

Article

Investigating the Investments Required to Transition New Zealand's Heavy-Duty Vehicles to Hydrogen

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Abstract: Reducing greenhouse gas emissions in the transport sector is known to be an important contribution to climate change mitigation. Some parts of the transport sector are particularly difficult to decarbonize; this includes the heavy-duty vehicle sector, which is considered one of the “hard-to-abate” sectors of the economy. Transitioning from diesel trucks to hydrogen fuel cell trucks has been identified as a potential way to decarbonize the sector. However, the current and future costs and efficiencies of the enabling technologies remain unclear. In light of these uncertainties, this paper investigates the investments required to decarbonize New Zealand's heavy-duty vehicle sector with green hydrogen. By combining system dynamics modelling literature and hydrogen transition modelling literature a customized methodology is developed for modelling hydrogen transitions with system dynamics modelling. Results are presented in terms of the investments required to purchase the hydrogen production capacity and the investments required to supply electricity to the hydrogen production systems. Production capacity investments are found to range between 1.59 and 2.58 billion New Zealand Dollars, and marginal electricity investments are found to range between 4.14 and 7.65 billion New Zealand Dollars. These investments represent scenarios in which 71% to 90% of the heavy-duty vehicle fleet are replaced with fuel cell trucks by 2050. 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. Policy recommendations are drawn from these results, and a clear opportunity for future work is outlined. Most notably, the results from this study should be compared with research investigating the investments required to decarbonize the heavy-duty vehicle sectors with alternative technologies such as battery-electric trucks, biodiesel, and catenary systems. Such a comparison would ensure that the most cost effective decarbonization strategy is employed.

Keywords: green hydrogen; hydrogen transitions; hydrogen economy; New Zealand; system dynamics modelling; modelling hydrogen transitions; heavy-duty vehicles; fuel cell trucks; decarbonization



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1. Introduction

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 [1]. This has resulted in what Edgar Morin calls the global “polycrisis”—a set of interlocked ecological and socio-economic crises [2]. The best-known among these crises must be that of climate

change. The majority of scientists now agree that anthropogenic climate change is taking place and that climate change is only one of many potentially deleterious repercussions of human activity [3,4]. Climate change is caused by the emission of greenhouse gasses, the most significant of which is carbon dioxide (CO₂). Before the 18th century, the global mean annual concentration of CO₂ remained steady at approximately 280 parts per million (ppm). Since the industrial revolution this concentration has increased dramatically to more than 400 ppm—higher than it has been in the past 800,000 years [5,6].

In order to mitigate the repercussions of climate change, it is necessary to disconnect economic growth from its historic attachment to environmental degradation, and particularly from the emission of greenhouse gasses, like CO₂, that cause climate change. There are various strategies for addressing climate change. These can typically be sorted into one of three approaches [7]. *Conventional mitigation technologies* aim to reduce CO₂ concentrations by reducing fossil-based CO₂ emissions. Although emission reduction strategies are important, it is worth noting that the removal of anthropogenic greenhouse gasses from the atmosphere by natural processes would take hundreds of thousands of years [7,8]. *Negative emissions technologies* aim to reduce CO₂ concentrations by capturing atmospheric CO₂ and sequestering it permanently. Examples of negative emissions technologies include the use of biochar, enhanced weathering techniques, and direct-air carbon capture and storage (CCS) [7]. *Geoengineering techniques* aim to alter the Earth's radiative energy budget, but are generally considered to be immature technologies that cannot be relied upon to significantly contribute to climate change mitigation [9]. All of these strategies 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 has recently garnered international attention for its potential to play a key role in decarbonizing these sectors is the hydrogen economy. The hydrogen economy is a suite of technologies working together to enable widespread use of low-carbon hydrogen as a fuel, feedstock, and energy vector [10]. Various low-carbon hydrogen production techniques exist. The resulting hydrogen (although chemically identical) is often assigned a colour to indicate the production method associated with it. The definition and usefulness of the colour-labels are sometimes disputed, but the commonly accepted definitions are [11]:

- i. **Green hydrogen:** Produced using electrolyzers powered by renewable electricity;
- ii. **Blue hydrogen:** Produced using fossil fuels along with CCS technology;
- iii. **Turquoise hydrogen:** Produced using pyrolysis, which yields solid carbon instead of CO₂; and
- iv. **Purple, pink, or yellow hydrogen (no consensus):** Produced using heat and electricity from nuclear reactors.

It is also possible to produce low-carbon hydrogen using biological processes. The resulting hydrogen is then known as biohydrogen. There is no consensus on the colour-label that should be assigned to biohydrogen. The four main production paths to biohydrogen are: bio-photolysis (direct and indirect), fermentation (dark fermentation and photo fermentation), gasification, and production via bio-electrochemical systems [12]. Although various low-carbon production paths exist, the use of electrolyzers powered by renewable electricity (green hydrogen) is currently considered to be the most mature, and is enjoying the most attention internationally [13,14].

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 carbon emissions economy by 2050 [15,16]. 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 the associated infrastructure development [17]. Furthermore, the New Zealand government has commissioned several documents con-

sulting various stakeholders and outlining the government's vision to become a world leader in the development of a hydrogen economy [18–20]. These documents make it clear that although New Zealand is open to alternative production processes, it is currently focusing on green hydrogen. Additionally, the existence of, and governmental support for, Hirlinga Energy—a company dedicated to the supply of green hydrogen—indicates a willingness to invest in the necessary technologies [21]. New Zealand and Japan are not the only countries considering the potential of a hydrogen economy. In recent years multiple governments including Germany, France, Australia, Japan, and Korea, have made commitments to, or expressed an interest in, the hydrogen economy as a national strategy towards renewable and sustainable energy [22]. This is a promising development as cost reductions in the associated technologies are dependent on the industry scaling up to a point where economies of scale can be exploited and further research and development justified [13,23,24].

In addition to the interest shown by academics and governments, private industry has also indicated much support for the future of hydrogen technologies. KPMG reports that in both 2018 and 2019 a strong majority of automotive executives believed fuel cell electric mobility to be the top trend in their industry [25]. This conviction is supported by a report co-authored by Deloitte and Ballard, which indicates that within 10 years fuel cell electric vehicles (FCEV) will become cheaper to run than battery or diesel alternatives in various applications [26]. 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 [27]. More broadly, a report by the Hydrogen Council, co-authored by McKinsey & Co., identified three market segments in which hydrogen was deemed to exhibit significant opportunities: Transportation, Heat and Power, and Industry Feedstocks [13]. 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.

Although there are various opportunities for hydrogen in New Zealand, this study focuses on long-haul goods delivery trucks with weights exceeding 30 tonnes. Heavy-duty vehicles (HDVs) are one of the hard-to-abate sectors that are particularly well suited to decarbonisation with hydrogen [14,28]. 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 with regard to the competitiveness of hydrogen as a decarbonisation strategy. Without more accurate estimates of the investment requirements, a transition to green hydrogen cannot be compared to alternative decarbonisation strategies. Therefore, the aim of this paper is to explore the investments required to transition New Zealand's HDV sector from diesel to hydrogen; given various policy and technology scenarios. A better understanding of the required investments would enable various public and private stakeholders to make informed policy and investment decisions.

2. Literature Review

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) was carried out. According to Cronin et al. [29], 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 [30]. Cronin et al. [29] suggest a process for conducting a traditional literature review that minimizes the potential for such bias to creep into the review. The process consists of four steps, namely: select a review topic, search and gather literature, analyse and synthesize the literature, and

write the review. Using this process, focal topics such as energy transitions, the hydrogen economy, systems thinking, and simulation modelling were reviewed.

The problems of unsustainability, and specifically anthropogenic climate change, are now well understood and unanimously agreed upon [3]. 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 [31]. These transitions towards a more sustainable future have come to be known as sustainability transitions [32]. According to Turnheim et al. [33], “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, namely: *socio-ecological*, *socio-technical*, *socio-economic*, *action-oriented*, and *Integrated Assessment Modelling (IAM)*. These approaches facilitate a better understanding of sustainability transitions and provide guidance for assessing and modelling such transitions. Of these five, the socio-technical approach was found to best suit an assessment of a transition to hydrogen [34]. Markard [35]—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 the Multi-Level Perspective [36].

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 [37] 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*” [38]. 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* [37]. Many countries have included hydrogen in their energy strategy or developed a separate hydrogen strategy [22,39]. Hydrogen is potentially able to facilitate progress in the energy transition as well as the transition of the other backbone systems [13].

Markard [35] 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 renewable energy technologies, 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*” [35]. 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.

An interesting finding from the literature review is the wide polarity of opinion regarding the financial feasibility of a hydrogen transition. The work of proponents, such as the Hydrogen Council [13] and Leaver et al. [40], stand in contrast to sceptics, such as Concept Consulting [41]. Furthermore, much of the literature is outdated considering the speed of technological innovation [42]. A recent surge of interest in hydrogen indicates that estimating the cost of transitioning New Zealand's HDVs from diesel to hydrogen would be a valuable contribution to the literature.

3. Methodology

A review of the systems thinking and energy modelling literature indicated that simulation modelling would be the most appropriate method for investigating hydrogen transitions at the chosen level of abstraction [43]. In order to determine an appropriate simulation method, the following set of requirement specifications were developed and subsequently used to evaluate various modelling approaches:

- 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.

System Dynamics Modelling (SDM), Agent-Based Modelling (ABM) and Discrete Event Modelling (DEM) were assessed according to these requirement specifications [31]. SDM was found to be the best option—out of those considered—for modelling a hydrogen transition in the heavy-duty vehicle sector of the New Zealand economy at the desired level of abstraction. This conclusion is supported by Haro [44] who suggests that SDM is a “*great tool to use*” in cases related to policy recommendation, and notes that SDM is “*unbeatable*” in the presence of “*abstract or subjective variables or relationships, or when the system is . . . complex and requires extensive aggregation*”.

Four approaches to the modelling process were considered. The modelling process suggested by Quarton et al. [45] 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 and Cavana [46], Sterman [47], and Albin and Forrester [48]. The main steps in each of these approaches are presented in Table 1.

By combining these approaches, a process specifically designed for modelling hydrogen transitions with SDM was created. The synthesized modelling process is presented in Figure 1. 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. [45] as well as 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 that draw heavily on the modelling approaches that focus 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 all four approaches. The fourth, and final, step of the hybrid process is the *discussion of results*. This step emphasizes 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.

Table 1. Summary of various approaches to modelling.

Steps	Approach 1: Modelling Energy Technologies Such as Hydrogen [45]	Approach 2: Systems Thinking and Modelling Methodology [46]	Approach 3: Systems Thinking and Modelling for a Complex World [49]	Approach 4: Generic Stages of SDM [48]
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	

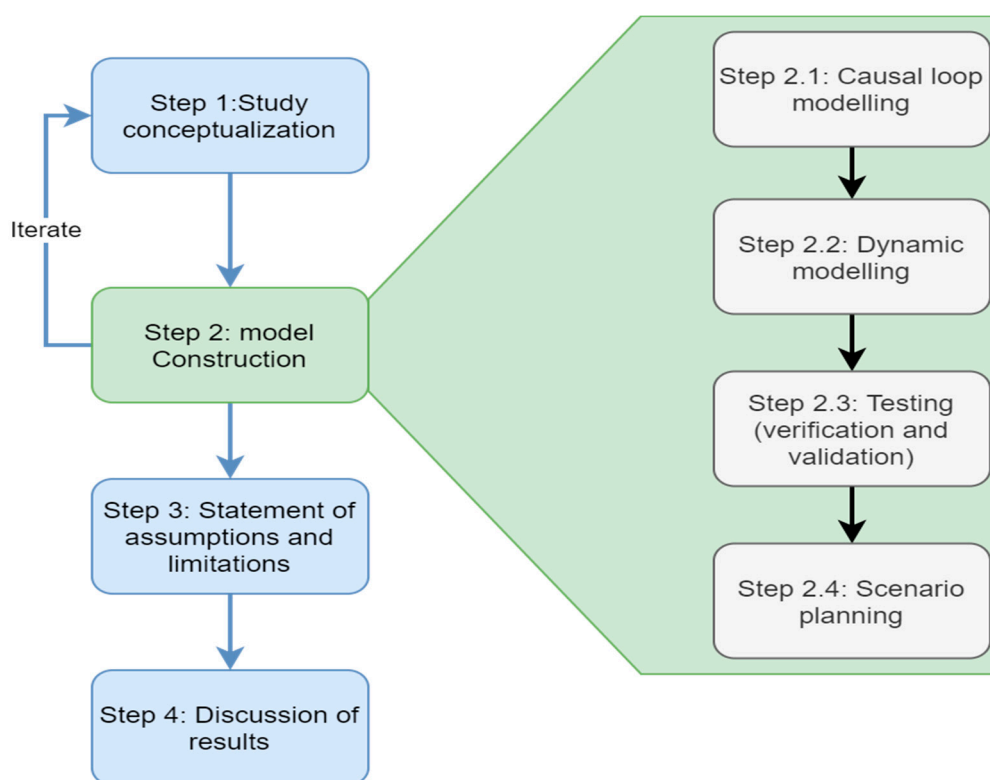


Figure 1. Depiction of the synthesized process for modelling hydrogen transitions with System Dynamics Modelling.

4. Model

The methodology articulated above was used to guide the modelling process. The first step of the process has already been addressed. This section will present how the second and third steps of the methodology were executed. It is worth noting that the first and second steps are iterative, and the results and figures presented here are of the final iteration.

Causal loop modelling, the first component of Step 2, was used to facilitate the identification of key variables and stakeholders, as well as to ensure that the purpose, scope,

boundary, and main feedback loops of the model are thoroughly understood and articulated. One of the key outputs of causal loop modelling is the dynamic hypothesis presented in Figure 2. The dynamic hypothesis is the foundation of the subsequent dynamic modelling process and presents the structure and feedback of the system under investigation. As model behaviour is a result of model structure, the dynamic hypothesis also provides insights into model behaviour [47].

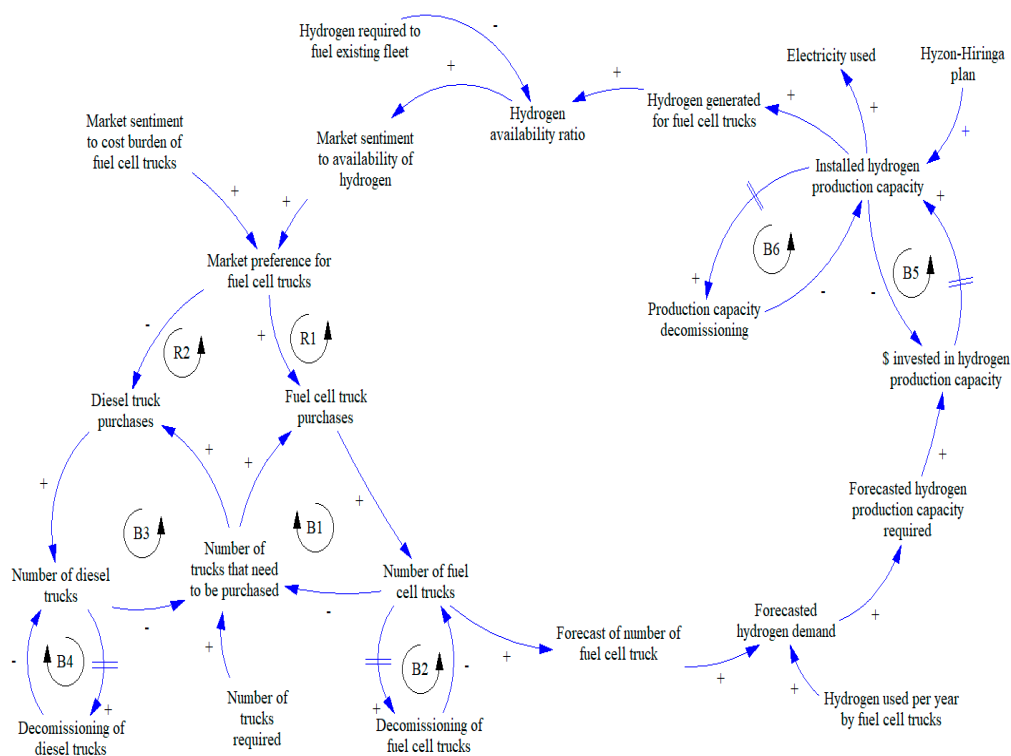


Figure 2. Dynamic hypothesis for investigating a transition from diesel to fuel cell trucks.

The next step in the modelling process is to construct a dynamic model based on the structure and insights provided by the dynamic hypothesis. The dynamic model uses stocks, flows, and auxiliary variables to dynamically model the various changes and feedbacks over time. 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 [50]. 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 caused by decoupling inflow and outflow rates provides the system with inertia and memory, and allows the model to accurately represent real-world systems [47]. 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 final model contained nine modules (or views), each of which were responsible for modelling a unique part of the system. The nine modules were named after the main aspect that they modelled, namely: leveled cost of hydrogen, total cost of truck ownership, market preference for fuel cell trucks, diesel trucks and associated emissions, fuel cell trucks and hydrogen demand, hydrogen production capacity, electricity requirements and cost, dashboard, and triangular distributions. The *dashboard* module was used to monitor the response of the system under various conditions, and the *triangular distribution* model was used to enable a sensitivity analysis. A module of central importance to the model is the *market preference for fuel cell trucks* module. This module endogenously calculates the fraction of new truck purchases that will be hydrogen powered as opposed to diesel powered. The market preference for hydrogen fuel cell trucks is based on a combination of

the cost burden of using fuel cell trucks, and the availability of hydrogen. As the model purchases fuel cell trucks the amount of hydrogen required to serve those trucks increases. In order to ensure an adequate supply of hydrogen, the expected number of fuel cell trucks is forecast to two years in the future. Based on this forecast the model makes the necessary investments to ensure that supply will meet (and slightly exceed) demand. Therefore, the extent of the market preference for fuel cell trucks determines the rate at which the modelled fleet transitions away from diesel and towards hydrogen.

The model was tested using various confidence building tests. These tests can be sorted into three categories suggested by Barlas [51], namely: direct structure tests, structure-oriented behaviour tests, and behaviour pattern tests. The 12 point “*System dynamics model correctness checklist*” of Lai and Wahba [52], as well as the guideline tests of Maani and Cavana [46], were used to guide the testing process. These tests provided confidence that the model was useful for its intended purpose and ensured that the model’s limitations were well understood. An unexpectedly challenging part of the model testing process arose from the limitations of the software. The chosen software (Vensim) is not able to perform a sensitivity analysis on a graphical function. The way in which data were structured required numerous important parameters to be defined using Vensim’s “lookup” function which generates a graphical function. To perform a sensitivity analysis on these functions, *Hearne’s Method* was employed in the manner described by Eker et al. [53]. This method uses model structure to generate “agitations” based on various input parameters. In this way the sensitivity analysis of graphical functions can be parameterized, enabling the software’s existing sensitivity analysis function to be employed. For more details regarding the application of Hearne’s method in this study see [43], and for more information regarding the method in general see Hearne [54] and Eker et al. [53].

The final step in model construction is scenario planning. Scenario planning is a key part of the modelling process, which enables various parameter values and policies to be explored. Maani and Cavana [46] emphasize the importance of keeping the problem under investigation in mind when designing scenarios. As stated before, 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. Various technologies influence the required investments, and the available data indicates 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 [55]. By designing scenarios carefully, it is possible to capture the wide spectrum of potential futures that might result from all these uncertainties. The challenge of scenario planning lies in generating as few scenarios as is necessary to explore the problem space given the problem that is being investigated. Maani and Cavana [46] suggest that in most cases four or less 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 [56–58]. After much consideration of the possible options, five scenarios were developed.

4.1. Scenario 1: No Hydrogen (Only Diesel)

The no hydrogen scenario sets a baseline for a diesel-only future. 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.

4.2. 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 [59]. 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.

4.3. 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.

4.4. 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.

4.5. Scenario 5: No Diesel (Only 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.

The third step in the synthesized modelling process is the statement of assumptions and limitations. Quarton et al. [45] 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. [45] 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 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 here apply to all five scenarios.

4.6. Assumptions

To ensure all assumptions are clearly communicated, Quarton et al. [45] argue that—as far as possible—the model and associated data should be made public. Therefore, to

maximize transparency, the entire model with all the associated data is made available online (The model and associated support materials are available at: www.github.com/RickKotze/thesis). The most important assumptions that were made during the modelling process are:

- i. It is assumed that cost reductions resulting from learning curves are driven by cumulative production quantities as per Wright's law of technological progress [23]. 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 [60];
- ii. Similar to the above, it is assumed that the standardization and regulation necessary for hydrogen technologies to flourish will be developed 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;
- iii. 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 [19];
- iv. It is assumed that the planned hydrogen refuelling network announced by Hirlinga Energy will be carried out as planned [21];
- v. The model works on the assumption that all green hydrogen generation is met with polymer electrolyte membrane (PEM) electrolyzers, and that these electrolyzers are located on-site at refuelling stations, i.e., in a distributed (not centralized) manner;
- vi. 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;
- vii. The contracted 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 [61]. 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 [62];
- viii. It is assumed that hydrogen fuel cell trucks have a comparable payload to diesel trucks [63]. 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. 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;
- ix. It is assumed that electrolyzers and fuel cell trucks will be readily available on the market;
- x. Only hydrogen fuel cell trucks are considered as a decarbonisation option. Biodiesel, battery-electric, and other decarbonisation alternatives do not compete with hydrogen in this model; and
- xi. 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 [64].

4.7. Limitations

All models have strengths and weaknesses that should be considered when analysing model outputs [65]. The tests performed on the model developed confidence in the model's usefulness, but also highlighted certain limitations of the model. The known limitations of greatest significance are as follows:

- i. The forecasting function used in the model 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*" [66]. As such the model is susceptible to bad forecasts, which can result in significant under- or over-investments in hydrogen production capacity. In practice, an entity such as Hirlinga Energy [67] 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 potential overinvestment should be considered when analysing the model's financial outputs;
- ii. 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. [53]. 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;
- iii. 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 cause sharp changes in model behaviour. Detailed descriptions of how the lookup tables were generated can be found in Kotze [43].
- iv. Data were collected from Nikola Motors [68]. The company has since fallen into disrepute, and there are claims that they overstated the maturity and competitiveness of their technologies [69]. 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 Nikola's data are incorrect;
- v. 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. Various sectors of the economy lend themselves to hydrogen, but only HDVs are investigated in this study. It is generally expected that if multiple sectors transition to hydrogen there will be overlapping benefits between the sectors [13]. Any such benefits are not considered in this model, as the HDV sector is modelled in isolation;
- vi. 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 operational 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 [70]; and
- vii. 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. [71].

5. Discussion of Results

This section presents an overview and comparison of the most important outputs from the modelled scenarios. To interpret the results, it is necessary to have an adequate understanding of the scenarios, assumptions, and limitations of the model as presented in the previous section. Key results from the modelled scenarios are presented in Table 2. A few of these key results will be explored in greater detail before drawing conclusions from the results of the model, as well as the modelling process.

5.1. Market Preference for Fuel Cell Trucks

The model outputs for the *market preference for fuel cell trucks* parameter are presented in Figure 3. This parameter determines the percentage of new truck purchases that will be fuel cell powered (as opposed to diesel-powered) and is therefore of great importance to the model. These results should be kept in mind when considering the other model outputs.

Table 2. Key results from modelled scenarios.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Market preference for fuel cell trucks in 2050	0	1	1	1	1
Number of diesel trucks in 2050	24,464	7437	5336	2830	2508
Number of hydrogen fuel cell trucks in 2050	0	17,026	19,128	21,634	21,956
Annual hydrogen generation in 2050 (MILLIONS OF KG)	0	82.17	90.05	100.40	101.73
Total hydrogen generated by 2050 (MILLIONS OF KG)	0	884.9	1124.9	1751.5	1868.1
Marginal electricity required in 2050 (GWh)	0	4930.49	4628.66	5160.94	5228.9
Total \$ invested in production capacity by 2050 (BILLIONS OF DOLLARS)	0	1.594	1.702	1.758	2.583
Total \$ invested in marginal electricity by 2050 (BILLIONS OF DOLLARS)	0	4.141	4.538	7.147	7.648

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*. What the shape of the response curves in Figure 3 indicate is that—as expected—once the market decides that the cost and availability of hydrogen outcompete diesel there will be a swift transition towards new truck purchases being predominantly fuel cell electric [68]. This can be seen in the steep increase experienced by scenarios two, three, and four in Figure 3. 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 3 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. These results mirror many of the latest forecasts made by reputable sources. The Hydrogen Council [13], the International Council on Clean Transportation [72], and the Energy Transitions Commission [73] agree that hydrogen fuel cell trucks will become cost-competitive with diesel alternatives before 2030. Standing in further support of this is the recent surge in publications of national hydrogen strategies [22]—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 [63,68,74,75].

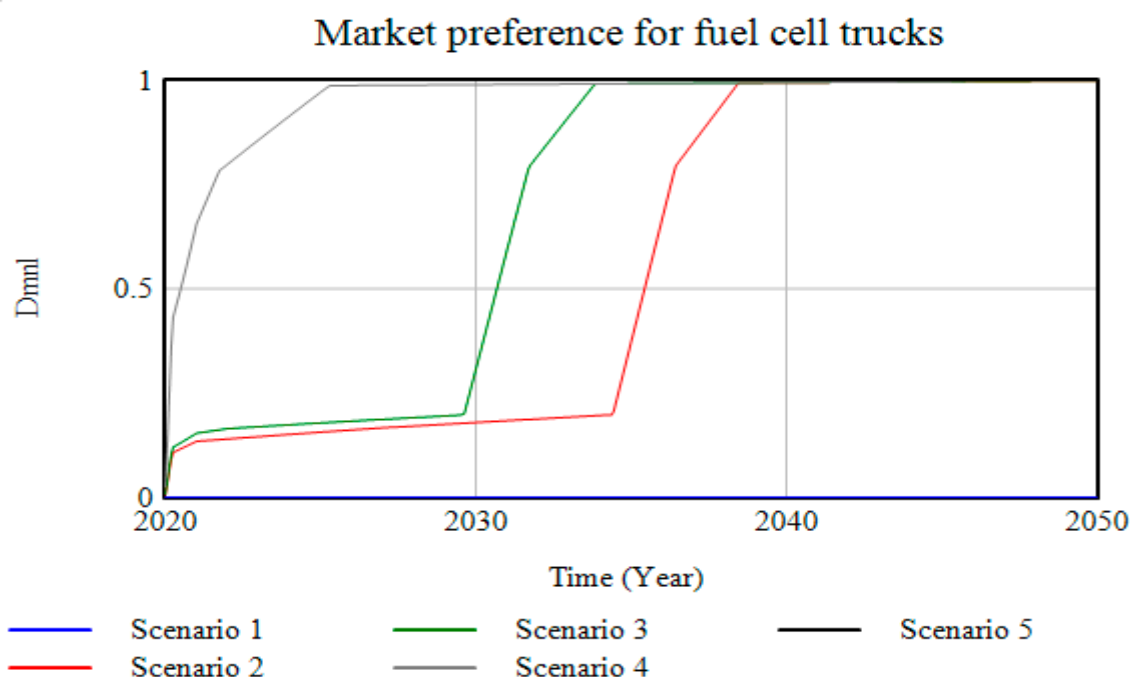


Figure 3. Market Preference for fuel cell trucks.

5.2. Fleet Composition

Figures 4 and 5 present the number of diesel trucks and the number of hydrogen fuel cell trucks in the model over the course of the modelling period. The fleet composition is altered by new purchases as well as by retiring older trucks. Scenario one presents a market which never develops a preference for fuel cell trucks, and therefore purchases exclusively diesel trucks throughout the modelled period. Scenario five presents a market which—effective immediately—prefers fuel cell trucks exclusively. This can be seen by the quick rise in the number of fuel cell trucks in the model, paired with the rapid decline of the number of diesel trucks. In scenario five 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. Although the impacts of this limitation are worth understanding, it does not undermine the usefulness of the model. In scenarios two, three, and four, the number of diesel trucks initially increases until an inflection point is reached. The timing of this inflection point is determined by the rapid increase in preference for fuel cell trucks, as indicated in Figure 3. The effects of this can also be seen in the rapid rise in fuel cell trucks once the market preference has increased. Scenario four closely tracks scenario five. This is, once again, due to the market preference of the two scenarios being very similar. It is interesting to note that by 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 at this point are “old” diesel trucks that have not yet been decommissioned.

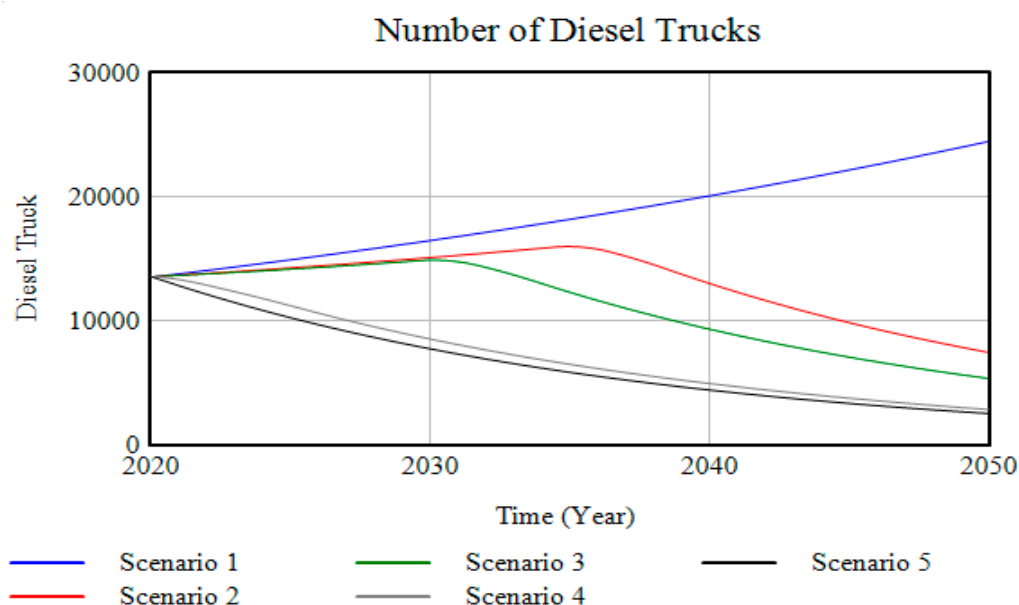


Figure 4. Number of diesel trucks.

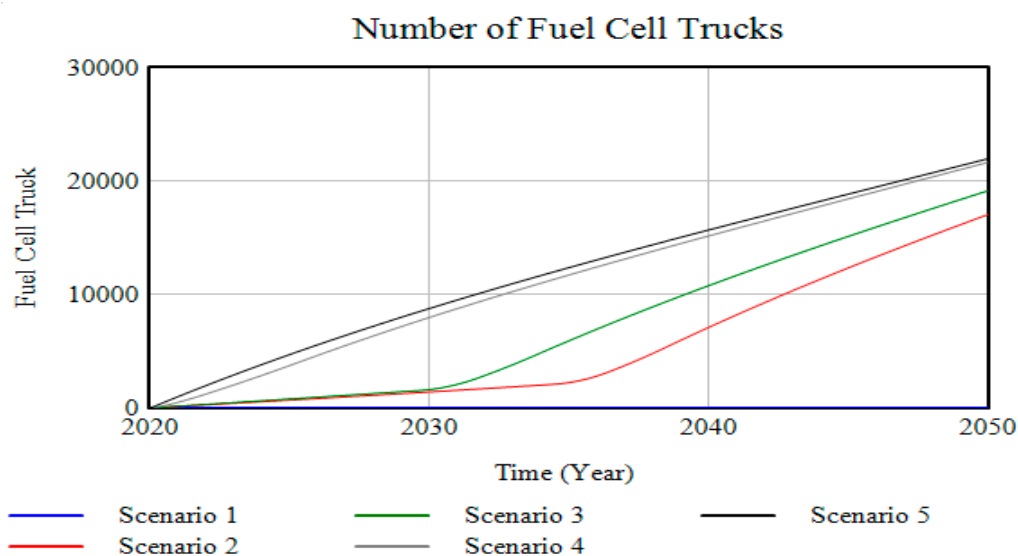


Figure 5. Number of fuel cell trucks.

5.3. Investments in Hydrogen Production Capacity

The total investments in hydrogen production capacity are presented in Figure 6. As expected, Scenario one sees zero investments as a market for hydrogen never develops. Interpreting the results of scenarios two, three, four, and five, requires a particularly good understanding of the parameter values used in the various scenarios (see the Supplementary Materials), as well as an adequate understanding of the hydrogen production capacity module and its limitations. Specifically, the impact of the poor forecast capabilities of the model is made apparent when analysing these data. In all non-zero investment scenarios, the total investments in hydrogen production capacity plateaus between approximately 2022 and 2025. This is understood to be due to an 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 forecast horizon is too

short, the model will wait too long before investing 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. Between 2035 and 2038 investments are more aggressive than the investments made after 2038. This is due to supply initially catching up to the steep increase in demand (which results from the steep increase in the market preference for fuel cell trucks). 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 (the pessimistic scenario) than in scenario three (the middle of the road scenario) 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 presented by 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 a comparatively low total investment in hydrogen production capacity by the end of the simulated period 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 regarding the future cost of hydrogen technologies.

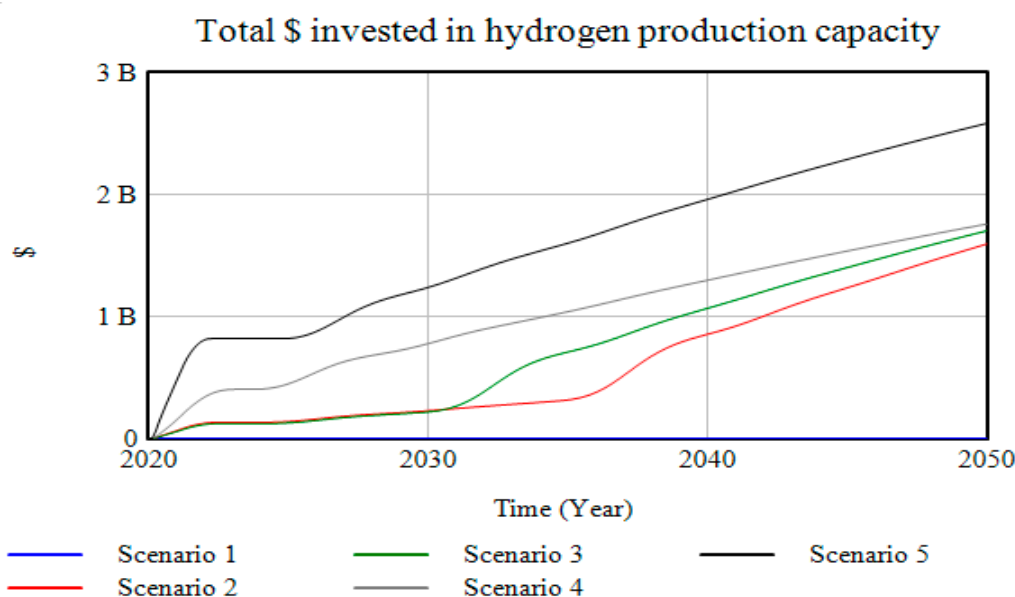


Figure 6. Investments in hydrogen production capacity.

5.4. Investments in Marginal Electricity

The total marginal electricity investments are presented in Figure 7. This represents 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 demand and the cost of marginal electricity production; the electricity demand is dependent of 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 2 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 scenarios 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 more than the investments in hydrogen production capacity. This finding is in line with various other studies that cite the cost of electricity as one of the key cost drivers of green hydrogen [13,76]. 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 [62], as well as the cost and efficiency of the commissioned hydrogen production capacity, which is determined by a variety of sources in each scenario.

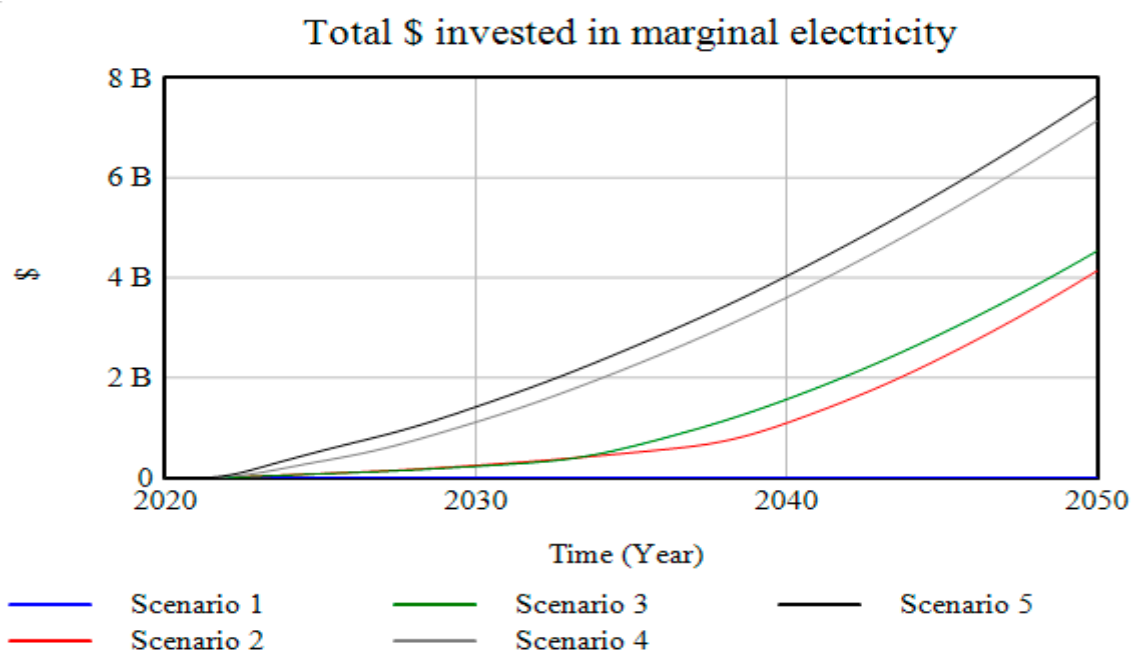


Figure 7. Marginal electricity investments.

6. Conclusions

The conclusion consists of two parts. First a list of recommendations and insights for policy makers is presented, thereby achieving the aim of the study. Subsequently, opportunities for future research and modelling are articulated.

6.1. Recommendations and Insights for Policy Makers

This study has found that even pessimistic assumptions of progress in hydrogen technology would lead to hydrogen fuel cell trucks becoming competitive with diesel trucks well before 2050, which is when many of New Zealand's decarbonization goals are due. Replacing diesel trucks with fuel cell trucks is found to be an effective strategy for decarbonizing up to 90% of the heavy-duty vehicle sector by 2050. Therefore, the decarbonisation potential of hydrogen is found to justify the current interest in the associated technologies. The transition to hydrogen can be seen 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 [22]. The overwhelming evidence, therefore, indicates that a transition to hydrogen 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 estimated in two parts. Investments required to purchase sufficient hydrogen production capacity are found to range between 1.59 and 2.58 billion New Zealand Dollars, while investments required to provide sufficient clean electricity are found to range between 4.14 and 7.65 billion New Zealand Dollars. These investments represent scenarios in which 71% to 90% of the heavy-duty vehicle fleet consist of hydrogen 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 paper, much of the data required to investigate how the hydrogen transition will unfold are burdened with large uncertainties. These uncertainties are reducing over time 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*" [77]. The resulting information will potentially yield valuable insights into the state of hydrogen technologies. If the New Zealand government were to conduct a similar request, there would be an opportunity to generate context-specific data that would enable better models to be built. Additionally, it is recommended that the New Zealand Ministry of Transport disaggregate the data that are published in the Annual Fleet Statistics Report [78]. Disaggregation of these data would enable more accurate calculations to be made regarding the different classes of truck; each of which present 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 [79] and Perez et al. [80] 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 to hydrogen. In fact, the Energy Transition Commission [73] 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 opportunity 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 an 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, to a certain extent, Hiringa Energy [67] seems ready to take on the responsibilities of such a role. Ensuring that the entity is well-funded and well-managed will be of great importance to a rapid and smooth hydrogen transition.

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 learned 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 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 thirty 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. Opportunities for 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 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 [81]. 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. The model structure could be expanded to capture the market 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 additional economic sectors. 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. An economic assessment of all available options would enable the most cost-effective strategy to be identified.

Supplementary Materials: The following are available online at <https://www.mdpi.com/1996-1073/14/6/1646/s1>, Table S1: Key parameter values (and data sources) used in each scenario.

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