Capture and storage of CO2

An Agent Based approach to the possibilities for carbon capture in the Port of Rotterdam

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1. Introduction

At the 2015 United Nations Climate Change Conference (COP21) in Paris, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached an agreement to combat climate change and ameliorate the policies of individual states within the UNFCCC related to climate change and its effects (UNFCCC, 2018). Individual countries strive to reach the emission reduction targets in 2030.

In this respect, the Dutch government has stimulated various policies such as an increase in renewable energy resources, more efficiency in industrial processes, recycling and the closing of coal thermal plants (Port of Rotterdam, 2018). However, joint research between Dutch institutes Kalavasta, Berenschot and CE Delft (2017) together with professors from TU Delft, Utrecht University and VU Amsterdam, has shown that the emission targets of CO2 are unlikely to be reached through the current policies alone.

The industrial activities in the Port of Rotterdam are particularly energy intensive, mainly since the heat/cold requirements contribute to 70% of the energy requirements. The energy is currently generated by only using fossil fuels.

Therefore, the government is specifically looking into opportunities for Carbon Capture and Storage (CCS) for the Rotterdam Port Authority. CCS is internationally recognized as a key instrument for the reduction of CO2 emissions (Port of Rotterdam, 2017). CCS is particularly important for the chemical sector, hydrogen producers and refineries with insufficient capabilities to reduce their CO2 emissions on the short term. It offers users the opportunity to reduce their CO2 emissions, while simultaneously developing structural innovative measures in their production processes.

1.1 Problem formulation

1.1.1 Stakeholders and interests

The investments needed for the development of the CCS infrastructure and the capture technology are high and may need to be subsidized. Economic viability is thus crucial for the technology to be implemented. For the transition to more sustainability in the port of Rotterdam, there are several important parties involved for the development of CCS infrastructure and technology.

Ministry of Economic Affairs and Climate Policy (Government)
The Ministry of Economic Affairs and Climate Policy aims to reach the emission reduction targets of the Paris Agreement, by reducing the emission of greenhouse gasses by 49% given the emission levels in 1990 (Government of the Netherlands, 2019a). The Ministry aims for the

reduction of the emissions in the following key sectors: the electricity sector, the industry, the built environment, the transport sector and the agricultural sector. Given the insufficient reduction of CO_2 emissions in the Netherlands, subsidies from the government would be particularly needed to finance opportunities for CO_2 storage in port areas of Rotterdam, Amsterdam and the Westland Area (Government of the Netherlands, 2019b) and to ensure more economic viability for the private sector.

Rotterdam Port Authority

The Rotterdam Port Authority has formulated its ambition to become the most sustainable port of the world. Given this ambition, the reduction of CO_2 emissions is crucial to reach the objective, in line with the emission reduction targets in the Paris Agreement of 2015. However, the CO_2 emissions in Rotterdam have increased with 40% compared to the emission levels in 1990. This is due to the opening of two coal plants in 2015 and 2016. While the opening of these plants leads to the emission of CO_2, it also creates job opportunities and economic growth for the harbour and the Dutch economy (Port of Rotterdam, 2016). To mitigate the negative climate impacts, CCS could be seen as a transition path to other alternatives such as electrification, which includes the use of heat pump and direct resistive heating. However, the investments needed for the development of the CCS infrastructure and the capture technology are higher compared to other electricity generation technologies. Therefore, the Rotterdam Port Authority finds it important that energy is sustainable, but also reliable and affordable.

Industries

The United Nations Conference on Trade and Development (UNCTAD) has estimated that globally, the required investments needed in key sectors related to the Sustainable Development Goals (SDGs) are approximately US$ 5 trillion to US$ 7 trillion (UN Global Impact, UNCTAD, UNEPFI & PRI, 2015). Therefore, financial support from institutional investors, private companies and foundations is needed to achieve sustainable industrial processes in the port. However, in the case of CCS, the initial investment costs needed for CCS can be prohibitively expensive in the context of the financial returns which are uncertain. The longer term commercial viability is still in the demonstration phase. Different industries might or might not join the CCS because of uncertainty with respect to the recovery of the initial investment, making it more or less costly to develop the infrastructure and technology (Global CCS Institute, 2014).

1.1.2 Research question

The characteristics and costs of CCS are not that well understood compared to more mature technologies such as combined cycle gas turbines (CCGT), wind, hydro and the traditional form of geothermal (Global CCS Institute, 2010). The economic viability therefore remains unproven. Insufficient insight in the economic viability of different interfaces of the infrastructure and technological components of CCS poses an important barrier to gaining the capital expenditures (CAPEX) for this technology. Therefore, this research is conducted to understand the implications of different government subsidies, private investments and characteristics of the CCS in the port of Rotterdam.

The scientific contribution of this research is therefore to gain more understanding on the impact of financial investments and different infrastructure and technological characteristics on the development of CCS in the Netherlands. The societal contribution of this research is to provide insight in the economic viability of CCS in the port of Rotterdam. The insights can help policy makers decide on the implementation of sustainable technologies in the port of Rotterdam, for the total reduction of Greenhouse Gas emissions in the Netherlands.

Therefore, the following research question can be formulated:

"*What is the effect of the height and type of government subsidies on the amount of CO2 stored by industries in the port region?"*

In the research question, it is assumed that subsidies from the government impact the willingness of the private sector to invest in capturing and storing CO2 emissions in the port region. By experimenting with different interfaces of the infrastructure, this impact can be assessed.

1.2 Research method

To answer the research question, an agent-based model will be developed using the software Netlogo. Agent-based models are a branch of computational models to simulate the actions and interactions of different entities to assess their effect on the system as a whole, in this case, the development and viability of CCS in the Rotterdam port region. Since there are multiple parties interacting for financial investments, port development and CO2 storage, agent-based modeling allows one to capture the behaviour of these parties in the environment (Abar, Theodoropoulos, Lemarinier & O'Hare, 2017).

1.3 Structure

Chapter 2 explains the conceptual building blocks for the agent-based model and the assumptions being made. Chapter 3 shows how the different parties together with their interactions have been modelled. Chapter 4 shows the results from the model, its experiments and its validation. Chapter 5 discusses the policy suggestions, limitations of the model and the future research opportunities. The overview of the literature being used can be found after chapter 5.

2. Conceptualization

This section conceptualizes the problem to find the relevant concepts and also provides the basis for the Netlogo model. The system identification clarifies the relevant concepts and the level of aggregation. The concept formalization will translate the concepts identified before into a structure which contributes to the programming.

2.1 The components of the Agent-Based Model

In order to experiment with different heights of subsidies and infrastructure types for the capture of CO_2 emissions, a model will be developed according to the components of an agent-based models. Before the components can be applied to the specific problem context for the Rotterdam Port Authority, the concept of an agent should first be defined. Figure 1 shows the general framework for agent-based models, in which agents operate. There is no universally accepted definition of what an agent is. However, Jennings et al. (1998) provided a definition which emphasizes on two important properties of an agent:

“An agent is a computer system, situated in some environment, that is capable of flexible and autonomous action in order to meet its desired objective.”

An agent is therefore *autonomous*, has particular properties and actions, and has a *social ability* (Chen, 2015). Autonomy means that the agent can operate within a certain environment, and has control over its actions and internal state. The precise interactions and behaviour are governed by rules the agent refers to. Being social means that within the environment, the agent is able to interact with other agents as well. All these actions change the state of an agent.

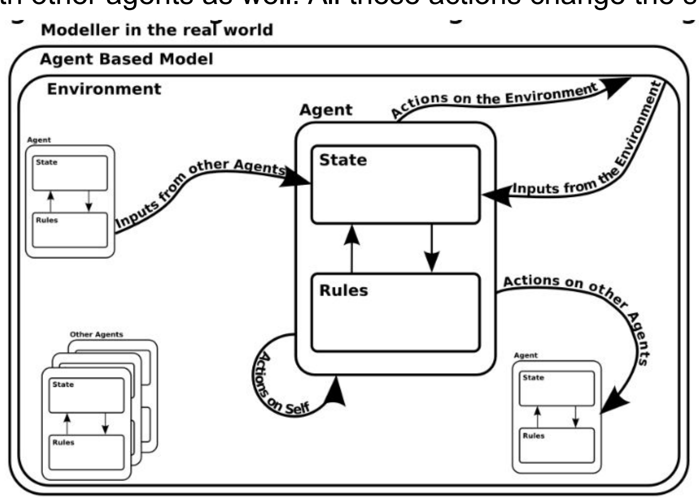

Figure 1: The general framework of an agent-based model (Nikolic, 2018a).

In the following paragraphs this framework will be applied to the problem context of the capture of CO_2.

2.1.1 Agents, agent properties, and agent behavior

The Ministry of Economic Affairs and Climate Policy aims to mitigate the CO2 emissions in order to meet the targets as set by the European Commission. This mitigation is possible by using the infrastructure of the Rotterdam Port Authority to capture CO2. Since the capture technology is still new, the private investments of the industry are necessary to realize the capture processes in the future. Therefore, these are the three stakeholders who will be considered for the model. Table 1 shows these stakeholders, their states and actions (Nikolic, 2018b).

Table 1: Agents, states and their actions

Agents	**States**	**Actions**
Ministry of Economic Affairs and Climate Policy	- Height of subsidy for the port - Height of subsidy for the industries	- Distribute subsidies for capture technology and storage development - Set CO2 emission price
Rotterdam Port Authority	- Budget - Payback-period	- Build storage (pipeline) using money received from subsidy and income CO2 captured - Decide on whether a storage that will be built is extensible or not - Set price for CO2 storage (1 ton) which recovers the CAPEX with a payback period of 15 years
Industries	- Payback period - Capture technology - Willingness to connect to storage - Oil usage - Co2 creation	- Decide to buy capture technology - Decide to join the pipeline - Decide how much of the produced CO2 is emitted and how much is captured - Connect with the storage they decide to make use of

The research question puts the emphasis on two important components of CCS: the height of subsidies and the different interfaces for the infrastructure.

The financial resources for CCS are included in the model, as can be seen in table 1. Part of the resources for building CCS storages is provided by the Ministry of Economic Affairs and Climate Policy through their budget. This budget is divided over the Port for building new storages and the industries that use the subsidy for building capture technologies. The remaining costs for the Port are paid by the industries that make use of their storages. The total budget of the Rotterdam Port Authority is therefore the sum of the subsidy from the government and the income received from industries who store CO2. It is assumed that, since CCS is not a mature technology yet, the government and the industries that use the technology are the only providers of income for the Port. Another assumption is that the Port receives a set amount of money every year, while the industries receive a subsidy that is based on the number of existing industries so that the government budget for this project is not exceeded.

Since the facilities for CCS will be built in the industrial area of the Port of Rotterdam, the industries have to pay the Rotterdam Port Authority for the storage of their CO_2 production. As the Port of Rotterdam has a better overview of its budget and costs it makes, the price for storing 1 ton of CO_2 is decided by the Port itself in order for them to be able to recover the CAPEX for the built storages. This is important to consider to assess the profitability of CCS for the Rotterdam Port Authority.

The decisions surrounding the interface of the storages (e.g. building the storage and deciding whether it is extensible or not) are made by the Port as well. This is not only because the storages for storing CO_2 are made in the industrial area of the Port. Another argument is that the Dutch government is solely a shareholder of the Port of Rotterdam and owns 30% of the shares (Port of Rotterdam, n.d.). The government is therefore not actively involved in the decision-making processes surrounding infrastructure designs in the Port.

The Ministry of Economic Affairs and Climate Policy and the Port of Rotterdam thus have an important role in the decision making in respectively the distribution of subsidy and the build of the pipeline. These have an effect on the industries if they are willing to buy capture technology and if they want to join the storages. The decisions of the industries are therefore only related to their own production of CO_2 and their investments in CCS. Since the long-term commercial viability is still in the demonstration phase, it was decided to only look at monetary decisions made by the industries. The industries can thus decide to join CCS and store part of their CO_2 production.

2.1.2 Environmental characteristics and stationary agents

Table 2 shows characteristics of the environment in which the agents (stakeholders from paragraph 2.1.1) are acting. It also shows information on stationary agents, which do not decide in the system, but have properties.

Table 2: Concepts

Concepts	States

Global variables	- CO_2-price
	KPI's
	- Total captured CO_2
	- Total emitted CO_2
	- Total costs to industry to store CO_2
	- Total amount of subsidy dispatched by government
	    - To port of Rotterdam
	    - To industries
	- Total amount of electricity used

Infrastructure (Storage / Pipeline)	- Location (onshore/offshore) - Type (extensible/fixed) - Distance from port - Maximum capacity per year

	- Price of construction
Capture Technology	- Maximum capture capacity (ton/year)

The concepts help to explain the limitations to make sure that the system encompasses the internal logic of the agents. There is the effect of the CO_2 price, which influences the industries on their decision-making. The government sets the CO_2 price. With CCS, the government aims to limit emissions to reach the targets of the European Commission. The changes in price of CO_2 emissions are thus made by the government as a policy lever to achieve the targets of the European Commission.

Furthermore, there are boundaries and specifications to the storage locations and connections. The costs for the Port are related to the location distance and the type of the storage facility. The location of a facility can be onshore or offshore. Offshore facilities have a larger distance from the Port and take longer to construct. Only if a facility is extensible, industries can connect to it after is was built. Extensible storages are more expensive, but will make sure no CO_2 space will be unused. The price of the construction of a storage is set by the Port in such a way that the costs are recovered after 15 years. A pipeline has a maximum capacity to transport CO_2 to the storage facilities. The capture technology also has a maximum capture capacity, which increases every year due to the evolving of innovation, and also decreases in cost.

Given these concept, the following Key Performance Indicators (KPI's) have been chosen to analyse (they can also be found in table 2):

- Related to the CO_2 production of companies
  The two KPI's which have been included are the total captured CO_2 and the total emitted CO_2. These are important to assess how different amounts of subsidy to both the Port and the industry impact the participation of the industry in CCS. The emitted CO_2 puts the captured CO_2 into perspective.
- Total costs industry to store CO_2
  The amount of subsidy which is given to the Port and the Industry impacts the costs for the storage of CO_2. The current investment costs of the technology are expensive. It is necessary to assess whether government aid will change this. The total costs can aid into deciding if investing in CCS is beneficial.
- Total amount of subsidy dispatched by government (to the port and industries)
  The total amount of subsidy dispatched is an important indicator to assess how fast the technology matures. The government grants impact the development of the technology for CCS and the building of facilities. Analysing different ratios of the amount of subsidy granted to the Port and the industry subsidies can show which way of granting is the most effective for the development of CCS.
- Total amount of electricity used is used as an indicator to measure how much electricity is used by the industries linked to carbon capture storages. This number gives an indication of the amount of CO_2 that is captured, as electricity is used in that process.

2.1.3 Time

To answer the research question it is important to have a time length in which the effect of subsidies are researched. Furthermore, the order in discrete models can have significant effect on the results of the model (Wilensky & Rand, 2007). It is also necessary to consider time in the agent-based modelling, precisely what can be accomplished in each discrete time step. These decisions will be reflected in this section.

The timeframe which was deemed applicable enough to study the effects of subsidies was set at 32 years. As the data provided for this case is only for 32 years, which is for the CO_2-emission price. While it would be possible to extrapolate the data for a longer timeframe, subsidiary instruments in this case is only necessary for the start phase of carbon capture technology. The Ministry of Economic Affairs and Climate Policy is mainly interested how to incentivize industries and the Port of Rotterdam for the implementation of carbon capture and storage. Therefore, the model only runs till the year 2050 to see if carbon capture catches on.

The order of the actions from the stakeholders is important as it is the sequence of the events in the model. The order is decided based on the information needed for each process. For example, first the industries produce CO_2, and only after that they decide to build a capture-technology or not, because the produced CO_2 is needed for that decision. In the decision to buy capture technology the industries also need to know the amount of subsidy distributed by the government, which is why this is calculated before that decision as well. Afterwards the Port of Rotterdam gets the subsidy from the government in order to create storages. After a new storage is created or it is decided not to create one and if there is available space in any of the storages, the industries will connect to these, seeing they already established their interests in the previous steps. The final step is to update the variables for the next period, like the CO_2 emission-price. The system follows a logical progression of what is necessary before every action is executed.

Each model step allows the agents to perform their actions, each step in the model represents a quarter of a year in real-time. The decision to divide the year in four steps helps increase dynamic decision-processes of the industries and the Port of Rotterdam, as the time to make a decision cannot be too long in fear of missing out or too short as it is not a realistic to make such investments in a short timeframe. Even though some changes in the system are made on a yearly basis, like the CO_2 emission-price, most actions take place four times a year.

2.2 Concept formalisation

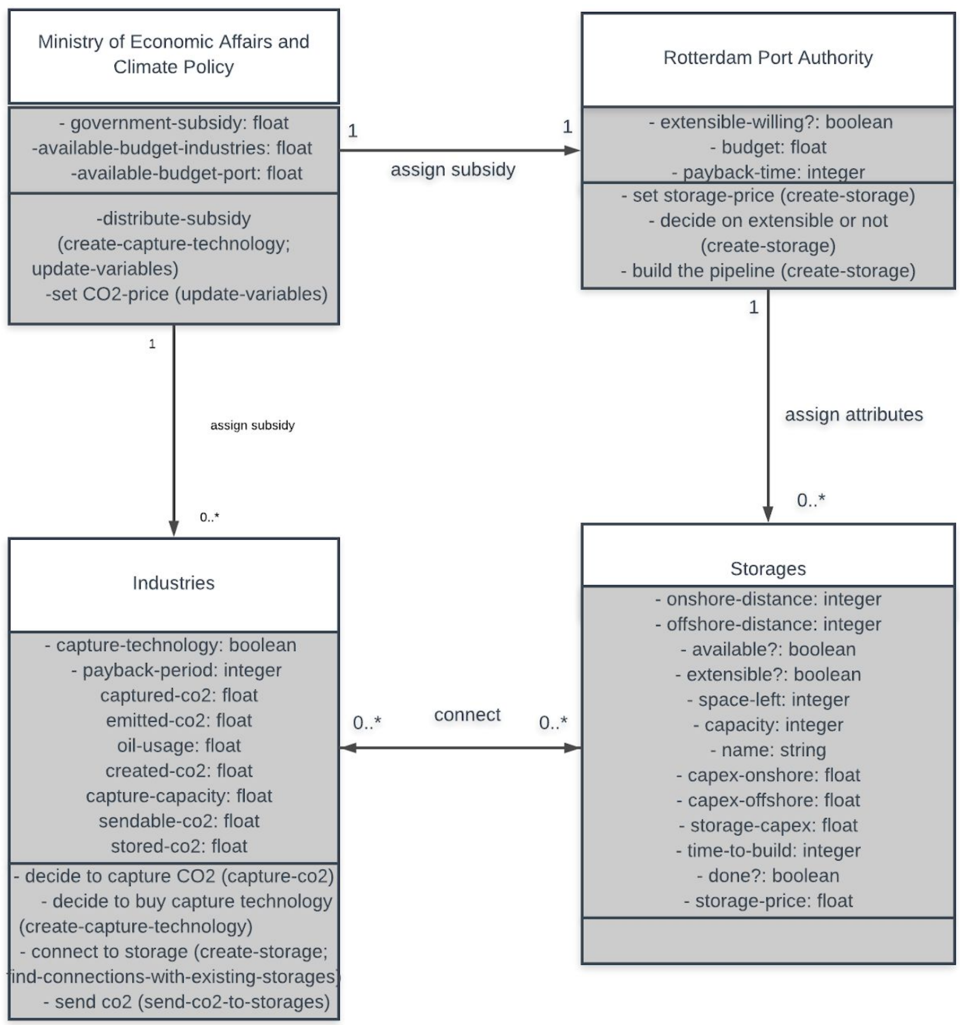

Figure 2: the formal representation of the concepts for the model.

The concept formalisation can be seen in Figure 2, with the use of an UML class diagram, the attributes and the actions of the stakeholders have been formalized. After each attribute their type is mentioned and after every action the function is named for the implementation in NetLogo. As mentioned in the previous section there were two concepts that are important for the system, which are not agents: infrastructure (storage / pipeline) and capture technology. The attributes for capture technology have now been included with the industries as each industry can own a capture technology and decide to improve it. The storages are their own class as they are able to connect to more industries. They also have a multiple instances so they cannot be attributed to another class.

The formalisation shows the interactions between the actors. The Ministry of Economic Affairs and Climate Policy only distributes the subsidy to the Port of Rotterdam and the industries. This connection highlights the issue how the subsidy is distributed to the industries, as their share should only be given to the ones implementing capture technology. This issue is highlighted in the assumptions in the next section. The Port of Rotterdam and the industries are connected to the storages. Some of the attributes of storages are fixed, such as locations, capacity, capital expenditure. The Port of Rotterdam however sets the storage price, decides if they want to make it extensible or not, and reduction of their funds for the pipeline.

2.3 Assumptions for rules in the model

The stakeholders and actions related to them, as well as important concepts for the capture technology, the infrastructure and the Key Performance Indicators (KPI's) have been defined. The interactions in the model will however be governed by rules. In order to specify these rules, several assumptions have been made to enhance their formulation.

General Assumptions

As shown in table 1, there are different actions which involve multiple actors. Therefore:

- The model will be built based on actions which include multiple actors rather than actions that are performed by single actions. Some actions are still performed by only 1 actor, but the main assumption is that the model follows the logical steps rather than following the actions of the individual actors.

The following aspects are changeable for experimentation:

- The budget for the subsidies for the government
- The distribution of the budget (port and industries)
- The electricity price
- The storage capacity
- The number of industries
- The maximum oil-demand by industries

Assumptions related to the Ministry of Economic Affairs and Climate Policy (Government)

The government has a fixed budget to put forward as subsidy. This amount is available for the Rotterdam Port Authority and the industries:

- For the Rotterdam Port Authority, a fixed percentage of the budget is available to use.
- For the industries the subsidy which is distributed depends on a fixed percentage for the industry and the *total* number of companies. Beforehand the government does not know how many industries are going to invest, so it assumes the largest possible number of investors. Moreover, the industries decide on investing in a capture-technology based on

the amount of subsidy which is granted. If the subsidy would solely depend on the number of companies who intend to invest, this could imply an increase in the amount of subsidy which needs to be put available for the private sector.
- If some of the industries choose not to invest, that part of the industry-subsidy is used out of the system. This implies that the entire budget of the government will be used either inside or outside the system boundaries.

Assumptions related to the Rotterdam Port Authority

With the income from CO2 storage and the subsidy given by the government, the Rotterdam Port Authority can invest in the construction of a storage facility to capture the CO2. With regards to whether the Port decides to invest or not:

- It is assumed that the decision to build or not depends on the CAPEX of the storage and the budget of the Port. Also, a new storage will only be built if no storage exists in which additional CO2 can be stored.
- When a storage is built and the price for storage is determined, the Port is assuming that the entire capacity will be used. In case this does not happen they will not receive the complete amount of payback after 15 years (payback-time).
- The pipelines and their storage can not be seen apart from each other. That is why in the system they are treated as one and the same. A storage has a capacity of CO2 per year, and also an onshore as well as an offshore distance. Also, industries connect to a storage rather than to a pipeline.

For the time to construct the pipeline:

- A fixed construction time of 1 year is considered plus a quarter per 20 kilometer, based on Noothout, Wiersma, Hurtado, Macdonald & Kemper (2014) To add the distance to the building time of a storage, and making it more attractive to build storages that are closer, an additional building time based on the distance is added. The usage of rounding, means that a distance of 1 kilometer adds 1 quarter to the building time, but also a distance of 20 kilometers adds 1 quarter. A distance of 21 kilometers adds 2 quarters.

Assumptions related to the industries

Companies have the opportunity to invest in the capture technology for CO2. In this decision:

- Beforehand, companies assume that there is always sufficient capacity for the storage of their captured CO2. So industries invest in capture technology regardless of whether there is place available is storages. If they can not store their CO2, the industries are forced to emit it nonetheless.
- When storing the captured CO2, the industries start with the cheapest storage facility.
- When an industry has already invested in capture-technology before, the decision for building a new and improved capture-technology is based on the extra CO2 this improved technology can capture, which is called the marginal capture capacity.

With regards to the investments:

- An industry will invest in a new capture-technology if the cost of building and storing, given the payback-time, is cheaper than emitting all the CO2 emissions.

- It is assumed that the companies have an unlimited budget to invest in the capture technology. Because the industries have no choice other than producing the CO2, the only choice they can make is to capture or to emit this CO2. That is why, only the difference in price between these two choices matter. Assuming a buffer in the budget of the industries assures that no budget is needed in the model at all.

Companies produce CO2:

- If a company decides to capture all of its CO2 emissions, but learns that there is no available capacity, then the company is forced to emit the remaining amount of CO2.

Connection to storage price (1 million) is also taken into consideration for the investment of capture technology: they assume that they are able to store their captured CO2 in one storage, which might be an underestimation of the real costs.

3. Model design

Based on the conceptualisation and assumptions in chapter 2, a narrative can be formulated to translate the concepts and assumptions for the implementation in the Netlogo software. As mentioned in the assumption, the model will be constructed based on the actions which impact individual agents in the model. Therefore, for clusters of actions, the rules governing them will be formalized and narrated. The discrete step characteristic of NetLogo makes the storytelling step by step possible.

3.1 Setting up the system

Before any action can be performed by the agents, the system has to be set up. This happens in the following order, using the following steps.

- Some globals are defined, like capture-capacity of the capture-technologies in year 1.
- The CO2 emission price is read from the csv file and saved for the next 32 years.
- The industries are set up in a grid and are given a random amount of oil-usage, which leads to CO2 emissions.
- The government is created and the way they distribute their subsidy budget is defined.
- The port is created and the desired payback-time for their investments is defined.
- The storage locations are established and the storages are created in the model, although they do not exist yet.
- Using the csv file on the storages, the location and costs are defined for all the storages. They still do not explicitly exist in the model

3.2 Money streams

The government has a budget. This amount is established at the beginning of the model and will remain the same during the runs. The budget will be entirely divided between the Rotterdam Port Authority and the industries, depending on a set percentage:

- government-subsidy = available-budget-port + available-budget-industries
- available-budget-port = government-subsidy * percentage-port
- available-budget-industries = (government-subsidy * (1-percentage-port)) * number of industries

After a quarter of a year, there is new budget for the government that it can distribute as subsidy in the same way. Notice that the port receives their part every quarter, but the industries only receive subsidy when they indeed invest in a new capture technology. This means the part of the budget that can be used for the industries might not be fully used and leaves the system.

The Port does not entirely depend on the government for its financial resources. Another part of its budget is provided by the industries who pay for the storage of CO2. The budget of the Port is initially set on 0 and can thus increase by receiving subsidy and by receiving the money for the storage of CO2 from all the participating industries:

- budget = 0
- budget = budget + available-budget-port
- budget = budget + sum of all storage-link-prices

With its budget, the Port can create storages. This leads to a decrease in the budget of the Port depending on the CAPEX for the storage:

- budget = budget - storage-capex

The industries do not have a budget but do make choices based on their potential costs: the investment for the creation of capture technology and the payment for the storage of CO2 or the price for emitting their produced CO2. The investment for the creation of capture technology will be done based on the expected costs: if emitting is more expensive than capturing CO2, only then will the industry create capture technology for itself:

- if emitting-costs > capturing-cost
  then set capture-technology? True

Emitting-costs are a sum of the electricity costs, the storage costs, and the building costs for a new capture-technology. Notice that when an industry already has a capture-technology, the benefits of building a new one only takes the marginal capture capacity into account, which are calculated as a difference between the current capture capacity and the max capture capacity of a technology at the time.

Whether industries will invest in capture technology thus depends on how expensive emitting is compared to capturing CO2. There are several cost components which are relevant for this. First of all one can distinguish the costs of emission, consisting of the created amount of CO2 and the price of CO2 which is determined by the government on a yearly basis and given in the available data files:

- emitting-costs = created-co2 * co2-price

Second of all there are the cost components of capturing CO2, (1) the electricity costs involved for the storage, (2) the actual storage costs, and (3) the costs for building the storage facility:

- capturing-costs = electricity-costs + storage-costs + building-costs

The electricity costs depend on (1) the amount of CO2 which is created by one industry, (2) the electricity price, and (3) the power needed to run the electricity facilities:

- electricity-costs = created-co2 * electricity-price * capture-opex-electricity
- electricity-price = 7.5 EUR / MWh
- capture-opex-electricity = 130 MWh / t CO2

The storage costs depend on the (1) price for storing and (2) the operational expenses to keep the storage facilities running. It is considered that the cheapest available storage is considered by industries because they want to keep their expenses low, while bringing more sustainability about in their business.

- storage-costs = (created-co2 * lowest-storage-price) + (storage-opex * created-co2)
- lowest-storage-price = the lowest storage-price of all available, existing storages
- storage-opex = 0.3 M EUR / Mt CO2

The building costs depend on (1) the CAPEX for storage, the capital expenditure to acquire the maximum capture capacity, (2) the subsidy for one industry, which compensates part of the expenses and (3) the payback-period of the investments:

- building-costs = ((capture-capex * max-capture)-subsidy)/payback-period
- subsidy = available-budget-industries/total number of industries
- capture-capex = 200 M EUR / Mt CO2

The capture-capex is assumed to decrease every year with a fixed amount:

- capture-capex = capture-capex * 0.9

3.3 Emitting and Storing CO2

3.3.1 Acquiring capture technology and capturing CO2

The industries produce CO2. This is the amount of CO2 which is emitted per used unit of oil:

- created-co2 = 3.2 * oil-usage

The emitted amount of CO2 is found when the captured amount is subtracted from the created amount, which will be equal to the amount of CO2 their capture-technology can capture:

- emitted-co2 = created-co2 - captured-c02

The maximum capture capacity is assumed to increase as more investments are put into capture technology:

- max-capture = 5
- max-capture = max-capture * 1.1

if emitting costs are more than the capturing-costs (section 3.2), the industry will invest in capture technology. The government subsidy then decreases with the subsidy for the industry who wants to acquire the capture technology.

- government-subsidy = government-subsidy - subsidy

The capture-capacity of an industry has a maximum amount (max-capture) which increases by 10% every year due to technological advancements. Sometimes, an industry wants to capture less CO2 than the maximum amount which is possible, because they produce less CO2 than they could possibly capture. Investing in a lower capture-capacity is cheaper in that case. Therefore, capture-capacity of the technology will either be the created amount of CO2 or the maximum-capture capacity of the capture-technology.

3.3.2 Storing or emitting

The captured CO2 can be stored in storage facilities. The Rotterdam Port Authority builds storage from the budget of the port, which is the subsidy given by the government and the income from the captured CO2:

- budget = available-budget-port

A new storage is built if the following conditions are met:

- If there is are no storages that are under construction at the moment
- If there are no storages that have space left and are extensible
- If the budget of the port is high enough to build an extensible storage

This means that a new storage is build whenever the only storages that exist are full or not extensible, which means no new storage is built when there is still a storage that can gain some CO2. This way no useless storages are built when the system stabilizes. When a new storage is created, it takes 1 year plus the distance / 20 in quarters to finish it. Every step this time to build is decreases by 1. This means a storage with a distance of 40 km takes 1.5 years to finish. It is assumed that the budget of the port has to be high enough for building an extensible storage, even if the storage turns out to be fixed. This way the port always has enough money.

The storage price is set according to the following logic:

- Sets the price for the storage of 1 ton of CO2 in such a manner that it recovers the CAPEX with a payback-time of 15 years.
- storage-capex = onshore-distance * capex-onshore + offshore-distance * capex-offshore
- storage-price = storage-capex / capacity / payback-time
- payback-time = 15

The existing links are *linking* the storages and industries:

- These links show:
  which storage is part of the connection (connected-storage),
  which company is part of the connection (connected-industry),
  which amount of CO2 is flowing through the link (co2-stream)
  And what the costs are for this particular stream (storage-price-link)

Connection to storages is dependent on the following:

- If the storage is fixed this will only be asked at the start of the creation of the storage, if it is extensible this gets asked every quarter (tick)
- Create a set of availability of willing-industries who captured CO2 but can not store this anywhere at the moment and availability of storages who have space-left and are extensible.
- A random industry will be chosen to connect to the storage.
- The maximum of what they can send is their sendable-co2 or the space-left in the storage

        - Sendable-co2 helps clarify how much of the captured-co2 they still need to store in a storage.
            - Sendable-co2 = captured-co2 - stored-co2

The storage facilities own:

- Availability of the storage
    - Availability is dependent if it is under construction and the time it takes
        - The list is predefined in which order storage facilities are opened
        - Time to build
            - The time to build depends on the kilometer and the available money for the Port.
            - The Port can build a storage in 1 year, plus 5% of the distance to the port. This means a storage with a total distance of 20 km takes 1.25 years to finish.
- Extensibility of the storage
    - The extensibility of a storage is dependent on the following:
        - If the sum of the captured CO2 that the industries still want to store is greater than the capacity of the storage, make it extensible, if not, make it extensible

By choosing the extensibility of a storage in this way, no space will ever be unused, because the port can count on enough industries connecting right away if there is enough captured CO2, and when the amount of captured CO2 is lower than the capacity of the storage/pipelines, it will be extensible and used later on.

- The storage price is set by the Port of Rotterdam
- The variables capacity, capex-onshore, capex-offshore, and storage-capex are loaded in from a given CSV file.

One a quarter (tick) the CO2 is actually sent towards the storages. Each of the green links is activated and the amount of CO2 that is captured but not stored by the industries, is emitted nonetheless, because the storages had no space for it.

3.4 Measuring Key Performance Indicators

There are several Key Performance Indicators (KPI's) (chapter 2) which will be measured.
First of all, as one has seen, there are several measures the industries can take when it comes to their the created CO2. They can choose to emit or store CO2:

- total-CO2 = total-emitted-CO2 + total-stored-CO2

One can assess the amount of CO2 which is emitted and the amount of CO2 which is stored over a period of 32 years:

- total-CO2 = total-CO2 + sum of the created-CO2 from all the industries
- total-stored-CO2 = total-stored-CO2 + sum of the stored-CO2 of all the industries
- total-emitted-CO2 = total-emitted-CO2 + sum of the emitted-CO2 of all the industries

This amount can also be assessed for each year, which shows the progress of the CCS.

- co2-emitted-per-year = sum of the emitted-co2 from all the industries

- co2-stored-per-year = sum of the stored-co2 of all the industries

The total subsidy for both the port and the industries is updated every time subsidy is spend by the government. This means every quarter for the port and every time a new capture technology is built for the industries.

Lastly, the capture of CO2 requires electricity:

- total-electricity-use = sum of the captured-co2 of industries * capture-opex-electricity

3.5 Visualizing the progress

The colors and shapes that NetLogo provides offers a valuable possibility for visualizing the state of the model. The non-existing storages are shown in grey, to make clear that no agent knows of their possible future existence. When the building of a storage is in progress, the storage is colored blue. A finished storage can be green, yellow, orange or red based on how much space it has left.

Industries have a label that shows how many CO2 they capture, which is presented in blue. When an industry buys a new capture-technology, this can be seen by looking at changes in this label. The color of the industries themselves represents their CO2 neutrality. If an industry stores more energy than it emits, the industry is colored green, if it is the other way around, the industry has a red color. This visualizes what part of the industries is making the desired steps in CCS.

The links between the storages and the industries will be green if they are operational. Because connections can be made, while the building is still in progress, it is important to recognize which of the connections can actually be used. Green links are operational, grey links are not. Using this color in the model as well, makes it possible to only let CO2 stream through operational links.

3.6 Model verification

For the verification, the states of the agents are assessed. Adjustments were made to each of these states to be able to view their influences on the system. If an unexpected result occurs to the system due to the state change, that part of the model is reconsidered and changed when needed.

3.6.1 Government

- The total budget of the government is divided in quarters. If the government has a subsidy-total of 150 million / year; the government-subsidy is 37.5 million / quarter which gets distributed. **Correct**.
- Government distributes to the Port Authority. The Port Authority gets subsidy every tick based on the parameter “percentage-port” which gives a certain percentage of the total

subsidy to the Port Authority. In the test case the Port gets 50% of 37.5 million / quarter which is 18.75 million per quarter. **Correct.**

- Government distributes to the industries only when they buy capture technology. In a case where 13 industries simultaneously bought capture technology the government distributed 9.75 million in that quarter. Of the 18.75 million remaining subsidy each industry had the right to the 0.75 million (based on 25 industries). Seeing only 13 industries got subsidy; 9.75 is correct. **Correct.**
- The CO2 emission price should change every 4 quarters (ticks) to reflect the changes in the new year. **Error found.** The price change was set one year too early, meaning the value of year 4 was used while it still should have been year 3. Fixed by starting the year variable from 0 instead of 1. **Fixed, correct.**

3.6.2 Rotterdam Port Authority

- The Rotterdam Port Authority has a budget that can be used for the construction of storage facilities. The Port Authority can decide on whether the storage will be extensible or not. As soon as the Port decides on constructing the storage facility, inspection of the Port's budget shows that the budget decreases and that money is spent. In the case that the Port received 18.75 million per quarter, 12.15 million euros remain after spending 6.60 million euros for an extensible storage with a CAPEX of 6.60 million euros. **Correct.**
- If there are no storages with space left and extensible and no storages which are currently under construction, then a new storage facility will be built. The first storage in the model is therefore an extensible storage. **Correct**.
- When there are enough industries who want to store CO2, the storage will be made into a fixed storage, because it will be full immediately. **Correct.**

3.6.3 Industries

- The payback-period is random between 1 and 20 years. **Correct.**
- An industry has a capture technology and a maximum capture capacity associated with the technology. The decision to buy capture technology is dependent if the costs for emitting is lower than for storing CO2. This has been verified by printing the costs while the model only has one industry. **Correct** with a disclaimer that there are instances that the emitting costs can drop down to 0 as marginal capture becomes 0. This happens when this year a new capture-technology has been build, which means only one year later the max-capture increases. This has no effect on the decision making as they will not buy a new technology with the same capacity.
- The decision to join the pipeline is based on how much CO2 they can send to the storage and if there is space left. This connection is made initially and cannot be renegotiated again. **Error found.** Sendable CO2 became negative which means that the decision to join a pipeline was affected. The stored-co2 was lagging one tick behind the preferred decision. This has been fixed by changing the order and calling the function send-co2-to-storages above the decision to join the pipeline. **Fixed, correct.**

- The decision of how much CO_2 is emitted and how much is captured is based on the calculation if emitting costs are higher than capture costs, if this is the case then, an industry will capture all the CO_2 they produce until they reach their capture capacity. **Correct.**
- The connection is made when a storage is under construction. The link will only turn green (meaning active) when the storage also finished building. **Correct.**

3.6.4 Storages and pipelines

- Verification if all the data from the CSV files are correctly interpreted through inspection. **Correct.**
- The storage is assumed to build at least one year plus the amount of kilometers divided by 20. It takes one quarter for 20 kilometers (extra). **Correct.**
- The storage cannot be linked if there is no more space left. **Correct** with the disclaimer that there might be rounding errors in the CO_2 stream. There was a case where the co2-stream was 6.7 which filled the capacity of a storage (7). This has been kept in the model as it is assumed that the Port and the industry would consider the connection for the remaining decimal to not be worth it.

4. Results

The results section explores the model using experiments under different circumstances. The results of these experiments will be also analyzed, generating an answer to the research question. Next to experimentation, this section holds the validation for the model.

4.1 Experimentation

The experiments are run through the BehaviorSpace of NetLogo. BehaviorSpace allows a parameter sweep using the conditions set. While the research question is only interested in the percentage of subsidy distributed to the port and the industries, there are other influential parameters affecting this decision. The parameters in Table 3 have been used with their respective values. In the last column, the reason for adding the parameter is given. As can be noticed from the table, only 2 parameters are actual levers that can be influenced by the government. The other parameters will be interesting to establish the influence of external factors on the system and will show how the system reacts in different scenarios.

Table 3. Parameters used in experimentation

Parameter	**Values**	**Explanation**
Percentage port	[0 - 10 - 20 - 30 - 40 - 50 - 60 - 70 - 80 - 90 -100] %	Distribution of the government subsidy to the Port and the remaining goes to willing industries who buy capture technology. This is one of the levers the government can pull, changing the value shows the real influence of subsidizing the system.
Subsidy total	[0 - 25 - 50 - 75 - 100 - 125- 150 - 175 - 200] M EUR	The total amount of subsidy the government can distribute. This is the second lever the government can pull. Experimenting with this factor can show the real influence of the size of the subsidies, which will provide an answer to the research question.
Max oil demand	[5 - 10 - 15 - 20] Mt/year	Companies have a random oil demand between 1 and

		the max which affects how much CO2 they produce. Changing this parameter explores the situation in which more or less oil is needed by companies, and how this influences the capture of CO2.
Electricity price slider	[1 - 10 - 50 - 75 - 100] EUR / MWh	The electricity price has an positive effect on the usage of capturing CO2. Changing the electricity price shows what happens to the system in different scenarios where capturing CO2 is more or less attractive.
Number of industries	[10 - 25 - 50]	Number of industries involved. Changing the number of industries can show what happens to the system if the port grows or shrinks in size.
Capacity multiplicative	[1 - 2 - 3 - 4 - 5]	Value showing what happens if the pipeline capacity is increased (original number times capacity multiplicative). Changing this parameter shows extent to which the storage capacity is a bottleneck in the capturing of CO2.

In order to minimize the presence of chance in the analysis. For every parameter setting, 5 runs are completed and only the mean value over these 5 runs is reported. The graphs show what happens to each of the KPI's because of a change in the according parameter.

4.2 Data analysis

In this section each of the parameters named in table 3 of section 4.1, will be investigated and the results of the adjustments to these parameters will be discussed. For every parameter, the six KPI's are shown in a graph so the influence of that particular parameter on the different parts of the system becomes clear.

Percentage port

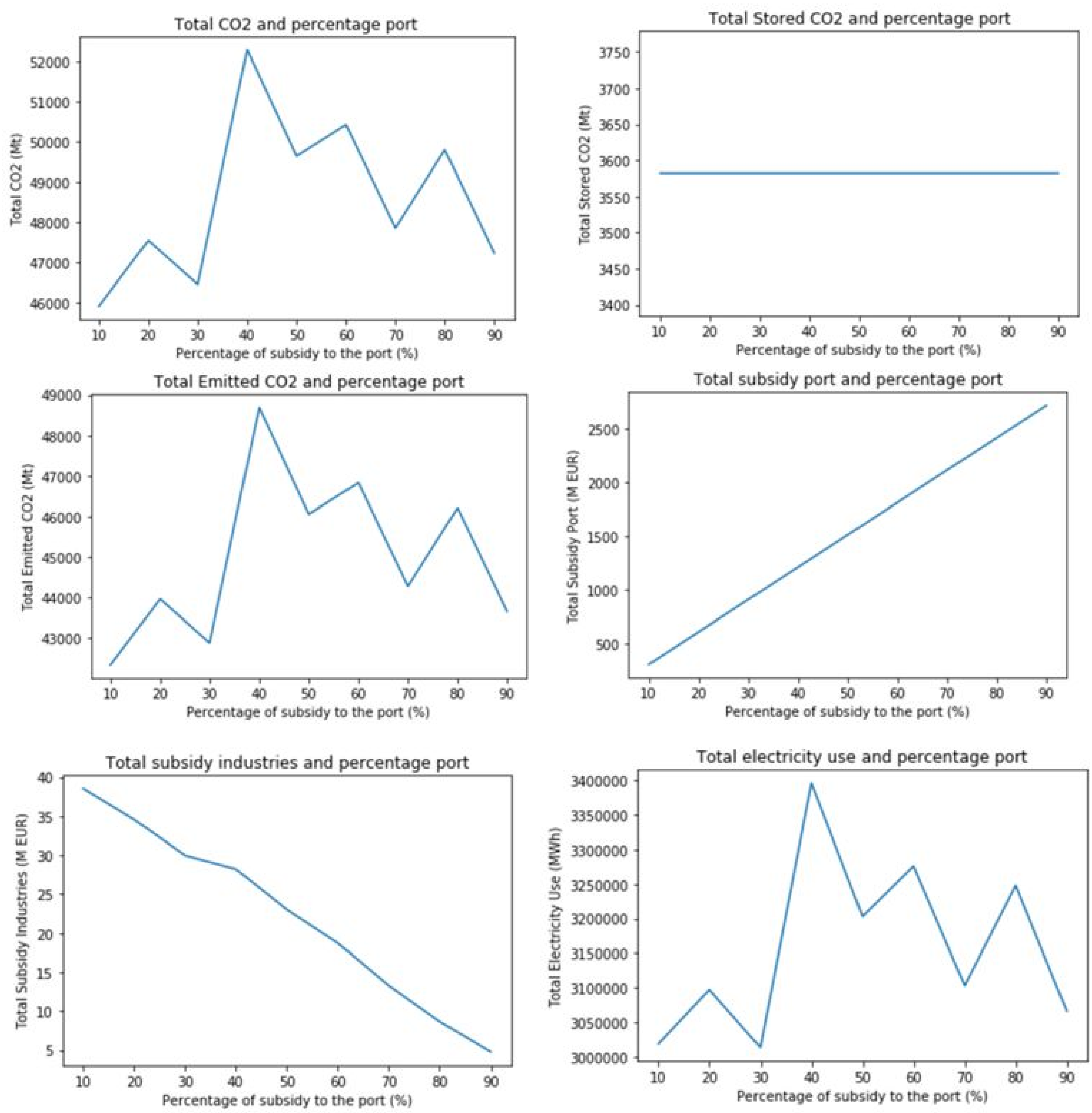

Figure 3. Effect of percentage of subsidy that goes to the port

As the main lever for the government to pull, it is interesting that the percentage of the available subsidy that goes to the port has not influence on the amount of CO2 that is captured in the system. Visual inspection of the model shows that in every run, the number of storages that can be built within the runtime is the same, which means the amount of CO2 that can be sent per year is the same at the end of the run for all runs, independent of the way in which subsidy is spread. Next to that, the step in which industries start investing in capture technology is the same for each run as well, meaning the subsidy has little influence on the decisions made by the agents. Thirdly, all of the storages are full from the moment they are built. This is why the emissions are this much higher than the stored CO2. It seems that the party that receives subsidy does not impact the health of the system, because the capture of CO2 will happen in every case. The problem seems to be in the capacity of the storages, which is too small. Note that a minimum of subsidy is needed for the port, as they need to have a buffer for building storages as soon as the industries start capturing CO2. As expected, a higher percentage for the port means less subsidy spent on the industries and more subsidy spent on the port.

Total Subsidy

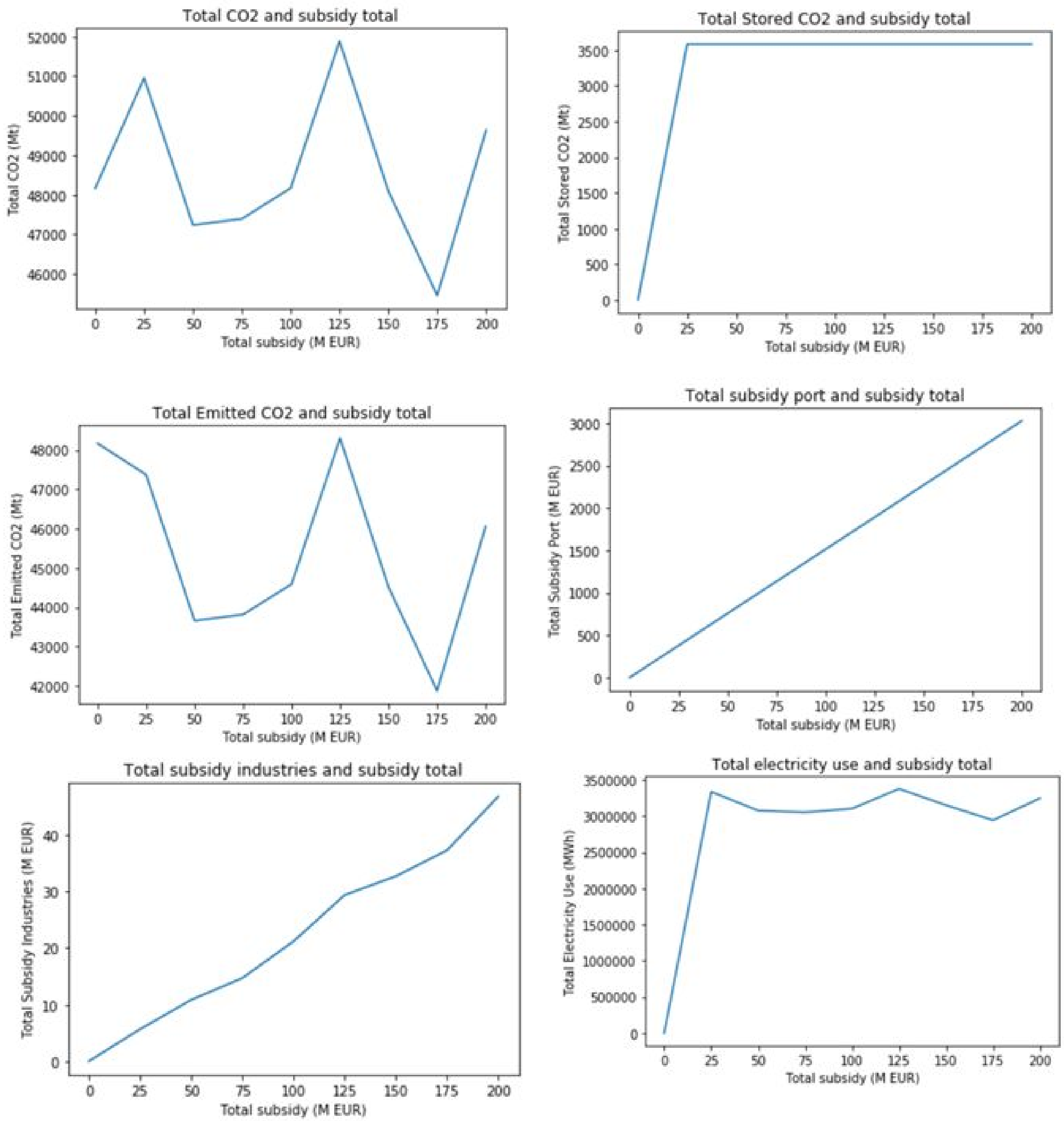

Figure 4. Effect of total amount of subsidy that is spent

The experiments on the total subsidy amount show that next to the independence on the way subsidy is divided, also the height of the subsidies have no influence on the system whatsoever. As long as the port has a reasonable budget, they can invest in storages, and the system will start rolling. These graphs show that the industries are not incentivized by the subsidies no matter the height. As carbon is captured in every run, this also means the industries are incentivised by something else, which means no interference is needed from the government. The other KPI’s behave like expected, as a higher subsidy means more payouts for both the port and the industries. Also the use of electricity is related to the amount of CO2 that is captured.

Oil demand

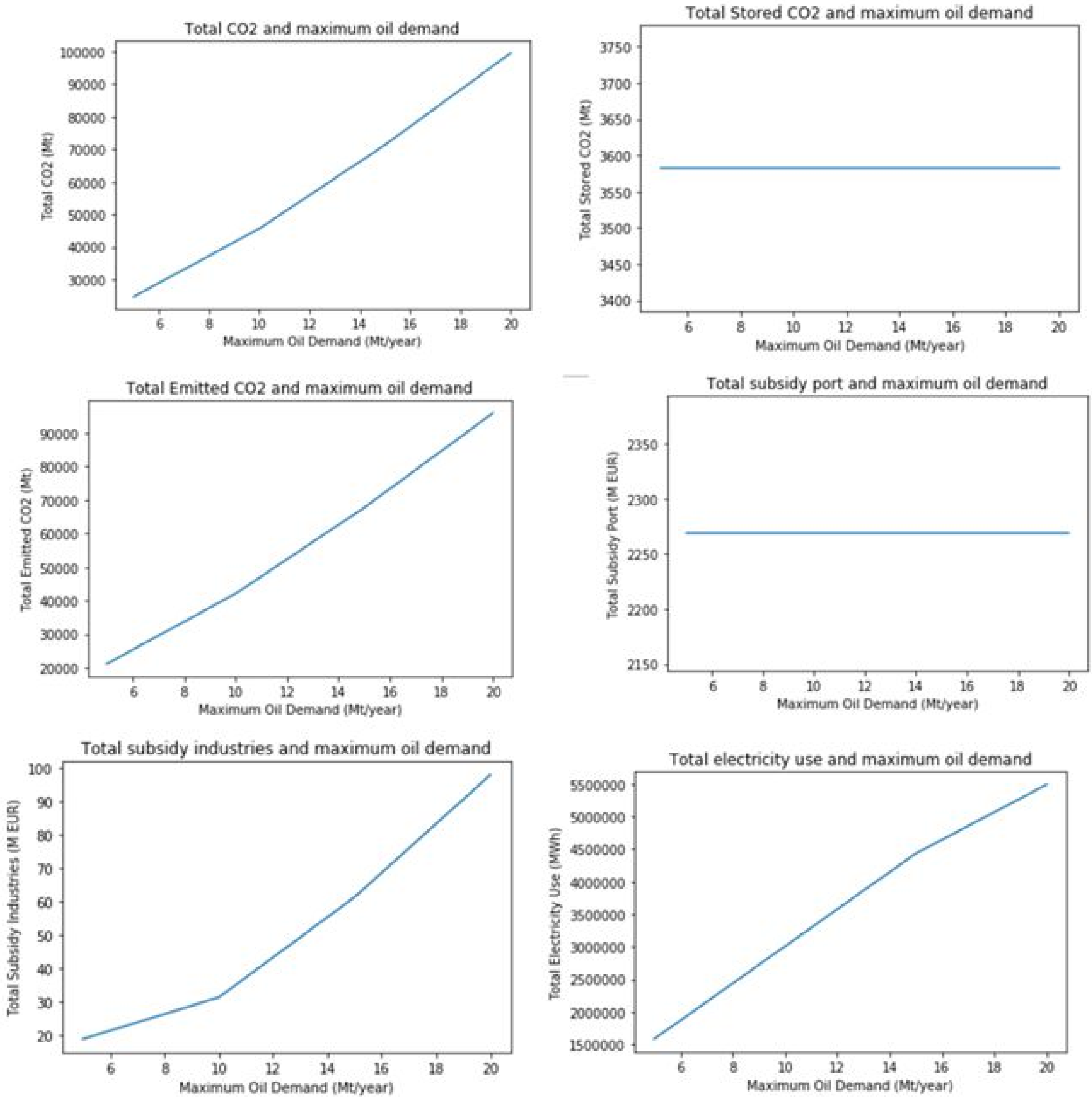

Figure 5. Effect of changing oil demands

As can be expected, an increase in oil usage, and thus a proportional increase in CO2 production, leads to more CO2 emissions and electricity use. What is unexpected, but can be seen in the other parameter graphs as well, is the stable amount of CO2 that is stored. As can be seen in the subsidies that were received by industries, more CO2 is captured by the industries when they create more CO2, but as the storages lack space, the industries can not store their CO2, which results in them emitting it after all. An increased storage capacity or the usage of more storages could therefore result in more CO2 being captured.

Electricity price

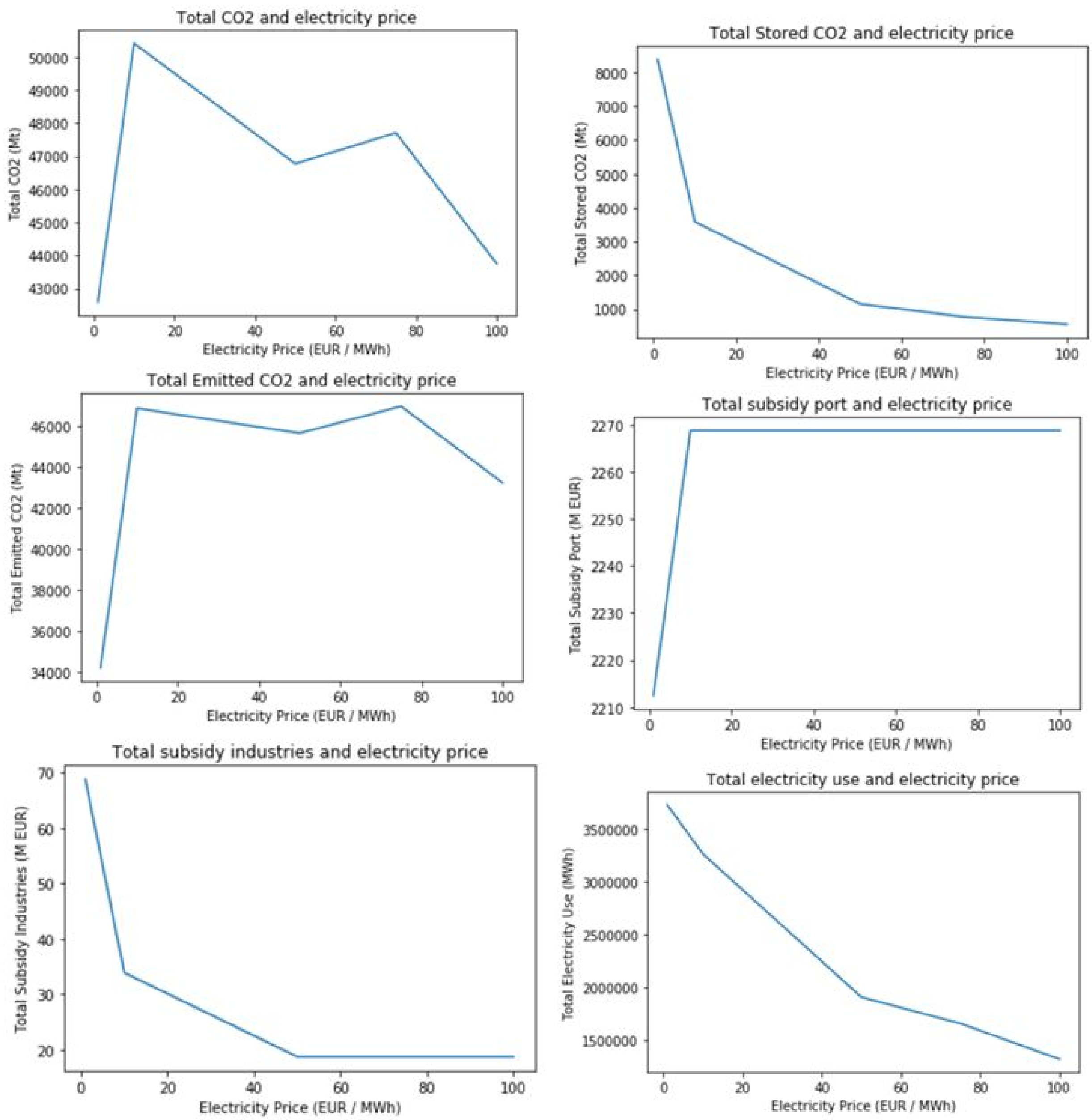

Figure 6. Effect of changing electricity price

The oil price has a negative impact on the total stored CO2 and the subsidy industries receive. As the electricity price increases, the capturing costs also increases. A considerable increase in electricity price will therefore result into less usage of the capturing of CO2. The total electricity use logically decreases with a higher electricity price. The total CO2 and emitted CO2 graphs shows indecisive conclusions. The jumps they make can be attributed to random noise as the model does not have any relation between electricity price and total CO2. Despite the repetitions randomness can still influence the results. More repetitions might decrease the random noise.

Number of industries

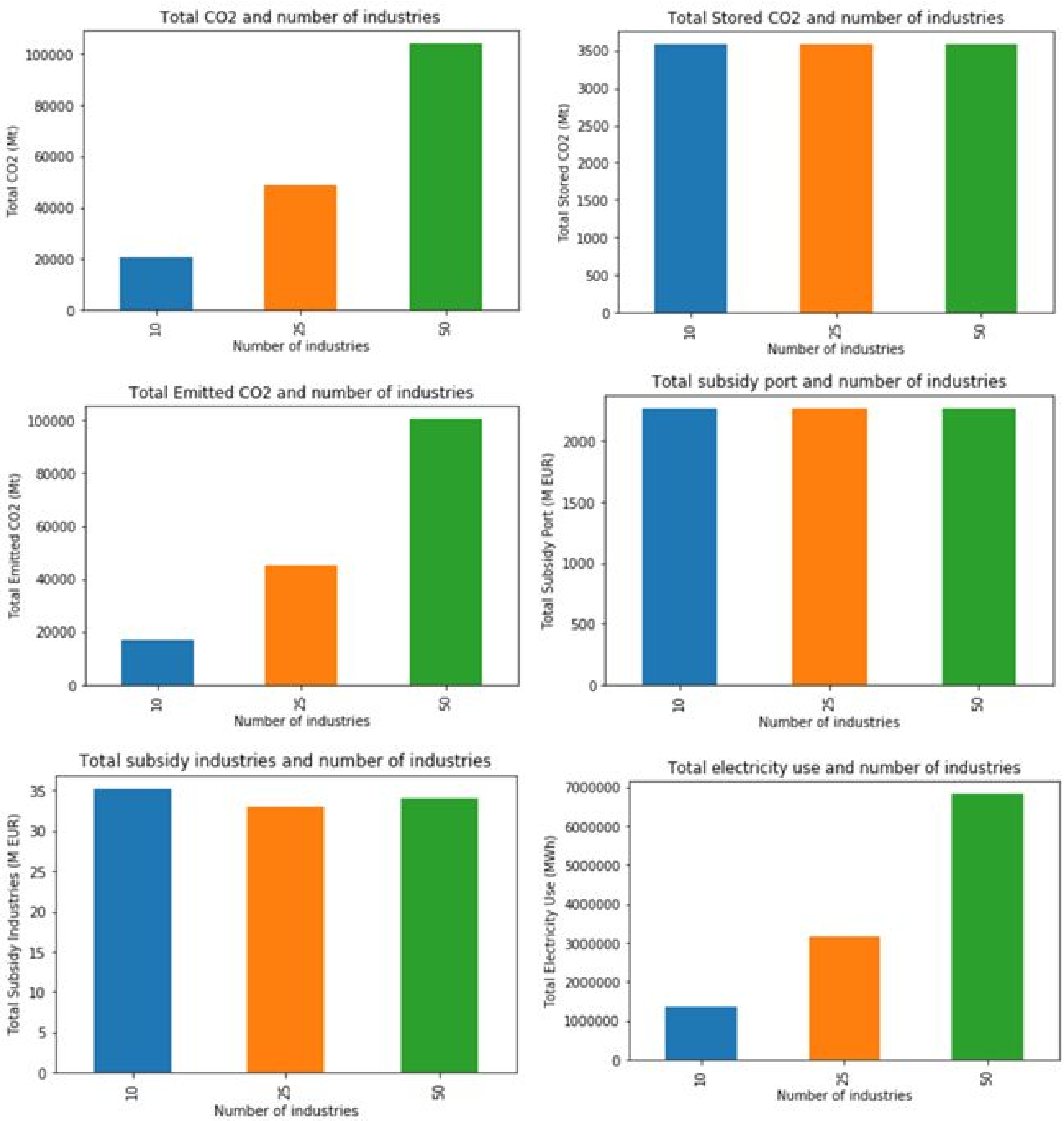

Figure 7. Effect of number of existing industries

Data visualization of the effect that the number of industries has on the KPI's shows that there are three factors this number has influence on: total CO2, total emitted CO2, and total electricity use. These can all be explained as these are aggregate scores, meaning more industries will lead to more production of CO2 and consumption of electricity. Furthermore, it is interesting what it does not affect: total stored CO2 and total subsidy industries. Total stored CO2 remains the same across all boards meaning they get filled easily without needing many industries. The subsidy also remains the same as it is distributed dependent on the amount of industries available, which means more industries receive subsidy, but the amount is less which balances out each other.

Capacity

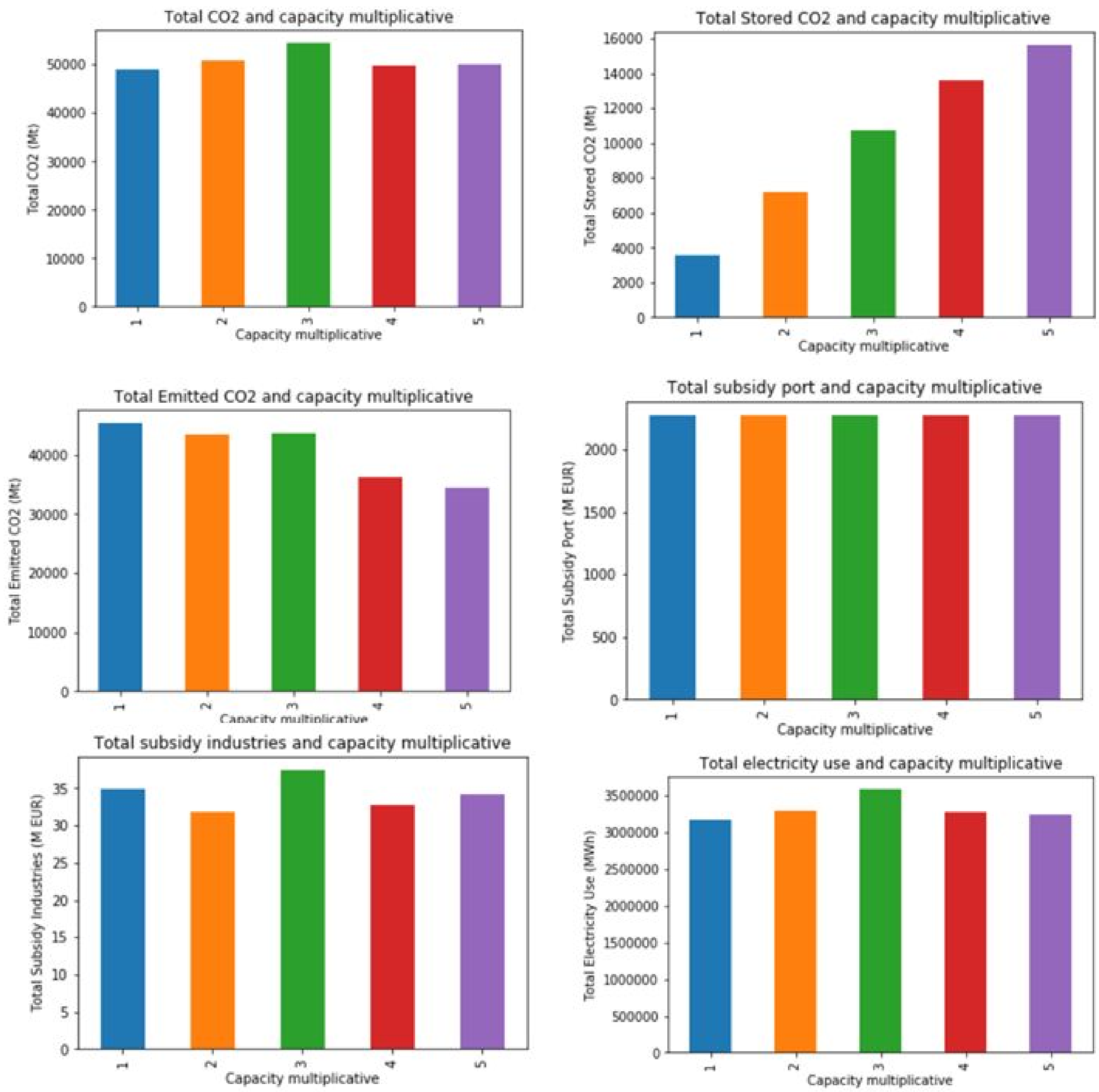

Figure 8. Effect of increased storage capacity

The KPI's are not influenced by the capacity multiplicative except for one: total stored CO2. The higher the capacity of the pipelines the more CO2 is stored. This means that under the standard conditions set the capacity was the biggest barrier for increased storage. This might have interesting implications for future policy measures as investment in technology might benefit the system more than subsidies.

4.3 Model validation

For the validation, the correspondence between the model outcomes and real-world phenomena are assessed. This will be done by considering two perspectives related to validation (Wilensky & Rand, 2015).

1. Different levels of aggregation of the validation process
   This includes microvalidation and macrovalidation. Microvalidation is analysing whether the behaviors and mechanisms of encoded in the agents are similar to real-world behaviours. Macrovalidation is ensuring that aggregate, emergent properties of the model correspond to those in the real world.

2. Different level of detail of the validation process
   Here, face validation and empirical validation are relevant. Face validation checks whether mechanisms and properties of the model look at real world mechanisms and properties. Empirical validation checks whether model outcomes resemble real-world data.

4.3.1 Microvalidation and Macrovalidation

In the model, the government grants subsidies to the Port of Rotterdam and the industries. The exact amount depends on the total budget and the percentage the government decides to grant to the Port and industries respectively. It can be assumed that underlying motivations and the outcomes of decision-making processes for the division are integrated in this percentage for the division.

The Port decides to build storage facilities when the only storages that exist are full or not extensible, which means no new storage is built when there is still a storage that can gain some CO2. One prerequisite for storages to remain operational in real life, is that they do not remain unused. Therefore, the real-world requirements to keep facilities operational are considered in the construction of storage facilities because the Port does not want the facilities to go unused for more than 10 years in a row (Ecorys & Trinomics, 2018).

Industries decide to buy capture technology only when the costs of creating and capturing CO2 are lower than the costs of emitting. This is in line with real-world considerations, especially since in the case of CCS, the initial investments which need to be made are high and there exists uncertainty in the return of investment (Global CCS Institute, 2014). It is therefore not strange that initially, it can take up to 10 years before the industries decide to store CO2 instead of emitting all their production. It has even been mentioned that this is very likely, and that initially, there will be more capacity available than necessary (Ecorys & Trinomics, 2018). The decision is made much faster when the oil demand is higher, which is realistic given that the cost of investing in capture technology per ton CO2 decreases fast.

4.3.2 Face Validation and Empirical Validation

The location of storage facilities are visible from the moment the model is setup. They have different onshore and offshore distance and capacity properties, but appear to be identical. However, depending on how much CO2 the industries emit and how large the storage capacity of facilities is, it will take longer or shorter for the storage to have reached its maximum utility. The color of the storages also easily shows whether the storage facilities have any space left for the storage of CO2: a green color indicates that the facility is operational and still has capacity left, while a red color indicates that there is no longer any space left.

In the Rotterdam Capture and Demonstration project (ROAD), the gas which was captured would be stored in depleted gas reservoirs under the ground (Zero Emissions Platform, 2013). In the model, the visible sign of the transport of CO2 is the link between industries and storage facilities. The link, a pipeline, shows the industry and the storages which are connected to each other, but does not directly indicate that CO2 is transported this way.

In the Netherlands, the only study on the capture of CO2 emission is the Port of Rotterdam CO2 Transport Hub & Offshore Storage project (Porthos-project). The majority of the CO2 would be transported to an empty gas field to the North Sea with an offshore distance of 25 km. The capacity of the reservoir would be about 2 million tons to 5 million tons of CO2 capture per year (Port of Rotterdam, 2018). In the provided data for this research, the average capacity of the pipelines alone is approximately 18 million ton of CO2 per year and the capacity of the storages can exceed 100 million tons of CO2 per year. However, in the existing model, the amount of CO2 which comes from individual industries is much higher than the total amount of CO2 emissions from an entire sector (CE Delft, 2016; CBS, 2018). Therefore the given capacities are in proportion to the amount of CO2 which is emitted.

5. Conclusion, policy suggestions, and limitations

In this conclusion section, the main research question will be answered based on the results analyzed from the agent-based model. The research question "*What is the effect of the height and type of government subsidies on the amount of CO2 stored by industries in the port region?".* This question and other potential influential factors, such as oil demand, electricity price, number of industries, and pipeline capacity, have been taken into the model.

A first important finding is that the way subsidy is distributed does not influence the amount of CO2 that is captured, as industries will eventually capture CO2 without any incentive from the outside. Because of an increasing CO2 emission price, a decreasing electricity price and an constantly increasing level of capture technology, the industries do not need any subsidy in order to invest in the capture of CO2. Apart from a minimal subsidy that the Port of Rotterdam needs in order to be able to invest in CO2 storages, also the Port does not gain from extra subsidy. As long as they can afford the storages when needed, the CO2 storage will happen optimally. Even though the subsidies will not have any reasonable effect on the amount of CO2 captured, this research has found a threshold in the capacity of the available storages. Also some scenarios were examined to strengthen the conclusion:

The electricity price is a big influence in the industries willingness to capture CO2 as the price is a big cost factor for the operation of the storage facilities; at least a higher influence than the spreading of subsidies. Furthermore, the number of industries have almost no impact in the way the subsidy is distributed at the moment. This shows that storage facilities can be interesting with even a small number of industries involved, but again shows that the current number of industries asks for a greater capacity in order to store more CO2. Lastly, pipeline capacity is the biggest factor to increase stored CO2. Because capturing CO2 becomes desirable over time, the biggest threshold is in the capacity. This insight is helpful for the long-term vision of the government. The findings in this research lead to the policy suggestion of not focussing on subsidies, other than a minimal budget for the port, but rather to focus on making enough space for the future change that the industries in the port will make towards capturing and storing their CO2. Right now this change seems far away, but this research has shown that when the change starts happening, enough storage is needed. However, it is important that storage facilities do not go unused for more than 10 years in a row. There must be sufficient insight in the demands for CO2 storage from industries for the constructions to be well-aligned, which is the next needed step in policy making. When it is known exactly how much CO2 can be captured, stored and what the costs of this are, the investing can start.

Limitations
There are several research proposals given the limitations of the model. Due to time and availability limitations, it was necessary to make assumptions regarding the behaviour of the stakeholders. For the industry for instance, it was assumed that in the trade-off between emitting or capturing CO2, the costs were the only criterium based on which the decision was made. In reality, the assumed buffer of money the industries have might not exist. Also, other motives can impact this trade-off, for example when sustainability is one of the core values of a business model. Future research can thus test the robustness of capturing CO2 by accounting for a wider range of criteria that companies can consider when making this decision.

For the spreading of the subsidy, the government is not efficient in the used model. Further research could include subsidy spreading according to the amount of CO2 that is captured, or spend the remaining subsidy on the port.

Furthermore, the model assumes a stable budget for the government within the entire timeframe of the model. In reality, economic recession can impact the budget of the government and therefore the available subsidy for the port and the industries. To account for the robustness of the capturing policy under different economic circumstances, more advanced research is necessary. One could even consider expanding the model to an EU-wide initiative, a case when subsidies can also be provided from a higher level.

Another interesting extension is assessing which uses of the stored CO2 can be facilitated given the exact amount that industries are willing to store. Research on the uses of CO2 emission after its capture provide different options, ranging from usage in biofuels to using stored CO2 as a building block for consumer goods. Research related to the uses can this way support structural policy making.

Lastly, the parameters that were investigated were only experimented with separately from each other. Interesting future research could be to combine changes in different parameters and see the effect of these combinations. In the python file “ABM Project.ipynb” code can be found that combines the changes in different parameters.This file can be used as a start in further analysis.

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