Analyzing the effect of state-owned enterprises on the emergence of a sustainable hydrogen economy under deep uncertainty

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Abstract

The concept of a hydrogen economy has gain renewed attention as a way to enable a cost-effective transition to a low-carbon society. The adoption of hydrogen as an energy carrier beyond its current non-energetic use is however faced with deep uncertainty, making decision-making on policy support difficult. The state-owned enterprise (SOE) is evaluated as a particular type of policy support that may be implemented. SOEs are generally uniquely positioned in the energy system, due to their connection to policy-makers, their access to capital and their ownership of existing assets. An agent-based model (ABM) is created to evaluate the effects of SOEs on the emergence of a sustainable hydrogen economy. The model is experimented with using an exploratory modelling and analysis (EMA) approach. The results show that the SOE can strongly reduce the carbon intensity of hydrogen production, depending on the specific mandate used. A national carbon tax can achieve this effect as well, but the SOE has the added benefit of providing capital to asset investments, stimulating knowledge sharing and enabling investment in riskier technologies. This last benefit is especially important if the SOE is used to enable early deployment of electrolyser technologies. Further measures would have to be taken to facilitate this deployment, because in the coming decades electrolysers will remain far from cost-competitive under most market conditions.

Keywords: Agent-based model, Exploratory modelling, Hydrogen economy, State-owned enterprise, Energy policy simulation

1. Introduction

In order to mitigate the effects of greenhouse gas emissions on the global climate, a transition to a low-carbon society needs to be made within the coming decades [1]. For the electricity sector, low carbon technologies are becoming increasingly cost-competitive with their fossil fuel counterparts. It is however unlikely that direct electrification can be used to substantially reduce the carbon intensity across all sectors, meaning that some form of molecules is necessary to enable the transition [2]. The concept of a hydrogen economy has therefore gained renewed attention as a cost-effective way to realize deep decarbonization [3]. Hydrogen molecules, produced from renewable energy sources, would in such an economy provide a substantial fraction of a countries' energy and services [4].

The emergence of such a hydrogen economy is faced with deep uncertainty. Until now hydrogen has only played a very marginal part in the energy system, which means that for a hydrogen economy many system design choices still have to be made. It is therefore uncertain which exact system configuration will emerge and to which extent hydrogen will become a part of the future energy system [5]. Many optimization models have been made and scenario analyses have been done in an attempt to address this uncertainty about the role of hydrogen [6, 7]. Though these studies show possible future worlds, it is not clear which is more probable, which is an indication that deep uncertainty is present [8].

That such a wide variety of system configurations is possible, is because hydrogen as an energy carrier would be strongly interconnected with the existing natural gas and electricity system, in many potential pathways [9]. A number of factors then affect how these potential pathways might develop. Of key importance is the price of hydrogen, which is strongly influenced by the commodity prices of natural gas and electricity, the main energy sources used to produce the hydrogen [10]. Another important factor is the stringency of climate policies, both on a national and international level [6, 11]. Sustainable hydrogen production technologies such as electrolysers require further development to improve their competitiveness [12, 13]. Then there is also a complex feedback loop from the development of hydrogen infrastructure and the emergence of a hydrogen economy [14, 15, 13]. Finally, all of these factors are strongly dependent on local conditions, which is why discussion about overall applicable policy support is difficult [9, 16]. These factors all contribute to the deep uncertainty concerning the emergence of a hydrogen economy, which makes it difficult for policy-makers to decide on policy support.

In this article the state-owned enterprise (SOE) is evaluated as one of the policies available to policy-makers to stimulate the emergence of a hydrogen economy. SOEs are enterprises in which has full, majority, or significant minority ownership [17]. They have an important role to play in the transition to a low-carbon society, given that they own over half of all fossil fuel production assets [18]. In terms of greenhouse gases, SOEs in the energy sector together emit more than 6.2 Gton in CO_{2-eq} per year [19]. Additionally, they are in direct contact with policy-makers which enables them to influence policy-making and use public resources.

The presence of an SOE in the energy system offers the state a vehicle through which it can pursue development strategies that are in the public interest [18]. In addition to these non-economic objectives an SOE also strives for profit maximization, similar to private companies. The difference between a private company and an SOE is then that the former has to operate within the boundaries of the law, while the operational freedom of the latter also has to be captured in law. Globally a wide range of legal forms for SOEs are possible, and numerous motivations exist for establishing an SOE. This might be one of the reasons why there is limited general research on the effects that SOEs can have on the transition to a low-carbon society, despite their unique position in the energy system.

As a specific type of policy measure the theoretical motivation for using an SOE can be at least be determined using the concept of state intervention. The neoclassical economic perspective legitimizes state intervention when there is a market failure [20]. Though it is concurred that the ideal market is a theoretical concept, unlikely to be reached in reality, the concept implies the existence of a market in the first place. In some cases transformation of the system is needed and new markets have to be created. If the creation of these markets is uncertain associated risk might be high enough to hamper investment from private companies, in which case state intervention can also be legitimized [21, 22]. Whether an SOE is the most suitable type of state intervention then depends on how well it fits with the system failure it seeks to correct.

Agent-based modelling (ABM) is particularly well-suited to capture problems that arise in complex adaptive systems, which the energy system is [23]. Additionally, with ABM the overall system structure does not have to be determined in advance, but emerges from interactions between agents [24]. This is specifically useful for the hydrogen economy, since there is no system structure yet. The agent-based models that have been made for the hydrogen economy show the development of hydrogen demand, specifically in the transport sector [7, 25]. Their focus is therefore not on the development of the production, which is of key importance as well.

This article presents an agent-based model that focuses on the development of hydrogen production from 2020 to 2050 in the Netherlands. Levers are defined that an SOE can use to influence the emergence of the hydrogen economy, specifically concerning the sustainability of production. The ABM is presented in section 2. Given the deep uncertainty, exploratory modelling and analysis (EMA) is used for experimentation of the model. The results of this experimentation are presented in section 3. The results are discussed in section 4 and the conclusions are drawn in section 5.

2. Agent-based model

Three important modelling choices are made, these are about the representation of hydrogen demand and the spatial and temporal representation in the model. For the demand, four sectors are identified with the main applications of hydrogen in those sectors [26, 27, 9]. In the built environment hydrogen can be used for low-temperature heat. In the energy sector hydrogen is used for dispatchable electricity generation. In the transport sector it is used for shipping and aviation and road transport. Finally in the industry sector it can be applied to generate high-temperature heat. It is clear that the dynamics that affect hydrogen demand in these sectors are highly heterogeneous. Therefore demand development is considered external to the model.

A number of studies focus on geographically explicit models of the hydrogen economy [7]. This is not the focus of this model, which is why the geographical representation is simplified. The demand is modelled as an aggregate demand for each of the four sectors. The distances from production to demand are accurately taken into account, to include transportation costs.

The level of detail in the representation of time is set to a single year. This is because the time scope is 30 years and increasing the level of detail would enhance the complexity beyond a level that would be useful for a first attempt at capturing the entire hydrogen economy. This means that variability of demand within a year is not shown in the model. As a consequence large-scale storage is not included in the model, even though the need for it is one of the main drivers for the hydrogen economy. This need however comes from the variability in hydrogen demand within a year.

2.1. Agents and their attributes

The key aspects of the hydrogen economy are production and demand. This is why the two main agents are production companies, from here on referred to simply as companies, and demand sectors, simply referred to as sectors. Two SOEs specific to the Netherlands are included as well: *Energie Beheer Nederland*, traditionally involved in exploration and production of hydrocarbons, and *Gasunie*, responsible for the public natural gas network.

The focus of the model is on companies that realize production assets to meet demand, using different hydrogen production technologies. Companies have a certain initial budget that they distribute between asset investments or knowledge investments according to their preference. Companies have a risk appetite that is used to asses the risk of production assets and they have a perception of the risks for each of the sectors and each of the production technologies. The perception of risks is based on the knowledge that companies have about each sector and each technology. The knowledge about the sectors is used by companies to estimate future demand shortages. Companies have specific instances of generic production technologies that are available from the environment. Each production technology has specific characteristics that determine their performance under different market conditions. The production technologies are: autothermal reforming (ATR), steam methane reforming (SMR), alkaline electrolyis (ALK), proton exchange membrane electrolysis (PEM) and the solid oxide electrolyser cell (SEOC). Production assets inherit these characteristics from the technology instances of the companies that realize them. Companies then have shares in these production assets and the assets in turn have contracts with the sectors. These contracts specify the transport technology used to supply the hydrogen to the sectors, the transport distance and the contract price, quantity and duration. Transport is done either through pipelines or gaseous trucks. Finally, the sectors have a yearly demand and contracted production.

2.2. Model procedures

The model procedures indicate the actions that are taken by the agents and the environment in a sequential order. These procedures are divided in a number of phases: a preparation phase, a planning phase, an initiation phase, an execution phase, and finally an operation phase. The five phases are repeated every year for 30 years. In the following sections the procedures shown in Figure 1 are presented, with the procedures marked in bold and the agents and links marked in italics. An overview of the technical system components is shown in Figure 2.

2.2.1. Preparation phase

At the start of the year, the *sectors* **update** their hydrogen demand for the coming year and calculate their demand shortage using the contracted production. The adoption of new technologies are generally assumed to follow an S-curve [28]. This is also true for the diffusion of good in network industries such as the hydrogen economy [14]. Therefore it is assumed that *sectors* update their demand according to the S-shaped function given in Equation 1:

$$d_s(t) = \frac{a_s}{1 + e^{-b_s(t-c_s)}} \tag{1}$$

where d_s is the demand for a specific *sector*, denoted with subscript s, at year t. The maximum demand for a specific *sector* is given by a_s, the slope of the curve by b_s and c_s then denotes the year where the inflexion point of the curve is reached.

The *environment* **updates** the available production technologies according to external technological development. It is assumed that the technologies are characterized by external development through learning-by-searching [29]. Data on learning curves is limited due to the marginal role of hydrogen in the energy system [30, 31]. Therefore it is assumed that the CAPEX of each production technology in euro per MW decreases linearly over time. The efficiency increases linearly over time as long as the technology readiness level (TRL) of the technology is lower than 9.

The *environment* randomly **determines** which policies will become active starting from the coming year. These policies are implemented by the national government and include a carbon tax, public infrastructure and hydrogen blending. The carbon tax in euro per ton CO_2 increases linearly every year and is paid by *companies* for greenhouse gas emissions of production. If a public infrastructure is implemented the transport costs for new *contracts* is set to zero. If blending is implemented, new *contracts* can deliver hydrogen to the sectors through use of the natural gas grid [32]. The transport costs are then assumed to be zero as long as an upper limit of 17 vol% of the natural gas grid capacity is not exceeded [33].

Idle *production assets* then **offer** their *contracts* to the corresponding *sectors* for a standard contract duration. Long-term contracts are central to the model because expert interviews show that these are used by private companies to reduce the high risks that are present at the start of the emergence of a hydrogen economy. The alternative to long-term contracts is a market, which requires a large number of producers and consumers that are interconnected through a hydrogen infrastructure. Growing such an infrastructure has historically taken a long time, which is why the creation of a market is not included in the 30 year time frame of this model [14, 10]. The *production assets* **determine** what hydrogen price they need to ask for the contract quantity specified in their *contracts* to retrieve total CAPEX with a profit, to the extent that it has not been retrieved yet, and to return a profit on their yearly total OPEX. This cost-plus principle is used because there is no market price and no incumbent or competing sustainable energy prices to meet due to the externalization of demand. The *production asset* will either be set to emit carbon or to produce sustainably, depending on what is has the lowest production costs. The *sectors* then **select** proposed *contracts* that offer the lowest price, as long as proposed *contracts* are still available and they still have a demand shortage. At *contract* acceptance, the *production asset* also contracts the price for its energy source.

2.2.2. Planning phase

The first step in planning investments is for *companies* to **set** their budget for asset investments and knowledge investments according to their total budget and investment preferences. The second step is to **set** the expected demand shortage of each *sector* for next year. This is done by drawing from a random normal distribution with the actual demand shortage as the mean and the market risk that a *company* has for that *sector* as the standard deviation. These expected demand shortages are used to determine how much assets to **initiate** in the next phase. The *sector* with the largest expected demand shortage is preferred for knowledge investments.

The *companies* then first **plan** individual knowledge investment, adding the individual knowledge budget to the cumulative knowledge investment of their preferred technology and preferred *sector*. *Companies* then **plan** shared knowledge investment in a similar way, but only if their preferences align with one or more other companies, with whom their shared knowledge budget is then shared. These deliberate investments in knowledge creation are distinct from learning-by-searching, which is related to technological development, and from learning-by-doing, which is related to experience companies obtain with technologies [34].

In the last step in planning investment *companies* **initiate** *production assets* for as long as they can do this successfully.

2.2.3. Initiation phase

The first step is to check the risk of the *production asset*. There are four types of risks that are relevant for new and renewable energy technologies: technology risk, market risk, regulatory risk and system risk [35]. The former two are included in this model. Technology risks may differ significantly between production technologies [36]. This risk decreases as a

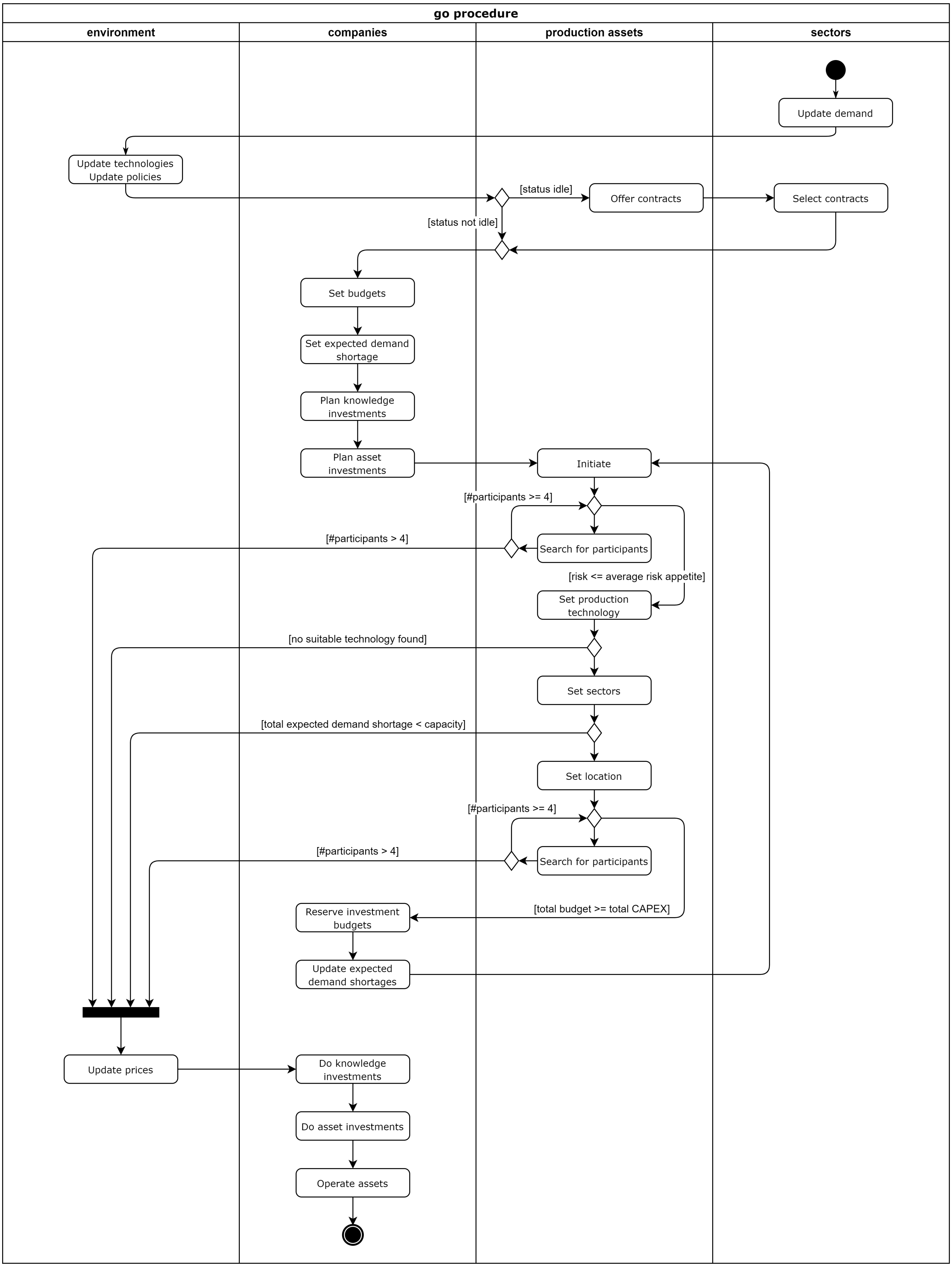

Figure 1: Activity diagram of the main procedures in the model

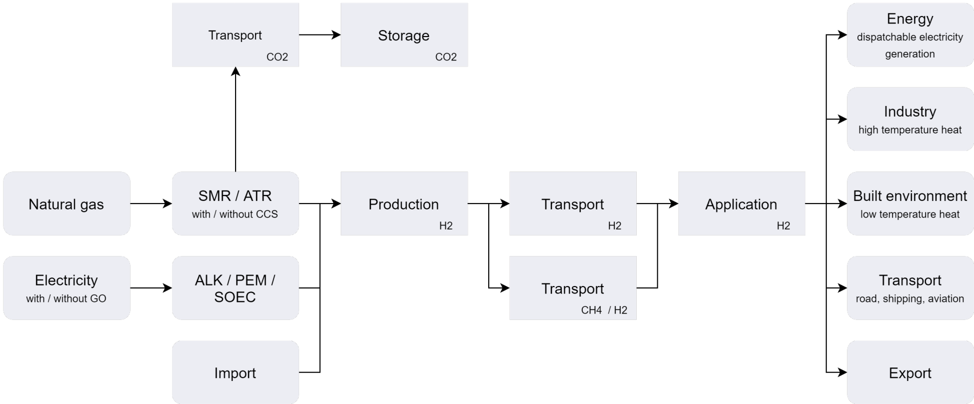

Figure 2: System diagram of technical components in the model

technology matures and is therefore set to be inversely dependent on the TRL following Equation 2:

$$r_{i,t} = 0.1 - 0.01TRL_{i,t} \tag{2}$$

with $r_{i,t}$ the risk of a technology i at a given year t and the $TRL_{i,t}$ of that technology in that year. The technology risk indicates the margin that a *company* has in accurately perceiving the production costs of a technology. The market risk indicates the margin that a *company* has in accurately perceiving the demand shortage of a certain *sector*. The initiating *company* selects the market risk of the *sector* with the highest expected demand shortage and adds the minimum technology risk of any of the participants for any technology. As long as this total minimum risk is higher than the average risk appetite of participants the *production-asset* randomly **searches** a new participant and distributes the shares according to a standard share distribution. If the number of participants becomes larger than 4, the initiation of the *production asset* is unsuccessful and the *company* stops the procedure.

The *production asset* then **sets** a production technology. This is done by taking for each technology the average specifications of the asset's participants and the minimum technology risk of the asset's participants. Then for each technology, using the minimum technology risk, a perception is made of the expected hydrogen production costs in euro per kg hydrogen. This perception is made for the CAPEX and the efficiency by drawing from a random normal distribution with the actual value as the mean and the technology risk as the standard deviation. Any technology with a technology risk that would cross the average risk appetite threshold or with a TRL below 7 is omitted from the selection. The technology with the lowest expected production costs is then selected. In the case that all the technologies have to be omitted from the selection, the initiation of the *production asset* is unsuccessful and the *company* stops the procedure.

For each production technology a fixed capacity is given, which is can now be inherited by the *production asset*. The asset then **creates** planned *contracts* with *sectors* with the highest expected demand shortage, for as long as the total expected demand shortage is smaller than the technology capacity. If the total expected demand shortage of all the *sectors* is smaller than the technology capacity, the initiation of the *production asset* is unsuccessful and the *company* stops the procedure. If it is successful, random distances are generated for *contracts*. These distance are drawn from a uniform distribution for which the range for the first *sector* is smaller than that of the subsequent *sectors*. Using the Fruchterman-Reingold layout algorithm the *production asset* is **set** at a location that visually matches the relative distances to each contracted *sector* as closely as possible.

Next, for each *contract* the cheapest transport technology is determined based on the contract quantity and distance, which is used to calculate the transport CAPEX of the asset. For transport by pipelines first the diameter of the pipeline needed to transport a certain quantity is calculated with Equation 4, which is then used to calculate the CAPEX in euro per meter with Equation 4 [11]:

$$d = 2\sqrt{\frac{C}{\rho v \pi LHV 10^{-6}}} \tag{3}$$

with d the diameter in mm, C the capacity in MW, ρ the density of hydrogen in kg/m^3,v the velocity of the hydrogen flow in the pipeline in m/s and LHV the lower heating value of hydrogen in MJ/kg.

$$c_{capex} = \beta_3 + \beta_2 d + \beta_1 d^2 \tag{4}$$

with c_{capex} in euro/m and β parameters from [11]. For transport by trucks first the CAPEX is calculated based on the number of trucks to be purchased using Equation 5. Then the expected total OPEX over the lifetime of the *production assets* is calculated using Equation 6:

$$c_{capex} = 2c_{capex,t}C_t\frac{dC}{v} \tag{5}$$

with c_{capex} in euro, $c_{capex,t}$ denoting the costs per truck in euro/truck, C_t the capacity in MWh/truck, d the contract distance in km, C the contract capacity in MW and v the average speed of the truck in km/h.

$$c_{opex} = 2c_{opex,t}l\frac{dq}{C_t} \tag{6}$$

with c_{opex} in euro, $c_{opex,t}$ the operational costs per truck in euro/km, l the lifetime of the *production asset* and q the contract quantity in MWh.

The total CAPEX of the *production asset* is the sum of the production technology CAPEX and the transport CAPEX. As long as for any of the participants their share in this total CAPEX is higher than their asset investment budget, the *production asset* randomly **searches** a new participant. If a new participant is added, the shares are redistributed according to the standard share distribution and the new participant **updates** the total CAPEX is updated with its technology specifications. If the number of participants becomes larger than 4, the initiation of the *production asset* is unsuccessful and the *company* stops the procedure.

If the *production asset* reaches this step the initiation is successful and the asset is planned. The participants then reserve their budget according to their share in the total CAPEX and update their expected demand shortages. The participants set the production technology of the successfully planned asset as their technology preference for knowledge investments.

2.2.4. Execution phase

The *environment* first **updates** the external prices and the electricity emission factor according to their external development. Then *companies* **do** their knowledge investments by updating their market risks and technology risks with the increased cumulative knowledge investments. It is assumed that knowledge investments are faced with diminishing returns [34]. These dimishing returns are given by Equation 7 from [30]:

$$r = r_0 \frac{C_i}{C_0}^{-\alpha} \tag{7}$$

where r represent the risk that a *company* has for a *sector* or technology, r_0 the inherent risk defined for that *sector* of technology, C_i the cumulative knowledge investment, C_0 standard knowledge costs and α the knowledge factor.

Then, *companies* **do** their asset investments by starting the construction of planned *production assets*. Instead of the perceived technology specifications the actual specifications are inherited by the *production asset* used and the total CAPEX is updated accordingly. The participants of the asset then each add the capacity of the *production asset* to their cumulative capacity for corresponding technology and update the production technology CAPEX to incorporate learning-by-doing cost reductions. Learning-by-doing is considered a cost reduction that *companies* obtain through experience with the realization of specific technologies in assets. The formula is given in Equation 8 from [30]:

$$c = c_0(\frac{P_i}{P_0})^{-\beta} \tag{8}$$

where c represents the CAPEX that a *company* has for a technology, c_0 the CAPEX of the generic technology, P_i the cumulative installed capacity that a *company* has for a technology, P_0 the typical capacity of that technology and β the learning-by-doing factor. The participants then finally subtract their share in the total CAPEX from their budget. When blending is used for hydrogen transport, the contract quantity is reduced from the available blending capacity.

2.2.5. Operation phase

In the final phase of the model the *companies* **operate** their assets. First, *production-assets* with accepted *contracts* start producing hydrogen according to the contract quantities, thereby consuming energy and possibly emitting or capturing carbon according to the contracted choice regarding sustainable production. *Companies* collect their profit or loss from the production of these assets.

Companies then disinvest in any *production assets* that have been idle for 4 years. *Production-assets* with accepted *contracts* are then asked to return to an idle state if these contracts expire. *Production assets* that are not under construction age and die if they have reached the end of their lifetime. Finally, the *production assets* that have been under construction are finished at set to an idle state.

2.3. SOEs

The SOEs are modelled as specific instances of the companies, with only slight differences to the actions they can perform compared to private companies. There are effectively four actions that the SOE can do, from here on referred to as levers. These are mandatory participation, non-mandatory participation, initiation and knowledge investments. No investment is considered the base case lever.

Mandatory participation means that private companies have to initiate the assets, but they are then required to include the SOE as a participant in the asset initiation procedure. The participation percentage ranges between 1% and 99% and is set in advance as a uniform share for all assets. Non-mandatory participation means that the SOE is allowed to participate in assets, but only when it is randomly selected as a participant by a private company. The percentage then depends on the standard share distribution. For initiation it is assumed that the SOE realizes assets on its own, meaning that has 100% ownership and does not look for other participants. Finally, the SOE can do knowledge investments, but since it operates in the public interest is can choose to publish knowledge projects in addition to the individual and shared knowledge projects. Publish knowledge investments are planned by adding the publish knowledge budget to the cumulative knowledge investment of the preference of the SOE for all companies.

SOEs have access to public resources [19]. This effectively means that an SOE generally will be able to obtain capital if required. In contrast to the private companies the SOE in the model therefore does not have an initial budget to which it is limited. It has no constraints on the investments it can do. Additionally, the SOE is willing to do investments with a higher risk, if it is in line with the public interest. In the model this means for asset investments that an SOE has a higher risk appetite than private companies and in exchange requires the hydrogen production to be sustainable.

Table 1: Overview of experiment designs marked with 'x' for active variables during experimentation.

Variable	**Base case value**	**Experiment value range**	**Reduced asset**	**Full asset**	**Percentage**	**Knowledge**
SOE asset investment	"no asset investment"	"no asset investment", "mandatory participation", "non mandatory participation", "initiation"	x	x	"mandatory participation"	x
Participation percentage (-)	0.40	0.01 - 0.99			x	
SOE individual knowledge budget (M€)	0.00	0.00 - 5.00				x
SOE shared knowledge budget (M€)	0.00	0.00 - 5.00				x
SOE publish knowledge budget (M€)	0.00	0.00 - 5.00				x
Natural gas price (€/MWh)	20	20 - 50	x	x	x	x
Electricity price (€/MWh)	40	30 - 130	x	x	x	x
EU ETS price (€/ton CO2)	25	20 - 200	x	x	x	x
CCS price (€/ton CO2)	40	40 - 120	x	x	x	x
GO price (€/MWh)	2	2 - 20	x	x	x	x
Electricity emission factor (ton CO2/MWh)	0.572	0.572 - 0.496	x	x	x	x
Fraction of maximum demand (-)	0.5	0.00 - 1.00	1.00	x		
Slope of demand (-)	0.25	0.00 - 0.50	0.50	x		
Public infrastructure available? (-)	false	true, false		x	x	x
Blending available? (-)	false	true, false		x	x	x
Carbon tax available? (-)	false	true, false		x	x	x
Companies mean total budget (M€)	525	262.5 - 787.5		x	x	x
Companies mean risk appetite (-)	0.045	0.0225 - 0.0675		x	x	x
SOE risk appetite increase (-)	0	0.00 - 0.05		x	x	x

3. Results

The model is first tested with a number of key variables to determine the input sensitivity of the model with base case setting. For the base case model setting fixed externals prices are used, meaning that the update prices procedure is not active. For the variables tested plus and minus 50% of the input values are taken as the experiment range [37]. To run the experiments the EMA workbench toolkit is used [38]. The model run duration is set to 30 years and each experiment is replicated 50 times, after which the average of these replications is taken. Feature scoring is applied to determine that the model is most sensitive to the mean risk appetite and mean total budget of companies. The risk appetite for companies is initialized using a random normal distribution and the budget is initialized with a random uniform distribution. This sensitivity to risk appetite shows that the risk dynamics are a determining factor in the emergence of hydrogen economy. The relevant dynamic is this regard is the difference between the risk appetite and the risks of technologies and sectors, it does not matter which of the two categories are varied. It means that if companies consider investing in the hydrogen economy too risky, a hydrogen economy will not emerge until risks have decreased. A similar dynamic is visible for the total budget, though much less strongly than for the risk. If companies consider investments in hydrogen production assets more capital intensive than what they are willing to make available initially, a hydrogen economy will not emerge.

A number of experiments have been done beyond input sensitivity testing. The first is an evaluation of base case model behaviour, where the external prices are fixed. The others include an evaluation of asset investment levers, with a reduced number of external variables and the full set of external variables, of the mandatory participation percentage and finally of the knowledge investment levers. An overview of which external variables are active in which experiment is given in Table 1. Again each experiment is run for 30 years and the mean is taken over 50 replications. The analysis of the results of these experiments is presented in the following sections.

3.1. No asset investment

3.1.1. Base case model behaviour

The development of the average hydrogen price over time in Figure 3, shows some step transitions. These transitions correspond to different years in which hydrogen production emerges and therefore a price emerges as well. The period covering these transitions is referred to as the 'warm-up' period. The hydrogen price in most replications shows a clear tendency downwards, which is due to learning effects. For a few replications the price actually increases in which case hydrogen production by electrolysis emerges. In general natural gas-based production is dominant.

The average hydrogen carbon intensity shows a warm-up period as well, but quickly after that two general states emerge between which the replications vary (Figure 4). In this case the higher carbon intensity level corresponds with the emission factor of SMR production, the lower level with ATR production, and replications in between have a mix of both SMR and ATR. The reason that this difference does not show in the average hydrogen price is because the ATR only has slightly lower production costs. Due to variations in the perception of production costs during asset initiation companies might than select SMR as the preferred technology.

The same replications that show an increasing hydrogen price over time, show a divergence from the lower carbon intensity level to an even lower state, which is due to sustainable hydrogen production by electrolysers. This means that, even though the production costs of electrolysers are significantly higher than natural gas-based production, electrolysers in some

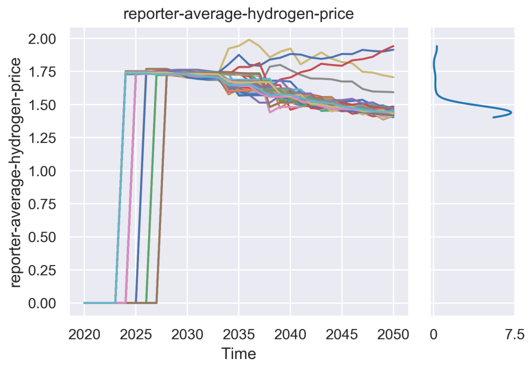

Figure 3: Base case plot for the hydrogen price over time for 50 replications.

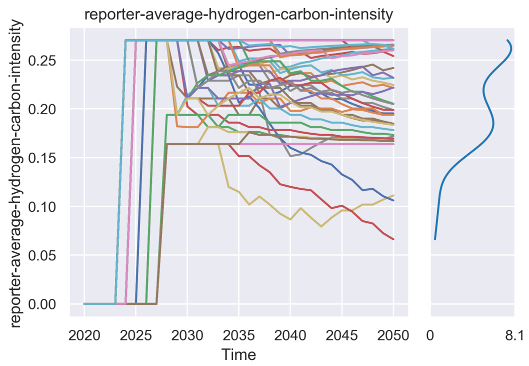

Figure 4: Base case plot for the hydrogen carbon intensity over time for 50 replications.

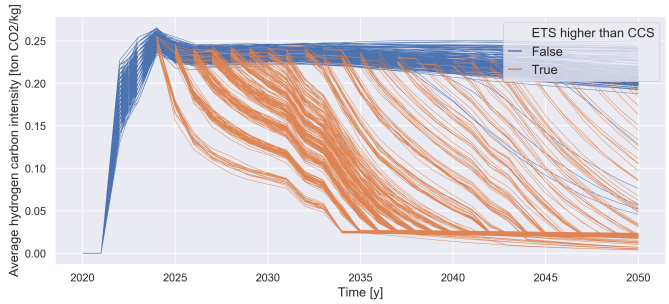

Figure 5: Reduced asset experiments plot for the average hydrogen carbon intensity over time showing the point in time where the ETS price surpasses the CCS price with "no asset investment" by the SOE.

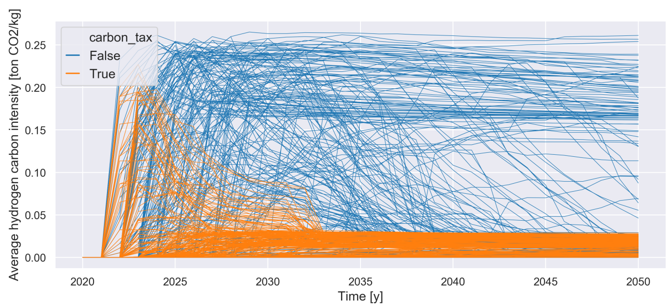

Figure 6: Full asset experiments plot for the average hydrogen carbon intensity over time showing the scenarios for the carbon tax with "no asset investment" by the SOE.

case become the preferred technology. This can only happen when companies have a relatively high technology risk for both SMR and ATR, as well as a relatively low risk appetite. If at some point through external technological development ALK then becomes less risky, it might for these companies be the only production technology that falls within risk appetite constraints. Through learning effects, such a technology can then quickly become dominant. This is also the case for SMR and ATR, but because these have a higher typical capacity, more investments are needed to reach significant learning effects.

3.1.2. Reduced asset experiments

In the reduced asset experiments the external prices are dynamic. In these experiments relevant results arise for the production method, the carbon intensity of hydrogen production and the demand shortage.

Similar to the base case model behaviour the dominant method of production with dynamic prices is still by natural gas. The development of the natural gas price over time therefore has a strong effect on the hydrogen price. Additionally, when production is sustainable this means that carbon is captured and stored. The required CCS capacity can become over 200 Mton by 2050. Only for a very narrow part of the scenario space, where the natural gas price is high and the electricity price low, do the production costs of electrolysis become lower than natural gas-based production. In the few cases that electrolysis does emerge it can lead to significant green electricity consumption of over 1000 PJ.

The carbon intensity of hydrogen production is shows a bimodality in its behaviour Figure 5. Initially, as hydrogen production emerges, the carbon intensity starts a high level. Over time however, part of the experiments transition to a lower carbon intensity level, while others remain at the high initial level. This transition takes place when the ETS price become higher than the CCS price and then takes time to complete.

In the model a relative demand shortage of zero means that the demand is perfectly met. In these experiments, with the demand curves of the sectors set at their maximum level and their maximum slope, private companies for a long duration fail to meet demand. After their initial budget has been invested, it takes time to return the investment so that new production assets can be realized. In the meantime demand continues to grow, causing the demand shortage to increase.

3.1.3. Full asset experiments

In the full asset experiments all the external variables are varied. Compared to the reduced asset experiments this means that the demand curves of the sectors are varied and national policies can be implemented by the national government.

By adjusting the fraction of maximum demand the final demand that a sector can obtained is changed. Depending on the slope this maximum level can however be after 2050. Varying the slope therefore has a double effect as it determines how long a low level of demand is maintained initially and what the final demand in 2050 is. A straightforward effect is that companies are better able to meet demand if the demand curves are lower. Other than that varying the demand curves does seem to impact the general behaviour of the model. It only shifts the moment of production emergence, because the total demand in the model needs to be bigger than the capacity of the preferred technology for assets to be realized. It should be stated however that due to the specific setup of the performance metrics used for the experiments, the demand variation is not as thoroughly explored as the other results and should therefore be interpreted with caution.

Concerning the national policies, both the realization of a public infrastructure and enabling blending do not have a large effect on model behaviour. Due to the geographical representation in the model, transport distances are limited to 25 km. Therefore, the transport costs do not make up a significant share of the overall hydrogen costs. The national carbon tax does strongly affect model behaviour. If it is available it is implemented in 2021 and then quickly surpasses the ETS price. This means that if it is implemented, the transition to a low carbon intensity level happens for all the experiments, independent of the ETS price. This behaviour is shown in Figure 6, where the variation in production emergence due to demand slope variation is also visible.

3.2. *Mandatory participation*

3.2.1. *Fixed participation percentage*

When this lever is implemented the SOE participates in all production assets for 40%. Th production is then set to sustainable by default. This lever mostly affects the hydrogen price, the carbon intensity and demand shortage.

Because the production is sustainable by default the hydrogen price is somewhat increased initially. The difference with no asset investment however is not that big, which shows that sustainability costs do not make up a large part of the hydrogen price. Additionally, over time the hydrogen price decreases due to learning effects to the extent that by 2050 it had dropped slightly below the price for no asset investment. The carbon intensity then is low right from the start of hydrogen production emergence, regardless of the level of the ETS price or the implementation of a national carbon tax. This is shown in Figure 7, where it can also be seen that the hydrogen intensity decreases to an even lower level in some case. In these case sustainable hydrogen production by electrolysis emerges, which is zero carbon, while sustainable natural gas-based production is low carbon.

With this lever private companies still have to contribute substantially to the capital investments necessary to meet demand. Even though the SOE is not budget constrained this means that when demand is high, the initial budget of the private companies will still run out at some point, causing demand shortages to rise. Because production in that sense lags demand, continuous reinvestment is done up to 2050. This just prevents the SOE from obtaining a net profit over the model run. It is however expected that if the model run time would be longer, the demand curves would level off and a net profit would be obtained.

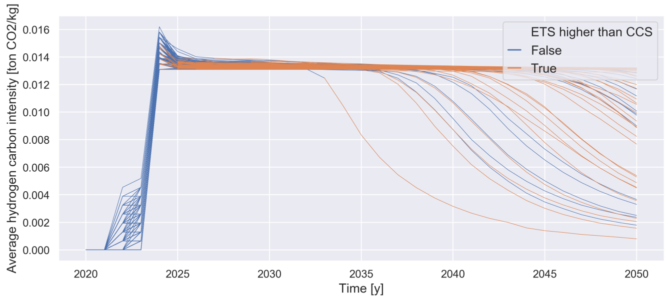

Figure 7: Reduced asset experiments plot for the average hydrogen carbon intensity over time showing the point in time where the ETS price surpasses the CCS price with "mandatory participation" by SOE.

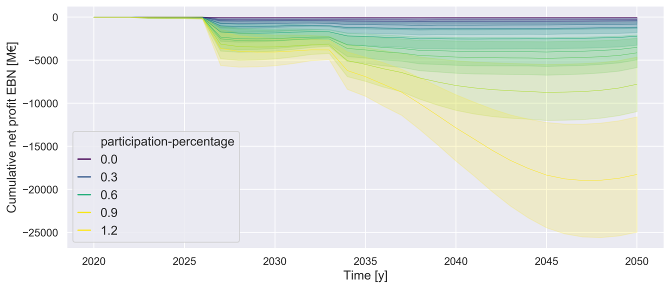

Figure 8: Participation experiments mean estimate for net profit of the SOE over time with standard deviation confidence interval. Net profit is defined as the cumulative investments minus the cumulative (operational) profit.

3.2.2. *Variable participation percentage*

By changing the participation percentage the contribution of private companies in terms of capital investments in the hydrogen economy changes as well. For low participation percentages, below 30%, companies need to contribute significantly to the capital investments required for asset realization. This in some cases can prevent the emergence of hydrogen production. For high percentages however, above 70%, the SOE faces the risk of making substantial losses due to overinvestment. this is shown in Figure 8, where lower participation percentages all converge on a net profit towards 2050, while the higher participation percentages obtain disproportionately large net losses. For higher participation percentages, companies only need the SOE as a sole participant to successfully realize assets. This means that companies on average obtain less knowledge about the planned investments during the asset initiation phase, which increase the likelihood of overcapacity.

3.3. *Non-mandatory participation*

3.3.1. *Reduced asset experiments*

When this lever is implemented the SOE is allowed to participate in all production assets if it is asked by private companies. The production is then again set to sustainable by default. This lever has a limited affect. Because the SOE only participates in some of the production, only part of the production assets are sustainable by default. This results in the higher carbon intensity level being slightly lower than for no asset investment. This lever also requires the private companies to contribute the most. From the different types of asset investment the least contribution of the SOE is therefore required. Similar to mandatory participation for a fixed percentage of 40%, the SOE just falls short of making a net profit for the same reason as discussed before.

3.3.2. *Full asset experiments*

For non-mandatory participation there appears to be a part of the scenario space where the SOE participates in almost all of the production. This stands out from the behaviour for the rest of the scenario space, as the SOE there participates in 20% to 40% of the assets. This high participation is reached when the risk appetite of companies is low. The companies then need the SOE to realize production assets, because the SOE can increase the average risk appetite.

3.4. *Asset initiation*

When this lever is implemented the SOE is allowed to initiate assets. Moreover, it guarantees a 100% share in the assets by not looking for participants. This levers most strongly affects the price and the carbon intensity of hydrogen production and the demand shortage.

It can be concluded from Figure 9 that over time the hydrogen price for asset initiation becomes lower compared to the other types of asset investment. This difference is due to learning-by-doing. In the case of asset initiation, the SOE is a participant in almost all of the hydrogen production and therefore also utilizes the cost reductions by itself. The price reduction for mandatory participation is lower because the cost specifications for production technologies are then averaged over the participants.

The bimodality discussed before is absent for this lever (Figure 10. This is because the SOE is a participant in almost all of the production, in which case production is sustainable by default and the carbon intensity is decreased. The ETS price then only affects the remaining production from the other companies, which only marginally reduces the average carbon intensity. The transition is still visible though, which means that other companies are able to successfully realize assets before the SOE and establish unsustainable hydrogen production. This is due to the fact that under these conditions SOE has a preference for the ATR, which has the highest capacity and therefore requires significant demand shortage to emerge. Companies with a preference for SMR can realize production assets before that. It is important to note that, due to the increasing demand, a higher carbon intensity later means more total carbon emissions than a higher carbon intensity initially.

Asset initiation is the only lever for which it can be guaranteed that the hydrogen demand is met. This is mainly due to the lack of capital constraints for the SOE, which allows it to keep investing in new assets, while the private companies have

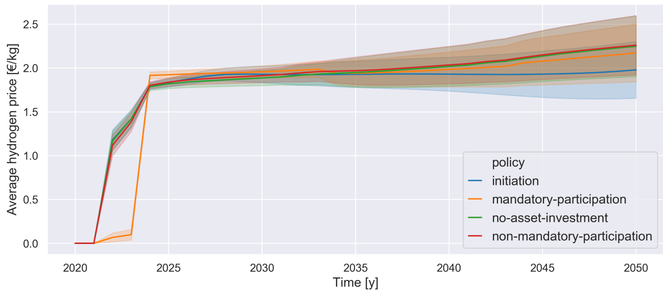

Figure 9: Reduced asset experiments mean estimate for average hydrogen price over time with standard deviation confidence interval showing the different SOE asset investment levers.

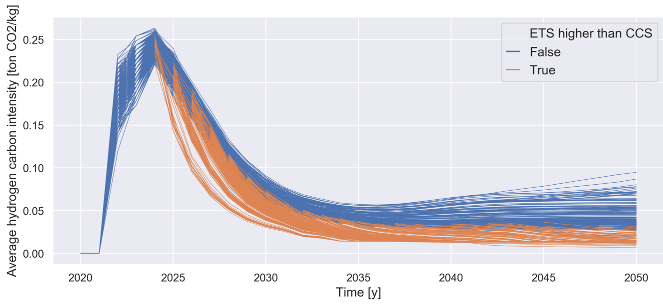

Figure 10: Reduced asset experiments plot for the average hydrogen carbon intensity over time showing the point in time where the ETS price surpasses the CCS price with ”asset initiation” by the SOE.

to be for returns on investments. The total hydrogen production is the highest for this lever. Because this production is mostly sustainable, the cumulative demand shortage and cumulative carbon captured by 2050 is also the highest for this lever, with up to 1200 Mton.

Finally, even though the level of investment by the SOE causes a slight overcapacity, this is the only lever for which net profits are obtained within the run time of the model. Substantial investments are required, to such an extent that the SOE crowds out private investment. The fact that net profits are obtained does confirm the hypotheses that net profits will be obtained when the production capacity catches up with demand and reinvestment no longer is required.

3.5. *Knowledge investments*

Feature scoring is used to get a first impression of the effects of knowledge investments on knowledge behaviour. Scenarios are generated for each of the asset investment levers, as the effect of the knowledge investments might differ per lever. From feature scoring it is concluded that knowledge investment have such a small effect on any of the performance metrics that further investigation is not necessary.

4. Discussion

4.1. Limitations of the model

The most notable limitation of the model is that the demand is externalized. For future work it is therefore recommended that additional models are made to simulate demand emergence in each of the four sectors. It is considered likely that these models could conceptually be connected to the existing model rather easily. An important consequence of this external demand is that the contracts in the model are priced on a cost-plus basis. This reduces the uncertainty that producer faces when realizing production assets, as it becomes unlikely that substantial losses will be incurred over the lifetime of a production asset. It is however important to realize that in reality the competitiveness of hydrogen compared to the incumbent energy source is of key importance in the emergence of a hydrogen economy [10].

Two other limitations of the model are found in the temporal and the geographical representation. The consequence of setting the level of detail in the temporal representation to a single year is that variability is not investigated. This is both a driver for the emergence of a hydrogen and a cause of concern, because not all hydrogen production technologies are capable of flexible production. This can significantly hamper the profitability of production assets [39]. The geographical representation then mainly prohibits an investigation of the interconnection of hydrogen networks. The existence or absence of such networks can be a determining factor for the risk of investments in hydrogen production [15]. This risk is not included the model.

4.2. Discussion of results

Despite the limitations address above it is concluded from expert validation workshops that the model gives a useful representation of the hydrogen economy. An important aspect in this is the hydrogen price, shown in Figure 9, which is in line with prices found for the Netherlands by [11]. The most important aspect of this article however, is to determine the effect of the SOE on the emergence of sustainable hydrogen economy. The remainder of this section therefore discusses the model results in light of this goal.

The SOE is able to concentrate learning effects, which can then reduce the hydrogen price. This would in principle be possible for any company that participates in a large part of the production, but if mandatory participation is applied the effect is reached without needing a near monopoly position of a single company. Conscious efforts to increase knowledge by the SOE do not appear to have significant effects, though this might be due to the fact that the maximum yearly investment had been set to 5 M€. Despite this, knowledge sharing about planned investments is effective in preventing overcapacity and therefore reducing the risk of incurring losses. In the model knowledge about the planning of investment in individual assets is shared between its participants, while in reality knowledge exchange extends beyond that. It is therefore likely that knowledge sharing between participants is a more important factor in reality than shown in the model, and the SOE can facilitate this sharing if it chooses to participate in asset investments.

The model results show that learning effect can lead to a dominant technology. It is therefore important for the SOE to evaluate the production technologies available. This is especially important if the assumption holds that the SOE can increase the average risk appetite in asset investments and then if technologies with less risk do perform worse on other specifications. A good example from the model is the fact that ATR is better suited for CCS and has a lower emission factor than SMR, but through risk perception SMR might still be the preferred technology for some companies. The SOE can then be used to steer the technology choice towards ATR.

Even though electrolysers are considered to currently have high risks, it seems unlikely that the SOE can increase their deployment through risk perception alone. This is because the production costs for electrolysers is substantially higher than that of natural gas-based production in almost the entire scenario space. Only a combination of low electricity prices and high natural gas prices can make electrolysis cost-competitive. These scenarios seem unlikely in the Netherlands specifically, because the electricity is predominantly produced from natural gas. This is not likely to present any problems for the emergence of a sustainable hydrogen economy to 2050, but after that CCS capacity can becoming a limiting factor. By that time it is likely that a switch has to be made to electrolysis if production is to be maintained. This is precisely why other studies have emphasized the need for policies to already focus on costs reductions for electrolysers now [12, 13]. If this is considered to be in the public interest it can be recommended to incorporate the deployment of electrolysers in the mandate of the SOE in some way.

The SOE can force sustainability in the assets in which it participates. Even in the case of non-mandatory participation is reduces the carbon intensity of hydrogen production. This non-mandatory participation is done based on a random selection by private companies that need participants during asset realization. In reality this selection will not be random. A private company will at least for the SOE weigh the possibly increased costs of sustainable production against the benefits of having more capital. If participation is mandatory all production is sustainable by default. The other levers all show a transition towards a lower level of carbon intensity, either through the implementation of a carbon tax or through a high ETS price. In the model this transition is due to the fact that the sustainability of the production is specified in the long term contracts. Existing contracts therefore have to expire before a switch to sustainable production can be made. This may or may not be the case in reality, but an effect that has not been included in the model is that for natural gas-based production, investments have to be made before the a switch to CCS can be made. Because production is predominantly natural-gas based across all scenarios it is therefore very likely that an initial high carbon intensity level will take time to transition to a lower level. This effect is further increased due to the fact that not all assets are the same, which means that for some, for example older assets, the switch will not be worth it. It should be noted that for a carbon tax, if it is indeed implemented in 2021, the transition does not take a long time. The added benefit of such a carbon tax is that it does not hamper the competitiveness of hydrogen production as it would be implemented for all energy production with carbon emissions.

Finally, from input sensitivity testing it is clear that the budget that private companies initially make available for hydrogen investments and the risk perception and risk appetite of those companies can be critical in the emergence of a hydrogen economy. In these cases in particular the SOE can step in to provide the capital and risk appetite needed to initiate the emergence of a hydrogen economy.

5. Conclusion

This article has focused on the role that SOEs can play in the reduction of greenhouse gas emissions in the energy sector. The motivation of this focus is due to the responsibility that SOEs have a major emitters and the unique position they have in their connection to policy makers. Specifically this article focuses on the effect that an SOE can have on the emergence of a sustainable hydrogen economy, with Netherlands as the country under investigation. By contributing to the realization of such a sustainable hydrogen economy, SOEs that traditionally might be based in fossil fuel production can create the conditions necessary for the decarbonization of their own operations.

The SOE is a form of state intervention and its application in the energy sector to realize a specific goal should therefore also be motivated from that theory. State intervention can be legitimized if new markets have to be created and the creation of these markets is faced with significant risks. The emergence of the hydrogen economy is faced with deep uncertainty and the associated risks are therefore high. It can therefore be concluded that state intervention is legitimized.

The question of which type of state intervention to then apply is more delicate and is precisely a question that policy makers are currently faced with. This research has used an agent-based modelling approach to explore the effects of the SOE as a particular type of state intervention under deep uncertainty. The results show that an SOE can support the emergence of a hydrogen economy if private companies consider the initial risk too high or are not willing to make enough budget available.

If companies are willing to take enough risks and can make enough budget available, a hydrogen economy can emerge. The extent to which it emerges is then dependent on the development of demand, which is not further explored in this article. The extent to which the SOE can influence the sustainability of this production is explored in this article. It is clear that the SOE can substantially reduce the carbon intensity of hydrogen production. The most effective way to do so is through mandatory participation, which would guarantee sustainable production from the start, independent of the level of the ETS price and the implementation of a national carbon tax. The implementation of a national carbon tax guarantees a minimal carbon price and also effectively reduces the carbon intensity if it is implemented. The added benefit of a carbon tax is that it creates a level playing field for sustainable hydrogen compared to incumbent and competing energy sources. The SOE however has different benefits, which include the provision of capital for asset investment and the provision of knowledge that arises during the asset realization process and which can be shared between participants. Additionally, the SOE can increase the average risk appetite of asset investment. This becomes important when the SOE would also get the mandate to specifically stimulate the deployment of electrolysers, that are characterized by higher risks. Hydrogen production by electrolysis is necessary in the long term, because sustainable natural gas-based hydrogen production can reach CCS capacity limits after 2050.

Finally, should the SOE be chosen as a suitable policy measure to stimulate the emergence of a sustainable hydrogen economy, the specific mandate needs to be determined. The most effective types of investment are asset investments either through mandatory participation or through asset initiation. Ultimately the choice between both comes down to the question to which extent the state wants to leave room for private investments and how much investments the SOE is allowed to make. If the state wants to leave much room for private investment and the total investments made need to be limited, mandatory participation is the most suitable option. If this is not the case, asset initiation is the most suitable option as it has the added benefit that demand is guaranteed to be met.

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