Carbon Capture and Storage in the Port of Rotterdam

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Executive Summary

The research question addressed in this report is:

What is the effect of the height and type of government subsidies and the type of infrastructure developed by the Port of Rotterdam on the amount of CO2 captured and stored from industries in the port region?

The relevant actors to this problem are identified as the Dutch Government (problem owner), the Port of Rotterdam (PoR), and the industries that operate in the port. The system is identified in a conceptual manner in such a way that it can be translated into a NetLogo model, which is finally analyzed using the EMA Workbench (Kwakkel, 2017) and SALib (Herman & Usher, 2017) packages in Python after converting the model to be Python readable using the pyNetLogo package (Jaxa-Rozen & Kwakkel, 2018).

The first experiment was a sensitivity analysis in SALib (Herman & Usher, 2017) that showed the impact of the available subsidy and the subsidy increase to reach the 2050 target on the CO2 emissions. A yearly increasing subsidy proved to be more effective and cost-effective to get industries on board. Additionally, the sensitivity analysis showed the model's sensitivity to the random seed, as industries' respective CO2 emissions and desired payback period are determined stochastically.

The second experiment was a multi objective optimization in EMA Workbench (Kwakkel, 2017) that further illustrated the policy trade-offs between subsidy granted to industries and the Port of Rotterdam. Constant monitoring of the CO2 emissions and corresponding adjustment of the available subsidies is especially important for an adaptive policy that performs acceptably in any state of the world.

Future research should focus on stakeholder engagement, both to increase mutual understanding and to improve the accuracy of the model results.

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Methodology

The problem will be addressed following the ten-step framework proposed by Van Dam, Nikiloc and Lukszo in 2013 for creating, analysing and using an agent-based model of a socio-technical system. This report will follow the same structure.

1. Problem formulation and actor identification

The Port of Rotterdam Authority (PoRA), and by extension the Dutch government, is facing important decisions regarding investment to prepare for the energy transition. The industry located in the port is highly energy intensive and is currently fully powered by fossil sources. However, electrification is regarded as a viable option by using heat pumps and direct resistive heating. These types of investments are expected to have a high impact, as 70% of the energy is used for heating and cooling requirements.

However, immediate transition to electrification is not feasible, given the large changes in capital expenditure (CAPEX). Carbon Capture and Storage (CCS) could be a transition path towards full electrification. Development of CCS is a costly operation and might require government subsidies to be adopted. Depending on industries' decisions to join or not join the CCS infrastructure, the costs of the infrastructure may or may not decrease.

This boils down to the following research question, which will be systematically investigated in the course of this report.

What is the effect of the height and type of government subsidies and the type of infrastructure developed by the Port of Rotterdam on the amount of CO2 captured and stored from industries in the port region?

Problem owner and other involved actors

The government of The Netherlands is the problem owner, as the reduction of CO_2 emissions is ultimately their responsibility. To realise their goals, cooperation of the PoRA and industry in the area are required.

2. System identification and decomposition

Next, the relevant system and level of aggregation are identified. An inventory is made of all relevant data collected (from primary and secondary sources).

2.1 Important objects to the system

The most important objects to the system are those described in table 2.1. This table presents the relevant agents and their associated states and actions. It is important for best practice to consider this thoroughly before beginning model construction in NetLogo.

Table 2.1: Identified agents with their associated states and possible actions.

Agents	**States**	**Actions**
Government	Fixed yearly budget for subsidies Current CO_2, oil, and electricity prices Distribution of subsidy KPIs	Update prices Decide on how to split annual subsidy amount Dispatch subsidy for capture tech to companies Dispatch subsidy for PoRA for pipeline development Increase CO_2 price Update KPIs
Port of Rotterdam	Price of storing CO_2 in CCS Price of connecting to CCS infrastructure Type of next CCS infrastructure - On-shore / off-shore - Extensible yes / no	Build a pipeline over time to a location - PoR uses all of its CCS money to build infrastructure (CCS subsidy income of CO_2 captured) When a CCS location is full - Build next pipeline Set price for storing 1 ton of CO_2 - Price is a slider which can be optimized - Update budget
Industry	Bool to show intent on joining CCS infrastructure or not Boolean for showing if the industry has built CCS infrastructure Payback period OPEX Have a specific CCS technology (fixed or extensible connection) Heat / cold requirement - Bool to show intent on joining CCS infrastructure or not - Boolean for showing if the industry	Decide intent based on: CAPEX of capture technology, OPEX with or without capture and their internal ROI. Decide to build if PoR has built new infrastructure Pay (to PoR) for using the CCS storage

The rest of the system should also be considered in an object-oriented manner, as this improves the modelling process. Aside from the so-called agents in table 2.1, other objects are considered that are relevant to the system, but do not explicitly act on other objects in the system. Table 2.2 identifies these objects and their associated attributes on a high level.

Table 2.2: Identified objects with their associated attributes.

Objects	Attributes

Infrastructure	- Location: onshore/offshore
	- Type: extensible/fixed
	- Distance from the port in km
	- Max capacity (T/year)
	- Price of construction of pipeline in km/MEUR
	  - On-shore / off-shore
	  - Extensible / fixed
	- Can only start storing CO2 when finished
	- Fixed / Extensible
	  - Additional companies can connect once building starts: yes/no
	- Has maximum capacity of Ton/year
	  - **Assumption:** Infinite total storage, only yearly flow rate is capped

Capture Technology	- ***defined intrinsic to industries breed, not an object.** - Has maximum capture capacity in Ton/year - CAPEX and electricity use based on capacity - Can be built in 1 year - Every year a 10% larger unit becomes available, for 10 % lower cost - Initial capacity and price

2.2 Interactions between agents

Before the addition of a variable subsidy provided by the PoR, the interactions in the system can be summarized by figure 2.2.1. It is important to understand that the information given by the government as shown in figure 2.2.1 is unidirectional, meaning that this information is independent of system behaviour. Crucially, as is discussed in section 2.3, the government will also have a role in changing the subsidy based on information from the rest of the system. This would be captured by additional arrows pointing from PoRA and Industry back to Government. The loop between Industry and PoRA indicates that the Industry and PoRA are highly dependent on each other.

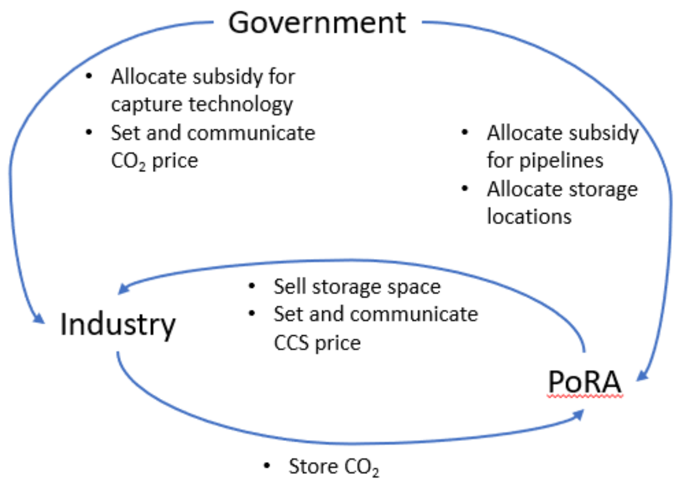

Figure 2.2.1: High level action map that gives the directionality of actions and on whom those actions are impactful.

2.3 Environment

The system definition provided in this report is meant to be conducive to the modelling process. As such, the environment is quite restricted. The prices for CO_2 emissions, oil, and electricity constitute the major environmental effects. For the purpose of this project, the government provides this information to the relevant actors. As such, the government could be considered as the environment if not for the fact that they also have a hand in changing the subsidy prices which requires feedback from the rest of the system. So, the government has a dual role in providing environmental information to the system, but also as *part of the system* that requires a bidirectional link with the industries and PoR. Ultimately, though, the environment is captured by the unidirectional information that the government hands out to the PoR and industries.

3. Concept formalisation

Concepts are translated/formalized into computer readable format. This can be done using a formal ontology, or a translation to computer primitives. The conceptual formalisation of the model is done by translating the anticipated variables for each agent (or object) into their primitive types. Then, units are supplied for a sanity check.

3.1 Agents and their data

The Government is an agent that acts similarly to an environment with the key difference being that they can adjust the subsidy levels in order to meet 2050 emissions targets. The Port of Rotterdam (PoR) agent is the intermediary between the Government and Industries. The PoR builds pipelines and sets the price for using the CCS infrastructure. The Industry agents main job is to determine if CCS is expected to be viable based on their knowledge of prices. The storage points are mainly used as placeholders and once they are placed, do not have any additional effect on the system. Finally, the Pipelines are a simple undirected link from either Industries to the PoR or storage points to the PoR. The Pipelines will not have any behavior in the NetLogo model.

Table 3.1:

Agent / Object	**Variable**	**Data Type**	**Units**
Government	Total yearly subsidy	Integer	€/year
	Subsidy per CO_2 emissions	Integer	€/tonCO_2
	CO_2 price	List of integers	€/tonCO_2
	Oil price	List of integers	€/tonOil
	Electricity price	List of lists	€/MWh
Port of Rotterdam	CCS connection price	Integer	€
	Available capacity	Double	tonCO_2/year
	OPEX for extensible	Integer	€/tonCO_2
	OPEX for fixed	Integer	€/tonCO_2
	Budget	Integer	€
	Price of next pipeline (to be built)	Integer	€
	Capacity of next pipeline	Double	tonCO_2/year
	Most recent (built) pipeline fixed (or not)	Boolean	N/A
Industry	Oil demand	Integer	tonOil/year
	CO_2 emissions per oil	Double	tonCO_2/tonOil

	CO_2 emissions	Double	$tonCO_2$
	OPEX oil (no CCS)	Integer	€
	Electricity use for CCS	Integer	$MWh/tonCO_2$
	Industry OPEX fixed	Integer	€
	Industry OPEX extensible	Integer	€
	CAPEX to join CCS	Integer	€
	Intent on building	Boolean	N/A
	Industry has built	Boolean	N/A
	Payback period	Integer	Year
	Extensible connection	Boolean	N/A
	Fixed connection	Boolean	N/A
	Previous CO_2 price	Integer	€/$tonCO_2$
	Expected CO_2 price	Integer	€/$tonCO_2$
	Previous oil price	Integer	€/$tonCO_2$
	Expected oil price	Integer	€/$tonCO_2$
Storage points	Location	String	N/A
	Pipeline capacity	Integer	$tonCO_2$/year
	Onshore distance	Integer	km
	Offshore distance	Integer	km
	CAPEX for onshore	Integer	€/km

	CAPEX for offshore	Integer	€/km
Pipelines	Start point	Undirected link path	N/A
	End point		

3.2 Note on units and visualization

Due to the nature of the project, the provided data and the resulting visualization the initial data was altered to reflect realistic values and thus promote proper model behaviour. Units were adjusted for comprehension, and in some cases values were adjusted to an appropriate order of magnitude. Finally, the model visualization is **not** to scale, however, any distance values used in the model evaluations do reflect the provided data on distances.

4. Model formalisation

To build a generative model, the agents' actions and their timing is described in a model narrative. This story of agents' actions and interactions gives rise to the emergent patterns of interest. This story is then transformed into corresponding pseudo-code to facilitate the modeling process. In the previous two sections, the attributes of agents (section 3) and interactions in the system (section 2) have been discussed. The remainder of this section will use the following structure: First, in subsection 4.1, the overarching sequence of actions in a tick is given, then in subsections 4.2 - 4.8, pseudocode is given for each of the procedures in the sequence as well as whom the procedure is most relevant for, and finally, in subsection 4.9, the assumptions needed for the model are provided.

4.1 High level sequence

The procedures outlined in this subsection will be numbered and this numbering is used to title the respective subsections. The sequence begins with **(1)** the Government reviewing the previous years CO_2 emissions to the air and increasing (or not) the subsidy level according to the goal of 0 emissions in 2050, or the final tick. Then, **(2)** the Industries who declared intent to build in the previous tick will check the availability of unused storage capacity. The 1 tick delay is meant to emulate a 1 year building period, otherwise the build procedure would occur at the end of the previous tick. **(3)** The PoR updates the availability based on how many industries connect and the pipeline type. Next, **(4)** the Industries decide if it is economically viable to build CCS infrastructure and thus declare their intent to build given that there is sufficient capacity. **(5)** The Government then hands out the remaining subsidy to the PoR so that **(6)** the PoR can decide to build a pipeline (or not) and update commodity prices for this year. Finally, **(7)** the Industries pay a yearly fee to the PoR for using their CCS storage points.

4.2 Procedure 1: updating subsidy to reflect 2050 target

This procedure is owned by the Government and its purpose is to make the yearly subsidy dynamic such that the 2050 emission target of 0 emissions is achieved. It also serves to reset the subsidy at the beginning of the year.

4.2.1 Pseudocode

```
1. Set emissions-diff to difference between CO₂ emissions of this and last
   year
2. If CO₂-emissions-this-year > emissions-diff * years-left-in-simm
   a. Then increase subsidy to both PoR and Industries according to percentage
      set by modeller in slider
   b. Reset subsidy for this year to new base amount
3. Else
  a. Reset subsidy for this year to base amount
```

4.3 Procedure 2: Industries building CCS infrastructure

This procedure is owned by the Industries. Its purpose is to allow for the Industries to check if there is available capacity and then decide to build based on that capacity. The reason this happens at the beginning of the tick is that it imitates a 1 year building delay because of the 'intent to build' procedure happening after it. So, industries are inherently always delayed a minimum of 1 year between when they decide on intent to build and actually build. This period of delay can be longer if the PoR has insufficient budget to build a new pipeline.

4.3.1 Pseudocode

```
1. If CO₂ emissions by some Industry with intent to build < available storage
   capacity (build)
    a. Set CCS-is-built to True for said Industry
    b. Check if connecting to fixed or extensible pipeline
      i.  Set boolean value to connection-fixed OR connection-extensible
    c. Take subsidy away from total available subsidy of government
    d. Create pipeline with PoR
2. Else
   a. Do nothing
```

4.4 Procedure 3: updating capacity availability

This procedure is pertinent to the PoR. The purpose is to subtract from the unused capacity as new Industries build infrastructure and use it. When the most recent pipeline is fixed, it is assumed that the previously unused extensible capacity is all used up before then using the fixed capacity, which is why the unused capacity would then be set to 0 in this case.

4.4.1 Pseudocode

```
1. If previous pipeline fixed and industries have connected to it
   a. Reset availability to 0
2. Else (pipeline is extensible)
   a. Remove availability as industries connect
```

4.5 Procedure 4: declaring intent to build

This procedure is owned by the Industries. It allows for the companies to declare their intent to build CCS infrastructure so that the PoR can react accordingly if more pipeline infrastructure is necessary. This is also more realistic, as Industries should not want to build CCS infrastructure if there is no pipeline for them to connect to.

4.5.1 Pseudocode

```
1. Compute values for OPEX-extensible (assume worst case), CAPEX-CCS, and
```

```
   OPEX-no-CCS
2. If OPEX-no-CCS > OPEX-extensible + CAPEX-CCS / payback-period - subsidy
   a. Set intent-to-build to True
```

4.6 Procedure 5: giving subsidy to PoR

This procedure is performed by the Industries. It is simply used to add to the PoR's budget before they build a pipeline, in case the extra subsidy is immediately necessary.

4.6.1 Pseudocode

```
1. Set PoR budget to previous budget + subsidy
```

4.7 Procedure 6: building a pipeline

This procedure is owned by the PoR. Though it seems that the building of the pipeline happens instantaneously, the effect of it is only felt in the next tick. This is why the Industries decide to build at the beginning of the tick, to model the 1 year delay. The PoR looks at Industries with a declared intent to build CCS infrastructure and then compares this to the available unused capacity, allowing them to see if there is more capacity necessary to fulfill requests.

4.7.1 Pseudocode

```
1. Get combined total-emissions from all industries with declared intent to
   build
2. If pipeline-availability < total-emissions and PoR-budget > price-of-
   pipeline
   a. If total-emissions > 0.7 * next-pipeline-capacity
       i. Build fixed pipeline
      ii. Subtract from budget
   b. Else
       i. Build extensible pipeline
      ii. Subtract from budget
```

4.8 Procedure 7: pay yearly fee for using CCS infrastructure

This procedure is owned by the Industries and its purpose is to add the yearly fee for using the PoR's storage points to the PoR's budget. Industries must check if they have extensible or fixed connection and then 'pay' the amount corresponding to their own CO_2 emissions.

4.8.1 Pseudocode

```
1. For all industries connected to extensible pipelines
   a. Set payment-extensible to CO2-emission * cost-to-use-extensible
```

```
   b. Set PoR-budget to PoR-budget + payment-extensible
2. For all industries connected to fixed pipelines
   a. Set payment-fixed to CO₂-emission * cost-to-use-fixed
   b. Set PoR-budget to PoR-budget + payment-fixed
```

4.9 Model assumptions

The assumptions in table 4.9.1 are made to ensure that the model behaves realistically. On occasion, some of the supplied variables were adjusted to better reflect reality. Anything that is not listed in this table is unchanged from the supplied .csv files and problem description.

Table 4.9.1: List of model assumptions.

Issue	Assumption Made
Setup	Oil demand for Industries is a uniform random number between 1 and 10 kilotons (as opposed to the supplied 1 to 10 megatons). It was found that kilotons made more sense in the model given the other supplied units (see section 3.1).
	Initial budget of PoR is arbitrarily set to €10M as the Government has no power over this value and the yearly subsidy is much more important for their research question.
Storage capacity	Set to be x3000 of the original amount and the units are changed to tons (eg. 3 megatons => 9000 tons). This value was chosen to better match the oil demanded and resulting CO_2 emissions of Industries. However, any multiplier of a similar order of magnitude to 3000 could also have been used for similar results (see section 3.1).
Price for Industries to use CCS infrastructure	Set with a slider at the beginning of the run. The price for using a fixed pipeline is 70% that of extensible pipelines.
Memory depth for price expectations	Industries only remember the previous two prices for CO_2 and oil when determining the expected future price. The main reason for using a depth of two rather than a larger one is that the effect of the expected price can only shift the build decision by 1 tick.
Usage of fixed pipelines	Fixed pipelines are used in cases when the sum of CO_2 emissions of Industries wishing to connect to CCS is over 70% of the sum of unused capacity and next (unbuilt) pipeline capacity.
	When a pipeline is built as fixed, the remainder of the unused extensible capacity from before is used, thus setting the new available capacity to 0.

Distribution of subsidy	Subsidy is distributed first to Industries that are building in this tick, then the remaining subsidy is given to the PoR. This is assumed because the PoR can only store CO2 if there are industries capturing CO2.
Frequency of subsidy to Industries	Subsidy is only given to an Industry (subtracted from the Government) in the tick that it decides to build (one-off).
Subsidy increase to reflect 2050 goals	The total level of the subsidy per year supplied by the government can only be increased and by a static percentage set by a slider.
	The €/tonCO_2 amount can only be increased and by a static percentage that is set separately from the total subsidy percentage increase value.
PoR budget required to build	In order to build a pipeline, the PoR must be able to maintain a positive budget after building.
Pipeline build frequency	PoR can only build one pipeline in a year.
Pipeline directionality and functionality	Pipelines are bidirectional, start and end point are irrelevant.
	No additional functionality, purely visual.
When Industries want to build	Industries will not pay to build CCS unless there is enough capacity. This way, at the end of the run, it is easier to see if PoR had enough time / money to build enough pipelines for all the industries.
Storages and Industry placement	Both placed arbitrarily in a region that looks good visually on the map. Their placement does not reflect how the model runs internally.

5. Software implementation

5.1 Modeling environment

The model is constructed using NetLogo (SOURCE) (version 6.1.0). This software allows easy implementation of agent-based models. However, this simplicity limits the complexity of the model.

5.2 Programming practices

5.2.1 Version control

A GitHub repository was created for version control. Code was only pushed when it was sufficiently documented. The large majority of the code was written using the 'extreme coding' practice in which one person would type while one or two other people would watch and give feedback and corrections on the fly.

5.2.2 Documenting code

Every variable was documented when first introduced using the syntax [type] [unit] - [explanation], for example: *co2-price ; int [Eur/ton of CO2] - Price of CO2 emissions*. Each procedure is put under a category according to who the procedure is most relevant to. The procedures each have a 'purpose' section that explains what the procedure is used for and when deemed necessary, the purpose of specific lines of code were explained separately. . At the top of the code tab and in the info tab, there is an explanation of how to use the code and how to interpret the visualization.

5.2.3 Naming conventions

Breeds are capitalized in the code so that they stand out more and all procedures and other variables are lowercase and separated with the '-' sign. Any global variables have 'global' attached to the end of them. 'temp' or 'curr' is attached to the beginning of variables that are only temporarily used in a procedure.

5.3 Base case

The base case defines values for the sliders as seen in NetLogo as these are the variables that are adjusted for experimentation. The base case values for these are shown in table 7.1.1.

Table 7.1.1: Values used for the base case.

Variable	Value
total-available-subsidy	€50,000,000
subsidy-for-industries	100 €/tonCO_2
total-subsidy-increase-for-target	2.0 %
industry-subsidy-increase-for-target	2.0 %
extensible-storage-price	10.0 €/tonCO_2

The values in table 7.1.1 were chosen because they represent a standard run with relatively normal values where in any given run, the outcome can be either that all Industries are connected to the CCS infrastructure or *almost* all (sans 1 to 3) industries are connected to the CO_2

infrastructure. This provides a base case with interesting enough behaviour to serve as a starting point for analysis.

6. Model verification

Model verification is extremely important as it confirms or denies whether the modeller has successfully managed to build an adequate representation of the system under scrutiny. To fully verify the model we make use of: (6.1) single agent behaviour testing; (6.2) interaction testing; and (6.3) multi-agent testing. Together these methods allow us to verify the model behaviour.

6.1 Single agent behaviour tracking

In order to verify agent behaviour we track single agents as they make decisions and evaluate whether the decisions being made are logical under the modelling assumptions. In order to evaluate agent decisions we make use of NetLogo to determine decisions and to feed agents extreme values. Additionally, we perform sanity checks in Excel for the Industries agent.

6.1.1 Industries

Normal values - verification

The sanity check for the industries is straightforward as the industries are modelled with an intent (boolean) to build or not build CCS. The intent is purely dependent on the operational expenses (OPEX) associated with either situation. This modelling assumption allows us to do a deterministic calculation of the point in time when the average industry could declare intent to build CCS. The average industry is one with an oil demand of 6000 ton/year and a payback period of 12,5 years. *Tables 6.1.1* and *6.1.2* show the result of this calculation. In short this test allows us to make explicit predictions of what we theoretically expect the industry agent to do when we provide well-defined inputs.

Table 6.1.1: Industry sanity check - no subsidy

Validation of a single INDUSRTY (agent) declaring intent to build CCS									
Mean oil demand	6000	t/yr							
Mean payback period	12,5	yr							
Subsidy industry	0	EUR/t CO2							
	Base case: NO CCS			Case 1: CCS					
Tick	Oil demand (t/yr)	CO2 emissions (t/yr)	Cost CO2 emissions (EUR/yr)	Capex CCS	Opex CCS elec. (EUR/yr)	Opex CCS exst. pipeline (EUR/yr)	Subsidy (EUR/yr)	Total cost CCS (EUR/yr)	CCS (1) or NO CCS (0)
1	6000	19200	€ 384.000	€ 276.480	€ 1.778.400	€ 5.760	€ -	€ 2.060.640	0
2	6000	19200	€ 384.000	€ 248.832	€ 1.689.480	€ 5.760	€ -	€ 1.944.072	0
3	6000	19200	€ 384.000	€ 223.949	€ 1.605.006	€ 5.760	€ -	€ 1.834.715	0
4	6000	19200	€ 576.000	€ 201.554	€ 1.524.756	€ 5.760	€ -	€ 1.732.070	0
5	6000	19200	€ 576.000	€ 181.399	€ 1.448.518	€ 5.760	€ -	€ 1.635.676	0
6	6000	19200	€ 576.000	€ 163.259	€ 1.376.092	€ 5.760	€ -	€ 1.545.111	0
7	6000	19200	€ 768.000	€ 146.933	€ 1.307.287	€ 5.760	€ -	€ 1.459.980	0
8	6000	19200	€ 960.000	€ 132.240	€ 1.241.923	€ 5.760	€ -	€ 1.379.923	0
9	6000	19200	€ 960.000	€ 119.016	€ 1.179.827	€ 5.760	€ -	€ 1.304.602	0
10	6000	19200	€ 1.152.000	€ 107.114	€ 1.120.836	€ 5.760	€ -	€ 1.233.710	0
11	6000	19200	€ 1.152.000	€ 96.403	€ 1.064.794	€ 5.760	€ -	€ 1.166.956	0
12	6000	19200	€ 1.152.000	€ 86.762	€ 1.011.554	€ 5.760	€ -	€ 1.104.076	1
13	6000	19200	€ 1.152.000	€ 78.086	€ 960.976	€ 5.760	€ -	€ 1.044.822	1
14	6000	19200	€ 1.344.000	€ 70.278	€ 912.928	€ 5.760	€ -	€ 988.965	1
15	6000	19200	€ 1.536.000	€ 63.250	€ 867.281	€ 5.760	€ -	€ 936.291	1
16	6000	19200	€ 1.536.000	€ 56.925	€ 823.917	€ 5.760	€ -	€ 886.602	1
17	6000	19200	€ 1.536.000	€ 51.232	€ 782.721	€ 5.760	€ -	€ 839.714	1
18	6000	19200	€ 1.536.000	€ 46.109	€ 743.585	€ 5.760	€ -	€ 795.454	1
19	6000	19200	€ 1.536.000	€ 41.498	€ 706.406	€ 5.760	€ -	€ 753.664	1
20	6000	19200	€ 1.728.000	€ 37.348	€ 671.086	€ 5.760	€ -	€ 714.194	1
21	6000	19200	€ 1.920.000	€ 33.614	€ 637.531	€ 5.760	€ -	€ 676.905	1
22	6000	19200	€ 2.112.000	€ 30.252	€ 605.655	€ 5.760	€ -	€ 641.667	1
23	6000	19200	€ 2.304.000	€ 27.227	€ 575.372	€ 5.760	€ -	€ 608.359	1
24	6000	19200	€ 2.496.000	€ 24.504	€ 546.603	€ 5.760	€ -	€ 576.868	1
25	6000	19200	€ 2.688.000	€ 22.054	€ 519.273	€ 5.760	€ -	€ 547.087	1
26	6000	19200	€ 3.840.000	€ 19.848	€ 493.310	€ 5.760	€ -	€ 518.918	1
27	6000	19200	€ 4.224.000	€ 17.864	€ 468.644	€ 5.760	€ -	€ 492.268	1
28	6000	19200	€ 4.608.000	€ 16.077	€ 445.212	€ 5.760	€ -	€ 467.049	1
29	6000	19200	€ 4.992.000	€ 14.470	€ 422.951	€ 5.760	€ -	€ 443.181	1
30	6000	19200	€ 5.376.000	€ 13.023	€ 401.804	€ 5.760	€ -	€ 420.586	1
31	6000	19200	€ 5.760.000	€ 11.720	€ 381.714	€ 5.760	€ -	€ 399.194	1

Table 6.1.1 shows the calculation of OPEX under the base case: no CCS and under case 1: CCS, with no government subsidy for industries. The table shows that the average industry should declare intent to build CCS on the 12th tick, which is consistent with our NetLogo model.

Table 6.1.2: Industry sanity check - <u>with subsidy</u>

Validation of a single INDUSRTY (agent) declaring intent to build CCS									
Mean oil demand	6000	t/yr							
Mean payback period	12,5	yr							
Subsidy industry	50	EUR/t CO2							
	Base case: NO CCS			Case 1: CCS					
Tick	Oil demand (t/yr)	CO2 emissions (t/yr)	Cost CO2 emissions (EUR/yr)	Capex CCS	Opex CCS elec. (EUR/yr)	Opex CCS exst. pipeline (EUR/yr)	Subsidy (EUR/yr)	Total cost CCS (EUR/yr)	CCS (1) or NO CCS (0)
1	6000	19200	€ 384.000	€ 276.480	€ 1.778.400	€ 5.760	€ 960.000	€ 1.100.640	0
2	6000	19200	€ 384.000	€ 248.832	€ 1.689.480	€ 5.760	€ 960.000	€ 984.072	0
3	6000	19200	€ 384.000	€ 223.949	€ 1.605.006	€ 5.760	€ 960.000	€ 874.715	0
4	6000	19200	€ 576.000	€ 201.554	€ 1.524.756	€ 5.760	€ 960.000	€ 772.070	0
5	6000	19200	€ 576.000	€ 181.399	€ 1.448.518	€ 5.760	€ 960.000	€ 675.676	0
6	6000	19200	€ 576.000	€ 163.259	€ 1.376.092	€ 5.760	€ 960.000	€ 585.111	0
7	6000	19200	€ 768.000	€ 146.933	€ 1.307.287	€ 5.760	€ 960.000	€ 499.980	1
8	6000	19200	€ 960.000	€ 132.240	€ 1.241.923	€ 5.760	€ 960.000	€ 419.923	1
9	6000	19200	€ 960.000	€ 119.016	€ 1.179.827	€ 5.760	€ 960.000	€ 344.602	1
10	6000	19200	€ 1.152.000	€ 107.114	€ 1.120.836	€ 5.760	€ 960.000	€ 273.710	1
11	6000	19200	€ 1.152.000	€ 96.403	€ 1.064.794	€ 5.760	€ 960.000	€ 206.956	1
12	6000	19200	€ 1.152.000	€ 86.762	€ 1.011.554	€ 5.760	€ 960.000	€ 144.076	1
13	6000	19200	€ 1.152.000	€ 78.086	€ 960.976	€ 5.760	€ 960.000	€ 84.822	1
14	6000	19200	€ 1.344.000	€ 70.278	€ 912.928	€ 5.760	€ 960.000	€ 28.965	1
15	6000	19200	€ 1.536.000	€ 63.250	€ 867.281	€ 5.760	€ 960.000	-€ 23.709	1
16	6000	19200	€ 1.536.000	€ 56.925	€ 823.917	€ 5.760	€ 960.000	-€ 73.398	1
17	6000	19200	€ 1.536.000	€ 51.232	€ 782.721	€ 5.760	€ 960.000	-€ 120.286	1
18	6000	19200	€ 1.536.000	€ 46.109	€ 743.585	€ 5.760	€ 960.000	-€ 164.546	1
19	6000	19200	€ 1.536.000	€ 41.498	€ 706.406	€ 5.760	€ 960.000	-€ 206.336	1
20	6000	19200	€ 1.728.000	€ 37.348	€ 671.086	€ 5.760	€ 960.000	-€ 245.806	1
21	6000	19200	€ 1.920.000	€ 33.614	€ 637.531	€ 5.760	€ 960.000	-€ 283.095	1
22	6000	19200	€ 2.112.000	€ 30.252	€ 605.655	€ 5.760	€ 960.000	-€ 318.333	1
23	6000	19200	€ 2.304.000	€ 27.227	€ 575.372	€ 5.760	€ 960.000	-€ 351.641	1
24	6000	19200	€ 2.496.000	€ 24.504	€ 546.603	€ 5.760	€ 960.000	-€ 383.132	1
25	6000	19200	€ 2.688.000	€ 22.054	€ 519.273	€ 5.760	€ 960.000	-€ 412.913	1
26	6000	19200	€ 3.840.000	€ 19.848	€ 493.310	€ 5.760	€ 960.000	-€ 441.082	1
27	6000	19200	€ 4.224.000	€ 17.864	€ 468.644	€ 5.760	€ 960.000	-€ 467.732	1
28	6000	19200	€ 4.608.000	€ 16.077	€ 445.212	€ 5.760	€ 960.000	-€ 492.951	1
29	6000	19200	€ 4.992.000	€ 14.470	€ 422.951	€ 5.760	€ 960.000	-€ 516.819	1
30	6000	19200	€ 5.376.000	€ 13.023	€ 401.804	€ 5.760	€ 960.000	-€ 539.414	1
31	6000	19200	€ 5.760.000	€ 11.720	€ 381.714	€ 5.760	€ 960.000	-€ 560.806	1

Table 6.1.2 shows the industry intent to build under a scenario with subsidy. When comparing tables 6.1.1 and 6.1.2 we clearly see that the moment industries declare intent moves up to tick 7. This finding is consistent with our NetLogo model.

From tables 6.1.1 and 6.1.2 we can conclude that industry agents make the intended decision when declaring intent to build CCS. After declaring intent, industry agents actually build CCS based on the available storage declared by the Port of Rotterdam agent, something which can not be tested in Excel. A final conclusions drawn from this analysis is that the logic in the NetLogo model responsible for industry agent intent is highly sensitive to the *capture-opex-electricity* variable. This variable is an order of magnitude larger than any other in the model and is therefore very influential.

Extreme values - verification

An additional sanity check involves feeding the industry agent with extreme values. The primary finding from this is mentioned above, namely a sensitivity to the *capture-opex-electricity* variable. This sensitivity has an effect on the intent and can shift it up or down the table. The level of subsidy provided to agents has a similar effect.

6.1.2 Port of Rotterdam

Normal values - verification

The Port of Rotterdam (PoR) agent is a single agent acting autonomously within the model. The main purpose for the PoR agent is to build off-/onshore carbon storage facilities and connect these to the mainland, thus supplying the industry agents with a sink for their captured carbon. The PoR agent does this by looking at: (1) whether any agents declared intent to build CCS; (2) whether the current storage capacity is sufficient to accommodate future industry agents CO2 output; (3) whether it has sufficient budget; and (4) whether it makes sense to build a fixed or extensible pipeline. We verify that the PoR agent adequately performs these checks in NetLogo. This behaviour is verified.

Due to the nature of the division of subsidy in the model, the PoR agent behaviour is mainly sensitive to the *total-available-subsidy* variable. Since the PoR agent is unable to build a storage facility without sufficient account balance, it can take a number of years, sometimes beyond the time-horizon of the model, before all industry agents with intent to build CCS can be facilitated by the PoR agent. Under extreme values, this effect is strengthened. This behaviour is confirmed.

6.1.3 Government

Normal values - verification

The government agent plays a limited role in the model implementation, regardless of the fact that the government is the problem owner. The only responsibilities carried out by the government agent are to: (1) update prices of oil and CO2 emissions; (2) adjust *total-available-subsidy* variable to meet 2050 carbon neutral target; and (3) adjust the subsidy going to industries to meet the 2050 carbon neutral target. As a result the government agent only inspects the total CO2 emitted to the atmosphere and the distance to zero. This means that the only variable influencing government agent behaviour is the total CO2 emitted to the atmosphere.

6.2 Interaction tests

To verify that agents are interacting as intended within the model we spawn the government and PoR agents as well as a single industry. This allows any further interactions between industry agents to be ignored. The model is evaluated one step at a time in order to record behaviour. Table 6.3.1 shows the instance of the model described above in a number of noteworthy ticks.

Table 6.2.1: Agent interaction record

Tick	Visual	Explanation
5		• At tick 5 the industry agent declares intent (yellow) to build CCS. • Agent intent prompts the PoR agent to build a pipeline to the next available storage location.
6		• In tick 6 we see that the industry agent does not build CCS but instead remains intent (yellow). • The PoR agent builds another pipeline because the capacity of the previous pipeline was not enough to facilitate the industry agent's CO2 emissions.
8		• The process above repeats itself until tick 8. • The PoR agent has now built 4 storages with accompanying pipelines to facilitate the industry agent's emissions.
9		• In tick 9 the industry agent gets confirmation that there is sufficient capacity available to store their CO2 emissions. • The industry connects and pays the connection fee to the PoR agent.

As shown in table 6.3.1, agent interaction is verified to work as intended. Industry agent demand for CO2 storage prompts the PoR agent to build storage until demand is met. Note that we assume that the Port of Rotterdam (real) is only capable of orchestrating a single pipeline build per year. Without this constraint the PoR agent could have built the required 4 pipelines in tick 5 as shown in table 6.3.1.

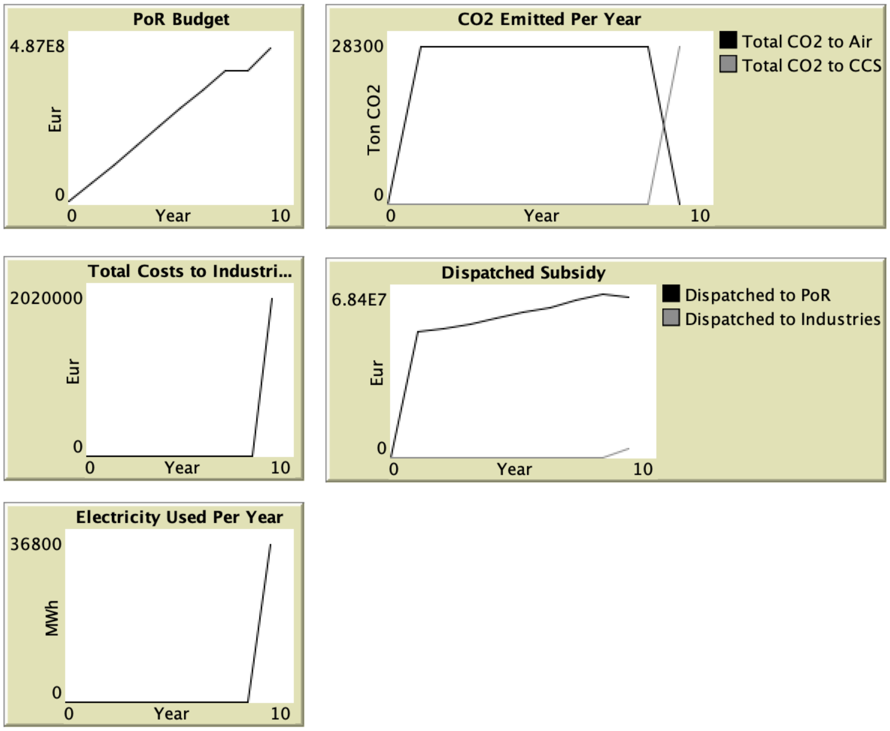

Figure 6.2.1: Key performance indicators for interaction test

To determine whether all three agents act appropriately internally we inspect the key performance indicators in Figure 6.3.1. We see that the PoR agent budget is rising steadily, which can be explained by the relatively insignificant investment required for the first 4 storage locations. We observe CO2 emitted per year at zero in tick 9 as the single industry has built CCS in tick 8. Cost to the industry agent as well as electricity used per year increase as CCS is an expensive business. Subsidy dispatched to industry increased as of tick 8, this comes out of the subsidy to the PoR agent. The values look good and allow us to conclude that the model interactions are verifiable.

6.3 Multi agent testing

In order to verify the entire model behaviour we run over twelve-thousand model runs using a full-factorial evaluation (behaviour space in NetLogo) and evaluate key performance indicator behaviour. The KPIs monitored are:

- Total-co2-emitted-to-air
- Total-co2-stored
- Total-electricity-used
- Total-industry-costs-to-store-co2
- Total-subsidy-to-industries
- Total-subsidy-to-PoR

Figure 6.3.1 shows the values taken by each KPI over the course of the full factorial model evaluation. We note that the KPIs *total-industry-costs-to-store-co2* and *total-subsidy-to-industries* are orders of magnitude smaller than the other KPIs and are therefore not clearly visualized.

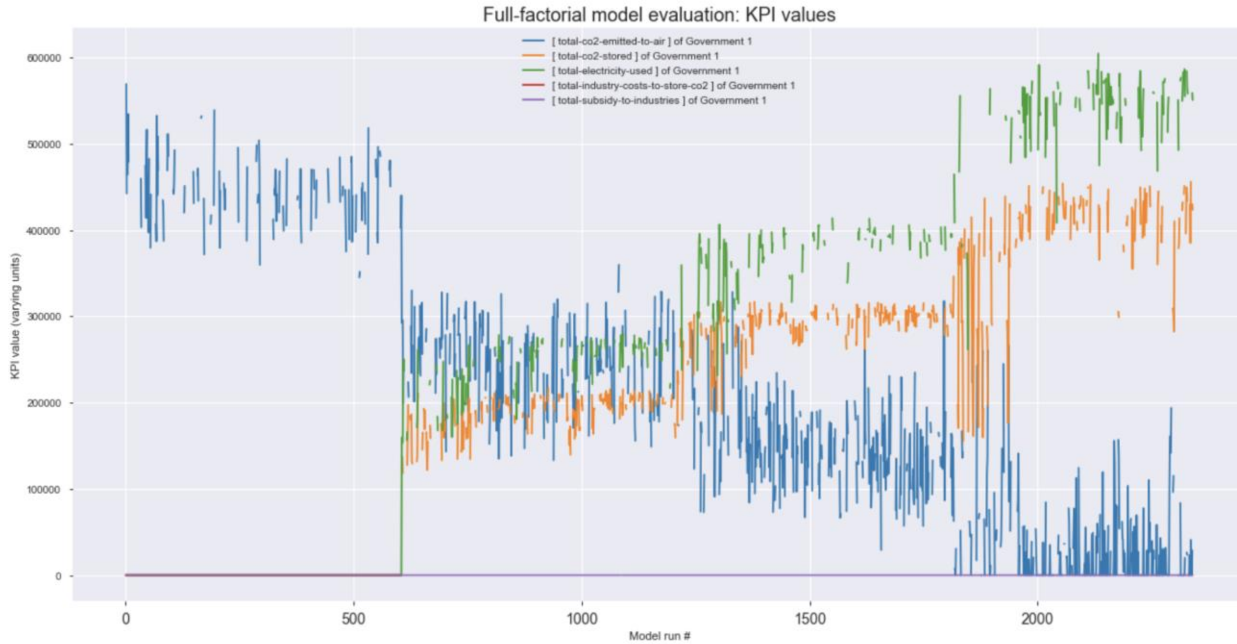

Figure 6.3.1: KPI value ranges under full-factorial model evaluation

The model behaviour shown in figure 6.3.1 illustrates that the mode behaves as expected. We see that total CO2 emitted to air and total CO2 stored are inversely related. Furthermore, we observe increased electricity usage with increased CO2 storage. A notable omission from figure 6.3.1 is the *total-subsidy-to-PoR* KPI. We omit this due to a difference in scale. Figure 6.3.2 shows the *total-subsidy-to-PoR* KPI plotted with the other KPI's. We observe big increases every ~600th model evaluation, this is due to the nature of full-factorial model evaluations and time constraints. However, when taking figures 6.3.1 and 6.3.2 together, we do observe that with increased subsidy to PoR the CO2 stored increases and CO2 emitted is reduced. We conclude that the model exhibits behaviour as expected and is therefore verified.

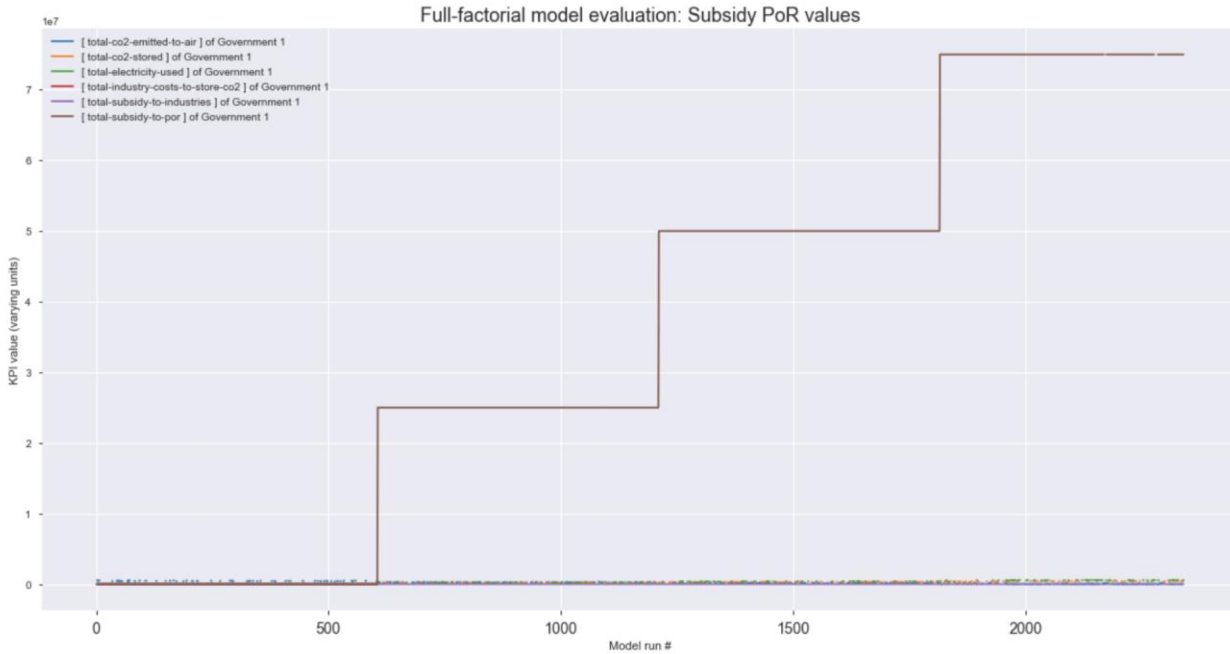

Figure 6.3.2: Total-subsidy-to-PoR value ranges under full-factorial model evaluation

7. Experimentation

7.1 Hypothesis

The methodology used throughout this report (Van Dam, Nikolic & Lukszo, 2012), suggests two types of hypotheses belonging to different modeling aims:

1. Models that attempt to provide an explanation for an observed real-world phenomenon. Its corresponding hypothesis is falsified when the observed regularities do not occur in the model.
2. Models that explore which futures display the behaviour of interest: which parameter settings speed up or prevent the appearance of the behaviour of interest

Given the exploratory nature of this research, which aims to find the height and type of government subsidy required for a successful implementation of CCS in the Port of Rotterdam, the second type of hypothesis is more suitable for this research. This second type of hypothesis requires large parameter sweep experiments to find the combinations of parameters guaranteeing success and/or failure.

7.1.1 Time

Given the goal of the government to reach zero emissions by 2050, all experiments are run for 31 ticks, corresponding to 31 years. If the emergent behaviour of interest has not occurred within this time frame, the policy is deemed unsuccessful, and should therefore be disregarded.

7.1.2 Scenario

This research merely focuses on finding the combinations of policy levers that guarantee success under a reference scenario. The parameters of the reference scenario, such as oil price and electricity price are set to be identical to the data provided by dr. ir. I. Nikolic.

7.2 Experimental setup

Two experiments are run sequentially. First, a sensitivity analysis (7.2.1) is performed to find the policy levers to which the outcomes are the most sensitive. This increases the problem understanding and gives a first impression of the most effective policy direction. Additionally, this analysis may already rule out certain policy levers.

Then, an optimization based strategy (7.2.2) is employed to find the combinations of policy levers that guarantee success, where success is in this case characterized by the amount of CO2 stored (and therefore not emitted to the air) for the lowest amount of granted subsidy possible.

Although the research question states ‘the amount of CO2 captured and stored from industries in the port region’ as the output variable of interest, the proxy of ‘CO2 emitted to air’ was used instead. In principal, these two variables have a one-on-one relationship, so this does not compromise the research question. However, it allows for using the CO2 emissions in 2050 as another output variable of interest, which measures whether the government achieves its goal of being CO2 neutral by 2050.

7.2.1 Experiment design - sensitivity analysis

The sensitivity analysis is performed using the pyNetLogo python package (Jaxa-Rozen & Kwakkel, 2018) for controlling the NetLogo model through python, complemented with the SALib package (Herman & Usher, 2018).

- Setup
    - Ticks [31]: each tick represents one year.
    - Model replications [14000 experiments]: a sample size of $n(2p+2)$ is required, where n=1000 (a baseline sample size which should be sufficiently large) and p=5 (the number of input parameters).

- Parameter settings
    - Number of industries [25] , with:
        - Oil demand = random uniform 1000-10000
        - Payback period = random uniform 1 - 20
    - Starting budget PoRA [10000000]
    - CO2 emissions per ton of oil [3.2]
    - Capex capture efficiency yearly update = 0.9 * old price
    - Yearly reduction in electricity price = 0.9 * old price
    - Fixed storage price = 0.7 * extensible storage price (which is variable)

- Parameter sweep
    - Total available subsidy [0 - 100000000]: Wide range sweep using LHS samples
    - Subsidy for industries (euros per ton of CO2) [0 - 200]: Wide range sweep using 100 LHS samples
    - Total subsidy increase for target (%) [0 - 15]: Wide range sweep using LHS samples
    - Industry subsidy increase for target (%) [0 - 15]: Wide range sweep using LHS samples
    - Extensible storage price ([eur / ton of CO2) [0 - 50]: Wide range sweep using LHS samples

- Output at each tick
    - Yearly CO2 emitted
    - Total CO2 emitted to air
    - Total amount of subsidy granted to Port of Rotterdam
    - Total amount of subsidy granted to industries

7.2.2 Experiment design - parameter sweep and multi-objective optimization

The parameter sweep is performed using the EMA Workbench python package (Kwakkel, 2017). This package allows for optimization over outcomes, besides merely scanning through the full parameter space. Four outcomes of interest are considered in the optimization, which are all minimized:

- the CO2 emitted yearly in 2050,
- the total CO2 emitted over the 31 simulated years
- the total subsidy granted to the port of Rotterdam
- the total subsidy granted to industries

The experimental setup is the same as for the first experiment, except for the setup parameters, found below.

- Setup
    - Ticks [31]: each tick represents one year.
    - Model replications [10]: To deal with the stochasticity in the model, ten replications with different random seeds are performed for each parameter set. In a less time-constrained situation, more replications would have been performed to guarantee robustness.
    - Number of functional evaluations = 10000

To account for the robustness of the policy, the ‘maximin’ robustness metric is used by only considering the scenario in which the policy performs the worst (McPhail, Maier, Kwakkel, Giuliani, Castelletti & Westra, 2018).

8. Data analysis

The experiments discussed in section 7 were performed and their results are discussed here. The code required for the execution of these experiments can be found in the supplementary information.

8.1 Sensitivity analysis

The SALib library in python (Herman & Usher, 2017) is used to calculate the first-order (S1), second-order (S2) and total (ST) Sobol indices to estimate each policy lever's effect on the output parameters of interest. 95% confidence intervals are used for each index. In this section, only the final visualization of a limited number of output parameters are visualized. A more thorough analysis of the data can be found in appendix A.

This analysis is performed for two outputs of interest: the CO2 emitted in 2050 and the total CO2 emitted over the simulated 31 years. These two outputs are chosen as they are expected to be most indicative of the successful policies. At this stage, we are not yet interested in the cost-effectiveness of the policies.

The sensitivity of 'total CO2 emitted to air' to the identified policy levers is visualized in figure 8.1.1, where the size of the circles indicate the extent to which the policy lever affects the variance in the total CO2 emitted to air. The black circles indicate direct effects, and the open circles the total effect (including the second-order effect, which is indicated by the grey bars).

Evidently, the available subsidy amount is an important indicator of success, but, interestingly, it is equally important that the subsidy is adjusted over time to facilitate the 2050 CO2 neutral goal. Remarkably, the subsidy dedicated for industries and their required storage price has a much lower effect. This is a first indication that the bottleneck is the building of pipelines to storage points (performed by PoRA), rather than the industry's willingness to capture and store their CO2.

Another interesting feature highlighted by this visualization is the important second-order interaction effects of the subsidy increase to reach the target and all other policy levers. Apparently, this is quite a powerful lever, but only when combined with other levers. Naturally, a percentage increase has a larger effect when the initial number was higher. Especially the interaction between the subsidy for industries, and the percentage increase to reach the target is a clear example of this.

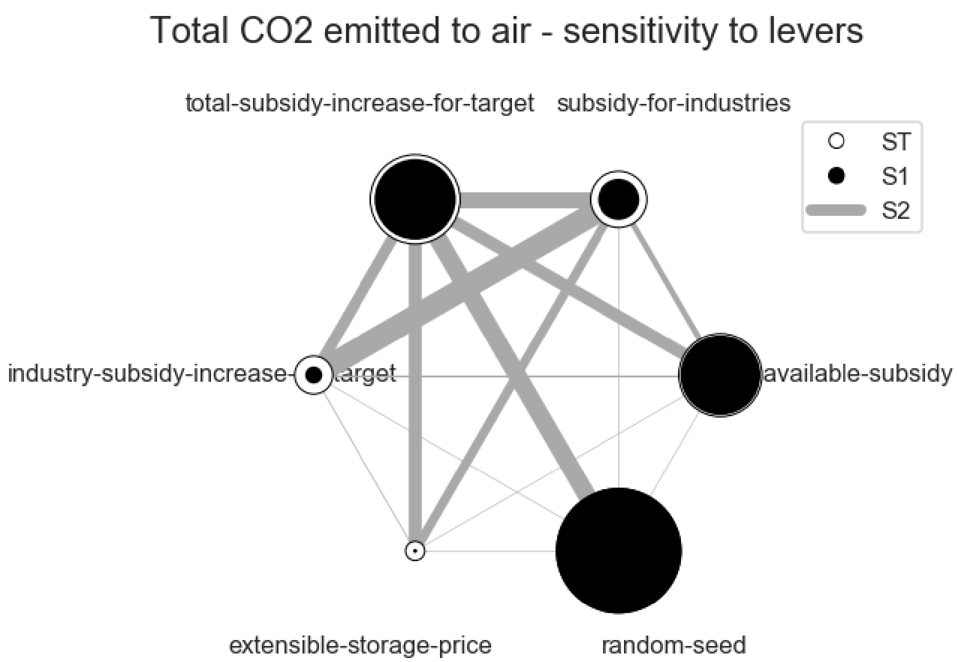

Figure 8.1.1: Total CO2 emitted to air: sensitivity to respective policy levers, where the size of the circles indicate the magnitude of the variance

Secondly, the sensitivity of the CO2 emissions in 2050 to the policy levers is visualized in figure 8.1.2. The results of this analysis are quite straightforward once one understands the results of the previous analysis, as they are quite similar. However, the adjustments for the 2050 target are, as expected, even more important.

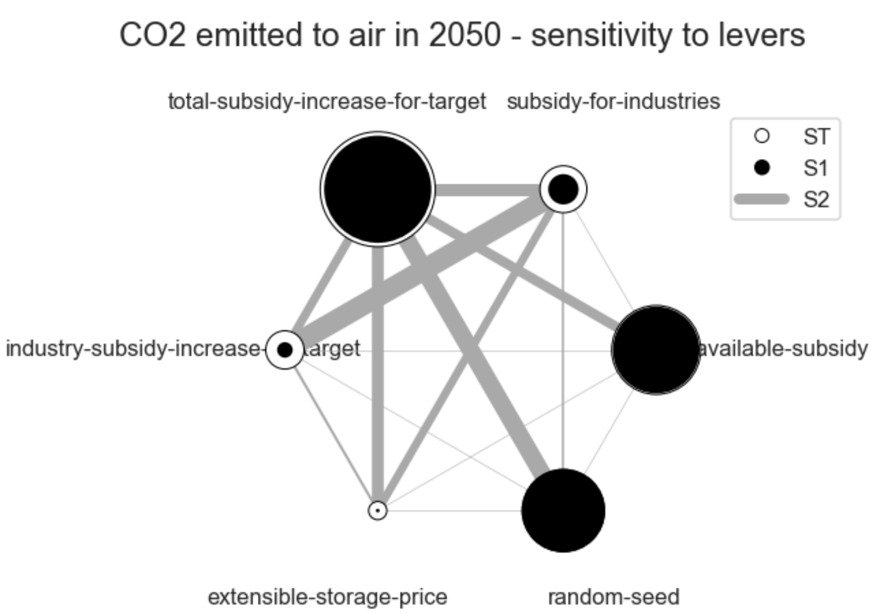

Figure 8.1.1: CO2 emitted to air in 2050: sensitivity to respective policy levers, where the size of the circles indicate the magnitude of the variance

8.2 Multi-objective optimization

The random seed dependency found in the previous section is accounted for by running a high number of replications and by choosing the same random seeds for each experiment.

Running the optimization algorithm for 10000 functional evaluations shows convergence (appendix B) and yields 772 candidate policies. Due to the nature of the model, some post-processing is required. Since only the total subsidy available and the subsidy to industries is specified, and the subsidy to the Port is derived from these, there are solutions where the subsidy granted to the Port is negative. Although these may be on the Pareto front, it is deemed undesirable. Therefore, these solutions are filtered from the solution set, yielding 387 policies.

Then, the policies with a 2050 yearly CO2 emission of less than 200000 tons and a total subsidy of less than 1.2 billion euros are selected, to guarantee success and a feasible policy. These constraints yield 10 final policies.

8.2.1. Candidate policies

These 10 policies are shown in table 8.2.1. Apparent is the choice between the subsidy provided to the port (as indicated in 'total available subsidy') and the subsidy for the industries. In the extreme example (the second row of the table), where the subsidy for the industries, a relatively high subsidy is required for the port, and, logically, a high percentage increase to reach the 2050 target.

In general, for a cost-effective policy, it is important to continuously increase the subsidy over the years. In this case, the industries joining CCS are also relatively evenly distributed over the years.

Table 8.2.1. Candidate policies

total-available-subsidy	subsidy-for-industries	total-subsidy-increase-for-target	industry-subsidy-increase-for-target	extensible-storage-price
2.612540e+07	29.621492	0.403408	2.502758	37.402502
3.200768e+07	0.015983	0.600408	0.878699	35.414221
1.111055e+07	130.961424	3.052423	1.982421	36.350752
1.575545e+07	162.602127	2.094201	2.234731	14.355974
3.652593e+07	114.771242	0.022700	5.361638	17.475801
2.446524e+07	121.294173	0.680880	4.366572	39.390625
3.359457e+07	119.780047	0.336561	6.492247	33.970289
3.470041e+07	180.564726	0.001717	7.551700	35.727899
2.240695e+07	176.007676	1.031710	3.638510	23.256350
4.261326e+06	179.040052	5.744051	1.018305	23.878749

8.2.2 Policy trade-offs

The performance of these policies are visualized using a tradeoff plot in figure 8.2.1. This plot grants insight into the policy trade-offs with which the government is faced when considering policy choices. Evidently, they may choose to either give most subsidy to the port, or most to the industries, or a mix of both. In general, policies that favour industry subsidy are more expensive in the end.

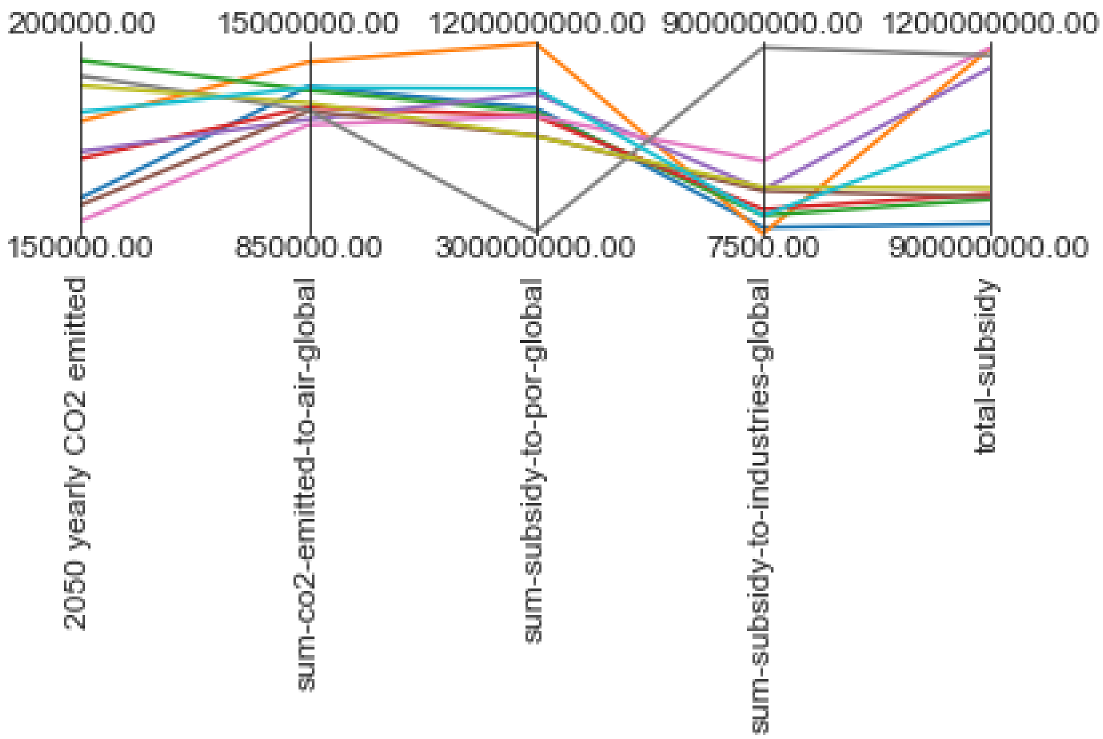

Figure 8.2.1. Trade-off plot showing the policy tradeoffs that the government faces.

At first glance, the results may look quite bad, especially when one considers that being CO2 neutral in 2050 is an explicit goal in the model. However, this is mostly caused by the chosen robustness metric, which only considers the scenario in which the policy performs worst. Scenarios include industries' respective CO2 emissions and preferred payback period. Therefore, the numbers presented in the trade-off plot are most probably not representative of reality. This metric is chosen to guarantee that the policy still performs acceptably under the worst circumstances.

In further research, more replications should be performed, and a different robustness metric may be chosen, to capture the policy's behaviour better. Ideally, one would design adaptive policies, that react to the actual state of the world (to a higher extent than merely increasing the subsidy amount).

To illustrate the possible effects of one of the more balanced policies was chosen and ran in NetLogo itself. This policy includes:

- Total available subsidy: 30 million Euros
- Subsidy to industries: 30 Euros/ton of CO_2 captured
- Increase for target (total): 0.5%
- Increase for target (industries): 2.5%
- Extensible storage price: 37.4 Euros/ton of CO_2

The resulting time-series plots are displayed in figure 8.2.2, below.

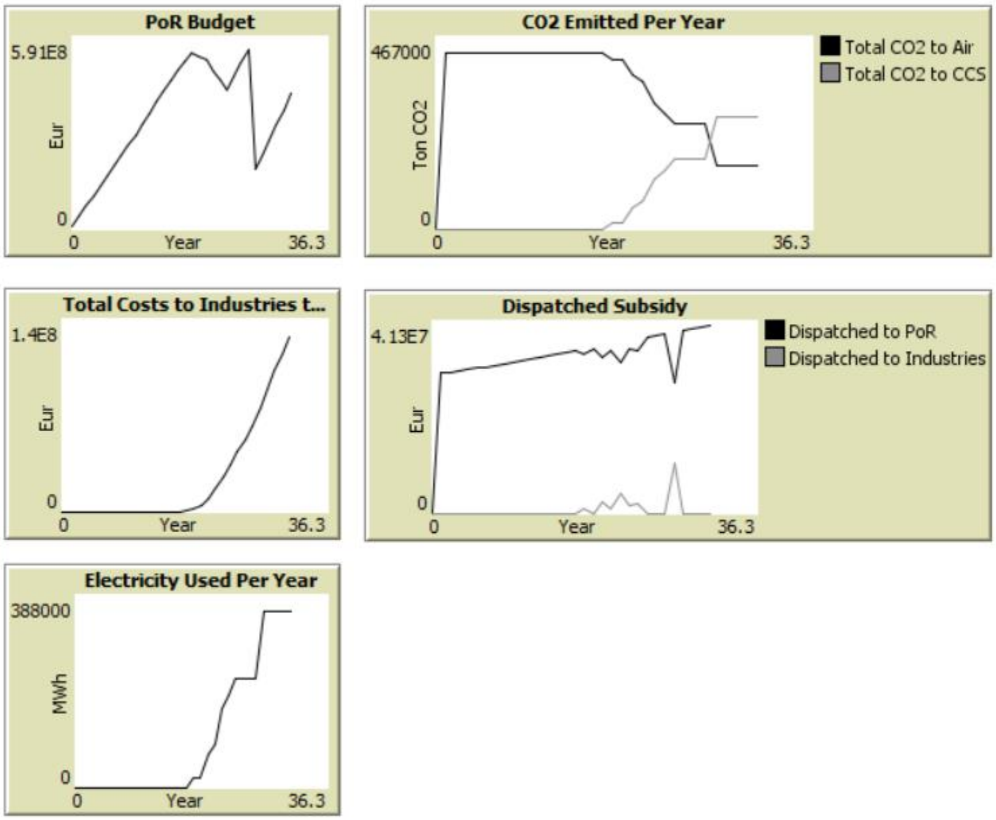

Figure 8.2.2. Results of a single run of the model policy in NetLogo.

9. Model validation

In their 2012 book, Nikolic et al. suggest four types of model validation, that may be employed to validate whether '*the right model was built for the purpose at hand*':

- Historic replay
- Expert validation
- Validation by literature comparison
- Validation by model replication

These four methods are briefly discussed in the following sections.

9.1. Historic replay

The model takes place across a 31-year period ending in 2050. Therefore, model validation is very difficult because the real data that would normally be used for model validation would trickle in very slowly over that time. Therefore, the quantitative accuracy of the results would be indeterminate in the relevant decision-making timeframe.

9.2. Expert validation

Experts in the fields of modelling & simulation and CCS may be consulted. The model could be validated according to how realistic the results and the modeling approach are according to the experts. Although expert validation would possibly be very insightful, this method falls outside of the scope of this project, as we do not have access to the relevant experts.

9.3. Validation by literature comparison

Some validation can be performed by comparing our model results to available literature. However, as the data used in the model is not representative of reality, this validation method is not possible for the project. The order of magnitude of the results is realistic though.

9.4. Validation by model replication

The last form of model validation consists of building a second model, either another agent-based model, but with a different system decomposition, or a model in a different modeling paradigm (discrete event or system dynamics). Due to the labour intensivity of this option, this validation technique is also outside the scope of this project.

10. Model use

The results presented in section 8 are mostly important to understand the most important trade-offs between policy directions and to get a first glance of the subsidy budget required to successfully implement CCS in the Port of Rotterdam. However, the model does not lend itself for hard advice regarding the actual numbers, but rather serves as an initial exploration of the order of magnitude and modes of behaviour.

If this project would have been done in collaboration with the relevant stakeholders in the Port, the most important modeling goal would be the understanding of mutual dependency, rather than the actual numbers presented. Ideally, these stakeholders would have been involved from an early stage, in order to improve their trust in the modeling process, and to increase the model's accuracy.

For now, it is interesting to note that constant monitoring of the CO2 emissions and corresponding adjustment of the available subsidies is important, and that subsidies granted to the Port seem to be more cost-effective than those granted to industries.

To extend the model, it would be interesting to consider more types of choice behaviour for industries, and negotiation possibilities between the Port and the industries. Additionally, it would be interesting to further explore the impact of fixed versus extensible pipelines on the choices of industries. Furthermore, only a few types of subsidies have been implemented in the model. Additional subsidy division schemes should be explored, if possible, in collaboration with the responsible government body.

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Appendix A. Full data analysis - sensitivity analysis

A.1 Output distributions

The distribution of outcomes of the model is visualized. This gives a first idea of the output space: when the full input space is sampled, the CO_2 emitted in 2050 and in total varies greatly. The subsidy dispatched to PoR and industries almost seem to show exponential decline. This is most likely caused by the zero sum game implemented for the subsidy distribution between PoR and industries.

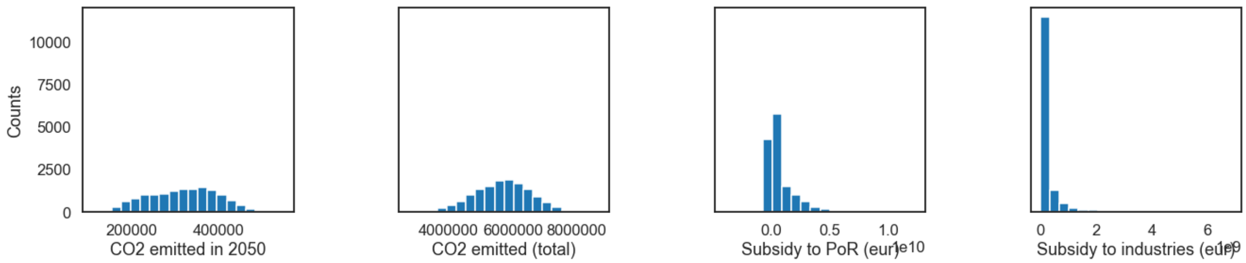
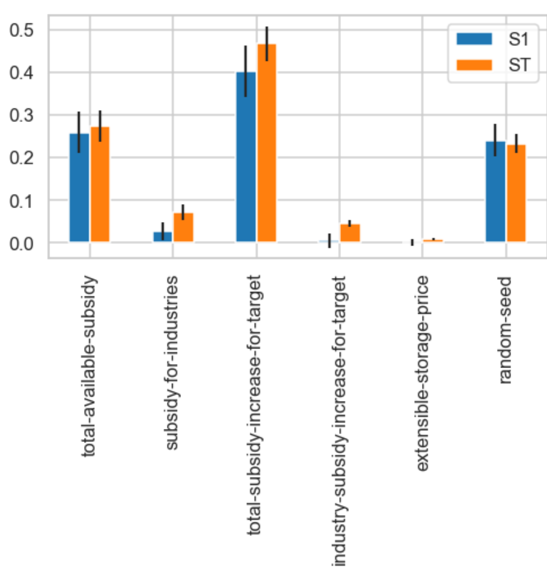


Figure A.1.1. Distribution of outcomes

A.2 Sobol indices

The bar charts below indicate the first-order and total indices for each policy lever for two output parameters: CO_2 emissions in 2050 and total CO_2 emissions. The error bars represent their estimated confidence intervals.



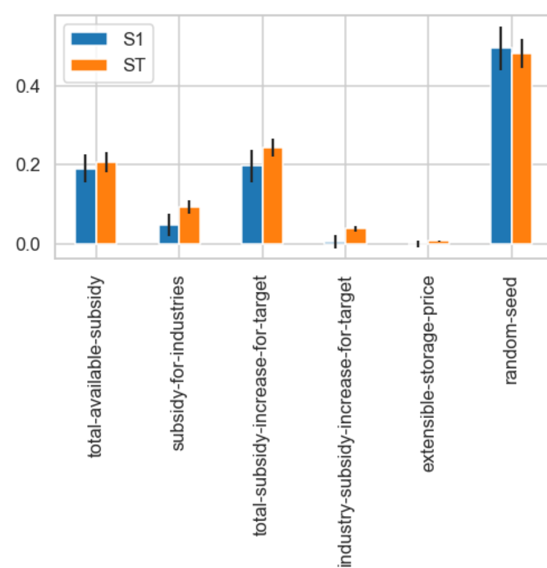


Figure A.2.1. 2050 CO_2 emissions

Figure A.2.2. Total CO_2 emissions

Appendix B. Convergence - multi-objective optimization

The convergence of the algorithm is tracked by the epsilon progress and the hypervolume. Both metrics seem to converge towards a solution.