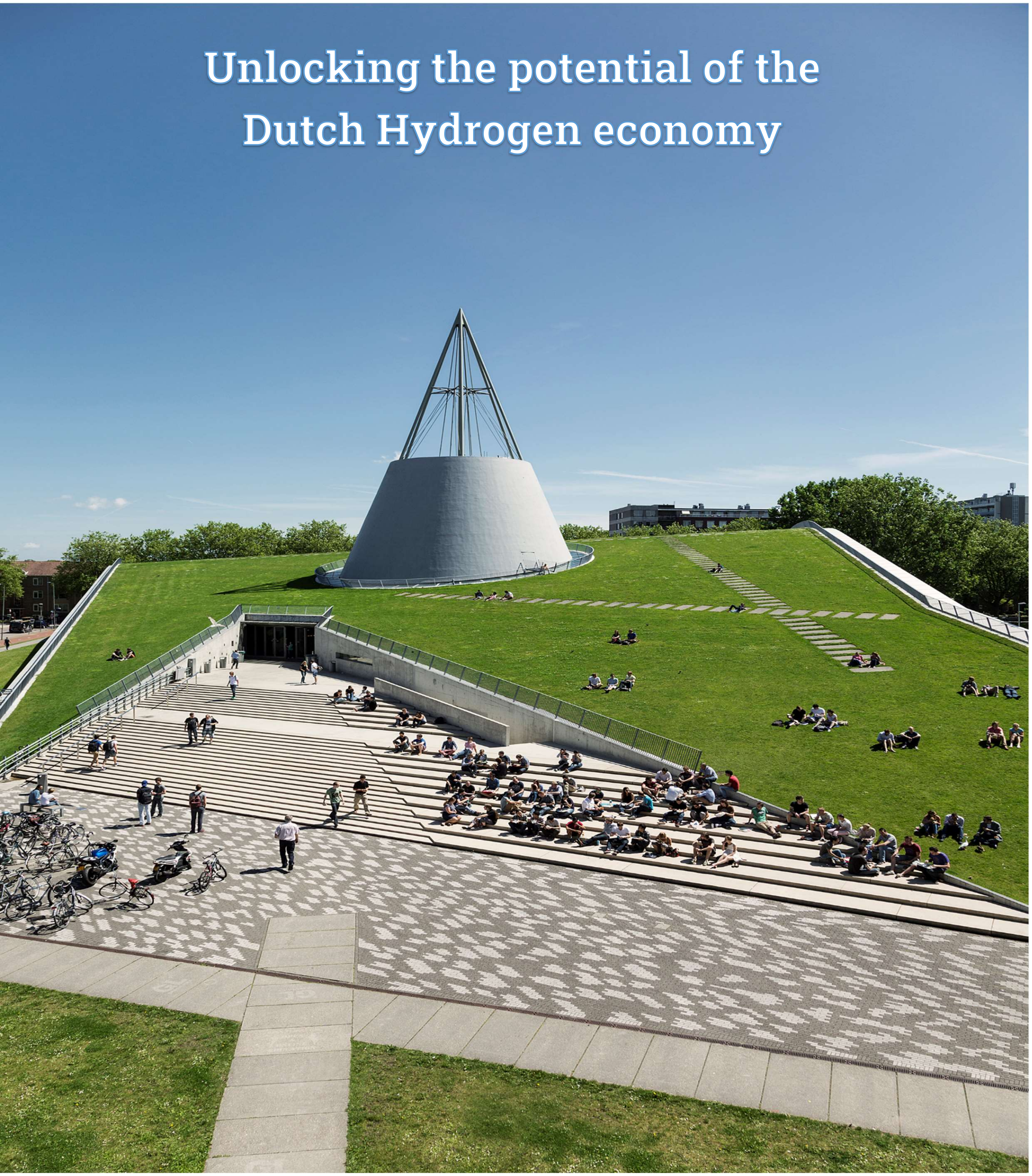
Unlocking the potential of the Dutch Hydrogen economy



Unlocking the potential of the Dutch Hydrogen economy

Multi-Objective Robust Decision Making

By

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in partial fulfilment of the requirements for the degree of

Master of Science
Engineering and Policy Analysis

at the Delft University of Technology,
to be defended publicly on Monday May 1, 2023 at 13:00.

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Preface

This thesis has been the logical conclusion of both my time at the TU Delft and my past work at the Hydrogen Chemistry Company. This thesis combines my two main academic interests, which are System Dynamics and the green hydrogen industry. While it has been challenging at first to adjust from a commercial view on green hydrogen to an academic mindset, I look back on an insightful and enjoyable journey the last months. I wish to thank my graduation committee, Willem Auping, Paula Ibarra and Rob Stikkelman for guiding me through the process, their valued feedback and our meetings which I have always looked forward to. Without your help this I could not have written a thesis of which I can be proud.

Bernhard van Haersma Buma
Voorburg, May 2023

Executive summary

The Netherlands is looking to decarbonize its economy and replace natural gas from Groningen and Russia with different energy carriers. Dutch government has been mainly stimulating renewable electricity production, CO_2 capture and storage (CCS) and sustainable heat generation (RVO, 2022) to address these challenges. While these technologies are an indispensable part of CO_2 reduction strategies, for full decarbonization of the economy more advanced technologies (Hammingh et al., 2022), new materials, mitigation solutions and negative emission technologies are required (Yang et al., 2022). To both reach full climate neutrality, and to replace Russian gas with green alternative, a renewable molecule is vital.

The main alternative for fossils that is currently deployed is green electricity. Green electricity is an effective way to replace fossil fuels, but not all industries can replace their liquid or gaseous fuels with electricity. For those industries the Netherlands envisions green hydrogen to be the sustainable alternative. In their climate agreement the Dutch government has set the goal to have 3-4 GW of green hydrogen production via electrolysis installed in 2030. Currently, this goal seems difficult to achieve as the green hydrogen industry struggles to kick off. This is in large due to the fact that there is a gap in literature and policies between research projects and full scale green hydrogen production. Policies are needed to accumulate economies of scale to reach a price level at which green hydrogen is competitive with fossil alternatives or other forms of low-carbon hydrogen. The goal of this research is to identify a robust policy strategy that will enable the Dutch industry and government to reach the goals for hydrogen production. The following research question will be leading throughout the research:

How can the Dutch hydrogen economy develop, and how can policy impact the deployment of green hydrogen production capacity?

This research' main objective is to analyse development of the green hydrogen industry in the Netherlands and to test existing and new policies under deep uncertainty. The first part of the research is to create a systems dynamics model to simulate the development of the green hydrogen industry. System dynamics models are well suited to simulate energy systems due to the ability to capture complex feedback interactions between a variety of sub-systems. To deal with uncertainty the Decision Making under Deep Uncertainty framework will be used in combination with the system dynamics model. This is a robust decision-making method to develop policies in systems subject to deep uncertainty (Walker et al., 2012). The DMDU framework is based on exploratory modelling to analyse possible policy levers and scenarios, followed by a robustness analysis. To find relevant policy levers a literature review covering the hydrogen industry and policy will be conducted first. The DMDU framework will applied to a system dynamics model using the EMA workbench.

By performing Exploratory Modelling techniques and a Multi-Objective Robust Decision Making analysis with a System Dynamics model, it can be concluded that the possible development pathway of the Dutch hydrogen industry is extremely uncertain. Without any policy, the green hydrogen industry is not likely to reach significant size. The uncompetitive price is not likely to decrease quickly if there is no policy support. The existing policy seems to be able to make an impact on the goals. By covering part of the funding gap between green hydrogen and alternatives, demand can grow with subsequently a larger hydrogen industry to meet the demand. However, the subsidies lack in long term value creation and does not address the issue of scarce renewable electricity. The IPCEI and SDE++ subsidies can kickstart the hydrogen economy by reducing the funding gap, but do not guarantee a real cost reduction, which is a requirement for a successful hydrogen economy. The rate at which the costs reduce is identified as a crucial uncertainty, as well as the speed at which industrial sectors can substitute other energy carriers for green hydrogen. If the market lags in the

adoption of green hydrogen, and the cost reduce slowly, the hydrogen economy will not achieve goals as stated in the climate agreement. With the existing policy in place, crucial barriers consist of risk with the development of renewable electricity, as the hydrogen industry cannot grow faster than the renewable electricity sector. Even with large amount of renewable electricity the hydrogen industry has to compete with other sector for the renewable electricity.

Two policies to complement the existing SDE++ and IPCEI subsidies have been proposed in this research. A Green Products policy and a Dedicated Electricity policy. The first one is to create value in the refinery sector through renewable fuel certificates, which will represent a new product. In addition, part of the tenders for offshore wind parks should be combined with electrolysis projects. The first policy is aimed at continuing the momentum for scale up that is created by the subsidies. The second policy reduces the renewable electricity barriers in the first stage of the development of the hydrogen economy. Combined the policies can support the creation of a hydrogen industry in the worst possible scenarios. However, there is no single dominating policy that outperforms the other policies on all outcome metrics. The policies that have been analysed showed that the size of the hydrogen economy is not correlated with the avoided CO_2 emissions. In addition, policy makers have to balance the trade-off between size of the hydrogen industry and the costs of the policy.

Based on the robustness analysis it is recommended to further investigate the relationship between the development of renewable electricity generation and the potential for the hydrogen economy. In addition, the potential impact on other industrial sectors of allocating a specific amount of offshore wind electricity to the hydrogen industry could be topic for further research. This policy measure can be beneficial for the hydrogen economy, but it can reduce the potential for decarbonisation through direct electrification. In addition, further research is advised to extend the model to include a more detailed energy sub-model and to add import and exports to the model.

Abbreviations

ABBREVIATIONS	MEANING
EMA	Exploratory Modelling and Analysis
MORDM	Multi-Objective Robust Decision Making
DMDU	Decision Making under Deep Uncertainty
WOZ	Roadmap offshore renewable electricity production
RES	Renewable Electricity Source
LCOH	Levelized Cost Of Hydrogen

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1 Introduction

The Netherlands is facing some tough energy challenges. The country is aiming to reduce of all CO_2 emissions in 2030 by 60%, with the goal of becoming climate neutral in 2050 (NWP, 2022). Besides the climate goals, the Dutch government is looking to phase out natural gas from the energy mix. Besides the fact that replacing natural gas with renewable electricity will have a positive effect on the climate goals, in recent years other factors have increased the need for quick replacement of natural gas. For one there has been increasing political pressure to quickly close the largest Dutch gas production site in Groningen due to the earthquakes around the gas field. Besides the domestic issue of earthquakes, there is external pressure to reduce natural gas consumption. The transition to substitutes for natural gas is being accelerated by the Russian invasion of Ukraine (Slingerland, 2022).

Dutch government has been mainly stimulating renewable electricity production, CO_2 capture and storage (CCS) and sustainable heat generation (RVO, 2022) to address these challenges. While these technologies are an indispensable part of CO_2 reduction strategies, for full decarbonization of the economy more advanced technologies (Hammingh et al., 2022), new materials, mitigation solutions and negative emission technologies are required (Yang et al., 2022). To both reach full climate neutrality, and to replace Russian gas with green alternative, a renewable molecule is vital.

Hydrogen has emerged as the desired new molecule to successfully address the Dutch energy challenges (Burg et al., 2020). When produced from renewable sources, hydrogen can address the challenges in multiple ways. A green hydrogen industry can replace the existing fossil based hydrogen industry (Kakoulaki et al., 2021). This fossil based industry produces hydrogen in a process called Steam Methane Reforming. This process converts natural gas in hydrogen and CO_2. The estimated total consumption of hydrogen in the Netherlands is around 180 PJ (NWP), of which most is used by refineries and ammonia production. The hydrogen industry is responsible for 12,5 million ton CO_2 emissions, almost 8 percent of the total Dutch CO_2 emissions (Hers, 2018). Transitioning to a renewable production method for hydrogen can both reduce CO_2 emissions and the demand for natural gas.

The CO_2 emissions from the existing hydrogen industry can be reduced by applying carbon capture technology to the production of fossil hydrogen. However, the industry will remain reliant on natural gas. To create a fully renewable industry, the conventional production method must be replaced by a different method to reduce demand for natural gas. The method to produce renewable, green hydrogen is called electrolysis (Kakoulaki et al., 2021). This is a process in which renewable electricity is used in an electrolyser where water is split into hydrogen and oxygen, without any other emissions.

Green hydrogen offers more solutions to energy challenges than only decarbonizing the existing fossil hydrogen industry. One of the opportunities is to use green hydrogen as a renewable feedstock to replace fossil fuels in industrial processes. There are industries that cannot replace fossil fuels with only renewable electricity, but need a molecule in chemical processes or need high temperatures that electricity is unable to achieve, such as the steel and cement industries (Seck et al., 2022). These industries are referred to as 'hard to abate' sectors (Rosa & Mazzotti, 2022). Besides decarbonizing hard-to-abate sectors, green hydrogen has potential to replace fossil fuels in more downstream markets such as mobility and domestic heating, (Hers, 2018). Green hydrogen can also be used in the fuels and chemical industry as a renewable building block for synthetic liquid fuels, and sustainable chemical products and materials (Weeda & Segers, 2020). As a last potential application, green hydrogen could have a role in the integrated energy system and security of supply in the Netherlands. Besides being a production method for hydrogen, electrolysis can be a method of electricity storage. The process of producing hydrogen can be reversed, where hydrogen is used to produce electricity (Weeda & Segers, 2020). This application will be increasingly important as electricity production will be increasingly from intermittent sources. To conserve the balance on the electricity grid in the future there is a need for grid stability services, which electrolysis can offer (Oliveira et al., 2021).

Due to the potential for hydrogen as a renewable energy carrier, this green molecule plays a central role in plans for CO_2 reduction. In the last few years, 28 national governments have published strategies and roadmaps for the development of hydrogen economies (Cheng & Lee, 2022). In these foreseen hydrogen economies the uses for the molecule outgrow the existing applications in heavy industries and thus, it is expected that hydrogen will play a role in our everyday lives. The Netherlands has stated explicit goals in the national climate agreement. It is planned to have up to 4 gigawatts of installed electrolyser capacity in operation in the Netherlands in 2030 (Weeda & Segers, 2020).

Despite the ambitious goals, the Netherlands is still far away from the climate agreement goals for hydrogen. While there have been public announcements that projects have been initiated to construct hydrogen production facilities up to 1 GW capacity, only a handful of small-scale (~1 MW) electrolysers are in operation in the Netherlands (Weeda & Segers, 2020). In total this is less than one percent of the installed hydrogen capacity in the Netherlands (CE Delft, 2018). The share of green hydrogen is not increasing quickly as green hydrogen is at least 2 to 3 times more expensive than blue hydrogen (Taibi et al., 2020). Both the capital costs and the hydrogen production costs are not cost competitive and contribute to the large price differences (Younas et al., 2022). Even though there are many useful applications of green hydrogen, some academia find that green hydrogen currently makes no sense from an economic point of view (van Renssen, 2020). However, there are outlooks that predict significant cost reductions for green hydrogen. Kakoulaki et al. (2021) have projected that the hydrogen production costs could have halved in 2030, compared to 2020. The Hydrogen Council (2020) published a report in which they state that in 2030 hydrogen could be cost competitive with other low-carbon alternatives and even some conventional ones.

The biggest driver of the foreseen cost decrease is an industry-wide scale up. Both the technology developers and the hydrogen producers will benefit from scale up. Hydrogen producers will experience benefits from economies of scale and improved skill and efficiency in planning and engineering (Taibi et al., 2020). In early stages of development of technologies, learning by-doing, learning by-researching and learning by-interacting are important drivers for cost reduction (Elia et al., 2021). Technology developers will be able to speed up innovation and increase overall efficiency of electrolysers (Dincer & Acar, 2017).

Falcone et al. (2021) state that there is a status quo in the hydrogen industry where green hydrogen is deemed an interesting sustainable molecule, but not adopted yet due to high costs. Based on other reports, they claim the price will drop with up to 70% in 2030, but not without additional policy and support. Younas et al. (2022) claim that the high production costs related with electrolysis are a critical challenge that makes electrolysis less attractive and is not likely to reduce soon. van Gerwen et al. (2019) have calculated promising green hydrogen cost curves until 2050. But even for this time period, they have not performed a scenario or uncertainty analysis. Taibi et al. (2020) predict hydrogen production costs could be as low as 2 USD in 2030 based on historic learning curves for renewable energy technology. This cost prediction is used by Oliveira et al. (2021) in their proposed pathway for adaptation of green hydrogen. Again, without any scenarios to incorporate uncertainty into their proposition. The lack of uncertainties and scenario analysis is exemplary for literature covering the development of the green hydrogen economy. Even though it is recognized as being highly uncertain (Falcone et al., 2021), cost predictions are not based on dynamic models that include uncertainties and scenarios. Even the leading policy proposal, formulated through cooperation between the government and industrial actors, do not foresee any outcomes other than their positive view (NWP, 2022). The main uncertainty that is mentioned in the report is that the hydrogen economy might develop even faster, making the report quickly outdated.

Most reports that have a positive outlook on the development of the hydrogen industry and do not include scenarios in their research. These reports focus on strong policy support for hydrogen production, and assume that demand will follow. There are not many reports that approach the hydrogen system from the demand side. If the policy goals for hydrogen production are all achieved, but there is no demand for the product, the policy approach can hardly be called a success. Exemplary for the lack of description of the demand development is the research by Yang et al. (2023) where the demand is modelled as a function of time, rather than a factor that can be influenced by the system behaviour.There are a few reports that have incorporated some form of uncertainty or scenario analysis into their research, but they are fairly limited. Gigler et al. (2019) used low, medium and high scenarios to draw out their proposed policy roadmap, but these are mostly qualitative and they give similarly positive outlooks. Odenweller et al. (2022) have made the only probabilistic uncertainty analysis of the scale up of hydrogen, but without including any concrete policies. This means that current literature cannot make accurate predictions about the future impacts of certain policies on the development of the hydrogen economy.

This research will contribute to the existing literature the barriers and drivers of demand for green hydrogen and the effect of policy on the green hydrogen industry. The combination of System Dynamic and Exploratory Modelling Analysis is novel and will add to the knowledge on the structure of the green hydrogen system. Based this analysis it is possible to better understand why certain policies can be effective, and why others are likely to be ineffective. The assessment of policies in many different scenarios will aid further policy development.

For this analysis a new System Dynamics model will be constructed, rather than building on an existing model. The existing modelling efforts have focussed on specific part or use-cases of hydrogen. Huang et al. (2022) only focus on a bottom-up analysis of the of the existing Chinese hydrogen consuming industries. Other research, often only attempts to model hydrogen demand in the transport sector (Shafiei et al., 2017; Yusaf et al., 2022), while this research aims to assess development of hydrogen demand in all possible end use markets. In addition, there is structural uncertainty within the hydrogen system due to the novelty of the subject. A completely new model will contribute to the structural understanding of the system.

The focus of this research will be the following research question:

How can the Dutch hydrogen economy develop, and how can policy impact the deployment of green hydrogen production capacity?

To answer this question four sub-questions will guide the research towards the conclusion and recommendations.

- What are drivers and barriers for the development of the hydrogen industry in the Netherlands, as described in literature?

- How does the model behaviour compare to the literature on the development of the hydrogen economy?

- What effect can existing and newly proposed policies have on the evolution of a green hydrogen economy?

- How can policy be effective under unfavourable conditions?

1.1 Relevance for EPA programme

During the EPA master program, the central focus has been on grand challenges and wicked problem. Typical for grand challenges and wicked problems that were subject during the EPA courses is the (deep) uncertainty surrounding these issues, and that there are different actors involved. The uncertainty makes conventional decision making methods insufficient to deal with these problems. The EPA problem includes methods to cope with the uncertainty that is often part of problems related to the energy sector. These approaches include the model based approaches that is used in this research of the development of the green hydrogen economy.

The green hydrogen economy is a product of the ongoing energy transition to battle climate change. Climate policy has been characterized as a wicked problem in literature (Li & Pye, 2018). This means that the problem is characterized by uncertainty and that there is no obvious right solution. In addition, energy problems have a strong interactions with other sectors that increase the complexity of the problem (Ahmad et al., 2016). The uncertainty and the relation between different actors makes the hydrogen sector a relevant subject for an EPA master thesis. In addition, it enables the use of modelling techniques learned during the EPA programme.

2 Methods

This research' main objective is to analyse the green hydrogen industry in the Netherlands and to evaluate existing and new policies under deep uncertainty. In the first part of the research, a System Dynamics model is created to simulate the development of the green hydrogen industry. To deal with uncertainty, a Decision Making under Deep Uncertainty (DMDU) approach will be applied to the System Dynamics model. There are many different DMDU approaches described in literature (Kwakkel & Haasnoot, 2019), but most are derived from the work by Lempert et al. (2006). For this research the methods described by Walker et al. (2012) will be leading. Their framework is based on exploratory modelling to analyse possible policy levers and scenarios, followed by a robustness analysis. To find relevant policy levers a literature review covering the hydrogen industry and policy will be conducted first. The DMDU framework will applied to a system dynamics model using the *EMA workbench.* This is an open source toolkit in Python for exploratory modelling, scenario discovery and robust decision making designed by Kwakkel (2017).

In the following figure, the research flow is explained in detail of the different phases of the research. These phases align with specific chapters that will answer the sub questions, and finally, the main research question. Specific methods used with their required input and proposed outputs are also explained.

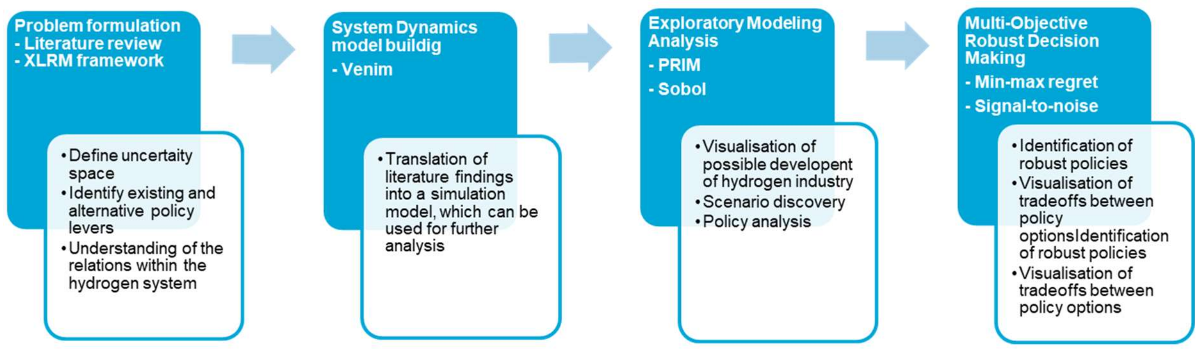

Figure 1: Research flow diagram

The DMDU approach consist of firstly framing the problem based on a literature review. In this stage the triggering issue, system structure, objectives and policies are specified, as well as the uncertainty space. Findings from the literature review will be translated to a system dynamics model. In this model the system description from state of the art literature will be quantified and implemented in the model as differential equations. With the new system dynamics model, an exploratory modelling analysis will be performed. As part of this analysis the input parameters of the model and impact of policies are explored under different combinations of input values that represent different scenarios. The exploratory modelling analysis will result in more insight into the green hydrogen system, and a better understanding of the crucial barriers and drivers. Based on the insights from the literature review and the exploratory modelling, a final policy proposal will be formulated. The proposed policy will be evaluated for the robustness under uncertainty in the Multi-Objective Robust Decision Making analysis. Generally the steps in the DMDU approach as shown in figure 1 are non-linear. DMDU is inherently iterative as insight gained in each step can impact earlier work.

2.1 Problem Formulation

The initiation of the research will be based on the problem formulation with the XLRM framework (Kwakkel, 2017). This framework is used to structure the system as a combination of external factors (X), policy levers (L), relationships within the system (R), and performance metrics (M). These factors are used in the following function: ***M = f(X,L).*** This function is visualized below in Figure 2. This framework is a static depiction of the hydrogen system that will be transformed into a system dynamics model in the next stage of the research.

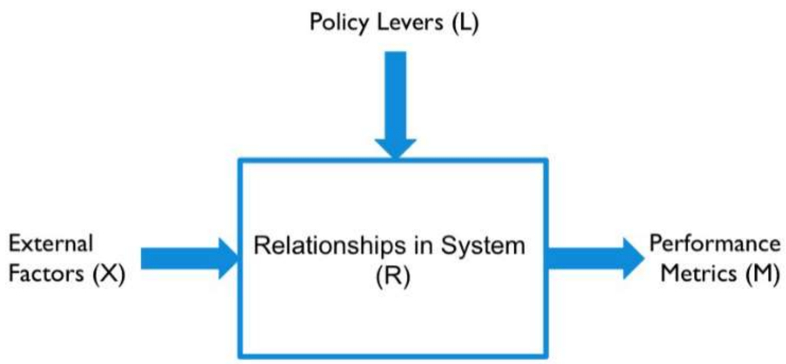

Figure 2: XLRM Problem Framework (Kwakkel, 2017)

Findings from the literature will be used to identify the policy levers, external factors, performance metrics and the relationships within the system. The relationships will be quantified in the system dynamics model. The external factors are to be analysed in depth in the exploratory modelling, and the impact of the policy levers will be covered in the robustness analysis

2.2 System Dynamics model building

In the second part of the research, a System Dynamics (SD) model will be constructed. System Dynamics is an approach to analyse the behaviour of systems, pioneered by Forrester (1961). The model will be based on the system described in the XLRM framework. Problems related to energy systems cover complexity can benefit from using simulation and modelling based approaches to provide a better understanding of energy systems (Saavedra et al., 2018). System dynamics is particularly suitable for providing a system thinking for complex energy production and markets with interactive factors, uncertainty, delays and non-linear behaviour (Qudrat-Ullah, 2015).

System Dynamics modelling has been used to simulate energy systems and policy analysis since the early seventies (Dehghan et al., 2022). The nature of energy systems naturally align with the principles of system dynamics modelling. System Dynamics models rely on accumulation, feedback, and delays to simulate, and energy systems are essentially all continuous feedback systems, where demand leads to investments, investments generate supply, and supply fulfils demand (Qudrat-Ullah, 2015). In the hydrogen system specifically the development and scaling up of the hydrogen industry can be considered to be a feedback loop. Investments in new production capacity will lead to economies of scale, that will drive costs down and attract more investments. The interactions within the feedback loop delays exists. Before new capacity can be added to the system, project planning and development will cause delays between investments, policy, and effects.

Building a system dynamics model is not a linear process. According to the creator of the modelling paradigm, (Forrester, 1987), building a System Dynamics model is an iterative process. Model building should be a circular process of creating a model structure, testing behaviour of the model, validating the model, and adapting the structure. The relationships within the model are built in differential equations, parameters and variables. These are represented in of stocks and flows connected through auxiliary variable. (Akhwanzada & Tahar, 2012). Figure 3 shows the simplest example of a feedback loop modelled in Vensim.

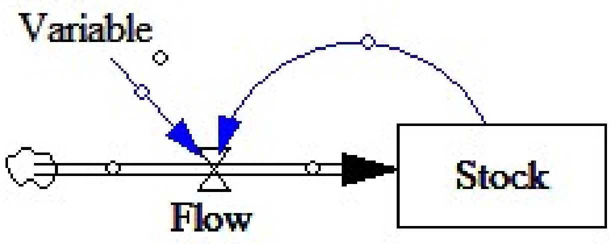

Figure 3: Building blocks of System Dynamics modeling in Vensim

To develop a quantitative System Dynamics model in Vensim, four building blocks are used: stock, flow, auxiliary variables, and a connector. A stock shows the level of any variable at a specific time. Flows are attached to a stock and is responsible for increasing or depleting stock's level. An auxiliary can be parameters or values calculated from other variables within the system. Finally, the arrows show the connection and control between system variables.

2.3 Exploratory Modelling Analysis

By only implementing policies in a base-case SD model, the uncertainty surrounding the energy transition and energy markets would not be appropriately considered. Thus, to include the uncertainty in this part of the research an Exploratory Modelling Analysis (EMA) is performed. Exploratory modelling is a method of running models numerous times under different conditions, firstly defined by (Bankes, 1993). This facilitates exploration of potential futures and uncertainties in systems (Walker et al., 2012). The exploratory modelling analysis is performed using the EMA workbench. This workbench offers functionalities that connect python with the Vensim system dynamics modelling environment (Kwakkel & Haasnoot, 2019). Since EMA workbench allows to extend the use of SD model to deep uncertainty, this approach will be used to analyse the deep uncertainty in the hydrogen industry (Pruyt & Kwakkel, 2012). EMA is not used only for optimizing a system with a specific goal in mind or to answer a specific question. The focus of EMA is to stimulate 'out of the box' thinking that support the development of policies. (Kwakkel & Pruyt, 2013)

The EMA workbench includes methods to run the model many times and includes samplers for the uncertainty space. In addition, the workbench includes all algorithms that will be performed throughout this research. For the analyses, the uncertain variables in the Vensim model, are coded in the EMA workbench as real parameters, for which uncertainty ranges are specified. With Latin Hypercube sampling every model run has a different set of parameter values, that are essentially new scenarios. The outcomes are retrieved from Vensim as prespecified time series outcomes. For the algorithms these time series are transformed into scalar outcomes. The policies are implemented as model levers, specifically as either real- or integer parameters. This allows the same sampling of values as with the uncertainties.

The exploratory modelling analysis consist of two different parts, scenario discovery and policy analysis. Scenario discovery has a focus on analysing the uncertainty space to find crucial barriers and drivers of the hydrogen system. During the subsequent policy analysis existing and a proposal for new policy will be added to the model. The effect of the policies will then be visualized to evaluate the effectiveness of the combination of policies. The two approaches will be further elaborated in the next two sections.

2.3.1 Scenario discovery

For a better understanding of the hydrogen system, the uncertainty space will be looked at in more detail. While there are many uncertainties in the model, not all influence the behaviour equally. For the following analyses, it is important to understand which uncertainties can be qualified as crucial barriers. Barriers and opportunities are central concepts in adaptive policy making. In order to design robust policies, it is crucial to identify combinations of uncertainties that have a significant impact on the ability of a policy to achieve its goal. For optimal effect, policy should either take advantage of the opportunity, or reduce the effect of the barriers (Hamarat et al., 2014).

The first method to determine the barriers is applying a rule induction algorithm called *Patient Rule Induction Method (PRIM)* to the model. The PRIM algorithm was designed by Friedman and Fisher (1999) as a tool for data analysis to be used for problem optimization. For this research PRIM will be used identify the scenarios under which the model performs poorly, or extremely well, and identify which of the uncertainties can be seen as the barriers, and which as the drivers. In these cases PRIM will return a set of uncertainties with the values that are the main causes for the suboptimal performance. This analysis will result in a set of crucial uncertainties and boundaries for the evolution of the green hydrogen system. The PRIM algorithm searches the input variable space, to find values result in outputs that are considerably different than the average value over the entire output domain. In addition it is usually desired that these regions be describable with *rules* to specify the input values. (Friedman & Fisher, 1999). PRIM describes these subspaces in the form of boxes of the model input space *(Pruyt & Kwakkel, 2012)*. The specific steps the PRIM algorithm uses are described in Figure 4.

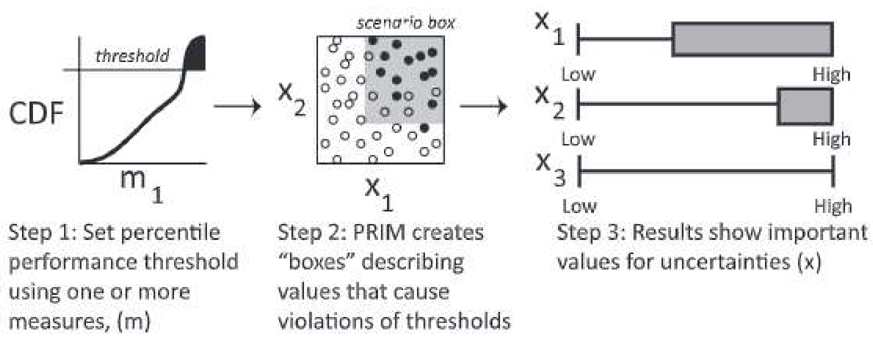

Figure 4: The three main steps of PRIM (Kasprzyk et al., 2013)

A second analysis of the uncertainties that will be conducted is a global sensitivity analysis called Sobols' sensitivity analysis (Sobol', 1967). Sobol uses variance decomposition to tells the fraction of total variance added by each variable. The contribution of uncertainties to the variance of an outcome is explained by the ratio of the partial variance to the total variance, the Sobol sensitivity indices (Quinn et al., 2020).

The algorithm distinguishes first-order effects and second order effects. First order interaction tells how much a factor adds to the variance of an outcome. The second order effect explains how much interaction between two factors adds to the variance of an outcome. The use of the Sobol algorithm to analyse the uncertainties that were identified with PRIM will add to the understanding of the crucial barriers of the hydrogen model. Both the PRIM and Sobol algorithms are part of the EMA workbench package.

2.3.2 Policy analysis

After the uncertainties in the model have been analysed in depth, the next part of the model analysis is assessing the impact of the existing policies that were identified, and new policy proposed based on the literature review. To achieve this, there first will be an analysis of the model behaviour without any policies. Only the external uncertainties will be varied in different model runs using the EMA Workbench. Using Latin Hypercube Sampling, the EMA Workbench will generate different scenarios for each model run within the same uncertainty space as in the scenario discovery. With these model runs the possible development of the hydrogen economy can be visualised. The outcomes of this first experiment will be the baseline to compare models with implemented policies to.

After the baseline is established, two more experiments will be conducted. First, the existing policies will be implemented and compared to the base ensemble. Second, new policy options will be added to the model to be analysed. The additional policy will be *adaptive* policy. Adaptive policy is different than conventional policy in the way it is implemented. Policy usually gets implemented at a specific time, for a predefined duration. Adaptive policy is implemented depending on predefined triggers or states of the systems. These triggers are based on the barriers and drivers identified in the scenario discovery.

To reflect on the hydrogen industry, currently all specific policy is in place until 2030. For the period after 2030, new policy will be designed. Adaptive policy would not be designed to be in place until a certain time or indefinite, but until a predefined variable reaches a certain state. This trigger could be when x amount of production capacity is installed. After this state is achieved, policy can be put on standby or be replaced with other policy. The adaptive policy will be added to the existing system dynamics model to enable an initial assessment of the effectiveness of the proposed policy.

2.4 Multi-Objective Robust Decision Making

In this stage of the research policy will be analysed for their effectiveness under unfavourable conditions by applying the Multi-Objective Robust Decision Making (MORDM) method as described by Kasprzyk et al. (2013). With this method the different objectives of hydrogen policy and the policy options will be tested for their performance under uncertainty. The ability to perform well under uncertainty is measured with the robustness of a policy. A robust policy is one that performs well, given a broad set of possible scenarios (Walker et al., 2012). In robustness analysis, the objective is not to find the single most optimal strategy, rather it is to find policies that perform well compared to certain thresholds, under any given scenario (Lempert, 2003).

The MORDM framework builds on the exploratory modelling and the problem formulation as explained in the earlier sections. It is important to note that finding robust policies is not a linear process. It is very much an iterative process in which model runs generate new insights that will require re-evaluation of earlier findings and updating of the model parameters. Below this process is visualized.

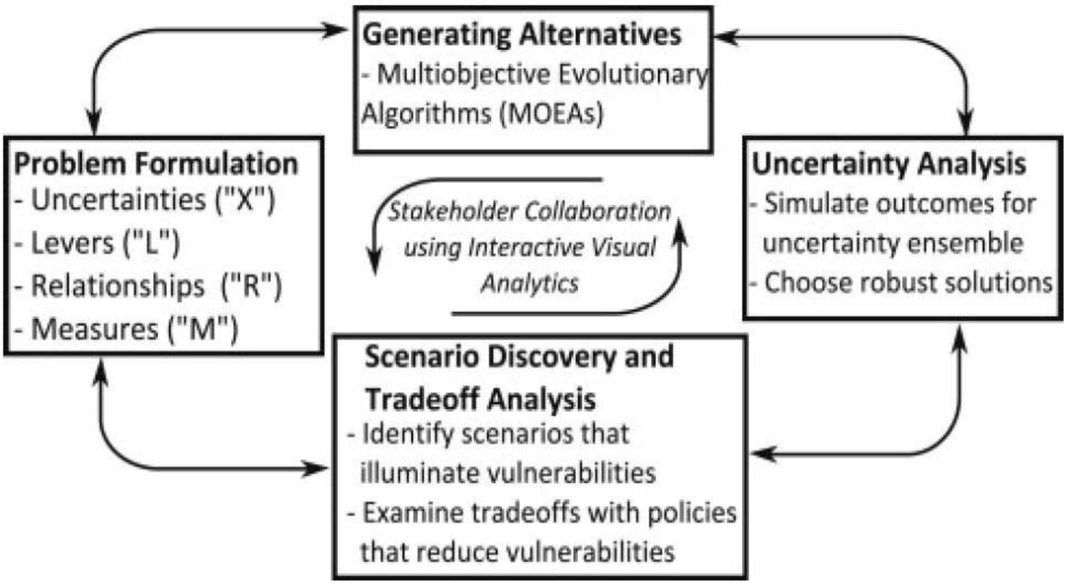

Figure 5: Robust Decision Making process (Kasprzyk et al., 2013)

To perform the robustness analysis, first the preferred policies will be included in the SD model. The impact of these policies will be analysed, as well as their crucial uncertainties and barriers. The uncertainty ranges under which the model results in the least favourable outcomes are identified using the PRIM algorithms in the scenario discovery section. The uncertainty space will be adjusted to the unfavourable scenarios to find policies that perform well even in the worst-case scenarios.

For the robustness analysis of the proposed policy options the policies will be included into the analysis as variable policy levers. The specific values for different policies will be determined using Latin Hypercube sampling. In the worst case scenarios as identified earlier, the policies will be tested for their impact on the outcomes of interest. The first analysis is to search for candidate solutions between different combinations of the policy levers. Candidate solutions are identified with the use of a Multi-Objective Evolutionary Algorithm. This algorithm is applied to the model using the *optimization* function in the EMA workbench, which calls on the ε-NSGA-II algorithm. This algorithm is based on the principle of finding non-dominated solutions, also called the Pareto set (Kollat & Reed, 2005). To be able to use this algorithm, the model outcomes must be defined as Scalar Outcomes for which the desired direction of the outcomes must be specified. The optimization can only be successful if it is defined for outcomes if policies should maximize them or minimize them. In addition, constraints can be defined to narrow down the amount possible candidate solutions before executing the algorithm.

For a successful analysis, many-objective evolutionary algorithms must have converged to the best possible solutions. With the ε-progress metric the progress and performance of the algorithm can be monitored. The ε-progress can be visualized to show the amount of new policies the optimisation returns. Once no new policies are found, the optimization is finished.

When the algorithm has converged to the optimal solutions set, the trade-offs between the solutions are visualized in a parallel axis plot. In these plots, each dimension is shown as a vertical axis. Each solution is represented by a line on this plot, which crosses the objective axes at the corresponding value. As this is a multi-objective problem, some policies can have different effects on the different key outcomes. Visualising these trade-trade off can provide valuable insight into the effect of policies.

The last step is to re-evaluate candidate solutions under uncertainty to test their robustness. In general, robustness metrics are a method to reduce the uncertainty about the expected outcomes of policies (Kwakkel et al., 2016). There is not one single method to assess robustness perfectly. In literature and multiple methods to determine the robustness of policies can be distinguished that all capture different aspects of robustness. The different robustness metrics are categorized in Figure 6.

		Characterizing performance of policy alternatives	
		Comparing alternatives	Performance of individual policies
Characterizing performance over SOWs	Threshold	Satisficing regret	• Domain criterion (Starr 1963) • Radius of stability, Info-Gap (Ben Haim 2001)
	Descriptive statistics	• Minimax regret (Savage 1954) • 90th percentile baseline regret (Kasprzyk et al. 2013) • 90th percentile best option regret (Herman et al. 2015)	Moments of the distribution (e.g., mean, variance), minimum, maximum, and functions thereof (Hurwicz, signal-to-noise, coefficient of variation)

Figure 6: Robustness metrics (Walker et al., 2012)

For this research descriptive statistics will be used. For an optimal robustness analysis, one comparative metric will be used, and one that focusses on performance of individual policy. The first method is visualizing how robust a policy is in terms of each key outcome with the signal-to-noise ratio, and investigate the robustness trade-offs. For this robustness evaluation, it is required to explore the scenarios for each solution. Each policy will be run under 1000 scenarios. Only policies that result in a green hydrogen economy that is at least the size of the existing grey hydrogen industry are of interest. For outcomes that are to be maximized, a high signal-to-noise ratio is preferred. For outcomes that are to be minimized, vice-versa. The signal-to-noise ratio is a descriptive, individual performance value, meaning it is valued independently of alternatives. It was first introduced as a method for robust optimization by Madu and Madu (1999). This approach explains how consistent the outcomes of a certain policy are. Robust policy should not have much variation in the outcomes when input parameters are varied. There are drawbacks to the signal-to-noise ratio. The issues are that combinations of the mean and variance are not always monotonically increasing, and that focusing on the variance or standard deviation means that there is no distinction possible between positive and negative deviations from the mean (Hamarat et al., 2014).

A second metric of robustness is the min-max regret criterion. This method originates from Savage (1954), who defines regret as the difference between the performance of the option in a specific scenario the performance of the best possible option in the same scenario. The min–max criterion aims at finding solutions with optimal performance in the worst case scenarios (Aissi et al., 2009). In contrast to the signal-to-noise ratio, the min-max regret analysis is a relative value criterion. This approach is based on a principle of regret of choosing a certain policy compared to other policies in for that outcome, rather than an independent valuation of the robustness of a specific policy. A both metrics for robustness are distinctly different, they will result in different outcomes.

In the next section the first part of the research, the policy analysis and problem formulation will be covered. Thereafter, section 4 will describe the system dynamics model that is used for the exploratory modelling analysis and the robustness analysis. The experimental setup for the last two analyses is explained in more detail in section 5.

3 Problem formulation

To break through the identified status quo in the Netherlands, the green hydrogen industry requires a clear policy support framework (Gigler et al., 2019). It is crucial for the upscaling of green hydrogen that producers receive some form of subsidies or indirect financial support schemes to cover current funding gaps (Taibi et al., 2020). Without being eligible for those schemes, the industry will not be able and willing to make the necessary investments to scale-up the hydrogen economy (Gigler et al., 2020). The Dutch government has developed multiple support schemes that can accelerate sustainable innovations. For every phase of development, expressed in *Technical Readiness Level,* tailored approaches exist in the Netherlands. Hydrogen currently is in one of the final phases, as is trying to move from demonstration (TRL 7-8) to deployment (TRL 9). Figure 7 visualizes the policies and support schemes for renewable energy solutions throughout the technological maturity phases.

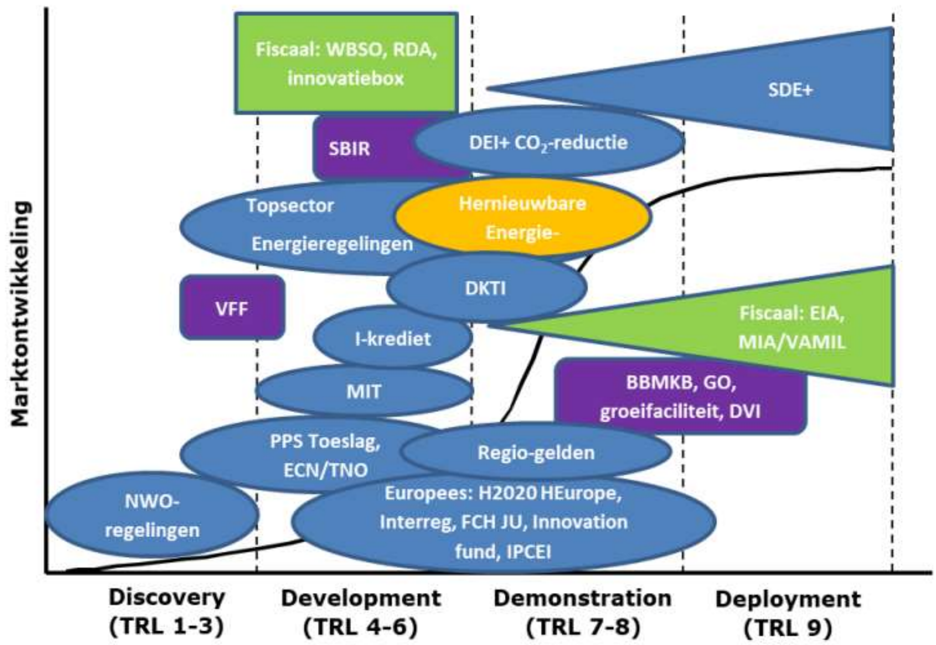

Figure 7: Dutch renewable energy policies (Gigler et al., 2019).

The Dutch approach to reduce emissions at large scale in its industrial sectors is focussed on an approach that combines a strong commitment to raising carbon prices with ambitious technology support, where the financial support comes from the Sustainable Energy Transition Incentive Scheme (SDE++) (Anderson et al., 2021). While the SDE++ is a fund of 13 billion euro that easily could make sure the green hydrogen goals will be achieved, the nature of this support scheme makes it difficult for any hydrogen project to receive funding. Projects can apply for funding in bidding rounds based on cost of CO_2 avoidance, with a cap of €300/ton CO_2. This cap is currently not achievable for green hydrogen, so it can not apply for SDE++ funding. Even if the costs can fall below the cap, carbon capture projects can be competitive at around €100/ton avoided CO_2 emissions. Thus, electrolysis has a small chance of receiving any support from the main policy instrument in the Netherlands.

In 2021 the Ministry of Economic Affairs informed the Dutch parliament that there are issues with using the SDE++ as a main tool for realising the energy transition. The main objective the SDE++ is to stimulate the use of the most cost-effective CO_2 reduction method (EZK, 2021). This goal cannot be achieved with innovative climate solutions like green hydrogen that are far from being cost-competitive yet, but are crucial for further decarbonisation after 2030. In an attempt to make green hydrogen projects eligible for the SDE++ funding, the cap of €300/ton CO_2 is proposed to be increased to €400/ton CO_2, with a specific budget of €750 million for renewable molecules (Rijksoverheid, 2023) .

Financial support for the development of production capacity the EU has initiated the *Innovation Fund* (IF) and the *Important Projects of Common European Interest* (IPCEI) programmes. Any innovative European hydrogen project can apply for funding to the IF in yearly subsidy rounds, and the IPCEI can exempt hydrogen projects from state aid rules, enabling national governments to support hydrogen projects more. Once a project has been granted IPCEI status, the *Rijksdienst voor Ondernemend Nederland*, can provide funding to those projects from designated funds. IPCEI and IF offer large amounts of funding to projects in the scale up phase. Once the green hydrogen industry is becoming more mature, they will not be able to claim to be innovative enough to justify funding under these schemes. Mature technologies can only apply for SDE++ funding.

Part of the green hydrogen policy in the Netherlands is transposition of the EU policy. The central legislation is the Renewable Energy Directive II. This directive includes targets and policy measures to guide the energy transition, but no direct funding. However, it also contains some barriers for the development of green hydrogen. Most crucial are the requirements for the electricity used for hydrogen production. The Renewable Energy Directive requires *additionality* of electricity, which means that new hydrogen production plants can only use renewable electricity from sources that were commissioned not earlier than the hydrogen production. As a result of this policy, the hydrogen industry can never grow faster than the RES capacity, until a nation's electricity supply is 90% renewable of more.

The RED II also has a large impact on the transport sector, and its' possible hydrogen demand. Hydrogen is a crucial molecule for refineries to produce fossil transport fuels. As well as any other industry, refineries would require to become more sustainable, which they can achieve by transitioning from grey hydrogen to green hydrogen. However, as internal combustions engines are possibly being banned for new vehicles in the EU in 2035, hydrogen demand from the European and Dutch petrochemical industry is likely to reduce. As part of the RED II, the use of fossil fuels in the fuel mix for transport has to be replaced by renewable fuels. Possible alternatives are the renewable fuels of non-biological origin, either as pure hydrogen or as synthetic fuels produced with hydrogen. These fuels can replace up to 20% of fossil fuel demand by 2050 (Hirvonen et al., 2019).

Renewable fuels qualified as such by the RED II that are delivered to the Dutch transport sector are eligible for Renewable Fuel Certificates. These certificates can be traded between fuel suppliers, and provide the green fuels with a and market value. This value is created by imposing bounding targets to all fuel suppliers to have a percentage of their fuel sales covered by the renewable fuel certificates. As an additional policy measure, certain fuels can receive a multiplier for their fuels. For every gigajoule of renewable green hydrogen, fuel suppliers receive 2.5 certificates. Biofuels produced from less desirable feedstocks will not receive a multiplier. This system provides renewable fuel producers with a direct monetary incentive to produce renewable fuels, without funding from the Dutch government. The premium is paid for by other fuel suppliers that need to reach their targets.

Other policies that are described in Figure 7 do not fit the scale at which the hydrogen industry is looking to operate. The large scape projects currently in development require more funding than they can possibly receive from other policies than the SDE++ and IPCEI funds. In the next section literature on the limitations of existing policy and potential new policies will be reviewed, whereafter a proposal for new policy to evaluate in this research is formulated.

3.1 Limitations of existing policy

Existing policy does not guarantee that there will be a green hydrogen industry of significant size in the Netherlands. The policy does not account for uncertainty in the development of the hydrogen industry, specifically the demand creation. The priority of Dutch hydrogen policy is to lower the price of hydrogen either through production support with the SDE++ or through investment subsidies through IPCEI. The assumption is made that lowering the production costs will break the existing stalemate and create sufficient demand. In actuality, the emergence of demand for green hydrogen in the future is not certain at all and depends on assumptions that are far from guaranteed (Detz et al., 2019). The largest part of decarbonisation in the industry is likely to be achieved through direct electrification (Hirvonen et al., 2019). Even if green hydrogen manages to achieve economies of scale and overcome technical barriers it is not guaranteed that a well-functioning market develops automatically (Mulder et al., 2019). The implementation of the existing and proposed regulation can also have adverse effects. By forcefully increasing the demand for green hydrogen, it can potentially increase the average hydrogen price and impose additional costs related to production process (CE Delft, 2022). Large scale decarbonisation can also decrease the price of Emission Trading System-rights due to a lower demand, which could increase the demand for fossil based fuels again (International Energy Agency, 2022). To overcome market failure and initial resistance to the adaptation of green hydrogen an integrated policy approach is needed (Bianco & Blanco, 2020). Without addressing these issues with regard to the demand side of green hydrogen, investments are at risk to be wasted (Falcone et al., 2021).

A key factor for the adaptation of green hydrogen in industrial sectors, often overlooked by policy makers, is creating sufficient demand for green products (Bianco & Blanco, 2020). Currently, demand for hydrogen does not come from the market, but is a consequence of demand for decarbonization (Dickel, 2020). Driven by demands to meet global climate targets and tightening climate regulations, more and more countries are publishing their climate and hydrogen strategies (Wappler et al., 2022). These hydrogen strategies force hydrogen towards different industrial sectors, rather than relying on stimulating market demand. Confusing policy targets for decarbonisation of industries using green hydrogen overlook the fact that many of the industrial sectors that are mentioned in the green hydrogen strategies still have alternative methods to reduce CO_2 emissions. Some literature argues that while a green hydrogen economy is technically feasible it makes no sense from an energy and economic point of view as the conversion losses are relatively high (van Renssen, 2020). Therefore, energy efficiency and direct electrification could remain the most important drivers of decarbonization

To scale up the hydrogen industry it is vital that there is sufficient demand to offtake the increased hydrogen supply, and that can pay for the premium costs related to the more expensive production method compared to conventional hydrogen or fossil fuels. These markets should be subject to focus policy makers to provide the most immediate advantages and enable economies of scale (Bianco & Blanco, 2020). Hydrogen should first be used to replace those quantities of oil and natural gas that are now used in the manufacture of chemical hydrogen. In these sectors the demands are concentrated in large units, e.g. ammonia plants and oil refineries (Manne & Marchetti, 1974).

Currently, policy makers and policy advisors seem to have a different focus than the existing consumers of hydrogen. The climate agreement resulted in the creation of a multiannual innovation program for hydrogen (Gigler et al., 2019). In this programme the authors advice to focus policy efforts on four key sectors: Industry, electricity production, mobility and built environment. The last three currently have a negligible hydrogen demand and are not likely to see demand increasing before 2030, in some scenario's not even in 2050 (Mulder et al., 2019). The other sector, industry, is a disappointing aggregation of a diverse sector. Industrial demand for hydrogen comes from refineries, fertilizer-, and methanol production, possibly in the future also the hard to abate sectors.

The latest version of a combined industry and governmental policy proposal dedicate more attention to both hydrogen us in the transport sector and the built environment than to create demand in the industry (NWP, 2022).

Focussing policy on the industry as a whole overlooks the fact that these possible off takers value hydrogen differently, and are not equally suited as early adopters of green hydrogen. CE Delft (2022) has analysed the impact of green hydrogen on the production costs in these industries. When 50% of the grey hydrogen is replaced by green hydrogen the production costs for methanol and fertilizer increases between 30 and 70%. In competitive industries this could immediately price them out of the global market. In contrast, refinery production costs would increase no more than 2.4%. At this relatively low cost, it is possible to design specific policy for this sector.

Even though in some sectors replacing grey hydrogen with green hydrogen has little effect on the final product price, actors are not substituting their hydrogen intake en-masse. This can be explained by the fact that there is no value chain for green hydrogen (Scita et al., 2020), and there is no market for the green products produced with green hydrogen, such as green steel and green shipping fuel (Bianco & Blanco, 2020). There is no valuation of the lower greenhouse gas emissions that green hydrogen can deliver, other than the avoided CO_2 costs, but this is no different for green hydrogen that it is for blue hydrogen. Hydrogen is not even counted in official energy statistics of total final energy consumption, and there are no internationally recognised ways of differentiating green from grey hydrogen. At the same time, the lack of targets or incentives to promote the use of green products inhibits many of the possible downstream uses for green hydrogen (Bianco & Blanco, 2020).

Green hydrogen faces a paradox in its business case. The potential volumes are in industry, while the potential profit margins are in transport (van Renssen, 2020). Hydrogen is valued based on the alternatives present in specific markets (Tlili et al., 2019). The earlier discussed existing end user markets for green hydrogen can be divided into markets where green hydrogen competes with fossil hydrogen, and markets where hydrogen competes with other energy carriers. Market entry prices can be extremely different between these markets. For methanol, the hydrogen molecule is indispensable as a feedstock for the chemical process. Therefore, green hydrogen only competes with the currently used grey hydrogen. In the transport sector, green hydrogen competes with conventional fossil fuels, electric cars and biofuels. While green hydrogen price is a multiple of its grey competition, hydrogen prices at fuel stations are almost equal to fossil fuel prices (Jovan & Dolanc, 2020). hydrogen supplied as a transport fuel needs to delivered on a pressure almost 10 times higher than hydrogen used as an industrial feedstock. Leading to higher operational costs, which adds to the LCOH in this sector.

There have been different propositions to create a market for green hydrogen. Often it is proposed to increase carbon taxes or artificially increase the EU Emission Trading System-price (Scita et al., 2020). Another option is to tax the industrial use of natural gas is taxed like it is now done for households in the Netherlands. As a result the industry will have a strong incentive to substitute away from natural gas to hydrogen (Mulder et al., 2019). However, higher carbon or natural gas prices would not specifically boost green hydrogen investments, but can also result in an increased interest in blue hydrogen. This could even result in a blue hydrogen lock in that would diminish the demand for green hydrogen (Rosenow & Lowes, 2021).

Another option mentioned option is a feed-in-tariff for green hydrogen. Feed-in-tariffs balance the costs between alternatives as the government would pay the cost gap to the producer of the renewable product. While it would specifically help lower the cost of green hydrogen to be competitive with both blue and grey hydrogen (Pastore et al., 2022), there are specific issues with this approach. With feed in tariffs, there are risks that markets can become too much dependent on the subsidies. In the wind power market it has been observed that feed-in-tariffs can endanger operation of RES after the scheme expires, and also distort wholesale market prices if the feed-in-tariff is installed to long (Rövekamp et al., 2021). In the post feed-in-tariff era there is a clear need for integration of renewables in the market with a new value chain and market based policy. CE Delft (2022) calls for *green product policy,* where the government actively tries to value for green products for which consumers would like to pay a premium.

Another issue, often overlooked by policy makers, whether the annual pace of development of the renewable electricity will be enough to meet the demand for both the electrification of end-uses and the development green hydrogen production capacity, and the cost that this additional capacity will entail (Bianco & Blanco, 2020). While large plans for off-shore windfarms have been announced, the hydrogen industry will need to compete with other market sectors that depend on renewable electricity to achieve their sectoral targets for emissions reduction. If all new off-shore RES capacity would be allocated to green hydrogen production, albeit unrealistic, the Netherlands would still struggle to reach the lowest goals for use of green hydrogen in industrial sectors (CE Delft, 2022). There is an urgent need to address these arising issues in a form of integrated sectoral policy approach.

Subsidies to promote large-scale deployment might bring down the cost of electrolysers, but this will not necessarily make green hydrogen production cheaper. As the main input, renewable electricity is indispensable for green hydrogen production. If the costs of electrolysers can achieve the desired cost decrease, eighty per cent of the hydrogen production cost depends on the electricity price. If all hydrogen produced from fossil sources would be replaced with green hydrogen production, this would result in an additional electricity demand of 3600 terawatt hours (Krishnan et al., 2020). This is more than the entire annual electricity production of the European Union. The European Union expects their hydrogen plans for 2030 to require between €24 and €42 billion. In addition, investments for the required renewable electricity production could reach up to €340 billion in the same period.

3.2 Green Products and Dedicated Electricity policy proposal

As found in the literature analysis, most of the existing policies for stimulation of the use of renewable energy does not fit the stage of development green hydrogen is currently in. There are policies for research projects, and policies for mature, cost-competitive alternatives, which do not fit the level of development of green hydrogen technology. Green hydrogen is past the research and development stage, but it still not cost competitive. The policies that do fit the development stage of green hydrogen are often out of reach for projects due to the high production costs of hydrogen. Policies are mostly not aimed at supporting a specific technology, but are aimed to achieve multiple objectives: Making sustainable technology competitive with fossil alternatives, reduce CO_2 emissions and accelerate the deployment of clean technologies in the most cost-effective way possible. As green hydrogen is far from cost effective, it often is unable to apply for subsidies. This policy proposal will include policies specifically aimed at green hydrogen production to make the molecule cost competitive in the future.

Most literature agrees that some form of financial stimulus is required to kickstart the development of the green hydrogen economy. However, in addition, value in the end markets for hydrogen must be created to build on the momentum generated by the financial policy levers. The refinery sector will be crucial in the proposed policy pathway. This sector is already one of the largest consumers of hydrogen, and cannot substitute this hydrogen for other energy carriers. The impact of hydrogen on the total product price is low compared to other industries.

The first proposal is the *Green Products Policy.* the objective of this policy to treat green hydrogen delivered to refineries as transport fuel to make it eligible to receive renewable transport certificates.

While the hydrogen will not directly be used as a transport fuel, it will reduce the overall emissions of the transport sector. This will allow green hydrogen producers to receive renewable fuel certificates that represent a certain market value. It is a direct value creation for green hydrogen in the end markets, while not requiring any direct subsidies. This policy has been discussed before by policy makers. However, there is not yet a detailed description and the proposal would depend on different European regulation (Hammingh et al., 2022). In the initial discussion of this policy it was proposed to only last from 2025 to 2030. In this research this policy will be in effect as long as the levelized costs of hydrogen are higher than blue hydrogen, the most direct low-carbon alternative. All renewable fuels that are eligible currently for this scheme receive a multiplier between 0.8 and 2.5. Direct use of green hydrogen as a transport fuel receives 2.5 times the amount of renewable fuel certificates. The multiplier for the use of green hydrogen in refineries will be described in the experimental setup in section 5.

Another policy option is the *Dedicated Renewable Electricity Policy*. With this policy the Dutch government will offer combined tenders for offshore wind parks and electrolysis. Currently, the rights to produce electricity from offshore wind parks are allocated by the Dutch government to developers through a tendering process. As green hydrogen producers can only practically use renewable electricity from the North Sea wind parks, they have to compete in this tender with direct users of the electricity. It is possible to only allow developer of green hydrogen projects to compete in new tenders (Guidehouse, 2020) This will increase the available electricity supply for green hydrogen production, as it does not have to compete over these new wind farms with other demand for RES. It can reduce uncertainty and project development times through integration. The combined tender will be included in the model as adaptive policy to be in effect while less than 90% of the total electricity production in the Netherlands is generated using renewable sources. The share of offshore wind tenders that will be only for green hydrogen projects will be defined in the experimental setup in section 5.

Both proposed policies are adaptations of plans that have been published earlier, but adapted to the current state of the green hydrogen industry. These two policy options will be analysed in combination with the existing SDE++ and IPCEI policies, to propose a comprehensive, robust policy strategy with an optimal combination of policies.

3.3 Relation to the System Dynamics model

Based on the existing literature on the hydrogen system and the XLRM framework can be used as a basis for the model structure. In Figure 8 the relevant external factors, policy levers, relationships in the system and the performance metrics that will be used in this research are visualised. The model will be solely be used to describe the Dutch hydrogen system, between 2020 and 2050. This timeframe corresponds with the Dutch Climate Agreement and the National Hydrogen Programme (NWP, 2022), as 2050 is the year in which the Netherlands aims to be carbon neutral.

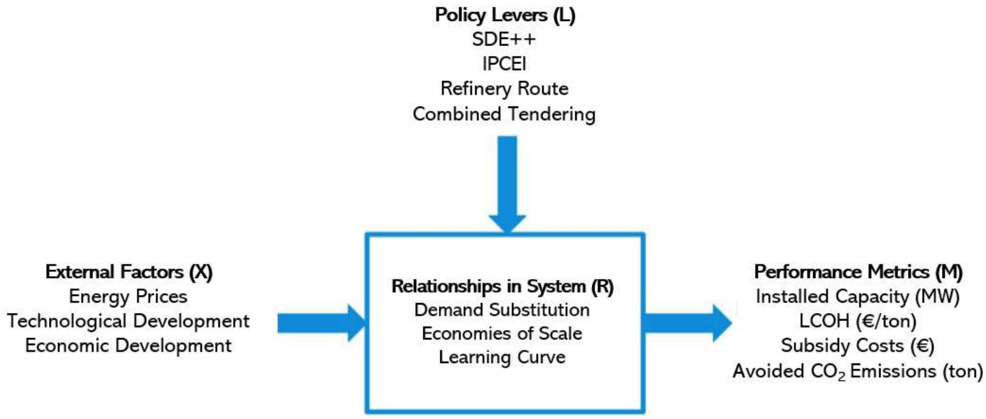

Figure 8: Hydrogen system description visualized in the XLRM-framework

4 Model description

In this section the system dynamics model that will be used as a base for the further analysis will be explained in more detail. The hydrogen system is part of a network which there are strong interconnection with other energy systems (Palmer et al., 2020). In Figure 9 the modelled green hydrogen economy is displayed in a sub-system diagram, following the modelling framework as explained by Morecroft (1982). This diagram shows the sub-models and relationships between them that will be modelled.

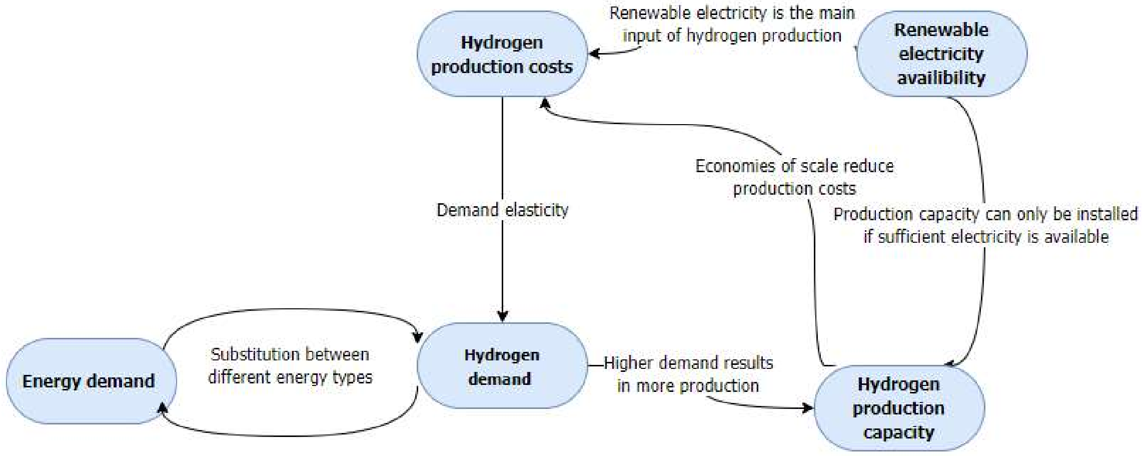

Figure 9: Sub-system diagram of systems related to the hydrogen industry

In general, two methods to model demand in energy and commodity markets are used in literature: The top-down (TD) and bottom-up (BU) modelling paradigms (Böhringer & Rutherford, 2006). In energy demand modelling, the TD and BU do not seem to result in significant difference between the two methods in terms of the accuracy of the forecast (Chin, 2016). However, if the methods do result in different outcomes, the presence of two differing predictions of energy use has a confusing effect on policy preparation (Koopmans et al., 1999).

The bottom-up approach focusses on evaluating the existing and expected future costs of hydrogen throughout its supply chain (Tlili et al., 2019). More specifically, the evaluation of production cost for different production technologies throughout the supply chain. According to Fleiter et al. (2011),the BU approach takes into account the evolution of the "end-uses and of their energy efficiency over time determines the future energy demand" (p.5). In this approach, the energy systems are analysed with level of detail such that other studies covering the development of technologies can be used to determine all relevant costs and efficiency over time (Böhringer & Rutherford, 2006).

The particular focus of the top-down approach is market and economy-wide feedbacks and interactions (McFarland et al., 2004). Top-down based models typically represent technology using relatively aggregated production functions for each sector of the economy. Top-down models can also overlook fundamental physical restrictions, such as the conservation of matter and energy (Böhringer & Rutherford, 2006). The top-down market development in the model will be mirrored to the development of other recently emerged renewable energy technologies. One of the major limitations is that the green hydrogen economy is still in early stages of development and a lot of key information is yet unknown or based on assumptions. The two main developments to be considered as reference are the cost decrease and increased adaptation of both photovoltaic and wind turbines. Both these technologies have successfully been able to increase scale and market share. In addition, these technologies were successful in reducing their levelized cost of energy output while in competition with far more mature fossil based production methods.

The most important implications of the top-down approach on the model are the demand elasticity and demand substitution of green hydrogen and the other energy carriers. The demand elasticity of green hydrogen is an important factor for policy makers to know. It can have a significant impact on the effectiveness different policies (Johnson, 2011). Due to the fact that the demand elasticity determines how the energy markets react to changing prices. Demand for a specific type of hydrogen is not only determined by its own production costs. Mazzucato (1998) explains how production costs compared to the average production costs result in substitution of demand. Lower than average costs increase the market share relative to the other products. The rate of substitution is determined also by the speed with which the market is able to adapt to developments of the relative costs. Three main drivers of bottom-up cost decrease will be the learning curve throughout the hydrogen supply chain. This learning curve is mirrored to development of the market for wind turbines as described by Beiter et al. (2021). They concluded that the learning curve is a combination of a number of cost reducing drivers. The learning curve can be roughly composed of three categories: Research and development, learning-by-doing, and economies of scale (Green, 2019).

For the system dynamics model the top-down and bottom-up approaches will be combined into a hybrid modelling approach. The hybrid approach as a combination of top-down and bottom-up modelling improves the quality of simulation of energy economics and policy impacts compared to uniform approaches (Timilsina et al., 2021). The feedback effects in the top-down approach work well with the nature of the system dynamic modelling approach. However, between the different methods of hydrogen production, electrolysis and steam methane reforming, too many differences exist to aggregate hydrogen production completely. To complement the top-down approach the model constructed for this research will use an aggregate approach to find the market entry costs for hydrogen production types. The development of green hydrogen production costs will be modelled in a disaggregate manner and will be specified for the different end user markets of hydrogen. The aim is to comprehensively analyse the different factors that influence the cost of production independently of the grey hydrogen production costs, and their translation into demand for green hydrogen.

The hydrogen industry is not an independent industry. Green hydrogen is mainly an energy carrier, that is in competition with other, conventional and renewable, energy carriers. In different industrial sectors, there are different alternatives. One of the markets for green hydrogen that is included in the model is transport. In this sector hydrogen is in competition with oil products, biofuels, synthetic fuels and electricity. In contrast, in the steel industry hydrogen an alternative to coal and natural gas. The development of demand, and the market value for the products differ between these industries. In the industrial energy demand there are multiple factors that influence demand. Firstly, there is demand development following the state of the economy. It is assumed here that energy demand growth rates are similar to GDP growth rates. In addition, similar to the top-down approach for hydrogen modelling, elasticity and demand substitution impact the demand for the different energy carriers. Lastly, the demand for fossil fuels will decrease through decarbonisation policies.

The renewable hydrogen industry is strongly related to the production of renewable electricity (Guidehouse, 2020). Without sufficient supply of renewable electricity, hydrogen cannot contribute to decarbonisation. The development of renewable electricity is a function of policy induced production through tendering of off-shore wind parks and the development as a result of decarbonisation efforts of existing electricity demand. The electricity demand is assumed to increase due to domestic electrification and industrial demand for electricity. The domestic electricity demand will increase as energy use from natural gas will be substituted for electricity. The industrial electricity demand is linked to the energy demand sub-model. It is assumed that in general, energy markets will become more energy efficient. Therefore, the demand for energy and electricity reduces with a yearly rate. In the electricity sub-model the hydrogen industry competes with direct electrification for the available renewable electricity. Direct electrification can use all sources of electricity, the hydrogen industry can only use offshore wind electricity, which is a derivative off the roadmap for offshore wind energy (NWP, 2022).

The last sub-model is the realisation of green hydrogen production projects. Projects are assumed to start as a result of demand increase. If the demand is larger than the currently installed production capacity green hydrogen projects will be initiated. In the initiation phase usually the project scope is defined and project teams are formed. After some time initiated projects will progress to the project development phase, where engineering begins. Some of the initiated projects are cancelled in an early stage. In the model this is assumed to occur when market demand for green hydrogen declines.

When a project is in the development phase, renewable electricity must be secured for the project. Projects can only progress to the next phase when sufficient renewable electricity is secured. If it takes too long to find a reliable supply of renewable electricity, projects are at risk of being cancelled. After projects take successful investment decisions, they will begin construction. It assumed that after the investment decision, projects are no longer at risk of being cancelled. After construction the production capacity is commissioned. Currently, the realisation of new green hydrogen production from initiation to commission takes about 8 years (CE Delft, 2022). By effect of learning by doing this timeline can be reduced to 5 years.

Table 1 shows the implementation of the modelling paradigms in the model and their mathematical explanations. Together they represent the relation between demand, costs, and market size.

Table 1: Implementation of modelling paradigms

VARIABLE NAME	FUNCTION	EXPLANATION	UNIT	SOURCE
DEMAND SUBSTITUTION	$\dot{s_i} = \gamma * s_i(\bar{C} - C_i)$ $i = 1, \ldots, n$	$S = Market\ share$ $C = Production\ costs$ $\gamma = Demand\ substitution\ rate$	Dimensionless	(Mazzucato, 1998)
SCALE FACTOR	$(\frac{C_1}{C_2}) = (\frac{S_1}{S_2})^n$	$C = Production\ costs$ $S = Unit\ size$ $n = Scaling\ factor$	Dimensionless	(Morgan et al., 2013).
PROGRESSION RATE	$PR = 2^a$	$a = growth\ factor$	Dimensionless	(Ibenholt, 2002)
LEARNING CURVE	$C_t = C_1 n_t^{\alpha} e^{u_t}$	$C = Production\ costs$ a $= elasticity\ of\ unit\ cost\ with$ $respect\ to\ cumulative\ volume$ $u = uncertainty\ factor$	Dimensionless	(Ibenholt, 2002)
ECONOMIES OF SCALE	$\dot{C_i} = -\alpha(S_i)C_i$ $\dot{C_i} = -\alpha(1 - S_i)C_i$	$S = Market\ share$ $C = Production\ costs$ $\alpha = Market\ adaptation\ speed$	Dimensionless	(Mazzucato, 1998)

4.1 Model verification and validation

Two important steps in the process of creating a model are the validation and verification of the model. Model verification consists of testing the appropriateness of model settings, correctness of the equations and dimensional consistency (Pruyt, 2013). The model does not contain any unit errors, and the integration method and time steps in the model have been deemed appropriate for this model.

Model validation is a less objective process than the verification. Validation in this context is confidence that the model is fit for its intended purpose, and whether or not it represents the system it simulates (Senge & Forrester, 1980). This can be achieved by comparing the simulated behaviour with the behaviour of the system in the real world in order to conclude if the model describes the general trend adequately (Dehghan et al., 2022). In the case of the hydrogen economy this is difficult, as there is not yet a significant hydrogen industry. Therefore, there is insufficient data to validate the model. However, it is possible to assess if the model is fit for the intended purpose of performing exploring potential future behaviour.

To test if the system dynamics model is fit for purpose, The model can be validated using test of the model structure or the model behaviour (Yusaf et al., 2022). Structural tests assess if model structures are a sufficient representation the real world system, and will produce plausible behaviour. Behavioural tests relate to the output of a model and if it results in sensible output behaviour. In this research the model will be validated as part of the exploratory modelling analysis.

During the exploratory modelling the model the model has proven not be sensitive to extreme variation of initial energy prices and values in the industrial sectors. However, the model proved to be sensitive for the parameters in the function for demand substitution, as shown in Table 1. This can be explained by the fact that this function is used for multiple calculations. It is crucial in calculating the demand for 9 energy types in 6 different industrial sectors. The possibility of this function resulting in an error with extreme values, somewhere in the model, is relatively high. In extreme cases, the model could fail to complete a model run. This only occurs if multiple parameters are given extreme values. If only one value is adjusted with extreme values the model runs without issues. Therefore, the model is deemed to be fit for purpose.

4.2 Experimental setup

In this section the model parameters that are used in the EMA workbench to perform the further analysis of the system will be explained. Firstly the uncertainty space will be described. Second, the policies that are analysed in the exploratory modelling analysis, followed by the experimental setup for the robustness analysis and the key performance indicators

The system dynamics model is constructed in Vensim DSS version 9.3.5 x64. The model consists of 294 variables**.** The energy carriers are subdivided into 9 types, including green-, blue-, and grey hydrogen. The development time of hydrogen projects and the industrial sectors are also subdivided. 48 parameters are considered uncertain. The model covers the hydrogen economy from 2020 until 2050, with timesteps of 0.015625 years. The integration method that will be used is the Euler method (Euler, 1768). The identified uncertainties in the model are used in the exploratory modelling analysis. There the model will be run using values sampled from a predefined range using Latin Hypercube sampling (McKay, 1979). The uncertainties and their uncertainty space are shown in Table 2 as how they are implemented as categorical parameters.

Table 2: Uncertainty space and assumptions

UNCERTAINTY	UNIT	MIN VALUE	MAX VALUE	SOURCE
GREEN HYDROGEN PRICE DEVELOPMENT SUBMODEL				
LEARNING RATE	1/Year	0.04	0.06	Assumption
INNOVATION CYCLE	Year	4	6	Assumption
RELATIVE ELASTICITY	Dimensionless	-0.8	-0.1	(Kim, 2019)
MARKET ADAPTATION SPEED	1/Year	0.1	0.8	Assumption
SCALING FACTOR	Dimensionless	0.5	5	Assumption
ELECTROLYSIS DEVELOPMENT	1/year	0.08	0.31	(Vartiainen et al., 2022)
MAX EFFICIENCY	Dimensionless	0.8	0.9	(Vartiainen et al., 2022)
CO2 ELASTICITY	1/Year	0.4	0.8	Assumption
MARKET MATURITY	Dimensionless	0.2	0.6	Assumption
INITIAL CAPEX	Euro/ton	4000	6500	(Schmidt et al., 2017)

OPERATION & MAINTENANCE COSTS	Dimensionless	0.05	0.15	(Schmidt et al., 2017)
GREEN HYDROGEN DEMAND SUBMODEL				
DEMAND SUBSTITUTION RATE	1/Year	0.1	2	Assumption
PRICE ELASTICITY OF DEMAND [GREEN HYDROGEN]	Dimensionless	-3	-1.5	(Kim, 2019)
PRICE ELASTICITY OF DEMAND [BLUE HYDROGEN]	Dimensionless	-2.5	-1	(Kim, 2019)
PRICE ELASTICITY OF DEMAND [GREY HYDROGEN]	Dimensionless	-1	0	(Kim, 2019)
SUBSTITUTION DELAY	Year	1.5	4.5	Assumption
PREMIUM VALUE [REFINERIES]	Euro/ton	0	2000	Assumption
PREMIUM VALUE [METHANOL]	Euro/ton	0	2000	Assumption
PREMIUM VALUE [AMMONIA]	Euro/ton	0	2000	Assumption
PREMIUM VALUE [STEEL]	Euro/ton	0	2000	Assumption
PREMIUM VALUE [TRANSPORT]	Euro/ton	0	2000	Assumption
PREMIUM VALUE [SYNTHETIC FUELS]	Euro/ton	0	2000	Assumption
ALLOCATION KEY SDE	Dimensionless	0	0.2	Assumption
ALLOCATION KEY	Dimensionless	0	0.2	Assumptions
RENEWABLE ELECTRICITY SUPPLY SUBMODEL				
ROADMAP WOZ	MW/year	1000	2000	(RVO, 2021)
ONSHORE RES INCREASE	1/Year	0.03	0.08	(Hers et al., 2022)
OTHER ADDITIONAL RENEWABLES	1/Year	0.03	0.08	(Hers et al., 2022)
RES SECURED FOR ELECTROLYSIS	Dimensionless	0.1	0.5	Assumption
INITIAL POTENTIAL FOR LECTROLYSIS	MW	200	1000	Assumption
DOMESTIC ELECTRIFICATION	1/year	0.3	0.7	Assumption
POLICY MARKET SIZE ADJUSTMENT [REFINERIES]	Dimensionless	0.01	0.04	Assumption
POLICY MARKET SIZE ADJUSTMENT [METHANOL]	Dimensionless	-0.03	0.03	Assumption
POLICY MARKET SIZE ADJUSTMENT [TRANSPORT]	Dimensionless	-0.03	0.03	Assumption
POLICY MARKET SIZE ADJUSTMENT [AMMONIA]	Dimensionless	-0.03	0.03	Assumption
POLICY MARKET SIZE ADJUSTMENT [EFUELS]	Dimensionless	-0.03	0.03	Assumption
ENERGY DEMAND SUBMODEL				
TRANSPORT FUEL SUBSTITUTION RATE	1/Year	0.1	0.2	Assumption
INDUSTRIAL ENERGY SUBSTITUTION RATE	1/Year	0.1	0.3	Assumption
LONG TERM PRICE EFFECT	1/Year	0.2	0.4	
SHORT TERM PRICE EFFECT	1/Year	0.1	0.3	
OIL PRICE	Euro/Barrel	90	110	(TradingEconomics, 2023)
COAL PRICE	Euro/Ton	90	110	(TradingEconomics, 2023)
INITIAL GAS PRICE	Euro/MWh	50	60	(TradingEconomics, 2023)

BIOFUEL PRICE	Euro/ton	1900	2100	(Neste, 2023)
EFUEL PRICE	Euro/ton	2400	2600	(Ridjan et al., 2014)
MARKET REACTION DELAY	Year	0.5	1.5	Assumption
ENERGY CARRIER DEMAND ELATICITY	1/Year	-0.5	-0.2	Assumption
AVERAGE GDP GROWTH	1/Year	0.01	0.03	
BUSINESS CYCLE	Year	4	7	Assumption
INNOVATION FACTOR[BIOFUELS]	1/year	0.01	0.04	Assumption
INNOVATION FACTOR[SYNTHETIC FUELS]	1/year	0.01	0.04	Assumption
INNOVATION FACTOR[ELECTRICITY]	1/year	0.01	0.04	Assumption

The policies that are to be evaluated for robustness are also implemented in the model. The first two policies are the existing subsidies. The first being the SDE++ funding that will be allocated specifically to green hydrogen. The second policy is the IPCEI funding that the Dutch government provides to green hydrogen producers.

There are two additional policies proposed to enhance the development of a green hydrogen economy. The first of the two additional policies is to make green hydrogen supplied to refineries eligible to receive renewable fuel certificates. Every transport fuel has a specific multiplier attached. The policy is modelled as the multiplier that this method receives. This policy is implemented only when the levelized costs of green hydrogen are higher than the levelized costs of grey hydrogen. The last policy is to open tenders for offshore wind farms specifically to hydrogen producers. The policy lever will be the share of offshore wind capacity that will be allocated to green hydrogen production. This policy is in effect when the share of renewable electricity in the Netherlands is below 90%. The implementation of the policies in the model is defined in the table below.

Table 3: Initial policy analysis values used in the exploratory modelling analysis

VARIABLE NAME	VALUE	SOURCE
INITIAL ICPEI FUNDS	783.5 M€	(RVO, 2022)
SDE++ FUND	750 M€	(Rijksoverheid, 2023)
MARKET VALUE CREATION [REFINERIES]	1	Proposal
SHARE RES ALLOCATED TO H2	1	Proposal

After the exploratory modelling, the multi-objective robust decision making framework will be used in the EMA Workbench. The policies from the exploratory modelling will be transformed into ranges, allowing Latin Hypercube sampling to test different combinations of policy. To find candidate solutions the model will be evaluated 50.000 times. The candidate solutions will be tested under uncertainty with 1000 different scenarios to find robust policy options.

Table 4: Policy levers for the multi-objective robust decision making analysis

VARIABLE NAME	MIN VALUE	MAX VALUE
INITIAL ICPEI FUNDS	0€	1500 M€
SDE++ FUND	0€	1500 M€
MARKET VALUE CREATION [REFINERIES]	0.5	1.5
SHARE RES ALLOCATED TO H2	0.3	0.8

The first outcome of interest is the total installed capacity of green hydrogen production. This value is to be maximized by the policy. The second outcome is the levelized costs of hydrogen, which is to be minimized. The third factor is the total amount of funding, a combined factor of the SDE++ and IPCEI funding. The Dutch climate agreement states that cost-effectiveness is an important factor in the design of climate policy, which makes it an outcome to be minimized in this research. The last outcome is the total CO_2 emissions in the Netherlands, which is also to be minimized. To narrow down the candidate solutions only policies that result in at least 25.000 Megawatt installed capacity with subsidy costs lower than €1.500 million are taken into consideration. In Addition, the CO_2 savings resulting from the hydrogen production should be at least as high as the emissions from the existing grey hydrogen industry, 20 Million ton.

To assess the performance of the hydrogen system four key performance indicators are defined. The first one is the installed electrolysis production capacity. This is the metric for the size of the industry. The second KPI is the levelized costs of hydrogen (LCOH), or production costs. One of the key goals the hydrogen policy as described in the Dutch climate agreement is reducing the costs of hydrogen. It is crucial for the success of the industry to have lower costs than the alternative, as otherwise demand for hydrogen would quickly disappear. The third key outcome is the CO_2 emissions that are avoided due to the use of green hydrogen. This is a performance indicator in a broader context that sees hydrogen as a method of reducing emission. CO_2 reductions for this KPI are composed of all fossil fuels that are substituted for green hydrogen. If there is a large green hydrogen industry, there are no avoided emissions if the hydrogen is for additional energy consumption and not to replace other fuels. The last KPI is the total amount of subsidies spent in a certain policy. Cost effectiveness of policy is an important political issue, where expensive policies are almost always undesirable.

VARIABLE NAME	UNIT	FUNCTON
PRODUCTION CAPACITY	MW	Hydrogen production capacity[Green hydrogen]/"tpa/MW"
LCOH	€/ton	Resource pricing[Hydrogen types]-Efficiency[Hydrogen types]
AVOIDED CO2 EMISSIONS	Million ton	ABS(SUM(CO2 avoidance[All but hydrogen!])+Hydrogen industry CO2 savings)
SUBSIDY COSTS	€Million	Initial ICPEI funds+"SDE++ fund"

Table 5: Key performance indicators used throughout the analyses

The importance of the KPI's can be different for different actor within the hydrogen system. Consumers of hydrogen will see the production costs of hydrogen as important, while the government will see cost-effectiveness of policies as crucial.

The different analyses require different specific approaches. For every analysis the model has been analysed throughout a number of scenarios. Table 6 shows an overview of the analyses that have been performed, and the amount of scenarios or model runs it has taken to generate the desired output.

Table 6: Overview of performed analyses and number of model runs

ANALYSIS	#MODEL RUNS	METHOD
EXTREME CONTIDIONS TEST	10.000	Open exploration
BASE ENSEMBLE	10.000	Open exploration, Patient rule induction method, Sobol
EXISTING POLICY	10.000	Open exploration, Patient rule induction method
POLICY PROPOSAL	10.000	Open exploration, Patient rule induction method
MODEL OPTIMIZATION	50.000	Multi-objective evolutionary algorithm
ROBUSTNESS	7.000	Signal-to-Noise, Min-max regret

5 Results

In this section the system dynamics model, based on the interactions explained in the previous section, will be used to assess the possible behaviours of the system through an exploratory modelling analysis in the EMA workbench. The literature analysis has shown that often it is assumed that hydrogen will be quickly introduced into the Dutch industry and become cost competitive around 2030. For this exploratory modelling analysis the behaviour of two model outputs will be analysed to test this prediction: The development of the Levelized Cost of Hydrogen (LCOH) and the total installed green hydrogen production capacity in the Netherlands. After this analysis, the scenarios with the least favourable outcomes will be isolated. For those scenarios key uncertainties that have impacted the model to produce the unfavourable outcomes are identified and discussed. The result section is further divided between the results of the Exploratory Modelling Analysis and the Multi-Objective Robust Decision Making.

5.1 Exploratory Modelling and Analysis

In this section the development of the hydrogen industry in the Netherlands will be analysed in three stages. First a base ensemble will be generated with the model. This model will include no policy. For this base ensemble the crucial barriers and drivers will be identified. Second, a model with currently effective policies will be compared to the base ensemble. Lastly, the model with existing policy will be compared to a model with additional policy.

5.1.1 Green hydrogen base ensemble

10.000 model runs of the base ensemble show that the green hydrogen economy is not likely to grow throughout the uncertainty space. Without any policy for green hydrogen will be able to reduce green hydrogen production costs, but in most cases the total installed hydrogen capacity will not grow significantly, as seen in Figure 10. There is initial growth visible due to existing projects that are under development being commissioned. However, the new installed capacity is insufficient for creating economies of scale. As there is only a few hundred MW installed in 2030 in most cases, the levelized costs of hydrogen has not reduced enough to generate additional demand. Green hydrogen will not become competitive in these cases. The model behaviour for the total installed capacity shows signs of limits to growth.

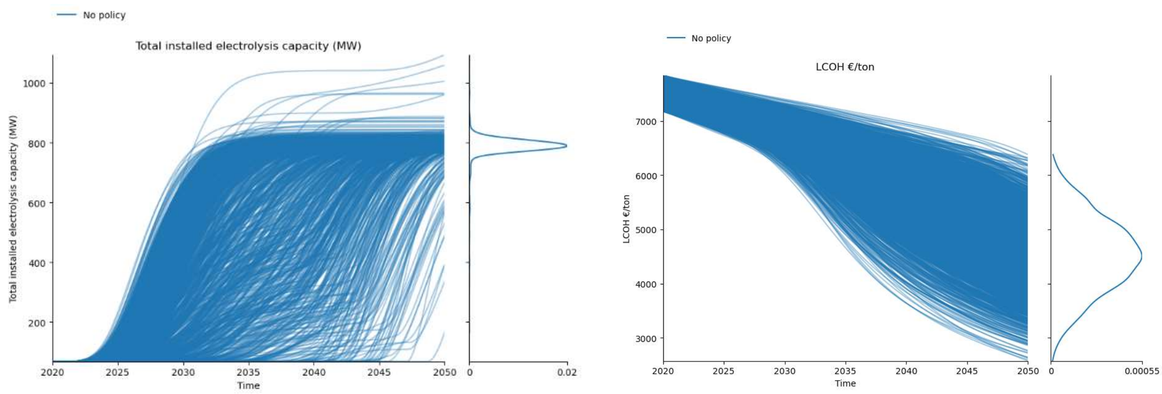

Figure 10: Base-ensemble outcomes of the total installed capacity and LCOH. On the right, the a density plot of the distribution of outcomes at the end of each simulation is visible.

In the model, demand for hydrogen will reduce as long as green hydrogen is not competitive with other energy carriers. As the graph above shows that the costs of hydrogen will not reduce quickly demand will shift to other energy carriers. As a result, there will be no demand for green hydrogen and consequently, no additional production capacity. In the base ensemble the starting point of the hydrogen production costs will in all cases be many times more expensive than the production costs of other types of hydrogen and other energy carriers. This will lead to a rapid reduction of the demand for green hydrogen. The demand changes due to two main drivers, substitution and elasticity. For a product with a higher price than the average energy price to see a growth in demand the demand should increase faster through elasticity than it reduces due to a shift in demand towards cheaper alternatives. Figure 10 shows that the price does not reduce quickly, especially before 2030. In the first ten years most of the demand for green hydrogen has disappeared, resulting in a small green hydrogen industry.

Next, for the outcome *Production capacity* the crucial uncertainties will be identified. Figure 11 shows the value ranges of the crucial uncertainties for outcomes with the lowest total production capacity for green hydrogen in 2050. The crucial uncertainties in the results with the lowest installed capacity are the demand substitution rate, efficiency increase of total energy use and the roadmap for offshore wind development.

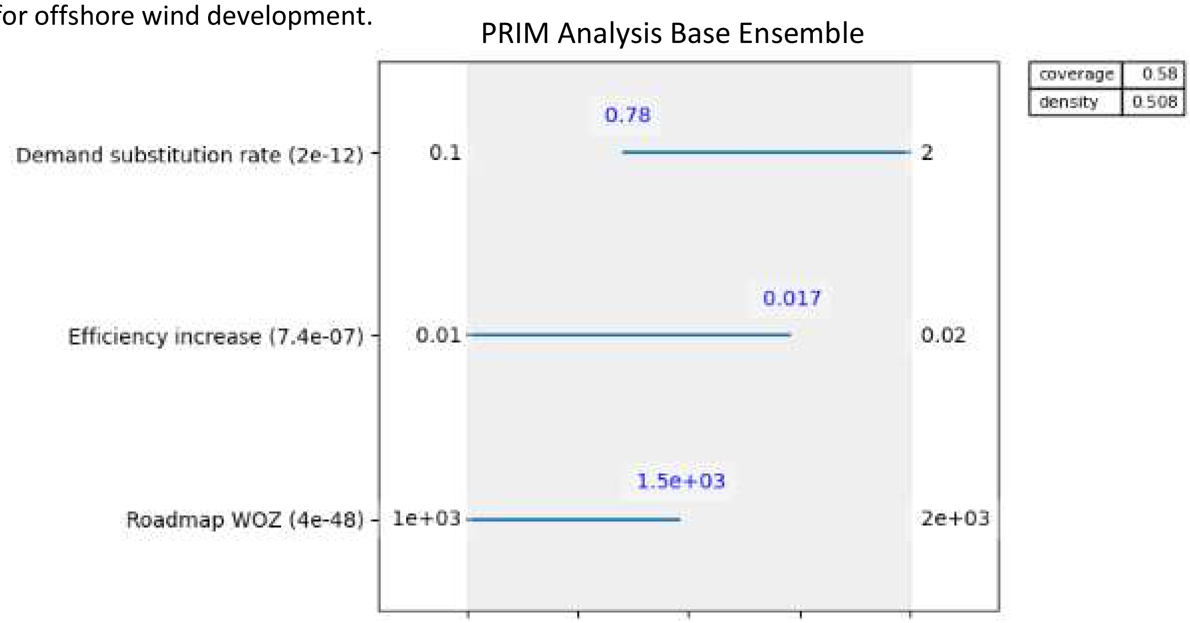

Figure 11: Barriers for market development: The uncertainty ranges that result in the 20% lowest outcomes of installed capacity

The demand substitution rate as a crucial uncertainty confirms the claims in literature that the price of hydrogen is a crucial barrier. Figure 11 shows that high demand substitution rate results the lowest outcomes for hydrogen production capacity. Due to the high starting price of green hydrogen, in these cases the demand will have all been shifted to substitute energy carriers or other hydrogen types, before production costs could decrease enough to be competitive.

The second barrier is the rate at which the energy consumption becomes more efficient in general. This based on the assumption that all industries and technology is in constant development to reduce energy consumption for their activities. It current electricity consumption becomes more efficient, more renewable electricity will be available for green hydrogen production. Low increasing efficiency has turned out to be a barrier for hydrogen production, as there is relatively less electricity available for the hydrogen industry.

The third barrier also relates to the development of the electricity sector. The realisation of the roadmap for offshore wind electricity production (Roadmap WOZ) is a direct barrier for hydrogen production, as there cannot be more hydrogen production capacity than there is offshore wind power capacity until 90% of all electricity in the Netherlands is produced from renewable sources. Pessimistic scenarios about the increase of offshore wind capacity directly lowers the potential for renewable electricity.

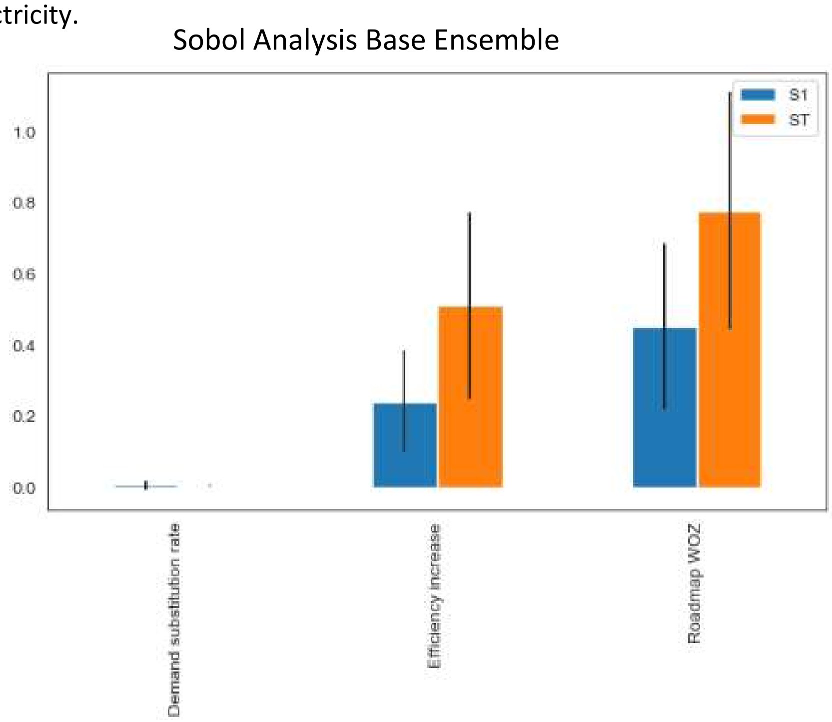

Figure 12: Level of interdependencies between crucial barriers for the development of the green hydrogen economy

Of the three uncertainties the roadmap for offshore wind development proves to be the most impactful to the size of the hydrogen industry, as the Sobol algorithm shows it to have the largest impact on the variance of the installed capacity. In addition, Figure 12 show that the barriers efficiency increase and roadmap WOZ are interrelated, as the first order effect significantly smaller the total effect.

This first analysis shows that a quick adaptation of green hydrogen is unlikely, and highly uncertain. The increase of production capacity mostly determined by the rate of development of electrolysis technology and rate at which demand for energy carriers is substituted and the development of offshore renewable electricity production.

5.1.2 Existing policy analysis

To analyse the impact of the existing policies for green hydrogen, alongside the base ensemble a model with the additional policy is run 10.000 times. The policies in the second model are the SDE++ subsidy scheme and the IPCEI fund. The resulting installed capacity and the levelized cost of hydrogen will be visualized to assess the effect of the policies.

The results below show that the policies have a positive effect on the installed electrolysis capacity and the levelized cost of hydrogen. However, critical observation shows a that the results for total installed capacity are highly uncertain In some cases green hydrogen can become a serious industry, with a size equivalent to around 2-3 times the size of the current fossil hydrogen industry. However, in most cases the green hydrogen industry will not increase significantly over the scenarios without financial policy.

Most outcomes that show large growth of the production capacity grow rapidly once the Dutch electricity mix reaches 90%. After this milestone is reached, the RED II requirements for additionality of renewable electricity do not apply, which massively increases the potential for electrolysis. Figure 13 shows that in some cases around 2035 the behaviour changes in some cases to generate significantly better outcomes. This relates to the Netherlands reaching more than 90% renewable electricity generation. Before reaching that milestone, there can never be more hydrogen production added than there is new electricity generation capacity. After, there is no limit to the amount of new production capacity installed, meaning it is only limited by the demand. In most cases the total installed capacity still shows limits to growth, while in some cases exponential growth is possible.

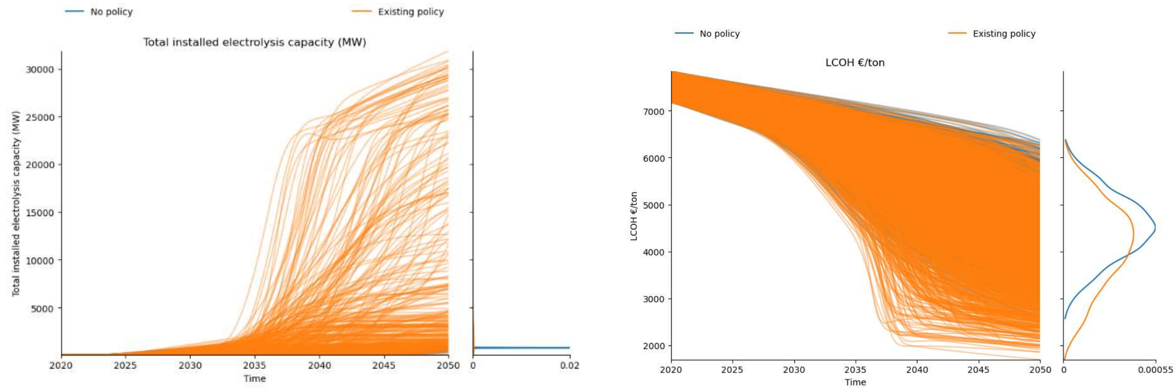

Figure 13: Impact of existing policies on the hydrogen market size and production costs

The development of the levelized costs of hydrogen shows a similar pattern to the installed capacity. It shows that it is possible to achieve a significant cost decrease, but in most cases the improvement over the base-case is limited. Subsidies are not able to reduce these costs, making it unlikely to result in a mature, independent green hydrogen industry after all funding has been awarded to projects. In the model the subsidies do not decrease costs, but they decrease the price of hydrogen.

With subsidies, producers can offer their products below their actual cost price as the difference is covered by subsidies. This makes the product more competitive, but doesn't change the production process. The production costs will only achieve if the artificial lower price results in a quick increase of production capacity. For a successful hydrogen industry, the subsidies should also reduce the production costs to a point where there are no subsidies required. As this is not the case, on average the hydrogen industry will still not reach a significant size.

The issue is here that the development of a hydrogen production plant takes many years. Projects can be initiated due to demand for lower priced hydrogen as a result of subsidies, they will only go in operation much later. There is a long period of time between granting funding and seeing effects of economies of scale. These effects often appear after the subsidy has all been awarded, returning to a market similar to how it was before the subsidies.

In the cases with larger installed capacities, the production costs will decrease as a result of economies of scale and the learning curve. If these prices become competitive with grey hydrogen, the rate of development of the green hydrogen industry will rapidly increase.

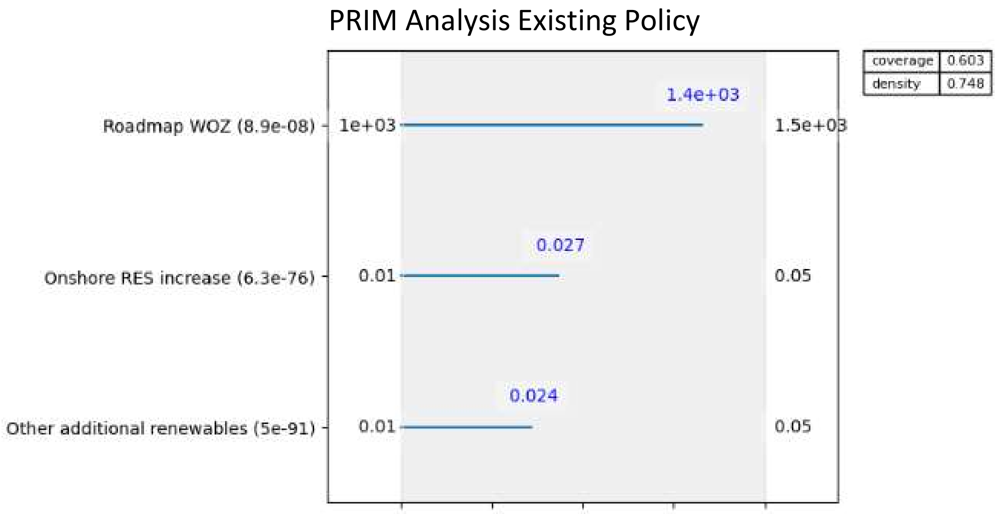

Figure 14: Barriers with existing policy for the 20% lowest outcomes of installed capacity

Another explanation for the model behaviour is that even with subsidies and low prices of green hydrogen, the industry is still limited by the amount of available electricity. If there is a period without available off shore wind electricity, there can still be no new production capacity commissioned. As there is no subsidy exclusively for green hydrogen, the subsidy funds will be slowly awarded to other technologies. In addition, the model has an effect where hydrogen projects get cancelled if there is too little progression. This is confirmed by the PRIM analysis. As visualized below all boundaries relate to the amount of renewable electricity.

If the Netherlands does not achieve to increase its renewable electricity generation quickly, the hydrogen industry is unable to scale up at the desired pace, resulting in reduced demand. This will cause the hydrogen economy underachieve relative to its potential. Additional policy should focus on securing sufficient renewable electricity.

5.1.3 Green Products and Dedicated Electricity policy analysis

The policies proposed in this research are likely to boost the green hydrogen economy and is able to achieve higher cost reductions compared to the first two model runs. Figure 15 shows that cost reductions will not only be higher, they are likely to occur earlier.

Where subsidies alone were not able to reduce the production costs, the combination with additional policy does make green hydrogen more cost competitive. As there is more potential for market growth due to the increased availability of electricity, economies of scale are more likely to occur in this case. Especially before 2040, which has been roughly the time where 90% of electricity production is renewable, there is a large difference in installed production capacity between the scenarios. In this period renewable electricity will always be scarce, but less so with the additional policy. This causes the industry to scale up quicker, resulting in economies of scale that will also occur earlier.

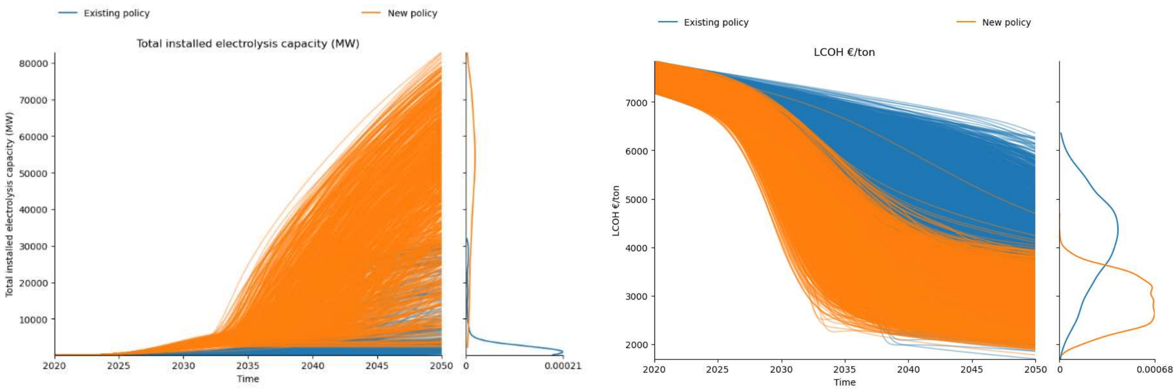

Figure 15: Comparison of the effect of the new policy on the production capacity and LCOH compared to existing policy, not including the base ensemble.

Even with additional policy, there is a trend visible that after 2030, in many cases the hydrogen production capacity does not increase anymore. Even with additional policy, in many cases green hydrogen will still be more expensive than hydrogen produced from natural gas, with the benchmark currently being around €2000 per ton of hydrogen (CE Delft, 2022). This is caused by a combination of factors. Firstly, electrolysis is an energy intensive process. The process is less efficient than natural gas reforming, while electricity is generally more expensive than natural gas. Even when technological development reduces the capital costs of electrolysers to a minimum, electricity costs will always be relatively high. In the model electricity prices reduce less than some hydrogen literature expect. This results in the LCOH graph that seems to have a bottom price of €3000. This price can only be reduced by cost reductions of electricity. Depending on the natural gas price, grey- and blue hydrogen can still be cheaper than green hydrogen in 2050.

A second reason hydrogen production does not always increase after 2030 is that more alternatives for green hydrogen exist than grey- or blue hydrogen. In the model all hydrogen types compete with fossil fuels, but also with electricity, biofuels and synthetic fuels. In some scenarios industries will use direct electrification or other fuels to decarbonize, or remain using fossil fuels, possibly with carbon capture technology.

The uncertainty and different trends that are visible show that additional policy does not necessarily reduce the uncertainty. The PRIM analysis shows the same barriers as in the base ensemble. This is not unexpected since the uncertainty space is consistent throughout the three different analysis. As the uncertainties in the model remain to be influential to the outcomes, the robustness of the proposed policy will be tested in the next section. The crucial uncertainties in the scenarios with additional policy shows that the roadmap for offshore wind development (WOZ), the demand substitution rate and the increasing efficiency of energy use are crucial uncertainties in undesirable outcomes. In general, low rate at which the hydrogen industry reacts to price changes and small amounts of available renewable electricity result in the lowest installed capacities at the end of the simulation. The value ranges will b implemented in the robustness analysis to find robust policies that are effective in these worst case scenarios

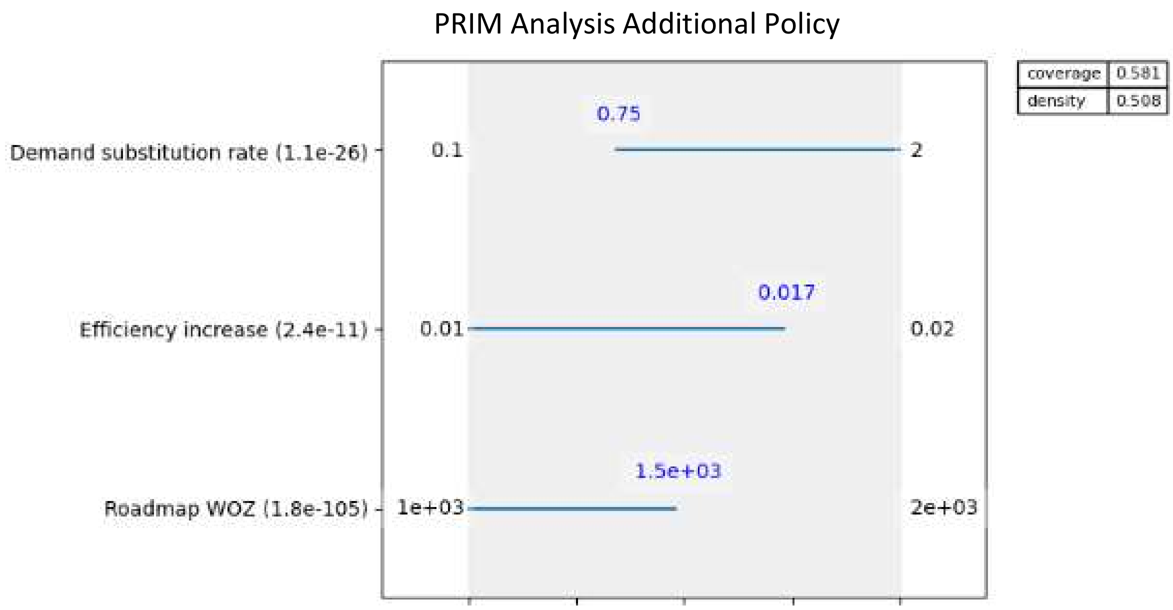

Figure 16:Barriers for worst case scenarios of the installed production capacity

While the additional policy enables green hydrogen producers to procure renewable electricity more easily, it cannot influence the development in electricity sector. That is why it can remain a barrier for the production. Even if policy states that all renewable electricity is available for green hydrogen production specifically, if there is no renewable electricity available this policy would have no effect. The same analogy results in the outcomes of Figure 16. As there were no policies designed specifically to address the economies of scale, the market adaptation speed and the relative elasticity are still crucial uncertainties.

5.2 Multi-Objective Robust Decision Making results

After the crucial uncertainties in worst case outcomes and the policy levers were implemented in the model, optimization of the model resulted in 64 policy options out of 30.000 model runs. Below the trade-offs are shown in a parallel axis plot. In this plot the factors at the top of the axes are the desirable optimal outcomes, the bottom values are the least favourable outcomes.

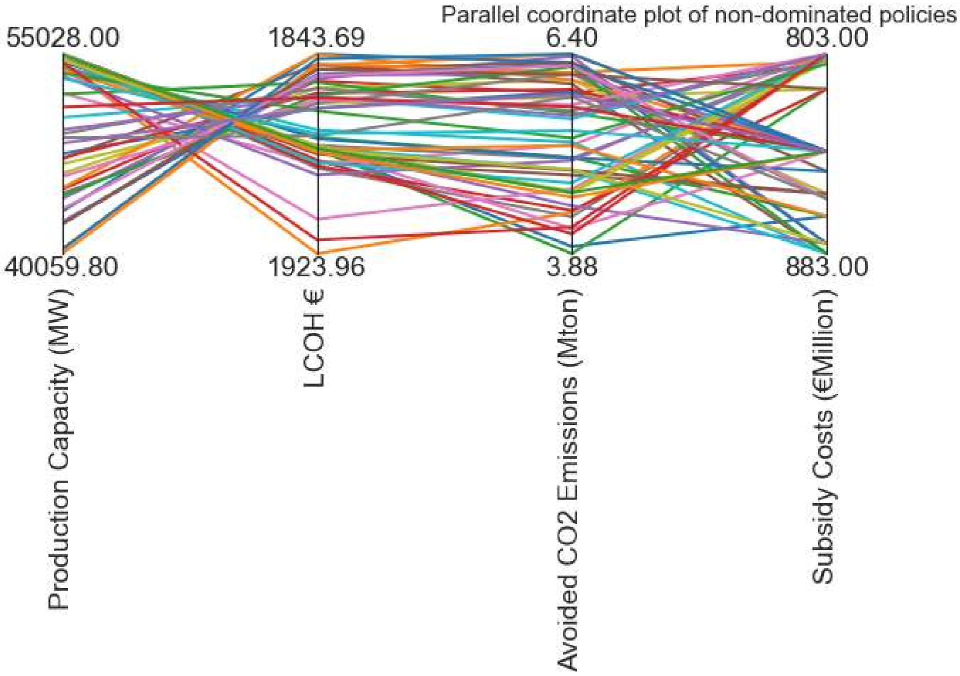

Figure 17: Candidate policies: The non-dominated outcomes

The first results of the analysis show that it is possible to have combinations of policies that are able to perform well in difficult scenarios. The policies in Figure 17 all have outcomes with at least 40 GW installed green hydrogen production capacity in 2050. However, the policies do not all have the same effect. The results shows clear trade-offs between the outcomes. The policies that show the best results for installed capacity do not always score well for production costs. This seems counterintuitive, but this relation can be explained by the fact that more hydrogen production equals more demand for electricity, and higher demand for electricity results in higher prices in the more competitive market. Between the production costs and the avoided CO_2 emissions there seems to be a positive correlation. The lower the costs of hydrogen, the more energy demand will switch from fossil fuels to green hydrogen, resulting in more avoided emissions. Between the CO_2 emissions and subsidy costs there is no clear correlation visible. The most interesting take away from the trade-off plot is that it seems like there is no strong correlation between the installed electrolysis capacity and the avoided CO_2 emissions. This can happen as avoided CO_2 emissions are a result of energy carriers being replaced by green hydrogen. However, this substitution is only partially caused by the development of the hydrogen economy. It is also a result of the price development of the other energy carriers, independent of the hydrogen price.

For further analysis only the most cost-competitive policies have been included in the analysis. This has resulted in a sub-set of 9 candidate solutions, shown in Table 7**.**

Table 7: Robust policies and the value of the policy levers

Policy	Initial ICPEI funds	SDE++ fund	Market value creation[refineries]	Share RES allocated to H2
0	68	101	1.246085	0.699431
2	17	200	1.307039	0.696956
7	4	726	1.175178	0.648587
13	17	200	1.147679	0.654226
14	79	761	1.110996	0.699810
26	42	550	1.195685	0.697731
33	3	17	1.396719	0.669480
51	42	454	1.101013	0.686924
52	42	440	1.088333	0.692338

A notable finding from the initial analysis of the policies is that most candidate solutions do not require significant subsidies. However, there are some outlier policies that include a significant SDE subsidy. Most of the candidate solutions include a significant SDE++ fund. This leads to the conclusion that the SDE++ subsidy has a larger impact on the outcomes than the IPCEI subsidy. The SDE++ can be more impactful than the IPCEI funding due to the way it is awarded to projects. Projects can get their entire funding gap covered by IPCEI, while SDE++ has a cap of €400 per ton avoided CO_2. This means that the IPCEI fund will be used up quicker, while with less different actors benefiting from it directly. SDE++ can support hydrogen projects for a longer period of time, even after the IPCEI fund is empty. In addition, the market value creation multiplier is only in policy 39 close to the maximum value of 1.5. Figure 18 shows the parallel coordinate plot for the 15% most cost effective policies.

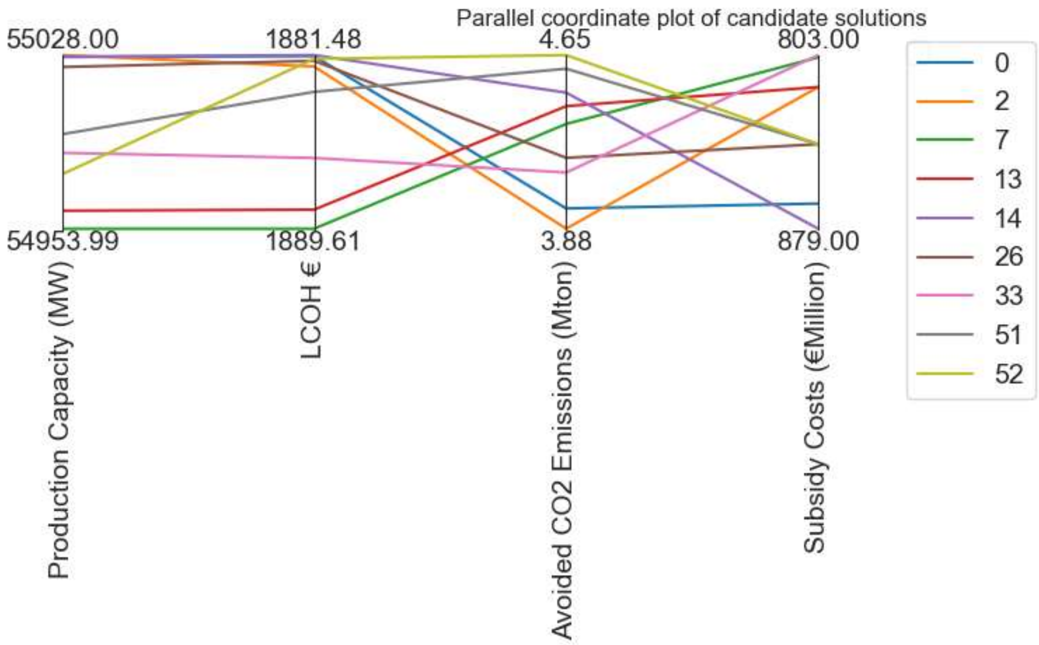

Figure 18: 15% most cost-effective policies

The plot shows that the 15% most cost-effective policies have some different trade-offs than the larger set of candidate policies in Figure 18. In the smaller subset there is no clear dominating policy option. The plot of the outcomes shows different types of behaviour and interesting correlations. Policy 52 has a relatively low score for installed capacity, but the most desirable outcomes for LCOH and avoided CO_2 emissions, while also being quite cost-competitive. In contrast, Policy 0 has high outcomes for the installed capacity and LCOH, but low for the other KPI's. The Installed Capacity and LCOH seem to be positively correlated, in this sub-set of policies, in contrast to Figure 17. This confirms the statements that low costs are an important driver for scale up of the economy. The LCOH and Avoided CO2 emissions prove to be positively correlated. Additional installed capacity does not necessarily avoids emissions in the way that the outcome is calculated. Green hydrogen that is supplied to an industry only avoids emissions if it replaces fossil fuels, not if it is used for additional production. Lower cost are the main driver for substitution of fuels, while the installed capacity is not a direct driver for substitution of energy demand.

5.2.1 Signal-to-noise ratio

With the nine candidate policies a signal to noise ration analysis has been conducted. Below the parallel coordinate plot again shows trade-offs between de policy options. A high score in the signal-to-noise plot is preferred for the installed electrolysis capacity and the avoided CO_2 emissions, lower values are preferred for the production and subsidy costs.

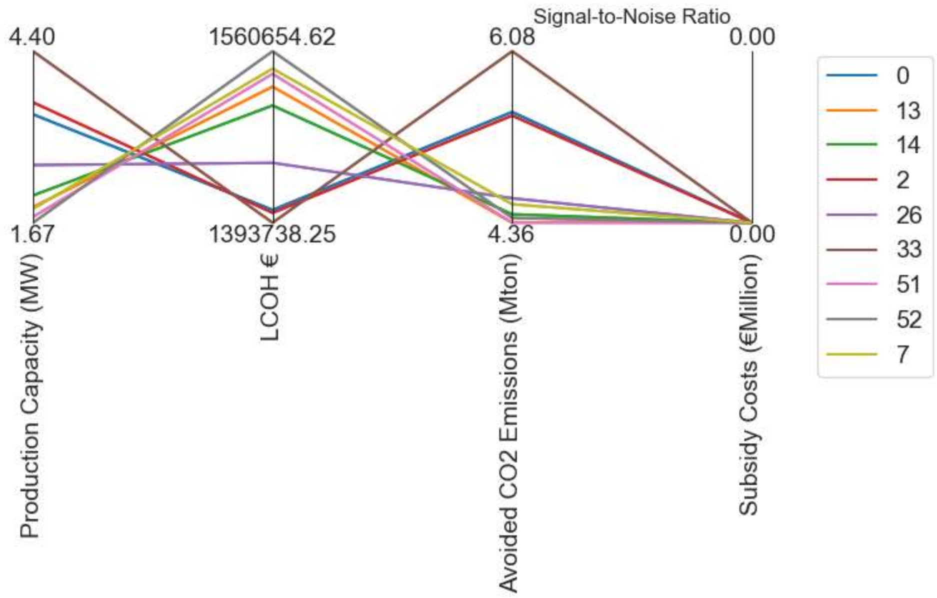

Figure 19: Signal-to-noise ratio robustness analysis

Overall the signal to noise ratio shows one notable robust candidate policy. Policy 2 shows the optimal signal-to-noise ratio in key performance indicators. All other policies show robustness in one or more outcomes, but lack robustness in others. Only for the subsidy costs the plot shows that most policies are robust, but this is not unexpected as these policies are only the most cost-effective ones. Most policies have low robustness scores for installed capacity and a high ratio for the production costs. This indicates that these are still the most uncertain outcomes, even when implementing additional policy. The outcomes of the exploratory modelling analysis already indicated this, as it was concluded that additional policy can be expected to be impactful, while the ensemble of outcomes covered a wide range of possible values in the end-state of the model.

5.2.2 Regret analysis

For a different view on robustness the min-max regret analysis has been conducted. In this analysis lower values are preferred for all outcomes. Similar to the signal-to-noise ratio, policy 39 shows the most robust policy for the installed capacity, while also being quite robust for production costs. However, where in the previous robustness metric policy 2 was the most robust policy overall, it average for regret on all KPI's in the regret analysis.

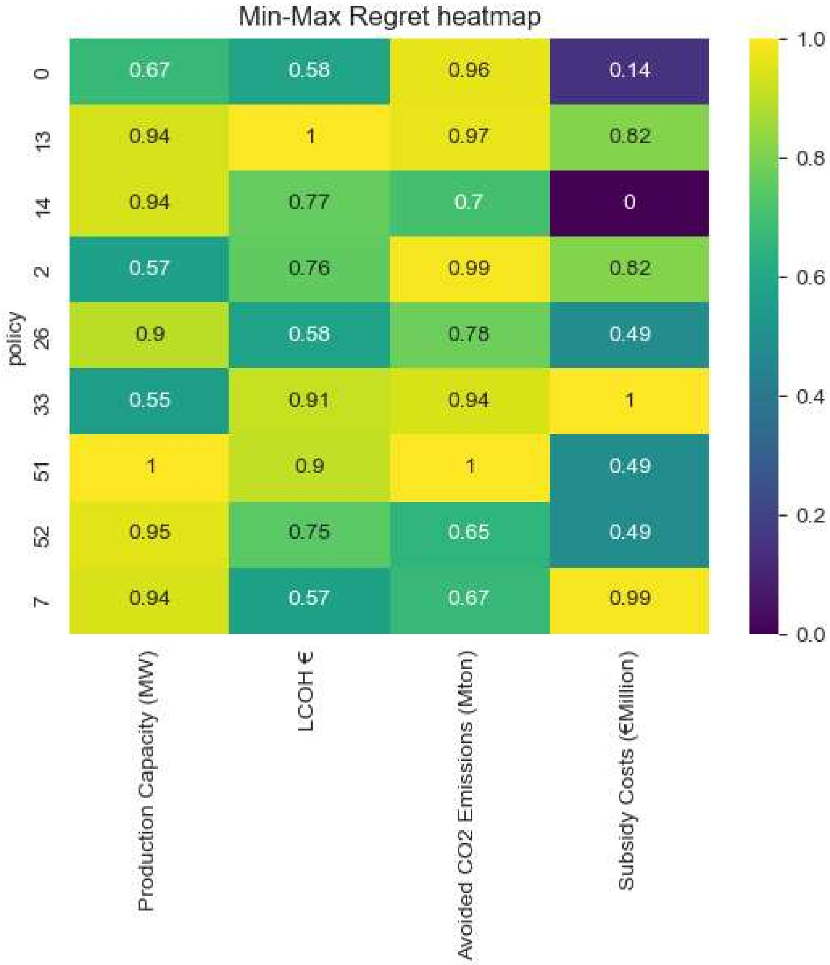

Figure 20: min-max regret heatmap with regret values of the policies for each of the outcomes

The regret values heatmap, shows a lack of a dominant policy. Even as the most robust policy for installed capacity, policy 33 still has a significant regret value. The heatmap shows no clear optimal solutions, rather a couple of viable policies. The desirability of policies will depend on the valuation by policy makers of the key performance indicators. If policy makers' primary concern is cost effectiveness, there are viable options with zero regret. For all other outcomes there are no policies that are dominant, they cannot be implemented without any regret.

The robustness trade-offs represent the complexities within the hydrogen system. No policy has a direct effect on a specific outcome, rather it impacts the entire system. In different parts of the system the effects of policies can be different. The analysis has not found any policies that are entirely robust. Both metrics show different outcomes, and both have no dominant policy. This does not mean that it is impossible to design robust policy. All analysed policies have positive outcomes in relation to the key performance indicators. It is important to realise that there are trade-offs between the different outcomes. Some combination of the policy levers result in outcomes that are dominant at one of the outcomes, while they can be dominated at others. Another dilemma posed by the robustness metrics is that they both have to be interpreted differently. The signal-to-noise ratio is an independent value, not related to the alternatives. The regret values are based on a comparison to other policies. Different policy makers will have different preference for an approach for designing policy. The difference is inherent to this analysis, and the outcomes could have been different if even more robustness metrics had been applied to the model.

6 Discussion

The results show that there are many possible development pathways the green hydrogen industry could follow. Without any policy, the green hydrogen economy is not likely to become larger than the size of the projects that are already in development. In the literature analysis the main driver of cost decrease of green hydrogen was identified as being the scale up of the industry. Lower costs would be the main factor of success for large scale implementation of green hydrogen production capacity. In the base ensemble the scale up will be to slow to generate significant cost reduction. This will lead for hydrogen demand to be substituted for other (renewable) energy carriers. In hard to abate sectors potential off-takers of green hydrogen can look to blue hydrogen as an affordable, low carbon alternative.

The outcomes dispute a core notion by policy makers that there is an ever growing demand for green hydrogen, for which the only issue is that of realising production capacity (NWP, 2022). The speed at which the market adapts to reducing costs of green hydrogen was a crucial barrier in undesirable outcomes of the model. When the production costs decrease, this will not instantaneously increase the demand for green hydrogen. This relation can be explained by the fact that possible hydrogen consumers need to take more into account than just the production costs of green hydrogen when considering using it in their industrial sectors. Even when green hydrogen is the cheapest type of transport fuel, consumers still need to buy a car that can drive on green hydrogen. The same is true for large industrial sectors that currently consume fossil fuels. Using alternative fuels or feedstocks in industrial processes can require large investments that possibly scare off investors. For a successful hydrogen economy it is more important to focus on the existing hydrogen industry than to attract new demand from other markets. Manne and Marchetti (1974) already proposed this approach almost 50 years ago. Existing hydrogen consumers will have less difficulty incorporating green hydrogen into their process than new potential hydrogen consumers like the steel industry or even the transport sector. This will enable a quicker scale up of the industry and subsequent cost reduction.

The analysis of the impact of SDE++ and IPCEI funding has shown these policies to have an effect on the possible development of the green hydrogen economy. However, in many cases the size of the industry does not outgrow the existing grey hydrogen industry. This is due to the fundamental issue with short term financial policy related to green hydrogen production as raised by Anderson et al. (2023). This type of financial incentive can reduce cost for a short amount of time, but is ineffective at realising structural change. They note that the currently deployed policy in the Netherlands strongly favours mature an cost-effective emissions reduction methods over green hydrogen production. This effect is visible in the outcomes of the exploratory modelling analysis as the end state results cover wide range, making it impossible to say that the SDE++ and IPCEI subsidies are effective policies. While the conclusion by van Renssen (2020) that policy required for a successful emergence of a hydrogen economy is not false, the nature of specific policies can lead to different results and end-states of the hydrogen economy. The SDE++ and IPCEI subsidies can in some cases be effective to kickstart the development of the industry. However, if the levelized cost of green hydrogen is not yet competitive when the subsidies are all awarded, there is no additional value for green hydrogen to outgrow the initial increase of the market. This is consistent with the findings in literature that stated that markets are at risk of becoming too much dependent on the subsidies. After subsidies expire, markets can be distorted (Rövekamp et al., 2021), leading to a rapid dissolving of the demand for the product.

The existing policy can stimulate growth of the green hydrogen economy. However, the green hydrogen economy is still in an early stage of development, with prices that are not close to being competitive. That makes it difficult for industries to quickly adopt the new energy carrier. Green hydrogen is not only not competitive with fossil fuels, it is even far more expensive than direct electrification, blue hydrogen or alternative sustainable technologies. As the demand green hydrogen is not an intrinsic demand for the new energy carrier, a result of regulations to meet and global climate targets (Dickel, 2020), there is in effect no demand for the product, only for the effect of the problem, which is lower carbon emissions. When looking at the costs of CO_2 avoidance with hydrogen, it will be an even more expensive product than for example direct electrification (Hirvonen et al., 2019). The limited subsidy funds are most likely not enough to quickly achieve the green hydrogen goals. Most industries will be looking to the most cost effective way to reduce carbon emissions, for which hydrogen is only one of the options. High polluting industries can even transition from coal to natural gas to reduce emissions short term, and wait out the development of green hydrogen.

If green hydrogen does not become cheaper and more widespread quickly, there will most likely be no hydrogen economy at all. This has happened before, in the first green hydrogen bubble. In the early 2000's, green hydrogen was seen as the most promising new method for decarbonisation. However, after a few years the interest in green hydrogen disappeared for the most part (Yap & McLellan, 2023). The possibility that this occurs again has been observed often in the results of the exploratory modelling analysis. It is crucial that the rate of development of the industry increases, and that there will be sufficient demand for the hydrogen as a product, not just for the CO_2 avoidance. If hydrogen can achieve the desired rate of development, results have shown that the industry can grow to a significant size. As Dou et al. (2023) described, if the rate of innovation of green hydrogen technology improves, hydrogen could be popularized beyond the industry and achieve similar significance to society as renewable electricity has.

The first analysis of this research has shown that there are crucial preconditions for green hydrogen to become more widespread. Contrary to what some literature believes (Tlili et al., 2019), there are barriers besides the high price of green hydrogen that can have an equally big impact on the success of the green hydrogen economy. In some scenarios the hydrogen price is reduced significantly, but the size of the industry is disappointing. The limiting factor there is the availability of renewable electricity. Due to European regulation, green hydrogen producers can only use additional sources of electricity, as long as the country where the production facility is located retrieves less than 90% of its electricity production from renewable sources. The Netherlands is still far away from that 90% renewable electricity goal, so in this crucial phase for the green hydrogen industry, it cannot grow faster than the renewable electricity supply. Even without the 90% renewable electricity constraint, it has been concluded by Lagioia et al. (2023) that there can only be a sizable hydrogen economy if a country manages to decarbonize its entire electricity production. An additional constraint is that only off-shore windfarms produce sufficient electricity for large scale hydrogen production. In all scenarios the green hydrogen industries still need to compete with other electricity consumers, and there is competition between hydrogen producers. This causes the electricity price to increase and as a result, green hydrogen could only become more expensive, while also being scarce. This contradicts the claims in literature that green hydrogen is almost certain to become a lot cheaper.

The proposed policy seems to have a positive effect on the potential for the green hydrogen industry to grow. Even when accounting for uncertainty in unfavourable scenarios there are robust policy options. An important note is that robust policies also include the existing SDE++ and IPCEI subsidies. These have a positive effect on the size of the hydrogen industry when combined with additional policy. Larger amounts of subsidy can have an even greater effect. However, the climate agreement states that climate policy has to be cost-effective . The cost effectiveness is not quantified, but needs to be taken into consideration. The objective of analysing additional policy was never to discredit the effect of subsidies as a stimulating measure. However, this research supports literature stating that subsidies alone are insufficient to secure the promising future for green hydrogen that is desired by policy makers. The amount of subsidies made available for the green hydrogen industry seems to have a positive effect on the size of the industry. Policy makers should decide what the optimal level of cost effectiveness is and what the desired size of the hydrogen industry would be.

This research confirms that targeting (petro)chemical industries where hydrogen is currently indispensable with specific policy is effective in creating a green hydrogen industry (Oliveira et al., 2021). In addition, overcoming the often discussed renewable electricity constraint (Bianco & Blanco, 2020; CE Delft, 2022; Lagioia et al., 2023), has proven to be a crucial part of robust policy for the green hydrogen economy. In all robust policies the policy lever for renewable electricity allocated to green hydrogen production approached the maximum value within the policy range. In combination with the existing policy, value creation in the petrochemical industry and combined tenders for off-shore wind positively impact the development of the hydrogen industry. The multi-objective robust decision making method has shown that it is possible to design robust policies. Even under the least favourable circumstances, the model showed positive outcomes. The objective of this research was to analyse policy to positively impact the development of the hydrogen economy, as a method to address the Dutch energy challenges. These objectives are summarized into four key performance indicators. The robust policy options do not all impact the different performance indicators similarly. There are clear trade-offs between the outcomes resulting from the robust policies. It is up to policy makers what the main goal of supporting the hydrogen economy is. Policies that result in the largest installed production capacity, do not always result in the same CO_2 reduction. Rapid substitution of fossil fuels with green hydrogen can lead to shock effects on the European Emission trading markets (International Energy Agency, 2022). Rapidly reduced demand will result in lower emission pricing. This, in turn, invites more use of cheap fossil fuels as their total costs will also decline. This relation makes it so marginal increase of hydrogen production capacity does not reduce CO_2 emissions in any case. In addition, it affirms the existing threat proposed by Lagioia et al. (2023) that green hydrogen production can only be a truly effective method for decarbonisation if all electricity production is renewable.

Throughout this research the four key performance indicators were all valued the same. The objective of having the largest possible green hydrogen economy was deemed just as important as the avoided CO_2 emissions, the production costs and the subsidies spent. For policy makers this could be different. The trade-offs between the policy options as discussed in the result section can be different depending on the importance policy makers see in the outcomes. If policy makers are interested in creating a hydrogen industry at any costs necessary, the trade-offs will be interpreted differently. This research does not intent to value one outcome above the other, but merely to provide insight into the effects policies can have on the hydrogen economy. Communicating with the avoided CO_2 costs instead of the installed hydrogen production capacity can make it easier for policy makers from different ministries and politicians of different parties to align interest. But focussing policy on that specific indicator will require compromise on other outcomes.

Even when the production costs of green hydrogen are becoming competitive, hydrogen consumers will not immediately switch from grey or blue to green hydrogen. New supply contracts need to be signed with new suppliers. Production processes need to be adjusted to green hydrogen (different purity and pressure than grey hydrogen). The challenge of adapting existing industrial processes is not to be underestimated. Quick adoption of green hydrogen is most likely to be successful in industrial sectors that are already familiar with the use or production of hydrogen. Regardless of the cost reduction that will be achieved in the near future, decarbonizing the refining industry seems to be the path of least resistance. It is one of the largest hydrogen consuming industries, for which the price of hydrogen is a small part of the final product price. However, the end goal is not to decarbonize refineries, as by 2050 the need for fossil fuels should be negligible. When value is created for green hydrogen in the refinery sector, it should be prevented that refineries get an extension of their life expectancy. If that would happen it could prevent the achievement of other goals related to decarbonisation. Refineries have to potential to kickstart large scale hydrogen production, all while other industries prepare for a transition to clean production.

If all green hydrogen is only produced for refineries, there is a small chance of realizing a successful green hydrogen in 2050. This is because different policies, the Renewable Energy Directive for example, foresee no mor use of fossil fuels in transport in 2050 (Hirvonen et al., 2019). The demand for green hydrogen from this industrial sector will therefore also disappear mostly. It is crucial to see this sector as an early enabler of scale up and cost decrease through economies of scale. From 2035 onwards, when internal combustion engines will be banned in the European Union, green hydrogen must also be competitive in other industries, that do have a role to play in a sustainable economy. These industries can be the fertilizer industry, or the steel industry. Additional policy could be focussed on building on the momentum generated by the refinery industry, to continue growth of the green hydrogen economy. There should be a point in time where demand for the energy carrier is not based on decarbonisation obligations (Scita et al., 2020). Instead, green hydrogen should become the most economic and cost efficient energy carrier. This is the only way to secure the longevity of the industry while not losing support for the policies and decarbonization efforts in general.

6.1 Limitations of the research

Inherent to this research is that it is limited by the fact that a model is always a simplification of reality. Especially in system dynamics, aggregation leaves out details about low level interactions and decision making that other modelling methods, like Agent Based modelling, can capture in their models. This does not mean that there is a certain right or wrong approach, but it makes it impossible to claim that the model is able to reproduce specific historical processes and that it is the exact representation of reality (Akkermans & Van Oorschot, 2018). Moreover, there is no real historic precedent or development to verify the model behaviour with. Due to the novelty of the subject, there is little experience and concrete evidence for how the hydrogen economy will develop. Most knowledge of the subject is derived from the literature on other renewable energy technologies. This is the most fair comparison, but it has already proven to be a limited approach. For example, the development of solar energy systems started around the same time as the first discussions about a green hydrogen industry, around the beginning of the century. Where solar technology has seen a massive increase in market size, the hype around green hydrogen disappeared, to return many years later without having experienced any development (Yap & McLellan, 2023). For this research literature and modelling paradigms that are strongly related to the green hydrogen sector were used to build the model. However, this holds no guarantee that this has resulted in the most accurate representation of the system.

It has been discussed by Palmer et al. (2020) that hydrogen industry is strongly linked to the development of the entire energy sector. Policies aimed to increase green hydrogen production, interact with other energy carriers as well, and vice versa. This research has focused on the green hydrogen and a certain level of interaction between the different energy carriers. The modelling of the development of demand for alternatives for green hydrogen is limited in this regard, as the way it is modelled is mostly aggregated, due to the scope of this research. In the model energy prices can change a few percent a year, while in reality, prices have doubled or halved in shorter amounts of time. Energy carriers have fragile price curves and can be subject to unpredictable price surge which can distort entire economies (Schnuelle et al., 2022). More realistic price development of energy carriers could have a significant impact on the presented results. However, to do justice to energy markets in this model, a completely separate research is required due to the intricacies of the energy markets.

A specific part of the related energy system that has not been modelled with the required level of detail is the development of renewable electricity production in the Netherlands. While this has been identified as a key factor for determining the success of the green hydrogen industry (CE Delft, 2022), the related sub-model could be far more elaborate. The way that it is modelled now makes it impossible to model the effect of electrolysers acting as a method of intermittent storage, something that has been described as a key application of green hydrogen. For the early stages of development this is unlikely to be a widespread application, since there is not yet real demand for electricity storage. When renewable electricity production will account for larger shares of the total production, energy storage with green hydrogen could become indispensable. It has at been acknowledged that due to the large scale integration of hydrogen into the energy system, the systems' structure could fundamentally change (Weeda & Segers, 2020). The system dynamics model does not account for future structure changes.

In this research a system dynamics model of the Dutch hydrogen economy has been presented. The model was deliberately scoped for the Netherlands, but van Renssen (2020) argues that the hydrogen economy as an international project. The sheer scale of the foreseen hydrogen demand indicates that Europe is likely to import large amounts of green hydrogen from countries in North Africa and the Middle East. The Netherlands is especially well suited with the Port of Rotterdam to facilitate large scale import of hydrogen (Taibi et al., 2020). The model used for this research lacks this factor of import and export of green hydrogen. In the model demand fulfilled by domestic production capacity. This is not necessarily realistic. While there is no guarantee that in the coming years there will be a large scale global trade of green hydrogen, there are efforts made to realize something similar. However, large scale imports of hydrogen do not necessarily mean that there will be less domestic green hydrogen production (van Wijk et al., 2019).

Besides limitations to the system dynamics approach, the scenario discovery section has some limitations. The Patient Rule Induction Method is an algorithm for identifying crucial uncertainties. This algorithm as used in the EMA workbench is optimized for linear problems (Shokri et al., 2018). Due to the feedback interactions embedded in the system dynamics model the behaviour is non-linear. This results in a suboptimal analysis with PRIM, as it is less capable of explaining the variance of the outcomes by analysing the uncertainty space.

7 Conclusion & recommendations

To address the climate challenges the Netherlands faces, the country is looking to create a green hydrogen industry. Despite recent efforts, there is still almost no installed production capacity. This research has tried to identify the crucial barriers and test policy that has already been implemented, and propose new policy options that can enhance the development of the green hydrogen industry. The success of the policy is measured in the resulting installed production capacity, production cost of hydrogen, the avoided CO_2 emissions and the costs of the policies. The research has been conducted based on the following research question:

How can the Dutch hydrogen economy develop, and how can policy impact the deployment of green hydrogen production capacity?

By performing exploratory modelling techniques and a multi-objective robust decision making analysis in combination with a system dynamics model, it can be concluded that the possible development pathway of the Dutch hydrogen industry is extremely uncertain. Without any policy the hydrogen industry is not likely to achieve a significant scale. In the model analysis of the scenarios without policy the rate at which costs decrease is insufficient to create significant demand for green hydrogen. Without any demand there will not be any economies of scale and the size of the industry does not increase after the current projects have been commissioned. Industries will address their decarbonisation obligations with other renewable energy carriers like biofuels electricity or even with carbon capture and storage. Insufficient electricity from offshore renewable sources and a high rate of substitution of demand towards other energy carriers are barriers for the scale up of the green hydrogen industry.

Existing policy can make an impact on the goals, but the current approach lacks in long term value creation and does not address the issue of scarce renewable electricity. The IPCEI and SDE++ subsidies can kickstart the hydrogen economy by reducing the funding gap, but do not guarantee a significant cost reduction, while this is a requirement for a successful hydrogen economy. The rate at which the costs reduce is identified as a crucial uncertainty, as well as the speed at which industrial sectors can substitute other energy carriers for green hydrogen. If the market lags in the adoption of green hydrogen, and the cost reduce slowly, the hydrogen economy will not achieve goals as stated in the climate agreement. With the existing policy in place, crucial barriers consist of risk with the development of renewable electricity, as the hydrogen industry cannot grow faster than the renewable electricity sector. Even with large amount of renewable electricity the hydrogen industry has to compete with other sector for the renewable electricity.

Two policies to complement the existing SDE++ and IPCEI subsidies, Green Products- and Dedicated Electricity Policy have been proposed in this research. The first one is to create value in the refinery sector through renewable fuel certificates. In addition, part of the tenders for offshore wind parks should be combined with electrolysis projects. The first policy is aimed at continuing the momentum for scale up that is created by the subsidies. The second policy reduces the renewable electricity barriers in the first stage of the development of the hydrogen economy. Combined the policies can support the creation of a hydrogen industry in the worst possible scenarios. However, there is no single dominating policy that outperforms the other policies on all outcome metrics. The policies that have been analysed showed that the size of the hydrogen economy is not correlated with the avoided CO_2 emissions. In addition, policy makers have to balance the trade-off between size of the hydrogen industry and the costs of the policy.

Based on the robustness analysis it is recommended to implement policies that create value for hydrogen rather than the existing value of avoided CO_2 emissions and to allocate a certain share of renewable offshore electricity to green hydrogen production. As part of these policies it is recommended to further investigate the relationship between the development of renewable electricity generation and the potential for the hydrogen economy. In addition, the potential impact on other industrial sectors of allocating a specific amount of offshore wind electricity to the hydrogen industry could be topic for further research. This policy measure can be beneficial for the hydrogen economy, but it can reduce the potential for decarbonisation through direct electrification.

Further research is advised to extend the model to include a more detailed energy sub-model and to add import and export to the model. Both the development of energy prices and the availability of imported hydrogen can greatly influence the demand for green hydrogen and the need for domestic production capacity. In Addition, the model is sensitive for extreme values for demand substitution, which also has been a crucial barrier in the exploratory modelling. it is recommended to further investigate the relationships that exists between changes in price of green hydrogen and the demand for the product.

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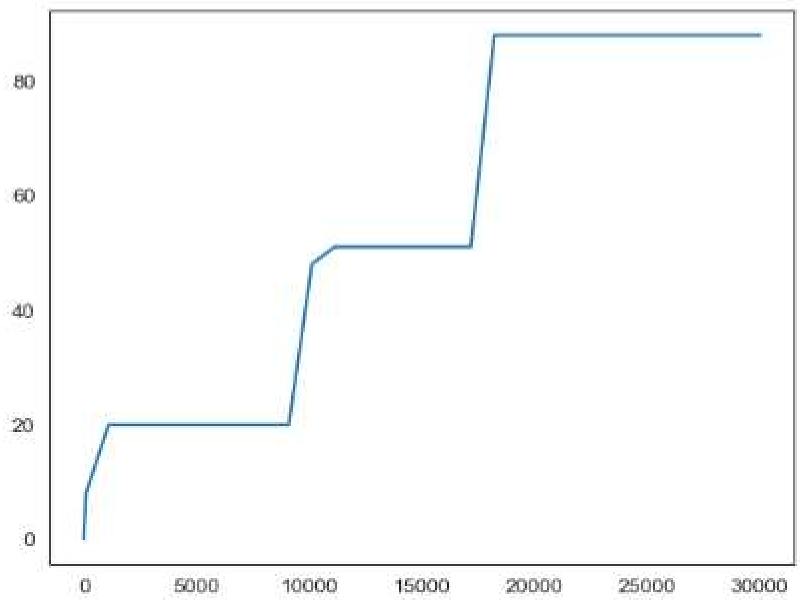
Appendix

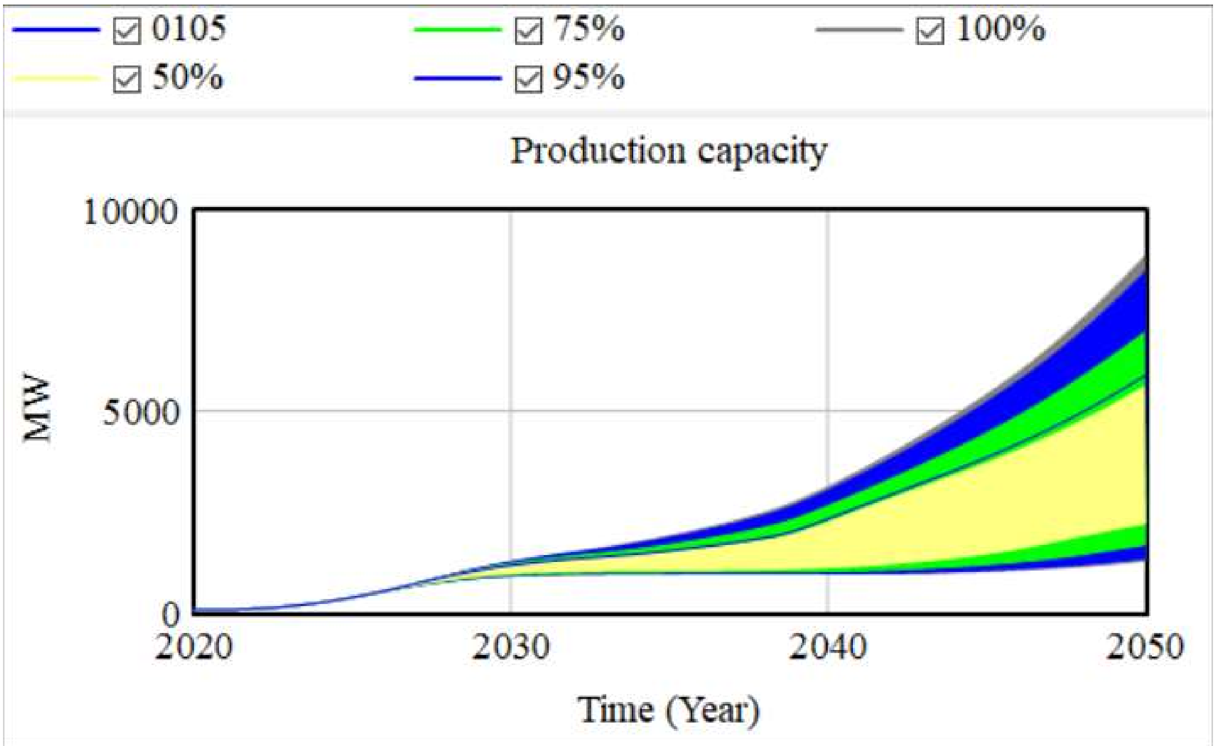
ε-Convergence

The ε-Convergence plot tracks the amount of new non-dominated policy options that the Multi-Objective Evolutonary Algorithm has found. After 20.000 model runs the algorithm has not found any new candidate policies. Therefore, 30.000 model runs has been sufficient for further analysis.



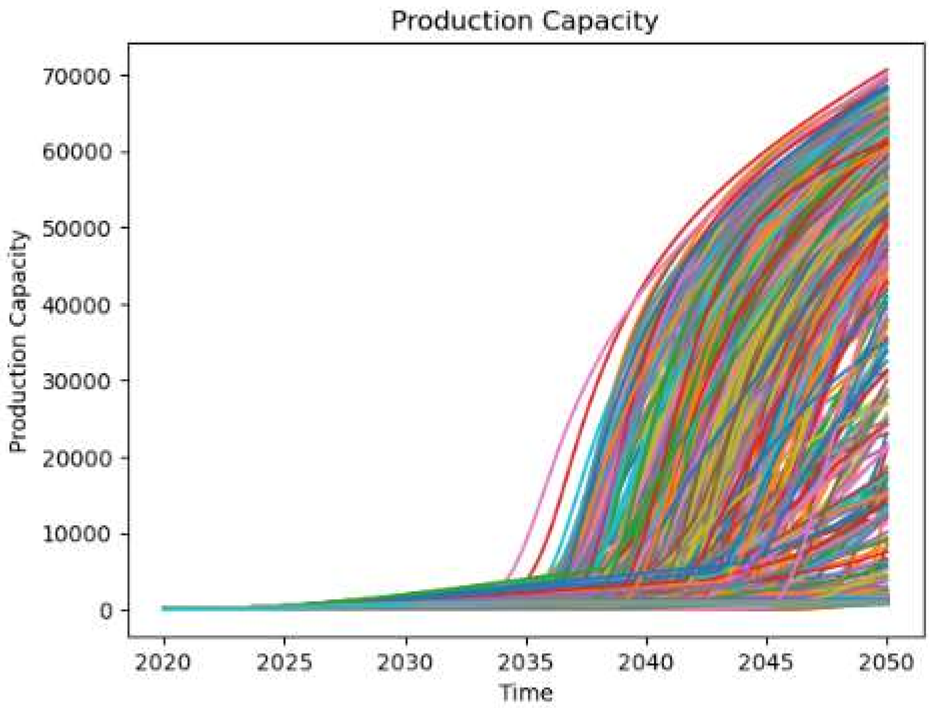
Extreme conditions test

The behaviour of the model can be validated by sampling around the entry values of the initial model (+/-10%). The validation has been performed with the EMA workbench which generated the following output: For this validation method the input parameter *Initial Electricity Price* has been varied between €1 and €200 per Megawatthour. This has not resulted in any structural issues. the behaviour of the model is as can be expected, with the electricity price influencing the production capacity of hydrogen. Extremely high or low electricity prices do not result in unrealistic values.



Model behaviour validation

To validate the behaviour the model behaviour is compared to existing literature on the topic. **Fout! Verwijzingsbron niet gevonden.** shows the possible behaviour of the system under a wide range of values. The final installed production capacity in all scenarios ranges from almost zero to around 80.000 Megawatt in the most extreme cases. Based on the highest values of the production capacity it can be concluded that the model does not produce results that cannot be defended with literature. While 80.000 Megawatt is not realistic, it is also not physically impossible. The high outcomes of the production capacity are consistent with the optimistic scenarios for the realisation of additional offshore renewable electricity production capacity in the Netherlands (NWP, 2022).



The figure below shows the theoretical maximum demand for green hydrogen in the Dutch energy end-use markets. The table has been retrieved from Berenschot (2020), and is based on the potential energetic and non-energetic uses of green hydrogen. The table has been used to validate the model behaviour.

Finale waterstofvraag (PJ)	2015[1]	KA[2] 2030	KNES 2050
Huishoudens	0	0	0 – 41
Gebouwen	0	0	0 – 13
Mobiliteit	0	11	12 – 104
Industrie (Non-energetisch)	0	3	14 - 134
Industrie (Energetisch)	0	0	95 - 253
Scheepvaart (bunkers)	NA	NA	398 - 740
Luchtvaart	NA	NA	125 - 315
Elektriciteitsproductie (Back-up)	NA	NA	0 – 129
Totaal	**0**	**14**	**770 – 1650 PJ**

The highest values of the installed production capacity translate to a energetic production of around 1300 PJ, which is within the possible scenarios.