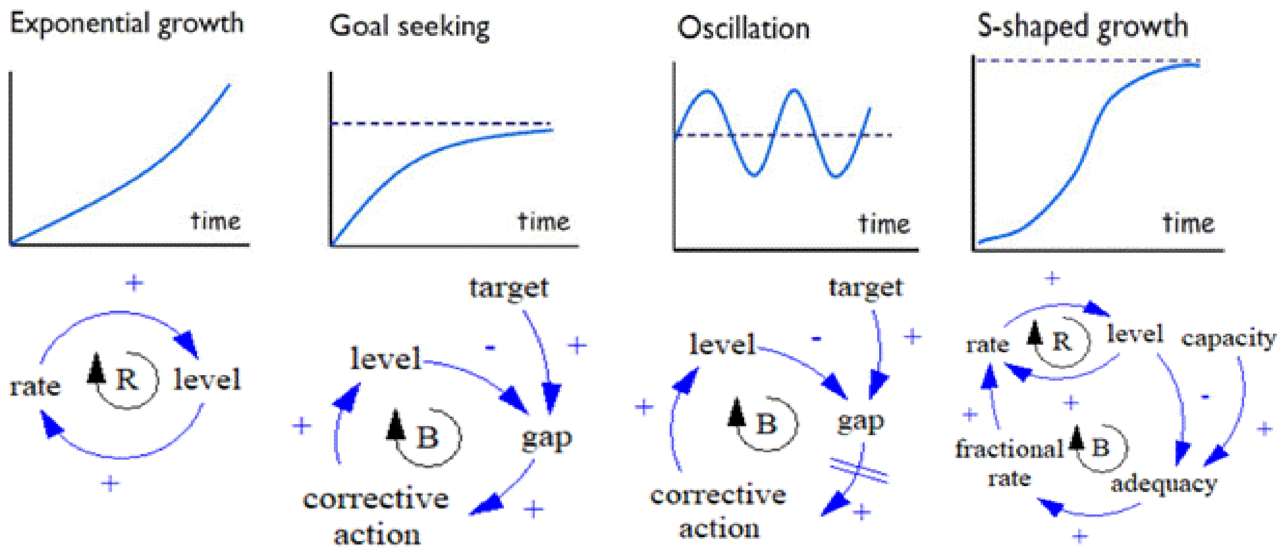


Figure 7: Comparison of various system structures and their relation to system behaviour (Maidstone, 2012)

3.2.3. Discrete Event Modelling

Discrete Event Modelling (DEM) is defined by Banks, *et al.* (2013) as a method for modelling changes in a system that happen at discrete points in time. Borshchev and Filippov (2004, p. 6) suggest that DEM is a *"modelling approach based on the concept of entities, resources, and block charts describing entity flow and resource sharing"*. Entities can occupy resources and will form queues when they are unable to occupy the desired resource. They move through the system based on rules that trigger events and change state variables. All events and state variables need to be declared, programmed, and initialized by the programmer; the system state is a snapshot in time of various state variables (Jacob, 2013). Therefore, it is only appropriate to use DEM for systems where state changes can be modelled as events that occur at discrete points in time (Banks *et al.*, 2013). When an event is triggered, state variables are changed instantaneously, and it can be said that nothing of interest occurs between events (Varga, 2005). DEM is best suited to low levels of abstraction such as manufacturing plants, business processes, call centres, and logistics. DEM typically makes use of stochastic elements which necessitate multiple simulation runs and appropriate statistical processing to interpret simulation results (Borshchev and Filippov, 2004). Figure 8 depicts a model of a production process designed using Tecnomatix Plant Simulation Software (Siemens, 2019). The entities (modelled as yellow and green circles) enter the model on the left-hand side. They then move through the production processes until they reach the assembly packaging process and finally leave the model.

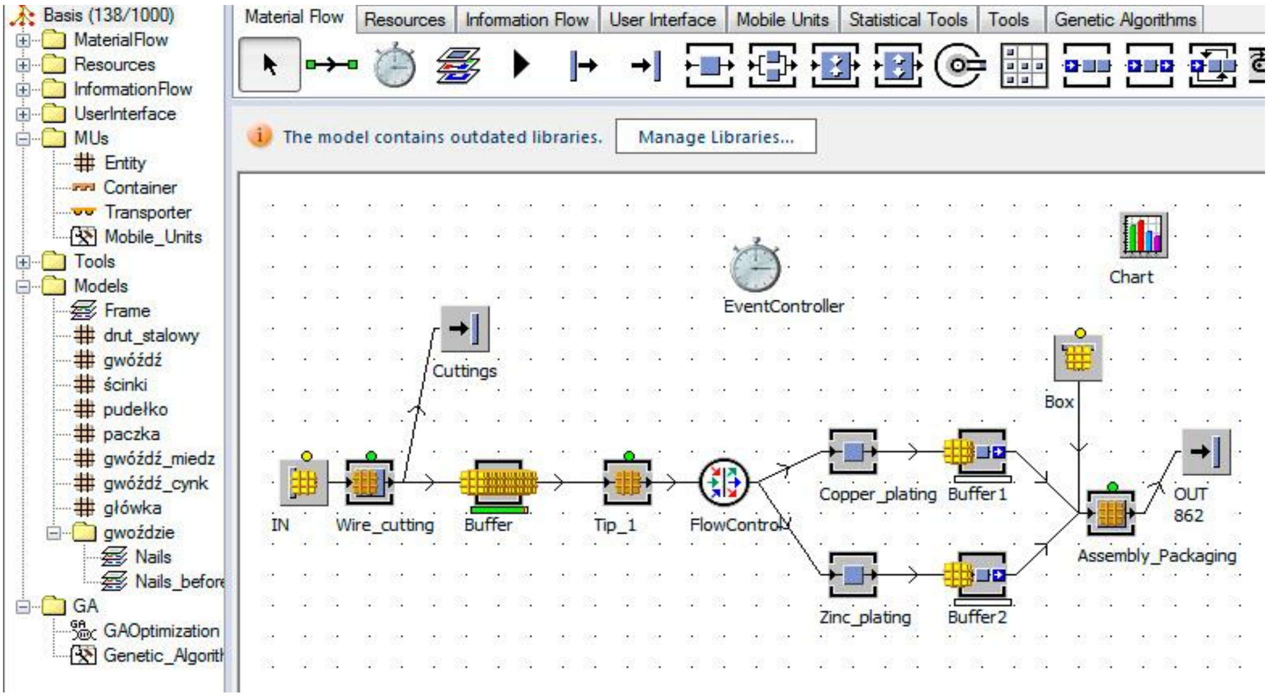


Figure 8: Depiction of a production process using Discrete Event Modelling

3.2.4. Agent-Based modelling

Agent-Based Modelling (ABM) can be defined as a simulation modelling technique that models a system as a collection of entities, called agents, that interact with each other and their environment while following simple rules (Balestrini-Robinson *et al.*, 2009; Bonabeau, 2002). Shalizi (2007) notes that agents are typically modelled as objects with behaviour defined at an individual level rather than at an aggregate level. Such models enable myriad interactions to take place as unique agents move around the model autonomously (Heppenstall *et al.*, 2012). For this reason, Siebers *et al.* (2010) suggest that ABM is best suited to systems that are intuitively represented by agents with individual characteristics, such as spatial aspects, strategic behavioural aspects, and relational aspects. Examples of agents include people, organizations, animals, swarms of animals, robots, and systems of collaborating robots – the level of abstraction depends on what the modeller hopes to learn (de Kock, 2019). Figure 9 presents the generic architecture of an agent-based model. ABM enables a wide spectrum of abstraction, which can provide deeper levels of insight into the complexity of a system. Although ABM can effectively model a wide range of systems, some shortcomings need to be considered. According to Balestrini-Robinson *et al.* (2009) the most significant shortcomings include:

i. The need for complete knowledge of every interaction at the individual level;
ii. The difficulty associated with determining which part of the model can be effectively represented as an independent stochastic event;
iii. The potential of creating an excessively complicated model that may add noise to the model.
iv. The difficulty associated with model creation, verification, and validation;
v. Computationally expensive; and
vi. Requires a very large number of model runs to account for agent interactions reducing the effectiveness of the Central Limit Theorem.

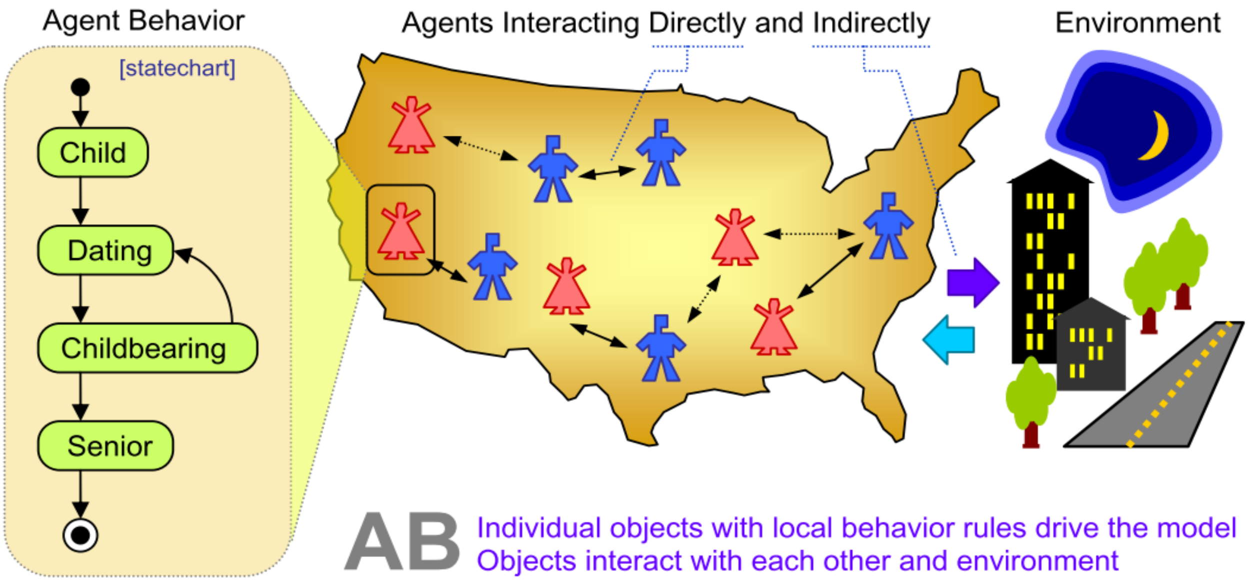


Figure 9: Example of the generic architecture of an agent-based model (Borshchev and Filippov, 2004)

3.2.5. Assessment and evaluation of modelling options

Now that three predominant modelling options have been presented, it is necessary to apply the assessment criteria from Section 3.2 to determine which of the options is most applicable to the problem at hand. Table 2 summarizes the ability of each modelling technique to meet the requirements. The table is a combination of the work done by Balestrini-Robinson *et al.* (2009), Probst & Bassi (2017), Bellu & Pansini (2009), and Quarton *et al.* (2020).

Discrete Event Modelling scores 'very poorly' on the requirement of temporal consideration. Continuity is important in energy transitions, and modelling them as a sequence of discrete events would not be sensible. Additionally, DEM is best applied to problems where a low level of abstraction is appropriate. Modelling a socio-technical transition in this way would require significant resources for development and processing. This leads to DEM scoring 'very poorly' on the requirement of Problem Identification. Additionally, DEM is considered to have 'poor' ease of creation (Balestrini-Robinson et al., 2009). Therefore, with inadequate performance in three out of five areas, DEM is ruled out even though it is noted for its ability to manage non-linearity and dynamic behaviours and interactions very well.

Table 2: Comparison of modelling options. Ratings represent the findings from various authors (Balestrini-Robinson *et al.*, 2009; Bellù and Pansini, 2009; Probst and Bassi, 2017; Quarton *et al.*, 2020)

Requirement Specification	Discrete Event Modelling	Agent Based Modelling	System Dynamics Modelling
Problem Identification	Very Poor	Very Poor	Excellent
Ease of Creation	Poor	Very Poor	Good
Non-Linearity	Very Good	Excellent	Very Good
Dynamic Behaviours and Interactions	Very Good	Very Good	Very Good
Temporal Considerations	Very Poor	Poor	Good

Siebers *et al.* (2010) suggest that Agent-Based Modelling is best suited to systems which are *intuitively* represented by agents. Although it is tempting to consider a model that includes all the various stakeholders in an energy transition interacting as autonomous agents – this would not be practical. The bottom-up approach of ABM would require excessive resources to develop and analyse (especially at the desired temporal resolution), and the model would be overly complicated. For this reason, ABM scores 'very poorly' on problem identification and ease of creation, and 'poorly' on temporal considerations. The 'excellent' consideration of non-linearity and 'very good' consideration of dynamic behaviours and interactions does not compensate for the inadequate performance in other areas.

System Dynamics Modelling can model a multitude of stakeholders while incorporating quantitative as well as qualitative data. This results in SDM scoring 'Excellent' in the problem identification category. SDM is also noted for being 'very good' at considering non-linearity, and dynamic behaviours and interactions (Balestrini-Robinson *et al.*, 2009). SDM is well suited to capturing the necessary temporal resolution at the desired level of abstraction without overrunning development and analysis resources – therefore scoring 'good' on both ease of creation and temporal consideration. SDM outperforms both ABM and DEM on the assessed criteria. Furthermore, Pruyt (2013, p. 1) notes energy transitions as one of the "*important application domains*" of SDM, and many examples can be found of SDM being used to model such transitions (Bolwig *et al.*, 2019; Leaver *et al.*, 2012; Papachristos, 2019). It is therefore found that SDM is the best option - out of those considered - for modelling a hydrogen transition in the heavy-duty vehicle sector of the New Zealand economy. This conclusion is supported by Haro (2020) who suggests that SDM is "*unbeatable*" in the presence of "*abstract or subjective variables or relationships, or when the system is … complex and requires extensive aggregation*". Haro (2020) goes on to say that SDM is a "*great tool to use*" in cases related to policy recommendation.

3.3. System dynamics modelling methodology

A brief overview of SDM has been presented in Section 3.3.4 – this section will build on that introduction. Various SDM modelling processes will be reviewed to determine the best approach to modelling a hydrogen transition in the heavy-duty vehicle sector of the New Zealand economy.

Subsequently, the basic tools and mathematical representations prevalent in SDM will be introduced. Lastly, the most applicable system dynamics verification and validation strategies are presented.

3.3.1. The modelling process

Four approaches to the modelling process were considered. The modelling process suggested by Quarton *et al.* (2020, p. 81) is designed *"for energy scenarios so that they can provide the best insight, and correctly quantify the potential of energy technologies such as hydrogen"*. Although their approach is particularly relevant to this study it is not designed specifically for SDM. To adapt their work to SDM three popular approaches to modelling with SDM were considered, namely those suggested by Maani & Cavana (2007), Sterman (2000), and Albin & Forrester (1997). The main steps in each of these approaches are presented in Table 3.

Table 3: Summary of various approaches to modelling

	Approach 1: Modelling energy technologies such as hydrogen (Quarton *et al.*, 2020)	**Approach 2: Systems Thinking and Modelling methodology (Maani and Cavana, 2007)**	**Approach 3: Systems Thinking and Modelling for a Complex World (Sterman, 2002a)**	**Approach 4: Generic stages of SDM (Forrester and Albin, 1997)**
Step 1	Describe the purpose of the study	Problem structuring	Problem articulation	Conceptualization
Step 2	Define the scope so that the purpose can be achieved satisfactorily and with sufficient accuracy	Causal loop modelling	Formulation of dynamic hypothesis	Formulation
Step 3	Build the simplest model that can accurately represent all the features and interactions of the system defined in the scope	Dynamic modelling	Formulation of simulation model	Testing
Step 4	Provide assumptions and limitations	Scenario planning and modelling	Testing	Implementation
Step 5	Discuss results considering assumptions, limitations, and model imperfection	Implementation and learning lab	Policy design and evaluation	

By combining these approaches, a process specifically designed for modelling hydrogen transitions with SDM was created. The first step of the hybrid process is *study conceptualization*. This step is a combination of the first two steps suggested by Quarton *et al.* (2020) and the initial steps recommended by the authors that focus on modelling with SDM. The second step of the hybrid process is *model construction*. This step is decomposed into four sub-steps which draw heavily on the modelling approaches focused on SDM. The sub-steps guide the modelling process through causal loop modelling, dynamic modelling, model testing, and scenario planning. The third step of the hybrid process is the *statement of assumptions and limitations*. This step draws on the work of both Quarton *et al.* (2020) and the SDM modelling processes. The fourth, and final, step of the hybrid process is the *discussion of results*. This step emphasises the importance of discussing results in relation to the assumptions and limitations listed in the previous step. Together, these four steps articulate a modelling process that is curated specifically for modelling hydrogen transitions with SDM. The synthesized modelling process is presented in Figure 10.

Before discussing the individual steps in greater detail, it is worth noting that Quarton *et al.* (2020) do not delve into the details of their suggested approach, but they do comment on the implications of following it. Most significantly, they highlight the supreme importance of model transparency. Furthermore, the authors consistently suggest that an "*unprecedented level of detail"* is required to effectively model energy transitions, yet they acknowledge that *"the greatest difficulty for a modeller is when the required level of detail is so high that the model becomes computationally very demanding but further simplification makes the model no longer fit for purpose"* (Quarton *et al.*, 2020, p. 88). They go on to suggest that their method leads to a level of transparency that allows results to be interpreted within the limitations of the study that was performed.

Step 1: Study conceptualization

This step combines the first two steps from Quarton *et al.* (2020) with the first step of each of the other authors. During this step, the purpose, scope, and boundary of the model are defined. Subsequently, key variables and stakeholders are identified, the model time horizon is defined, and preliminary information and data are collected. This step is iterative in nature, with each iteration leading to a clearer understanding of these concepts. Although all of these concepts are important, it is worth noting that the definition and articulation of the purpose of the model will guide the entire modelling process (Sterman, 2002b). Sterman (2000) notes that one of the most common causes of model failure is an ill-defined purpose or inadequate consideration of model purpose during the modelling process. The key components of the first step can be summarized as follows:

i. Describe the purpose of the model;
ii. Define the scope of the model;
iii. Define the model boundary;
iv. Identify key variables and stakeholders;
v. Define the model time horizon; and
vi. Collect preliminary information and data.

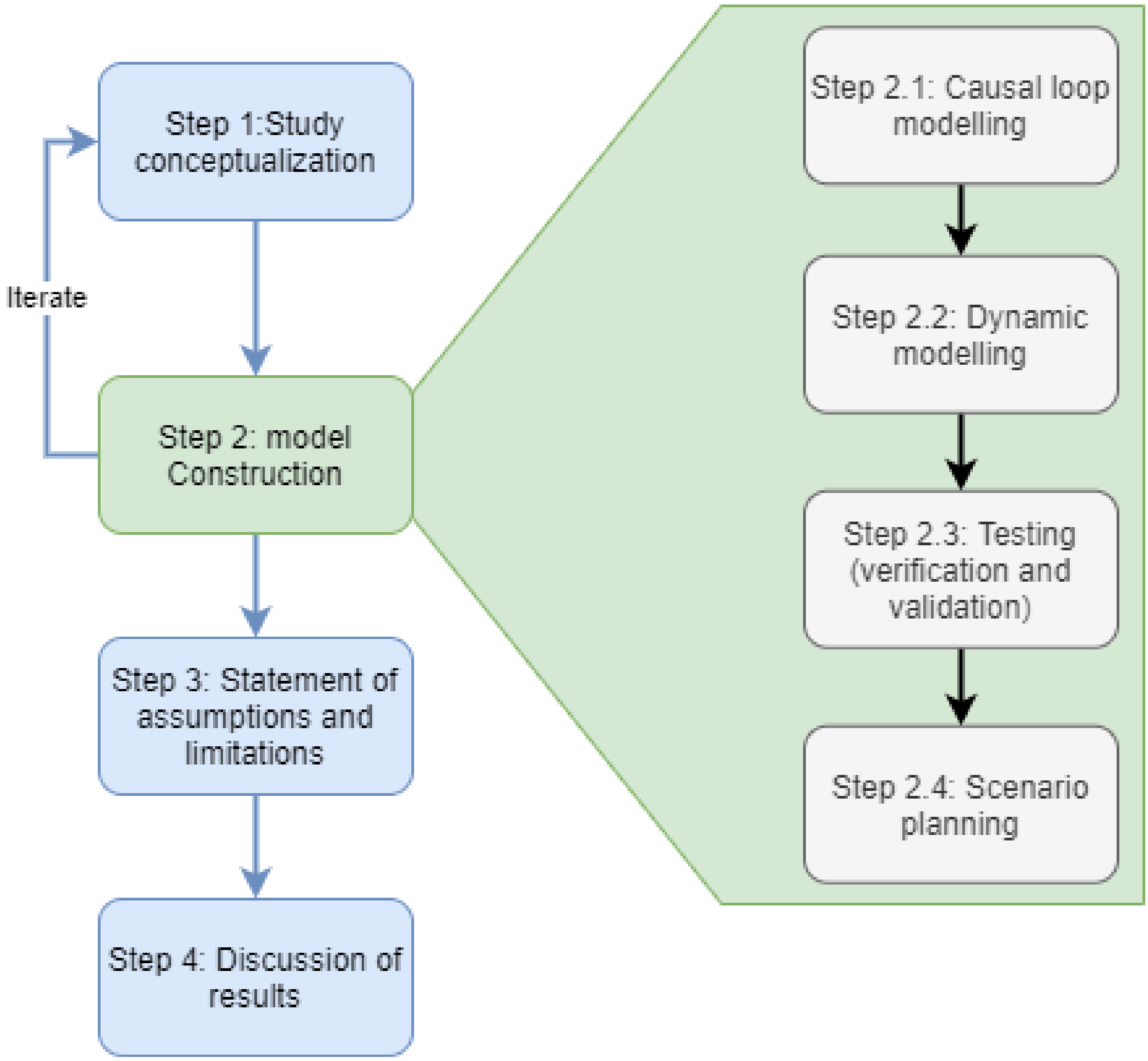


Figure 10: Depiction of the synthesized process for modelling hydrogen transitions with System Dynamics Modelling

Step 2: Model construction

The second step of the modelling process is decomposed into four sub-steps. The first three sub-steps draw heavily on the approaches that focus on SDM, while the final sub-step focuses on developing scenarios that are appropriate to hydrogen as articulated by Quarton *et al.* (2020).

The first step in model construction is causal loop modelling. The main tool used in causal loop modelling is a causal loop diagram (CLD). CLD's provides a framework through which the structure and behaviour of the system under investigation can be understood (Maani and Cavana, 2007). Fundamentally, a CLD simply indicates the causal relationships and delays between the variables under consideration. This leads to the identification of feedback loops and assists in determining whether the key components developed in the study conceptualization phase are sufficient for the model purpose. If a CLD highlights a potential shortcoming in one of these components, the component is reconsidered – possibly leading to an improved conceptualization of the model

(Sterman, 2000). The development of a dynamic hypothesis is an important part of the SDM approach. According to Sterman (2000), a dynamic hypothesis is a CLD that explains the dynamic behaviour of the system as a result of the feedback structure between the identified variables. Lastly, a CLD assists the modeller in identifying whether a given variable should be modelled as a stock, flow, auxiliary, or exogenous variable during dynamic modelling. CLD's are discussed in greater detail in Section 3.3.2.

The second step in model construction is dynamic modelling. The main tool used in dynamic modelling is a stock and flow diagram (SFD), also known as a level and rate diagrams (Vensim, n.d.). SFD's exploit the benefits of computers by representing much more information than can be contained in a conceptual model. To do so, the modeller needs to mathematically define the causal relationships that were identified in the CLD (Maani and Cavana, 2007). Once the dynamic model has been validated it enables sensitivities to be tested, and the results of various scenarios to be compared. An SFD also provides the opportunity to test potential system interventions in a virtual environment with minimal consequences, rather than in the real system - if it is feasible to do so (Sterman, 2000). Additionally, an SFD provides another opportunity to test the current conceptualization of the study and make adjustments if necessary (Sterman, 2000). SFD's are discussed in greater detail in Section 3.3.2, and the mathematical representations used in SFD's are presented in Section 3.3.3.

The third step in model construction is model testing. Testing can be understood as the process of developing a satisfactory level of confidence in the model by performing various test on the model. There is no single method for testing an SDM model, but there are various guidelines that outline test procedures (Forrester and Senge, 1979). Section 3.3.4 considers model testing in greater detail and presents test procedures suggested by various authors. Model testing is always carried out with model purpose in mind and provides an opportunity to identify unacceptable flaws in the model (Sterman, 2000).

The last step in model construction is scenario planning. According to Maani & Cavana (2007), the problem under investigation and the purpose of the model should always be kept in mind while planning scenarios. They also suggest that the full range of possible outcomes should be considered, rather than only the selection of the outcomes that seem to be the most probable (Maani and Cavana, 2007). While it can be tempting to run a very large number of scenarios, Maani & Cavana (2007) suggest that typically it is sufficient to focus on two to four scenarios that are relevant, plausible, and depict a wide range of outcomes. Quarton *et al.* (2020) emphasize the importance of considering the relevant policies, and an appropriate level of decarbonisation ambition. They also motivate the use of consistent, realistic, and substantiated data assumptions. Above all, Quarton *et al.* (2020) call for transparency regarding the values that are used, and the assumptions that are made in each scenario that is modelled. Therefore, the third step in the modelling process addresses assumptions and limitations directly.

Step 3: Statement of assumptions and limitations

The focus of the third step in the modelling process is to ensure transparency regarding assumptions and model limitations. If there are significant differences in the assumptions and limitations relating to particular scenarios, then these differences need to be clarified for each scenario. This enables a better interpretation of results and lends credibility to the accuracy of these results. Additionally, transparency allows other modellers to analyse and critique the model. Quarton *et al.* (2020) suggest that true transparency is achieved by publishing much of the model, including mathematical formulations.

Step 4: Discussion of results

In this step, a report is compiled to present the modelling process along with important finding, recommendations, and reflections. A discussion of results needs to be presented with reference to the assumptions and limitations of the model. All models are imperfect, but framing results in the context of the model constraints can garner trust and make the model much more useful (Quarton *et al.*, 2020). The four steps presented above are used in the modelling process of this study. The following section discusses the tools of SDM that are used to carry out the study.

3.3.2. Tools of System Dynamics Modelling

Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs) were mentioned as part of the second step of the modelling process. Together these form the fundamental tools with which SDM is carried out. This section will describe these tools in greater detail.

Causal Loop Diagrams (CLDs)

CLD's will be described with reference to the example presented in Figure 11. As can be seen, CLDs consist of variables connected by (blue) arrows that indicate the causal relationship between the two variables that it connects. The causal relation is indicated by a plus (+) or minus (-) sign at the head of each arrow. A plus sign indicates a positive correlation between the two variables, meaning that if the variable at the base of the arrow were to change, then the variable at the head of the arrow would change in the same way or direction – assuming all other variables remain constant (Sterman, 2000). This can be understood by considering that in Figure 11 an increase in the birth rate variable would lead to an increase in the population variable. A minus sign indicates a negative correlation between the two variables, meaning that if the variable at the base of the arrow were to change, then the variable at the head of the arrow would change in the opposite way – assuming all other variables remain constant (Sterman, 2000). This can be understood by considering that in Figure 11 an increase in the death rate variable would lead to a decrease in the *population* variable (Sterman, 2000).

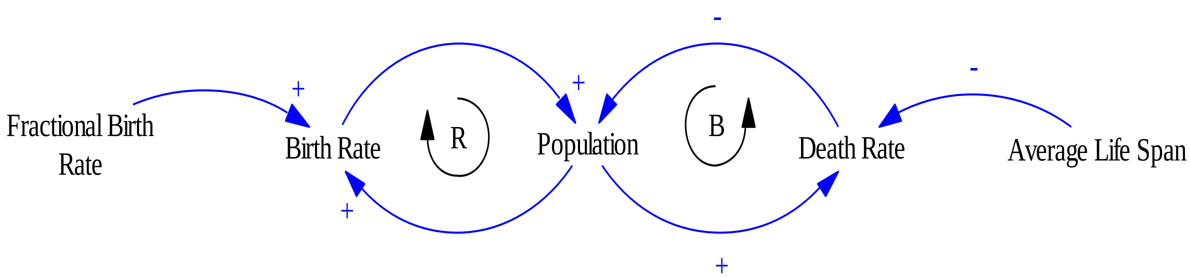


Figure 11: CLD of a population

As can be seen in Figure 11 feedback loops typically form within the CLD. These feedback loops are of great interest, and one of the main reasons for drawing CLDs. By displaying causal relationships and feedback loops in an intuitive way, a CLD enables us to quickly present hypotheses regarding the causes of dynamics within a system and puts on display prevalent mental models (Sterman, 2000).

The feedback loops in Figure 11 are indicated by black arrows. On the left-hand side, the arrow surrounds an "*R*", indicating that this is a Reinforcing (or positive) feedback loop. If left to themselves, such feedback loops tend to push the associated variables further and further in a given direction – this typically causes exponential growth. On the right-hand side, the arrow surrounds a "*B*", indicating that this is a Balancing (or negative) feedback loop. Such feedback loops tend to exhibit "*goal-seeking*" behaviour when they exist by themselves (Maidstone, 2012, p. 3).

In CLDs time delays are indicated by placing two parallel lines through the middle of the arrow indicating a causal connection between two variables – this can be seen in Figure 12.

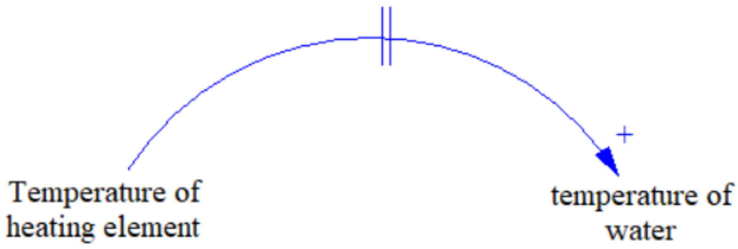


Figure 12: Demonstration of how a delay is indicated on a CLD

CLDs are used to facilitate understanding of the structure and behaviour of the system under investigation. CLDs assist modellers to identify key variables and determine whether they are stocks, flows, auxiliary variables, or exogenous variables. This is particularly helpful for the formation of Stock and Flow diagrams (Maani and Cavana, 2007).

Stock and Flow Diagrams (SFDs)

Stocks and flows are central ideas in dynamics (Sterman, 2000). As stated in Section 3.2.2, stocks represent stores, collections, or accumulations of a certain items, and flows define how these items move between the stocks and into or out of the system boundary (Maidstone, 2012). Stocks create delays in a system if the outflow and inflow are not matched – like a swamp accumulating water by releasing it slower than the water flows in. The disequilibrium in the dynamics of a system caused by decoupling inflow and outflow rates provide the system with inertia and memory, and allow the model to accurately represents real-world systems (Sterman, 2000). Lastly, stocks can be understood as a representation of the state of a system at a given time – it is by considering the various stocks that we gain insight into the system and decide how to intervene. The population causal loop diagram introduced earlier is presented as a Stock and Flow Diagram in Figure 13 below. Stock and Flow Diagrams are composed of six main components. Table 4 presents a summary of these components.

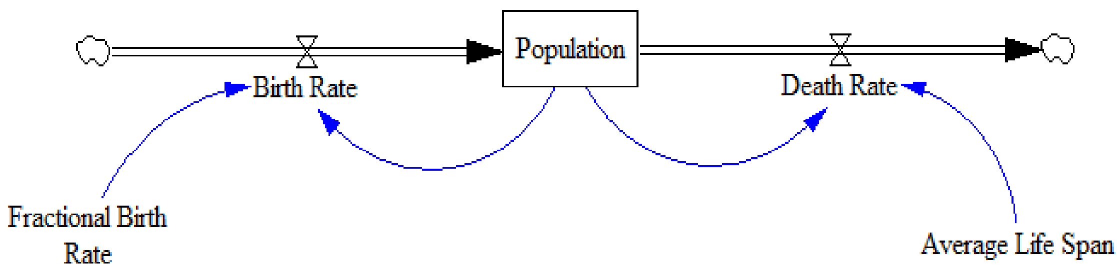
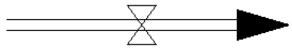
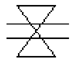
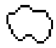


Figure 13: Stock and Flow Diagram of a given population

Table 4: Summary of elements in a Stock and Flow Diagram

Element	Description	Symbol
Stock	A reservoir whose content can accumulate and dissipate over time based on the inflow and outflow that it experiences.	
Flow	Flows enable items to enter the system, leave the system, and flow between stocks within the system. Flows are – appropriately – depicted as pipes.	
Valves	Valves are like taps that regulate the rate of flow at a given point.	
Clouds	Clouds represent sources and sinks for flow.	
Variables	As with CLD's, auxiliary variables influence the behaviour of the system	
Connectors	As with CLD's, connectors indicate the causal relationships between the two elements that it connects.	

3.3.3. Mathematical representations

It is important to understand that the images depicted above represent "*precise and unambiguous*" mathematics (Sterman, 2000, p. 194). Stocks integrate their flows over time, and can be represented by the following equation.

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]dt + Stock(t_0) \qquad (1)$$

This equation states that the level of a stock at a given time t is equal to the integral of the difference between the inflows (from the initial time t_0 to time t) plus the level of the stock at the starting time t_0. Similarly, the derivative of the stock at a given time represents the rate of change of the stock – this can be represented by the differential equation below (Sterman, 2000) .

$$\frac{\delta Stock(t)}{\delta t} = Inflow(t) - Outflow(t) \qquad (2)$$

Sterman (2000, p. 209) notes that although the integral and differential equations presented above look much more rigorous than a stock and flow diagram – it is important to remember that they are "*precisely equivalent and contain exactly the same information*". This speaks to the power of the intuitive graphical user interface that SDM utilises.

3.3.4. Verification and validation of SDM

Maani & Cavana (2007, p. 70) suggest that verification is the process of ensuring that "*the structure and parameters of the real system have been correctly transcribed into the model*", and validation is the process of "*demonstrating that the model actually generates the same type of behavior that would be expected from the real system*". Verification and validation are often succinctly juxtaposed by modellers who state that verification asks whether we have built the model right, and validation asks whether we have built the right model (Cook and Skinner, 2005).

It is not possible to fully verify or validate a model (Sterman, 2002b). This is because all models are simplifications of real-world systems, and therefore will be imperfect representations of the real system (Sterman, 2000). Despite the impossibility of full verification and validation, it remains the responsibility of the modeller to demonstrate that the model has been constructed in a way that renders it useful to its purpose and its intended audience (Sterman, 2000). Typically, this is achieved by performing various tests on the model. Barlas (1996) proposed that such tests could be sorted into three main categories, namely:

i. **Direct structure tests**: Tests which assess the validity of the model structure as compared to the real system without simulating the behaviour;
ii. **Structure-oriented behaviour tests:** Tests which assess the validity of the model structure indirectly by comparing the model behaviour during simulation to the real/anticipated behaviour of the system that is being modelled; and
iii. **Behaviour pattern tests:** Tests which measure how accurately the model can reproduce the behaviour patterns exhibited by the real system.

Barlas (1996) emphasizes that all three test categories are dependent on the model purpose, and should be carried out with reference to this purpose. In short - if a model has no purpose, it cannot be said to be valid for that purpose. Table 5 presents a variety of tests sorted into the categories suggested by Barlas (1996).

It is important to note that behaviour pattern tests are only conducted once enough confidence has been garnered in the model structure by executing direct structure tests and structure-oriented behaviour tests. This implies that the tests are typically performed in the order presented above. Barlas's (1996) depiction of the "*logical sequence of formal steps of model validation*" is presented in Figure 14. The flowchart indicates that a subsequent step in the process is only taken if sufficient confidence is established in the current step – otherwise, the necessary work is first done to establish such confidence.

Maani and Cavana (2007) propose that the following guidelines be followed throughout the modelling process to help build confidence in a model:

i. The CLD must describe the articulated problem;
ii. Equations in the SFD must match the sign of the causal connector arrows in the CLD;
iii. The model must the dimensionally valid;
iv. The model must not produce any unrealistic values;
v. The model behaviour must be plausible;
vi. The model must maintain "*conservation of flow*" across the model boundary; and
vii. The model must respond "*properly*" to extreme condition tests.

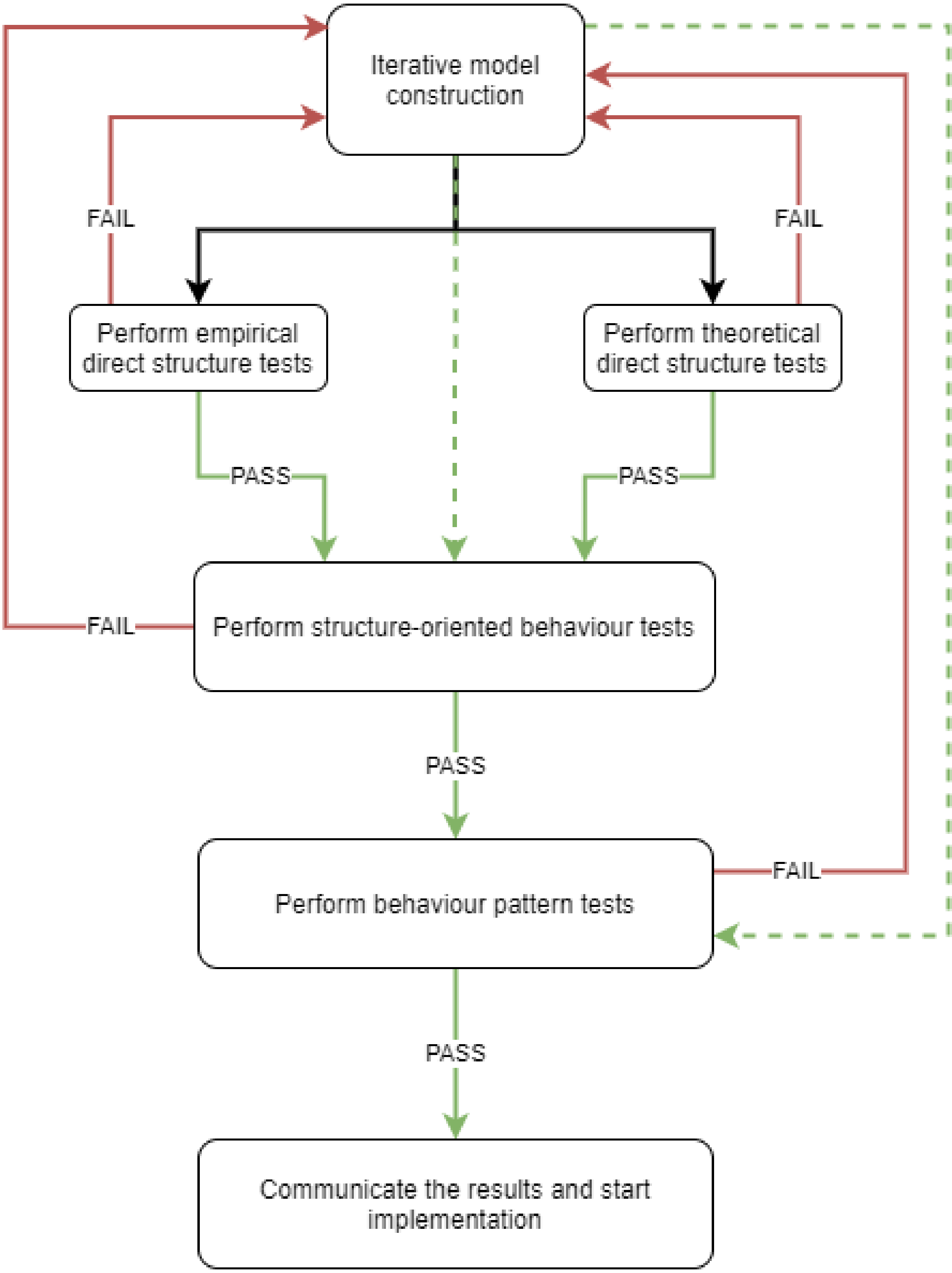


Figure 14: Barlas's (1996, p. 194) Flowchart indicating the "*logical sequence of formal steps of model validation*"

Table 5: Various confidence building tests sorted into the categories suggested by Barlas (1996). Based on the work of (Sterman, 2000), Pruyt (2013), Maani & Cavana (2007), and Senge & Forrester (1979). This list is non-exhaustive.

Direct structure tests	
Structure Verification	Is the model structure adequately similar to the structure of the real system?
Parameter Verification	Do model parameters accurately correspond to both qualitative and quantitative parameters in the real system?
Extreme Conditions	Are the rate equations plausible given a realistic minimum and maximum stock level?
Dimensional Consistency	Are rate equations dimensionally consistent, and do they include "*scaling*" parameters that have little minimal significance in real life?
Structure-oriented behaviour tests	
Boundary Adequacy	Does the model have an appropriate level of aggregation, and does the model include all relevant structure?
Behaviour Sensitivity	Can a realistic change in model parameters result in the model failing behaviour tests?
Behaviour Anomaly	If implausible model behaviour occurs, can it be justified by making feasible alterations to the original assumptions?
Behaviour pattern tests	
Behaviour Reproduction	How accurately does the model behaviour match the observed behaviour of the real system?
Changed Behaviour Prediction	How accurately does the model predict how the real system will change if a governing policy is changed?
Policy Sensitivity	To what extent would feasible alterations in model parameters lead to a variation in policy recommendations?
System Improvement Test	Do policies that are determined to be beneficial by the model, lead to improvements in the real system?

Lastly, Lai & Wahba (2003, p. 1) have compiled a "*System dynamics model correctness checklist*" which suggests 12 "*pointers*" to follow when building a model. These are briefly presented below:

i. **Units Check**: Ensure that the left- and right-hand side of all equations have the same units. Most software can perform this test automatically;
ii. **Naming Variables**: Ensure that a naming convention is established and followed;
iii. **No constants embedded in equations:** All constants should be shown explicitly as individual elements;
iv. **Do not mention parameter values in the documentation:** Documentation should simply describe what the equations mean. This avoids the necessity to update the documentation every time that a model parameter is changed;
v. **Choose appropriately small time steps:** the time step should be approximately one-eighth the value of the smallest time constant in the model;
vi. **Stock Values can be changed only by flows:** No constants or auxiliary variables may directly enter a stock equation – other than to define initial values;
vii. **Every flow should be connected to a stock:** Flows are only used to increase or decrease a stock – nothing else;

viii. **Flows should not be linked to auxiliary variables or to other flows:** Due to the temporal nature of flows, it is inappropriate to link a flow to anything other than a stock;

ix. **Stocks should not be linked to stocks:** A stock is the integral of a flow. Stocks cannot be directly linked to each other without a flow;

x. **Using IF THEN ELSE, MIN/MAX and other logic statements:** Preference should be given to table functions over these functions, as they do not accurately represent change in the real world;

xi. **Use of Initial Values:** Initial values should always be used when an initial value is required. They should follow some labelling convention; and

xii. **Curving Connectors**: A model with curved connectors (the arrows that link one variable to another) looks better. Aesthetics are important to facilitate model understanding and the identification of feedback loops.

It should be clear that although full verification and validation of a model is not possible, there exist myriad tools and tests that can demonstrate the ability of a model to serve its intended purpose. Therefore, if a model passes all these tests, stakeholders should be convinced of the usefulness of the model. The importance of verification and validation is therefore paramount in the modelling process and should be given due attention.

3.4. Chapter 3 conclusion

This chapter started with an overview of systems thinking and identified the systems of interest to this study as Complex Adaptive Systems. The suitability of simulation modelling as a tool to better understand Complex Adaptive Systems was established, and subsequently criteria for assessing modelling options were developed. The criteria were applied to three of the most popular modelling techniques, namely System Dynamics Modelling (SDM), Discrete Event Simulation, and Agent-Based Modelling. Of the three techniques that were assessed, SDM was identified as the most appropriate modelling technique for this study. A methodology for modelling hydrogen transitions with SDM was developed by combining aspects of the SDM literature with the hydrogen transition modelling literature. The resulting modelling process ensures that aspects of particular importance to hydrogen transitions are not neglected. The four main steps in the process are study conceptualization, model construction, statement of assumptions and limitations, and discussion of results. The second step - model construction - is comprised of causal loop modelling, dynamic modelling, model testing, and scenario planning. After discussing the steps of the modelling process, the main tools and mathematical representations of SDM were presented. The last section of the report reviewed various techniques for testing the model to garner confidence in the model and ensure that the model limitations are well understood.

Chapter 4
Application of System Dynamics Modelling

In the previous chapter, the hydrogen-specific modelling process of Quarton *et al.* (2020) was combined with well-established system dynamics modelling literature to create a customized process for modelling hydrogen transitions with system dynamics modelling. Each step of the synthesized process was discussed in Section 3.3.1. In this chapter, the application of the first three steps of the modelling process is documented. These steps are indicated by the dotted red line in Figure 15. By completing these steps, the fourth and fifth research objectives are addressed in this chapter. To improve the readability of the report, the final step of the modelling process will be addressed in the subsequent chapters.

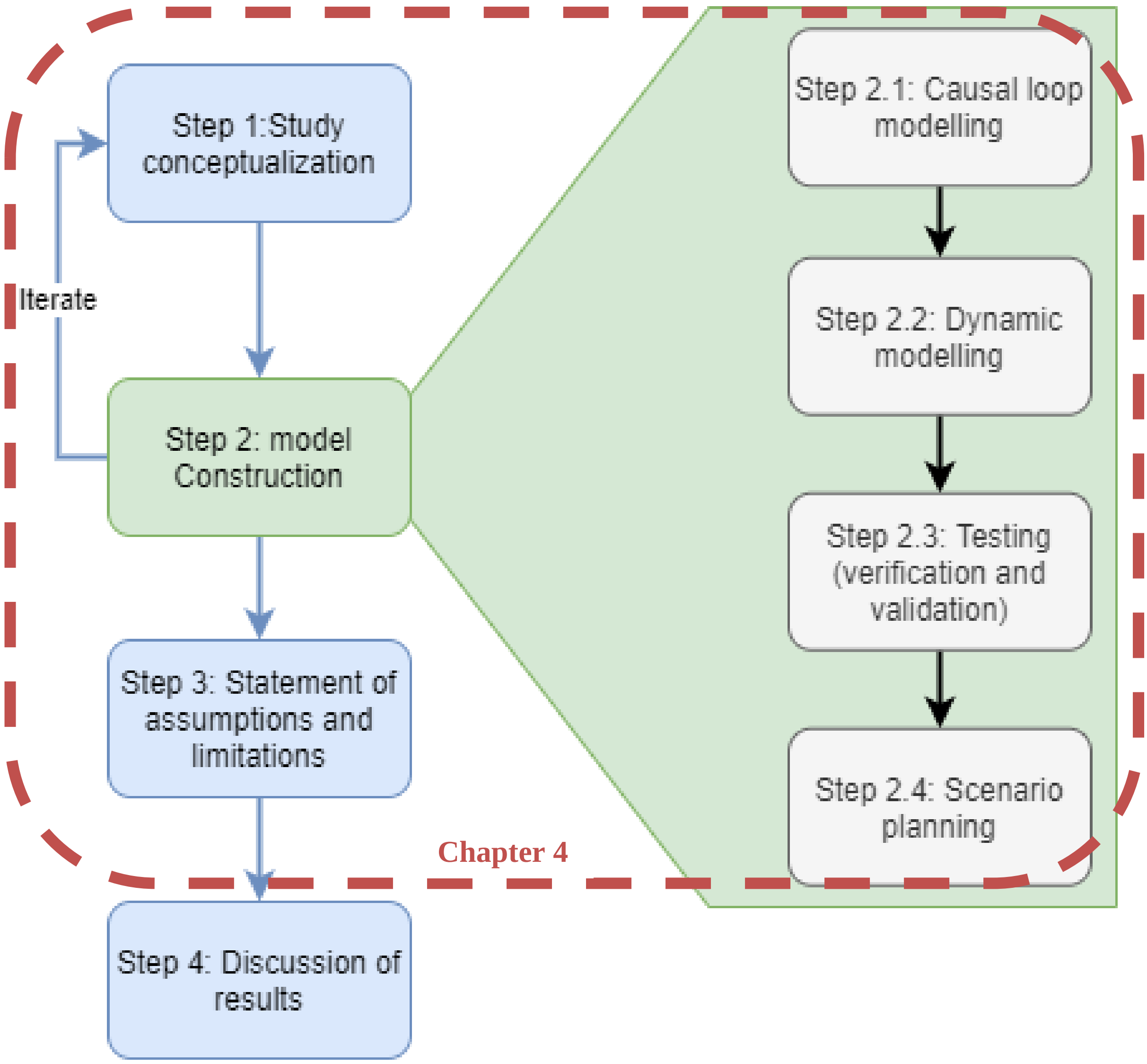


Figure 15: Steps in the modelling process addressed in Chapter 4

4.1. Study conceptualization

In this section, the first step of the synthesized modelling process is presented. The purpose, scope, and boundary of the model are defined before presenting the key variables and stakeholders. Lastly, the model time horizon, time units, and integration method are presented, along with preliminary information and data sources.

The purpose of the model

As stated in the research objectives, the overall aim of the *study* is to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. The purpose of the *model* is to enable the systematic analysis of the complex systems of interest in a way that captures the dynamic behaviour of these systems and their interconnections. An effective model would enable various technology and policy scenarios to be simulated and compared, thereby allowing the prioritization of interventions for a hydrogen transition in the HDV sector. Specifically, the model should help stakeholders understand the net investments required for such a transition.

The scope of the model

All models are simplified representations of real systems. If a model is over-simplified, there is a high likelihood that the model will not behave in a way that is representative of the real system – at least not on the desired level of abstraction. If a model is excessively complicated it will become very difficult to use the model effectively and interpret results accurately. It is therefore important to define the scope of a model so that its behaviour is representative of the real system at the desired level of abstraction, without making it excessively difficult to use or understand (Quarton *et al.*, 2020). Additionally, the resource constraints of the modelling process need to be considered during the scope definition stage. If a model is developed over an extended period by a large team of expert modellers, the scope of the model will be significantly larger than if the same system were to be modelled by a single junior modeller over a more constrained period. The scope of the study at hand should therefore be defined at a level appropriate to a master's degree. With this in mind, the following limitations were placed on the scope of the model:

i. The model must be simple enough to complete the modelling process in the required amount of time, and with the available computer software and hardware;
ii. Only "*Green Hydrogen*" produced by polymer electrolyte membrane (PEM) electrolysis and powered by renewable energy is considered. This is because PEM electrolysers are deemed to be the most appropriate technology for the needs of the HDV sector (Perez, 2020);
iii. The model is built on the assumption that green hydrogen is produced in a distributed (not centralized) manner;
iv. Only well-established technologies are considered in the model. Although there are currently several promising developments underway in various technologies that support hydrogen, batteries, and other decarbonisation strategies, these will not be considered. Specifically, only technologies that can be feasibly implemented within the next ten years will be considered – such feasibility was determined by the prevailing sentiment in the literature; and
v. Alternative decarbonisation technologies such as battery-electric vehicles and biodiesel vehicles are not considered. Hydrogen fuel cell vehicles are compared only to the prevalent HDV technology, namely diesel-fuelled internal combustion engines.

vi. The study focuses on long-haul goods delivery trucks with weights exceeding 30 tonnes as these trucks are best suited to hydrogen. For ease of reference, the terms "*truck*" and "*HDV*" are used interchangeably to refer to these vehicles.

Stakeholders, key variables, and data sources

The *BusinessNZ Energy Council (BEC)* is considered as the main stakeholder for this study. BEC is a group of New Zealand's energy sector organisations taking a leading role in creating a sustainable energy future (BEC, 2018).

The key variables of the model are largely based on the factors identified in Section 2.4.3. Table 6 presents the key variables along with the main data sources used to collect information about the given variable.

Table 6: Data sources for main variables

Variable(s)	**Data Source(s)**
Electrolyser Capex	(Concept Consulting, 2019b; IRENA, 2019; Nikola Corp, 2020a; Tedeschi *et al.*, 2011)
Balance of Plant (BOP) costs	(Concept Consulting, 2019c; Hecht and Pratt, 2017; Saba *et al.*, 2018; Schoots *et al.*, 2008)
Capex of fuel cell trucks	(Concept Consulting, 2019c; Hall and Lutsey, 2019; Hunter *et al.*, 2020; Nikola Corp, 2020a)
Fuel economy of fuel cell trucks	(Borrás, 2020; Marcinkoski *et al.*, 2019)
Carbon Tax	Estimates taken from the Interim Climate Change Committee, New Zealand (2019)
Cost of Electricity	(Concept Consulting, 2019c; EMI, 2020; Perez, 2020; Perez *et al.*, 2020)
Electricity required per Kg of hydrogen produced	(James and Randolph, 2019; Nel Hydrogen, 2020; Perez, 2020; Peterson *et al.*, 2020; VividEconomics, 2018)
Truck Vehicle Kilometres Travelled (VKT)	(Ministry of Transport, 2020a; Perez, 2020)
Number of trucks required on the road	(Ministry of Transport, 2020a)
Marginal cost of electricity	(John Culy Consulting, 2019)
Coverage of hydrogen refuelling stations	(Hiringa Energy, 2020c)

The model boundary

The model boundary is defined around New Zealand's main economy on the North and South Islands, and specifically, the heavy-duty truck fleet, which has been identified as a sector of the economy that presents significant opportunities for hydrogen (Leaver, 2019). The influence of international demand for locally produced green hydrogen is excluded from the model.

The model time horizon and integration method

The simulation is from 2020 to 2050, which is the year New Zealand has earmarked for carbon neutrality (New Zealand Parliament, 2019). The model runs in units of years, and the time steps are set to 0.0625 to increase integration accuracy while preserving computation time. The Euler method of integration was chosen over then Runge-Kutta method based on the level of data uncertainty and lack of specificity-requirements (Musango *et al.*, 2015). Various System Dynamics Modelling software packages are available, and Vensim DDS (Ventana Systems Inc., 2015) was chosen due to the modeller having the most experience with Vensim.

The main elements necessary to conceptualize the study have now been addressed. Study conceptualization is the first step in the modelling process. The second step in the modelling process - model construction - is divided into four sub-steps (causal loop modelling, dynamic modelling, model testing, and scenario planning), each of which are addressed in a dedicated section.

4.2. Causal loop modelling

The first step in model construction is causal loop modelling. Causal loop diagrams, as introduced in Section 3.3.2, are an essential part of any system dynamics modelling process. Causal Loop Diagrams (CLDs) assist in visualising the interconnections and feedback between variables. Constructing a CLD of a given system is an iterative process involving various stakeholders working together to decide what model structure might best represent the behaviour of the real system. The resulting CLD, often called a dynamic hypothesis, is the foundation of the subsequent modelling process. Through the course of the project, many dynamic hypotheses were considered and either rejected or updated, reflecting the iterative nature of the modelling process. This section presents the various CLDs that together form the latest dynamic hypothesis, which is presented in Figure 17. Reading through these descriptions sequentially can be quite laborious and repetitive, it is therefore suggested that the reader first consults the dynamic hypothesis, and then decide which feedback loops they are interested to read about in greater detail. The preliminary variables identified during the causal loop modelling process are presented in Table 11 of Appendix A.

4.2.1. Number of fuel cell trucks CLD (B1 & B2)

Figure 16 presents a section of the dynamic hypothesis that describes the main factors influencing the *number of fuel cell trucks*. By following feedback loop B1 it can be seen that more *Fuel cell truck purchases* lead to an increase in the *number of fuel cell trucks*¸ which decreases the *number of trucks that need to be purchased* resulting in a decrease in *fuel cell truck purchases.* Therefore, loop B1 is a balancing feedback loop. Loop B2 indicates that an increase in the *number of fuel cell trucks* will cause a delayed increase in the *decommissioning of fuel cell trucks*¸ which in turn would decrease the *number of fuel cell trucks.* Therefore, loop B2 is also a balancing feedback loop. The *number of fuel cell trucks* has a positive causal relation with the *forecast of number of fuel cell trucks.*

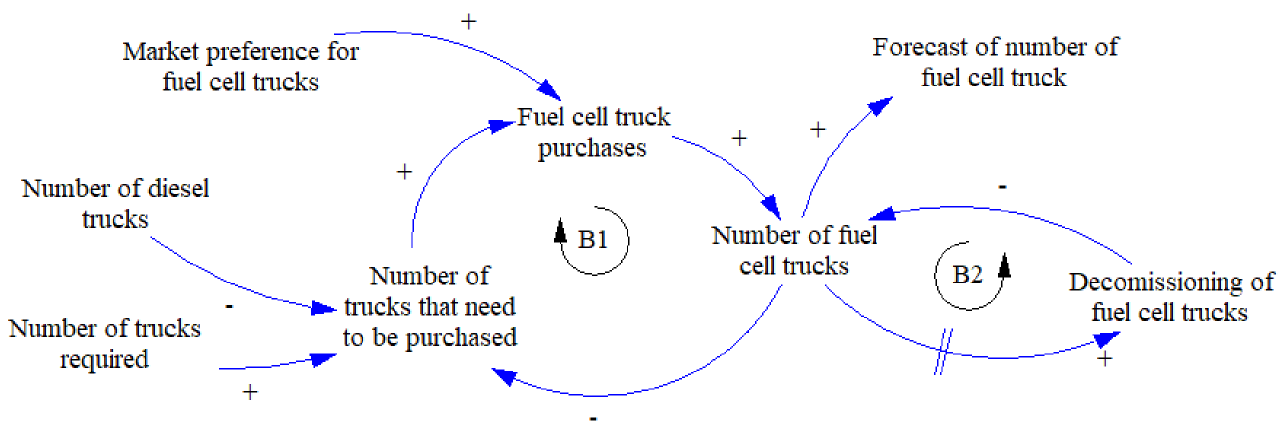


Figure 16: Number of fuel cell trucks CLD

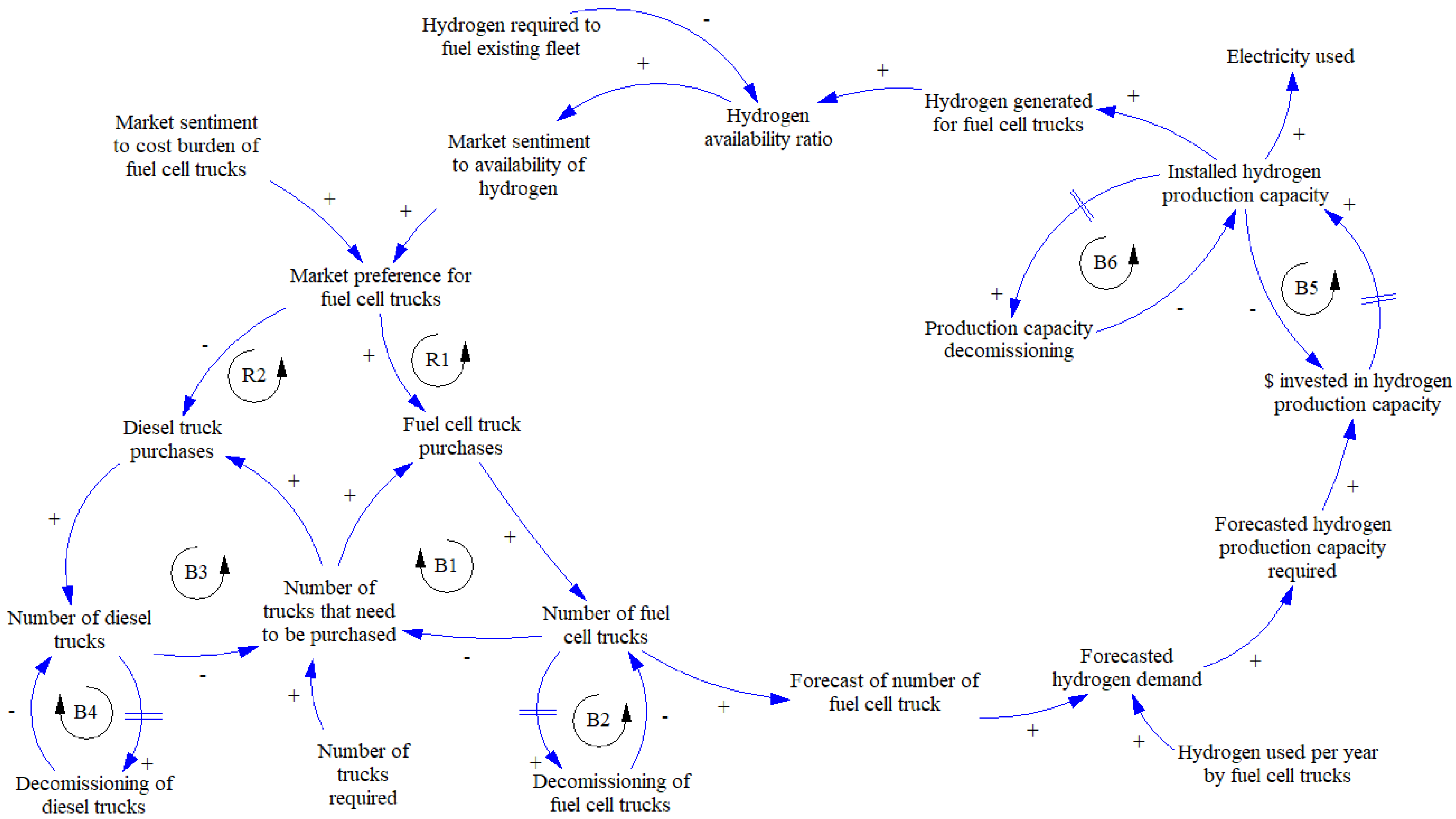


Figure 17: Dynamic hypothesis for investigating a transition from diesel to fuel cell trucks

4.2.2. Number of diesel trucks CLD (B3 & B4)

Figure 18 presents a section of the dynamic hypothesis that describes the main factors influencing the *number of diesel trucks*. The structure described here is very similar to the structure described in the previous paragraph. By following feedback loop B3 it can be seen that more *Diesel truck purchases* lead to an increase in the *number of diesel trucks*¸ which decreases the *number of trucks that need to be purchased* resulting in a decrease in *diesel truck purchases.* Therefore, loop B3 is a balancing feedback loop Loop B4 indicates that an increase in the *number of diesel trucks* will cause a delayed increase in the *decommissioning of diesel trucks*¸ which in turn would decrease the *number of diesel trucks.* Therefore, loop B4 is also a balancing feedback loop. The *installed hydrogen production capacity* has a positive causal relation with the *electricity used,* which is of great interest to this study.

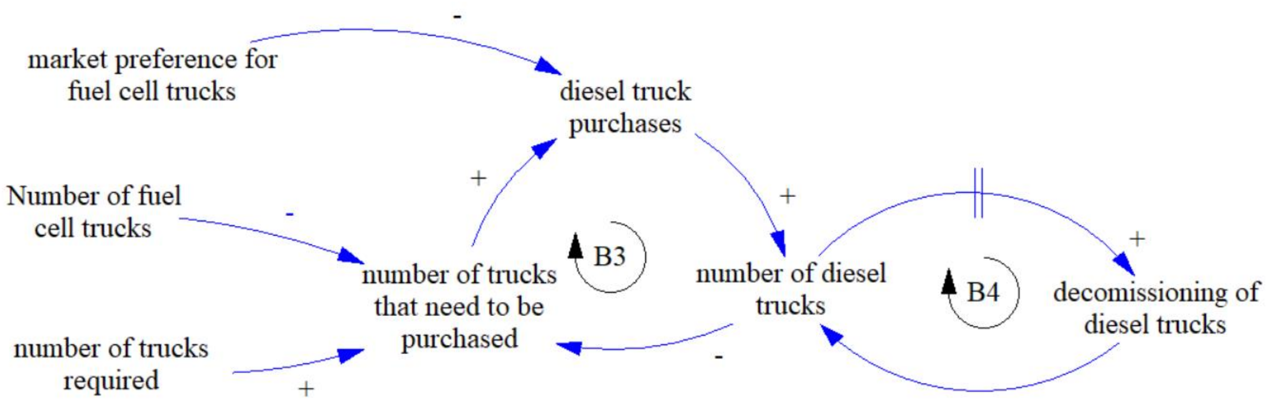


Figure 18: Number of diesel trucks CLD

4.2.3. Investments in hydrogen production capacity CLD (B5 & B6)

Figure 19 presents a section of the dynamic hypothesis that describes the main factors influencing the *$ invested in hydrogen production capacity,* and the associated *installed hydrogen production capacity*. By following feedback loop B5 it can be seen that an increase in the *$ invested in hydrogen production capacity* leads to a delayed increase in the *installed hydrogen production capacity,* which in turn reduces the *$ invested in hydrogen production capacity.* Therefore, loop B5 is a balancing feedback loop. By following feedback loop B6 is can be seen that an increase in the *installed hydrogen production capacity* would lead to a delayed increase in the *production capacity decommissioning,* which in turn would decrease the *installed hydrogen production capacity.* Therefore, loop B6 is a balancing feedback loop.

4.2.4. Fuel cell purchases CLD (R1)

Figure 20 presents a section of the dynamic hypothesis that describes the main factors influencing *fuel cell truck purchases.* By following feedback loop R1 it can be seen that the more the *fuel cell truck purchases* the more the *number of fuel cell trucks* the more the *forecast of number of fuel cell trucks,* the more the *forecasted hydrogen demand*, the more the *forecasted hydrogen production capacity required*, the more the *$ invested in hydrogen production capacity*, the more the *installed hydrogen production capacity,* the more the *hydrogen generated for fuel cell trucks,* the more the *hydrogen availability ratio*, the more the *market sentiment to availability of hydrogen*, the more the *market preference for fuel cell trucks*, the more the *fuel cell truck purchases*. Therefore, loop R1 is a reinforcing loop. This loop influences the *installed hydrogen production capacity* which, as mentioned before, has a positive causal relation with the *electricity used,* which is of great interest to this study

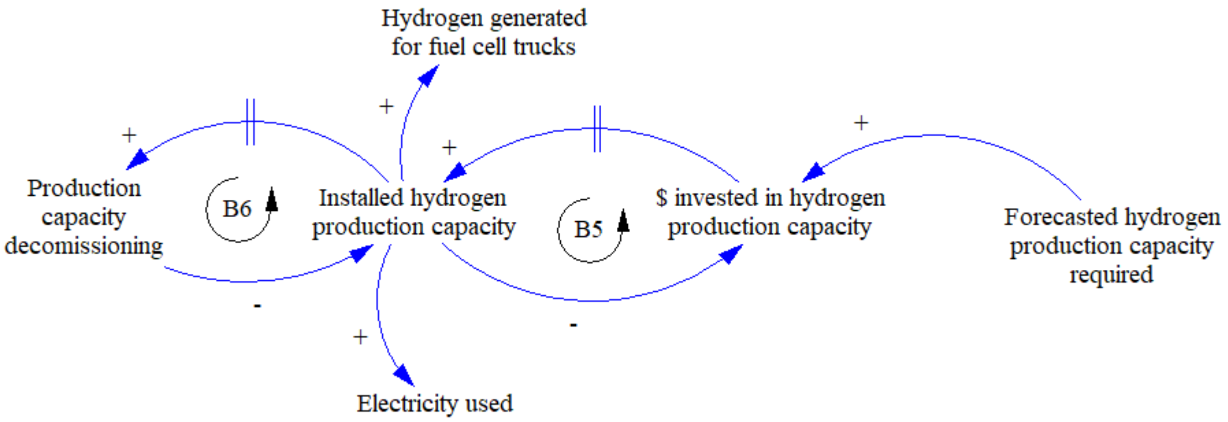


Figure 19: Dollars invested in hydrogen production capacity CLD

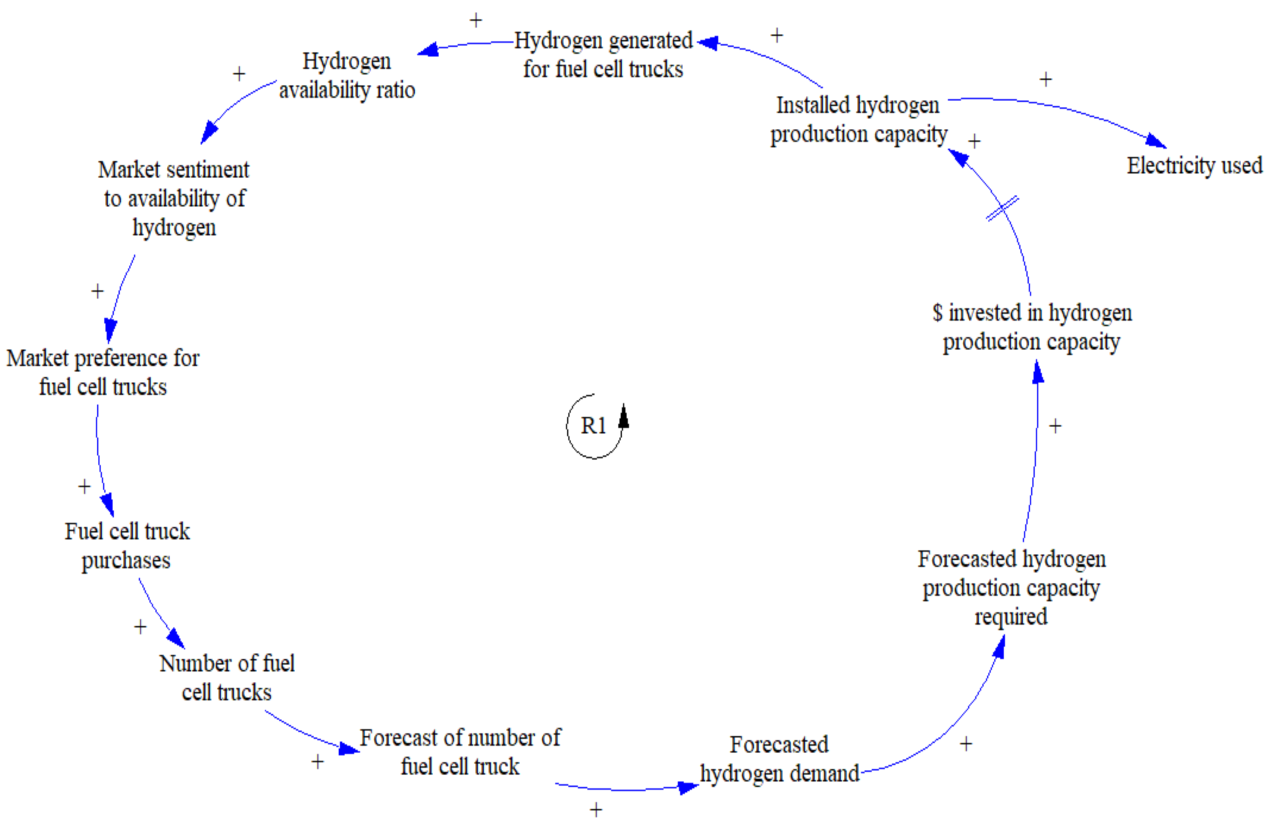


Figure 20: Fuel cell truck purchases CLD

4.2.5. Diesel truck purchases CLD (R2)

Figure 21 presents a section of the dynamic hypothesis that describes the main factors influencing *fuel cell truck purchases*. The structure described here is very similar to the structure described in the previous paragraph. By following feedback loop R2 it can be seen that the more the *diesel truck purchases* the less the *number of trucks that need to be purchased* the less the fuel cell trucks purchases, the less the *number of fuel cell trucks*, the less the *forecast of number of fuel cell trucks*, the less the *forecasted hydrogen demand*, the less the *forecasted hydrogen production capacity required*, the less the *$ invested in hydrogen production capacity*, the less the *installed hydrogen production capacity*, the less the *hydrogen generated for fuel cell trucks*, the less the *hydrogen availability ratio*, the less the *market sentiment to availability of hydrogen*, the less the *market preference for fuel cell trucks*, the more the *diesel truck purchases*. Therefore, loop R2 is a reinforcing loop. This loop influences the *installed hydrogen production capacity* which, as mentioned before, has a positive causal relation with the *electricity used*, which is of great interest to this study.

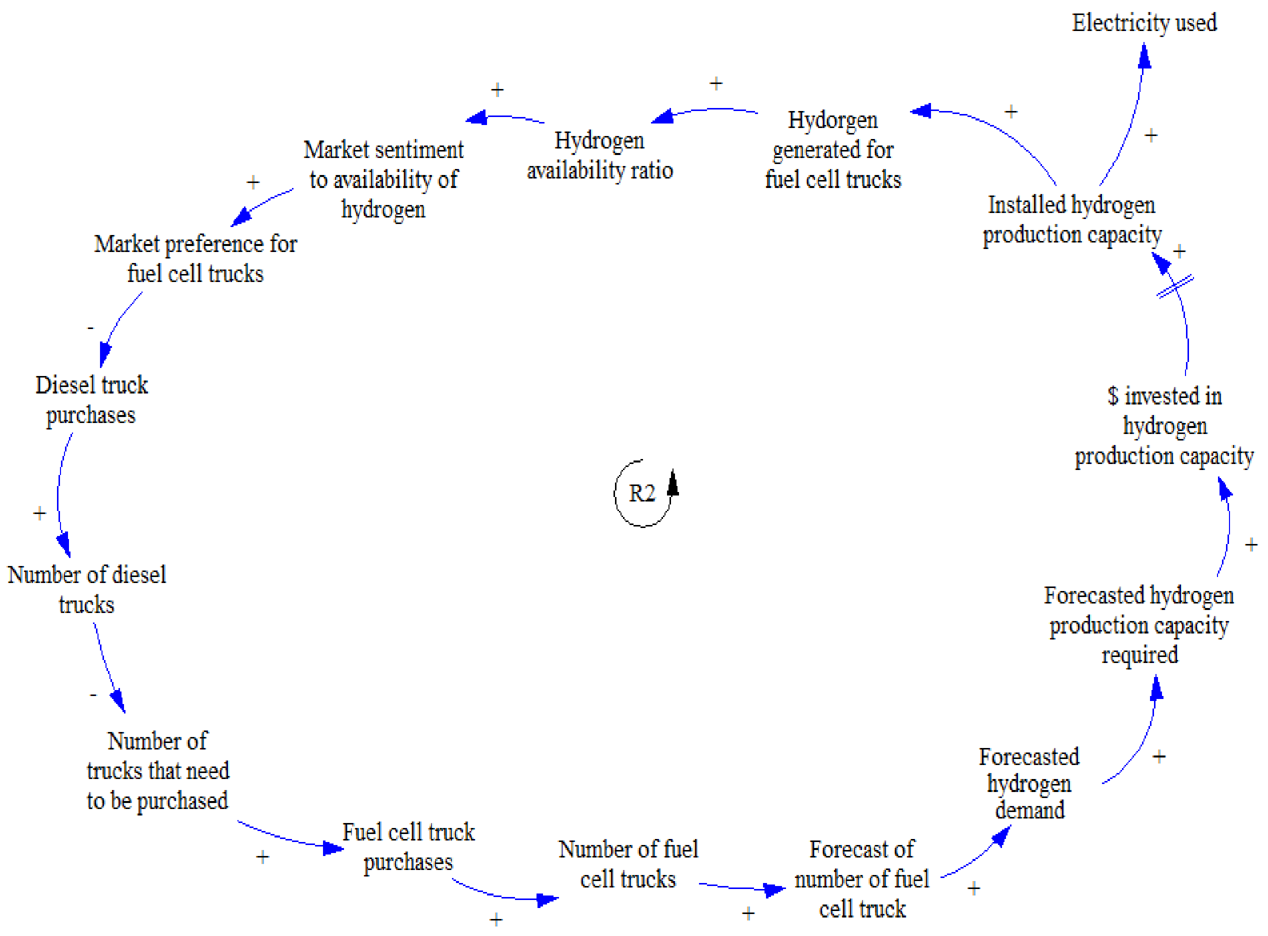


Figure 21: Diesel truck purchases CLD

4.3. Dynamic modelling

The second step in model construction is dynamic modelling. This section provides a brief overview of the stock and flow modules that were used to model the transition of New Zealand's heavy-duty vehicles from diesel to fuel cell power. The stocks and flows of each module are described mathematically, with t_0 representing the model start date of 2020, and t_n representing the model end date of 2050. The variables that were used in the final dynamic model are presented in Table 12 of Appendix A, and the individual modules are presented in Appendix B. The most important variables and assumptions of each module are discussed in this section, while a deeper look at the assumptions and limitations of the model are presented in Section 4.6. Reading through these descriptions sequentially can, again, be quite laborious and repetitive, and it is therefore suggested that the reader decides which modules they are interested in understanding better. As an introduction, a high-level overview of the model is presented in Figure 22. This overview is similar to the dynamic hypothesis presented in Figure 17.

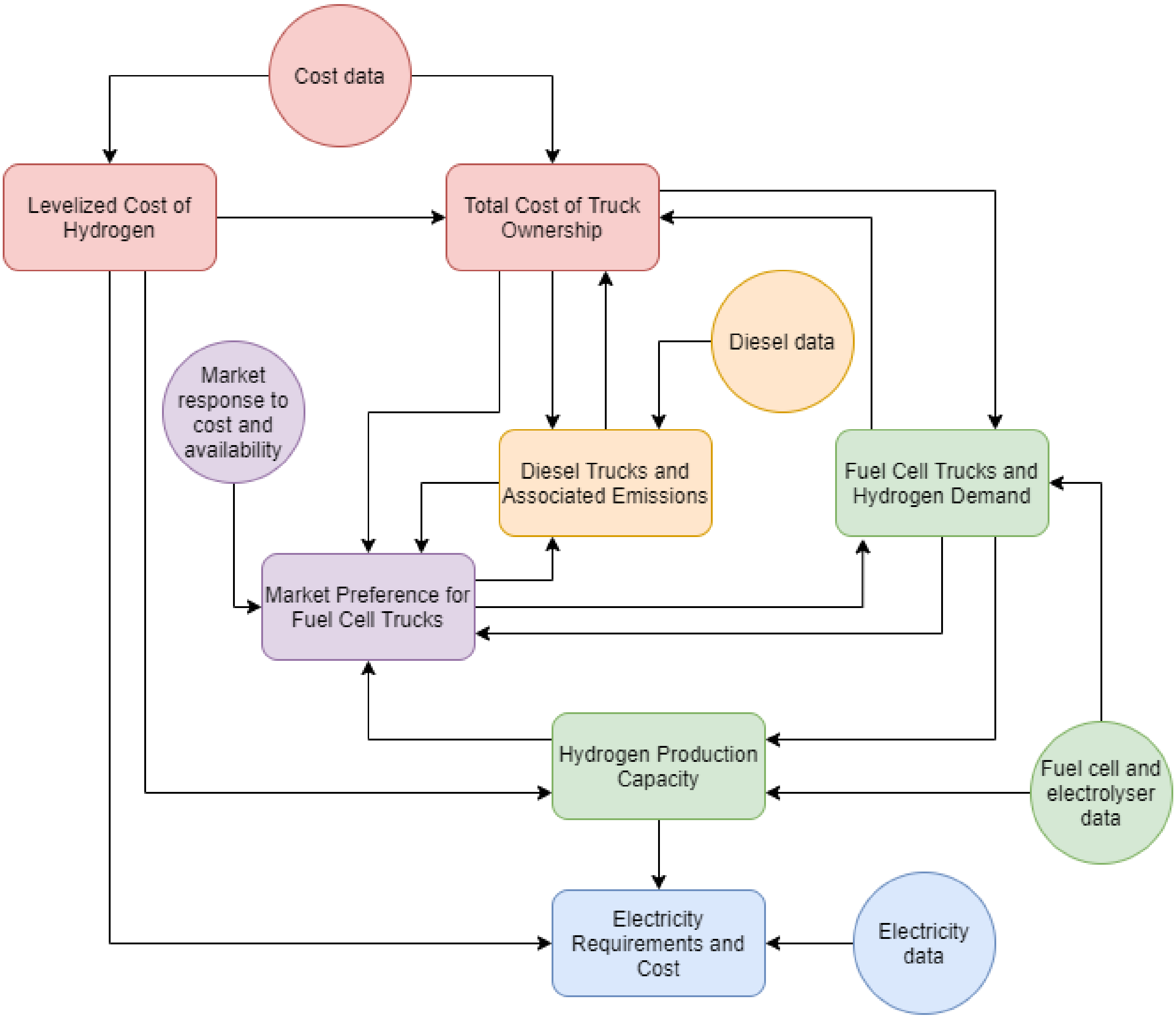


Figure 22: High-level overview of the dynamic model, with main modules presented in rectangles, and exogenous data inputs presented in circles

4.3.1. Levelized cost of hydrogen module

The purpose of this module is to dynamically calculate the levelized cost of hydrogen (LCOH) over time. The module is presented in Figure 34 of Appendix B. The module contains no stocks or flows, but the calculation of the levelized cost of hydrogen is of significant importance to the model. The concept of a levelized cost of hydrogen (LCOH) is similar to that of levelized cost of energy (LCOE). According to Sklar-Chik *et al.* (2016, p. 126), the LCOE can be understood as "*the present value of energy costs divided by the energy generated*". The LCOH is measured in $/kg and calculated based on the discounted cashflow approach presented in Genç, Çelik and Genç (2012) and Genç, Çelik and Karasu (2012) and used by Perez (2020). This method calculates LCOH as per the following equations. Many of the parameter assumptions outlined by Concept Consulting (2019c) were utilized in calculating LCOH in this module.

$$LCOH = \frac{ECC * CRF + C_{EE} + C_{OM}}{m_{H2}} \quad [\$/Kg] \quad (3)$$

Where,

$$ECC = P_r * C_{kW} \quad [\$] \quad (4)$$

$$CRF = \frac{(1+r)^n * r}{(1+r)^n - 1} \quad [Dmnl] \quad (5)$$

With variables defined as per Table 7.

Table 7: Variables used to calculate the levelized cost of hydrogen

LCHO	Levelized cost of hydrogen
ECC	Capital cost of hydrogen production system
CRF	Capital recovery factor of hydrogen production system
C_{EE}	Cost of electricity input
C_{OM}	Cost of operation and maintenance
m_{H2}	Hydrogen produced per year
P_r	Rated power of the electrolyser in the hydrogen production system
C_{kW}	Cost of the hydrogen production system per kW of installed electrolyser capacity
r	Discount rate
n	Lifetime of hydrogen production system

4.3.2. Total cost of truck ownership module

The purpose of this module is to dynamically calculate the total cost of ownership (TCO) of fuel cell trucks and diesel trucks. The module is presented in Figure 35 of Appendix B. The module contains no stocks or flows, but the calculation of the TCO is of significant importance to the model. The TCO is measured in $/truck/year and is calculated according to the method used by Concept Consulting (2019c), which considers fuel costs, CO_2 costs, vehicle capital costs, distance-based running costs, and "*other*" running costs. It is therefore important to note that the annual distance travelled by a truck, often referred to as the Vehicle Kms Travelled (VKT), will have an impact on the TCO of a truck, as well as on the emissions from diesel trucks. The data associated with VKT are provided by the New Zealand Ministry of Transport (2020b), but the manner in which the data are presented creates some challenges for effective modelling. These challenges influence the TCO less than the emissions calculations and are discussed in greater detail in Section 4.6.

Another limitation found within this module is based on the assumption that the trucking fleet increases roughly according to the average historic GDP growth rate. This assumption results in the trucking fleet almost doubling over the course of the 30-year model run. It is unlikely that such a doubling would be accommodated on the road network, and the New Zealand government is already planning to move freight off of roads and onto rail (New Zealand Government, 2019). It is beyond the scope of this project to account for this transition. The expansion of the fleet does not have a significant impact on the TCO of trucks - truck VKT remains roughly unchanged - but does have a significant impact on various other modules, most notably the modules that determine the number of trucks that need to be purchased.

Lastly, it is worth noting that for many of the parameters used in this module, a very wide spread of estimates was found for both current and future states. This sentiment is substantiated by the United States National Renewable Energy Laboratory (Hunter *et al.*, 2020, p. 22), who state that "*there is limited public, robust data on many of the total cost of ownership parameters*".

4.3.3. Market preference for fuel cell trucks module

The purpose of this module is to determine the market preference for fuel cell trucks. The market preference for fuel cell trucks can be understood as the percentage of new truck purchases that will be fuel cell trucks. The module is presented in Figure 36 of Appendix B. The module contains no stocks or flows, but the calculation of the market preference is of significant importance to the model. The market preference for fuel cell trucks is determined by a combination of the market's response to the *cost burden of buying a fuel cell truck* parameter, and the *market response to the availability of hydrogen* parameter.

The *cost burden of a fuel cell truck* parameter compares the total cost of ownership of a fuel cell truck to that of a diesel truck. The *market response to the cost burden of a fuel cell trucks parameter* is governed by an S-curved function that calculates the market's willingness to buy a fuel cell truck based on a given cost burden. The shape of the S-curve is based on the assumption that the market has a high sensitivity to the cost burden of fuel cell trucks, and therefore market preference will drop steeply if fuel cell trucks are more expensive than diesel trucks, and rise steeply if fuel cell trucks are less expensive than diesel trucks (Nikola Corp, 2020b). Furthermore, it is assumed that the market has a preference for fuel cell trucks based on their low emissions, and if all other factors are equal, then the market prefers fuel cell trucks.

The *market response to the availability of hydrogen* parameter attempts to account for the influence that a lack of hydrogen refilling stations would have on the markets willing to buy fuel cell trucks. The recent announcement of Hiringa Energy's plans to build a hydrogen refuelling network in the near future are incorporated in the model (Hiringa Energy, 2020c). The coverage provided by the Hiringa network plays a major role in calculating the *market response to the availability of hydrogen* parameter. The availability of hydrogen can grow faster than the announced Hiringa network, if the model drives sufficient investments in hydrogen production capacity, although it is expected that the Hiringa network will achieve its goal of creating such a network long before market forces alone would. For so long as hydrogen refilling stations cover less than 100% of the road network the market has a negative response resulting in a low preference for fuel cell trucks. Once the entire road network is covered the market willingness to buy fuel cell trucks is not affected by the availability of hydrogen. The response of the market to various levels of coverage is based on the Pareto principle (Sanders, 1987). If 20% of freight routes are covered, then it is assumed that 80% of the existing trucking fleet will be served. The remaining 20% is added linearly as the coverage progresses from 20% to 80%.

Both the *market response to the cost burden of a fuel cell trucks* parameter, and the *market response to the availability of hydrogen* parameter are qualitative phenomena that have been quantified in an attempt to capture the effect of these aspects in the real-world system. There is no data available regarding the exact response that the market will have to the cost burden of fuel cell trucks or the availability of hydrogen. Educated guesses and assumptions were made based on the available data. The exact shape of these responses can be contested, and this should be considered a limitation of the model.

4.3.4. Diesel trucks module

The purpose of this module is to model the fleet of diesel trucks, and their associated emissions. The module is presented in Figure 38 of Appendix B. This module contains two stocks and three flows. The *Number Of Diesel Trucks* stock *(D(t))* has two flows, namely: the inflow of *diesel truck purchases (r_{di})*, and the outflow of *decommissioning of diesel trucks (r_{do})*. Equation 6 describes the *Number Of Diesel Trucks* stock variable and the effects that the different flows have on this variable over time.

$$D(t) = D(t_0) + \int_{t_0}^{t_n} [r_{di} - r_{do}]dt \tag{6}$$

From this equation, it can be seen that the *Number Of Diesel Trucks* stock variable increases as *diesel truck purchases* increases, and decreases as *decommissioning of diesel trucks* increases. D*iesel truck purchases* are calculated by multiplying the number of trucks that need to be purchased at a given time by the complement of the *market preference for fuel cell trucks* parameter. The rate of diesel truck decommissioning is determined by the *Number Of Diesel Trucks* stock and the *Average lifetime of a diesel truck* parameter. The initial *Number Of Diesel Trucks,* indicated in the equation by $D(t_0)$, is based on the most current estimates of the trucking fleet provided by the New Zealand Ministry of Transport (2020b)

The *Emissions From Diesel Trucks* stock *(E(t))* has only one flow, namely: the inflow of *annual emissions from diesel trucks (r_{de})*. Equation 7 describes the *Emissions From Diesel Trucks* stock variable and the effects that the flow has on this variable over time

$$E(t) = E(t_0) + \int_{t_0}^{t_n} r_{de}\, dt \tag{7}$$

From this equation, it can be seen that the *Emissions From Diesel Trucks* stock increases as *annual emissions from diesel trucks* increases. *T*he initial emissions from diesel trucks is set to zero at t_0 so that accumulated emissions are representative of the modelling period. The rate of *annual emissions from diesel trucks* is determined by multiplying the *Number Of Diesel Trucks* stock variable with the *average emissions per diesel truck per year* parameter. The *average emissions per diesel truck per year* parameter is calculated using three key variables, namely: the fuel economy of a diesel truck, the average distance travelled by a truck in a year, and the carbon emissions per liter of combusted diesel. The average distance travelled by a truck in a year is calculated using the compromised VKT data introduced in Section 4.3.2. The compromised data leads to significantly lower than expected emissions for diesel trucks. Even though the calculated emissions are too low, the shape of the emissions curves is believed to be representative of the associated truck distributions. The cause of this error is well understood, and as the purpose of this study is not to measure emissions from diesel trucks this error is not believed to undermine the usefulness of the model. This finding is listed in the limitations of the study.

4.3.5. Fuel cell trucks module

This module is similar to the diesel trucks module. The purpose of this module is to model the fleet of fuel cell trucks and their associated hydrogen requirements. The module is presented in Figure 39 of Appendix B. The module contains two stocks and three flows. The *Number Of Diesel Trucks* stock *(FC(t))* has two flows, namely: the inflow of *fuel cell truck purchases* (r_{fci}), and the outflow of *decommissioning of fuel cell trucks* (r_{fco}). Equation 8 describes the *Number Of Fuel Cell Trucks* stock variable and the effects that the different flows have on this variable over time.

$$FC(t) = FC(t_0) + \int_{t_0}^{t_n} [r_{fci} - r_{fco}]dt \tag{8}$$

From this equation it can be seen that the *Number Of Fuel Cell Trucks* stock variable increases as *fuel cell truck purchases* increases, and decreases as *decommissioning of fuel cell trucks* increases. *Fuel cell truck purchases* are calculated by multiplying the number of trucks that need to be purchased at a given time by the *market preference for fuel cell trucks* parameter. The rate of fuel cell truck decommissioning is determined by the *Number Of Fuel Cell Trucks* stock and the *Average lifetime of a fuel cell truck* parameter. The initial *Number Of Fuel Cell Trucks,* indicated in the equation by $FC(t_0)$, is set to zero based on the most current estimates of the fuel cell fleet provided by the New Zealand Ministry of Transport and various news reports (Maetzig, 2019; Ministry of Transport, 2020a).

The *Total Hydrogen Demanded by Fuel Cell Trucks* stock *(HD(t))* has only one flow, namely: the inflow of *demand for hydrogen by fuel cell trucks* (r_{hd}). Equation 9 describes the *Total Hydrogen Demanded by Fuel Cell Trucks* stock variable and the effects that the flow has on this variable over time

$$HD(t) = HD(t_0) + \int_{t_0}^{t_n} r_{hd}\, dt \tag{9}$$

From this equation it can be seen that the *Total Hydrogen Demanded by Fuel Cell Trucks* stock increases as *demand for hydrogen by fuel cell trucks* increases. The rate of *demand for hydrogen by fuel cell trucks* is determined by multiplying the *Number Of Fuel Cell Trucks* stock variable with the *hydrogen required per fuel cell truck per year* parameter. The initial hydrogen demand is set to zero to reflect that there is no demand for hydrogen from fuel cell trucks in 2020.

An important variable that is calculated in this module is the *forecast of number of fuel cell trucks.* This forecast determines the expected future demand for hydrogen, and therefore the hydrogen production capacity that would be required to meet that demand. The forecast function used is a simple trend extrapolation function, which is a gross simplification of how a forecast would be calculated in a real-world market. Because the forecast function is so simple it often amplifies market volatility, leading to over- or under-estimated forecasts that can have significant effects on the supply-demand ratio of hydrogen as over- or under-investments are made in hydrogen production capacity.

In the real-world, the forecasted future hydrogen demand would be calculated with great care by a combination of players such as Hiringa Energy (Hiringa Energy, 2020a), the BusinessNZ Energy Council (BEC, 2018), and the New Zealand Ministry of Transport (Ministry of Transport, 2020c). Improving the forecast is beyond the scope of this project, and the potential for erratic forecasts should be considered a limitation of the model. To improve the probability that supply will outstrip demand, the forecasted hydrogen production capacity required to meet demand is increased by 20% in the hydrogen production capacity module. This is based on the IEA (2014) obliging it's member states to hold oil stock equivalent to 90 days (approximately 25% of the year) of it's net imports, as well as an expectation that once hydrogen outcompetes diesel there will be a very rapid increase in hydrogen demand.

4.3.6. Hydrogen production capacity module

The purpose of this module is to model the hydrogen production capacity required to meet the expected future demand for hydrogen from fuel cell vehicles. The module is presented in Figure 40 of Appendix B. The module contains three stocks and four flows. The *Total $ Invested In Hydrogen Production Capacity* stock *(PC(t))* has one flows, namely: the inflow of *$ invested in hydrogen production capacity per year* (r_p). Equation 10 describes the *Total $ Invested In Hydrogen Production Capacity* stock variable and the effects that the flow has on this variable over time.

$$PC(t) = PC(t_0) + \int_{t_0}^{t_n} r_p \, dt \tag{10}$$

From this equation it can be seen that the *Total $ Invested In Hydrogen Production Capacity* stock variable increases as *$ invested in hydrogen production capacity per year* increases. The *$ invested in hydrogen production capacity per year* is calculated by determining the deficit between the forecasted hydrogen capacity required to meet demand (with the 20% safety factor added) and currently installed hydrogen production capacity. If the forecast indicates that more production capacity is required, then the appropriate dollar amount is invested to expand the existing capacity. If the currently installed capacity is sufficient then no investments are made. The initial value of the *Total $ Invested In Hydrogen Production Capacity* stock is set to zero implying that no investments have been made before 2020.

The *Installed Hydrogen Production Capacity* stock *(HC(t))* has two flows, namely: the inflow of *hydrogen production capacity commissioned* (r_{cc}), and the outflow of *hydrogen production capacity decommissioned* (r_{cd}). Equation 11 describes the *Installed Hydrogen Production Capacity* stock variable and the effect that the flows have on this variable over time.

$$HC(t) = HC(t_0) + \int_{t_0}^{t_n} [r_{cc} - r_{cd}] \, dt \tag{11}$$

From this equation it can be seen that the *Installed Hydrogen Production Capacity* stock variable increases as *hydrogen production capacity commissioned* increases, and decreases as *hydrogen production capacity decommissioned* increases. The *hydrogen production capacity commissioned* is calculated from the *$ invested in hydrogen production capacity per year*. The *hydrogen production capacity decommissioned* is calculated based on the current *Installed Hydrogen Production Capacity* and the *lifetime of the hydrogen production system* parameter. The initial value of the *Installed Hydrogen Production Capacity* stock is set to zero implying that no capacity is installed in 2020.

The *Total Hydrogen Generated* stock *(HG(t))* has one flow, namely: the inflow of *hydrogen generated per year* (r_{hg}). Equation 12 describes the *Total Hydrogen Generated* stock variable and the effect that the flow has on this variable over time.

$$HC(t) = HC(t_0) + \int_{t_0}^{t_n} r_{hg}\, dt \tag{12}$$

From this equation, it can be seen that the *Total Hydrogen Generated* stock variable increases as *hydrogen generated per year* increases. The *hydrogen generated per year* is calculated by multiplying the *Installed Hydrogen Production Capacity* with the *Kg hydrogen produced per year per installed kW of hydrogen production capacity* parameter. The initial value of the *Total Hydrogen Generated* stock is set to zero implying that no hydrogen has been generated before 2020. This module also calculates the *hydrogen generation/demand factor*, which is an indication of the hydrogen supply-gap/surplus.

4.3.7. Electricity requirements and cost module

The purpose of this module is to model the marginal electricity investments required to power the *Installed Hydrogen Production Capacity*. The module is presented in Figure 41 of Appendix B. The module contains one stock and one flow. The *Total $ Invested In Marginal Electricity* stock *(ME(t))* has one flow, namely: the inflow of *$ invested per year in marginal electricity* (r_{cm}). Equation 13 describes the *Total $ Invested In Marginal Electricity* stock variable and the effects that the flow has on this variable over time.

$$ME(t) = ME(t_0) + \int_{t_0}^{t_n} r_{cm}\, dt \tag{13}$$

From this equation, it can be seen that the *Total $ Invested In Marginal Electricity* stock variable increases as *$ invested per year in marginal electricity* increases. The *$ invested per year in marginal electricity* is calculated based on the assumptions that all electricity for hydrogen generation will be sourced on the margin of existing electricity production capacity, and that there is an infinite amount of marginal electricity available from existing sources. The cost of marginal electricity is derived from the work of John Culy Consulting (2019). The initial value of the *Total $ Invested In Marginal Electricity* stock is set to zero implying that no marginal electricity investments have been made before 2020.

4.3.8. Sensitivity analysis module

The purpose of this module is to enable a sensitivity analysis of the lookup variables in the model. The module is presented in Figure 37 of Appendix B. The software used (Vensim) does not provide built-in functionality for conducting a sensitivity analysis of graphical functions. In this module, the limitations of the software are overcome by developing model structure that enables a sensitivity analysis of the graphical functions in the model. The module generates triangular distributions based on several input parameters. The resulting triangular distributions are used to distort the lookup function under investigation. By varying the parameters that generate the triangular distribution with the built-in sensitivity analysis it is possible to conduct a sensitivity analysis on the lookup function. The "*parametrization*" of the sensitivity analysis is based on the seminal work of Hearn (2010) as articulated by Eker *et al.* (2014, p. 189). The next section will present the results of the sensitivity analysis enabled by this module, along with several other verification and validation tests that were conducted to foster trust in the model.

4.4. Model testing

The third step in model construction is model testing. As described in Section 3.3.4, it is important to perform various verification and validation test on a model to demonstrate that the model has been constructed in a way that renders it useful to its purpose and its intended audience (Sterman, 2000). These tests are not only performed on the model once the model is believed to be near completion; rather, the model is iteratively tested throughout the modelling process. This section will outline several tests that were conducted to garner trust in the model.

4.4.1. Guideline tests

The model is first tested according to the guidelines tests of Maani and Cavana (2007), as presented in Section 3.3.4. The first step is to determine whether the CLD describes the articulated problem. The dynamic hypothesis presented in Figure 17 presents the problem faced when investigating transitions from a diesel fleet to a fuel cell fleet. Various dynamic interactions of a quantitative and qualitative nature result in multiple feedback loops that influence the behaviour of the system. It is therefore accepted that the dynamic hypothesis presents an acceptable description of the problem under investigation.

The second step is to ensure that all equations in the SFD match the polarity of the causal connectors in the dynamic hypothesis. This means that if an arrow in the CLD has a positive sign, then the equation in the SFD must clearly indicate a positive relation. An example of this is that in the dynamic hypothesis the *number of trucks that need to be purchased* is increased by the *number of trucks required*, and decreased by the *number of fuel cell trucks* and the *number of diesel trucks.* This corresponds with the equation for *number of trucks that need to be purchased* in the SFD, which is presented in Equation 14.

$$\begin{gathered} Number\ of\ trucks\ that\ need\ to\ be\ purchased\ = \\ number\ of\ heavy\ trucks\ required\ in\ a\ given\ year - \\ (number\ of\ diesel\ trucks + number\ of\ fuel\ cell\ trucks) \end{gathered} \tag{14}$$

The third step is to ensure that the model is dimensionally valid. For this, Vensim's built-in Units Check tool was used. The tool responded with the message "*Units are OK*". The built-in functionality significantly simplifies this check, and enables the model to be checked regularly

The fourth and fifth step state that the model behaviour must be plausible, and the outputs must be realistic. The model behaviour has been thoroughly considered, and no outputs have been found to be significantly erroneous to undermine the usefulness of the model. Limitations regarding the model outputs for emissions from diesel truck and investments in hydrogen production capacity are discussed in Section 4.6.

The sixth step is to ensure that the model maintains "*conservation of flow*" across the model boundary. This means that "*the total quantity of a variable that has entered and left the model, together with what is still in the model should be accounted for*" (Maani and Cavana, 2007, p. 71). All eight stock variables were tested, and it was determined that all stocks, and therefore the model in general, maintains conservation of flow.

The seventh test is to ensure that the model responds "*properly*" to extreme conditions. Vlachos *et al.* (2007, p. 381) state that "*the test exploits the fact that we, human beings, are weak in anticipating the dynamics of a complex dynamic system in arbitrary operating conditions, but are much better in anticipating the behaviour of the system in extreme conditions*". Extreme conditions test work best when the model response can be compared to historic data with similarly extreme conditions. In this study there is no historic data available, so the response of the model to extreme conditions was analysed compared to expectations. Multiple extreme conditions tests were carried out. Initial conditions, such as the initial number of diesel trucks and the initial hydrogen production capacity, were set very low, or very high; and parameters such as *electricity required per kg of hydrogen produced* were manipulated with step functions to see how they would respond to extreme conditions in the middle of the run period. An example of one of the more interesting extreme conditions test that were carried out is when the market was modelled as being indifferent to the *cost burden of buying a fuel cell truck*. This results in the availability of hydrogen being the only factor determining the market preference for fuel cell trucks (as stated in Section 4.3.3, it is assumed that if all else is equal the market prefers fuel cell trucks due to their lower carbon emissions). The model responded to this extreme condition as expected, and fuel cell truck purchases were strongly correlated to the availability of hydrogen. The model, therefore, passes all of the guideline tests suggested by Maani and Cavana (2007). Although these tests have already developed confidence in the model, the model correctness checklist of Lai and Wahba (2003) is also applied.

4.4.2. Correctness checklist

As presented in Section 3.3.4, Lai and Wahba (2003) suggest that a 12 point checklist be applied to improve trust in the model. A few of the items on the checklist overlap with the guideline tests suggested by Maani and Cavana (2007), but the results to all 12 steps are presented:

i. **Units check** – The model units were checked with the built-in Vensim functionality. This was done regularly, especially when changing the model structure;

ii. **Naming Variables** – The Vensim "capitalize by type" setting was activated to ensure that the suggested naming convention was followed throughout the model;

iii. **No constants embedded in equations** – No constants were embedded in any equations for purposes other than switching between scenarios;

iv. **Do not mention parameter values in the documentation** – no parameter values are mentioned in the main documentation. As per Lai and Wahba's (2003) suggestion, the main documentation describes the equations and the data sources, while parameter values are presented in Table 13 of Appendix D;

v. **Choose appropriately small time steps** – the time step was set to 0.0625 which is sufficiently small for the purpose of this study. It was observed that decreasing the model time step does not result in variations in the model output;

vi. **Stock values can be changed only by flows** – all stock variables were checked, and it was found that the value of stocks only changed by means of flows running into or out of the stock. The exception to this rule is that initial values, which determine the value of a stock at the start of the modelling period, were used;

vii. **Every flow should be connected to a stock** – as can be seen in the figures presented in Section 4.3 all flows were connected to a stock;

viii. **Flows should not be linked to auxiliary variables or to other flows** – as can be seen in the figures presented in Section 4.3 no flows were connected to auxiliary variables or to other flows;

ix. **Stocks should not be linked to stocks** - as can be seen in the figures presented in Section 4.3 no stocks were linked to other stocks;

x. **Use of IF THEN ELSE, MIN/MAX and other logic statements should be limited** – the use of logical statements was used predominantly to enable scenario analysis and sensitivity analysis. Table functions were used extensively to limit the use of logical statements within the model calculations;

xi. **Use of Initial Values** - All stocks were assigned initial values based on data sources that are listed in the model itself; and

xii. **Curving connectors** – As can be seen in the figures presented in Section 4.3 curving connectors were used to improve model aesthetics.

The model therefore passes all of the requirements of Lai and Wahba's (2003) checklist. The results of these tests improve the confidence that has already been developed in the model. The sensitivity of the model to various parameters will be tested in the following section.

4.4.3. Sensitivity analysis

Although Vensim has the capability to run sensitivity analyses on model parameters that are defined as constants, the software does not have built-in functionality for running sensitivity analyses on parameters that are defined as graphical functions (also known as lookup functions). This is a significant shortcoming of the software, as graphical functions are often associated with high degrees of uncertainty (Eker *et al.*, 2014). Many parameters in this study were defined using lookup functions as they provide an easy and intuitive way to represent changes in value over time. If there were only a small number of graphical functions to be tested it would have been permissible to apply a simple approach such as manually distorting the points that comprise the function, or multiplying the function by a constant factor (Eker *et al.*, 2014). As the model contains many graphical functions, and the sensitivity analysis is of significant importance to the verification and validation process, it was decided that a more robust approach than manual manipulation was required. Hearne (2010, p.

107) was one of the first to suggest an approach to conducting sensitivity analysis on graphical functions "*in an automated way without the need to specify alternative functional forms*". His work has been taken further, and applied to system dynamics, by Eker *et al.* (2014). In short, their method generates a distortion function that has *"a specific form but variable parameterization"*(Eker *et al.*, 2014, p. 189). This distortion function is then multiplied with the graphical function under investigation to cause an agitation within the original function – this can be visualized as a "*wiggling*" of the original graphical function. The built-in parameter sensitivity analysis tool can then be used to generate various agitations of the graphical function. In this way, the problem of graphical function sensitivity analysis is reduced to parametric sensitivity analysis. In this study a triangular distribution was chosen as the function form that would be generated by the distortion function. Although there are limitations associated with this method, it was found to be sufficient for the purposes of this study. The model structure used to generate the distortion functions can be seen in Figure 37. Vensim's subscript functionality is employed, which prevents the need for repetition in the model structure.

Once the parameterization of the sensitivity analysis was complete, it was possible to conduct the sensitivity analysis. The results of univariate sensitivity analyses can be seen in Appendix C. Of greater interest to this study is the results of the multivariate sensitivity analysis, which considers how sensitive the model is too small changes in the value of multiple variables being investigated at the same time. Sensitivity to the following variables was tested: *electrolyser capex, cost of electricity, fuel cell truck capex, electrolyser efficiency, fuel economy of a fuel cell truck,* and the *market response to the cost burden of fuel cell trucks*. These variables were chosen based on insights from the literature as well as insights from the model building process. The results of the multivariate sensitivity analysis on key model outputs are presented in Figure 23 to Figure 26. These results are from a "*middle of the road*" scenario as discussed in greater detail in Section 4.5. As expected, the *market preference for fuel cell trucks* is one of the most sensitive variables. This variable represents the market's elasticity to the cost and availability of hydrogen as opposed to diesel. The function governing this response was developed based on various quantitative and qualitative data and defined as an input-output or "*lookup*" function in the model. Therefore, even a small change in the inputs to this function can cause a significant change to the output. The other variables exhibit relatively low sensitivities to the multivariate analysis, although it can be seen that certain modelling periods are more sensitive than others.

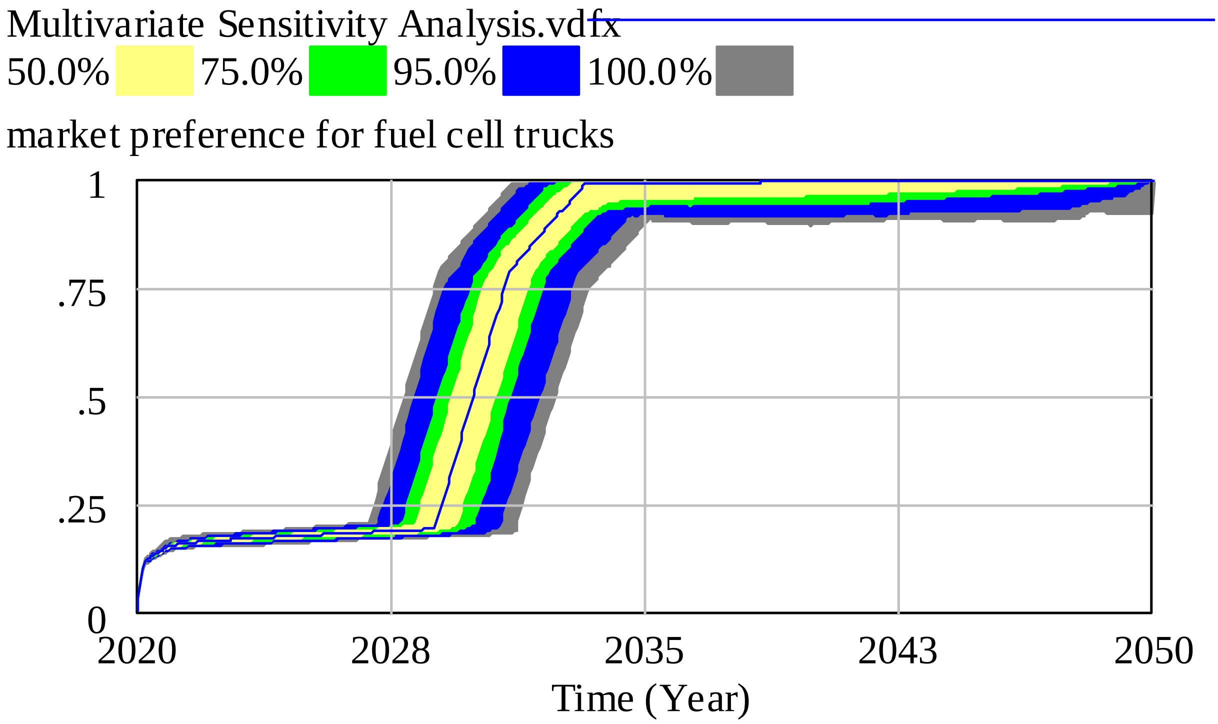


Figure 23: Effect of multivariate sensitivity analysis on market preference for fuel cell trucks

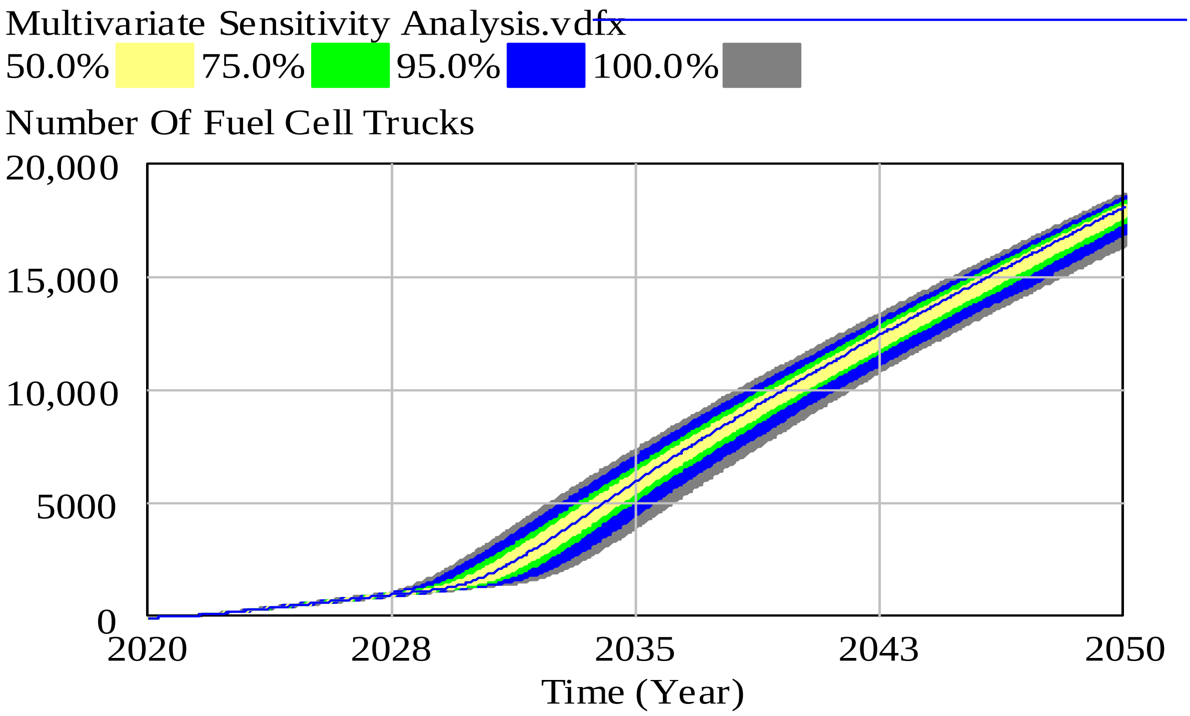


Figure 24: Effect of multivariate sensitivity analysis on number of fuel cell trucks

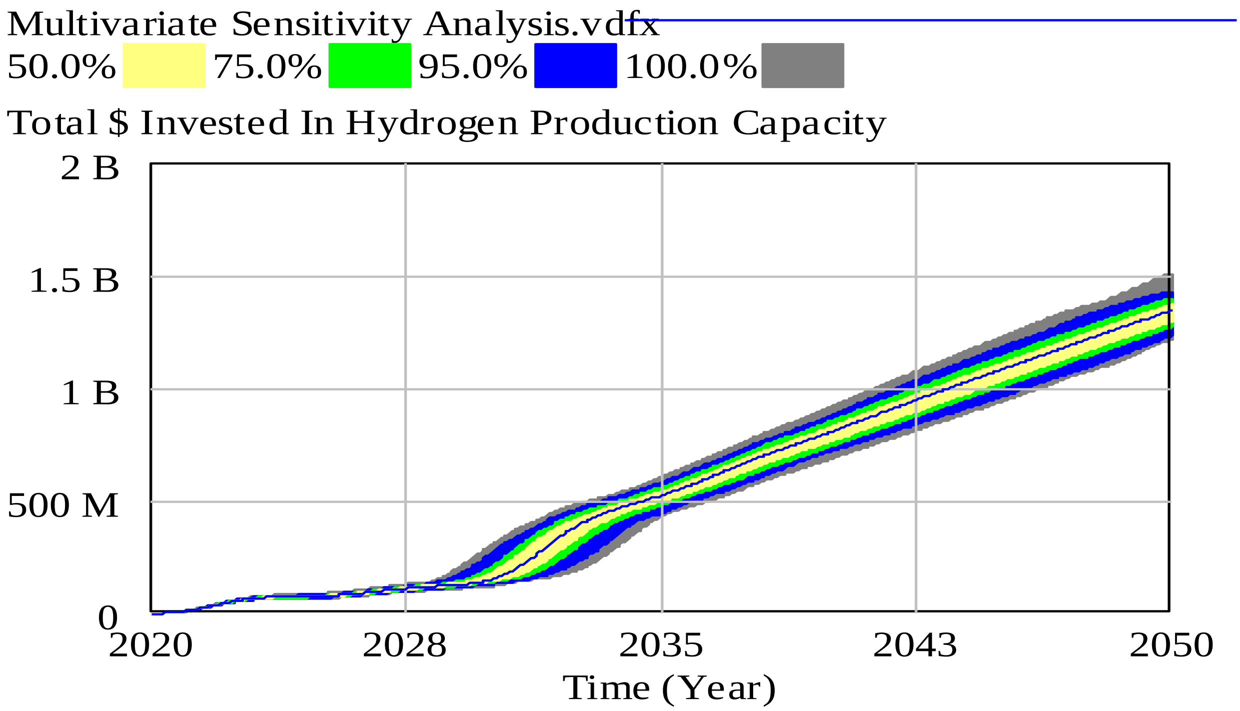


Figure 25: Effect of multivariate sensitivity analysis on investments in hydrogen production capacity

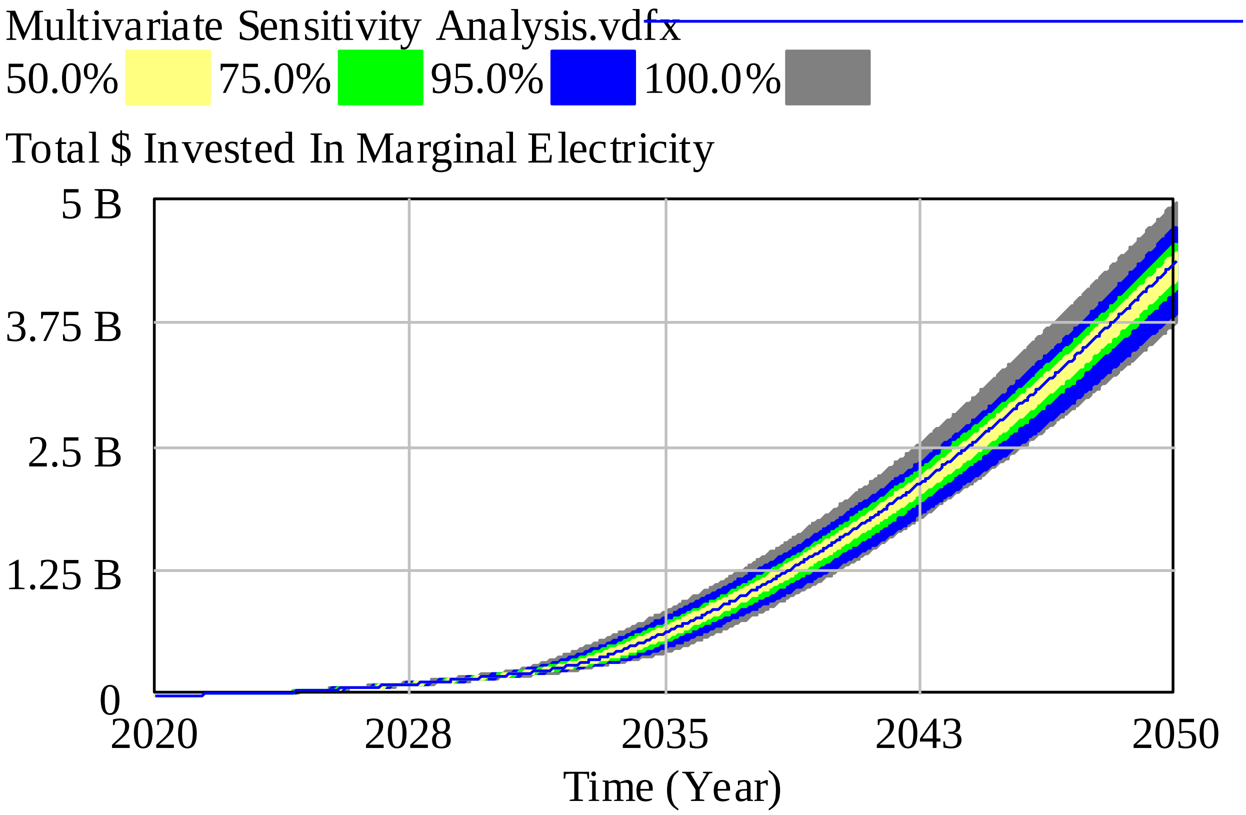


Figure 26: Effect of multivariate sensitivity analysis on investments in marginal electricity

4.4.4. Summary and conclusion of model testing

The model was subjected to various tests suggested by Maani and Cavana (2007) and Lai and Wahba (2003) both during model construction and at model completion. The model passed all these tests. The need for a more thorough sensitivity analysis than that offered by the chosen software was, however, identified. To this end, Hearne's (2010) method as described by Eker *et al.* (2014) was applied to the mode to enable a parameterized sensitivity analysis of graphical functions. Univariate and multivariate sensitivity analyses were then conducted, finding that the model sensitivities were well aligned with expectations. Based on the outcome of the numerous tests and analyses, the model has displayed sufficient cause for confidence. The model is therefore viewed as accepted. In light of the position held by Quarton *et al.* (2020, p. 80) that "*above all, transparency is essential*" the model in its entirety, along with support materials, is publicly available online[4]. Additionally, model variables are annotated roughly according to the method suggested by Martinez-Moyano (2012), which should improve the ease with which the model and the various assumptions can be understood. The following section will describe the planning of various scenarios of interest, followed by a section outlining the various assumptions and limitations of the scenarios and the model as a whole.

4.5. Scenario planning

The final step in model construction is scenario planning. This section describes the development of the various scenarios that were subsequently modelled. As articulated in Section 3.3.1, scenario planning is a key part of the modelling process which enables various parameter values and policies to be explored. Maani & Cavana (2007) emphasize the importance of keeping the problem under investigation in mind when designing scenarios. In the case of this study, the primary aim of the research is to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. The key model outputs that indicate the necessary investments are the investments in hydrogen production capacity and the investments in marginal electricity. However, considering these two factors alone does not provide enough insight into the extent of the transition. Therefore, these two factors are considered along with the market preference for fuel cell trucks, the number of diesel trucks on the road, the total emissions from diesel trucks, the number of fuel cell trucks on the road, and the installed hydrogen production capacity. Various technologies influence these key model outputs, and the data indicate large uncertainties in both the current and future state of many of these technologies. Additionally, there is uncertainty regarding policies such as carbon taxes and the prohibition of the sale of new vehicles with internal combustion engines – as recently seen in California (State of California, 2020). By designing scenarios carefully, it is possible to capture the wide spectrum of potential futures that might result from all these uncertainties.

In designing the scenarios, four fundamental input parameters related to technology were selected, namely: electrolyser cost, fuel cell truck cost, the fuel economy of a fuel cell truck, and the cost of electricity. Additionally, two policy parameters were considered, namely: a carbon tax policy, and a policy preventing the purchase of diesel trucks. Lastly, the possibility of zero decarbonisation was considered as a reference for the theoretical maximum carbon emissions from the heavy-duty vehicle sector. When a policy prevents the model from purchasing either a fuel cell truck or a diesel truck,

[4] Model and support materials are available at: www.github.com/RickKotze/thesis

the model resorts to filling the need for trucks exclusively with the remaining option. Except for the zero decarbonisation policy (which would be binary), it is possible to imagine a high, low, and medium state for each of these input scenarios. By varying the state of the input parameters in this way it is possible to generate hundreds of scenarios. Even if the policies preventing the purchase of a given vehicle are ignored, and the other variables are only allowed to take a high or a low value - there would still be sixteen scenarios representing the case where electrolyser cost is kept low. This is presented in Table 8.

It is therefore clear that the challenge in scenario planning lies not in generating as many scenarios as possible, but in generating as few scenarios as is necessary to explore the problem space given the problem that is being investigated. Maani and Cavana (2007) suggest that in most cases less than four well-planned scenarios should be sufficient. This is in line with the approach typically taken by the energy sector, in which three or four scenarios are considered, namely: a high or 'optimistic' scenario, a low or 'pessimistic' scenario, a medium or 'middle of the road' scenario, and a 'business as usual' scenario (Fuel Cell and Hydrogen Energy Association, 2020; Interim Climate Change Committee, 2019; IPCC, 2018). After much consideration of the possible options, five scenarios were developed. These scenarios are described in detail as an understanding of the scenarios is essential to interpreting the model outputs accurately. In line with the modelling practices suggested by Lai and Wahba (2003) the parameter values used in each scenario are not presented in the main documentation, but rather in Table 11 of Appendix D.

Table 8: Example of possible scenarios

Scenario Number	Electrolyser capex	Fuel cell truck capex	Fuel economy of fuel cell truck	Electricity cost	Carbon tax
1	L	L	L	L	L
2	L	H	L	L	L
3	L	L	H	L	L
4	L	L	L	H	L
5	L	L	L	L	H
6	L	H	H	L	L
7	L	L	H	H	L
8	L	L	L	H	H
9	L	H	L	H	L
10	L	H	L	L	H
11	L	L	H	L	H
12	L	H	H	H	L
13	L	L	H	H	H
14	L	H	L	H	H
15	L	H	H	L	H
16	L	H	H	H	H

Scenario 1: No hydrogen

The no hydrogen scenario sets a baseline for a diesel-only future. In some sense, this may be seen as a business-as-usual scenario, with the future reflecting the past behaviour of the market – namely all new truck purchases are diesel-fuelled. Therefore, this scenario can act as a baseline to which the other scenarios can be compared. As a rule, this scenario would result in no investments being made towards a hydrogen transition, regardless of the extent to which hydrogen technologies mature. Therefore, total sectoral emissions would be at a maximum in this scenario as no decarbonisation strategy is employed. Although this scenario is worth considering in comparison to the other scenarios, by itself it does not contribute to the main aim of the study.

Scenario 2: Low hydrogen

The second scenario might also be called the pessimistic scenario. In this scenario, parameters are chosen to reflect the literature that is more pessimistic about the future state of essential hydrogen technologies. Many of the parameters are based on the work of Concept Consulting (2019c), whose work, as discussed in Section 2.4.1, should be familiar to many stakeholders currently active in this space. In this scenario, the initial cost of hydrogen technologies is typically higher than the other scenarios, and learning curves are weaker – resulting in costs decreasing more slowly over time. Additionally, fuel cell technologies are modelled at their least efficient estimates, and carbon taxes are set very low. This scenario outlines the lowest, and slowest, uptake of fuel cell trucks.

Scenario 3: Average hydrogen

This scenario might also be called the middle of the road scenario. An effort was made to take the average of the estimates found in the literature for each parameter. International data, as well as data specific to New Zealand, were considered. In effect, this scenario offers a "*best-guess*" at how each of the key parameters will unfold over the course of the modelling period. In most cases, this scenario uses more optimistic parameter values than scenario 2, and therefore the hydrogen uptake in this scenario is expected to be slightly faster. The parameter assumptions used in scenario 3 were employed in the generation of the sensitivity analysis presented in the previous section.

Scenario 4: High hydrogen

This scenario might also be called the optimistic scenario. In this scenario, parameters are chosen to reflect the literature that is optimistic about the future state of essential hydrogen technologies. In this scenario, the initial cost of hydrogen technologies is typically lower than the other scenarios, and learning curves are stronger – resulting in costs decreasing faster. On the other hand, fuel cell technologies are modelled at their most efficient estimates, and carbon taxes are set higher than the other scenarios. This scenario outlines a very ambitious uptake of fuel cell trucks.

Scenario 5: Immediate hydrogen

This scenario is established to define the upper bounds of hydrogen uptake. The scenario represents the immediate implementation of a policy that requires all new truck purchases to be fuel cell trucks. By definition, no diesel truck purchases are made in this scenario, resulting in this scenario achieving the lowest carbon emissions, regardless of the costs required to do so. Except for the parameter used to implement the ban on diesel truck purchases, this scenario uses the same parameter values as scenario 3. In other words, this scenario assumes that hydrogen technology develops as per the "*best guess*" estimates of scenario 3, but that diesel truck purchases are prohibited.

4.6. Statement of assumptions and limitations

Quarton *et al.*(2020) suggest that model assumptions and limitations should be reviewed prior to discussing model results. This is so that the results can be discussed with a better understanding of the model's imperfections. Quarton *et al.*(2020) also suggest that model assumptions and limitations should be addressed with respect to *each scenario* if there are any significant differences in the assumptions and limitations of the scenarios. For the most part, the five scenarios designed in Section 4.5 share the same set of assumptions and limitations. However, as scenario one and scenario five employ a forcing function to prevent the purchase of either fuel cell trucks or diesel trucks, their results should be considered with this additional limitation in mind. Other than that, the assumptions and limitations discussed in this section apply to all five scenarios.

Assumptions

When interpreting the results generated by a model it is important to understand the assumptions underlying the model itself. This is especially important when interpreting models of complex systems and models that investigate novel technologies, as assumptions can have significant implications for scenario results (Quarton *et al.*, 2020). To ensure all assumptions are clearly communicated, Quarton *et al.*(2020) argue that - as far as is possible - the model and associated data should be made public. As stated in Section 4.4.4, the entire model, with all the associated data is made available online to ensure full transparency. The most important assumptions that were made during the modelling process are:

xiii. It is assumed that cost reductions resulting from learning curves are driven by cumulative production quantities as per Wright's law of technological progress (Nagy *et al.*, 2013). This implies that technology learning curves operate at a global scale and that New Zealand is not able to significantly influence these learning curves by itself as international investments (and therefore production quantities) in hydrogen technologies are expected to be orders of magnitude larger than the investments made by New Zealand (European Commission, 2020b);

xiv. Similar to the above, it is assumed that the standardization and regulation necessary for hydrogen technologies to flourish will be progressed internationally. This would mean that New Zealand would be responsible only for adapting international progress into a local context. The costs to New Zealand of implementing the necessary standardization and regulation are therefore deemed to be insignificant;

xv. The assumption is made that the New Zealand government would support the hydrogen transition by putting the necessary standardization and regulation in place once market signals indicate that it is necessary to do so. This assumption is supported by the active interest and support that the government has shown in hydrogen transitions to date (MBIE, 2019b);

xvi. It is assumed that the planned hydrogen refilling network announced by Hiringa Energy will be carried out as planned (Hiringa Energy, 2020c);

xvii. The model works on the assumption that all green hydrogen generation is met with polymer electrolyte membrane (PEM) electrolysers, and that these electrolysers are located on-site at refuelling stations, i.e.: in a distributed (not centralized) manner;

xviii. As most low carbon futures are built around electricity, it is assumed that any necessary upgrades or improvements to the New Zealand electricity grid would be required regardless of the exact technology used. Therefore, the cost of such improvements is not assigned to enabling hydrogen specifically and is not considered in this model;

xix. The price of electricity is assumed to remain roughly within historic ranges as it is assumed that an increase in demand would result in the commissioning of additional power plants that would balance out the supply-demand ratio with mature renewable electricity technologies that are expected to provide electricity at progressively lower costs (EMI, 2020). Additionally, the model assumes that all electricity for hydrogen generation will be sourced on the margin of existing electricity production capacity and that there is an infinite amount of marginal electricity available from existing sources. The cost of marginal electricity is derived from the work of John Culy Consulting (2019);

xx. It is assumed that fuel cell trucks have a comparable payload to diesel trucks (Hyundai, 2020). It is also assumed that the lifetime of fuel cell trucks is similar to diesel trucks and that the number of trucks required on the road increase roughly according to the growth in GDP. It has already been mentioned that such growth is contentious as it is expected that at some point a portion of freight will move to rail. Additionally, the model does not account for autonomous driving or similar changes to the basic structure of how the heavy-duty vehicle sector is currently operating;

xxi. It is assumed that electrolysers and fuel cell trucks will be readily available on the market;

xxii. Only hydrogen fuel cell trucks are considered as a decarbonisation option. Biodiesel, battery-electric, and other alternatives do not compete with hydrogen in this model; and

xxiii. The model targets a 20% surplus of hydrogen to prevent hydrogen stockouts. This is in line with current practices surrounding diesel, and it is assumed that these practices will extend to hydrogen (IEA, 2014).

Limitations

All models have strengths and weaknesses which should be considered when analysing model outputs (Sterman, 1991). Although all models have weaknesses, these weaknesses do not necessarily prevent the model from being useful to its intended purpose. Instead, the model output should be considered while holding an understanding of its limitations in mind (Sterman, 1991). The tests performed on the model in Section 4.4 have developed confidence in the model's usefulness but have also highlighted certain limitations of the model. The known limitations of greatest significance are listed below:

i. The forecasting function used is the standard "*FORECAST*" function offered by the software package used (Vensim). As noted in the software documentation, this is a trend extrapolation function which "*performs very badly at turnarounds*" (Vensim, n.d.). As such the model is susceptible to bad forecasts, which can result in significant under- or over-investments in hydrogen production capacity. In practice, a regulating body such as Hiringa Energy (2020a) would monitor the supply and demand of hydrogen closely. For the sake of this model, it is assumed that a supply shortfall (if it occurs) is either met by steam methane reformation technology or results in lost sales and that an excess of supply is absorbed over time. The overinvestment should be considered when analysing the model's financial outputs;

ii. The most current estimate for Vehicle Kms Travelled (VKT) provided by the New Zealand Ministry of Transport (2020b) is based on data from 2018 and provide an average VKT for all trucks, rather than disaggregating the data into the various classes of truck. This is problematic as it can be assumed that there are significant variations in the VKT of the various truck classes, and that heavy-duty vehicles would have a higher-than-average VKT. It is beyond the scope of this study to collect disaggregated data on the various truck classes, and this is noted as a limitation of the study. The impact of this data aggregation is most significant in the calculation of emissions from diesel trucks. The reduced VKT results in significantly reduced emissions, although the trend of the emissions profile over the study period is expected to be representative of the manner in which carbon emissions would change for the associated vehicle adoption rates;

iii. The method that was used for carrying out a sensitivity analysis, and the limitations of this method, are described in detail in Eker *et al.* (2014). The most notable limitations of this method include its lack of analysis at the model start and finish times, and the potential that the resulting lookup functions will be non-monotonic;

iv. The market's response to the cost and availability of hydrogen is defined by lookup functions. These lookup functions are synthesized from qualitative and quantitative data, and thus are subjective. Every effort was made to make these lookup tables as sensible and accurate as possible, but in some instances the lookup functions do cause sharp changes in model behaviour as can be seen in Figure 23. Detailed descriptions of how the lookup tables were generated can be found in Section 4.3.3;

v. Data were collected from Nikola Motors (Nikola Corp, 2020b). The company has since fallen into disrepute, and there are claims that they overstated the maturity and competitiveness of their technologies (Hindenburg Research, 2020). As the model does not make exclusive or extensive use of the data collected from Nikola Motors, it is expected that the model would not be significantly compromised even if their data are incorrect;

vi. The nature of hydrogen technologies – and a hydrogen economy – is that there are significant and compounding benefits to be realized as hydrogen becomes more prevalent. This document discussed various sectors of the economy that lend themselves to hydrogen, but only HDVs are modelled. It is generally expected that if multiple sectors transition to hydrogen there will be overlapping benefits between the sectors (Hydrogen Council, 2020). Any such benefits are not considered in this model, as the HDV sector is modelled in isolation;

vii. First order differential equations are used to model the decommissioning of trucks and hydrogen production capacity. This is standard practice in system dynamics modelling. Although this method works well in many cases it does have certain limitations. Of consequence to this model is the possibility that diesel trucks remain in use for too long, and thereby prevent the purchase of the fuel cell trucks that would replace them. For more on this see *Mathematics behind System Dynamics* by Choopojcharoen and Magzari (2012); and

viii. Only carbon dioxide emissions are considered for diesel trucks. This is because other emissions account for less than 1% of total emissions according to Collier *et al.* (2019).

4.7. Chapter 4 conclusion

In the previous chapter, a methodology for modelling hydrogen transitions with system dynamics modelling was established by combining hydrogen transitions literature with system dynamics modelling literature. The application of the first three steps of the resulting methodology was documented in this chapter. First, the study conceptualization was articulated by defining the purpose, scope, and other essential parameters of the study. The second step, model construction, was documented according to the four sub-steps of which it is comprised. The first sub-step presented the dynamic hypothesis of the problem and discussed the various causal loop diagrams. The second sub-step presented the stock and flow diagrams, or modules, that together formed the dynamic model. In the third sub-step, the model was put through various tests and a sensitivity analysis was performed. Because the software that was used (Vensim) does not include built-in functionality for conducting a sensitivity analysis on graphical functions, the graphical functions were parameterized using Hearne's method as presented by Eker *et al.* (2014). The model passed all the tests, and the results of the sensitivity analysis did not undermine the usefulness of the model. In the fourth sub-step, model scenarios were planned. The possibility of generating hundreds of scenarios was identified, but the approach suggested by Maani and Cavana (2007) and followed by the energy sector was taken instead. In this approach, only as many scenarios as is necessary to explore the problem space - given the problem that is being investigated – are generated. It was found that five well-planned scenarios would suffice. Finally, in the last section of the chapter, the key assumptions and limitations of the model were listed.

This chapter not only presented key aspects of the model but also developed trust in the model's usefulness. This was achieved by showing that the model passes various confidence-building tests suggested in the system dynamics modelling literature while conforming to the requirements of modelling hydrogen transitions. By presenting the model's limitations and key assumptions, a high level of transparency was achieved. To maximize model transparency the model is made available online. These efforts garner a high level of trust in the model's usefulness. The next chapter presents a discussion of the results of the modelled scenarios.

Chapter 5
Discussion of results

The final step of the modelling process is presented in the last two chapters of the report in order to improve the readability of the report. This chapter presents an overview and comparison of the most important outputs from the modelled scenarios, and the following chapter presents conclusions and recommendations drawn from these outputs. To interpret the results presented in this chapter accurately, it is essential to have an adequate understanding of the modelled scenarios, as well as the assumptions and limitations of the model. To revise the modelled scenarios see Section 4.5, and to review the parameter values used in each scenario see Table 13 of Appendix D. To revise the model assumptions and limitations see Section 4.6. Although the model has various shortcomings, the model testing carried out in Section 4.4 has provided sufficient confidence in the model's behaviour and output. Key results from the modelled scenarios are presented in Table 9 and subsequently discussed. A discussion of the results of the modelled scenarios addresses the fifth research objective and enables the final research objective to be achieved in the next chapter.

5.1. Market preference for fuel cell trucks

The model outputs for the *market preference for fuel cell trucks* parameter are presented in Figure 27. As discussed in Section 4.3.3, this parameter determines the percentage of new truck purchases that will be fuel cell powered. The complement of the new purchases required is diesel-powered. As this is the main mechanism controlling the distribution of new truck purchases, it is of great importance to the model, and these results should be kept in mind when considering the other model outputs. In scenarios one and five this parameter is forced to zero and unity, respectively. By forcing the value of the parameter in this way, the policy of 100% diesel truck purchases and 100% fuel cell truck purchases is achieved, leaving little to be discussed for those scenarios. In scenarios two, three, and four, this parameter is calculated as the product of two lookup functions, namely: the *market response to the cost burden of fuel cell trucks*, and the *market response to the availability of hydrogen*. Both lookup functions are discussed in more detail in Section 4.3.3. It is important to note that the output resulting from the combination of the two lookup functions has more abrupt changes than would be expected in the real-world system. This is noted as a limitation of the study in Section 4.6 but is not believed to be sufficiently erroneous as to prevent the model outputs from being useful.

What the response curves in Figure 27 indicate is that – as expected – once the market decides that the cost and availability of hydrogen outcompete that of diesel, there will be a swift transition towards new purchases being predominantly fuel cell electric (Nikola Corp, 2020b). This can be seen in the steep increase experienced by scenarios two, three, and four in Figure 27. It is also understood that until the hydrogen option outcompetes the diesel option, there will be minimal interest in the hydrogen option. This can be seen by the initial period of low interest before the rapid increase begins. Figure 27 shows that all three scenarios that are calculated – and not forced – reach a value of 100 percent by the model end period of 2050. This means that even in the pessimistic scenario, presented by scenario two, fuel cell trucks will eventually outcompete diesel trucks. It is also worth noting that as the model only considers diesel and fuel cell trucks, the market is shared by only these two technologies. In reality, there will likely be various alternative decarbonisation options to consider.

Table 9: Key results from the modelled scenarios

	Scenario 1		Scenario 2		Scenario 3	Scenario 4		Scenario 5	
	Value	As % of Scenario 3	Value	As % of Scenario 3	Value	Value	As % of Scenario 3	Value	As % of Scenario 3
Market Preference for fuel cell trucks	0	0%	1	100%	1	1	100%	1	100%
Number of diesel trucks in 2050	24464	482%	7122	140%	5078	2687	53%	2508	49%
Total emissions by 2050 (MILLIONS OF TONS)	12.12	169%	8.477	118%	7.179	4.517	63%	4.316	60%
Number of fuel cell trucks in 2050	0	0%	17341	89%	19385	21776	112%	21956	113%
Annual hydrogen generation in 2050 (MILLIONS OF KG)	0	0%	83.404	92%	91.096	100.988	111%	101.73	112%
Total hydrogen generated by 2050 (MILLIONS OF KG)	0	0%	925.734	79%	1171.11	1808.87	154%	1868.2	160%
Marginal electricity required in 2050 (GWh)	0	0%	5004.25	107%	4682.35	5190.78	111%	5228.9	112%
Total $ invested in hydrogen production capacity by 2050 (BILLIONS OF DOLLARS)	0	0%	1.369	94%	1.452	1.274	88%	2.021	139%
Total $ invested in marginal electricity by 2050 (BILLIONS OF DOLLARS)	0	0%	4.332	92%	4.726	7.394	156%	7.649	162%

Although these results might seem very optimistic to a novice eye, they do in fact mirror many of the latest forecasts made by reputable sources. The Hydrogen Council (2020), The International Council on Clean Transportation (Hall and Lutsey, 2019), and the Energy Transitions Commission (2020) agree that hydrogen fuel cell trucks will become cost-competitive with diesel alternatives before 2030. Standing in further motivation to this is the recent surge in publications of national hydrogen strategies (WEC, 2020) – many of which make explicit their plans for hydrogen fuel cell trucks in the near future. These indicators are also in line with the increased attention given to hydrogen by the trucking industry (Cummins Inc., 2019; Hirsch, 2020; Hyundai, 2020; Nikola Corp, 2020b).

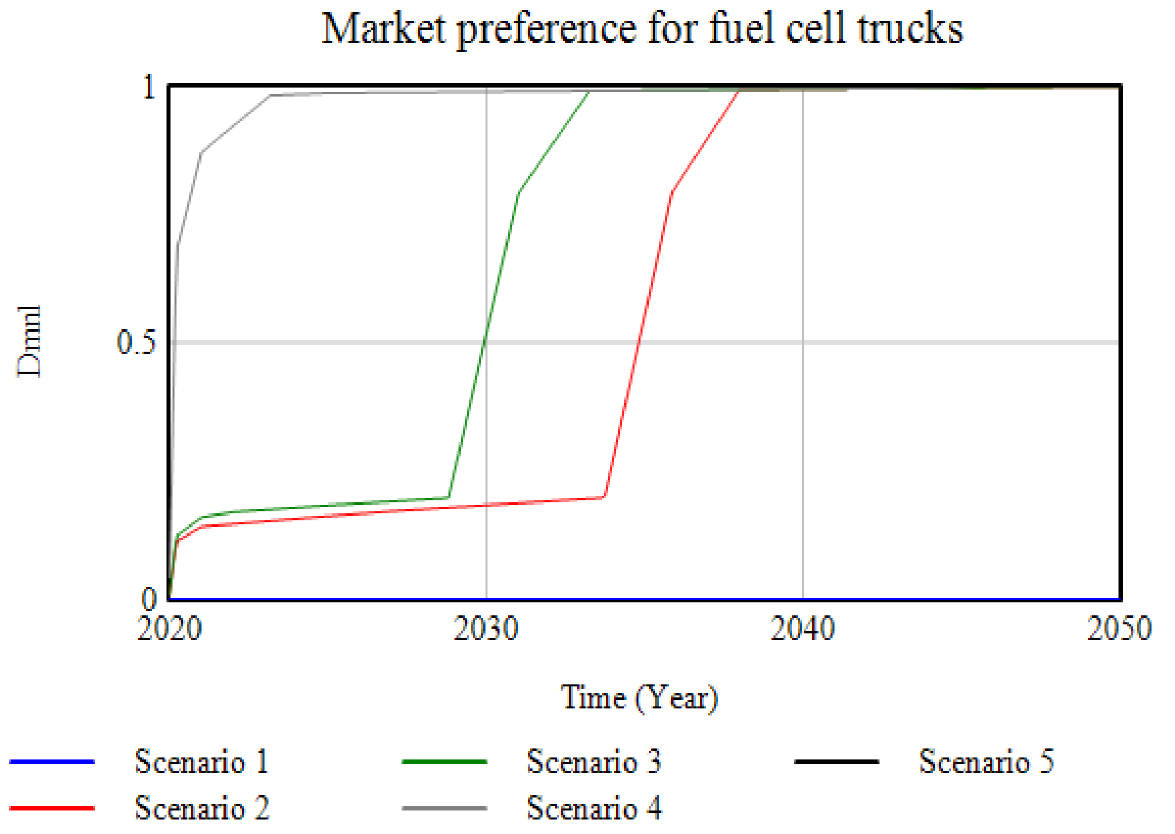


Figure 27: Market preference for fuel cell trucks in various scenarios

5.2. Diesel trucks and associated emissions

The number of diesel trucks in various scenarios is presented in Figure 28. As expected, scenario one results in the highest numbers of diesel trucks on the road at any point in time. This is because scenario one does not allow any fuel cell truck purchases. Therefore, all new purchases are filled exclusively by diesel trucks, regardless of how hydrogen technology develops. As noted before, the assumption that the number of trucks required in New Zealand will grow apace with GDP for the entire modelling period is contentious as it is likely that New Zealand will expand their rail network, reducing the increase in freight transported by trucks. The growth of the trucking sector is traced out by scenario one, which can be seen as the business-as-usual scenario, extending the current trend in which all new truck purchases are diesel-fuelled. Conversely, scenario five allows no diesel purchases at any point in the modelled period. Therefore, the number of diesel trucks in scenario five represents the initial number of diesel trucks aging out of the model. The first order differential equation that is used to determine the number of trucks decommissioned each year is limiting in that it retains diesel trucks in the stock for longer than would be expected. This limitation is addressed in greater detail in Section 4.6. Although this limitation is worth understanding, it does not undermine the usefulness of the model.

The number of diesel trucks in scenarios two, three, and four, can be derived from the *market preference for fuel cell trucks* presented in Section 5.1. Scenario four tracks closely to scenario five as the market preference turns to hydrogen very soon after the start of the modelling period. Because the two scenarios exhibit similar market preferences, they also exhibit a similar number of the two types of trucks. Scenario three and four display very different behaviour. Initially, scenarios three and four track closely to scenario one, indicating an increase in the number of diesel trucks. Eventually, both scenarios experience a steep decline in the number of diesel trucks. Scenario three observes this reduction in diesel trucks earlier in the modelling period than scenario two. This is a result of the market preference moving towards fuel cell trucks earlier in scenario three than in scenario two. This, in turn, is due to scenario two taking a more pessimistic view of the way in which hydrogen technologies will develop. It is interesting to note that at the end of the modelling period scenarios two, three, four, and five seem to be converging. It can be seen that all scenarios are within 13% of scenario three by 2050. This is to be expected as all three scenarios have achieved a 100% preference for fuel cell trucks. Effectively the only diesel trucks in the model are "*old*" diesel trucks that have not yet been decommissioned.

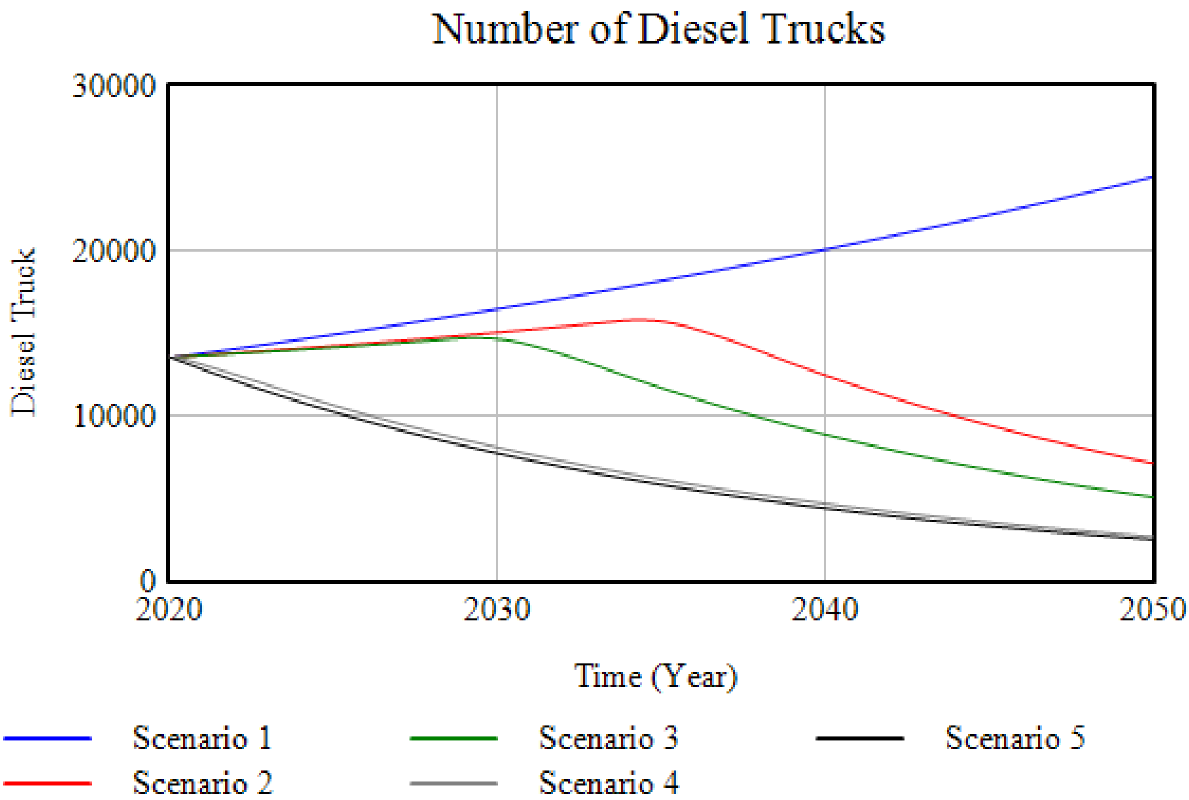


Figure 28: Number of diesel trucks in various scenarios

The emissions from diesel trucks in the various scenarios are presented in Figure 29. The emissions are closely associated with the number of diesel trucks in each scenario. This is because the number of diesel trucks is the main factor in calculating the annual emissions from diesel trucks. Of particular interest is the plateauing of emissions in all scenarios except scenario number one (in which diesel truck purchases continue unabated). As the number of diesel trucks on the road decrease, so the emissions from these trucks decrease. The total emissions would logically reach a final value when the last diesel truck is decommissioned, resulting in no further emissions taking place. If stakeholders are driven to hydrogen based on an interest in reducing emissions, then these results are of particular interest. As previously noted, only carbon dioxide emissions are considered for diesel trucks. This is because other emissions account for less than 1% of total emissions according to Collier *et al.* (2019).

One of the limitations discussed in Section 4.6 is that the model calculates very low emissions from diesel trucks. Although the purpose of this study is not to estimate emissions, it is worth exploring this limitation in greater detail. To begin with, it should be noted that annual emissions are calculated by multiplying the number of diesel trucks on the road by a parameter called *average emissions per diesel truck per year.* As there is no reason to believe that the modelled number of diesel trucks is incorrect, the *average emissions per diesel truck per year* parameter should be explored. As discussed in Section 4.3.4, the *average emissions per diesel truck per year* parameter is calculated using three key variables, namely: the fuel economy of a diesel truck, the average distance travelled by a truck in a year, and the carbon emissions per liter of combusted diesel. The average distance travelled by a truck in a year, also called the vehicle kilometres travelled, has already been identified as being too low due to the aggregation of the data made available by the New Zealand Ministry of Transport (2020b). Additionally, the data used for the fuel economy of trucks was taken from the work of Collier

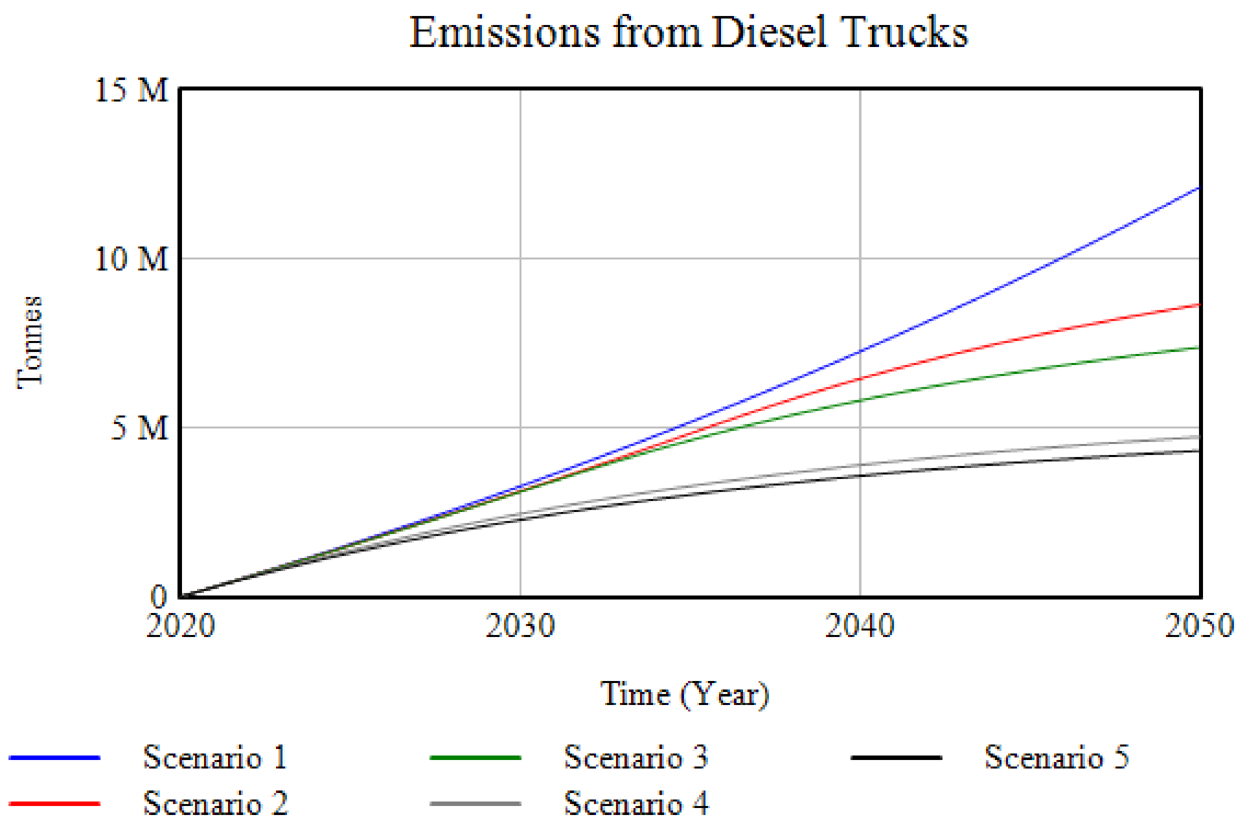


Figure 29: Cumulative emissions from diesel trucks in various scenarios

et al. (2019), whose work does not focus on the New Zealand context. Given the mountainous terrain in New Zealand, it is expected that the fuel economy of trucks in New Zealand is significantly less than what is suggested by Collier *et al.* (2019) (Crozier, 2006). Based on these two known limitations, the value of the *average emissions per diesel truck per year* parameter is expected to be the cause of the lower-than-expected emissions from diesel trucks. As there is no known reason to believe that the modelled number of diesel trucks is incorrect, it can be deduced that the profile – or shape – of the outputs presented in Figure 29 should be accurate for the associated number of diesel trucks. Therefore, the modelled output is still a useful representation of how emissions from diesel trucks would change over time if the associated number of diesel trucks on the road changed as per the modelled output. However, the actual emissions (the numbers on the y-axis) are expected to be much higher in reality. When considering the extent of decarbonisation, the percentage of the fleet that is comprised of fuel cell trucks can also be used as an indicator. Lastly, it is worth noting that although these inaccuracies in the data result in significant limitations when calculating the emissions from diesel trucks, there is no reason to believe that they significantly impact any other part of the model. Therefore, this limitation does not undermine the usefulness of the model.

5.3. Fuel cell trucks and hydrogen generation

The number of fuel cell trucks in each scenario is presented in Figure 30. In scenario one, the number of fuel cell trucks remains zero throughout the modelling period as this scenario prohibits the purchase of fuel cell trucks. In scenario five the model is prohibited from purchasing diesel trucks, resulting in the maximum possible number of fuel cell trucks being purchased. For the other scenarios, as described previously, the number of fuel cell trucks that are purchased is determined by the *market preference for fuel cell trucks*. The number of fuel cell trucks therefore corresponds to the decreasing number of diesel trucks seen in Figure 28. As the number of diesel trucks reduces, the number of fuel cell trucks must increase to meet the total number of trucks required on the road. In addition to this, the number of trucks required on the road increases over time. This results in a given *market preference for fuel cell trucks* – let's say 50% – resulting in a greater *number* of fuel cell trucks being purchased at a later stage in the model than at an early stage. More simply put: 50% of

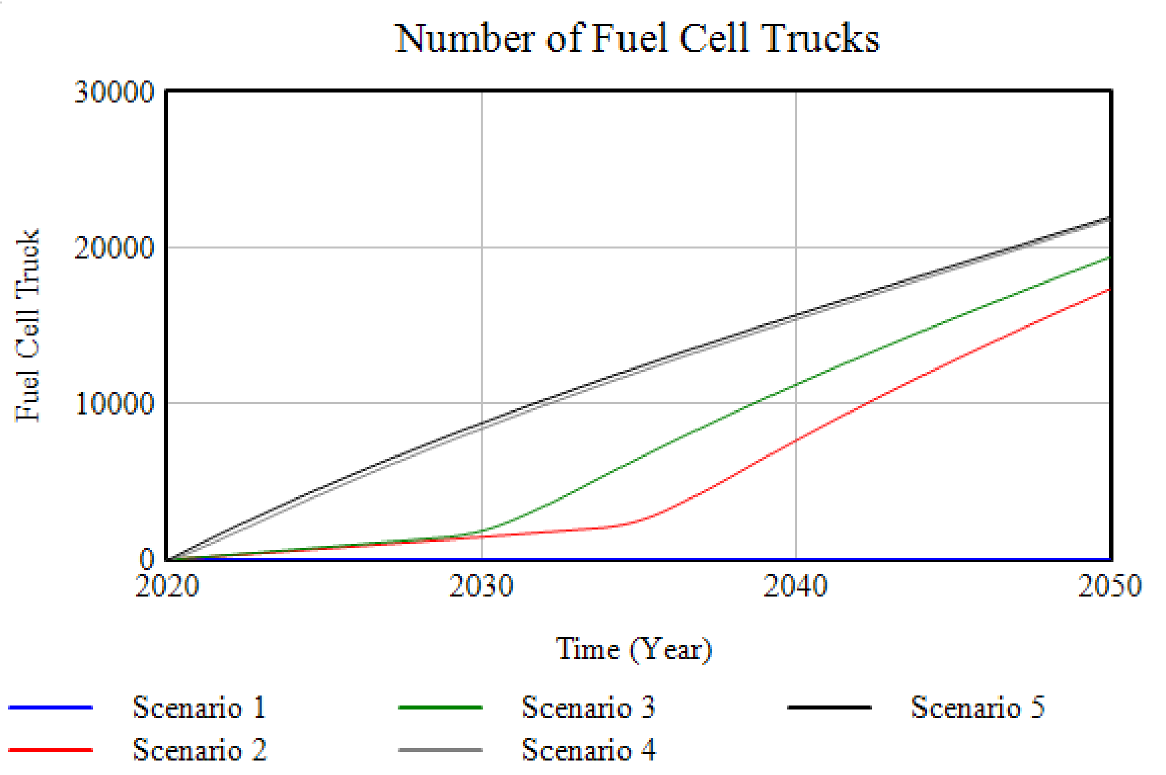


Figure 30: Number of fuel cell trucks in various scenarios

a big number is more than 50% of a smaller number. The result of this is that even though scenario two develops a preference for fuel cell trucks later than scenario three, the number of fuel cell trucks in scenario two increases faster once this happens. As mentioned in Section 4.6, the limitations of using a first order differential equation to calculate the number of diesel trucks decommissioned each year can lead to an extended lifetime for some of the trucks. If the diesel trucks are not retired, then fuel cell trucks are not purchased to replace them. Although this is understood to be a limitation of the model, it does not undermine the usefulness of the model.

The total hydrogen generated in each scenario is presented in Figure 31. Scenarios four and five track very close to each other, which is to be expected considering the similar number of fuel cell trucks in each scenario. Scenario one remains at zero throughout the model timeline as there is no demand for hydrogen. When considering the total hydrogen generation, it is important to remember that the various scenarios assume different fuel economies (see Table 13 of Appendix D for parameter values). This difference results in scenario two generating 92% as much hydrogen in 2050 as compared to scenario three, while only supplying hydrogen to 89% as many fuel cell trucks. The total hydrogen generated by 2050 remains lower in scenario two than in scenario three as the number of fuel cell vehicles starts increasing much earlier in scenario three than scenario two.

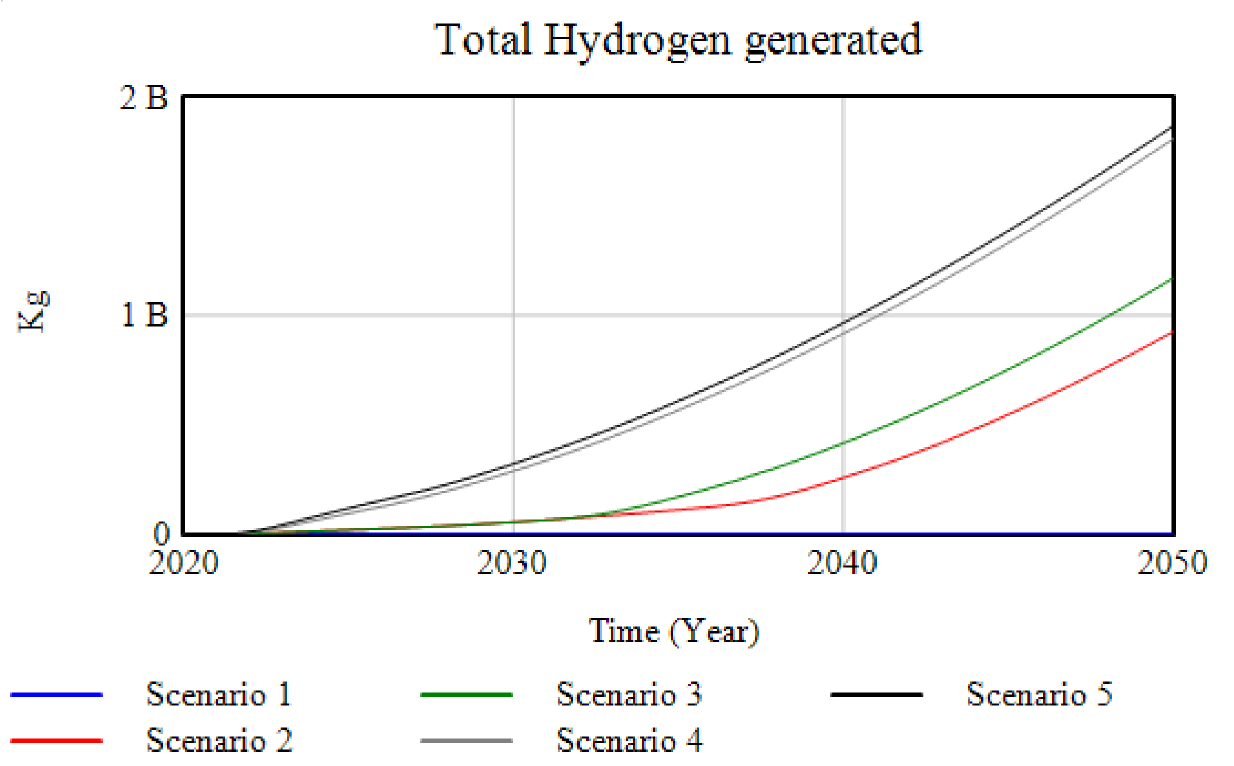


Figure 31: Total hydrogen generated in various scenarios

5.4. Investments in hydrogen production capacity

The total investments in hydrogen production capacity for the five scenarios is presented in Figure 32. It can be seen that – due to the lack of demand explained in previous sections – there are no investments in hydrogen production in scenario one. The outputs of the other scenarios are not as easily interpreted. Interpreting the results of scenarios two, three, four, and five, requires a particularly good understanding of the parameter values used in the various scenarios, as well an adequate understanding of the hydrogen production capacity module (presented in Section 4.3.6) and its limitations. Specifically, the impact of the poor forecast capabilities of the model, as discussed in

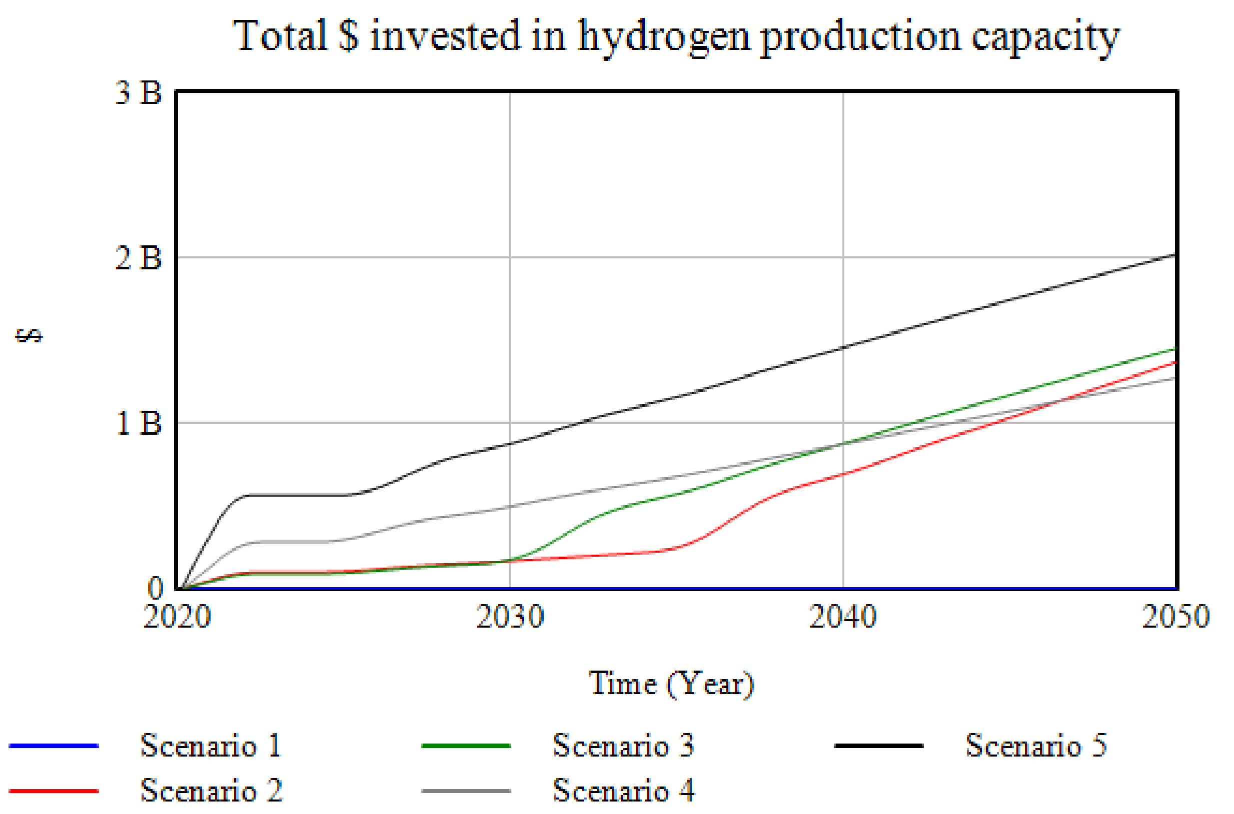


Figure 32: Total investments in hydrogen production capacity in various scenarios

Section 4.6, is made apparent when analysing this data. In Figure 32 it can be seen that in all four scenarios that employ the forecast function, the total investments in hydrogen production capacity plateaus between approximately 2022 and 2025. This is understood to be due to overinvestment in prior years. The overinvestment, in turn, is attributed to an inflated forecast of the number of fuel cell trucks. This overinvestment can be decreased by reducing the time horizon to which the forecast function projects, which would result in a smaller extrapolation error. However, the utility of doing so is undermined by the creation of a new problem. If the time horizon is too short, the model will take too long to invest in new hydrogen generation capacity. If investments are made too late then production capacity is not commissioned in time and a supply shortfall results. A preliminary analysis indicates that the magnitude of this error is less than 10% over the 30-year period that is modelled. Although this is a non-trivial error, it does not compromise the insights afforded by the study to a significant degree.

Bearing in mind the initial overinvestment, and subsequent plateau, caused by the forecast function, the hydrogen production investments are easily understood. In scenario two there is a period of relatively low investments until about 2035, at which point investments increase to supply hydrogen for the rapidly increasing number of fuel cell trucks – as presented in Figure 30. At this point, the initial investments in production capacity occur faster than the subsequent investments due to supply catching up to the initial steep increase in demand. Beyond 2040 the total investments in hydrogen production capacity increase steadily due to the steady and consistent increase in the number of fuel cell trucks.

Scenario number three progresses in a manner very similar to scenario two, but it is clear to see that the rate of investments in scenario two is noticeably steeper than scenario three between 2040 and 2050. This is due to the cost of hydrogen production capacity being more expensive in scenario two than in scenario three during the final years of the model run. As production capacity is more expensive in scenario two, the model needs to invest more money to achieve the desired increase in production capacity. In scenario five the cost of hydrogen production capacity is the same as in scenario three, resulting in the near-parallel responses of scenarios three and five in the final decade of the model.

Scenario number four, the optimistic scenario, has a particularly interesting output. The initial overinvestment is followed by the approximately two-year plateau. However, when reinvestments begin again after the plateau it can be seen - by the low gradient of the slope of the line - that these investments are significantly lower than in the other scenarios. This is to be expected as this scenario is using the most optimistic parameter values. As a result, this scenario has the lowest total investments in hydrogen production capacity by the end of the simulated period (except for scenario one which does not invest in hydrogen), even though the total hydrogen generated over the course of the model is near a maximum in this scenario. The exact opposite of this phenomenon can be seen in scenario two – the pessimistic scenario – which generates 79% as much hydrogen as scenario three but invests 94% as much into hydrogen production capacity. This wide distribution of results is expected due to the wide distribution of estimates for the future cost of hydrogen technologies which were found in the literature and incorporated into the scenarios.

5.5. Investments in marginal electricity

The total marginal electricity investments are presented in Figure 33. As mentioned in Section 4.3.7, this is the investment required to provide the electricity necessary to power the *Installed Hydrogen Production Capacity*. As expected, scenario one sees no investments in marginal electricity. This is due to a lack of demand resulting in no hydrogen production capacity being commissioned. For so long as there is no production capacity there will be no electricity required to power the production capacity. When discussing the other scenarios, it is necessary to consider the factors influencing the annual investments in marginal electricity. Although the investments in marginal electricity are calculated very simply as the product of the electricity required and the cost of the marginal electricity; the electricity required is dependent on the efficiency of the hydrogen production system. Specifically, an increase in the *electricity required per kg of hydrogen produced* parameter increases the electricity required to meet the market's demand for a given amount of hydrogen. This increase in the electricity requirement reflects an increase in the required investment in marginal electricity. Scenarios three, four, and five, are modelled with the same efficiency assumptions, while scenario two is modelled with a more pessimistic efficiency assumption. The resulting efficiency reduction explains why Table 9 indicates a small difference (8%) in the marginal electricity investments between scenarios two and three even though scenario two only sees 79% of the hydrogen generation that scenario three does. This can be contrasted with scenario three, four, and five, in which investments in marginal electricity are strongly correlated with hydrogen generation. In all scenarios, the investments in marginal electricity are significantly (three to six times) more than the investments in hydrogen production capacity. This result is heavily dependent on the cost of marginal electricity, which in this report is set according to the findings of John Culy Consulting (2019), and the cost and efficiency of hydrogen production capacity, which is determined by a variety of sources in each scenario.

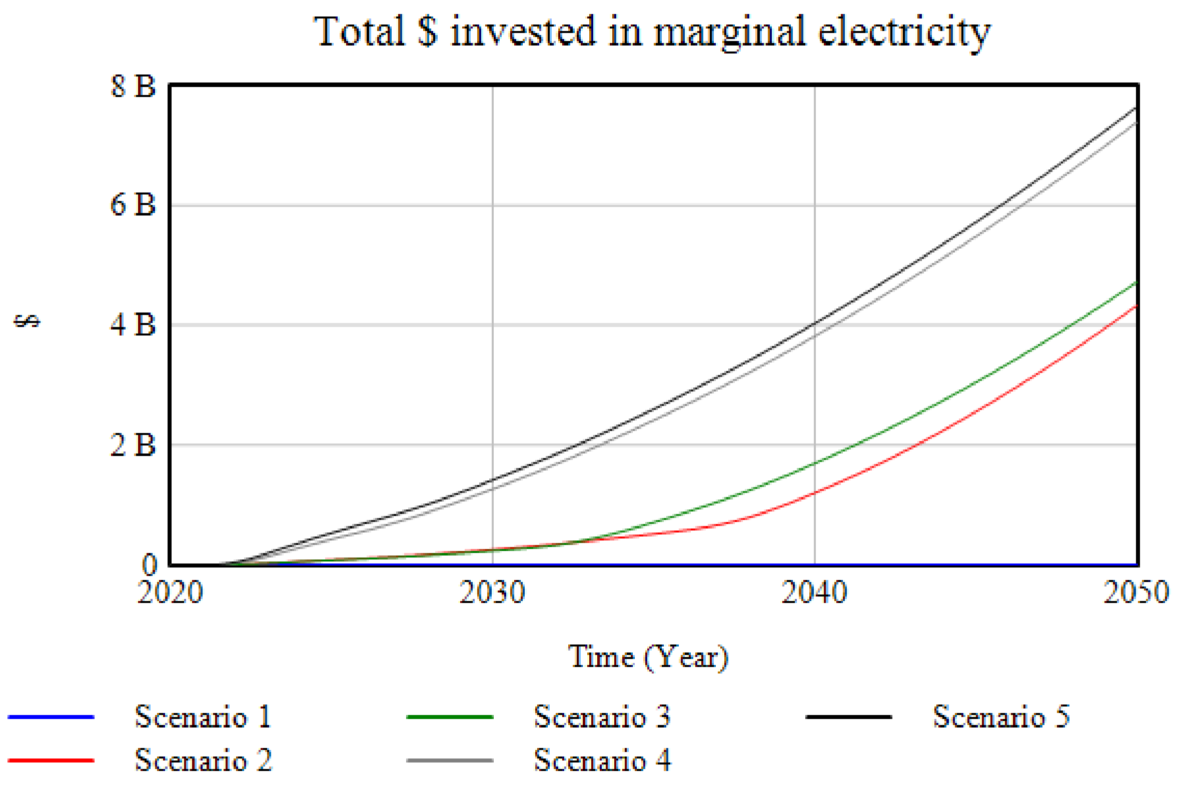


Figure 33: Total investments in marginal electricity in various scenarios

5.6. Chapter 5 conclusion

In this chapter, the key model outputs from the scenarios designed in Section 4.5 are presented and discussed. The specific outputs that were discussed are the market preference for fuel cell trucks, the number of diesel and fuel cell trucks, the emissions from diesel trucks, the hydrogen generated for the fuel cell trucks, the investments in hydrogen production capacity, and the investments in marginal electricity. These outputs were discussed with reference to the limitations and assumptions outlined in Section 4.6. The importance of a thorough understanding of the differences between the five scenarios, and the limitations and assumptions of the model became clear during the discussion. By presenting and discussing the results of the model in the various scenarios, this chapter enables recommendations to be drawn from the results of the model. These recommendations will be discussed in the following chapter, thereby achieving the final research objective.

Chapter 6
Conclusions and recommendations

In this chapter, the learnings, recommendations, and conclusions of the study are presented. The final research objective is addressed in the first section of the chapter by providing prioritized recommendations and insights for transitioning the heavy-duty vehicle sector of New Zealand to hydrogen. These recommendations and insights are derived from the model outputs discussed in the previous chapter, as well as from learnings made during the modelling process. Subsequently, recommendations for future research are presented. The research objectives are then reviewed to ensure that all stated objectives were achieved. In the final section of this chapter, the report is drawn to a conclusion.

6.1. Recommendations and insights for policy makers

This section considers the output from the modelled scenarios as well as insights from the modelling process to develop prioritized recommendations and insights for transitioning the heavy-duty vehicle sector of New Zealand to hydrogen. Therefore, the sixth and final research objective is addressed in this section.

This study has found that even pessimistic assumptions of progress in hydrogen technology would lead to fuel cell trucks becoming competitive with diesel trucks well before 2050. Additionally, the study found that replacing diesel trucks with fuel cell trucks is an effective strategy for reducing emissions from the heavy-duty vehicle sector by 2050. This justifies the current interest in hydrogen and motivates the case for hydrogen not only as a decarbonisation strategy but also as an opportunity for economic growth. These findings are in line with the many national hydrogen strategies that have recently been published (WEC, 2020). The overwhelming evidence, therefore, indicates that the hydrogen transition, at least in the heavy-duty vehicle sector, is an opportunity that New Zealand should engage with in order to maximize the potential benefits.

The investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen have been split into two parts, namely: hydrogen production capacity investments, and the investments required to supply marginal electricity to the hydrogen production systems. Investments in hydrogen production capacity are found to range between 1.37 and 2.02 billion New Zealand Dollars, while marginal electricity investments are found to range between 4.33 and 7.65 billion New Zealand Dollars. These investments represent scenarios in which 71% to 90% of the heavy-duty vehicle fleet are decarbonised with fuel cell trucks by 2050. The wide range of these findings reflects the large uncertainties in estimates of how hydrogen technologies will develop in the next thirty years.

As indicated throughout this study, much of the data required to investigate how the hydrogen transition will unfold are burdened with large uncertainties. These uncertainties are reducing as hydrogen enjoys more international attention and investment, but there is still much progress to be made in this regard. The United States Department of Energy announced a "*request for information in support of medium- and heavy-duty truck research and development*" (DOE, 2020). The resulting information will potentially yield significant insights into the state of hydrogen technologies. If the

New Zealand government were to conduct a similar request there would be an opportunity to gain valuable, and context-specific, data that would enable better models to be built. Additionally, it is recommended that the New Zealand Ministry of Transport disaggregates the data that are published in the Annual Fleet Statistics Report (Ministry of Transport, 2020b). Disaggregation of these data would enable more accurate calculations to be made regarding the different classes of truck; each of which presents unique opportunities and barriers for hydrogen.

This study has reaffirmed that decarbonising the heavy-duty vehicle sector of New Zealand will require a significant amount of renewably generated electricity. The study finds that in 2050 approximately five terawatt-hours of clean electricity will be required to generate hydrogen for heavy-duty vehicles. These findings are similar to those of Perez (2020) and Perez *et al.* (2020) who indicate that this represents approximately half of the total consented, yet unbuilt, renewable energy projects in New Zealand. The finding that large amounts of low-carbon electricity will be required for decarbonisation is by no means a new discovery, nor is it unique to the heavy-duty vehicle sector or hydrogen. In fact, the Energy Transition Commission (2020, p. 26) states that "*electrification will be the primary route to decarbonisation*". This cross-sectoral need for large amounts of clean electricity demonstrates that renewable electricity is a low risk, technology-agnostic, investment for the New Zealand government. Therefore, ensuring that enough clean electricity is available at the lowest possible cost is not only a recommendation for a hydrogen future, but for a low-carbon future in general.

While developing the model, it became clear that there is a paramount need for a regulating authority to facilitate and oversee the hydrogen transition in New Zealand. The key responsibilities of such an authority would include collecting and publishing important data, facilitating crucial relationships, matching supply and demand to prevent over- or under-investment, and ensuring that standards and regulations are developed in a way that supports hydrogen technologies in New Zealand. Fortunately, Hiringa Energy (2020a) seems ready to take on the responsibilities of such a role. Ensuring that the regulating entity is well-funded and well-managed will be of great importance to a rapid and smooth transition to hydrogen.

The scope of this study was limited to investigating hydrogen's application in only the heavy-duty vehicle sector of New Zealand. Although much can be learnt from studies of this scope, the true value of hydrogen should be considered, and ideally investigated, on a much larger scale. Understanding and pursuing synergies between the various hydrogen-compatible sectors identified in Section 2.4.2 will be an important part of the hydrogen transition.

The final recommendation relates to terminology. The term "*hydrogen economy*" evokes different ideas to different people, but in many cases the phrase seems connected to inflated ideas of what hydrogen is realistically going to be used for in the next fifty years. Such exaggerations, especially concerning technologies that have already experienced a hype cycle, can undermine the perceived legitimacy of the technology. Public opinion is of great consequence in the adoption of a new technology, and it may be wise to steer clear of hyperbolic language that could compromise a layperson's understanding of hydrogen's feasible applications.

6.2. Recommendations for future research

In this section, reflections on the modelling process are presented, and opportunities for future research and modelling are identified. The purpose of this section is to outline learnings from the modelling process which are not necessarily evident in the model results.

6.2.1. Reflections on the modelling process

System Dynamics Modelling proved to be an appropriate modelling technique for investigating the investments required to transition the heavy-duty vehicle sector of New Zealand to hydrogen; by applying systems thinking. While the initial steps of the modelling process, specifically those leading to the construction of the dynamic hypothesis[5], proved to be extremely useful for problem articulation, a few of the later steps were found to be more troublesome. In particular, the dynamic modelling process took much longer than expected. This was due, at least in part, to the lack of a consolidated and supported learning platform for the chosen software (Vensim). Regardless of the software used, future modellers should make sure to not underestimate the time required for model construction and model testing.

Two of the feedback loops that were of great interest during the original problem articulation phase were eventually relegated to the point of being excluded from the model. One of the feedback loops showed how investments in hydrogen technologies would lead to reductions in the cost of those technologies; the other considered the need for standardization and regulation as the hydrogen market developed. In both cases, the feedback loops were relegated due to a realization that the feedback mechanisms operate on a global, not national, level. This meant that modelling them at the chosen level of abstraction would be non-sensical. Although it is difficult to prevent such an occurrence from happening, holding the possibility in mind during the problem articulation phase might expedite the identification of such a phenomenon, thereby saving significant amounts of time.

Except for the abovementioned challenges, the synthesized modelling process that was followed in this study proved to be of great value to modelling hydrogen transitions with system dynamics modelling. The work of Quarton *et al.* (2020) contributed significantly to the standard approaches outlined in the system dynamics literature, most notably by providing hydrogen-specific insights during scenario planning. Additionally, the knowledge that the modelling process was specifically curated to hydrogen was a source of confidence that was much appreciated.

6.2.2. Future research and modelling

Significant opportunities for future research and modelling were identified during the course of the study. These opportunities can be broadly categorized according to the nature of the work to be done, namely: data collection, model expansion, and a comparison of model results.

Regarding data collection, the available literature provides a wide range of values for key parameters that are essential to modelling a hydrogen transition. This is true not only of the way in which hydrogen technologies will develop over the course of the next three decades but also of the current

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[5] Readers that are interested in learning more about the details of constructing a dynamic hypothesis are referred to the work of de Haan and de Heer (2015)

state of these technologies. Acquiring better data is paramount to developing an improved understanding of the opportunities, barriers, and investment requirements associated with hydrogen. It is expected that the quantity and quality of data will increase significantly in coming years as more countries invest in hydrogen, and the technologies become more common. Policies such as tax incentives are also expected to be set in place in the near future (Ministry of Transport, 2020d). Therefore, there will be opportunities for primary as well as secondary data collection in the future. The model can be updated or expanded to reflect the new data and policies as they emerge.

The second avenue for model improvement lies in improving the mathematics, and structure of the model. A good example of where this can be done is the forecast of the expected number of fuel cell trucks. This forecast can be improved by developing a better mathematical function than the one currently in place. Alternatively, the model structure could be expanded to capture the driving forces that lead to new fuel cell trucks being purchased. The forecast could then be based on the way technology costs are reducing, and how the market is expected to react to such changes in the future. There are many other opportunities for further model expansions, including the possibility of including the other economic sectors identified in Section 2.4.2. There are known synergies between these sectors, and exploring a multi-sectoral application of hydrogen technologies would be much more insightful than studying the sectors in isolation. Such a model would more accurately investigate economies of scale and potential cost-sharing opportunities. Additional scenarios, like expediting the decommissioning of the diesel fleet, might also be explored.

This study has taken a hydrogen-specific approach to decarbonisation. The goal of decarbonising the economy should be technology-agnostic – meaning that no single technology should enjoy any inherent privileges. Therefore, the results of this study should be compared to alternative decarbonisation options, including technologies such as batteries, biodiesel, and catenary systems. The potential for road freight to be moved to rail presents yet another opportunity for decarbonisation. A comparison of all available options would enable the most cost-effective strategy to be identified.

6.3. Reflecting on the research objectives

In Section 1.3 it was stated that the study aims to provide policy- and decision-makers with a better understanding of the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen; by applying systems thinking. To achieve this aim, six specific objectives were established. Table 10 indicates where in the document each of the six specific objectives are addressed. It can therefore be seen that by applying systems thinking and following the steps of the research approach articulated in Section 1.4, all the research objectives have been achieved. Additionally, the aim of the study has also been achieved. As previously noted, the investments required to transition New Zealand's heavy-duty vehicle sector from diesel to hydrogen have been calculated in two components. Marginal electricity investments are found to range between 4.33 and 7.65 billion New Zealand Dollars and hydrogen production capacity investments are found to range between 1.37 and 2.02 billion New Zealand Dollars. These investments represent scenarios in which 71% to 90% of the heavy-duty vehicle fleet are decarbonised with fuel cell trucks by the end of the modelling period. The wide range of these findings is a result of the large uncertainties in estimates of how hydrogen technologies will develop. The use of systems thinking has proven to be a useful and appropriate approach to achieving the aim and objectives of this study.

Table 10: Addressing research objectives

Research Objective	Section
RO1: Contextualize hydrogen transitions in New Zealand and identify the main factors influencing a hydrogen transition in the sectors of the economy that are best suited to hydrogen.	Chapter 2
RO2: Develop a set of requirement specifications to determine an appropriate method for investigating a transition to hydrogen in New Zealand's heavy-duty vehicle sector.	Chapter 3, specifically Section 3.2.1
RO3: Evaluate various modelling approaches and identify an appropriate approach that satisfies the developed requirement specifications.	Chapter 3, specifically Section 3.2.5
RO4: Utilize the modelling approach identified and selected in RO3 to develop, verify and validate a model that captures the dynamics of the heavy-duty vehicle sector.	Chapter 4
RO5: Identify and develop scenarios to explore how various policies and technological developments influence the hydrogen transition in the heavy-duty vehicle sector.	Chapter 4, specifically Section 4.5, and Chapter 5
RO6: Provide recommendations and insights for transitioning the heavy-duty vehicle sector of New Zealand to hydrogen.	Chapter 6, specifically Section 6.1

6.4. Chapter 6 conclusion

In the first section of this chapter, the model results, as well as learnings from the modelling process, were considered to develop prioritized recommendations and insights for transitioning the heavy-duty vehicle sector of New Zealand to hydrogen. Subsequently, recommendations for future research and modelling were presented. Finally, the research objectives of the study were revisited, and it was found that all the objectives, as well as the main aim of the report, had been achieved.

Across the globe, the call for energy transitions - and sustainability transitions more broadly - is being heard louder and clearer each year. To heed this call, it will be necessary to radically redesign the global economy in a short period of time. This sort of mobilization will not be easy, and it will not happen without significant collaboration, creativity, and financial support. One of the many toolsets that we have at our disposal is hydrogen and the suite of technologies that enable hydrogen to address the emissions of various economic activities that are otherwise very difficult to decarbonise. Although the concept of using hydrogen in this way is not common, it is gaining traction at great speed. While conducting this study it was a challenge to keep up to date with the latest developments in the field. If governmental support and market indicators are a worthy representation of the promise that hydrogen holds, then it seems as though hydrogen will play a significant role in decarbonising the economy. This study set out to address a gap in the literature. By reviewing the available literature and using system dynamics modelling to better interpret the available data, much was learned.

Although many questions were answered, many new questions emerged. Yet, the urgency of the climate challenge is such that we cannot wait until the day that all the answers are available before taking action. It is possible to minimize the risk of investing in the energy transition by making investments in technology-agnostic factors. Such investments include investments in renewable electricity generation, transmission, and distribution; and investments in support of organizations like Hiringa Energy that can work towards a better understanding of the problem space while signalling an opportunity to the international market. If there is one conclusion to be drawn from the available evidence, then it is that we currently have no good reason to *not* consider the opportunities that hydrogen holds for the environment and the economy.

References

Acaroglu, L. (2017), "Tools for Systems Thinkers: The 6 Fundamental Concepts of Systems Thinking", available at: https://medium.com/disruptive-design/tools-for-systems-thinkers-the-6-fundamental-concepts-of-systems-thinking-379cdac3dc6a (accessed 28 September 2020).

Balestrini-Robinson, S., Zentner, J.M. and Ender, T.R. (2009), "On Modeling and Simulation Methods for Capturing Emergent Behaviors for Systems of Systems", *12th Annual Systems Engineering Conference National*, available at: https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2009/systemengr/9041WednesdayTrack6Zentner.pdf.

Ball, M. and Weeda, M. (2015), "The hydrogen economy - Vision or reality?", *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 40 No. 25, pp. 7903–7919.

Ballance Agri-Nutrients Limited. (2019), "Submission from Ballance", available at: https://www.mbie.govt.nz/dmsdocument/10570-ballance-agrinutrients-ltd-a-vision-for-hydrogen-in-new-zealand-green-paper-submission-pdf.

Banks, J. (1999), "Introduction to simulation", *Proceedings of the 2011 Winter Simulation Conference (WSC)*, IEEE, pp. 1374–1388.

Banks, J., Carson II, J.S., Nelson, B.L. and Nicol, D.M. (2013), *Discrete-Event System Simulation: Pearson New International Edition*, Pearson Higher Ed.

Barlas, Y. (1996), "Formal aspects of model validity and validation in system dynamics", *System Dynamics Review*, Vol. 12 No. 3, pp. 183–210.

BEC. (2018), "BEC Homepage", available at: https://www.bec.org.nz/ (accessed 1 June 2020).

Bell, E. and Bryman, A. (2016), *Research Methodology*, Oxford university Press.

Bellù, L.G. and Pansini, R.V. (2009), "Quantitative Socio- Economic Policy Impact Analysis", Rome, available at: http://www.fao.org/docs/up/easypol/774/quant_socio-economic_pia_068EN.pdf.

Bettany-Saltikov, J. (2012), *How to Do a Systematic Literature Review in Nursing: A Step-by-Step Guide*, McGraw-Hill Education (UK).

Bockris, J.O. and Appleby, A.J. (1972), "Hydrogen economy: an ultimate economy", *Science*, Vol. 176 No. 4041, pp. 1323–1323.

Bockris, J.O.M. (2013), "The hydrogen economy: Its history", *International Journal of Hydrogen Energy*, Elsevier Ltd.

Bolwig, S., Bazbauers, G., Klitkou, A., Lund, P.D., Blumberga, A., Gravelsins, A. and Blumberga, D. (2019), "Review of modelling energy transitions pathways with application to energy system flexibility", *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, 1 March.

Bonabeau, E. (2002), "Agent-based modeling: Methods and techniques for simulating human systems", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 99 No. SUPPL. 3, pp. 7280–7287.

Borrás, J. (2020), "In a World First, Hyundai Fuel Cell Semis Ship to Customers", *Clean Technica*, available at: https://cleantechnica.com/2020/07/07/in-a-world-first-hyundai-fuel-cell-semis-ship-to-customers/ (accessed 29 September 2020).

Borshchev, A. (2013), *The Big Book of Simulation Modeling: Multimethod Modeling with AnyLogic 6*, AnyLogic North America.

Borshchev, A. and Filippov, A. (2004), “From System Dynamics to Agent Based Modeling”:, *From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. The 22nd International Conference of the System Dynamics Society*, available at: http://www2.econ.iastate.edu/tesfatsi/systemdyndiscreteeventabmcompared.borshchevfilippov04.pdf.

Brown, E.G., Mckinney, J., Bond, É., Crowell, M., Odufuwa, E., Author, P., Ii, J.P.B., *et al.* (2015), *Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California* , available at: https://ww2.energy.ca.gov/2015publications/CEC-600-2015-016/CEC-600-2015-016.pdf (accessed 19 October 2020).

Brown, T. (2018), “ThyssenKrupp’s ‘green hydrogen and renewable ammonia value chain’”, available at: https://ammoniaindustry.com/thyssenkrupps-green-hydrogen-and-renewable-ammonia-value-chain/ (accessed 22 September 2020).

Brundtland, G.H., Khalid, M., Agnelli, S., Al-Athel, S. and Chidzero, B. (1987), “United Nations Report of the World Commission on Environment and Development: Our common future”, *United Nations Report of the World Commission on Environment and Development: Our Common Future*, available at:https://doi.org/10.1007/978-1-4020-9160-5_1126.

Buckley, W.D. (1998), “Chapter 59”, *Society- a Complex Adaptive System: Essays in Social Theory*, available at: http://coevolving.com/transfer/2013-ISSS-Buckley/1968_Buckley_SocietyAsAComplexSystem_ocr.pdf?source=post_page--------------------------- (accessed 22 September 2020).

Chan, S. (2001), “Complex Adaptive Systems”, pp. 1–9.

Choopojcharoen, T. and Magzari, A. (2012), *Mathematics behind System Dynamics*, available at: https://web.wpi.edu/Pubs/E-project/Available/E-project-052812-144829/unrestricted/MathematicsBehindSystemDynamics.pdf (accessed 14 October 2020).

Cilliers, P. (2002), “Why we cannot know complex things completely”, *Emergence*, Vol. 4 No. 1–2, pp. 77–84.

COAG. (2019), *Australia’s National Hydrogen Strategy*, available at: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf (accessed 22 September 2020).

Collier, S., Ruehl, C., Yoon, S., Boriboonsomsin, K., Durbin, T.D., Scora, G., Johnson, K., *et al.* (2019), “Impact of Heavy-Duty Diesel Truck Activity on Fuel Consumption and Its Implication for the Reduction of Greenhouse Gas Emissions”, *Transportation Research Record*, Vol. 2673 No. 3, pp. 125–135.

Concept Consulting. (2019a), *Hydrogen in New Zealand Report 1 – Summary*, available at: http://www.concept.co.nz/uploads/2/5/5/4/25542442/h2_report1_summary_v4.pdf.

Concept Consulting. (2019b), *Hydrogen in New Zealand Report 3 – Research*.

Concept Consulting. (2019c), *Hydrogen in New Zealand Report 2 – Analysis*, available at: http://www.concept.co.nz/uploads/2/5/5/4/25542442/h2_report2_analysis_v4.pdf.

Cook, D. and Skinner, J. (2005), "How to Perform Credible Verification,Validation, and Accreditation for Modeling and Simulation ", *The Journal of Defense Software Engineering*, Vol. 18 No. 5, pp. 18–24.

Cook, J., Oreskes, N., Doran, P.T., Anderegg, W.R.L., Verheggen, B., Maibach, E.W., Carlton, J.S., *et al*. (2016), "Consensus on consensus: A synthesis of consensus estimates on human-caused global warming", *Environmental Research Letters*, IOP Publishing, Vol. 11 No. 4, available at:https://doi.org/10.1088/1748-9326/11/4/048002.

Crabtree, G.W., Dresselhaus, M.S. and Buchanan, M. V. (2004), "The hydrogen economy", *Physics Today*, Vol. 57 No. 12, pp. 39–44.

CRL Energy Ltd. (2008), *Transitioning to a Hydrogen Economy*, available at: https://niwa.co.nz/sites/niwa.co.nz/files/import/attachments/Identification_of_preferred_hydrogen_chains.pdf.

Cronin, P., Ryan, F. and Coughlan, M. (2008), "Undertaking a literature review: a step-by-step approach", *British Journal of Nursing*, Vol. 17 No. 1, pp. 38–43.

Crozier, M.J. (2006), "New Zealand's terrain", *The Encyclopedia of New Zealand*, available at: https://teara.govt.nz/en/zoomify/8780/new-zealands-terrain (accessed 16 November 2020).

CSIRO. (2018), *National Hydrogen Roadmap*, available at: https://safety4sea.com/wp-content/uploads/2018/08/CSIRO-National-Hydrogen-Roadmap-2018_08.pdf.

Cummins Inc. (2019), "Cummins closes on its acquisition of Hydrogenics", available at: https://www.cummins.com/news/releases/2019/09/09/cummins-closes-its-acquisition-hydrogenics (accessed 14 November 2020).

Deloitte and Ballard. (2020), *Fueling the Future of Mobility Hydrogen and Fuel Cell Solutions for Transportation*, available at: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf (accessed 22 September 2020).

DOE. (2020), "Energy Department Request for Information in Support of Medium- and Heavy-Duty Truck Research and Development", available at: https://content.govdelivery.com/accounts/USEERE/bulletins/2a576db (accessed 21 October 2020).

E4Tech. (2019), *The Fuel Cell Industry Review 2019 Fuel Cell Industry Review*, available at: www.FuelCellIndustryReview.com.

Eames, M., McDowall, W., Hodson, M. and Marvin, S. (2006), "Negotiating contested visions and place-specific expectations of the hydrogen economy", *Technology Analysis and Strategic Management*, Vol. 18 No. 3–4, pp. 361–374.

EEA. (2016), *Transforming the EU Power Sector: Avoiding a Carbon Lock-In*, available at: https://www.eea.europa.eu/publications/transforming-the-eu-power-sector.

EEA. (2018), *Perspectives on Transitions to Sustainability, EEA Report*, available at:https://doi.org/10.2800/10240.

EEA. (2019), *Sustainability Transitions: Policy and Practice*, available at:https://doi.org/10.2800/641030.

Eker, S., Slinger, J., Daalen, V. and Yücel, G. (2014), "Sensitivity analysis of graphical functions", Vol. 30 No. 3, pp. 186–205.

EMI. (2020), "Wholesale price trends", available at: https://www.emi.ea.govt.nz/Wholesale/Reports/W_P_C?DateFrom=20150901&DateTo=20200831&RegionType=NZ&_rsdr=L60M&_si=v%7C3 (accessed 29 September 2020).

Energy Transition Commission. (2018), *Reaching Net-Zero Carbon Emissions from Harder-to - Abate Sectors by Mid - Century*, available at: https://www.ieta.org/resources/COP24/Misc Media Files/Dec7/SE16 (3).pdf.

Energy Transition Commission. (2020), *Making Mission Possible Delivering a Net-Zero Economy*, available at: www.linkedin.com/company/energy-transitions- (accessed 21 October 2020).

Engle, M. (2020), "Critically Analyzing Information Sources: Critical Appraisal and Analysis", *Cornell University Library*.

European Commission. (2020a), *Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration*, available at: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en.

European Commission. (2020b), *A Hydrogen Strategy for a Climate-Neutral Europe*, available at: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

Fleming, L. and Sorenson, O. (2001), "Technology as a complex adaptive system: Evidence from patent data", *Research Policy*, North-Holland, Vol. 30 No. 7, pp. 1019–1039.

Forrester, J.W. and Albin, S. (1997), *Building a System Dynamics Model Part 1 : Conceptualization*, available at: https://ocw.mit.edu/courses/sloan-school-of-management/15-988-system-dynamics-self-study-fall-1998-spring-1999/readings/building.pdf.

Forrester, J.W. and Senge, P.M. (1979), *Tests for Building Confidence in System Dynamics Models*, available at: http://static.clexchange.org/ftp/documents/roadmaps/RM10/D-2926-7.pdf (accessed 22 September 2020).

Genç, G., Çelik, M. and Genç, M.S. (2012), "Cost analysis of wind-electrolyzer-fuel cell system for energy demand in Pnarbaş-Kayseri", *International Journal of Hydrogen Energy*, Pergamon, Vol. 37 No. 17, pp. 12158–12166.

Genç, M.S., Çelik, M. and Karasu, I. (2012), "A review on wind energy and wind – hydrogen production in Turkey : A case study of hydrogen production via electrolysis system supplied by wind energy conversion system in Central Anatolian Turkey", *Renewable and Sustainable Energy Reviews*, Vol. 16, pp. 6631–6646.

Gintis, H. (2006), "Complexity economics", *Journal of Economic Literature*, Vol. 54 No. December 2006, pp. 1018–1031.

Gross, S. (2020), *The Challenge of Decarbonizing Heavy Duty Transport*, available at: https://www.asiascot.com/wp-content/uploads/2020/10/Challenge_of_decarbonizing_heavy_transport.pdf (accessed 14 November 2020).

de Haan, A. and de Heer, P. (2015), *Solving Complex Problems*.

Hall, D. and Lutsey, N. (2019), *Estimating the Infrastructure Needs and Costs for the Launch of Zero-Emission Trucks*, *The International Council on Clean Transportation*, available at: https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf.

Haro, F. (2020), "Is System Dynamics Dead or Alive? – Noorjax Consulting", available at: https://noorjax.com/2020/05/17/is-system-dynamics-dead-or-alive/ (accessed 22 September 2020).

Hearne, J.W. (2010), "Sensitivity Analysis To Model Functions", *Natural Resource Modelling*, Vol. 23 No. 2, pp. 107–120.

Hecht, E.S. and Pratt, J. (2017), *Comparison of Conventional vs. Modular Hydrogen Refueling Stations, and on-Site Production vs. Delivery*, available at: https://www.energy.gov/sites/prod/files/2017/03/f34/fcto-h2first-reference-station-phase2-2017.pdf.

Heppenstall, A.J.J., Crooks, A.T., See, L.M. and Batty, M. (2012), "Agent-based models of geographical systems", *Agent-Based Models of Geographical Systems*, No. January, pp. 1–759.

Hindenburg Research. (2020), "Nikola: How to Parlay An Ocean of Lies Into a Partnership With the Largest Auto OEM in America", available at: https://hindenburgresearch.com/nikola/ (accessed 14 October 2020).

Hiringa Energy. (2020a), "Green Hydrogen New Zealand", available at: https://www.greenhydrogennz.com/ (accessed 22 September 2020).

Hiringa Energy. (2020b), "Hydrogen Refuelling Infrastructure", available at: https://www.hiringa.co.nz/ (accessed 14 October 2020).

Hiringa Energy. (2020c), "Hiringa Energy and HYZON Motors to Deploy Fuel Cell-Powered Heavy Trucks in New Zealand in 2021", *Press Release*, available at: https://www.hiringa.co.nz/post/hiringa-energy-and-hyzon-motors-to-deploy-fuel-cell-powered-heavy-trucks-in-new-zealand-in-2021 (accessed 29 September 2020).

Hirsch, J. (2020), "Paccar CEO Feight Details Electric, Hydrogen Truck Strategy", *Trucks.Com*, available at: https://www.trucks.com/2020/07/27/paccar-outlines-electric-hydrogen-truck-strategy/ (accessed 14 November 2020).

Hofkes, M.W. (1996), "Modelling sustainable development: An economy-ecology integrated model", *Economic Modelling*, Vol. 13 No. 3, pp. 333–353.

Hunter, C., Penev, M. and Reznicek, E. (2020), *Market Segmentation Analysis of Medium and Heavy Duty Trucks with a Fuel Cell Emphasis*, available at: https://www.hydrogen.energy.gov/pdfs/review20/sa169_hunter_2020_o.pdf (accessed 29 September 2020).

Hydrogen Council. (2017), *Hydrogen Scaling up : A Sustainable Pathway for the Global Energy Transition.*, *Hydrogen Scaling up: A Sustainable Pathway for the Global Energy Transition*, available at: www.hydrogencouncil.com.%0Awww.hydrogencouncil.com.

Hydrogen Council. (2020), *Path to Hydrogen Competitiveness: A Cost Perspective*, available at: https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

Hyundai. (2020), “Xcient | HYUNDAI Truck & Bus”, available at: http://trucknbus.hyundai.com/global/en/products/truck/xcient (accessed 14 October 2020).

IEA. (2014), *Energy Supply Security - Emergency Response of IEA Countries*, available at: https://www.energy.gov/sites/prod/files/2018/08/f54/IEA Emergency Response of IEA Countries_2014.pdf (accessed 16 November 2020).

IEA. (2019), *The Future of Hydrogen: Seizing Today's Opportunities*, *Report Prepared by the IEA for the G20, Japan*.

Interim Climate Change Committee. (2019), *Accelerated Electrification Evidence, Analysis and Recommendations*, available at: https://www.iccc.mfe.govt.nz/assets/PDF_Library/daed426432/FINAL-ICCC-Electricity-report.pdf (accessed 29 September 2020).

IRENA. (2019), *Hydrogen: A Renewable Energy Perspective, International Renewable Energy Agency*, available at: www.irena.org.

IRENA. (2020), *Global Renewables Outlook*, available at: https://irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020.

Jackson, M.C. (2003), *Systems Thinking: Creative Holism for Managers*.

Jacob, M. (2013), “Discrete Event Simulation”, *Resonance*, Vol. 18 No. 1, pp. 78–86.

James, B.D. and Randolph, K. (2019), *Analysis of Advanced Hydrogen Production Pathways Overall Objectives Technical Targets DOE Hydrogen and Fuel Cells Program*, available at: https://www.hydrogen.energy.gov/pdfs/progress19/h2f_p102_james_2019.pdf (accessed 29 September 2020).

John Culy Consulting. (2019), *ICC Modelling: Estimated System Incremental and Marginal Cost in 2035*, available at: https://www.iccc.mfe.govt.nz/assets/PDF_Library/109233134e/FINAL-Culy-ICCC-modelling-Estimated-system-incremental-and-marginal-costs.pdf (accessed 29 September 2020).

Kim, Y., Chen, Y.-S. and Linderman, K. (2015), “Supply network disruption and resilience: A network structural perspective”, *Journal of Operations Management*, Vol. 33, pp. 43–59.

de Kock, C. (2019), “Analystics and Syntheses: Lecture 7 - Agent-Based Modelling”, SunORE Department of industrial Engineering.

Kotze, R. (2015), “Science and Philosophy - Dancing with Complex Systems”.

KPMG. (2019), *Global Automotive Executive Survey 2019*, available at: https://automotive-institute.kpmg.de/GAES2019/downloads/GAES2019PressConferenceENG_FINAL.PDF (accessed 22 September 2020).

Lai, D. and Wahba, R. (2003), *System Dynamics Model Correctness Checklis*, available at: http://myweb.ncku.edu.tw/~wtwang/course-SD-evening/D-4851.pdf (accessed 22 September 2020).

Leaver, J. (2019), “Hydrogen and New Zealand's Heavy Vehicle Fleet”, available at: https://unitec.researchbank.ac.nz/handle/10652/4719 (accessed 17 December 2019).

Leaver, J., Gillingham, K. and Baglino, A. (2012), *System Dynamics Modelling of Pathways to a Hydrogen Economy in New Zealand: Final Report*.

Lenton, T.M. and van Oijen, M. (2002), “Gaia as a complex adaptive system”, *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, Vol. 357 No. 1421, pp. 683–695.

Maani, K. and Cavana, R. (2007), *Systems Thinking, System Dynamics: Managing Change and Complexity*, Pretice Hall.

Maetzig, R. (2019), “Should we drink to the New Zealand future of hydrogen vehicles?”, available at: https://www.stuff.co.nz/motoring/117778660/should-we-drink-to-the-new-zealand-future-of-hydrogen-vehicles (accessed 22 September 2020).

Maidstone, R. (2012), “Discrete Event Simulation, System Dynamics and Agent Based Simulation: Discussion and Comparison”, pp. 1–6.

Marbán, G. and Valdés-Solís, T. (2007), “Towards the hydrogen economy?”, *International Journal of Hydrogen Energy*, Vol. 32 No. 12, pp. 1625–1637.

Marcinkoski, J., Vijayagopal, R., Adams, J., James, B., Kopasz, J. and Ahluwalia, R. (2019), *Hydrogen Class 8 Long Haul Truck Targets*, available at: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf (accessed 29 September 2020).

Markard, J. (2018), “The next phase of the energy transition and its implications for research and policy”, *Nature Energy*, Springer US, Vol. 3 No. 8, pp. 628–633.

Markard, J., Raven, R. and Truffer, B. (2012), “Sustainability transitions: An emerging field of research and its prospects”, *Research Policy*, Elsevier B.V., Vol. 41 No. 6, pp. 955–967.

Markard, J. and Truffer, B. (2008), “Technological innovation systems and the multi-level perspective: Towards an integrated framework”, *Research Policy*, Vol. 37 No. 4, pp. 596–615.

Martinez-Moyano, I.J. (2012), “Documentation for model transparency”, *System Dynamics Review*, John Wiley & Sons, Ltd, Vol. 28 No. 2, pp. 199–208.

MBIE. (2018), *Memorandum of Cooperatoin between the Ministry of Economy, Trade and Industry of Japan and the Ministry of Business, Innovation and Employment of New Zealand on Hydrogen*, available at: https://www.meti.go.jp/press/2018/10/20181029004/20181029004-1.pdf (accessed 19 December 2019).

MBIE. (2019a), *Discussion Document: Accelerating Renewable Energy and Energy Efficiency*, available at: https://www.research.net/r/Accelerating-renewable-energy-and-energy-efficiency (accessed 22 September 2020).

MBIE. (2019b), *A Vision for Hydrogen in New Zealand*, *Energy Strategies for New Zealand*, available at: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/.

MBIE. (2019c), *Energy in New Zealand 2019*, Vol. 15, available at: https://www.mbie.govt.nz/dmsdocument/7040-energy-in-new-zealand-2019#:~:text=Energy in New Zealand 2019 provides annual information on and,of the calendar year 2018.&text=A.

MBIE. (2020), “Analysis of Hydrogen Vision Submissions”.

Meadows, D.H. (2008), *Thinking in Systems: A Primer*, Chelsea green publishing, available at: https://books.google.co.za/books?hl=en&lr=&id=CpbLAgAAQBAJ&oi=fnd&pg=PR9&dq=• %09Meadows,+D.+H.,+2008.+Thinking+in+Systems&ots=LAj8r9vDO3&sig=N_vyEkEfIjFI

F612teZe4k3vywM#v=onepage&q&f=false (accessed 22 September 2020).

Meadows, D.H., Meadows, D., Randers, J. and Behrens III, W.W. (1972), *The Limits to Growth: A Report to The Club of Rome*, available at: http://www.ask-force.org/web/Global-Warming/Meadows-Limits-to-Growth-Short-1972.pdf (accessed 22 September 2020).

Mebratu, D. (1998), "Sustainability and sustainable development: Historical and conceptual review", *Environmental Impact Assessment Review*, Vol. 18 No. 6, pp. 493–520.

Mendeley. (2020), "Mendeley - Reference Management Software & Researcher Network", available at: https://www.mendeley.com/?interaction_required=true (accessed 17 November 2020).

MFE. (2019), "Climate Change Response (Zero Carbon) Amendment Act", available at: https://www.mfe.govt.nz/climate-change/zero-carbon-amendment-act (accessed 22 September 2020).

Midgley, G. (2007), "Systems thinking for evaluation", *Systems Concepts in Evaluation: An Expert Anthology*, pp. 11–34.

Ministry of Transport. (2020a), "Monthly electric and hybrid light vehicle tables | ", available at: https://www.transport.govt.nz/mot-resources/vehicle-fleet-statistics/monthly-electric-and-hybrid-light-vehicle-registrations-2 (accessed 22 September 2020).

Ministry of Transport. (2020b), *2018 New Zealand Vehicle Fleet Annual Statistics*, available at: https://www.transport.govt.nz/mot-resources/vehicle-fleet-statistics/ (accessed 29 September 2020).

Ministry of Transport. (2020c), "Green Freight Project ", available at: https://www.transport.govt.nz/multi-modal/climatechange/green-freight-project/ (accessed 1 October 2020).

Ministry of Transport. (2020d), "Vehicles exempt from paying road user charges", available at: https://www.transport.govt.nz/land/road-user-charges-ruc-and-petrol-excise-duty-ped/roaduserchargeslegislationchanges/vehiclesexemptfrompayingrucqandas/ (accessed 21 October 2020).

Ministry of Transport. (2020e), "RD025 Average vehicle fleet age (years)", available at: https://www.transport.govt.nz/mot-resources/transport-dashboard/2-road-transport/rd025-average-vehicle-fleet-age-years/ (accessed 19 October 2020).

Mohseni, S. and Brent, A.C. (2019), "Economic viability assessment of sustainable hydrogen production, storage, and utilisation technologies integrated into on- and off-grid micro-grids: A performance comparison of different meta-heuristics", *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. xxx No. xxx, p. xxx.

Moliner, R., Lázaro, M.J. and Suelves, I. (2016), "Analysis of the strategies for bridging the gap towards the Hydrogen Economy", *International Journal of Hydrogen Energy*, Vol. 41 No. 43, pp. 19500–19508.

Mouton, J. (2001), *How to Succeed in Your Master's and Doctoral Studies*, Van Schaik.

Musango, J.K., Brent, A.C., Smit van Niekerk, J.B., Jonker, W.D., Pienaar, A.P., York, T.A., Oosthuizen, J., *et al.* (2015), *A System Dynamics Approach to Understand the Implications of a Green Economy Transition in the Western Cape Province of South Africa*, available at: http://www.environment.gov.za/sites/default/files/docs/greene_conomy_summit.pdf. (accessed

22 September 2020).

Nagy, B., Farmer, J.D., Bui, Q.M. and Trancik, J.E. (2013), "Statistical Basis for Predicting Technological Progress", *PLoS ONE*, Public Library of Science, Vol. 8 No. 2, p. 52669.

Nel Hydrogen. (2020), *The World's Most Efficient and Reliable Electrolysers*, available at: https://nelhydrogen.com/wp-content/uploads/2020/03/Electrolysers-Brochure-Rev-C.pdf (accessed 29 September 2020).

NERI. (2019), *Feedback on Hydrogen Green Paper*, available at: https://www.neri.org.nz/resource/Files/Submissions/NERI response to Hydrogen Green Paper.pdf (accessed 22 September 2020).

New Zealand Government. (2019), *The Draft New Zealand Rail Plan*, available at: https://transport.cwp.govt.nz/assets/Import/Uploads/Rail/The-Draft-NZ-Rail-Plan-December-19.pdf.

New Zealand Parliament. (2019), "Climate Change Response (Zero Carbon) Amendment Bill", available at: https://www.parliament.nz/en/pb/bills-and-laws/bills-proposed-laws/document/BILL_87861/climate-change-response-zero-carbon-amendment-bill (accessed 22 September 2020).

Van Niekerk, J.B.S. (2015), *Implications for the Agriculture Sector of a Green Economy Transition in the Western Cape Province of South Africa: A System Dynamics Modelling Approach to Food Crop Production*, available at:https://doi.org/10.7166/28-1-1611.

Nikola Corp. (2020a), "Nikola Orders Enough Electrolysis Equipment From Nel to Produce 40,000 kgs of Hydrogen Per Day", available at: https://nikolamotor.com/press_releases/nikola-orders-enough-electrolysis-equipment-from-nel-to-produce-40000-kgs-of-hydrogen-per-day-79 (accessed 29 September 2020).

Nikola Corp. (2020b), *Investing in a Cleaner Future*, available at: https://nikolamotor.com/NikolaInvestorPresentation3-3-2020.pdf (accessed 29 September 2020).

NZPC. (2018), *Low-Emissions Economy*, available at: https://www.productivity.govt.nz/sites/default/files/Productivity Commission_Low-emissions economy_Final Report_FINAL.pdf.

O'dell, J. (2019), "Here's Everything We Know About the Tesla Semi-Truck", available at: https://www.trucks.com/2019/09/05/everything-we-know-about-the-tesla-semi-truck/ (accessed 19 October 2020).

Oosthuizen, J. (2016), *Investigating a Green Economy Transition of the Electricity Sector in the Western Cape Province of South Africa: A System Dynamics Approach*, *South African Journal of Industrial Engineering*, available at:https://doi.org/10.7166/27-4-1522.

Østreng, W. (2006), "Reductionism versus Holism", *Consilience*, pp. 11–14.

Ozin, G. (2017), "Hydrogen Storage in Liquid Organic Hydrogen Carriers - Advanced Science News", available at: https://www.advancedsciencenews.com/hydrogen-storage-liquid-organic-hydrogen-carriers/ (accessed 22 September 2020).

Papachristos, G. (2019), "System dynamics modelling and simulation for sociotechnical transitions research", *Environmental Innovation and Societal Transitions*, Elsevier B.V., Vol. 31, pp. 248–

261.

Perez, R.J.E. (2020), *Analysis of the Levelized Cost of Green Hydrogen Production for Very Heavy Vehicles in New Zealand*.

Perez, R.J.E., Brent, A.C. and Hinkley, J. (2020), "Analysis of Green Hydrogen Transportation Fuel from Renewable Energy in New Zealand", *7th Asia-Oceania Conference of the International Association for Energy Economics (IAEE)*, International Association for Energy Economics, Auckland, pp. 12–15.

Peters, W. (2020), "PGF investment in green hydrogen | Beehive.govt.nz", available at: https://www.beehive.govt.nz/release/pgf-investment-green-hydrogen (accessed 22 September 2020).

Peterson, D., Vickers, J., Desantis, D., Ayers, K., Hamdan, M., Harrison, K., Randolph, K., *et al.* (2020), *DOE Hydrogen and Fuel Cells Program Record*, available at: https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf (accessed 29 September 2020).

Poli, R. (2013), "A Note on the Difference Between Complicated and Complex Social Systems", *Cadmus*, Vol. 2 No. 1, pp. 142–147.

Preuster, P., Papp, C. and Wasserscheid, P. (2017), "Liquid organic hydrogen carriers (LOHCs): Toward a hydrogen-free hydrogen economy", *Accounts of Chemical Research*, Vol. 50 No. 1, pp. 74–85.

Probst, G. and Bassi, A. (2017), *Probst, Gilbert, and Andrea Bassi. Tackling Complexity: A Systemic Approach for Decision Makers*, Routledge.

Pruyt, E. (2013), *Small System Dynamics Models for Big Issues: Triple Jump towards Real-World Dynamic Complexity*, *Proceedings of the 2009 System Dynamics Conference*, Vol. 22, available at:https://doi.org/10.1007/SpringerReference_7284.

Quarton, C.J., Tlili, O., Welder, L., Mansilla, C., Blanco, H., Heinrichs, H., Leaver, J., *et al.* (2020), "The curious case of the conflicting roles of hydrogen in global energy scenarios", *Sustainable Energy and Fuels*, Royal Society of Chemistry, Vol. 4 No. 50, pp. 80–95.

Rotmans, J. and Loorbach, D. (2009), "Complexity and transition management", *Journal of Industrial Ecology*, Vol. 13 No. 2, pp. 184–196.

Saba, S.M., Müller, M., Robinius, M. and Stolten, D. (2018), "The investment costs of electrolysis – A comparison of cost studies from the past 30 years", *International Journal of Hydrogen Energy*, Vol. 43 No. 3, pp. 1209–1223.

Sanders, R. (1987), "The Pareto principle: its use and abuse", *Journal of Services Marketing*.

Schoots, K., Ferioli, F., Kramer, G.J. and van der Zwaan, B.C.C. (2008), "Learning curves for hydrogen production technology: An assessment of observed cost reductions", *International Journal of Hydrogen Energy*, Vol. 33 No. 11, pp. 2630–2645.

Shalizi, C.R. (2007), "Methods and Techniques of Complex Systems Science: An Overview", *Complex Systems Science in Biomedicine*, pp. 33–114.

Siebers, P.O., MacAl, C.M., Garnett, J., Buxton, D. and Pidd, M. (2010), "Discrete-event simulation is dead, long live agent-based simulation!", *Journal of Simulation*, Vol. 4 No. 3, pp. 204–210.

Siemens. (2019), “Tecnomatix”, available at: https://www.dex.siemens.com/plm/tecnomatix (accessed 28 September 2020).

Sklar-Chik, M.D., Brent, A.C. and de Kock, I.H. (2016), “Critical review of the levelised cost of energy metric”, *South African Journal of Industrial Engineering*, South African Institute of Industrial Engineering, Vol. 27 No. 4, pp. 124–133.

Smit, R. and Campbell, A. (2007), *Cost and Impacts of a Transition to Hydrogen Fuel in New Zealand*, *Ministry of Business, Innovation and Employment*, available at: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/technical-papers/pdf-library/hydrogen_fuel.pdf.

Sovacool, B.K. and Brossmann, B. (2010), “Symbolic convergence and the hydrogen economy”, *Energy Policy*, Elsevier, Vol. 38 No. 4, pp. 1999–2012.

State of California. (2020), “Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California’s Fight Against Climate Change | California Governor”, 23 September, available at: https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/ (accessed 13 November 2020).

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., *et al.* (2015), “Planetary boundaries: Guiding human development on a changing planet”, *Science*, Vol. 347 No. 6223, pp. 736–748.

Sterman, J.D. (1991), “A Skeptic’s Guide to Computer Models”, *Managing a Nation*, Vol. 2, pp. 209–229.

Sterman, J.D. (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*.

Sterman, J.D. (2002a), “System Dynamics: Systems Thinking and Modeling for a Complex World”, *MIT Sloan School of Management*, Vol. 147 No. 3, pp. 248–249.

Sterman, J.D. (2002b), “All models are wrong: Reflections on becoming a systems scientist”, *System Dynamics Review*, John Wiley & Sons, Ltd, Vol. 18 No. 4, pp. 501–531.

Stevenson, T., Batstone, S., Reeve, D., Poynton, M. and Comendant, C. (2018), *Transitioning to Zero Net Emissions by 2050: Moving to a Very Low-Emissions Electricity System in New Zealand*.

Sweeney, L.B. and Sterman, J.D. (2000), “Bathtub dynamics: initial results of a systems thinking inventory”, *System Dynamics Review*, John Wiley & Sons, Ltd, Vol. 16 No. 4, pp. 249–286.

Swilling, M. (2012), “Just Transition and the Next Long-Term Development Cycle: Warnings from the South African Case”, *International Conference on Sustainability Transitions*, available at: http://www.ist2012.dk/index.php/IST/IST2012/paper/viewPaper/16.

Taylor, A. (2020), “Fast tracking renewable hydrogen projects”, available at: https://www.minister.industry.gov.au/ministers/taylor/media-releases/fast-tracking-renewable-hydrogen-projects (accessed 22 September 2020).

Tedeschi, L.O., Nicholson, C.F. and Rich, E. (2011), “Using System Dynamics modelling approach to develop management tools for animal production with emphasis on small ruminants”, *Small Ruminant Research*, Elsevier B.V., Vol. 98 No. 1–3, pp. 102–110.

Thomas, V. (2019), *Investigating Intervention Strategies for the Management of Diabetes in South*

Africa : A System Dynamics Approach.

Turnheim, B., Asquith, M. and Geels, F.W. (2020), “Making sustainability transitions research policy-relevant: Challenges at the science-policy interface”, *Environmental Innovation and Societal Transitions,* Elsevier, Vol. 34 No. December 2019, pp. 116–120.

UNEP. (2011), *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth*, available at: https://www.ourenergypolicy.org/wp-content/uploads/2014/07/decoupling.pdf (accessed 22 September 2020).

Varga, A. (2005), “Discrete Event Simulation”, *Service Design for Six Sigma*, pp. 331–364.

Vensim. (n.d.). “Reference Manual - Stock and Flow Diagrams”, available at: https://www.vensim.com/documentation/usr05.htm (accessed 13 November 2020a).

Vensim. (n.d.). “Reference Manual - Forecast Function”, available at: https://www.vensim.com/documentation/fn_forecast.htm (accessed 14 October 2020b).

Ventana Systems Inc. (2015), “Vensim Software | Vensim”, available at: https://vensim.com/vensim-software/ (accessed 22 September 2020).

Venture Taranaki. (2019), *H2 Taranaki Roadmap,* available at: https://about.taranaki.info/Taranaki2050/Work-Group-Files/H2-Taranaki-Roadmap.pdf (accessed 19 December 2019).

VividEconomics. (2018), *Gas Infrastructure Futures in a Net Zero New Zealand*, available at: https://www.vivideconomics.com/wp-content/uploads/2019/09/16098-First-Gas_Future-of-Gas-Report-Dec18-FINAL-high-res.pdf (accessed 29 September 2020).

Vlachos, D., Georgiadis, P. and Iakovou, E. (2007), “A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains”, *Computers and Operations Research*, Pergamon, Vol. 34 No. 2, pp. 367–394.

Wagner, I. (2019), “Average price of new Class 8 trucks - U.S. 2010-2018”, available at: https://www.statista.com/statistics/937418/new-truck-average-price-in-the-united-states/ (accessed 19 October 2020).

WEC. (2019), *New Hydrogen Economy: Hope or Hype?*, *Innovation Insights Brief*, available at: https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf.

WEC. (2020), *International Hydrogen Strategies,* available at: https://www.researchgate.net/publication/345162082_INTERNATIONAL_HYDROGEN_STRATEGIES_A_study_commissioned_by_and_in_cooperation_withthe_World_Energy_Council_Germany.

Van Wyk, B. (2015), “Research design and methods Part I”, University of the Western Cape, available at: https://www.uwc.ac.za/Students/Postgraduate/Documents/Research_and_Design_I.pdf.

Appendix A: Variable identification

This appendix presents the preliminary variables identified during causal loop modelling, as well as the variables that were used in the final dynamic model. The preliminary variables are identified as either exogenous (independent of other variables), endogenous (calculated using other variables), or excluded variables. The variables that were used in the final dynamic model are identified as either stock variables (variables that measure accumulation within the system), flow variables (variables governing the increase and decrease of a stock variable), or auxiliary variables (constants or estimates). Table 11 presents the preliminary variables, and Table 12 presents the variables that were used in the final dynamic model.

Table 11: preliminary variables identified

Variable Name	Description
Exogenous variables	
Number of trucks required on the road	The total number of trucks required on the road
Annual hydrogen requirements per fuel cell truck	The average amount of hydrogen used by a fuel cell truck in one year
Cost of diesel truck	The capital cost of a diesel truck
Cost of fuel cell truck	The capital cost of a fuel cell truck
Cost of diesel	The cost of diesel
Cost of hydrogen	The cost of hydrogen
Electrical efficiency of electrolysers	The amount of electricity required to produce one Kg of hydrogen
Emissions per liter of diesel burnt	The carbon emission from the combustion of a single liter of diesel fuel
Lifetime of a truck	The average number of years that a truck will be on the road
Lifetime of an electrolyser	The average number of years that an electrolyser will function
Price of electricity	The price that the consumer pays per kWh of electricity
Cost of electricity	The cost of producing a kWh of electricity
Endogenous variables	
Market sentiment to cost burden of fuel cell trucks	The market elasticity towards fluctuations in the cost of a fuel cell truck compared to the cost of a diesel truck
Hydrogen required to fuel existing fleet	The hydrogen that would be required to fuel all of the vehicles currently on the road, if they were all fuel cell trucks
Number of trucks that need to be purchased	The difference between the number of trucks needed on the road and the number of trucks that are on the road (either diesel or hydrogen fuelled)
Existing hydrogen production capacity	The kW of installed electrolyser capacity
New production capacity commissioned	The kW of new capacity that has been confirmed, but is not yet active

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Production capacity decommissioned	The kW of electrolyser capacity that is taken out of service
Number of diesel trucks on the road	The number of diesel trucks that are on the road at any given time
Number of fuel cell trucks	The number of fuel cell trucks that are on the road at any given time
Forecast of number of fuel cell trucks	The expected number of fuel cell trucks that will be on the road in a year or two from the current time
Investments in hydrogen production capacity	The total NZ$ invested into hydrogen production capacity
Total emissions from diesel trucks	The total emissions from diesel trucks since the start of the model
Total electricity used to generate hydrogen	The total electricity that has been used to generate hydrogen
Total investments in electricity	The total NZ$ that have been invested in making electricity available to electrolysers
Excluded variables	
Water efficiency of electrolysers	The liters of water required per kg of hydrogen produced
Impact of regulating hydrogen	The impact that regulation has on the market sentiment
Impact of standardization	The impact that standardization has on the cost of producing green hydrogen
Cost of a battery electric truck	The cost of a battery electric truck
Green hydrogen generated for non HDVs	The amount of green hydrogen generated for use is light- and medium-duty vehicles
Learning curve of diesel technologies	The rate at which diesel technology gets cheaper each year
Green hydrogen exported	The amount of green hydrogen exported from New Zealand to other countries
Green hydrogen imported	The amount of green hydrogen imported to New Zealand from other countries
Market sentiment towards hydrogen safety	The extent to which the market is concerned about hydrogen safety
Government subsidies	The percentage of the cost of hydrogen technologies that is paid for by the government
Hydrogen transportation cost	The cost of transporting hydrogen from the site of generation to the site of use
Range of fuel cell truck	The distance that a fuel cell truck can drive on a full tank of hydrogen
Range of a diesel truck	The distance that a diesel truck can drive on a full tank of diesel

Table 12: Variables used in dynamic model

Variable name:	Variable type:
Number of Diesel Trucks	Stock
Emissions from Diesel Trucks	Stock
Number of Fuel Cell Trucks	Stock
Total Hydrogen Demanded by Fuel Cell Trucks	Stock
Total $ Invested in Hydrogen Production Capacity	Stock
Installed Hydrogen Production Capacity	Stock
Total Hydrogen Generated	Stock
Total $ Invested in Marginal Electricity	Stock
Diesel truck purchases	Flow
Decommissioning of diesel trucks	Flow
Annual emissions from diesel trucks	Flow
Fuel cell truck purchases	Flow
Decommissioning of fuel cell trucks	Flow
Demand for hydrogen by fuel cell trucks	Flow
$ invested in hydrogen production capacity per year	Flow
Hydrogen production capacity commissioned	Flow
Hydrogen production capacity decommissioned	Flow
Hydrogen generated per year	Flow
$ invested per year in marginal electricity	Flow
2020 number of heavy trucks required on the road	Auxiliary
a2	Auxiliary
Ammortization period for diesel truck	Auxiliary
Ammortization period for fuel cell truck	Auxiliary
annual investments	Auxiliary
availability of hydrogen	Auxiliary
Average Distance Travelled by a truck in YEAR	Auxiliary
Average lifetime of a Diesel Truck	Auxiliary
Average Lifetime of Fuel Cell Truck	Auxiliary
b2	Auxiliary

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Balance of Plant CAPEX TABLE	Auxiliary
Balance of Plant Costs	Auxiliary
CAPEX of Diesel Truck	Auxiliary
CAPEX of Fuel Cell Truck	Auxiliary
Capital costs of hydrogen production capacity	Auxiliary
Capital recovery factor of hydrogen production system	Auxiliary
Carbon emissions Per liter of Diesel	Auxiliary
Carbon Tax per liter of Diesel	Auxiliary
Carbon Tax per tonn of carbon	Auxiliary
Carbon tax scenario 2	Auxiliary
Carbon tax scenario 3	Auxiliary
Carbon tax scenario 4	Auxiliary
convert kW*h to kWh	Auxiliary
Convert kWh to GWh	Auxiliary
Cost of Diesel	Auxiliary
Cost of electricity per GWh	Auxiliary
Cost of electricity per year	Auxiliary
COST OF ELECTRICITY SCENARIO 2	Auxiliary
Cost of Electricity Scenario3	Auxiliary
Cost of Electricity Scenario4	Auxiliary
Cost of green hydrogen for fuel cell trucks	Auxiliary
Cost of Marginal electricity	Auxiliary
Cost per Km for Diesel Trucks	Auxiliary
Cost per Km for fuel cell truck	Auxiliary
Discount Rate	Auxiliary
Distance Based costs for Fuel Cell trucks	Auxiliary
Distance-Based costs for Diesel Truck	Auxiliary
distortion function - cost of electricity	Auxiliary
distortion function - electrolyser capex	Auxiliary
distortion function - Fuel Cell Truck Capex	Auxiliary
distortion function - Fuel economy of fuel cell truck	Auxiliary

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distortion function - kwh/kg	Auxiliary
distortion function - market response to cost burden of fuel cell truck	Auxiliary
distortion functions	Auxiliary
ELECTRICITY REQUIRED PER KG OF HYDROGEN - SCENARIO 2	Auxiliary
Electricity Required per Kg of Hydrogen - Scenario 3	Auxiliary
Electricity Required Per Kg of Hydrogen produced	Auxiliary
Electricity required per year	Auxiliary
electricity used per year per kW of hydrogen production capacity	Auxiliary
Electrolyser Capex	Auxiliary
Electrolyser Capex scenario 2	Auxiliary
Electrolyser Capex Scenario 3	Auxiliary
Electrolyser Capex Scenario 4	Auxiliary
electrolyser utilisation factor	Auxiliary
emissions from diesel trucks at start time	Auxiliary
exagerated forecast of required hydrogen production capacity for fuel cell trucks	Auxiliary
Expected Diesel Price	Auxiliary
FINAL TIME	Control
forecast of hydrogen demand	Auxiliary
Forecast of number of Fuel Cell Trucks	Auxiliary
Forecast safety factor	Auxiliary
Fuel Cell economy Scenario 2	Auxiliary
Fuel Cell economy Scenario 3	Auxiliary
Fuel Cell percentage of total	Auxiliary
Fuel Cell Truck Capex - Scenario 3	Auxiliary
Fuel Cell Truck Capex - Scenario 4	Auxiliary
Fuel Cell Truck Capex - scenario2	Auxiliary
Fuel economy of Diesel Truck	Auxiliary
Fuel Economy of Fuel Cell Truck(Kg/Km)	Auxiliary
Grid Network loss factors	Auxiliary

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hours in a year	Auxiliary
hydrogen already generated	Auxiliary
Hydrogen availability due to Hiringa scenarios	Auxiliary
Hydrogen availability due to Hiringa TABLE	Auxiliary
hydrogen demand initial value	Auxiliary
hydrogen generation/demand factor	Auxiliary
hydrogen production capacity CAPEX per kW	Auxiliary
Hydrogen Production capacity decomissionned	Auxiliary
Hydrogen production capacity required to meet forecasted hydrogen demand	Auxiliary
Initial Hydrogen production capacity for fuel cell trucks	Auxiliary
INITIAL TIME	Control
innitial number of Fuel Cell Trucks	Auxiliary
installation time	Auxiliary
Installed Hydrogen production Capacity	Auxiliary
investment period (smoothing)	Auxiliary
investments already made in hydrogen production capacity	Auxiliary
Kg hydrogen produced per year per installed kW of hydrogen production capacity	Auxiliary
Kg to tonn conversion	Auxiliary
Kilograms of hydrogen produced	Auxiliary
Levelized Cost of hydrogen	Auxiliary
Levelized cost of hydrogen including storage costs	Auxiliary
Lifetime of Hydrogen production system	Auxiliary
Load factor of electrolyser	Auxiliary
m2	Auxiliary
Marginal Electricity Required	Auxiliary
Market preference for fuel cell trucks	Auxiliary
Market response to cost burden of buying a fuel cell truck TABLE	Auxiliary
Market response to cost burden of fuel cell trucks	Auxiliary
Market Response to hydrogen availability ratio TABLE	Auxiliary
Market Response to the availability of hydrogen	Auxiliary

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Number of heavy trucks required	Auxiliary
Number of heavy trucks required in a given year	Auxiliary
Number of trucks forecast ATIME	Auxiliary
Number of trucks forecast HORIZON	Auxiliary
One = Forced to 100% Fuel Cell preference	Auxiliary
One = Hiringa filling station scenario	Auxiliary
one kW	Auxiliary
Operations and Maintenance as a percentage of capital costs	Auxiliary
Operations and maintenance costs	Auxiliary
Other costs for Diesel Trucks	Auxiliary
Other costs for fuel cell truck	Auxiliary
p2	Auxiliary
per year (unit correction for time in power function)	Auxiliary
Premium at the pumps	Auxiliary
SAVEPER	Control
Scenario Number	Auxiliary
Storage Cost Over Time TABLE	Auxiliary
Storage Costs	Auxiliary
Theoretical power rating of electrolyser	Auxiliary
TIME STEP	Control
timeperiod of calculation	Auxiliary
Toggle on/off: distortion function - cost of electricity	Auxiliary
Toggle on/off: distortion function - electrolyser capex	Auxiliary
toggle on/off: distortion function - Fuel economy of fuel cell truck	Auxiliary
toggle on/off: distortion function - kwh/kg	Auxiliary
toggle on/off: distortion function - market response to cost burden of fuel cell truck	Auxiliary
Toggle on/off: distortion function - Fuel Cell Truck Capex	Auxiliary
Total Electricity used per year to generate hydrogen	Auxiliary
Total Hydrogen generated	Auxiliary
total investment	Auxiliary

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Vehicle Km travelled in a given year	Auxiliary
Vehicle Km travelled over time TABLE	Auxiliary

Appendix B: Stock and flow diagram modules

This appendix presents the various stock and flow diagram (SFD) modules that comprise the model. The built-in Vensim naming convention is used, therefore variables are automatically capitalized by type. Colours have been used to differentiate variables relating to scenario analysis (red), and variables relating to sensitivity analysis (orange), from the rest of the model. Additionally, Vensim automatically indicates variables that originate from other modules (shadow variables) in a grey shade within sharp braces e.g.: <load factor of electrolyser>

The model is available online at: www.github.com/RickKotze/thesis

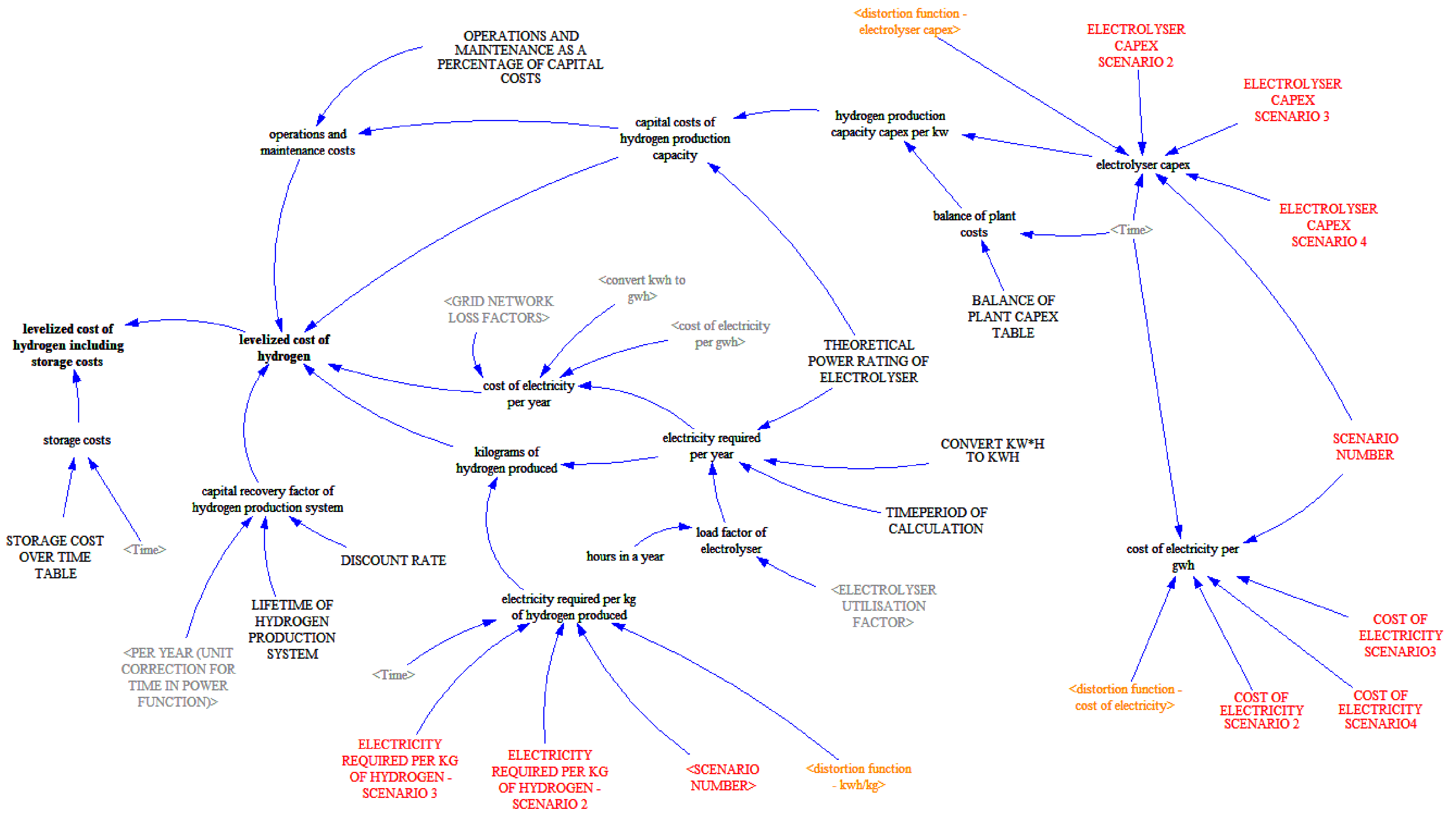

Figure 34: SFD of Levelized cost of hydrogen module

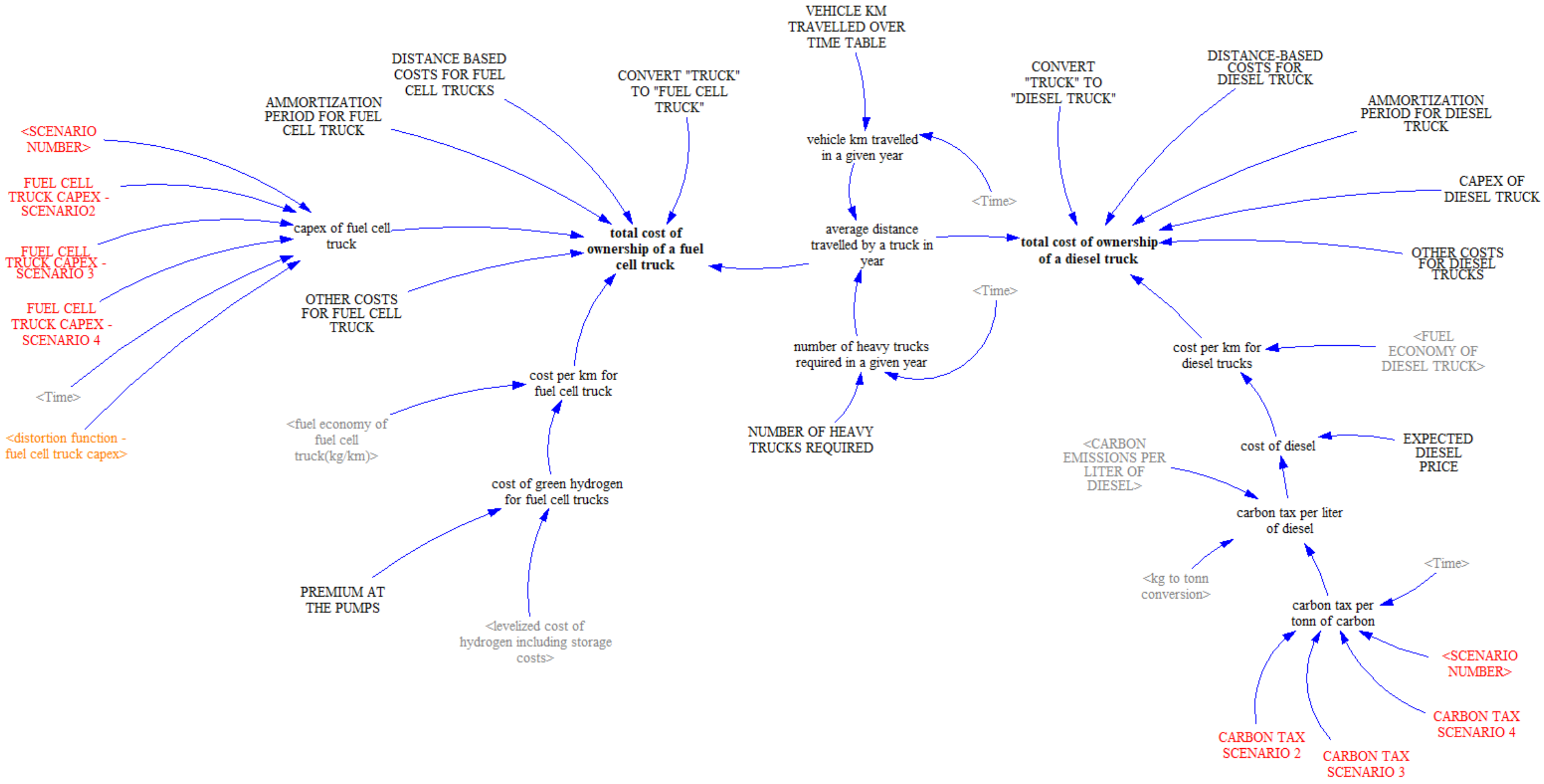

Figure 35: SFD of Total Cost of Ownership module

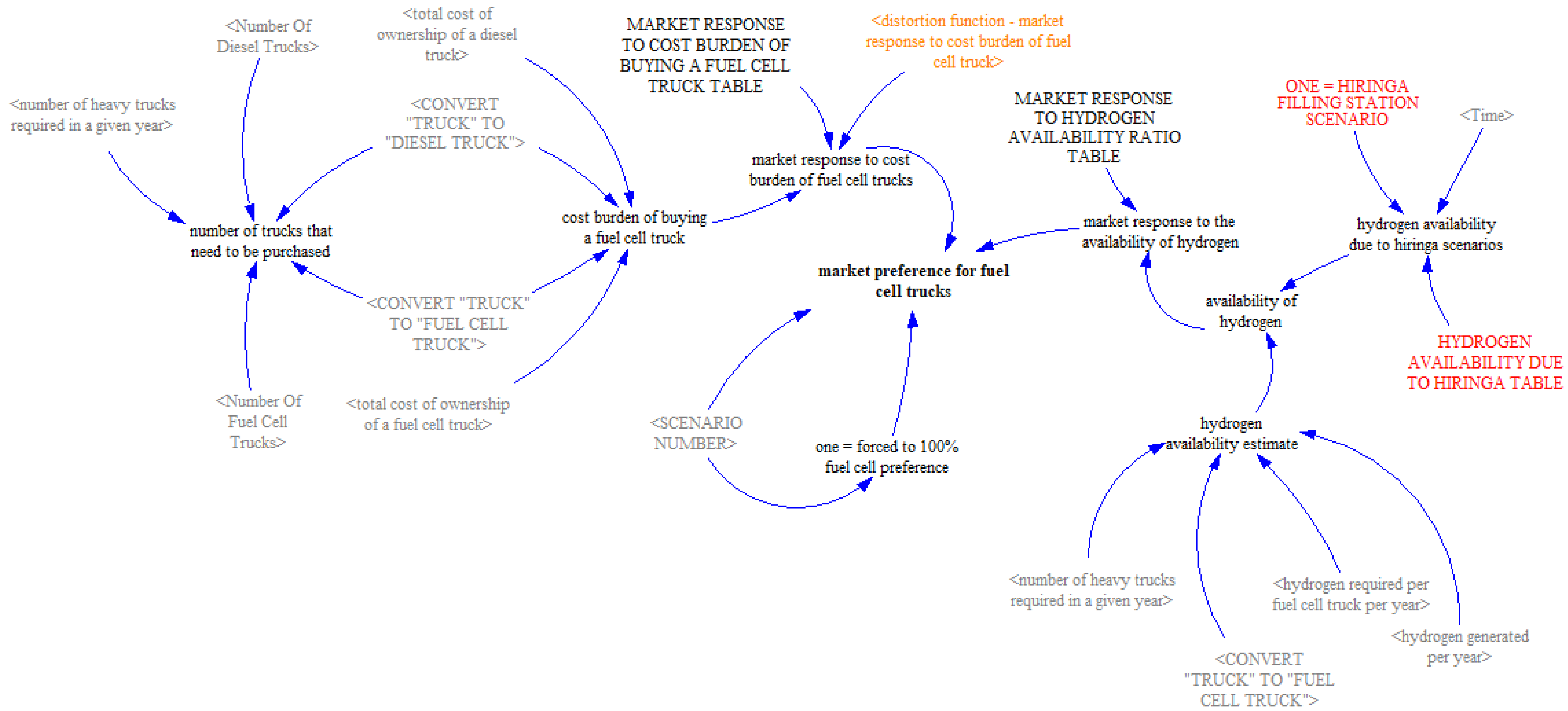

Figure 36: SFD of market preference module

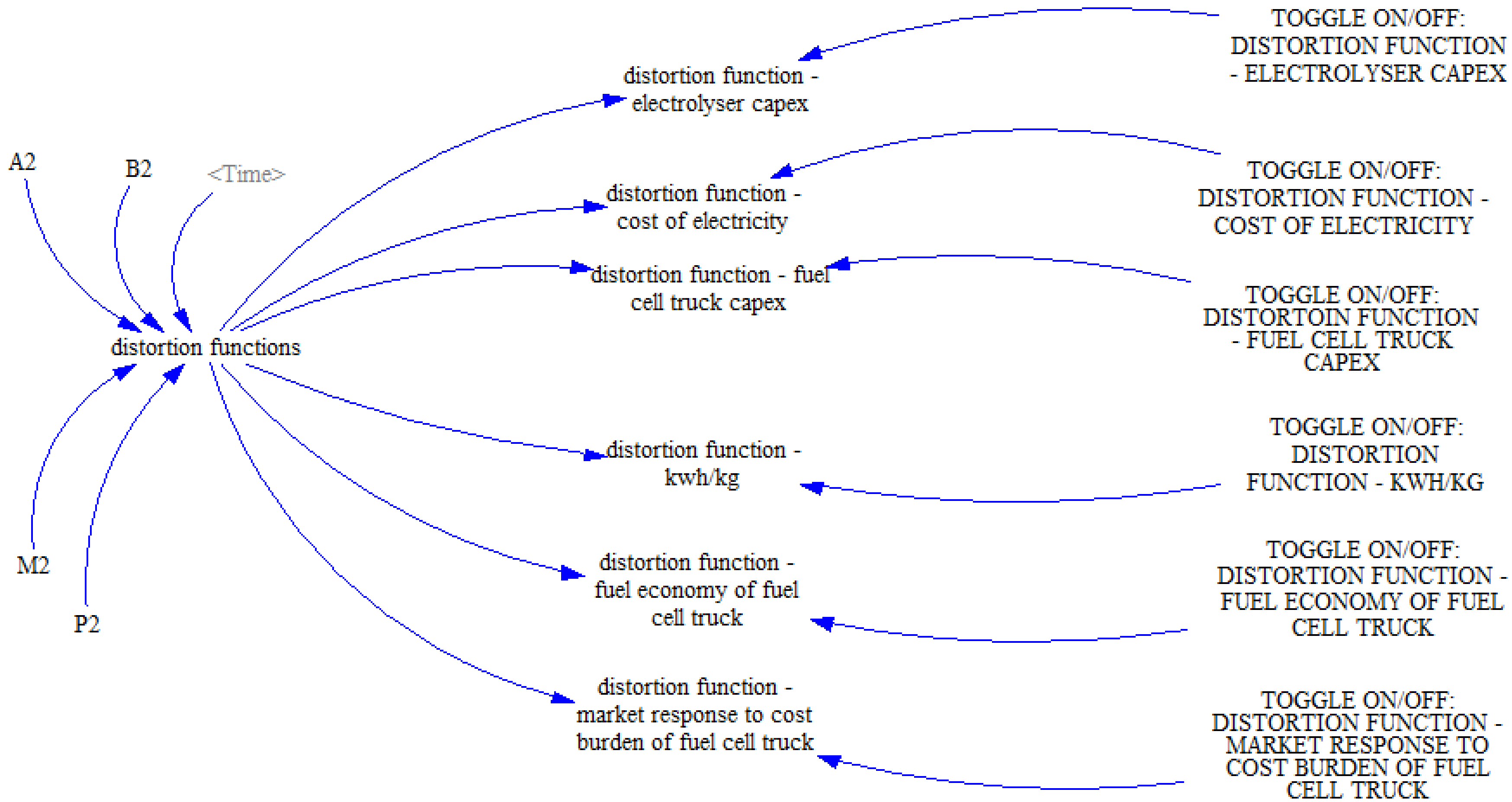

Figure 37: SFD of sensitivity analysis module

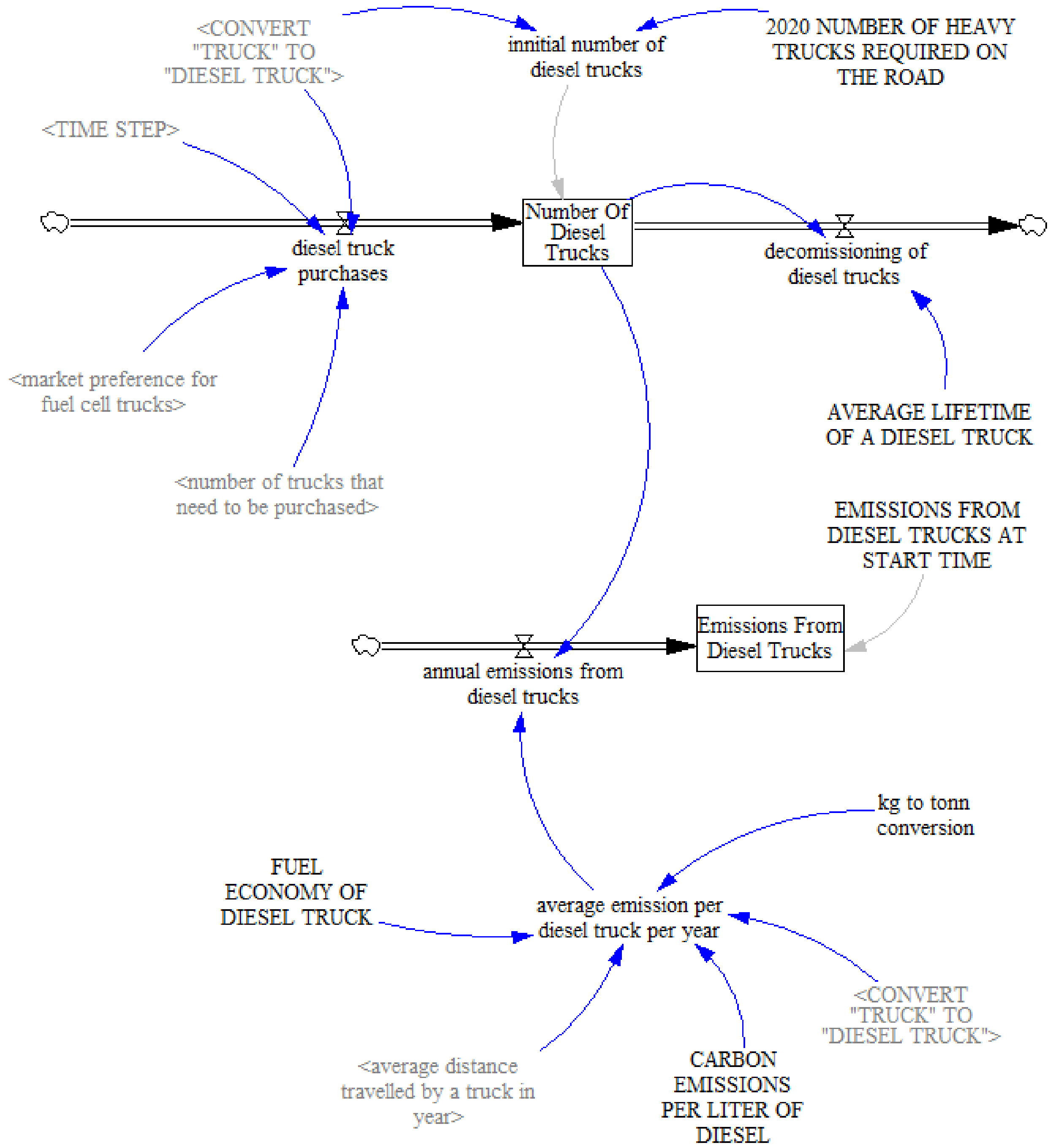

Figure 38: SFD of diesel trucks module

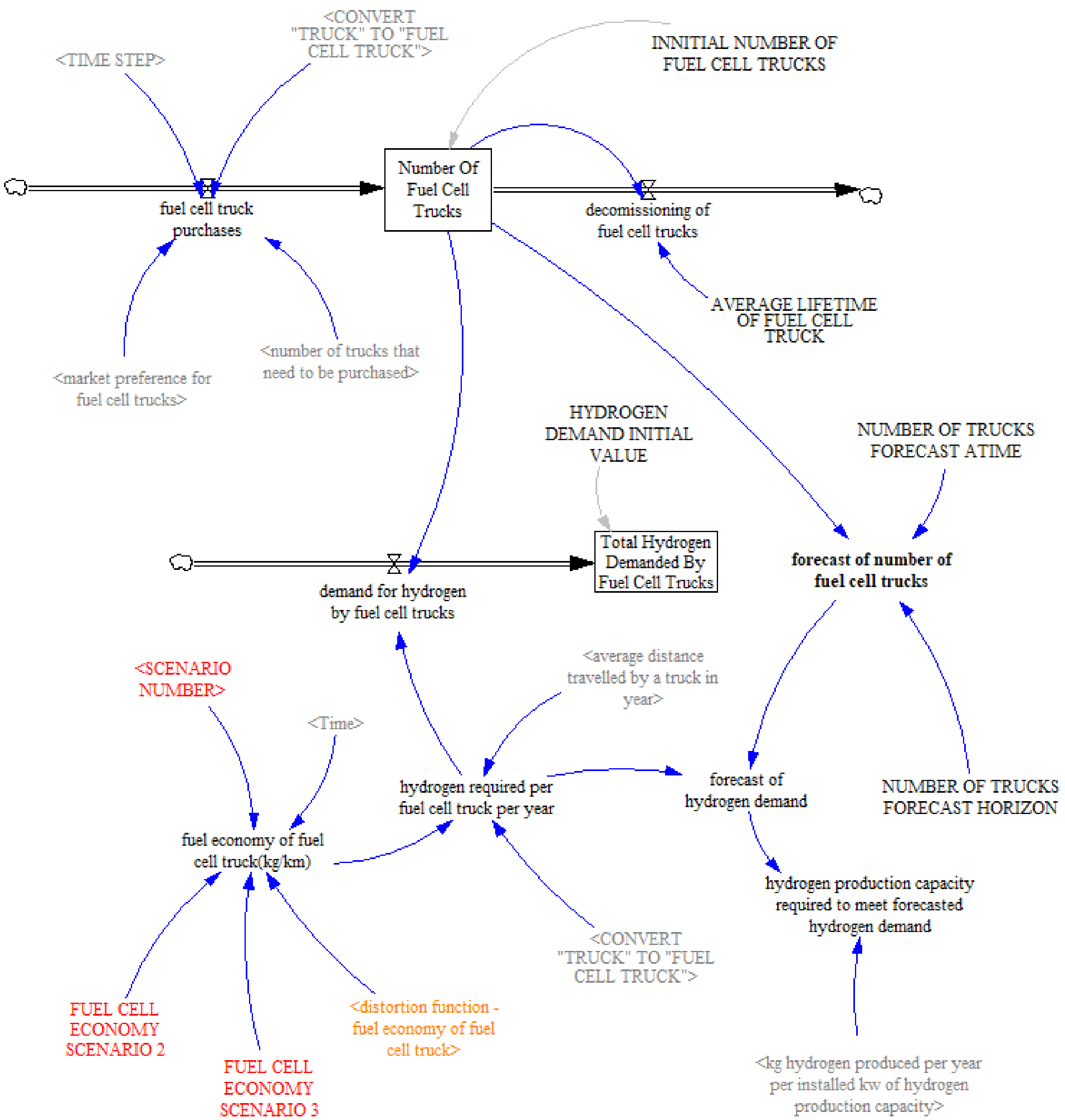

Figure 39: SFD of fuel cell trucks module

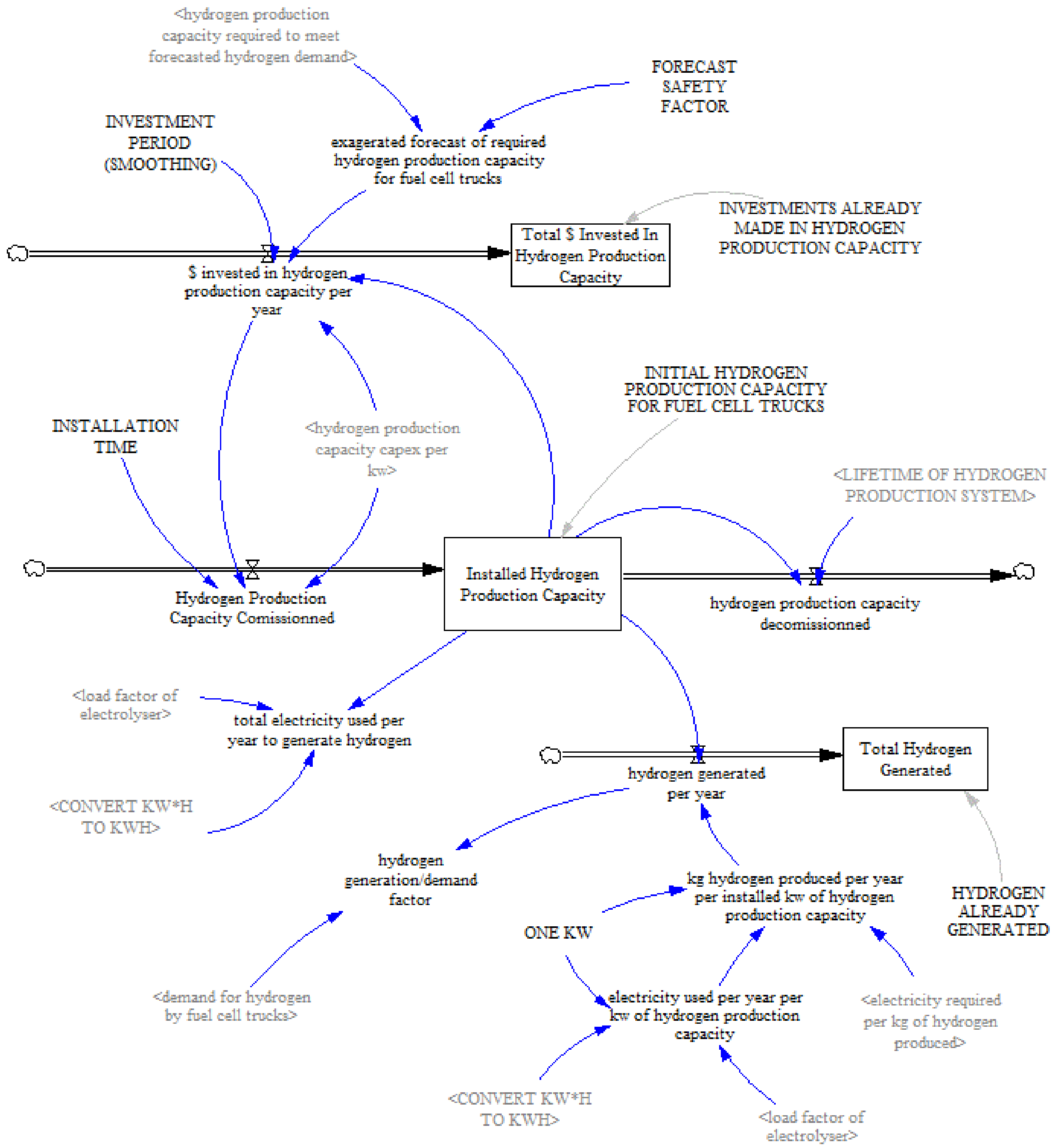

Figure 40: SFD of hydrogen production capacity module

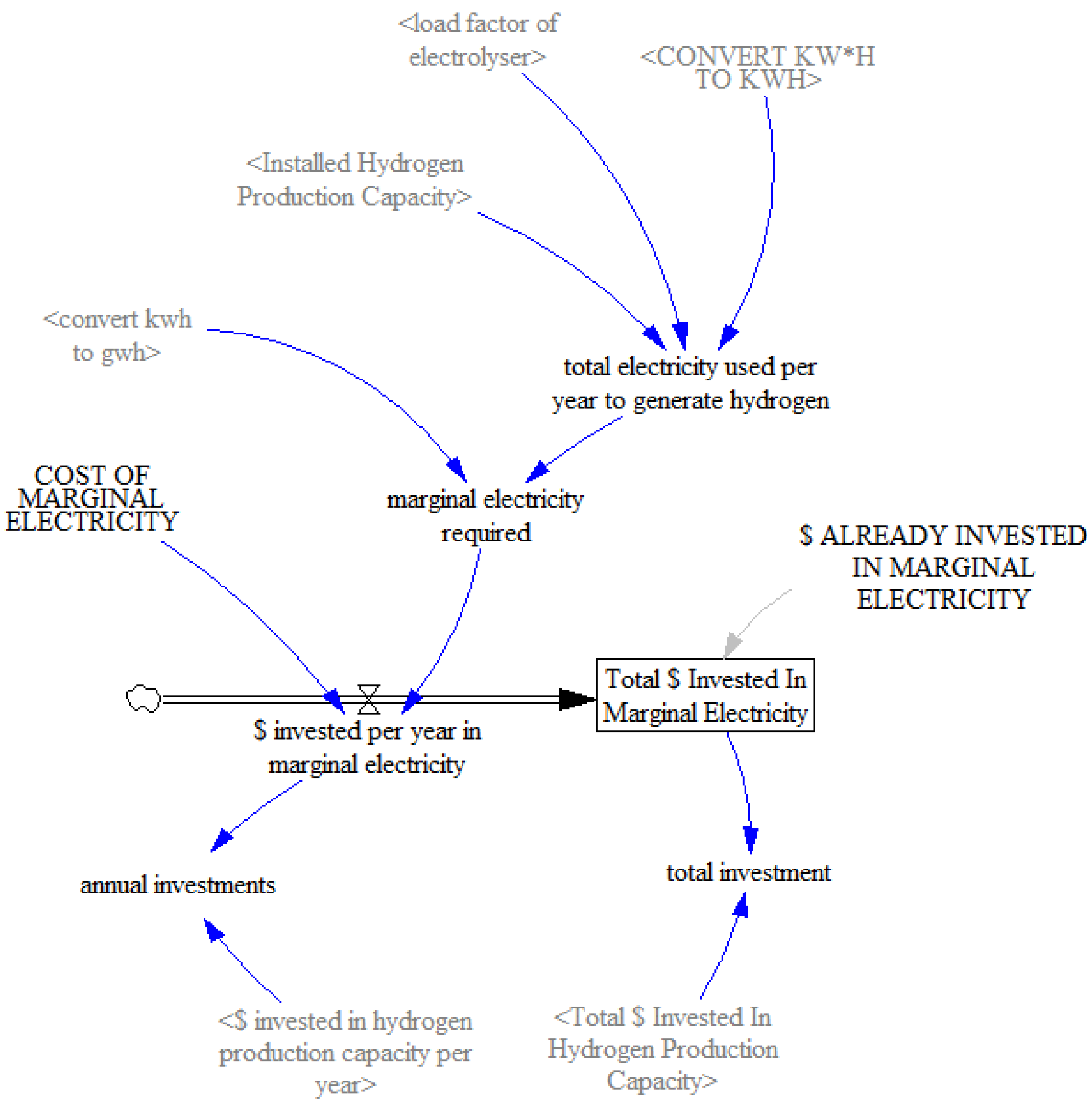

Figure 41: SFD of electricity requirements and cost module

Appendix C: Univariate sensitivity analysis

A univariate sensitivity analysis assists model verification and validation by ensuring that the sensitivity of model outputs to certain model inputs is well understood. A given parameter is varied by a small amount and the effect of this variation on key model outputs is observed. In this appendix the results of increasing and decreasing certain parameters by 10% is investigated. This variation is achieved by use of Hearne's (2010) method as described by Eker *et al.* (2014). The results of the univariate sensitivity analysis are of less interest to this study than a multivariate sensitivity analysis (as presented in Section 4.4.3). This is because this study is interested in understanding the range of outcomes across all uncertainties, as opposed to understanding the range of outcomes across the uncertainties of only one parameter. The results of this univariate sensitivity analysis were as expected. With the exception of the *market preference for fuel cell trucks* parameter, the key model outputs show an acceptably small sensitivity to the tested input parameters. The *market preference for fuel cell trucks* parameter is understood to be more sensitive than the other parameters as it is a lookup function which transforms a single input parameter into an output. Therefore, even a small change in the inputs to this function can cause a significant change to the output. The results of the univariate sensitivity analysis were therefore acceptable, and added to the integrity of the model. The results of four parameters will be presented, namely: *market preference for fuel cell trucks, number of fuel cell trucks, total $ invested in hydrogen production capacity,* and *total $ invested in marginal electricity*. Five parameters will be varied, namely: *electrolyser capex, cost of electricity, capex of fuel cell trucks, electricity required per kg of hydrogen production, fuel economy of fuel cell trucks*, and *market response to the cost burden of fuel cell trucks.* The outputs will be grouped according to the varied parameter. These outputs were generated with the parameter assumptions of scenario 3, as presented in Section 4.5.

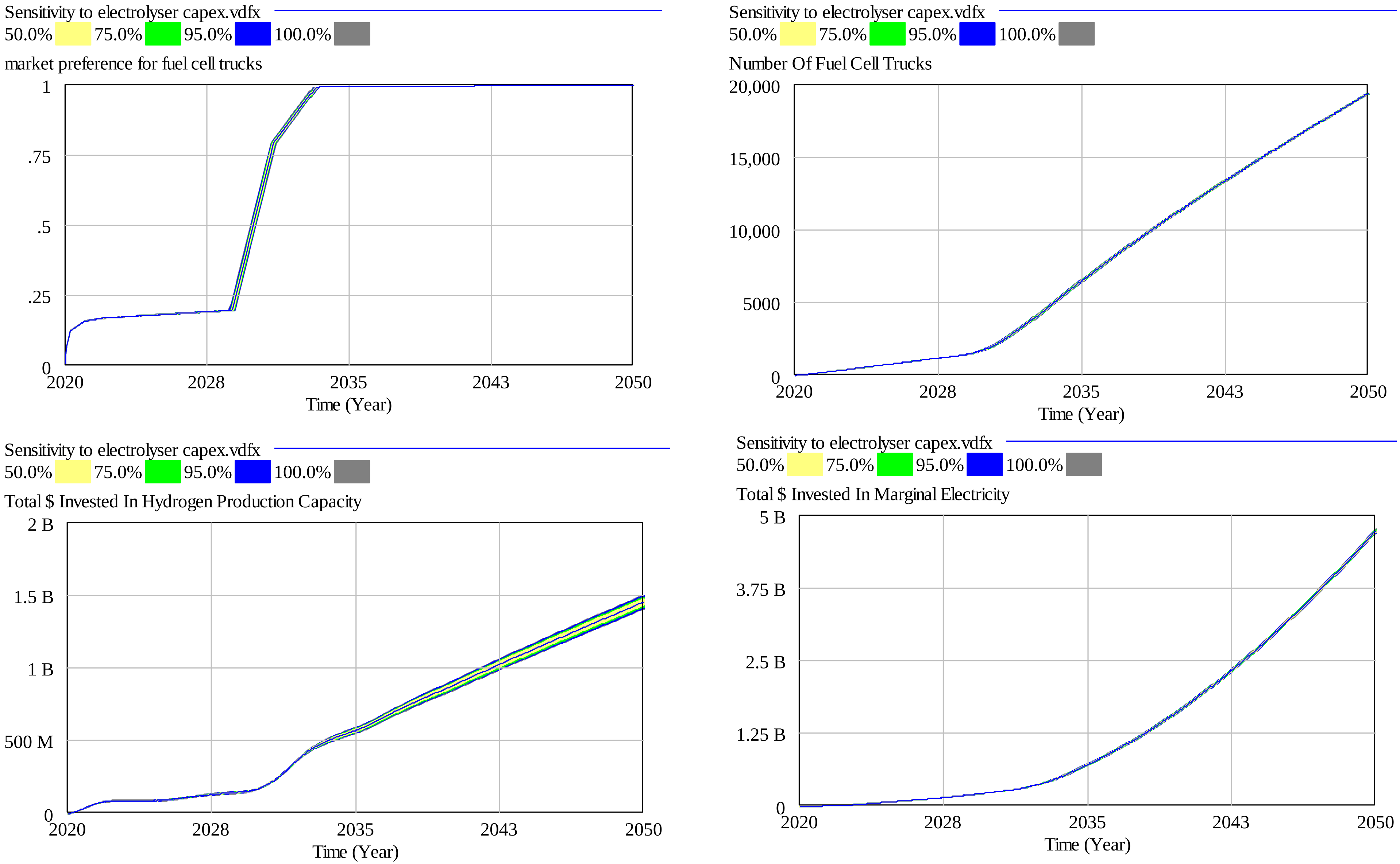

Figure 42: Model sensitivity to variations in electrolyser capex

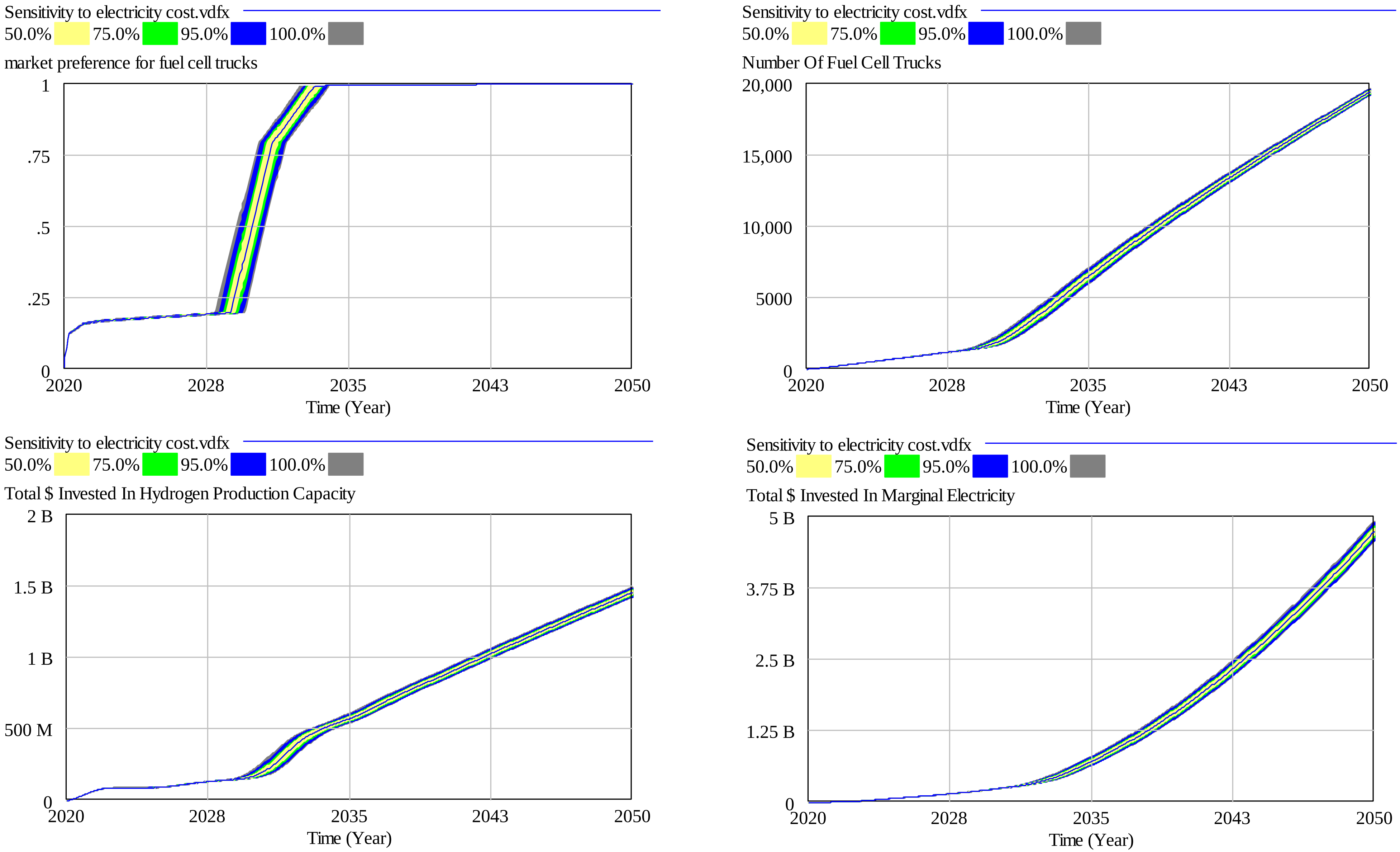

Figure 43: Model sensitivity to variations in electricity cost

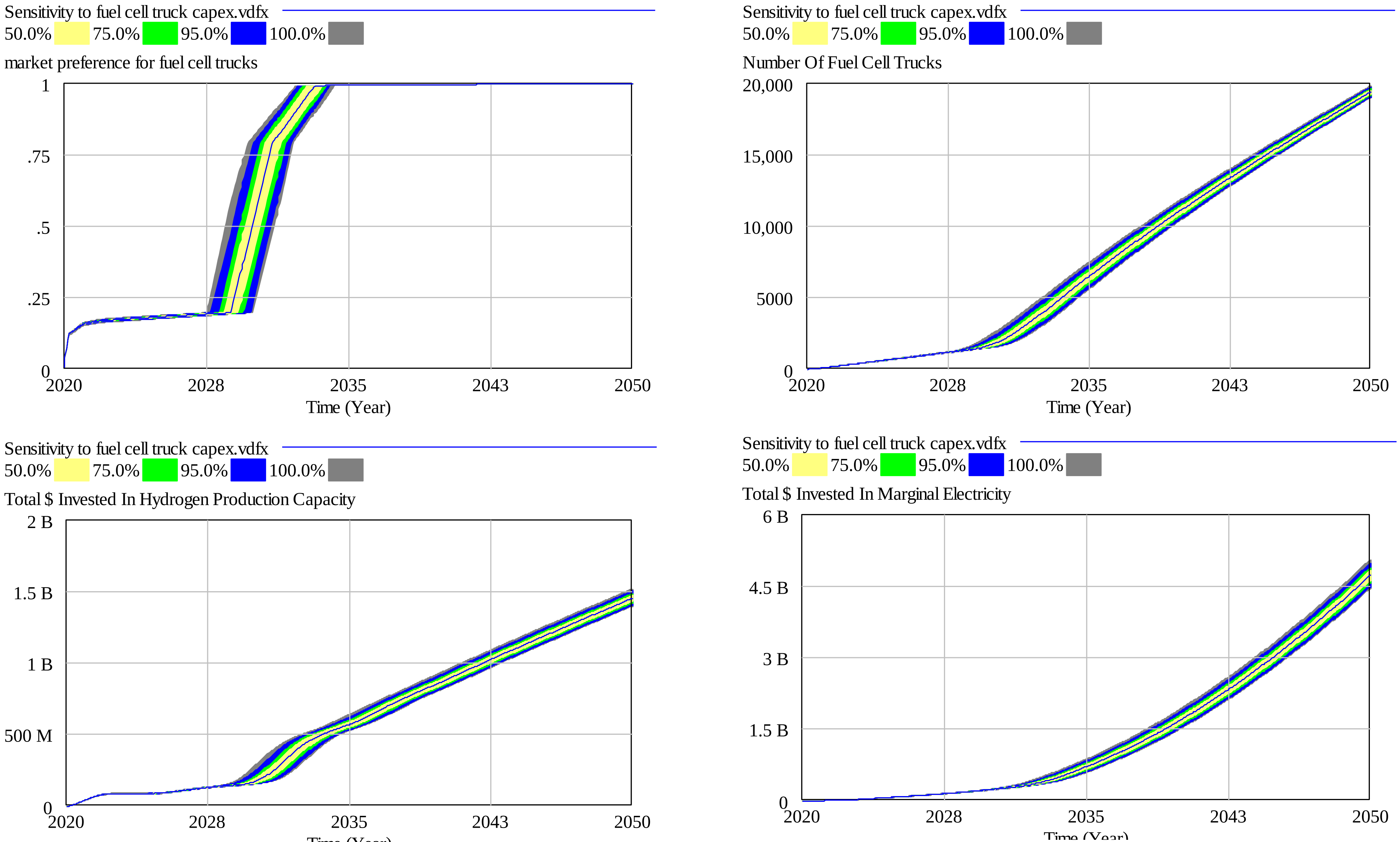

Figure 44: Model sensitivity to variations in the cost of a fuel cell truck

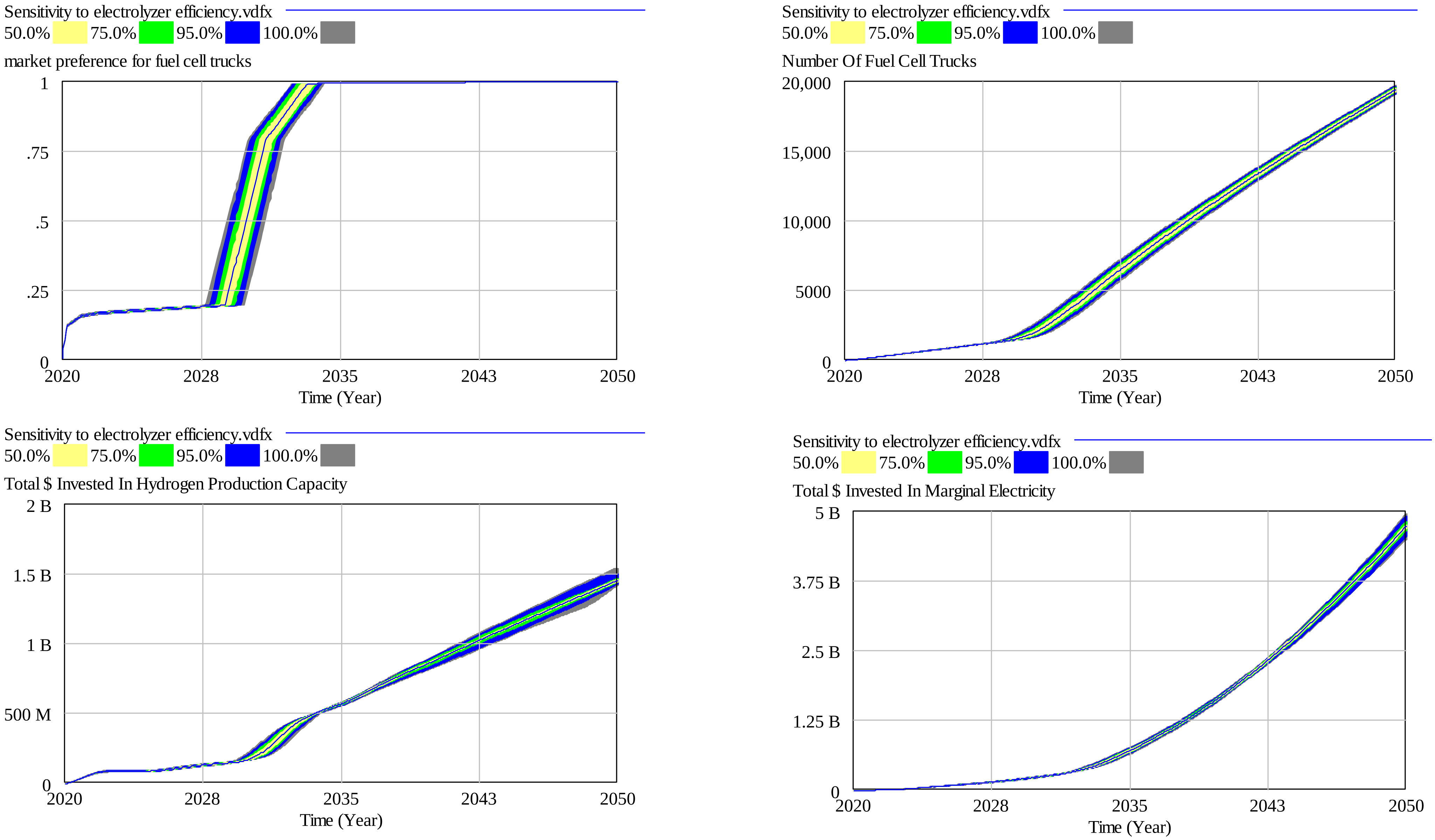

Figure 45: Model sensitivity to variations in electrolyser efficiency

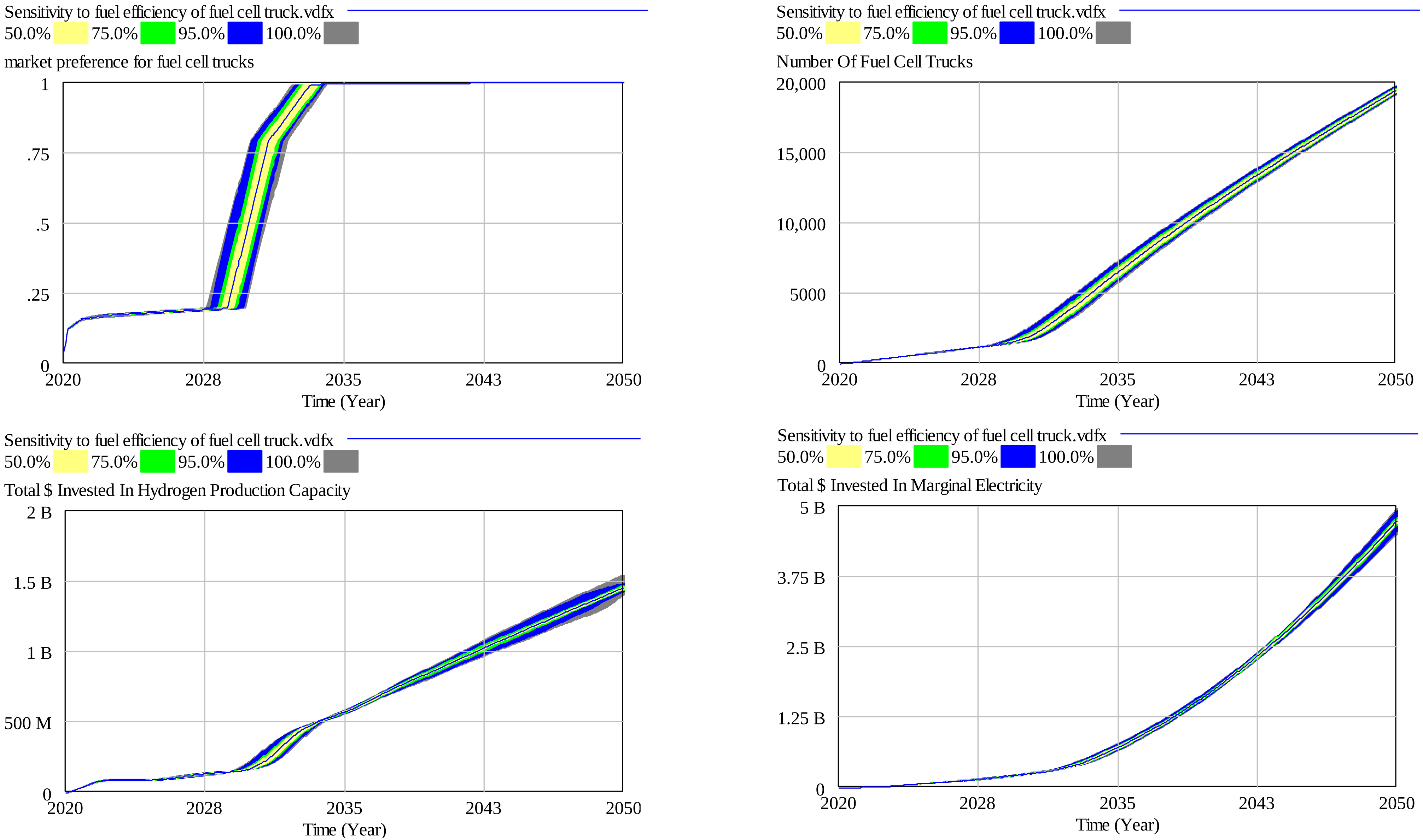

Figure 46: Model sensitivity to variations in the fuel efficiency of fuel cell trucks

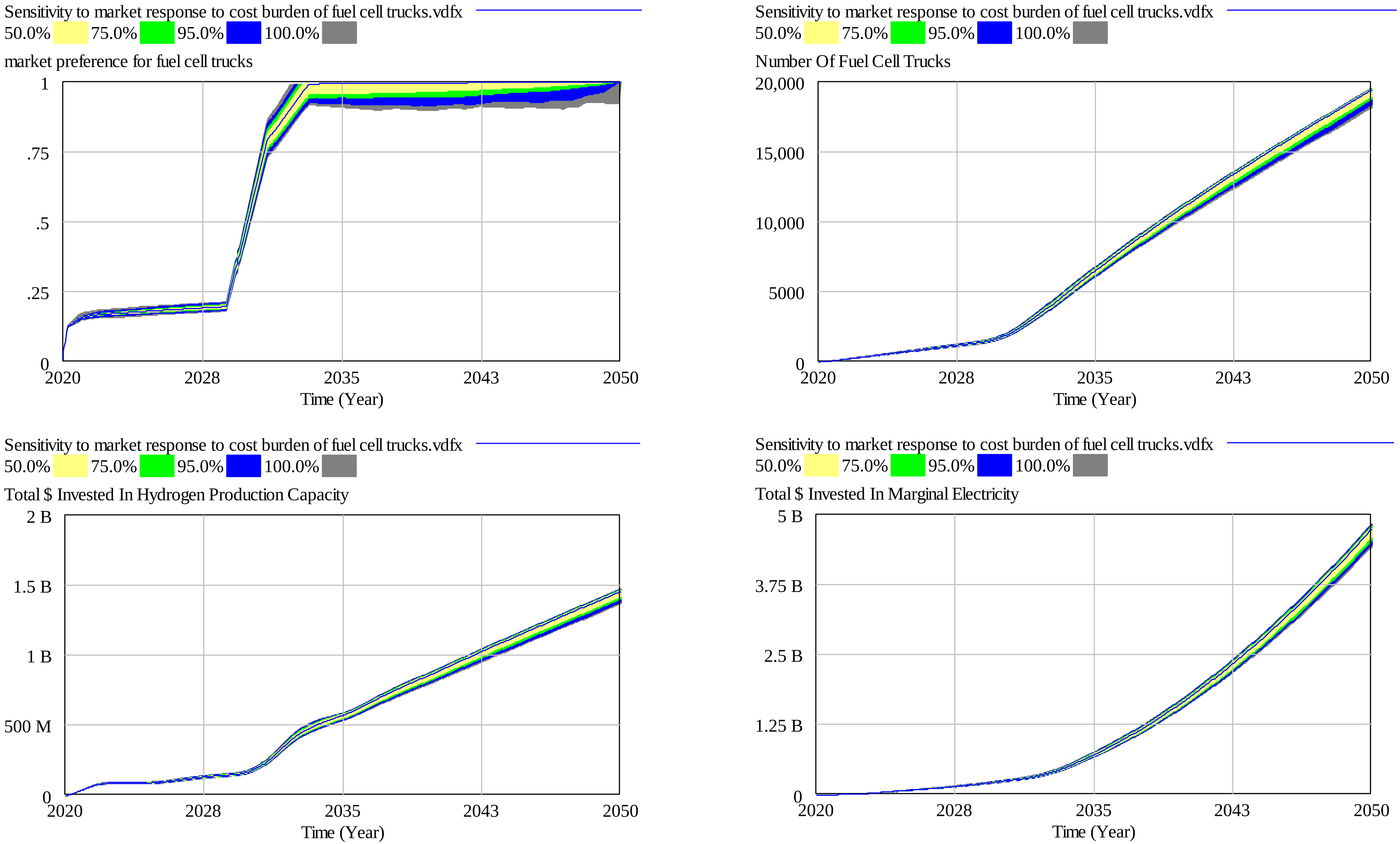

Figure 47: Model sensitivity to variations in the market response to the cost burden of fuel cell trucks

Appendix D: Scenario parameters

The key parameter values, along with the main data sources for all five modelled scenarios are presented in Table 13. For ease of reference scenarios with parameter values equal to scenario three are indicated as “same as scenario 3”. This appendix provides further transparency regarding the data used in the modelled scenarios.

Table 13: Parameter values for the modelled scenarios

Parameter	Units	S1: No Hydrogen	S2: Low Hydrogen Future	S3: Expected Hydrogen Future Average of estimates	S4: High Hydrogen Future (ambitious estimates)	S5: All new trucks are H2	Data source(s)
initial capex of electrolyser capacity	**$/kW**	*Same as Scenario 3*	1422	1261	531	*Same as Scenario 3*	(Concept Consulting, 2019b; IRENA, 2019; Nikola Corp, 2020a; Tedeschi *et al.*, 2011; VividEconomics, 2018)
change over time		*Same as Scenario 3*	711 by 2027	563 in 2050	300 in 2050	*Same as Scenario 3*	
Balance of Plant (BOP) for Hydrogen production capacity	**$/kW**	*Same as Scenario 3*	*Same as Scenario 3*	1368	*Same as Scenario 3*	*Same as Scenario 3*	(Brown *et al.*, 2015; Hecht and Pratt, 2017)
change over time		*Same as Scenario 3*	*Same as Scenario 3*	reduces 3% annually through a consistent technology learning rate of 13-15% (3% pa)	*Same as Scenario 3*	*Same as Scenario 3*	(Concept Consulting, 2019c; Schoots *et al.*, 2008)
initial estimate of Truck average lifetime	**years**	*Same as Scenario 3*	*Same as Scenario 3*	17.8	*Same as Scenario 3*	*Same as Scenario 3*	(Ministry of Transport, 2020e)
initial Carbon Tax on diesel	**$/ton**	*Same as Scenario 3*	*Same as Scenario 3*	0	*Same as Scenario 3*	*Same as Scenario 3*	(Interim Climate Change Committee, 2019)
carbon tax in 2050		*Same as Scenario 3*	50	100	150	*Same as Scenario 3*	

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Parameter	Units	S1: No Hydrogen	S2: Low Hydrogen Future	S3: Expected Hydrogen Future Average of estimates	S4: High Hydrogen Future (ambitious estimates)	S5: All new trucks are H2	Data source(s)
initial capex of Fuel Cell Truck	**$/truck**	*Same as Scenario 3*	*Same as Scenario 3*	500,000	215082.72	*Same as Scenario 3*	(Borrás, 2020; Concept Consulting, 2019c; Hall and Lutsey, 2019; Marcinkoski *et al.*, 2019; Nikola Corp, 2020b)
change over time		*Same as Scenario 3*	164450 in 2039	down to NZ$ 401,460 in 2022 then down to NZ$ 164450 in 2039	164450 in 2039	*Same as Scenario 3*	
initial fuel economy of Fuel Cell Truck	**Kg/Km**	*Same as Scenario 3*	0.08	0.066489362	*Same as Scenario 3*	*Same as Scenario 3*	
fuel cell truck fuel economy in 2050		*Same as Scenario 3*	*Same as Scenario 3*	0.056306306	0.050403226	*Same as Scenario 3*	
capex of Diesel Truck	**$/truck**	*Same as Scenario 3*	*Same as Scenario 3*	179235.6	*Same as Scenario 3*	*Same as Scenario 3*	(Concept Consulting, 2019c; O'dell, 2019; Wagner, 2019)

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Parameter	**Units**	**S1: No Hydrogen**	**S2: Low Hydrogen Future**	**S3: Expected Hydrogen Future Average of estimates**	**S4: High Hydrogen Future (ambitious estimates)**	**S5: All new trucks are H2**	**Data source(s)**
Price of Electricity in 2020	**$/MWh**	*Same as Scenario 3*	*Same as Scenario 3*	100	*Same as Scenario 3*	*Same as Scenario 3*	(Concept Consulting, 2019c; EMI, 2020; Perez, 2020)
Price of electricity in 2050		*Same as Scenario 3*	100	75	50	*Same as Scenario 3*	
initial Electricity required per Kg of Hydrogen produced	**kWh/Kg**	*Same as Scenario 3*	*Same as Scenario 3*	60	*Same as Scenario 3*	*Same as Scenario 3*	(Hydrogen Council, 2020; James and Randolph, 2019; Nel Hydrogen, 2020; Perez, 2020; Peterson *et al.*, 2020; VividEconomics, 2018)
change over time		*Same as Scenario 3*	no change	51.4 by 2035	*Same as Scenario 3*	*Same as Scenario 3*	
initial estimate of truck VKT	**Km/year**	*Same as Scenario 3*	*Same as Scenario 3*	892.675M	*Same as Scenario 3*	*Same as Scenario 3*	(Ministry of Transport, 2020a; Perez, 2020)
change over time		*Same as Scenario 3*	*Same as Scenario 3*	Increases according to GDP at 2% pa	*Same as Scenario 3*	*Same as Scenario 3*	
initial estimate of number of trucks required on the road	**trucks**	*Same as Scenario 3*	*Same as Scenario 3*	13570	*Same as Scenario 3*	*Same as Scenario 3*	(Ministry of Transport, 2020a)
change over time		*Same as Scenario 3*	*Same as Scenario 3*	Increases according to GDP at 2% pa	*Same as Scenario 3*	*Same as Scenario 3*	

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Parameter	**Units**	**S1: No Hydrogen**	**S2: Low Hydrogen Future**	**S3: Expected Hydrogen Future Average of estimates**	**S4: High Hydrogen Future (ambitious estimates)**	**S5: All new trucks are H2**	**Data source(s)**
cost of marginal electricity	**$/MWh**	*Same as Scenario 3*	*Same as Scenario 3*	78	*Same as Scenario 3*	*Same as Scenario 3*	(John Culy Consulting, 2019)
Forced Functions:		Market Preference for fuel cell trucks set to 0%	*Same as Scenario 3*	none	*Same as Scenario 3*	Market Preference for fuel cell trucks set to 100%	

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