Towards including policy modelling in linear optimization cluster modelling

A multi commodity and inter cluster perspective

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Towards including policy modelling in linear optimization cluster modelling

A multi-commodity and inter-cluster perspective

by

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Summary

How well spent is public money concerning sustainability goals? How effective and efficient are these policies? Even though it is widely acknowledged that actions against climate change are urgently needed in the near future, policy makers little insight in how potential policies can be designed most effectively. Industrial clusters in which high shares of energy intensive industry are located, have much potential in reducing green house gas emissions as a large share of the total emissions can be attributed to this sector. If these industrial clusters are connected (i.e. share commodity flows), the potential is increased even further.

Policies are needed in order to structure this transition towards sustainable industrial clusters. However, the author found that there is an extensive knowledge gap in including policies within cluster modelling. The current methods of viewing policies is as part of scenario analyses. This, for example, excludes the opportunity of evaluating a wide range of possible policies. These could consist of mutually dependent or dynamic environment dependent policies, in which the specifics of the policy depend on the current state of the system. Consequently, there is little insight in the implications of policy interventions. Therefore, the major potential of industrial clusters to transition towards sustainability is probably not fully used.

In this research, the author strives to enable policy modelling by creating easily applicable modules to include policies within cluster modelling by answering the following question:

> *What are the effects of merging sustainability policy models and industrial cluster models?*

First, to answer this question, an exploratory approach is used by conducting literature and policy analysis. Herewith, policy/design parameters of environmental policies are identified, which combined determine the scope of the policy intervention and are further referred to as scope variables. as these scopes . These scope variables consist of: policy mechanism, source, commodity scope, policy type and target industries. The policy mechanism differs between the most classic choice that has to be made when implementing a policy: encourage or discourage behaviour. I.e. will the policy take the form of a subsidy or a tax. The policy source specifies which governmental organisation issues the policy and thus needs to organise the cash flows that have to be received or paid depending on a.o. the mechanism used. The commodity scope determines which commodity is used to reach the goal of the policy. Production using different commodities have different characteristics like emissions and cost price which thus have to be targeted differently by policies. The policy type differs between a policy that consists of a lump sum (one time) flow of money to stimulate investments in a certain direction (investment based

policies) or a policy that focuses on the output (generation based policies). Generation based policies are feed-in-tariff like structures that can be put in place in which the policy can consist of an amount of money per unit produced or emitted. Lastly the target industries determine which actors are eligible for the policy. This variable determines which specific sectors or industries have to pay the tax or can gain from subsidies? Following the creation of these scope variables, a modelling approach is utilised to formalise these findings and create two structurally different policy modules in the multi integer linear programming language of Linny-R. These consists of a generation based policy module and an investment based policy module that together can cover all the potential policy scopes.

Furthermore, a stylised cluster model is created by the author to foresee in the need for a simulation environment to test differently scoped policies. In the simulation environment, the policy scopes are applied within a geographical boundary. The stylised cluster model includes four different commodities that can be utilised in three different clusters in North West Europe. The included commodities consist of natural gas, hydrogen, electricity and CO_2. This selection is made to provide production options that clusters can choose from and that can be targeted by the policies using the commodity scope variable. The geographical scope of this research includes the industrial clusters of the port of Antwerp (Belgium), the port of Rotterdam (the Netherlands) and the Chemelot cluster (Geleen, the Netherlands). The characteristics of this stylised testing environment are twofold. Firstly, the different potential of the included clusters to transition to these commodities. Secondly, the varying commodity prices. This leads to different behaviour of the clusters when incentivised by policy interventions.

Next, the policy modules are merged in the stylised testing environment created in the simulation software to test the effects of varying policy scopes and measure the effectivity and efficiency of the policies concerning environmental impacts.

The application of the policies in the testing environment show that differently scoped generation based policies lead to widely varying effectivity and efficiency. Hence, including policies within cluster modelling can be of great value for policy makers and actors within the industrial sectors to create insight in the proposed policy measures and increase the effectivity and efficiency of public financial means and time. Unfortunately, the inclusion of investment based policies is not yet possible in the version of Linny-R used in this research. This is due to computation limitations in both Linny-R as well as the solver.

To conclude, the author is able to merge policies within industrial cluster modelling by designing policy modules that allow for differently scoped policies. By merging these policy modules in industrial cluster models, it becomes

clear that different scopes of policies can have widely varying efficiency and effectivity in reaching environmental goals. The policy modules created in this research allow for a plug-and-play approach for academics and policy makers in future projects to determine the effects of policies on industrial system. However, despite the goal to create an easily applicable means to include environmental policies within industrial cluster modelling, not both investment and generation but only generation based policies can yet be included by means of a working module. Additionally, the author recognises the added value of including both different kind of policies (not solely environmental policies) as well as different geographical orientations. From these observations, there are three opportunities for further research. Firstly, towards developing and testing of investment based policy inclusion for which the basis is laid in this research. Secondly, value can also be added concerning generalising the scope variables of policies. Consequently different policies than environmental ones can be evaluated. Lastly, future research can focus on resembling existing geographical regions more closely to draw applicable conclusions on which policy to apply.

Key-words: *Policy modelling, industrial clusters, policy scope variables, commodity networks, multi integer linear programming, Linny-R*

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Additionally, I would also like to thank all those dear to me, especially my close friends and housemates, who have kept me sharp and with both feet on the ground.

This project was the first time conducting research on my own. This was a whole new experience which I look back on with mixed feelings. Around me, I saw a lot of students break under the pressure they themselves and the university put upon them. This provided a strong incentive for me to do things differently. I'm proud to say that the work before you was created without tears shed, morale broken or (moderate) stress levels exceeded even near the end when the tables could have turned easily.

I'm happy to say that the process of writing this thesis has increased my interests on this topic and have made me eager to contribute to speeding up the transition towards a sustainable world. The levels of complexity that I first learned about during my studies at Delft University of Technology and that I was now able to recognize and apply in this research are the most interesting learning points for me. Going through this process of writing my thesis, has made me aware on how to come from a world full of opportunities to choose from towards a complete project. I found that I should just pick a point to start and find your way from there. Just like in a vehicle: ”You can't steer if you're not moving, so start moving”.

Now that the end of this chapter of being a student is near, I would like to make use of this special moment to recognize who have made me who I am, who have made all the chapters of my life possible and who have always been there for me to go to for support. To my mom and dad, thank you very much for the limitless love and advise you provide me with. Also a big thanks to my brother, who as no one else can, keeps me on the edge and makes me expect the unexpected. Lastly, I'd like to praise Mathilde who's dedication and perseverance has served as a great example for me to get most out of every opportunity I get.

Delft, 14 July 2021 Willem Steven Wolleswinkel

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1 Introduction

In this chapter the context both from a social as well as an academic perspective is provided from which this research originates. Using these perspectives, the research question is identified which is followed by the approach and methodology that is used to answer this research question.

1.1 Social relevance and the potential of industrial clusters

Massive undertakings are needed to reduce greenhouse gas (GHG) emissions in order to maintain global warming below 2 degrees Celsius. The industrial sector is one of the most emitting sectors in the western economy (Littlewood et al., 2018). In 2019, Gerres et al. found that energy intensive industries that are organised in industrial clusters is responsible for two-thirds of the industrial carbon dioxide emissions in the EU. Hence, this sector has large potential to contribute to the needed reductions.

In this research, the definition of a cluster presented by Porter (1998) is used in which a cluster is delineated as a geographical concentration of interconnected companies, specialized suppliers and associated institutions. Already in 1920 the economic benefits of clusters became apparent in literature (Marshall, 1920). According to Guelpa et al. (2019), for similar reasons clusters offer greenhouse gas reduction potential because energy sources can be better managed which leads to a reduction in consumption and waste. This is in line with the conclusions of McCauley & Stephens (2012) who researched the energy savings potential of green industrial clusters in the US. This potential becomes even more apparent through the research of Hansen et al. (2016) who point out that industrial and electricity production processes currently produce more waste heat than the total heat demand is in Europe. By making use of synergy effects in industrial clusters, emission reductions can be realized.

On a higher aggregation level, linking industrial clusters through utility networks with other industrial clusters or energy intensive areas, may have an even larger potential in reducing GHG emissions (Lui et al., 2021; Butturi et al., 2019; da Graça Carvalho, 2012). Likewise, Bhardwaj (2021) states that a focus on cluster levels creates much bigger opportunities in light of the need for 30 Mton CO_2 reduction that is the current climate goal for the industrial sector in the Netherlands.

1.2 Socio-technical complexity and the need for policies

The higher aggregation level of linking industrial clusters, inherently comes with complexity on multiple levels. According to Verwater-Lukszo & Bouwmans (2005), this complexity originates in four different characteristics of utility networks in industrial clusters. Firstly, there is physical/technical complexity. This because of the large number of elements in the networks. The relations between these elements are all functional and causal but do not result in completely predictable behaviour. Secondly, there are actors involved in the use and development of the infrastructures. These actors vary in size and have relations that are not only functional but also institutional, legal and economical. Thirdly, the interactions between the actors and the physical infrastructure create an interconnected complex network where the actors determine the development and use of infrastructure. Therefore, the infrastructure influences the behaviour of actors. Lastly, the interactions between these complex networks cause the existence of interconnected infrastructures where the boundaries between the separate infrastructures become vaguer.

In addition, linking utility networks and industrial clusters requires coordination. This because utility networks in these regions are originally developed independently and only by means of time grew to become intertwined and mutually dependent (Guelpa et al., 2019). Guelpa et al. (2019) continue stating that to create order in these emerged commodity networks, research to policy effects is needed. McCauley & Stephens (2012) mention that policy strategies to encourage a sustainable energy transition only focus at deployment, demonstration or development of specific technologies rather than on a comprehensive integrated policy which would potentially lead to higher effectivity. This coincides with the conclusions of Damen et al. (2009); Ball et al. (2007); van den Broek et al. (2010); Brownsort et al. (2016) who emphasise the importance of policies in the field of sustainability and the current lack of including policies within the models used, rather than as static scenario inputs. According to Urgenda (2021), using the current way of policy making and evaluation does not reach the full potential that policies can have. Haas et al. (2008) specifically points at a lack of understanding what policy scheme delivers best results at lowest price.

Consequently, the purpose of this thesis is to provide a means to include policies within cluster modelling by answering the following research question:

What are the effects of merging sustainability policy models and industrial cluster models?

To answer this research question, the author identifies the following sub-questions:

1. *What is the current state of literature regarding the modelling of utility networks and sustainability policies in the context of industrial cluster modelling?*
2. *How can policies be formalised and standardised in an applicable module?*
3. *What modelling language is suitable for including policies in models?*
4. *What is the commodity and cluster context to which the modules can be applied?*
5. *How can the effect of policies in cluster modelling be determined?*

By answering this research question, a means is provided regarding the implementation of policies within cluster modelling. To this end, a case is chosen to which this means can be applied. The focus is on the region of North-West Europe. More specifically, the industrial region of Antwerp, Rotterdam and Chemelot (located in Geleen, NL). According to Cervo et al. (2019), the region of North-West Europe is of high potential for deployment of increased industrial cooperation.

1.3 Approach and methodology

To be able to foresee in a design to include policies in cluster modelling, two approaches are used: an exploratory and a modelling approach. In the following sections the use and choice for these approaches are explained.

To answer the research question, first insight has to be gained in the structure of policies. Exploratory research aims to comprehend a range of possibilities rather than one conclusive answer (Saunders et al., 2009). This interferes with advantages named by QuestionPro (2020) who state that an exploratory approach is valuable for laying the foundation to conduct further research on. Hence, an exploratory approach provides the necessary bases on which this research can be further elaborated.

The next step in the research is combining the information gathered in the exploratory part. Applying a modelling approach in the second part of this research forces the author to conceptualize and formalize the information gathered. This leads to applicable and generalised modules that can provide measurable insights in the effects of different policies on the sustainability transition of industrial clusters.

The advantage of using both an exploratory as well as a modelling approach in this research, is the fact that they complement each other in the different phases of this research. The flexibility to adapt and set the exact scope of the research is sought after by using the exploratory approach in the first phase. This is supplemented in the second phase by the more sturdy modelling approach that supports in translating the findings of the first phase to a usable end product.

Off course, both approaches bring shortcomings which have to be recognized. Insights gained from application of an exploratory approach are not generally applicable (Fredrickson, 1986). This links with one of the dangers of applying a modelling approach: no matter the model, it still remains a representation of the system rather than the system itself. This creates the risk of misalignment of the outcomes of the model and the behaviour of the real system (Trago, n.d.). Directly related is the need for determining how to implement the findings into the real system after applying the modelling approach (Wielinga et al., 1992). These shortcomings can partly be compensated for by thoroughly validating the model used. To this end, the author uses the case of North-West Europe to gain insight in the effects of the policies. The disadvantages connotated with the separate use of these approaches are prevailed over by applying a subsequent use of a more broad and flexible approach and a more strict approach that forces to come to a specific formalization of concepts. To completely overcome these hazards however, further research is needed in which the model is validated even further to widen the scope and increase the applicability.

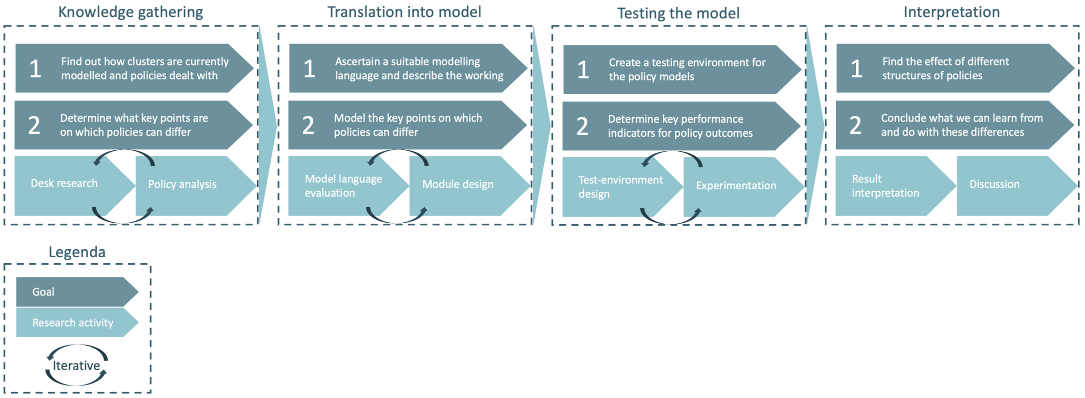


Figure 1: The four phases of this research corresponding to the structure of the report

To answer the main research and sub questions, different research activities and tools are applied by the author. These are visualised in Figure 1. As can be seen, the research can be divided in four phases consisting of two steps. First a knowledge gathering phase is needed that matches with the exploratory approach described above. These can be found in Chapter 2 and in the first section of Chapter 3. In Chapter 2, desk research by means of a literature review is used to find out how currently clusters are modelled and how they take policies into account. The goal of this is twofold, firstly the validation of the knowledge gap that leads to the research question and secondly the creation of an overview of the current way of including policies in cluster modelling. After delineating this, Chapter 3 provides the conceptualisation to categorise policies. This is done by finding additional literature specific on the topic of classifying policies and evaluating these categories by analysing different sustainability policies. In this phase the first sub question can be answered and the concepts needed for the second sub-question are determined.

In the second phase, the concepts identified in the first phase are translated into a model. To this end, the second part of Chapter 3 is used to identify and describe a suitable modelling language that can be used to apply the modelling approach as described earlier this Chapter. This followed by a presentation and explanation of the policy modules that are the result of the translation of the different characteristics of policies. To come to this result, the modelling language is evaluated and the policy modules are designed iteratively. Because of this method and close contact with the developer of the used modelling language, missing features can be implemented over the course of the research. The combination of the first and second phase provides an answer to the second sub-question. After completing this second phase, an answer to the third question is found as well.

Now that there is a translation of policies into a model, a testing environment is needed to evaluate the policies. Additionally, performance indicators are selected that are used for measuring the impact of policies on a system. Hence, in this phase of the research, a stylised testing environment is created that is suitable for analysing the impacts of policies (see in Chapter 4). Subsequently, in Chapter 5 the performance indicators as well as a design for the experiments can be found. These Chapters combined allow for experimentation with the policy modules in a controlled environment. The author applies an iterative approach of designing the testing environment and experimenting with the policy modules to come to a final setup in which the full reach of policies can be analysed. This phase is the last phase that provides a base needed for answering the main research question. The fourth and fifth sub-questions are answered by completing this phase.

The experiments that are set up and conducted in the previous phase lead to the last phase which answers the main research question. In this phase, first the outcomes of the experiments are described and interpreted. Resulting in the goal of this research being reached and insight is gained in the effects of different policy structures (can be found in Chapter 6). This is followed by a discussion of the results of this studies and placement of this research in a wider academic and social context (Chapter 7). Combining the four phases (eight steps) allows the author to conclude in Chapter 8 and answer the research and sub questions as posed earlier in this Chapter.

2 Literature Review

After having sketched the context and societal relevance of the research, this chapter is focused on the academic landscape that validates the research question. In the first part of this Chapter (section 2.1), core concepts that are needed for the review are defined. These concepts are used in the search for relevant literature to specify the scope of the search and create understanding of the interpretation of these concepts. This is followed by the selection and presentation of literature on the current methods of modelling industrial cluster infrastructures and the potential inclusion of policies (Section 2.2). Using this overview, knowledge gaps are identified (see Figure 2). The goal of this chapter is to answer the first sub-question:

What is the current state of literature regarding the modelling of utility networks and policies in the context of industrial cluster modelling?

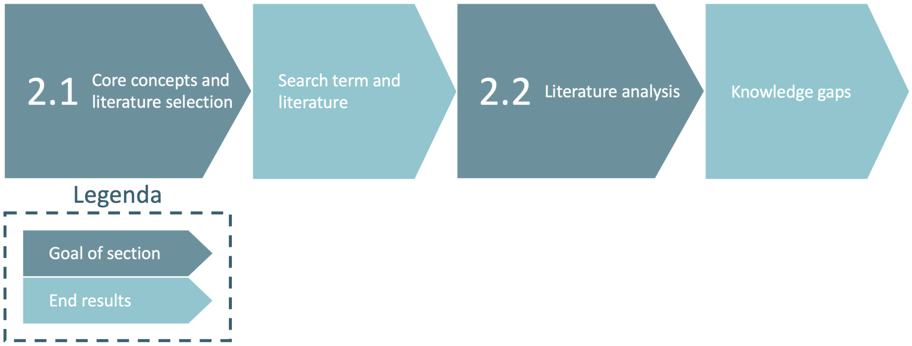


Figure 2: The structure of chapter 2.

2.1 Core concepts and specification of literature search term

In this section, core concepts that are needed for the literature search are introduced. In the following paragraphs the concepts that are used in the search string are marked bold and the interpretation of this concept is provided.

Industrial clusters (Porter, 1998) or **Industrial symbiosis** (Chertow, 2000) are identified as the core of this research. These concepts are defined as: initially separate companies/industries that engage in a collaborative approach to gain competitive advantage involving physical exchange of materials, energy and/or other by-products. This also touches upon the concept of **commodities** that is used by the author to scope the research in Chapter 4.

Commodity and **utility networks** or **infrastructures** are used by the author to specify the research. Apart from intermediate and end products specifically produced to be used in the industrial cluster, Eilering & Vermeulen (2004) includes two types of utilities that are exchanged in this context: waste streams and by-products. In literature, dissimilar definitions regarding this infrastructure are used. Kurtz et al. (2019) define the infrastructure as the transport network including the means needed for operations (s.a. pressure stations). On the contrary, van den Broek et al. (2010) separate the transport infrastructure from the potential storage and pressurizing infrastructure. In this research, the author uses the complete set of infrastructure needed to facilitate the transportation of the commodity (i.e. the definition used by Kurtz et al. (2019)).

Lastly, **policies** are important in this research. The author classifies the literature reviewed on the potential inclusion of policies. Because of the scope on sustainability in industrial clusters, environmental policies that stimulate a transition are the most interesting. Distinctions are made concerning the different ways of including policies in the reviewed models that are used in literature. Specifically the view on using the policies in a modelling context is important for this research.

The author uses these core concepts to create a comprehensive overview of the existing research that uses a modelling technique to evaluate the investments in utility networks and or industrial clusters. Because of the vast amount of literature available on industrial cluster models and policies, the terms are used simultaneously in the following search string:

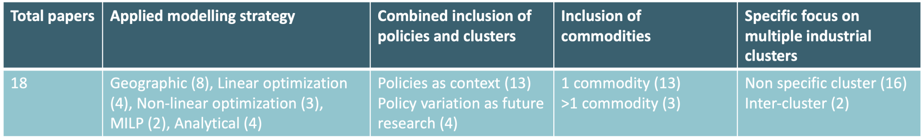
industr AND (cluster* OR symbiosis) AND model AND europe* AND market AND (commodity OR utility OR hydrogen OR co2 OR syngas) AND (network OR infrastructure) (AND polic*)*

Scopus and Google scholar (both used in incognito mode to prevent bias) served as an initial starting point for the selection of papers regarding this subject. A more specific selection was made by evaluating the contents on the applicability of utility network modelling or using utility networks within industrial sectors both keeping in mind the scope on including policies within cluster models. Application of the reversed snowballing technique as presented by Wee & Banister (2016) led to further extension of the selected papers.

2.2 Knowledge gaps in policy and cluster modelling

Now that a selection of the papers has been made, a comprehensive overview of the reviewed literature can be found in Appendix A. An overview with the highlights used to identify the knowledge gaps can be found in Table 1. The

Table 1: Highlights of reviewed literature



Total papers	Applied modelling strategy	Combined inclusion of policies and clusters	Inclusion of commodities	Specific focus on multiple industrial clusters
18	Geographic (8), Linear optimization (4), Non-linear optimization (3), MILP (2), Analytical (4)	Policies as context (13) Policy variation as future research (4)	1 commodity (13) >1 commodity (3)	Non specific cluster (16) Inter-cluster (2)

goal of this section is to validate the identified knowledge gap on which the main research question is based after which insight is created in how clusters are modelled and policies integrated in these models.

The papers included in this review are evaluated on the (range of) commodities they include, in which way they apply a model in this context and to what extent policies are included in the models. Firstly, policies are included in the modelling approaches as exogenous variables that are varied in scenario analyses. This scenario analysis approach to policies can be found in a.o. Hustad & Bjønnes (2002); Ball et al. (2007); Brownsort et al. (2016); Schneider et al. (2020); Stiller et al. (2010); Damen et al. (2009). It is expected that using current methods of designing and evaluating policies, not the full potential is reached Urgenda (2021). Using scenario analyses, environmental policies (e.g. carbon prices) are varied to a certain extent (Hustad & Bjønnes, 2002; Schneider et al., 2020; Damen et al., 2009; Kim et al., 2010). Ranges of these prices are included and the sensitivity is determined. If more than one policy is included (e.g. a CO_2 tax in combination with electrification subsidies (Stiller et al., 2010)), this is done using different scenarios that are composed of assumptions on both of the policies leading to less specific policy analysis. Because the focus of these studies is not on finding the best policy but rather what are the most profitable investment decisions given certain policies, not all policies are evaluated to find which is best in reaching its climate goals. Additionally this excludes the option to review more complex policy structures that are dependent on other policies or intermediate outcomes of the model (so called solution-dependent variables) (Domschke et al., 2010). These observations are key in providing a starting point from which this research originates. This, as stimulation and organisation regarding development of commodity infrastructures (i.e. policy design) are needed to utilise the full potential that industrial clusters have in contributing to sustainability (Guelpa et al., 2019). Furthermore, future research topics are identified that are in line with this line of reasoning. For example, Domenech et al. (2019) and Damen et al. (2009) identify the specifics and role of public policy and investment stimulation as a topic for further research. Moreover, the studies of Dohse (2007) and Ball & Wietschel (2009) recognize the importance of the structure of policies on a higher geographic level (i.e. national/international) in the effectivity of developments in an industrial cluster. A quantitative model that can be used for analysis of the effectivity of different policies in which these policies are included in the model rather than as exogenous scenario analyses, can thus still contribute to the comprehensiveness of the field. In addition it can conduce the selection of the best policy to utilize the full sustainability potential of industrial clusters. This knowledge gap is used by the author to scope the research towards the methodological development of including policies within cluster modelling.

Secondly a focus on the modelling strategies used in the included literature. Most studies that include a quantitative model on industrial clusters, specifically focus at the geographical layout (Kjärstad & Johnsson, 2009; Brownsort et al., 2016; Stewart et al., 2014; Strachan et al., 2009; van den Broek et al., 2010; Murthy Konda et al., 2011; Mendelevitch, 2014; Stiller et al., 2010). Often these models are GIS (Geographic Information System) based and the key objective is to find the most efficient network to connect supply and demand. As mentioned for the first knowledge gap, in these papers the investment question is only answered quantitatively (i.e. the costs of the network and which formation is optimal). Apart from GIS modelling, a range of other means for modelling are used in literature. These include linear optimisation (Hustad & Bjønnes, 2002; Kjärstad & Johnsson, 2009; Strachan et al., 2009; Damen et al., 2009), non-linear optimisation (Ball et al., 2007; Ball & Wietschel, 2009; Murthy Konda et al., 2011), multi-integer linear programming (Mendelevitch, 2014; Kim et al., 2010) and analytical models (Dohse, 2007; Domenech et al., 2019; Hospers, 2002, 2003). The choice for modelling strategy differs because of the different research goals striven after in included literature. Optimization models are often used for research with a more economic approach to determine the most efficient infrastructure. Geographic models extend this by including a wider range of variables and are often combined with economic optimization models such as Stiller et al. (2010); Strachan et al. (2009). Lastly the analytical models are used as frameworks to determine the qualitative potential of different regions and sustainability policies. Concluding on the modelling strategies used in literature, a wide variety on research goals and corresponding modelling strategies are used in the included literature. This observation is used in the next chapter to determine the modelling language used in this research.

Thirdly, the focus on commodities in the literature. A noticeable outcome concerns the singularity of most papers in their choice of commodity. Only three of the eighteen papers include more than one commodity in their studies (Ball et al., 2007; Domenech et al., 2019; Damen et al., 2009). However, all of the studies that do include multiple commodities have a primary focus on one commodity (either CO_2 or H2) and only partly included one other commodity in their research (e.g. gas or a combination of H2 and CO_2). The remaining papers either have a specific focus on one commodity network or do not scope their analysis at a specific commodity. This singularity in focus is acknowledged in literature to leave room for further research. I.e., development of multiple utility networks in one study (taking into account the knowledge gap of integrating policy analysis in modelling) is recognized as knowledge gap by a.o. Damen et al. (2009) and Ball & Wietschel (2009). Hence, a multi-commodity view on cluster modelling could add value.

The last knowledge gap entails the analysis of utility networks between industrial clusters. The linking of the industrial clusters in light with policy integration to measure its effects, is not yet researched in the included literature. The focus in the research of almost all reviewed literature lacks inclusion of a focus on policies that regard infrastructure development between industrial clusters. Literature on commodity network development with a wide geographic scope all show the potential of these networks in contributing to the energy transition (Ball et al., 2007; Murthy Konda et al., 2011; Stiller et al., 2010; Strachan et al., 2009). However, these studies do not have a core focus on the added value of using these networks for climate gains between industrial clusters nor do they explicitly include an inter-cluster view. However, when looking at CCS, a more industrial cluster view is already adopted (Brownsort et al., 2016; van den Broek et al., 2010). For example, van den Broek et al. (2010) look at a wider network for CO_2 transport (i.e. the Netherlands) in which mainly industry is identified as major CO_2 source. vandenBroek2010DesigningModel identified Linking these clusters in order for efficient transport and storage as highly relevant. This is due to relatively early discovery of the economic added value of CCS in light of fossil fuel winning by means of enhanced oil recovery (Mendelevitch, 2014; Hustad & Bjønnes, 2002). Additionally, Hospers (2002, 2003) conduct research to the blue banana (i.e. a banana shaped belt running from London to Milan and clustering all centers of innovation and growth). They include an industrial (cluster) view but have a focus on economic development and growth as a result of this region rather than on enabling the climate potential of this region. Furthermore, they adopt an actor relation view opposed to the utility network/commodity view as identified as relevant earlier. Nevertheless, applying this wider/inter- cluster view is highly relevant (van den Broek et al., 2010; Brownsort et al., 2016; Hospers, 2002, 2003) and there is still room for utilising this in light of the policy integration and multi-commodity perspectives as mentioned above.

To conclude, the author identifies one main knowledge gap that is used as the origin of this research: there is an urgent need for including policies within the cluster modelling to reach full potential in reducing emissions in industrial clusters. Given this, three other inputs for research are identified: 1. many different modelling strategies are used in literature depending on the goal of that research, 2. adopting a multi-commodity perspective and 3. applying this to an inter-cluster setting. Especially the combination of these inputs show the academic relevance of this research. While basing the main research question of this studies on the need for including policies within industrial cluster modelling, the remaining scopes are used to define the context in which this question is answered.

3 Policy module design

The goal of this chapter is twofold. Firstly, this chapter introduces what is needed to create the policy modules that can be used to evaluate the effects of policies on developments in and between industrial clusters. Secondly, this chapter aims to create understanding in why and how the modelling language is used. Reaching these goals answers the following sub-questions:

How can policies be formalised and standardized in an applicable module?

What modelling language is suitable for including policies in models?

Section 3.1 elaborates upon the policies in two parts. First different policy scopes are defined using literature after which these scope variables are exemplified by analysing existing policies. To be able to formalize the findings of the policies into a model, in Section 3.2 the modelling language Linny-R is introduced and a basic explanation is provided. After having collected both the conceptualization of policies and a basic understanding of the modelling language, in Section 3.3 the policy modules are created. These are then explained and exemplified using the earlier defined scope variables.

The structure of this chapter is visualised in Figure 3 starting in the next section. In the subsequent sections of this chapter this figure is reused to provide an overview of the location in this chapter.

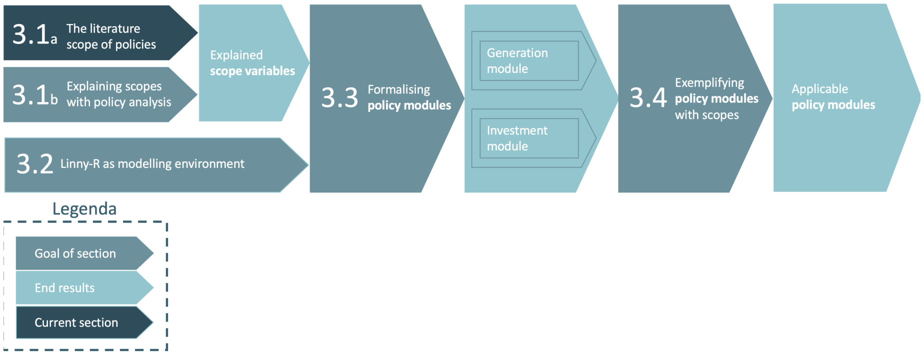


Figure 3: The structure of chapter 3 and the location of the following section.

3.1 Policy conceptualisation

This section is used to create insight in the categories in which policies can be differentiated (see Figure 3). To this end, literature and policy analysis are used to come to these categories. The goal of this section is to provide the basis to answer the following sub-question.

How can policies be formalised and standardized in an applicable module?

The literature used for the conceptualisation of the categories is found by looking for studies that classify different types of policies. Because of a limited amount of literature regarding classifying policies in the industrial sector, a wider variety of literature is taken as a basis. Using the papers of Haas et al. (2011, 2008) on strategies for promoting sustainability in the electricity sector, a snowballing technique was used to find further literature on policy classification.

In total, five categories are found on which policies can be differentiated. The first point considers the difference between stimulation and discouraging policies. These are mentioned by the majority of the included papers (Sumaila et al., 2016; Rubini, 2012; Haas et al., 2011; FAO, 2003; Debreu, 1954; Bian & Zhao, 2020). In all the included sectors (from industry to fishery), this fundamental difference is acknowledged and two papers (Debreu, 1954; Bian & Zhao, 2020) are written specifically focused on this distinction. Secondly, the source of the policy is identified as category. Bian & Zhao (2020) focus on encouraging climate policies (subsidies) to reach emission abatement and identify the governmental level (regional, national and inter-national) from which the subsidy originates as essential. Regarding Haas et al. (2011), more specifically the European governmental structure is used and national vs. European policies are leading in their analysis. These sources of funding are also used in the fishery sector to differentiate between policies in a similar way, though they are focused on global rather than European coverage and thus include international fishery conventions (Sumaila et al., 2016; FAO, 2003).

Thirdly, the papers regarding the fishery sector acknowledge the attention that can be paid to the different means used in fishery (Sumaila et al., 2016; FAO, 2003). Different means (e.g. types of nets and boats) are used to catch fish and are targeted differently by policies. FAO (2003) identifies small scale sustainable fishing nets to be stimulated in third world countries to promote self-reliance. Translating this to the industrial sector, this can be interpreted as the different commodities that can be used as means to foresee in production demands. For example, stimulation of a specific sustainable fuel to make industry switch from the use of fossil fuels. Fourthly, different ways to implement a policy are identified (Haas et al., 2008, 2011; Menanteau et al., 2003). This means that a choice has to be made to stimulate direct investments or focus on the output of that investment. Haas et al. (2008, 2011) refer to this as generation or investment focused policies in the renewable electricity sector. Generation in this case is the immediate stimulation of electricity output where investment based policies stimulate developments in production means by (lump-sum) investment subsidies. Menanteau et al. (2003) research the renewable energy sector and mention stimulation of investment in physical infrastructure (e.g. windmills and solar) as well as financial support of the electricity output of these renewable energy sources by means of feed-in-tariff like structures in which for example a minimum price is guaranteed by the government against which the produced electricity can be sold.

Lastly there is the question on who is eligible for the policies. This is a question asked both in fishery as well as renewable energy literature. In the fishery sector this question is referred to as recipients (Sumaila et al., 2016; FAO, 2003) and examples concern specific subsidies for small scale sustainable fisheries, aquaculturists (fish farms) and marine fishery. Also Haas et al. (2011) specifies that the question who to stimulate must be answered for a policy to be implemented. With their focus on renewable energy they mention different sectors that can be targeted. These can consist of a.o. industrial heat or electricity on both industrial as well as consumer level. In Table 2, an overview is provided of how the five categories that are identified in the paragraphs are found in the mentioned literature.

Besides these five categories, the fishery reports (Sumaila et al., 2016; FAO, 2003) identify an extra set of variables. These variables are related to the capacity of the policies (i.e. the size of the policy) and are used overarching the specific categories identified above. In this research, these are capacity related variables are used later in this chapter to translate the policies into a model and are further referred to as capacity variables.

Table 2: Origin of the scope variables found in different literature on policy classification.

Source	Field	Categories				
		1. Mechanism	2. Source	3. Commodity	4. Type	5. Target
Sumaila et al. (2016)	Fishery	subsidies vs. taxes	sources of funding	what to stimulate		who is eligible
Rubini (2012)	Renewable energy	stimulation (grants, loans, tax discounts) vs. discouragement (taxes)				
Haas et al. (2011)	Renewable energy				generation based vs. investment focused strategies	who to stimulate
Haas et al. (2008)	Renewable energy	direct (subsidies) vs. indirect (taxes)	source of policy		generation based vs. investment focused	
FAO (2003)	Fishery		sources of funding	target means		recipients
Menanteau et al. (2003).	Renewable energy	en- vs. discouragement			output based	
Debreu (1954)	general	subsidy vs. taxes				
Bian & Zhao (2020)	industry	encouragement vs. taxes	governmental level			

Resulting from the analysis of these papers, the author coalesces the insights into five categories that determine the scope of different policies. Hence, these categories are further referred to as **scope variables** and are summarised in the list below.

1. Policy mechanism (i.e. encourage vs. discourage)

2. Policy source (e.g. EU vs. national)
3. Commodity scope (e.g. single vs. multi-commodity)
4. Policy type (i.e. investment vs. generation)
5. Target industries (e.g. specific industries vs. all industries)

In the following part of this section (see Figure 4), these scope variables are explained by applying them to the a set of sustainability policies found in Dutch, Belgium and European repositories. In the following subsections, each scope variable is explained and exemplified in greater detail by means of linking them to existing policies. This provides a concrete understanding of the meaning and implications of the different scopes when they are used to classify policies. The policies used for this purpose consist of: Minimum CO_2 price (Eerste Kamer, 2021), Porthos subsidy (Porthos, 2020), Hydrogen subsidies (NL and BE) (Federal government of Belgium, 2020; Rijksdienst voor Ondernemend Nederland, 2020), green heat calls (NL and BE) (Rijksdienst voor Ondernemend Nederland, 2021; De Vlaamse minister van justitie en handhaving energie en toerisme, 2021), EEG German Feed-In-Tariffs (Bundesministerium für Wirtshcaft und Energie, 2021), EU innovation fund (European Commission, 2021) and the Europen Emission Trading System (European Commission, 2015)

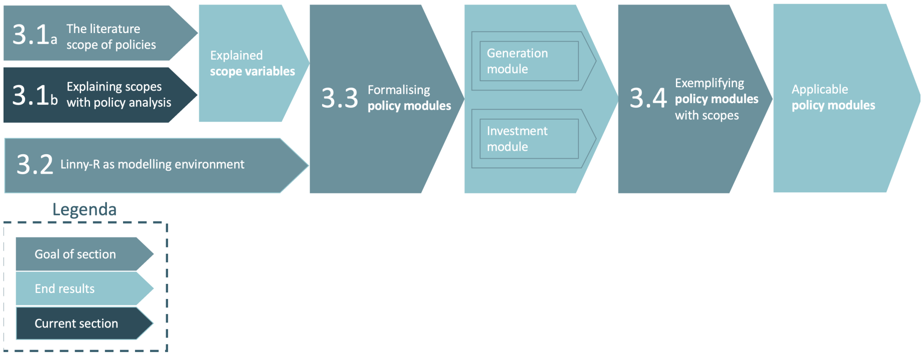


Figure 4: The current section is end of 3.1b.

3.1.1 Policy mechanism

The first important distinction that can be made in policies is between the encouragement and discouragement of using a commodity. The choice between these mechanisms, subsidies vs. taxes, is an age old and well researched topic in literature over the past decades (Debreu, 1954; Bian & Zhao, 2020). The minimum CO_2 price is a classic example of a tax, it directly discourages the emission of CO_2 by putting a price on it. The other policies mentioned above, are examples of governments that encourage the use of other commodities (a subsidy). All in all, the distinction between stimulating and discouraging behaviour is used by the author to classify different policies.

3.1.2 Policy source

Worp (2020) states the importance of European policy compared to national (Dutch) policies. Reason for this is the consequences of policies that are noticeable across borders. EU policies and guidelines get translated to national laws. This can lead to (minor) differences between active policies in member states. One of the potential disadvantages of national differences in climate policies is the concept of carbon leakage. The fear for carbon leakage (the shifts of companies that emit GHGs to less regulated countries) is already a decades long obstacle in reaching stronger climate regulations because of the potential loss of employment opportunities and tax gains (Babiker, 2005; Aichele & Felbermayr, 2015). Increasing the region to which the policy is applicable (e.g. EU wide) can reduce this effect (Murphy & McDonnell, 2017). Additionally, different policies can cause different pathways to sustainability to be most profitable. Thus, leading to different outcomes between countries.

An example in which separate countries chose different climate policies consists of the planned minimal carbon price for electricity generation in the Netherlands. This national policy is an extension of the the European Emission Trading System (EU ETS) in which the difference between the real price of the EU ETS and the minimum price determined by the Dutch government is taxed at a rate of 100% (Ministerie van financiën, 2019). Varying policies in different countries that lead to different cost prices of production, cause different behaviour of affected actors. Hence, the policy source and the corresponding geographical scope that the policy targets, influences the consequences of the policy and is thus important to take into account.

3.1.3 Commodity scope

This difference is in line with a knowledge gap identified in Chapter 2. Should policy focus on one commodity at a time or make an integrated design in which multiple commodities are included. In the research by Sumaila et al. (2016) and the report of (FAO, 2003) the commodity scope is mentioned as an important aspect on which policies can differ. An example out of which this difference becomes more apparent, is the Dutch SDE++ policy in which the main goal is decarbonization of heavy industry. The subsidy is in this case available for all initiatives for private investments into decarbonization technologies (Clean Air Task Force, 2020). The Dutch government specifies this subsidy even further. Recently (May 2021), the Dutch government announced that a substantial share of the SDE++ subsidy (€2.1 billion) is allocated for the specific subsidy of CCS by Porthos in the port of Rotterdam Porthos (2020). Hence, this policy is partly targeting a specific commodity and partly available for initiatives regardless of the commodity used. The rest of this research focuses at the CCS specific subsidy that is based upon the official explanation of the Dutch government concerning this compensation for the difference in ETS and CCS prices (RVO publicaties, 2020).

On the other hand, the Netherlands introduced a subsidy scheme specifically for the development of hydrogen as an energy carrier. This subsidy ('subsidieregeling waterstof - tender') stimulates innovating projects that have a high chance of success concerning the development of a viable business case after the subsidy has been given out (Rijksdiens voor Ondernemend Nederland, 2020). In Belgium a large subsidy has recently been announced concerning hydrogen. The largest part of this subsidy which is specifically focused at the development of a hydrogen network, will be implemented in Flanders (the region in which Antwerp is located). This subsidy scheme is set up on European level and on national level, the countries get to allocate the resources more specifically to different projects. Flanders can mark an initiative as an IPCEI (important project of common European interest), it does so if (a.o.) the project connects to the hydrogen value chain focused at innovative use of hydrogen as an energy carrier (Federal government of Belgium, 2020). Concluding, the commodity that is within the scope of a policy is important for the structure and potential outcome of the policy.

3.1.4 Policy type

Policies can add value for the receiver in different aspects of the project. Using this criterion the author differentiates between investment related and generation related policy interventions. Depending on the risks involved for the project, different subsidy schemes can be more effective.

The difference between investment or output related subsidies can most clearly be illustrated using feed-in tariffs for renewable energy sources and straight investment subsidies (Menanteau et al., 2003). According to Haas et al. (2011), feed-in tariffs are the most widely used promotion instrument in Europe. They're very effective as a fixed tariff for generation is guaranteed. Germany, Italy and Denmark were one of the firsts to implement such a scheme and Germany is now a front runner in the energy transition (Haas et al., 2011). Based on the German law on renewable energy (EEG), feed-in tariffs are a price that is agreed upon for generation for a certain period of time (typically 15 years). In case the market price is below this agreed upon tariff, the difference in market price and the feed-in tariff is compensated by the government (Bundesministerium für Wirtshcaft und Energie, 2021).

In case of straight investment subsidies, a part of the the investment risk is covered by providing a subsidy. An example of this is the European innovation fund (European Commission, 2021). This fund consists of an amount of maximum €10 billion for the period between 2020-2030 depending on the carbon price. Projects in the energy intensive industry and renewable energy sector with highly innovating ways to reduce carbon emissions and big flagship projects are eligible for a share of this fund. The investment risks with these projects are covered by granting up to 60% of the capital expenditures and estimated operational costs of the innovation. The contrast with the feed-in tariffs is that after the realization of the project, the business case has to be viable without further support.

3.1.5 Target industries

This classification criterion is important to make the distinction between the recipients of policies (who is targeted by a specific policy?). Many policies are specifically focused at certain sectors. However, some are more specific than others. The biggest climate policy in Europe, the EU ETS, is an example of a specific policy. Certain sectors like electricity and heat, energy intensive industry (e.g. oil refineries and steel works) and aviation within the EU are targeted by the ETS (European Commission, 2015). The wider aviation sector is still excluded from the ETS (till end of 2023). Also waste, agriculture and transport are not included (International Carbon Action Partnership, 2021).

More specific policies include for example the Dutch subsidy for renewable energy (HER+) (Rijksdienst voor Ondernemend Nederland, 2021). This subsidy (amounting €50 million) is only for projects that are focused on the development of renewable energy sources. Industry that e.g. produces fertilizers are consequently not eligible for this subsidy. Additionally also CCS and hydrogen projects are excluded from this subsidy. Also the hydrogen subsidy, which is part of the 'Topsector Energie', is specifically applicable to energy projects and hence doesn't stimulate carbon reduction investments in e.g. chemical industries. In Belgium more specific subsidy schemes can be found as well. In the 'call groene warmte' (green heat call) for example, a subsidy is provided for companies that invest in the utilization of rest heat originating from the electricity sector (De Vlaamse minister van justitie en handhaving energie en toerisme, 2021). Who is targeted by policies determines which actors are pushed to change behaviour and which are not. Hence, setting this scope can have a big influence on the outcomes of the policy.

To conclude on the scopes on which policies can be differentiated, the five as described above allow for a comprehensive classification based on literature and policy analysis. In the table (see Table 3.1.5) an overview is provided of the policies used above to describe the different scope variables. An interpretation by the author using official sources of these policies leads to a classification according to the scope variables identified in this chapter.

Table 3: A classification of the included policies along the introduced scope variables

Policy	**Mechanism**	**Source**	**Commodity scope**	**Policy type**	**Target industries**
ETS	Tax	EU	CO_2	Generation	ETS eligible
Min CO_2 price	Tax	NL	CO_2	Generation	ETS eligible
SDE++/Porthos	Subsidy	NL	CCS	Generation	All industries
Hydrogen subsidy	Subsidy	NL	H2	Investment	RES electricity
Hydrogen subsidy	Subsidy	BE	H2	Investment	All industries
HER+	Subsidy	NL	Multi commodity	Investment	RES development
Green heat call	Subsidy	BE	Waste heat	Generation	RES electricity
EEG FiT	Subsidy	EU	Electricity	Generation	RES electricity
EU innovation fund	Subsidy	EU	Multi commodity	Investment	Energy industry

3.2 Selecting the right modelling language

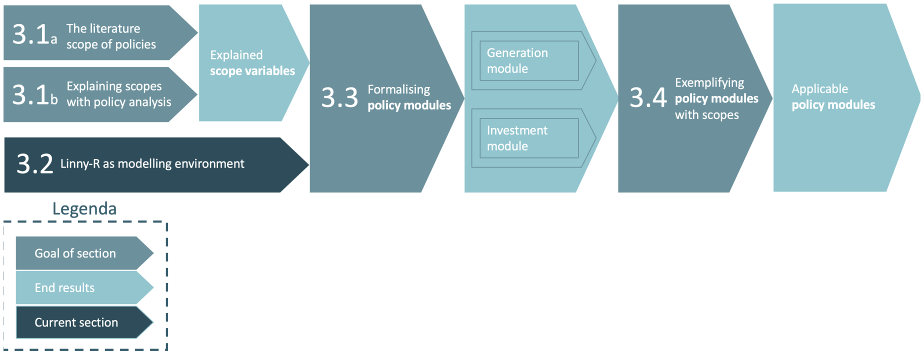


Figure 5: The current section is end of 3.2.

In this section the choice and the working of the modelling language Linny-R is argued for (see Figure 5). Concluding from Chapter 2, a variety of modelling strategies are used in the evaluated studies that correspond with their research goal. The goal in this research is to include policies within cluster modelling. To provide an environment in which full focus can be on including these policies, simplifications have to be made regarding the included processes that are potentially target of the policies. Additionally it must be noted that it is not within the scope of the author to include policies within all the different types of models used in the reviewed literature in Chapter 2. Hence, to focus on policy inclusion in a model without including unnecessary complexity, the author uses Linny-R as a language for Mixed Integer Linear Porgramming (MILP).

Linear programming is widely applied to the energy and industry sector to optimise transmission or transport networks as well as production and storage (Parlesak et al., 2016). Using linear optimization results in the before mentioned needed simplifications of the processes considered. This because processes in industrial clusters have more complex than linear relations (Kashyap, 2017). Despite the fact that linear optimisation is not the most efficient algorithm to solve more complex problems, it provides some advantages that make it highly applicable such as powerful solvers and the flexibility to identify and add constraints (Rodríguez-Sánchez et al., 2012). Taking into account the limitations concerning the needed simplifications of the real systems, it is expected that a well functioning translation of the scope variables into modules can be made. The goal of this section is to answer the following sub-question:

What modelling language is suitable for including policies in models?

Linny-R is a graphical representation language that allows for easy and intuitive (Mixed Integer) Linear Programming modelling. Because of the option that is provided by Linny-R to create 'plug and play' modules, the author is enabled to create policy modules that can be implemented in existing models in which policies can be important for potential outcomes. An example of a Linny-R model can be found in Figure 6. Linny-R makes use of products (oval shapes) and processes (rectangular boxes) that can be connected. A connection between a product and a process (an arrow) creates a supply chain. These links correspond to a flow and rate. In this example there is a demand for product Z. Actor 1 can foresee in this demand by using process 1 to convert products A and B into the demanded product Z. In Linny-R, actors can only generate cash flow by means of processes. Hence, actor 1 can generate a cash flow by enabling process 1 rather than selling product Z. Despite the fact that the results would be the same, this is an important distinction to make in light of the financial impacts of the policies. The number two on the connection between product A and process 1 represents the rate. Two amounts of A and just one amount of B are needed to create 1 of product Z. However, as a by-product also 1 amount of waste is produced. The dotted product is a data product that is used to read out information of the processes (or products). Process 1 is limited in production by climate goals. The line with a miniature graph represents an inverse relationship between climate goals and the level at which process 1 can produce. This constraint corresponds to the maximum production level of the process and the maximum to which climate goals can be enabled. These maximums are referred to as 'upper bounds'.
To provide an example, if the climate goals are 40% of what they could be in their most strict form (i.e. 100%), only 60% of the maximum production

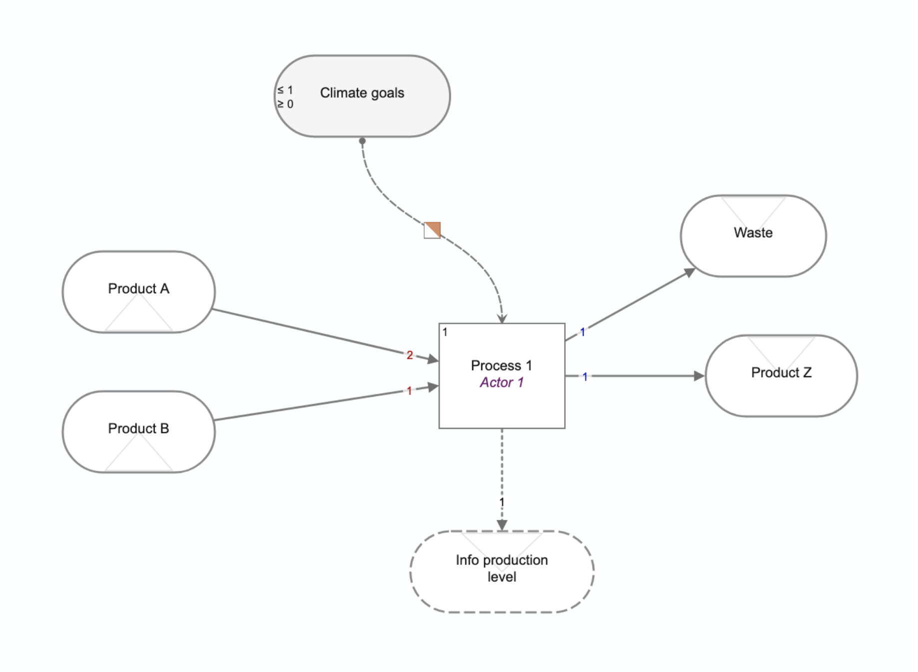


Figure 6: An example of a process (rectangle) in Linny-R that can produce product (oval) Z by converting products A and B into Z and waste. The dotted product is a data product that is used to read out information of the process. The extent to which process 1 can operate is inversely related to climate goals by means of a constraint.

capacity can be utilised by process 1.

Linny-R is is developed by Dr. Pieter Bots and is a software tool which optimizes cumulative cash flows of actors (Henriques & Stikkelman, 2017). Consequently, Linny-R chooses the cheapest means for production to foresee in the demand. For example, Linny-R will always chose to use natural gas over hydrogen in an industrial cluster if it is cheaper than hydrogen given that there are no limitations on the use of natural gas. Introducing a cost related to waste or a subsidy for using a specific commodity can influence the cheapest production means and thus the outcome of the model.

To optimize, Linny uses either LP_solve 5.5 (developed by Michel Berkelaar) (lp_solve, 2021) or Gurobi (developed by a.o. Robert Bixby) (Gurobi, 2021). In this research, Gurobi is used as it is most efficient in terms of computing time (Gurobi, 2021). As mentioned before, using Linny-R and these linear optimization solvers.

To conclude, Linny-R is a suitable modelling language for including policies within models. It is a (mixed integer) linear optimization tool that allows for development of plug and play policy modules. It consists of products and processes that can be connected to create supply chains for production. This tool provides the basis that is kept in mind when conceptualising and later formalising the policies in the following sections.

3.3 Formalising the module

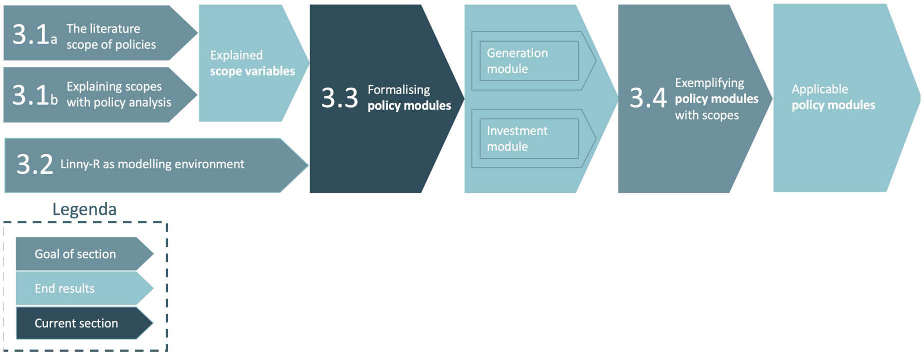


Figure 7: The current section is 3.3.

The goal of this section is to combine the previous sections of Linny-R and the scope variables of policies into policy modules (see Figure 7). To combine all types of policies identified before into a Linny-R module, two structurally different modules are needed to differentiate the policy type as scope. This because investment and generation based policies work differently in a model and require different boundary constraints to function. In line with FAO (2003) the capacity variables of size and duration are found in both modules. These consist of the following: size per unit, maximum yearly allowances, a maximum total cost and the duration of the policy. Using these capacity variables, in the following paragraphs first the generation based policy is explained after which the differences made for formalising investment policies are touched upon. After setting up the two policy modules, the implementation of these modules regarding the remaining scope variables are explained.

3.3.1 Generation-module

In this section the different attributes of the generation module (visualised in Figure 8) are explained. Firstly the 'level of subsidized process' product. It must be noted that even though the name suggests a subsidy, a tax can be introduced by means of a 'negative subsidy' in which money has to be paid rather than gained. This is done be applying either negative or positive prices to the policy module. The 'subsidized process' as the title insinuates, is the process that uses the commodity that a government is subsidizing. This is an already existing process in the model to which a data product is linked that measures the level of that process. The module is plugged into this product and is then included in the model.

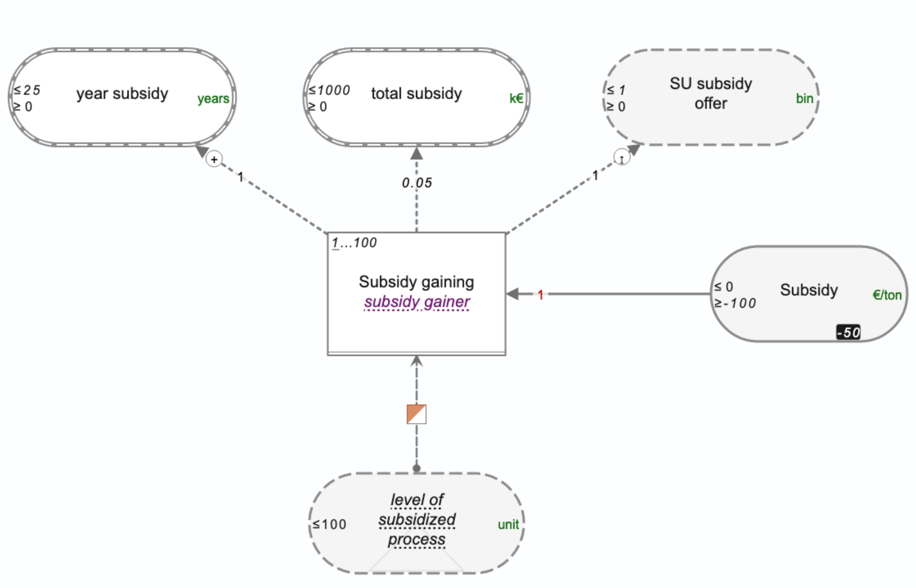


Figure 8: The module of generation based policies in Linny-R

Because the subsidy gaining actor owns the process of 'subsidy gaining', the cash flows from the subsidy are accumulated by the same actor as the owner of the process to which the subsidy applies. In other words, this results in the actor that is eligible for the subsidy actually receives the subsidy.

A constraint line (with the miniature graph) connects the 'level of subsidized process' with the subsidy gaining process. This combined with the same upper bound that the process and the data product have, ensures that subsidy is gained according to the output delivered (generation). Elementary this means that for every ton that is processed, a subsidy of x €/ton is provided to the actor involved (size per unit in FAO (2003)). In case the policy exists longer than one year, this subsidy per ton can (but doesn't always) vary over time. An example of this can be found in the Porthos subsidy that is announced by the Dutch government in May 2021 (Reuters, 2021; Stones, 2021). This subsidy compensates for the difference in price between emitting CO_2 and storing the CO_2 in depleted gas fields. Hence, the subsidy per ton is different every year.

Concerning the yearly allowances. As every time step simulates one year, a limit can be set on a max amount of tonnes subsidized per year. Limiting the yearly allowances is used as a proxy for excluding certain target industries in industrial clusters. This as due to scoping decisions, the specific industries are not separately modelled by the author (further discussed in Chapter 4).

Lastly, the total amount of years the policy lasts can be limited (policy duration) and the total costs of a policy is a variable (total costs). These variables are visualised in the figure under the products 'year subsidy' and 'total subsidy'. Additionally, the author added an extra variable that can be used if the duration does not consist of an end date of the policy. If in stead of an end date, a period that a policy lasts (e.g. five years no matter when the policy is adopted) is used, the latest moment that the policy is adopted can be specified. This is done using the 'SU subsidy offer' (Start Up subsidy offer) that represents the time that the policy is being offered and thus sets the latest moment that the switch can be made to the subsidised process. This variable is further referred to as policy offer time.

To conclude, there are five capacity variables that are used for the construction of generation based policies. These five capacity variables are framed as the following terms: size per unit, yearly allowances, maximum total costs, policy duration and policy offer time. Together they determine the capacity of the policy but hypothetically can be set independently if no budgetary constraints are set

3.3.2 Investment-module

The investment module is developed from the same reasoning as the generation-module. However, rather than measuring the level of the subsidized process and deliver subsidy based on the output of this process, it now is important to measure when the subsidized process is taken in use for the first time. To this end, slight changes had to be made opposed to the generation module. The investment module visualised in Figure 9 and the differences with the generation module are explained below.

Because of the goal on environmental policies, the most important difference that can be noticed is the extra constraint line that is included. This constraint line ensures that if the policy is adopted, the emissions of the process

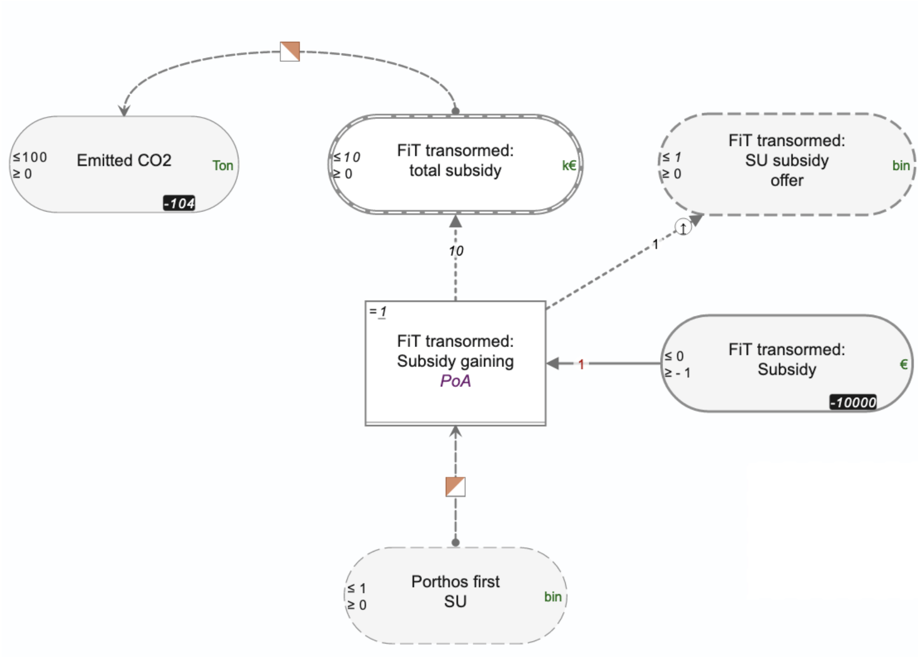


Figure 9: The module used for investment based policies

to which the policy applies are reduced structurally. This is needed because the money is transferred over only one time step. After that time step, the incentive to reduce emissions disappears. To prevent switching back to emitting emissions, the constraint line is needed.

Other modifications consist of the lost need to measure yearly allowances and total costs as the money is only transferred once. The price that corresponds to the size per unit in the generation module now is the total size of the policy. Lastly a modification is made in the 'first SU' data product. This measures when the process used for the first time and ensures that the money can only be transferred once. Hence, the smaller set of capacity variables needed for modelling investment policies are the size and duration of the policy. Because these are a subset of the capacity variables needed for the generation module, those will be used in further references.

To conclude, two policy modules are created that are structured differently. These policy modules correspond to the 'policy type' which is one of the scoping variables identified in Section 3.1 of this chapter. Additionally it was mentioned that stimulating and discouraging policies can easily be constructed in the modules by just applying positive or negative prices. Now that it is possible to differentiate between policy types (investment and generation based policies) and policy mechanisms (stimulating and discouraging policies), they can be applied to the remaining scopes (policy source, commodity scope and target industries).

3.4 Exemplifying the modules using scope variables

The goal of this section is to show how the modules look if the remaining scope variables are varied (see Figure 10). To show this, the generation module is used as example but it is applicable to both modules similarly. Figures are used as visualisation, and the implementation of the different scopes is explained.

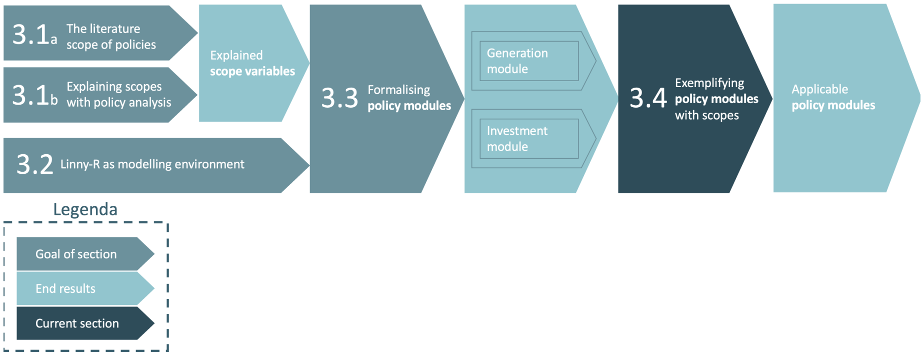


Figure 10: The current section is 3.4.

First the **policy source**. The structure of the modules does not change significantly by changing the policy source. In Figure 11 this is visualised by adding 'from source' at both the 'subsidy' as well as the 'total count'. Off course, when implementing differently sources policies the source has to be specified by name.

Second the **commodity scope**. The modules are already generally applicable for different commodities as the data product 'level of subsidised process' doesn't require a specific commodity input. However, if the commodity scope is extended to include a wider variety of commodities, multiple modules have to be included that share the capacity (size and duration) variables. This is visualised in Figure 12. The most important difference is the extra data product that is added to ensure that the the years that the policy is available are only accounted for once. It is now measured when at least one of the included commodities uses the policy.

It is also possible to not include a specific commodity scope but only look at the emissions. In this case, the policy is inversely related to the emission of

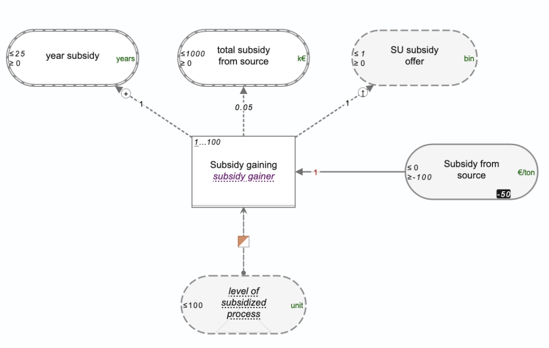


Figure 11: The module adapted for a specific source

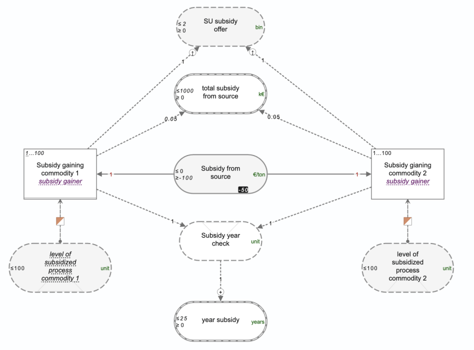


Figure 12: The module adapted for multiple commodities

(for example) CO_2. This is visualised in Figure 13. This results in a general stimulus to reduce emissions .

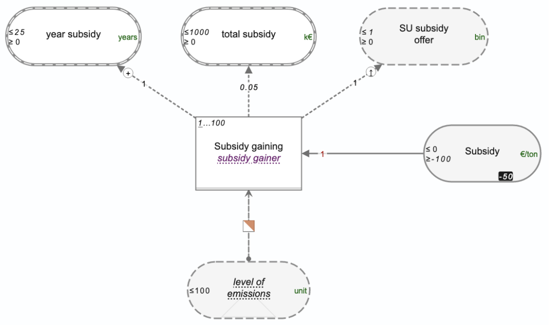


Figure 13: The module adapted for to stimulate emission reductions

Lastly **target industries**. As mentioned before, modelling specific industries is not within the scope of this research. If however specific industries are only eligible for a policy, in future research only processes of these industries can be attached to the module in the same way as presented for the commodity scope. In this research limiting the maximum amount of units per year that are eligible for the policy is used as a proxy for different target industries.

To resume, in this chapter it is has become clear how policies can be included in Linny-R and how the different scope variables can be varied to create different types of subsidies. The different scopes of policies consists of: policy mechanism, policy source, commodity scope, policy type and target industries. To comprehend these scopes, two policy modules are created: a generation module and an investment module. To test these modules, a stylist testing environment is created in the next chapter.

4 Designing the stylised cluster model

The goal of this chapter is to create a stylised cluster environment. This environment is used to test the policy modules created in the previous chapter. Because of the scope of this research to the methodological inclusion of policies within linear optimization models, the inclusion of commodities and clusters have to provide an environment in which the different scopes of policies can be tested. Therefore it provides a basis on which in the next chapter an answer can be provided to the following sub-question:

What is the commodity and cluster context to which the modules can be applied? How can the effect of policies in cluster modelling be determined?

To create this testing environment, first an overview is provided of the main commodities that are of interest in the scope of flow exchanges between industrial clusters. Secondly the model that is created is presented and the assumptions regarding the interconnections within the geographical scope (Antwerp, Rotterdam and Chemelot) and the included commodities are explained. In the last part of this chapter, the policy module is introduced in this stylised environment to verify the module and external influences from this environment (see Figure 14).

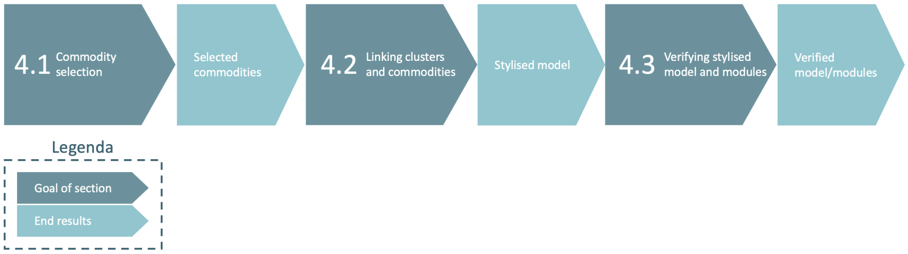


Figure 14: The structure of chapter 4.

4.1 Commodities

The included commodities in the testing environment to evaluate policies consist of: natural gas, electricity, hydrogen en CO_2. An overview of commodities that are of interest within an industrial cluster including background knowledge and the scoping decision to include these four commodities can be found in Appendix B.

In the following subsections, the main reasoning for including these four separate commodities and their relevance regarding the analysed policies is presented.

4.1.1 CO_2 and CCS

As discussed in the previous chapter, emissions (specifically CO_2 emissions) are of interest for sustainability policies. One of the production options included in the model is carbon capture and storage (CCS). This is included in the form of the Porthos project located in the port of Rotterdam (Porthos, 2020). CO_2 is captured and transported to depleted gas fields in the North Sea in which it is stored. Besides the technical implications, the Porthos project is of interest also from a policy perspective. Recently Porthos and its initial clients have been granted an EU subsidy worth €102 million and a Dutch subsidy worth €2.1 billion (Stones, 2021; Porthos, 2020). The CCS price for Porthos is assumed to be the effective cost price for customers. It thus includes the transport and storage costs as well as a profit margin for the Porthos company.

4.1.2 Hydrogen

Hydrogen has large potential in fulfilling a role in the future energy system (Wang et al., 2020). This as it can be produced without emitting CO_2 and it can be slotted in many sectors. Often, hydrogen can be used as an easy to implement replacement of natural gas that is used to generate high heat, as feedstock for industry (like fertilizers) or as fuel for heavy duty transport. Lynn Orr (Professor Emeritus, Energy Resources Engineering, Stanford University) states that hydrogen will be the main direction for making heavy industry sustainable (Orr, 2021). According to the Port of Rotterdam, it is expected that green H2 will be imported from countries with high solar and wind potential which can be used to create green H2 (Gemeente Rotterdam, 2020). Currently 400.000 tons of hydrogen are already being produced and used in the port of Rotterdam. Use is currently focused on refineries and chemical industries. Future use is planned to be used for industrial heat and storage to reach electricity grid stability (Port of Rotterdam, 2020a). For this research, the production of hydrogen is outside the scope and only the industrial use of hydrogen is considered.

4.1.3 Electricity and Gas

Electricity and gas networks in the North western Europe are well developed as these commodities are already used for over a century (van der Linde & Stapersma, 2018). However, the electricity network is expected to be put under pressure due to the increasing shares of renewables and electrification in the coming decades (Droste, 2018; Blonsky et al., 2019; NOS, 2021). This electrification can partly take place in an industrial setting and thereby help to decarbonise the industry (Schiffer & Manthiram, 2017). Nevertheless, electrification options are limited in e.g. petro-chemical industry and can not fully replace fossil fuels (Clingendael international energy programme, 2018).

Natural gas is currently widely used in the industrial sector (Honoré, 2014). In this research it is assumed to be a proxy for the current (fossil based) production method. Therefore, the most important characteristic of using natural gas as a production commodity is the emission of CO_2.

4.2 Formalization of the stylised model

The goal of this section is to introduce the stylised model that is used for testing the policy modules. This is done by introducing the characteristics of the dependencies of the different industrial cluster to the included commodities.

For scoping purposes, the different clusters are modelled as a demand that must be fulfilled and an owner of that cluster that makes the decisions and generates cash flows. To foresee in the demand, the corresponding actor can choose different processes that use different commodities.

In Figure 15 the cluster of Antwerp is visualised with the options for using different commodities to foresee in the demand. Important to note regarding the different commodities are the following: the prices of commodities, the emissions that are related to using that commodity and lastly, the potential of switching to that commodity. The prices of the commodities differ between themselves and over time. Only if natural gas is used, CO_2 is emitted. The clusters have different characteristics that determine how suitable that cluster is for using a specific commodity for their production.

In the following paragraphs the different clusters are introduced that all resemble a similar structure as visualised in Figure 15. The potential for different commodity inputs are elucidated per cluster.

Rotterdam is a petro-chemical cluster (Port of Rotterdam, 2016), the potential of electrification in the petro-chemical industry is low (Clingendael international energy programme, 2018). This is due to the heat limits that coincide with electricity usage. It is assumed that Rotterdam has the potential to only partly switch to an electrified production. On the other hand, they state that hydrogen and heat have the most potential in carbonizing the industry.

Opposed to Rotterdam (a petro-chemical cluster), the Chemelot cluster is a more chemically oriented cluster (Chemelot, 2020). This implies that other commodity connections are of interest. Chemelot uses primarily natural gas

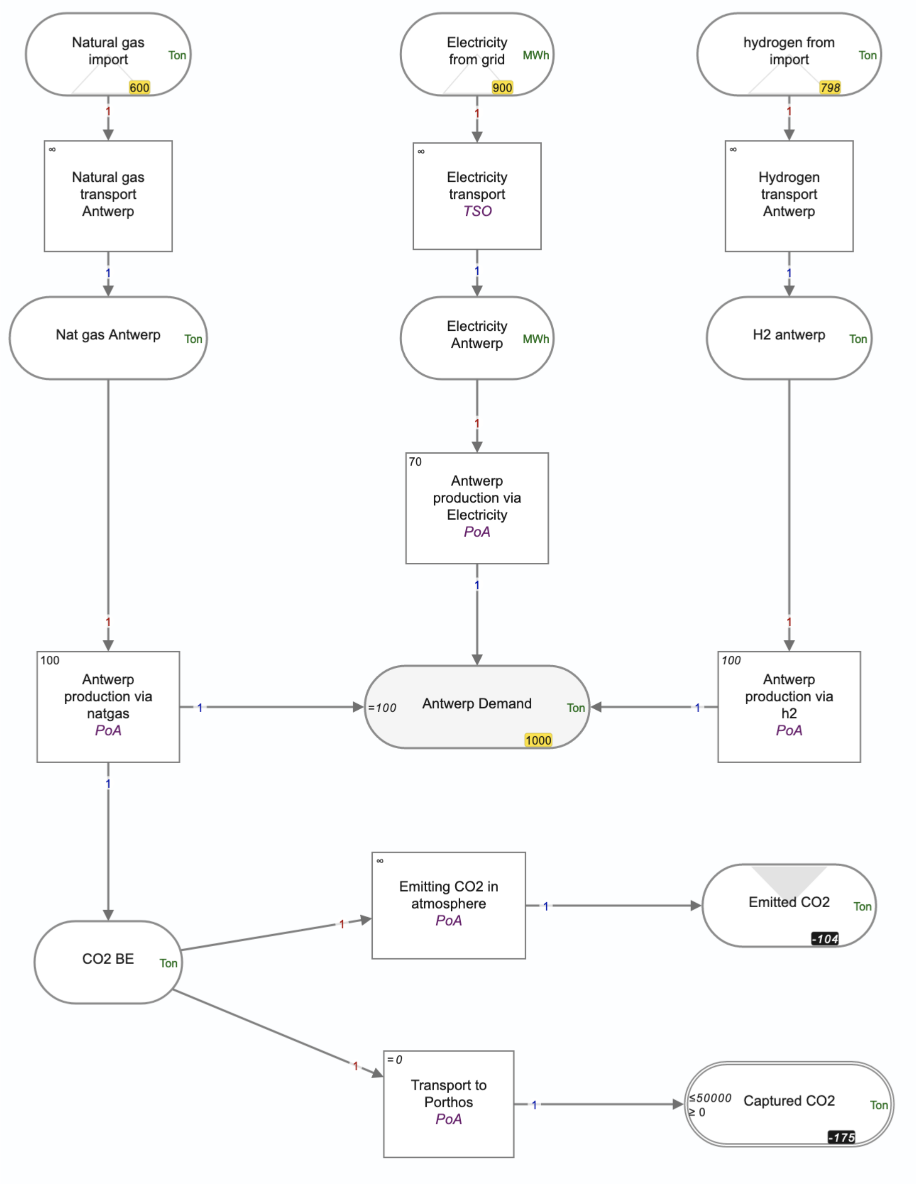


Figure 15: The inclusion of Antwerp as example of how also the Rotterdam and Chemelot clusters are included in the stylised testing environment.

(and NAFTA) for their current production. According to their publications, they expect to replace these with renewable process inputs (Chemelot, 2020). It is stated that great amounts of heat is required for production, this is now fossil heat but will be replaced by electrical heat. The goal is set to completely switch to sustainable sustainable/electrical heat. Even though there are direct limitations to using electricity as main input for industrial processes (Philibert, 2019), it is assumed that Chemelot has a high potential for electrification (Chemelot, 2020).

Lastly, the Port of Antwerp both has refineries and steam crackers needed for the petroleum industry as well as chemical production (Port of Antwerp, 2020). Therefore, the author has assumed a simplification in which Rotterdam has very limited/no electrification possibilities, Chemelot aims at switching to (renewable) electricity usage opposed to natural gas and the Port of Antwerp has the opportunity to use both electricity as well as hydrogen in their pursuit to a renewable future.

Concerning emissions, CO_2 can be emitted in each cluster. If no interventions are made in the system, it is most profitable to use natural gas and emit CO_2 at the start of the optimization. Increasing CO_2 prices and/or other policy interventions stimulate a switch in production method. This as switching to using different production methods can reduce the CO_2 emissions. Additionally, the CO_2 can also be stored.

To conclude, a combination of commodities offer different options to produce in three clusters. These clusters have characteristics leading to differing potential concerning the use of the commodities. Varying commodity prices trigger the clusters in using different commodities over time to foresee in their demand. This creates a stylised model that is suitable for including the policy modules within this cluster model and conduct experiments with different policy scopes.

4.3 Verification

Now that the stylised model is presented and clarified as testing environment, this section is used to verify the policy modules and the testing environment itself. This is done by running experiments on a mix of extreme values to compare expected behaviour against model behaviour.

The verification takes place on two different levels of the model. First, the external variables are varied. Hence, the CO_2 price, and the difference between commodity prices are varied to see if the stylised model (without policy interventions) has the expected behaviour. Secondly, the capacity policy variables (introduced in Chapter 3) are scrutinised. These consist of: size per unit, yearly allowance, duration, total costs and policy offer time. This allows to test whether a policy without varying the scopes has the expected effects on behaviour.

For the verification of the model behaviour different simplifications of the model are used. For the verification of the external variables, a model consisting of all three clusters and no policy interventions is used. To verify the capacity variables, a model is used in which only one cluster (Antwerp) and two production options (natural gas and hydrogen) are included. In this cluster one policy module is applied to stimulate the switch to the not emitting production option. These simplifications are needed to compare the model behaviour to the hypothesised results.

The details of the verification can be found in Appendix E. It can be concluded that the model shows the expected behaviour when testing the external variables. If extreme values are used for the external variables, either great amounts or no hydrogen is used. This is expected as due to the extreme values, hydrogen and/or emitting CO_2 is either relatively expensive or cheap.

Both the generation and investment based modules are tested. Concluding the generation module, policies work as expected. Higher subsidy costs lead to less emissions (and more hydrogen usage). This taking into account certain thresholds. These thresholds are an interplay between the capacity variables and the commodity prices as a switch between commodities is only made if the policy results in the other commodity being cheaper. If the policy is made more attractive (and thus more costly) by increasing the policy per unit, one has to take into account that there might arise a situation in which it is profitable to switch back after the duration of the policy. Hence, when designing policies, this has to be taken into account. It can be more effective to increase the duration of the policy than the unit size or yearly allowances.

Regarding the investment module however, the author concludes that due to computational limits of Linny-R, this module does not result in the expected behaviour. This is due to missing constraints that are used by the solver to come to an optimum. It is not possible to force a process to correctly report when it start up if a positive consequence (like a subsidy) is tied to this start up. This allowed the optimizer to generate cash flow for actors from the implemented policy while not applying to the conditions of that policy. The specifics and deduction of these missing constraints are in depth discussed in Appendix C. However,

To conclude, in this chapter a stylised testing environment is created consisting of four commodities (hydrogen, natural gas, electricity and CO_2) and three clusters (Antwerp, Rotterdam and Chemelot). By means of testing extreme values, both the model and the policy modules are verified. Due to computational limitations of Linny-R, only the generation module can be used for further experiments as the investment module did not optimise within reasonable computation times.

5 Experimental set-up

In this section the author strives to create insight in two aspects. Firstly, performance indicators are introduced to define how policies can be measured. This is in line with the overall goal of this research to provide means to include and show the importance of including policies within a model. Secondly an overview is provided of the experiments that lead to insight in the effect of varying the scope of policies (see Figure 16). These subsequent steps are taken to answer the following sub-question:

What is the commodity and cluster context to which the modules can be applied?

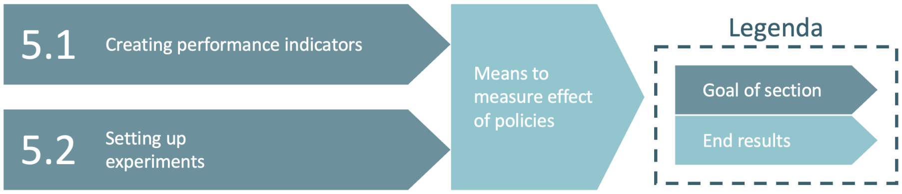


Figure 16: The structure of chapter 5.

5.1 Performance indicators

To determine the evaluative criteria, the objectives of the analysed policies are used. As mentioned before, the policies in scope of this research are climate related. The goals set for these different policy schemes are often wider than the climate related scope considered in this research. Even if the main goals of the policy are climate related, the additional goals can consist of e.g. job provision (Ministry of economic affairs and climate policy, 2019) or reaching a global exemplary function (European Commission, 2021).

For the innovation fund by the EU, the objectives are set to be ”creating financial incentives for new investments in innovative green technologies”, ”boosting growth and competitiveness by helping ”first-movers” to become global leaders” and ”supporting clean technologies to come to the market”. The ’topsector energie’ also includes goals to reduce energy use which is a more specific form of CO_2 reduction as it e.g. excludes CCS. Additionally, the goal is set that the Netherlands has to become a front runner in clean technology by 2030.

However, the main goal of these policies is to minimize the global warming by reducing the emission of GHGs. This is the goal that is most important considering the scope of this research. To create insight in how well policies work in reaching these climate goals, both effectivity and efficiency are of interest.

Effectivity of a policy measures how much emission reduction is reached compared to no change of policy intervention. The efficiency of this policy is measured in €/avoided emissions. This provides insight in how well spent budget is in reaching this goal. If different policies are tested in similar environments, these performance indicators allow to judge which policy is best in reaching the goal to the furthest extent and/or most efficiently.

To conclude, climate policies often have a wider set of goals that do not directly contribute to climate improvements. In this research however, the main evaluative criteria consider only climate related goals and consist of the effectivity and efficiency of the policy in reducing emissions. Effectivity is interpreted as reduced emissions and measures reduced emissions relative to no change of policy intervention. Efficiency is interpreted as how well spent money is in reducing emissions. This way, conclusions can be drawn on the effectivity and efficiency of policies when the scope variables are varied.

5.2 Experiment planning

The goal of this section is to present the planned experiments and provide insight into how these experiments contribute to answering the main research question of this studies. It must be noted that due to the conclusions drawn from the verification of the modules, the experiments can only be conducted based on the generation based policy module.

The experiments are used to create insight into the effect of different scopes of policies in an industrial cluster model. To this end, the scope variables are split in two pairs: scopes that are representative of the specific policy and scopes that can be varied easily within the modelling context. This first pair consists of the policy mechanism (encouraging/discouraging) and commodity scope. If these scopes would vary, the policies would not be recognizable as such anymore (e.g. a hydrogen subsidy could become a CCS tax). The second pair consists of policy source and target industries. These determine which clusters and which part of industries within these clusters are eligible for the policy. Because the different sectors are not modelled separately, these parts of industries correspond to targeting sectors that cumulatively are responsible for a quarter, half or all of the production.

Hence, to cover the first group of scopes, an interpretation of different existing policies are taken as input. The second group of scopes are then varied within these input policies to create a comprehensive insight in the effect of varying the different scopes of subsidies. For every experiment, a situation without additional policy intervention is taken as a basis. The result of varying policy interventions with different scopes can then be interpreted and compared against this base case.

Table 4: Overview of the different inputs for the experiments. Four experiments are run with different policies as input. Within these experiments, nine runs (3 sources • 3 target industry sections) create a comprehensive insight into the effect of varying the policy source and target industries.

Policy input	**Mechanism**	**Commodity**	**Source**	**Target industries**
Min CO_2 price	Tax	CO_2/Not-specified	NL	1/4
			BE	1/2
			EU	1/1
SDE++ Porthos	Subsidy	CCS	NL	1/4
			BE	1/2
			EU	1/1
Hydrogen	Subsidy	H2	NL	1/4
			BE	1/2
			EU	1/1
Inverse CO_2	Subsidy	CO_2/Not-specified	NL	1/4
			BE	1/2
			EU	1/1

In Table 4 an overview is provided of the different inputs for experiments. Four experiments are run with different example policies as input. Within these experiments the policy source and target industries are varied resulting in nine different configurations/runs. The experiments are shortly introduced in the rest of this section. In Appendix D, the in depth assumptions of the different experiments are discussed.

The first experiment consists of an additional CO_2 tax. This policy is based on the minimum CO_2 price that the Dutch government introduced in 2020 as addition on top of the already existing European emission trading system. In the runs of this experiment this minimum CO_2 price is applied on Dutch, Belgium and EU level and on these levels different parts of the industry are targeted. This is in line with the basic setup for the following experiments.

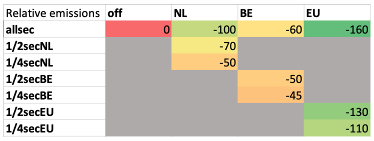
The second experiment consist of the Porthos subsidy which has been discussed earlier. The price difference between CCS and the cost of emitting CO_2 is the basis of this policy intervention.

The third experiment is based on a hydrogen subsidy. To support hydrogen usage and development, a supplement of money is provided if hydrogen is used to foresee in the demand of the different clusters.

The last experiment uses an inverted CO_2 subsidy as input. Here a subsidy is granted if emission reductions are realised by the different clusters. For this subsidy, the means they use to realise these reductions are not of interest for the policy.

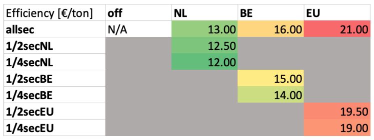
The results of the experiments are separately presented in figures using a colour scale from red to green. The effectivity of the policies are measured as emissions compared to no additional policy interventions (and are thus negative if the policy works). The efficiency is measured in € per ton avoided emissions and are thus best if they are low. The better the policy works, the greener the result of that scope. It must be noted that the colour schemes are reset for every separate experiment. To compare the four different experiments, the colour indications cannot be used effectively.

In Figures 17 and 18, an example output of one of the experiments is visualised. Two figures are included to both show the relative effectivity as well as the efficiency of the policy intervention. The grey cells indicate that the specific policy source and target industry share do not match (e.g. targeting a quarter of the Belgium sectors with a Dutch policy does not make sense and is thus gray).



Relative emissions	off	NL	BE	EU
allsec	0	-100	-60	-160
1/2secNL		-70		
1/4secNL		-50		
1/2secBE			-50	
1/4secBE			-45	
1/2secEU				-130
1/4secEU				-110

Figure 17: Example effectivity output of an experiment



Efficiency [€/ton]	off	NL	BE	EU
allsec	N/A	13.00	16.00	21.00
1/2secNL		12.50		
1/4secNL		12.00		
1/2secBE			15.00	
1/4secBE			14.00	
1/2secEU				19.50
1/4secEU				19.00

Figure 18: Example efficiency output of an experiment

To summarise, four experiments with each nine runs are conducted to create insight in the effect of varying the different scopes of policies. It is expected that scoping policies nationally results in more efficient policies compared to EU policies as national differences can be taken into account more easily. Additionally, targeting a smaller share of sectors is likely to result in more efficient policies as there potentially is 'low hanging fruit'. For both scope variables however, it is expected that the effectivity is the highest when the reach is the biggest (i.e. most countries and sectors respectively). Concerning the encouraging vs. discouraging policies, it is expected that variances in this scope have similar potential. Lastly the commodity scope, the author expects specific focus on a commodity to be less efficient than leaving the decision how to reduce emissions up to market forces. This because the included clusters have different paths to reduce emissions most efficiently. These are not utilised when targeting only one commodity. The following chapter is used to present and interpret the results of varying the scopes of policies with which the research question of this studies can be answered.

6 Results

In this section the results are presented. Because of the assumptions made in the stylised testing environment, the units do not resemble real life figures and the outcomes of effectivity and efficiency can only be used to compare subsidy scopes within this study. Additionally, the colour schemes used to present the results of the experiments are based on the numbers within that specific experiment. Hence, the colours cannot be used to compare outcomes between the experiments. This chapter is structured as follows: in the following sections the results of the experiments are introduced and interpreted. At the end of the chapter the different results from the experiments are reflected upon to create a comprehensive insight in the potential effects of the different scopes of policies (see Figure 19).

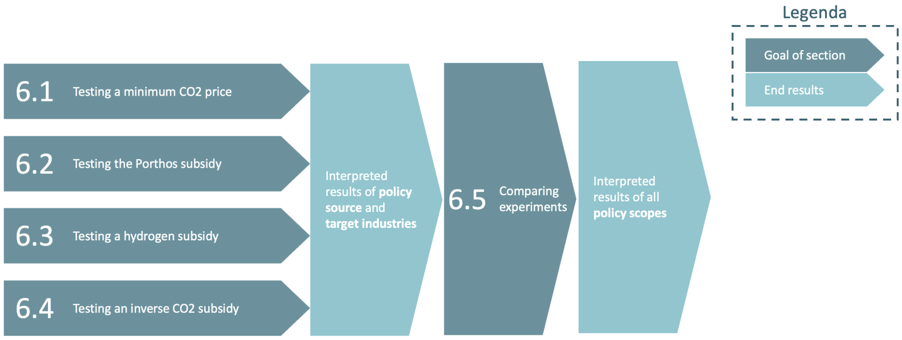
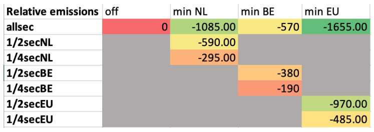


Figure 19: The structure of chapter 6.

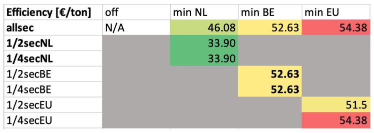
6.1 Minimum CO_2 price

In the relative emissions table, the CO_2 emissions saved compared to the base case of no minimum CO_2 price are visualized (see Figure 20). In the efficiency table, the reduced tax incomes (policy costs) are compared to the reduced emissions which results in the efficiency performance indicator of €/ton reduced CO_2 (see Figure 21). The figures can be read as follows: in the columns, the different policy sources can be found. In the rows the corresponding shares of included target industries are located. The gray cells indicate that the specific row and column do not match as they concern shares of target sectors in different countries. The colours indicate how well the source and target sector of that cell score compared to no policy intervention. It can be seen that the effectivity increases when more sectors and countries are included (red to green diagonal gradient in Figure 20) and the efficiency trend reduces when more sectors and countries are included (green to red diagonal gradient). An exception concerns the Dutch all sector minimum CO_2 price, Here both the effectivity as well as the efficiency scores relatively positive.



Relative emissions	off	min NL	min BE	min EU
allsec	0	-1085.00	-570	-1655.00
1/2secNL		-590.00		
1/4secNL		-295.00		
1/2secBE			-380	
1/4secBE			-190	
1/2secEU				-970.00
1/4secEU				-485.00

Figure 20: Relative emissions compared to only ETS price varied over sectors. Including more countries and sectors leads to more reductions in emissions.



Efficiency [€/ton]	off	min NL	min BE	min EU
allsec	N/A	46.08	52.63	54.38
1/2secNL		33.90		
1/4secNL		33.90		
1/2secBE			**52.63**	
1/4secBE			**52.63**	
1/2secEU				51.5
1/4secEU				54.38

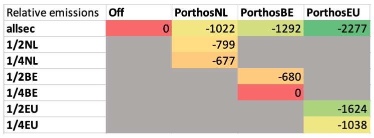
Figure 21: Efficiency of the minimum CO_2 price varied over sectors. The Dutch CO_2 price is most efficient. In Belgium the efficiency doesn't vary with different shares of sectors. The most effective policy intervention is least efficient.

It can be concluded that increasing the CO_2 price according to the minimum CO_2 price introduced in the Netherlands in 2020, provides a strong incentive to reduce emissions. Hence, this increased CO_2 price leads to less tax incomes. From applying the minimum CO_2 price on NL, BE and EU level and comparing this to the CO_2 price of only using the emission trading system (ETS), it can be concluded that applying the minimum price only in the Netherlands to specific sectors (up to 50% of all emissions) is most efficient (i.e. lowest €/ton reduced emissions). However, applying the increased CO_2 price on EU level is most effective (i.e. most reduced emissions). In addition it can be noted that the different included sectors that are eligible for the minimum CO_2 price in Belgium do not influence the efficiency, this can be explained due to only the port of Antwerp that is included opposed to both Chemelot and the port of Rotterdam that are included in the Netherlands. Mutual differences between Rotterdam and Chemelot lead to different model behaviour when more sectors are included.

To conclude, this tax is most effective when all sectors are included on a European level. It however is most efficient if only up to half the sectors are included in a sole Dutch setting. It becomes clear that depending the goal of the policy makers, a different choice of the policy source and target industries would be chosen.

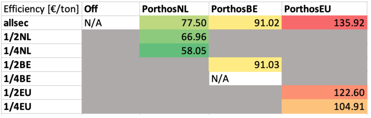
6.2 SDE++ Porthos subsidy

The experiment concerning the Porthos subsidy contains a variable subsidy based on the price difference between CCS and CO_2 emission prices. In the figures below the relative emissions (see Figure 22) as well as the efficiency (see Figure 23) are presented of a Porthos subsidy on NL, BE or European level. In the columns the subsidy source (i.e. national and EU) is presented while in the rows the outcomes are visualized concerning the shares of industries (i.e. target industries) that are eligible for the subsidies.



Relative emissions	Off	PorthosNL	PorthosBE	PorthosEU
allsec	0	-1022	-1292	-2277
1/2NL		-799		
1/4NL		-677		
1/2BE			-680	
1/4BE			0	
1/2EU				-1624
1/4EU				-1038

Figure 22: Relative emissions of the Porthos subsidy on different subsidy sources and target industries. EU has the highest potential followed by Belgium. In the Netherlands excluding sectors has only limited effect.



Efficiency [€/ton]	Off	PorthosNL	PorthosBE	PorthosEU
allsec	N/A	77.50	91.02	135.92
1/2NL		66.96		
1/4NL		58.05		
1/2BE			91.03	
1/4BE			N/A	
1/2EU				122.60
1/4EU				104.91

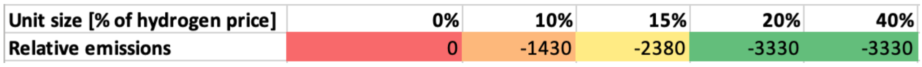
Figure 23: Efficiency of the Porthos subsidy on different subsidy sources and target industries.The Dutch CCS subsidy is most efficient. In Belgium the efficiency doesn't vary with different shares of sectors. The most effective subsidy scope is least efficient.

When looking at Figure 23, it can be concluded that the Porthos subsidy is most efficient in the Netherlands (shades of green) and the least efficient when implemented on EU level (shades of red). This can be explained because of the different circumstances between the included countries and the specific focus on CCS. In Belgium CCS clearly is a less efficient option to reduce emissions compared to the Netherlands. In case of a European subsidy, this results in money that can be spent efficiently in the Netherlands now is used less efficiently in Belgium. Additionally, it is assumed that an EU subsidy is uniform for every country. Because of the differences in CO_2 price, more money has to be spent in the Netherlands than would have been needed if it was organized nationally taking into account the national subtleties. However, when looking at Figure 22 it can be seen that most emission reductions can be reached when the Porthos subsidy is implemented on EU level. It also becomes visible that in case of a Belgium scope, targeting only a quarter of the sectors does not result in a change of behaviour and no emission reduction is reached.

To conclude, the Porthos subsidy has the least potential emission reduction in the Netherlands but the reductions realised are efficient. Again most effect can be reached when a European wide subsidy is implemented but this would be a are relatively expensive subsidy. In the Netherlands and on EU level, only including a share of the sectors leads to a more efficient subsidy.

6.3 Hydrogen subsidy

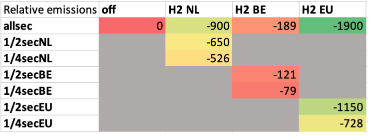
For this experiment, first a sensitivity analysis is conducted to determine the height of the subsidy that matches with the rest of the numbers in the model. This is needed because there is no price base mentioned in the subsidy that can be used to determine the unit size of this subsidy. To this end, the height of the subsidy is varied relative to the hydrogen price used in the stylised cluster model. This is done for a subsidy on EU level for all sectors until no further improvements in reduced emissions are realized. This is the point where the subsidy doesn't increase in effectivity if more money is allocated. This point is reached at 20 % of the hydrogen price (see Figure 24). This is taken as the subsidy per unit in the experiments.



Unit size [% of hydrogen price]	**0%**	**10%**	**15%**	**20%**	**40%**
Relative emissions	0	-1430	-2380	-3330	-3330

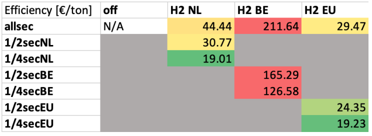
Figure 24: Decreased emissions as function of the subsidy height that is relative to the hydrogen price.

Varying this subsidy over the different subsidy sources and target industries leads to the following results (see Figures 25 and 26).



Relative emissions	**off**	**H2 NL**	**H2 BE**	**H2 EU**
allsec	0	-900	-189	-1900
1/2secNL		-650		
1/4secNL		-526		
1/2secBE			-121	
1/4secBE			-79	
1/2secEU				-1150
1/4secEU				-728

Figure 25: Relative emissions of the H2 subsidy on different subsidy sources and target industries. EU has highest potential followed by the Netherlands.



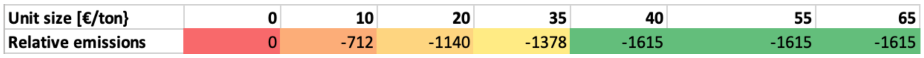
Efficiency [€/ton]	**off**	**H2 NL**	**H2 BE**	**H2 EU**
allsec	N/A	44.44	211.64	29.47
1/2secNL		30.77		
1/4secNL		19.01		
1/2secBE			165.29	
1/4secBE			126.58	
1/2secEU				24.35
1/4secEU				19.23

Figure 26: Efficiency of the H2 subsidy on different subsidy sources and target industries. Belgium is most expensive source scope. On EU is more efficient than Dutch .

It can be concluded that implementing this subsidy on EU level for all sectors is most effective. However, the subsidy becomes more efficient when not all sectors are included. It can thus be concluded that there is low hanging fruit (i.e. parts of the cluster) that can reduce emissions against lower costs compared to a subsidy that is available for all sectors. This is visible on EU as well as national levels. Additionally, Belgium requires relatively high amounts of subsidy compared to the reduction of emission they can reach in the field of hydrogen (i.e. Belgium has a lower efficiency). This is because there are relatively cheaper ways to reduce emissions using either electricity or CCS. Hence, more money is needed to reduce emissions when specifically hydrogen is supported.

6.4 Inverse CO_2 subsidy

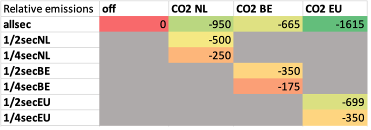
For this subsidy, a similar sensitivity analysis is conducted as for the hydrogen subsidy experiment. In Figure 27 this analysis is visualised to determine the size per unit that is used for the inverse CO_2 subsidy. Again, an EU subsidy for all sectors is taken as basis on which the sensitivity analysis is conducted. Up from a subsidy of €40/ton the emissions are not further decreased. Hence, for the experiments, the size per unit is set to 40 €/ton.



Unit size [€/ton}	0	10	20	35	40	55	65
Relative emissions	0	-712	-1140	-1378	-1615	-1615	-1615

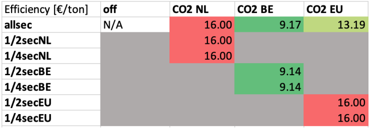
Figure 27: Decreased emissions as function of the size per unit for not emitting CO_2.

If this subsidy is varied over different subsidy sources and target sectors, the following figures are the output (see Figures 28 and 29).



Relative emissions	off	CO2 NL	CO2 BE	CO2 EU
allsec	0	-950	-665	-1615
1/2secNL		-500		
1/4secNL		-250		
1/2secBE			-350	
1/4secBE			-175	
1/2secEU				-699
1/4secEU				-350

Figure 28: Relative emissions of the inverse CO_2 subsidy on different subsidy sources and target industries. EU has highest potential followed by the Netherlands over all sectors.



Efficiency [€/ton]	off	CO2 NL	CO2 BE	CO2 EU
allsec	N/A	16.00	9.17	13.19
1/2secNL		16.00		
1/4secNL		16.00		
1/2secBE			9.14	
1/4secBE			9.14	
1/2secEU				16.00
1/4secEU				16.00

Figure 29: Efficiency of the inverse CO_2 subsidy on different subsidy sources and target industries. Barely varies over sectors and is most efficient in Belgium. Overall most efficient subsidy compared to other experiments.

In this subsidy, the fact that the model assumes full information over the future as well as a perfect market, becomes somewhat misleading. By stimulating a reduction in emissions (i.e. inverse CO_2 subsidy), the model always uses the most efficient way to reduce these emissions if the subsidy is high enough. However, in real life investment decisions are made by companies and the actual impact and prices etc. are uncertain. Nevertheless, it can be concluded from the experiments that because of these assumptions, different behaviour than before can be noticed. Varying over sectors does influence the effect but doesn't influence the efficiency of the subsidy when allocated nationally. Varying between NL, BE and EU shows that in Belgium most efficiently money can be allocated to reduce emissions followed by the EU if all sectors are included. In NL it is least efficient because of the national differences and the uniformity of the subsidy.

To conclude, an inverse CO_2 subsidy is most efficient when applied in Belgium. Including different shares of sectors has only very limited impact on the efficiency when the subsidy is scoped from EU perspective. Regarding the effectivity, also here an EU subsidy has most effect followed by implementing an inverse CO_2 subsidy in the Netherlands.

6.5 Comparing the experiments

When comparing the different policies to conclude on the scope variables of commodity type and mechanism, the combined outcomes of the the effectivity and efficiency have to be taken into account. The effectivity varies between hundreds and thousands of tons avoided emissions. Also the efficiency with which these policies reach their emission reductions vary over a large range (from ten to over a hundred € per avoided ton CO_2 emissions). It must be noted that due to the differences in capacity variables between the policies (e.g. different duration and unit size), looking at solely the effectivity of policies can be misleading. Hence, when analysing this effectivity, also the efficiency has to be taken into account. From all experiments the most effective and the most efficient selection of scopes is taken to conclude on the scope effects. In the Figures 30 and 31, an overview is provided of the normalised results of this selection. The number one in these figures represent the best scoring policy on effectivity and efficiency respectively. In both the effectivity as well as the efficiency figure also the other performance indicator is provided to create a comprehensive overview. It must be noted that because the results are normalised, the effectivity is best if it scores high and the efficiency is best when it scores low. Hence, in the graphs high bars are preferred concerning the effectivity and low bars represent better scoring policy scopes considering efficiency.

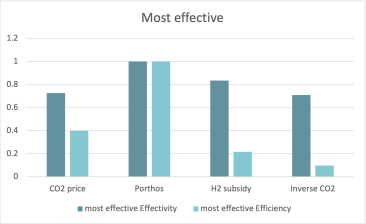


Figure 30: The most effective scope selection of the different policies normalised against the best scoring (Porthos) policy with the normalised efficiency of that result included.

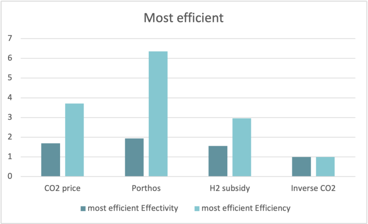


Figure 31: The most efficient scope selection of the different policies normalised against the best scoring (Inverse CO_2) policy with the normalised effectivity of that result included.

When evaluating the most effective policy (Figure 30), for each of the policies the most effective scope consists of an EU wide and all sectors included policy. The Porthos subsidy scores best when only considering the effectivity. However, the difference in effectivity between the Porthos subsidy and other policies (darker blue) is relatively small compared to difference in efficiency of those other policies (lighter blue). Especially the H2 subsidy and the inverse CO_2 subsidy have a substantially better efficiency compared to the loss of effectivity of these policies.

Looking at the most efficient policy (see Figure 31), the inverse CO_2 subsidy scores best. Because efficiency, by definition, already compensates for policy costs, direct comparisons can be made between the experiments. For each of the policies, the highest efficiency was reached when the policy scope was focused on a smaller section (either half or quarter of the total sectors) and on national level. Also here, it can be noted that policies with higher effectivity have substantially lower efficiency. In the most extreme case, more than six times the amount of money per ton is needed to not even double the reduction in emissions (Porthos vs. inverse CO_2). The inverse CO_2 subsidy being most efficient can be explained as the commodity scope in this case does not force the use of one specific commodity. This opposed to the Porthos and H2 subsidy. Hence, it can be concluded that concerning the commodity scope variable, not targeting one specific commodity with a policy scores best on efficiency.

Furthermore, the scope of encouraging or discouraging. The minimum CO_2 price and the inverse CO_2 subsidy are similar policy interventions but differ in being a tax or subsidy respectively. It can be concluded that encouraging has the potential to be more efficient while keeping the similar potential in effectivity (looking at the most effective selection of remaining scopes). When the most efficient scope selection is made for these policies (Figure 31), the efficiency worsens substantially for relatively small increases in effectivity. Again, it must be noted that all the findings above are only valid for the stylised testing environment. When conducting these experiments in real systems, other conclusions can arise. Nevertheless, the author is able to conclude that selecting different scopes of policies, potentially has large consequences for the effectivity and efficiency of that specific policy.

7 Discussion

In this section the limitations of the research are reflected upon. This is done on three levels using concepts of validity defined by Bryman (2003), firstly on the measurement validity (i.e. do the modules allow for modelling environmental policies?). Secondly on external validity (i.e. can the results be generalised beyond the specific research context?) and lastly on the ecological validity (i.e. how does this research relate to the academic and societal context?). Each limitation is followed by recommendations for future research to further increase the usability of the policy module.

Firstly the measurement validity. The policy modules created in this research are made to cover different scopes of policies. These scopes are identified in literature and exemplified by applying them by means of policy analysis. Additionally, also capacity variables are identified which combined with the scope variables lead to the formalization of the modules. These different scopes are based on the limited literature that is available on categorising policies. Value can be added by validating these scopes to a greater extent by means of e.g. expert interviews.

To continue on the measurement validity, two policy modules are created to cover the structurally different investment and generation based policies. After verifying the modules, the investment module did not show the expected behaviour. This is due to missing boundary constraints within the optimizer. This makes it possible for the optimiser to cheat and profit from the policy while actually still using different production means that are not eligible for that policy. In Appendix C these missing constrains are discussed and deduced. Furthermore, owing to Pieter Bots, the option to include the needed constraints in the model has recently been included and must be thoroughly tested. After this, if the solver used and the resulting computation times allow, the investment module can be verified as well.

Secondly the external validity. Varying the different scopes of policies lead to a wide spread of both the effectivity and the efficiency of policies as well as the originating model behaviour. It must be noted however that because a stylised testing environment was used to come to these conclusions, they are not directly applicable in policy design. This is due to the assumptions made on the characteristics and inclusion of commodities and industrial clusters. To further increase the external validity (i.e. applicability of the results), an environment has to be modelled to resemble a real system in more detail. To this end, more attention can for example be paid to the more complex relations between actors in industrial clusters and the inter-connectivity of commodities. Examples of this consist of including relations between actors and the resulting supply and demand patterns that arise (Desideri Perea, 2021). Additionally the policy modules can also be tested in a different/wider geographical environment to increase the applicability. This can for example include regional governmental policies (more specific geographical scope), more countries (wider geographical scope) and non EU structures such as state and federal levels in the US (similar aggregation level in a different system). When varying the geographical scope, the policy scopes should be questioned as well. Does this classification also suffice when policies are modelled for e.g. the middle east and international cooperation that misses a supra-national level.

Continuing on external validity. Methodologically, the choice for the modelling language of Linny-R brings limitations in the usability of the modules. Because of a lack of consensus on a modelling language used for industrial cluster settings, the modules in Linny-R do not provide a 'plug-and-play' solution to include policies in other than linear optimization modelling types, such as system dynamics and non-linear optimisation models. However, the conceptualisation of policies and the formalisation choices made to come to the modules may provide useful insights and guidelines for extending policy modelling in different modelling languages. It would be interesting to discern between formalisation choices needed in different modelling contexts.

Lastly the ecological validity (i.e. the placement of the research within the existing academic and societal context). This research originates from the conclusions of a.o. Damen et al. (2009); Ball et al. (2007); van den Broek et al. (2010); Brownsort et al. (2016); Guelpa et al. (2019); McCauley & Stephens (2012) who emphasise the need to include policies within modelling. In the literature review following this proclamation (see Chapter 2), the context is shaped of the current way of cluster modelling and the way of dealing with policies influencing the system. It becomes clear that policies are seen as external forces on the system that are included by means of scenario analyses. Comparing this to the creation of the policy modules, this research foresees in the demand for a means to include policies within modelling. This, as steps lack to view policies as variables of a system that can be included within a modelling context rather than keeping policies as external context in which a system operates. The added value of this research is that by including policies using policy modules, it becomes possible to tweak policies more exactly compared to the more vague and broad scenario analyses currently used in literature. Additionally, it becomes possible to include dependent and interdependent policies if they are internalised in the model. This as the exact values and scopes of the policies can differ given the conditions of the system or the value of other policies at that specific moment (i.e. solution dependent variables). This is not possible when policies are included as exogenous variables/scenario inputs which is the current state. This thus enables a researcher or policy maker to determine the most effective/efficient scope of policies. It also provides a basis for the creation of a model in which the policies are optimised given the the expected commodity prices and amounts used, rather than using the modules to evaluate policies that are designed beforehand.

To recapitulate on the limitations mentioned above, future research is highly relevant with regard to increasing the three types of validity of the policy modules (i.e. measurement, external and ecological validity). To this end, the environment in which the modules are applied can be made to resemble real industrial clusters more closely. This way, conclusions can be drawn on which policy interventions should be used. Additionally, generalising the conceptualisation of the different policy scopes to fields that differ from sustainability policies in cluster modelling. Besides, these conclusions can be extended if the investment module presented in this research was further developed and tested. Lastly, when placing this research in academic context it is concluded that further research can add value in comparing the used policy formalisation to use in different modelling languages.

8 Conclusion

In this research, the author strove to create a means to include and analyse policies within cluster modelling. To this end, a subsidy module is built and tested in a stylised cluster model. The goal of this chapter is to answer the research question. This is done by first answering the separate sub-questions after which a concise answer to the research question is provided.

What is the current state of literature regarding the modelling of utility networks and sustainability policies in the context of industrial cluster modelling?

From the current state of literature, three knowledge gaps are identified and used in this research. Firstly, there is no definitive way of including policies within cluster modelling. This validates the main research question proposed by the author that originates in this knowledge gap. Additionally, it was found that the modelling language used in existing literature is linked to the goal of that specific research. Hence, there is no conformity on how to model industrial clusters. This was used by the author to choose linear optimization using Linny-R to include policies within industrial cluster modelling. Moreover, studies conducted in the reviewed literature are relatively specific scope and there is a knowledge gap in applying a multi-commodity and inter-cluster perspective when including policy modelling in this context.

Apart from the first knowledge gap, these additional knowledge gaps are used by the author as context in which the main research question is answered and provide the reasoning behind the scoping decisions made to answer the following sub-questions.

How can policies be formalised and standardised in an applicable module?

By using literature and conducting policy analysis, five scope variables are identified that determine the structure of a policy. These scope variables consist of: policy mechanism (encouraging/discouraging), source (national/international), commodity scope (e.g. CO_2, H2 or electricity), policy type (generation/investment) and target industries (e.g. electricity or chemical sector).

To cover these different scopes that policies can have, two policy modules are created (generation and investment modules) that can be applied in a plug-and-play process to industrial cluster models. These modules are visualised in Figures 32 and 33. Apart from the scope of policies, five capacity related variables are derived from literature that determine the size and duration of the policy. These consist of: size per unit, yearly allowances, total costs, policy duration and offer time. Together these capacity variables determine the size and duration of the policy and thus the policy costs.

Hence, policies can be formalised by varying the scope variables to create different configurations of policies and by using the capacity variables, the last detail can be filled out.

The main contribution from the author is the creation of the policy modules that allow for structured and applicable further research towards the effects of including policies within cluster modelling.

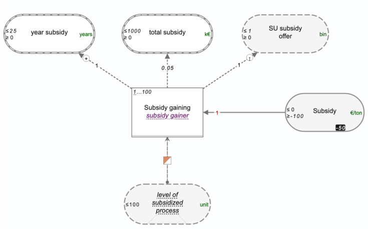


Figure 32: The generation based policy modules

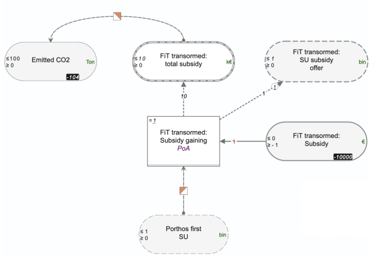


Figure 33: The investment based policy module

What modelling language is suitable for including policies in models?

The modelling language used to include policies in cluster modelling is the multi integer linear programming language called Linny-R. A knowledge gap identified in literature states that there is no consensus in a modelling method for modelling a cluster environment. To focus on implementing policy modelling within this cluster environment, Linny-R is chosen as graphical representation language to include policies in a mixed integer linear optimization model. This is suited because linear optimization allows for relatively fast optimization because it omits all the complexities of other modelling methods that are not of influence on this scope of policy modelling. Linny-R thus allows for relatively simple and fast models to find the optimal policy scope.

What is the commodity and cluster context to which the module can be applied?

The commodity and cluster context in which the policies can be included consists of a stylised cluster model that is developed as testing environment to place the policy modules in context. This cluster model adopts an inter-cluster and multi-commodity perspective which is based on knowledge gaps identified in literature. The included clusters consist of the Port of Antwerp, Port of Rotterdam and Chemelot (Geleen, NL). These clusters have the option to use different commodities to produce. The included commodities focus on: natural gas, hydrogen, electricity and CO_2. These commodities are characterised by prices that can vary over time. Furthermore, the clusters have different potential in using the range of commodities. This leads to varying choices of commodities for the different clusters. To conclude, this stylised environment allows for testing of the different scopes of policies.

How can the effect of policies in cluster modelling be determined?

The effect of policies in cluster models can be determined by measuring the effectivity and efficiency of the policies. Because the focus of this research is on environmental policies, this aspect of the policies is important to measure. To this end, two performance indicators are identified. Firstly there is the effectivity of a policy. This measures the extend to which CO_2 emissions are reduced compared to a situation without change in policy interventions. Secondly the efficiency is measured. This provides insight in how expensive the policy intervention is compared to the effect and is measured in euro per ton reduced emissions. By varying the scope variables and evaluating the results using these performance indicators, it becomes possible to draw conclusions on the consequences of differently scoped policies.

Main research question: What are the effects of merging sustainability policy models and industrial cluster models?

Varying the scope variables of policies lead to a wide range of consequences regarding the effectivity and efficiency of policies. First the policy mechanism, it can be concluded that an encouraging policy with a similar effectivity as the discouraging policy scores better on efficiency. Secondly the commodity scope. It can be concluded that the included policies with a specific scope have a higher effectivity potential than policies that do not identify a specific commodity scope. However, this last type of policy is considerably more efficient. Concerning the policy source and target industries, it can be concluded that the wider the scope, the more effective the included policies were in reducing emissions. However, a smaller scope (i.e. on national level and only a section of the industries targeted) has a higher efficiency.

Lastly the policy type. After designing policy modules for both generation based as well as investment oriented policies, the author concludes that Linny-R is not suitable for modelling investment policies. This because of computational limitations of both the modelling language as well as the solver. A lack of boundary conditions concerning the identification of when processes are firstly used, caused the solver to profit from policies while not respecting the actual policy conditions. Adding these extra constraints in the boundary conditions increased the computation times of the solver dramatically. Hence, only generation based policies are evaluated in the results of this research.

It must be noted that because a stylised testing environment was used to come to the conclusions on policy scopes, they are not directly applicable in policy design. Nevertheless, the author can conclude that both the effect as well as the efficiency of policies can vary greatly depending on the chosen scope. Furthermore, these varying effects and efficiencies originate in the changing model behaviour due to the inclusion of policy interventions. Hence, including policies within cluster modelling is important for policy makers as well as actors in the field to gain insight in which scope of policy can have the biggest impact on making the industrial sector sustainable against the lowest costs.

Future research

In the discussion, four limitations of this research are identified. These lead to a total of four recommendations for further research which consist of firstly the identification of the policy scopes. These scopes are found using a limited amount of data from a variety of different sectors. Increasing the validity of these scopes could add value and could be realised by e.g. expert interviews in the field of industrial cluster policies. Additionally the scopes could also be generalised to cover a wider set of policies than solely considering this sector.

Secondly, value could be added in continuing development of the investment based policy module by thoroughly testing the proposed boundary conditions and evaluating optimizers in Linny-R. If reasonable computational times are realised, further experiments could be run to also evaluate the effect of this scoping decision.

Thirdly, the stylised testing environment used in this research. Using a stylised environment results in conclusions that are not directly transferable to policy design. Future research could focus on applying the policy modules to industrial systems that more closely resemble real-life systems to find which policy scopes are most effective and or efficient in that environment. This could, for example, be done by setting a different geographic purview or including more complex actor relations.

Lastly the modelling choice. The choice for Linny-R as modelling language excludes the wide variety of modelling languages and strategies used in previous literature. Research towards the generalisability of the translation of sustainability policies to applicable modules in different modelling languages, could add value in the form of increased applicability. To conclude, future research can add value in increasing the applicability of the results of this studies. Especially further validating the policy scopes and potentially generalising these to comprise a wider focus than industrial clusters is an essential step that has to be taken to cover and enable evaluation of all policy designs.

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A Appendix table

Author	Year	Title	Commodity	Purpose	POLICY	MODEL	MISSING
Dohse	2007	Cluster-Based Technology Policy—The German-Experience		Analysis of whethe regional or national policies have more impact on development of industrial clusters that add to national goals	Economic support of involved companies, technology exchange (separate). Tool for policy analysis is future research for policy makers	Analytical region models to evaluate the development of clusters in specific regions with respect to international competetiveness + use for policy making. Analytical model	No quantitative analysis of policies + scenario input
Hustad and Bjønnes	2002	The Norwegian CO2–Infrastructure Initiative:The Economics and Socio-Economics of using CO2 for Enhanced Oil Recovery in the North Sea Bassin	CO2	analyse the potential of a CO2 infrastructure for the specific purpose of EOR	policies on CO2 mitigation (markets, energy requirements etc.)	Economic model to minimize costs of CO2 sequestration and transport to wells for EOR. Economic optimization	Focus on CCS + specific purpose

Ball, Wieschel and Rentz	2007	Integration of a hydrogen economy into the German energy system: an optimising modelling approach	H2	analyse the potential of an H2 infrastructure for automotive use given an exogenous demand	only CO2 emission cap is included as policy	Linking the electricity and heat market with a hydrogen network to find a cost optimal hydrogen infrastructure based on geographical location of supply and demand. Linear and non-linear programming	Focus only on hydrogen + only CO2 restrictive policies
Ball, Wietschel	2009	The future of hydrogen - opportunities and challenges	H2 (+CO2)	Highlighting the opportunities and challenges of hydrogen for policy development	GHG emissions reduction, energy security and air pollution reduction are identified as increasingly favoured policies by authorities + use of hydrogen is not justifiable from only climate policy perspective	Inputs for a model are identified: available feedstock, population, geographical factors and POLICY SUPPORT which is identified as key in the initial take off of hydrogen. Finding the right policy however remains a question for future research. Linear and non-linear programming	quantification of the model inputs and the effects of policy support + Hydrogen should not be evaluated in isolation but put in respect to other commodities as well (knowledge gap)

Brownsort, Scott and Haszeldine	2016	Reducing costs of carbon capture and storage by shared reuse of existing pipeline—Case study of a CO2capture cluster for industry and power in Scotland	CO2	Potential of reusing gas pipelines in Scotland to store CO2 in gas fields in the North Sea, Using models to estimate the costs of transport infrastructure	Emission reduction policies + proposed CO2 infrastructure funding	Model for geographically planning the infrastructure and estimating costs based on emission estimates. Results show that using existing infrastructure creates direct savings. GIS model	Focus only on CO2 + only co2 restrictive policies
Schneider, Lechtenböhmer and Samadi	2020	Risks and opportunities associated with decarbonising Rotterdam's industrial cluster		Scenario analysis to identify risks in decarbonisation of Rotterdam industrial cluster. This provides a basis for policy makers	decarbonisation policies as core of the study including current measures and extra measures up to 95% reduction in 2050. Recommendations for policy implementations are output of the study	qualitative scenario creation and quantitative scenario analysis using a bottom up simulation model. Simulation modelling	only CO2 restrictive policies as input, no effect of investment policies

Kjärstad and Johnsson	2009	Ramp-up of large-scale CCS infrastructure in Europe	CO2	Finding conditions needed for rapid development of CCS infrastructure in Europe to mitigate CO2 emissions from the power and head sector	Conclusions drawn on needed policy/institutional change	Techno-economic model to evaluate CCS infrastructure based on costs. Focus is on geopgraphical design of infrastructure with captured CO2 as input derived from electricity production. GIS + linear optimization	Focus on only CCS infrastructure + onshore + no policies as input for scenario analysis
Stewart, Scott, Haszeldine, Alinger and Argent	2014	The feasibility of a European-wide integrated CO2 transport network	CO2	Determine the scale, strucutre and estimated costs of an integrated EU Co2 tranport network using a model based on different amounts of CCS.		Optimization model to minimize the pipeline length that joins all sources to sufficient storage for 25y operation period. Use of Geo model to determine storage potential in EU. GIS modelling	Focus only on CO2 infrastructure + no policy integration

Domenech, Bleischwitz, Doranova, Panayotopoulos and Roman	2019	Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy	+	Finding the key enablers in formation of industrial clusters	Finding the right policies is essential in utilising potential	Conceptual model on correlation. It is found that high-value goods are more likely to be involved in a large distance network of industrial symbiosis. For companies, the most prominent reason to cooperate is cost savings and risks concerning costs and benefits are the greatest barrier. Analytical model	Effect of policies on potential shifts in the results −>the role of PUBLIC POLICY is identified as knowledge gap

Strachan, Balta-Ozkan, Joffe, McGeevor and Hughes	2009	Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system	H2	Using a link between economic modelling and GIS (GIS-Markal) to determine the potential of a H2 network (and the geographic design) in reaching UK climate goals	UK stimulating H2 policies and emission reduction policies	linear programming optimization model to review the role of H2 in a future decarbonised energy system by means of scenario analysis. Different sectors are included in the model that compete for a finite energy resource. Linear optimization	just on H2 infrastructure and just on UK with a focus of hydrogen demand for transport in urban areas
van den Broek, Brederode, et al.	2010	Designing a cost-effective CO2 storage infrastructure using a GIS-based linear optimization energy model	CO2	Determining the size and costs of a CO2 network in the netherlands regarding CO2 emission reduction targets of 20 respectively 50%	CO2 storage specific policies s.a. onshore storage restrictions and infrastructure developments	Combined linear programming optimization model and GIS (GIS-Markal) to determine the needed infrastructure and investment costs. Linear optimization + GIS	Focus only on CO2 infrastructure in NL + pipeline trajectories

Konda, Shah and Brandon	2011	Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: The case for the Netherlands	H2	Using optimization models to determine a geographical network of development of a hydrogen infrastructure incl. transport and production based on transport demand	Scenarios considering the addoption of hydrogen vehicles are used. Conclusions are drawn on needed policy for the high risk investments that are concerned with developing this infrastructure	Optimization model is used to determine the costs and the geographical development of infrastructure concerning production and transport layout. Non-linear optimization	Focus only on H2 infrastructure layout
Mendelevitch	2014	The role of C02-EOR for the development of a CCTS infrastructure in the North Sea Region: A techno-economic model and applications	CO2	Analysing the opportunities of using CCS for enhanced oil recovery (i.e. extract more oil while storing CO2)	policies and regulation on climate are identified as valuable further research topics.	Mixed integer modelling is used to find a cost optimal geographical infrastructure and use of CO2 for EOR. MILP + GIS	Focus is only on CO2 + specific deployment of the co2 + no policies are eveluated
Stiller, Bünger, Møller, Svensson, Espegren aand Nowak	2010	Pathways to a hydrogen fuel infrastructure in Norway	H2	GIS based model to optimise production and transport infrastructure based on demand from transport sector. GIS modelling	Policies on GHG emission constrains (CO2 tax, electricity subsidies and traffic limitations) are evaluated to conclude on their effectiveness.	GIS based model to determine the geographical development of production and transport infrastructure. GIS modelling	Focus is only on H2 + transport + geographical

Damen, Faaij and Turkenbug	2009	Pathways towards large-scale implementation of CO2 capture and storage: A case study for the Netherlands	CO2 (+H2)	Using a model to quantify the the infrastructural costs and requirements in different scenarios based on climate reduction policies. Economic linear optimization	Climate policy as the basis for the scenario input. Evaluation of wider policies as future research. Economic + linear optimization.	A spreadsheet model is used to determine the infrastructural requirements and costs of different pathways	Only CO2 infrastructure is included and hydrogen only in a minor part. Inclusion of multiple commodities is identified as knowledge gap.
Kim, Yoon Chae, Park	2010	Economic and environmental optimization of a multi-site utility network for an industrial complex	Steam	Optimizing a utility network to maximize profits while taking into account environmentally constraints	Climatae policies = environmental constraints	MILP model to determine the minimal costs of a utility network with which climate constraints can be met. The model focuses on technicalities of the production processes to account for the needed inputs and extra outputs. MILP	Only on steam infrastructure, only climate policy as driver for model and only within a cluster.
Hospers	2002	Beyond the Blue Banana? Structural Change in Europe's Geo-Economy	n.a.	provide a framework to evaluate the potential of industrial cooperation in EU context	Regional policies on development of industrial sites	Analytical framework to determine the potential of development of these regions in industrial context	No quantitative analysis and lack of commodity networks

Hospers	2003	Beyond the blue banana? Structural change inEurope's geo-economy	n.a.	Develop a framework that shows the potential of the blue banana opposed to newly identified innovation regions	Regional and EU policies and industrial support ideas to regain centrality of blue banana in innovation strategies	Analytical framework that includes a qualitative analysis of policies	quantitative analysis and focus on commodity network inclusion

B Appendix commodities

First a stocktaking is done of the different possible flows based on (demand) reports of the three different clusters involved. Then, a selection of these commodities is made to scope this research. This selection is further elaborated upon to provide insight in the current situation and the possible outlooks. Also expected prices and projections of market size are included as a basis for the data inputs that are needed for this research. This appendix serves mainly as background information used by the author to assume simplifications considering the stylised testing environment that has been created in order to test the policy modules.

B.1 Stocktaking

According to an outlook published by Gasunie and TenneT, Electrification is one of the main ways to ensure emission reduction in the industrial sector (Gasunie & TenneT, 2020). PtX technologies are key in the developments in this electrification. They predict that hydrogen and methane will dominate the end-use energy demand in the energy intensive industry sector. In the same document, they state that the investment decisions of energy intensive industries (and other main energy consumers) regarding their energy input (i.e. electric, gas-based or hybrid) have to be coordinated as they have a big influence on the eventually needed structure of the energy system. Gasunie & TenneT (2020) state that concerning energy carriers, two scenarios are likely to occur. Either a 'high electrification' or a 'high gas' scenario will be the future demand pattern in the industry. In both scenarios, the relative electricity demand will almost triple (from 15% to 39 or 44% depending the scenario). In the 'high gas' scenario, most demand will be for hydrogen as energy carrier, in the 'high electrification' scenario, the decrease in this demand is compensated by the import of other green energy carriers.

1. electricity (47 TWh/a in 2050)
2. methane (1 TWh/a in 2050)
3. hydrogen (68 TWh/a in 2050)

According to the port of Rotterdam 'energy port', steam and heat have to be added to this this list. However, due to the technical characteristics of the distance over which the commodities have to be transported, these can be excluded (Port of Rotterdam, 2020b). In the 'facts and figures' report of 2016, the Port of Rotterdam mentions other commodities that are of importance for companies included in the 'multi-core' pipeline structure in the Rotterdam industrial cluster. This pipeline can be leased and contains four pipelines that are designated to transport chemicals and gases within the industrial area (Port of Rotterdam, 2016).
This leads to the following list of commodities based on the multi-core and industrial gasses analysis:

oxygeoxo-alcohols
oxygen
vinylchloride monomeer
butane
isopreen extraction feed
nitrogen
argon
syngas
CO2
CO
steam
acetylene
electricity
methane
hydrogen
natural gas
heat

As can be concluded from the table above, many commodities are of interest in industrial clusters. The most important commodities that are included in the first iteration of this research are: Hydrogen, Electricity, Natural gas and CO2. Both electricity and natural gas infrastructure are already present in the current ecosystems.

In the following paragraphs, these four commodities are introduced by evaluating the current infrastructures and proposed/ongoing projects in this field. Also data concerning demand and supply forecasts are of interest for the model. These are also included in the following reconnaissance. This is done with a view considering both the Netherlands and Belgium as these are the countries in which the industrial clusters of Rotterdam, Chemelot and Antwerp are located.

B.2 Current situation

Currently, limited infrastructure is already available and connects the different industrial clusters. Depending on the commodity of interest, this infrastructure is far developed or still in its infantry.

B.2.1 CO2 capture and storage infrastructure

According to Evar et al. (2012), in the 70s of last century, the academic research to CCS initialized by combining the already present ideas of capturing CO2 from concentrated sources and injecting this CO2 in the subsurface. More knowledge was gained from the 90's onward as both academic and political interests increased due to the more prevalent effects of climate change. Starting in the mid 2000's, in anticipation of upcoming regulatory change in favour of CCS, pilot projects and even commercial options were developed. Nevertheless, remaining small scale projects. At this moment still, the pilot phase of CCS is not yet over.

There are multiple operational and planned projects that concern the transportation and storage of CO2. In the Netherlands, there are already four projects of which two pilots (in the North Sea (planned) and around the Chemelot campus (operation from 2011 to 2013)), one commercial (in the Eemshaven planned for operation in 2024) and one hub (in the port of

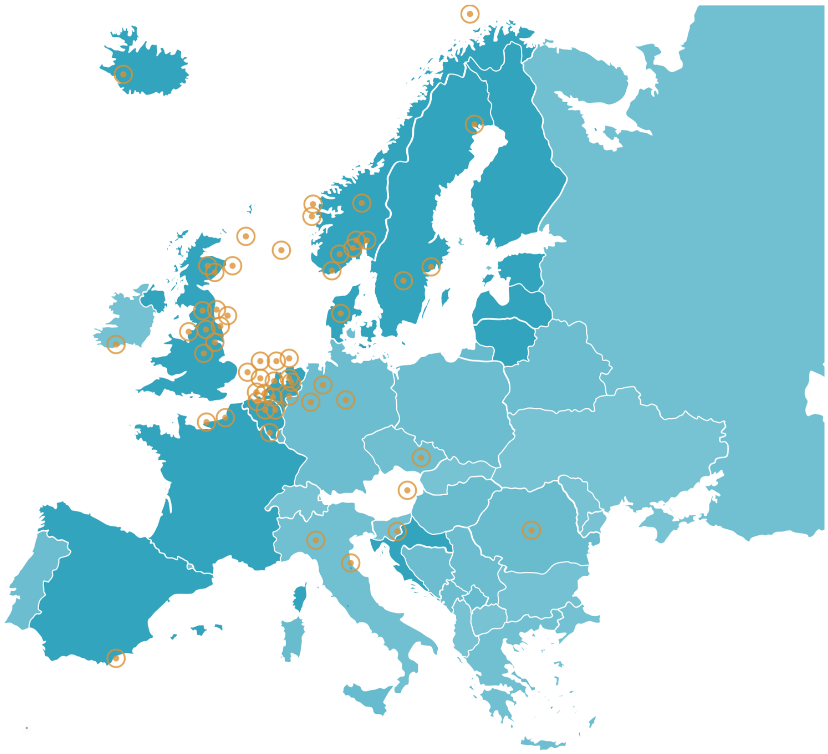


Figure 34: CCS projects in Europe are mostly situated around the North-West.

Rotterdam the Porthos project is planned to become operational in 2024) (Global CCS institute, 2021). As can be seen in figure 34, many projects are located around the North-West of Europe. The Netherlands is prominently represented in the amount of projects set up. The availability of gas fields in the North Sea on Dutch territory plays a role in this.

The first CO2 capture and storage facility is the Sleipner CO2 storage facility Safar Zitoun et al. (2020). Located at a gas field with high concentrations of CO2 present in the natural gas, it separates the CO2 and injects it back into the bedrock. Starting in 1996 and storing about 0.9 MT/y it has currently stored over 17 MT. There is still much storage left as it is estimated that the sandstone formation can contain up to 600 billion tons of CO2. The costs are currently around the $17 US/ton CO2.

The Porthos project is an important project when the policy view is taken into account. This because it is marked as a project of common interest (PCI) by the EU and they recently got granted a subsidy worth of 102 Million Euro. Additionally, also on national level, Porthos can gain advantage

by the SDE++ policy. Companies can in this way get compensated for difference in costs of capturing the CO2 and the savings of the reduced need for CO2 ETS rights. In this way both in investment as well as output and on national vs. international, the Porthos projects is stimulated.
Lastly is the Porthos project of interest because of the geographical location which is aligned with the scope of this research. In the model, the CO2 transport will largely resemble the developments of the Porthos project. It must be noted however that the Porthos project is not the first CO2 transport and storage project in this region with this scope. In 2017 a research project funded by the EU investigated the opportunities of creating a CO2 hub in the port of Rotterdam. From the foundation of this project, Porthos arose. Already in this report, the last phase (from 2030 onward) includes links with the rest of the Netherlands, Antwerp, the Ruhr region and potentially La Havre.
For the modelling of CO2 transport and storage, prices have to be set that resemble the real situation over the years. According to the zero emissions platform (an EU funded advisor to the EU commission on the deployment of CCS and CCU) and the CCS association (a trade association focused on the deployment of commercially viable carbon capture, utilisation and storage based in Europe), the price of CCS in power and industry sector will be between €60-90 per tonne of CO2. This will most likely decrease with a share of 12% per year to about €16 per tonne in the 2040s. As described in the policies chapter, the difference between the costs of CCS and emitting CO2 can prone to taxes or subsidy schemes. The price of emitting CO2 is estimated to be €35/tCO2 in 2030, it is expected that it is not sufficient to replace gray hydrogen with blue hydrogen. For this, co2 prices around €50/tonne are needed (Peters et al., 2020).

B.2.2 Hydrogen

As already mentioned in the main text, hydrogen has large potential in fulfilling a role in the future energy system (Wang et al., 2020). This as can be produced without emitting CO2 and it can be slotted in many sectors. It can be used as a replacement of natural gas for production of high heat, as feedstock for industry (like fertilizers), as fuel for heavy duty transport. Lynn Orr (Professor Emeritus, Energy Resources Engineering, Stanford University) states that hydrogen will be the main direction for providing the required high heat for industry (Orr, 2021). According to the Port of Rotterdam, it is expected that green H2 will be imported from countries with high solar and wind potential which can be used to create green H2 (Gemeente Rotterdam, 2020). Currently 400.000 tons of hydrogen is already being produced and used in the port of Rotterdam. Use is currently focused on refineries and chemical industries.
In Europe, hydrogen has become a hot topic. The board of the 'European Hydrogen Backbone' has published a report in July 2020 which is focused at projections on development of a hydrogen infrastructure in the upcoming

twenty years (Wang et al., 2020). A revision of the initially outlook (containing 23.000km covering ten countries) was published in April 2021 and contains a network consisting of 39.700 km ranging over nineteen countries (Jens et al., 2021). The largest part (69%) of these pipelines consist of revised natural gas infrastructure. Also in the Netherlands specifically many different visions are developed concerning the development of a hydrogen infrastructure. However, currently, little of this infrastructure is present. Because the Dutch natural gas network is well developed, opportunities to convert these pipelines to hydrogen infrastructure can be exploited and the Netherlands maintain the status as energy junction of Europe (Gemeente Rotterdam, 2020). According to Bainier & Kurz (2019) transport of hydrogen becomes an issue. They investigated the options of blending in hydrogen into the natural gas network. This would be interesting in the Netherlands and Belgium because of the widespread presence of gas networks (see subsection B.2.3). They conclude that with a complete substitute of hydrogen in the gas network (i.e. 100% hydrogen), about four times more energy is needed for the transport of the same amount of energy. This is due to the lower mass density of hydrogen that is not offset by the higher mass calorific density (Liemberger et al., 2019; Bainier & Kurz, 2019). Hence, more hydrogen has to be transported to deliver the same energy, the pressure requirements triple to reach demand. Huisman (2021) wrote his thesis on coming to a robust European hydrogen network based on a transformation of natural gas infrastructure over a time horizon of 30 years. Because of the well developed Dutch natural gas network and the strong industrial activity located in North Western Europe, he concludes that this region can play a crucial role in the transition towards a renewable hydrogen based network.

The municipality of Rotterdam published the four main drivers for hydrogen infrastructure development (Port of Rotterdam, 2020a). These consist of the use of hydrogen as a feedstock, as fuel for industrial heat, fuel for heavy transport and for storage to provide in grid stability. To link these four uses for hydrogen to potential stimulating policies that a public body can have, the municipality identifies four categories in which they can provide support. Firstly, the realising, a public body can take the role of 'launching customer', this way they can reduce investment risks. Secondly, a financial support in the form of a subsidy can provided for different phases in the realisation of new projects. Thirdly a facilitating role can be played by a public body. In this case they can deploy their network to set constraints and support base in favour of the development. Lastly the monitoring, opportunities and threats can be identified and the progress of the developments should be reported.

Apart from the focus on transportation infrastructure in the paragraphs above, production is of interest as well. Currently, large electrolysers for the production of green hydrogen are needed. Also high shares of renewable energy are needed with a capacity that is double compared to the electrolyser due to the intermittent characteristics of renewables (Port of Rotterdam, 2020a). It is expected that a large share of the renewable hydrogen has to be imported from countries with a high renewable potential like North-Africa (Timmerberg & Kaltschmitt, 2019; Wang et al., 2020; Jens et al., 2021). In this research it is assumed that the hydrogen import will be supplied by in and around the Port of Rotterdam area. This assumption leads to the potential exclusion of imported hydrogen from North Africa that is transported by pipelines in Italy and Spain (van Wijk & Wouters, 2020). To conclude, the hydrogen flows in the model will thus originate from either on site production in the different clusters or imported from north sea production or countries with surplus green hydrogen.

The production costs of hydrogen are in the range of 1.3€/kg for gray hydrogen, 2 €/kg for blue hydrogen and 6€/kg for green hydrogen. Over they years, blue and grey hydrogen are expected to become more expensive due to increasing fossil fuel and CCS prices. Green hydrogen is on the other hand expected to become ever cheaper due to standardization and economies of scale in production of electrolysers. This is expected to result in capital expenditure decreases of 65% (from €1 billion to €350 million per GW). According to CE Delft et al. (2020) this results in blue and green hydrogen converging to the same costs range of €2 to 3 per kg in 2030. This would be a similar cost as imported green hydrogen from North-Africa because the reduction in electricity costs would be offset by the added transportation costs. In the model it is chosen to represent Hydrogen in a mass unit (Tonnes). 100 kton corresponds to 12.09 PJ and 1.11 bcm and 3.39 TWh. This is all based on the lower heating value of hydrogen (net calorific value) (Gasunie, 2019).

B.2.3 Electricity and natural gas

The infrastructure for electricity and natural gas production and transport are further developed than the infrastructure of CO2 and hydrogen as described earlier in this chapter. Concerning electricity, it is expected that electrification both industrially and under consumers causes increased pressure on the electricity grid (Blonsky et al., 2019). This leads to a need for an increase in grid reinforcements which most likely increases the tariffs that are allowed to be charged for transmission (ACM, 2021). This is because of the present 'reinforce unless' mentality that is present in the electricity transmission sector. It is striven for to effectuate a change towards more sustainable solutions to keep the tariffs reasonable (Droste, 2018).

In the Netherlands the electricity transmission grid operator (TSO) is TenneT. For this service, a fee is charged to the user. On industrial level (with a direct link to the high voltage grid), the users of electricity enter into a personalized contract with TenneT. In case of smaller sized consumers, an intermediary party is added. The distribution system operator in that case links the high voltage grid and the low voltage consumer. In Belgium the TSO is Elia. A similar structure is used as in the Netherlands in which major industrial electricity users are directly under contract with Elia and the

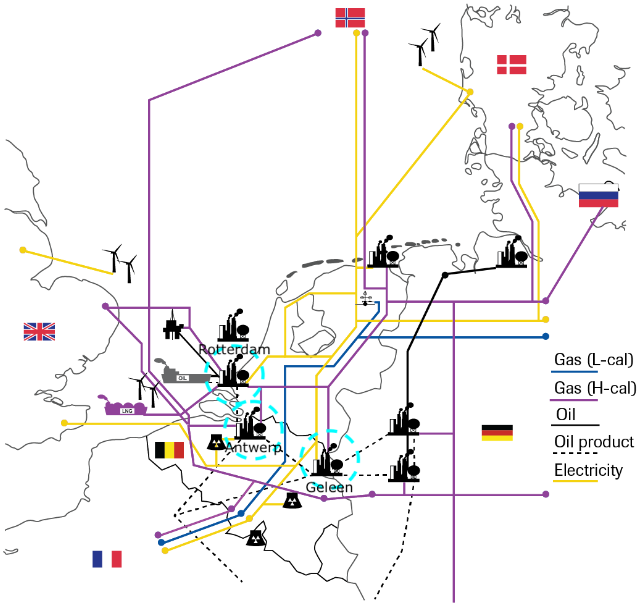


Figure 35: Well developed gas and electricity networks in the Netherlands and Belgium. *Source: Clingendael, 2018*

smaller consumers use intermediaries (Elia, 2021). The efficiency of electricity transmission is relatively low compared to that of gastransport (Heida & Haas, 2019). Transmission losses account for about 7.5% of the total amount of electricity that is transported in Europe (Eurostat, 2004; Doukas et al., 2011). Based on European statistics on electricity prices, it is assumed that industrial electricity prices in the Netherlands are 30% cheaper than in Belgium (i.e. 81 €/MWh and 116 €/MWh respectively) (Eurostat, 2017).

Apart from additional information on imports and exports, in the figure below (figure 35) it can be noticed that the industrial clusters of Rotterdam, Antwerp and Geleen (Chemelot) are already interconnected via the existing national gas and electricity grids.

The gas network in the Netherlands is owned and operated by Gasunie. In Belgium this is done by Fluxys. There are two types of gas, low calorific gas (G-gas) and high calorific gas (h-gas). Both in the Netherlands and Belgium a combination of these types of natural gasses are used. Power plants use h-gas and consumers use g-gas in the Netherlands. In Belgium this is different as all gas is imported. The northern regions of Belgium and Brussels use G-gas imported from the Netherlands. The rest of Belgium uses high calorific gas that mostly comes from gas fields located in Norway or the middle east (Gas.be, 2021). The same design as in the electricity sector is found in the gas transport. Most consumers are linked to the gas network using inter-

mediaries and a distribution grid. Industrial users do not make use of the distribution grid and are directly linked to the transmission grid of Gasunie. The efficiency of natural gas transport is high and in this research it is assumed that the transport losses in the Netherlands are negligible (Lelieveld et al., 2005).
Because of the current shift in policies that aim at reducing the Dutch gas consumption, it is likely that the price of gas will increase relatively to the price of electricity. This is done by means an energy taxes in the Netherlands, the energy tax on natural gas increases over the years where the electricity tax is decreased (Belastingdienst, 2020). According to PWC, in Belgium electricity is relatively expensive compared to gas. This is because of the lack of taxes and social charges that are included in the gas prices (PWC, 2020).
For this studies it is assumed that the national grids make transport of both electricity and gas possible. This is a simplification because of bilateral contracts that exists between specific parties. These contracts differ from the regular design of the gas and electricity markets for industrial users.

C Appendix Linny-R Limitations

In cooperation with Pieter Bots (Associate Professor at Delft University of technology, faculty of Technology, Policy an Management) the author was able to indicate and delineate many limitations in the beta version of Linny-R that was used in this research.

With special thanks to Pieter Bots, the mathematical explanation of the constraints described in chapter **??** that limit the possibilities of experimenting with a lumpsum subsidy can be presented below:

From the Java script that Linny-R uses to formulate the constraint functions that can be fed into the solver, the following part leads to the limitation is functioning.

```
// NEXT: add constraints that will set values of binary variables
// NOTE: This is not trivial!
/*
   Each node with +/0 output arrow also has a BINARY on/off variable OO.
   Each node with 0 output arrow then also has an "is zero" variable IZ.
   Each node with "start-up" output arrow also has a BINARY variable SU.
   For each timestep t:
    - OO = 1 if process level or stock level > 0, and 0 otherwise
    - IZ = 1 - OO
    - SU = 1 iff OO[t] - OO[t-1] > 0
```

```
Assuming L[t] to be the stock or level of a node, two constraints
are added for each t to give the (binary!) start-up variable SU
this behavior:
(a)  L[t] - LB[t]*OO[t] >= 0
(b)  L[t] - UB[t]*OO[t] <= 0
where UB and LB ar the bounds of the node.

NOTE: When LB[t] = 0, then (a) does not force OO[t] to become 0 if L[t] = 0!
      Therefore, start-up is calculated correctly only for processes
      having LB > 0.

To achieve SU, we add this constraint:
(c)  OO[t-1] - OO[t] + SU[t] >= 0
     (so SU[t] > 0 if process ON at t, but not at t-1)

To ensure that SU[t] will not become 1 if 0 suffices to meet (c),
a penalty must be associated with SU[t] (for t = 1...n) in the
objective function.
```

As a result of constraint (c), the start-up variable (SU[t]) can be 1 even if the on/off variables (OO) at t and t-1 are both 0 or both 1. Hence, the SU[1] can switch on even if there is no actual start-up.

To prevent SU[1] =1 if OO[t]=0 an extra constraint can be added that forbids SU[t] to be 1 if OO[t] is 0. This could be reached by including the constraint: $SU[t] - OO[t] >= 0$. In the following table (table C, an overview is provided of the effect of this extra constraint on the other variables including OO[t-1], OO[t] and SU[t]:

Variables			newly added constraints	
OO[t-1]	OO[t]	SU[t]	(OO[t-1]-OO[t]+SU[t])>=0	(OO[t]-SU[t])>=0
0	0	0	0	0
0	0	1	0	-1
0	1	0	-1	0
0	1	1	0	0
1	0	0	0	0
1	0	1	0	-1
1	1	1	1	0

The yellow cells are tackled with the newly added constraints. However, the orange cell still causes a problem. This is the situation in which the process is already on but the solver is still allowed to set the start-up variable to 1 even though there is no actual start up.

To solve this last problem, one more constraint has to be added: $OO[t-1] + OO[t] + SU[t] <= 2$. This stops the solver from being able to set the start-up variable to 1 even if in both t and t-1 the process is on. This is visualized in table C.

Variables			Constraints		Last constraint
OO[t-1]	OO[t]	SU[t]	(OO[t-1]-OO[t]+SU[t])>=0	(OO[t]-SU[t])>=0	(OO[t-1]+OO[t]+SU[t])<=2
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	0	1
0	1	1	0	0	2
1	0	0	0	0	1
1	0	1	0	-1	1
1	1	1	1	0	3

Also in this table the yellow circumstances that cause the problem are tackled with the constraints. To prevent the solver for giving an error if there is no previous time step, these constraints are only included after time step t=1. Hence, by inserting these three new constraints in the solver, the lump sum module should work. Nevertheless, in the words of Pieter Bots, these three constraints are very 'expensive'. This means that by adding these constraints, the solver takes extremely long computational times to solve (even relatively simple) models that include binary variables.

Therefore, the author had to conclude that even with these constraints included in Linny-R, it is not viable to verify and run experiments with the lump sum module.

D Appendix model parameters

This section provides the basic parameters that are used for he different subsidy modules and the basic model that the modules are used in.

linny-R version: 0.98 Solver: Gurobi

D.1 Model settings

time span: 50 years Block length: 50 years

Demand Antwerp Rotterdam: 100 Demand Chemelot: 150

Price hydrogen: 800 €/ton price Gas: 600 €/ton price electricity NL: 675 €/MWh price electricity BE: 750 €/MWh

Price CO2 NL: till 2030: $60 + 10 * t$, till 2039: 150, 2040 onward: $150 + 6 * t$ It is assumed that the minimum CO2 price determines the price up to 2040 in/after which the CO2 price rises less steep. Till that point, Belgium will have lower CO2 prices. Price CO2 BE: $35 + 6 * t$

Price of Porthos: $MAX(120 - t; 60)$

D.2 Potential to use different commodities:

Antwerp:
natural gas: 100%
hydrogen: 100%
electricity: 70%
Rotterdam
natural gas: 100%
hydrogen: 100%
electricity: 50%
Chemelot
natural gas: 100%
hydrogen: 100%
electricity: 100%

D.3 Module settings

5 data sets with the basic settings of the general variables:

1. subsidy /ton (SH) (35 €/ton)
2. subsidy /year (SY) (100 tons/year)
3. subsidy offer time (OT) (5 years)
4. subsidy time (STi) (30 years)
5. subsidy total (ST) (1.000 k€)

For the four different experiments, these general variables are set differently but kept constant over the different runs. In the following paragraphs the value of these general variables are presented.

D.4 Experiment settings

Minimum CO2 price

1. tax /ton (SH) (till 2030: $60 + 10 * t$, till 2039: 150, 2040 onward: $150 + 6 * t$)
2. tax /year (SY) (all tons/year)
3. tax offer time (OT) (not used)
4. tax time (STi) (every year, with different prices)
5. tax total (ST) (not limited)

SDE++ Porthos

1. subsidy /ton (SH) (delta CO2 price and CCS price €/ton)
2. subsidy /year (SY) (maximum capacity of Porthos tons/year)
3. subsidy offer time (OT) (not used)
4. subsidy time (STi) (until 2036 (15y))
5. subsidy total (ST) (2.1 M€)

Hydrogen subsidy

1. subsidy /ton (SH) (20% of hydrogen price €/ton)
2. subsidy /year (SY) (100 M€/year)
3. subsidy offer time (OT) (not used)
4. subsidy time (STi) (until 2031 (10y))
5. subsidy total (ST) (2.2 M€)

Inverse CO2 subsidy

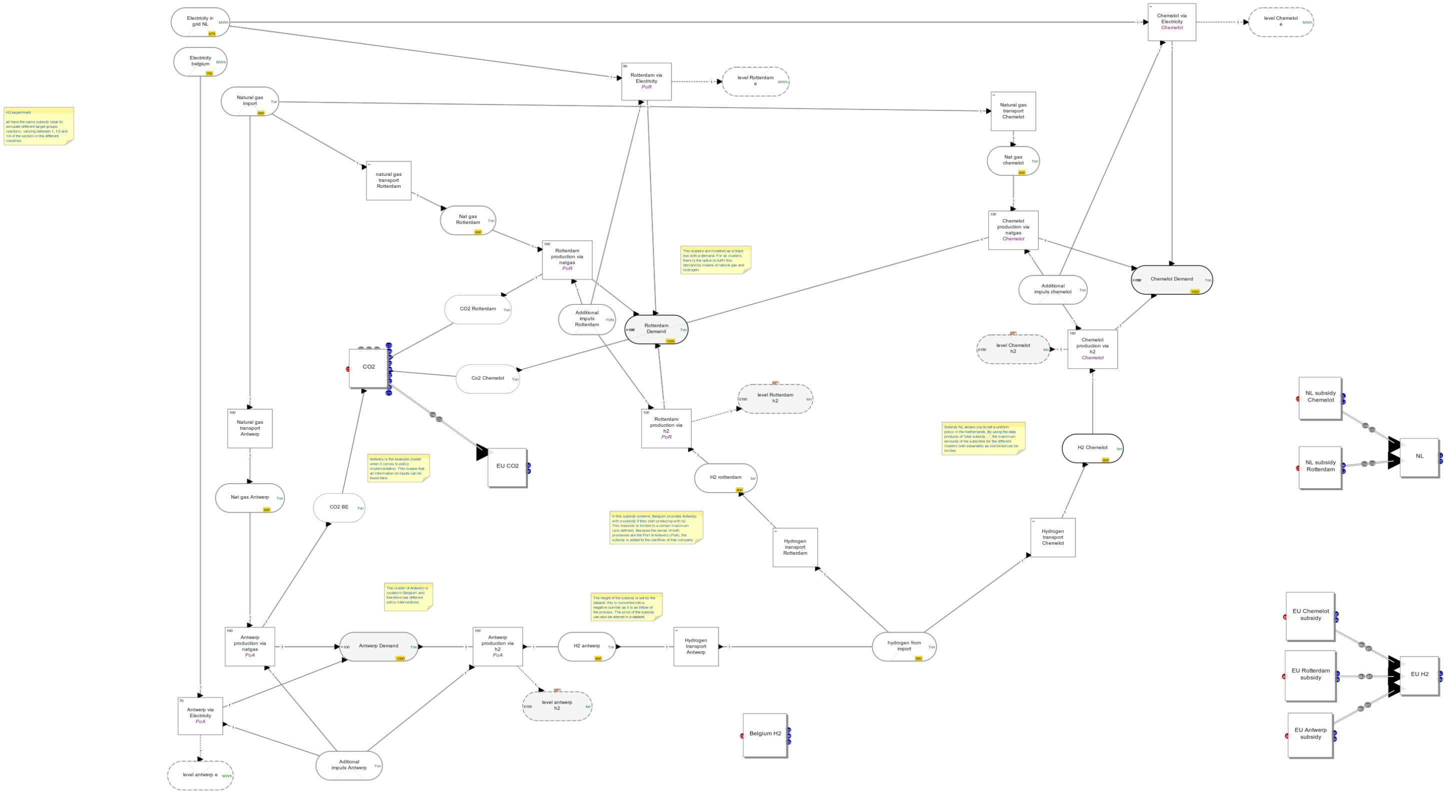
1. subsidy /ton (SH) (40 €/ton)
2. subsidy /year (SY) (all tons/year)
3. subsidy offer time (OT) (not used)
4. subsidy time (STi) (2036 years (15y))
5. subsidy total (ST) (unlimited)

In figure 36 an example of a visualization of the complete model used can be found. This particular model was used for experiments regarding an H2 subsidy.

The light gray ovals are the different clusters. As can be seen, these are linked with different processes that they can use to foresee in their demand. These rectangular process all contain an actor (in purple). These actors match with the cluster they're linked to.

The yellow pieces are in-model explanations of how the model and the different policy modules work. These are included to foresee in the plug-and-play design aspect of the modules.

The big arrows that are visible are between so called 'clusters'. Except for the CO2 cluster, these clusters contain different policy modules that stimulate or discourage model behaviour in different parts of the model.



H2 experiment

all have the same subsidy /year to simulate different target groups (sectors). varying between 1, 1/2 and 1/4 of the sectors in the different countries

The clusters are modeled as a black box with a demand. For all clusters, there is the option to fulfill this demand by means of natural gas and hydrogen.

Subsidy NL allows you to set a uniform policy in the Netherlands. By using the data products of 'total subsidy ...', the maximum amounts of the subsidies for the different clusters both separately as combined can be limited.

Antwerp is the example cluster when it comes to policy implementation. This means that all information on inputs can be found here.

In this subsidy scheme, Belgium provides Antwerp with a subsidy if they start producing with h2. This however is limited to a certain maximum (pre-defined). Because the owner of both processes are the Port of Antwerp (PoA), the subsidy is added to the cashflow of that company.

The cluster of Antwerp is located in Belgium and therefore has different policy interventions.

The height of the subsidy is set by the dataset. this is converted into a negative number as it is an inflow of the process. The price of the subsidy can also be altered in a dataset.

Figure 36: An example of the structuring of the model used for experiments with the H2 subsidy

E Appendix verification

In this appendix, hypotheses of the effect of varying these parameters are presented after which the results are discussed.

The following verification experiments are run on the feed-in-tariff module. As a base case the three industrial cluster are included. Natural gas, hydrogen and CO2 are taken into account in this verification and all clusters have the option to produce using natural gas and hydrogen. If they use natural gas, CO2 is emitted and taxed against a certain ETS price. Hydrogen is more expensive than natural gas, the CO2 price rises over time so economically it becomes feasible to switch to hydrogen for every cluster at a certain point in time. The difference in price between natural gas and hydrogen is set to be 200 and the CO2 price at t=0 90. To verify the working of the subsidy, the output parameter is the total amount of tons produced using the hydrogen process as the module steers towards an earlier switch to the hydrogen process.

E.0.1 Hypotheses external variables

CO2 price. The model used for the verification of the CO2 price consists of a basic model containing two different production options. One of these options emits more CO2 than the other but the commodity used is cheaper compared to the less CO2 emitting process. No subsidy is added in order to provide insight in the direct effects of the CO2 price. It is expected that without a varying CO2 price below the cost price difference between natural gas and hydrogen, no incentive is provided to make the switch. Likewise, if the CO2 price is higher than this difference, it is profitable directly from the start to use hydrogen.

With an increasing CO2 price, it is expected that the switch to hydrogen is made when the CO2 price becomes above the price difference between natural gas and hydrogen. Likewise with a decreasing CO2 price, it is expected that first hydrogen is used and the process switches to using natural gas if the CO2 price becomes lower than the price difference.

Concerning the cash flow of the involved actor, it is expected that no CO2 price leads to the highest values. Whether a decreasing or increasing CO2 price leads to higher cash flows depends on the different starting points and rates. Additionally, using a decreasing CO2 price, the minimum cash flow generated, is what the actor starts with (i.e. production using hydrogen). Only when it generates more cash, it is switched to natural gas with an increasing cash flow every time step due to the decreasing CO2 price. An increasing CO2 price on the contrary starts with the highest cash flow (i.e. the minimum CO2 price) and ends with the lowest (i.e. production using hydrogen). As in the example model, a starting CO2 price (for increasing CO2 price) is used that is higher than the end CO2 price (for decreasing CO2 price), it is expected that a decreasing CO2 price leads to higher cash flows.

Commodity price difference. The model that is used for verification of the commodity price difference is the same as the CO2 price. Only now a linearly increasing CO2 price is assumed to provide insight in the direct effect of the commodity price difference.

It is expected that the model switches production option as the cost price of the CO2 intensive process exceeds that of the less CO2 emitting process. If the price difference is bigger than the price of CO2, it is expected that no switch is made between the processes. In case of a negative price difference (i.e. the environmentally option is cheaper than the CO2 emitting process), this option will be used for the entirety of the run. Lastly, a small difference in price causes an earlier switch.

To conclude, if the price of the environmentally friendlier option is closer or even negative with respect to the price of the CO2 emitting option, less CO2 will be emitted.

E.1 Results external variables

In figure 37 the outcomes of the above described behaviour tests are presented. It can be concluded that the model behaves as expected with varying external variables. The data visualized concerns the total used hydrogen for production. The CO2 price (rows) consists of a static price of 90 and both increasing and decreasing prices with a value of 7 per year. The price difference (columns) are also varied to the more extreme cases (i.e. a negative price difference of €200 and a positive price difference of €500). Additionally, also two moderate price differences are included (i.e. €150 and €250). The results are in line with the hypotheses and show that less hydrogen is used if the price difference becomes larger.

In addition, the CO2 price has a large effect that is in line with the hypothesis. A static and decreasing lead to no use of the hydrogen process except if that process is already cheaper in the beginning. In case of a negative price difference, the conclusions can be drawn the other way around. In this case, a decreasing CO2 price make it profitable to switch to the emitting process. The static CO2 price in this case create a situation in which it is profitable to use the hydrogen process for the entirety of the run.

CO2 vs. ComPrice ✔

Scenario space	Configurations			
	150	250	-200	500
increasing	4200	2800	5000	0
decreasing	0	0	4100	0
static	0	0	5000	0

Figure 37: An overview of the cumulative hydrogen usage with the varying external variables CO2 price and commodity price difference.

E.2 Verification of FiT-Module

To verify the FiT-module, extreme cases are used and the model behaviour is compared to the hypotheses. To this end the total production with hydrogen and costs of the subsidy are the measured as performance indicators. In this experiment a basic model with only one cluster, two production options and one feed in tariff module is used. A commodity price difference of €200 and a CO2 price of 90 + 7*t are assumed. As presented in the formalization of policies (chapter ??), there are two types of subsidy limitations. Using the above described model, the size limitations are verified. The offering time constraint is verified using multiple FiT-modules on the hydrogen process and is assumed to be stable in the subsidy size verification.

E.3 Subsidy size variables hypotheses

It is expected that without a subsidy, the process switches at the point that the CO2 price is higher than the difference in cost price. A higher subsidy would lead to an earlier switch and thus more hydrogen usage. However, because of the offering time constraint, the effect of the subsidy is expected to behave binary.

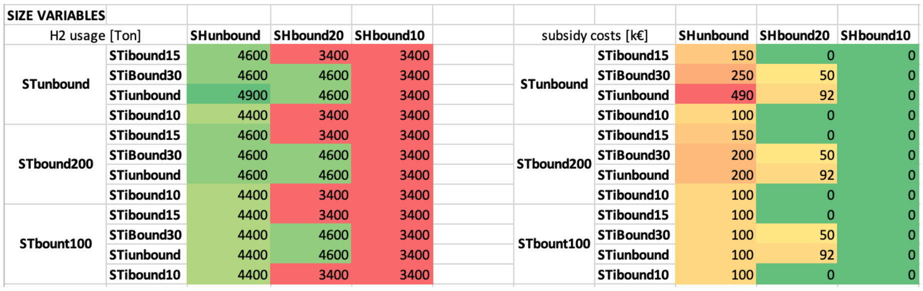
The variables below are different means in limiting the size of the subsidy. It is expected that one of these variables is the limiting factor in the subsidy. Varying that variable is expected to either increase or decrease the hydrogen usage in the cluster.

1. **Subsidy height (/ton)**. It is expected that the subsidy height is limiting if the duration of the subsidy exceeds the time frame of the model and the total subsidy size is not constrained. Concerning the total subsidy that can be gained, the subsidy height can be a non-

constraining factor. However, the subsidy height must be constraint per time step for the model to work.

2. **Subsidy duration**. It is expected that an infinite duration of the subsidy leads to a switch to hydrogen as soon as the subsidy is high enough to compensate for the price difference between hydrogen and the combined price of natural gas and CO2. However, when the time horizon is reduced (and known to the actors) it can generate more cash flow if the switch is postponed past this point. This way, the actor can still make use of the entire subsidy while still profiting from relatively low carbon prices. Trivially till the point that the subsidy duration is longer than time span of the model and the natural point of switching, a longer time horizon leads to higher cash flows.

3. **Subsidy size**. The same behaviour as described for the subsidy duration is expected. This is in case the total amount of subsidy is limiting the subsidy that can be gained by the involved actors (i.e. if not the subsidy duration is the limiting factor).



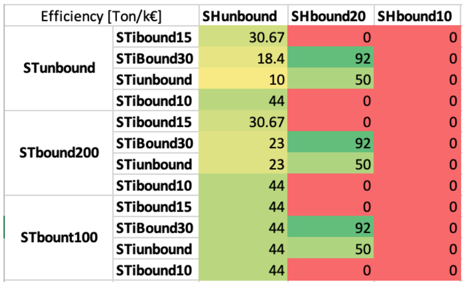
SIZE VARIABLES				
H2 usage [Ton]		SHunbound	SHbound20	SHbound10
STunbound	STibound15	4600	3400	3400
	STiBound30	4600	4600	3400
	STiunbound	4900	4600	3400
	STibound10	4400	3400	3400
STbound200	STibound15	4600	3400	3400
	STiBound30	4600	4600	3400
	STiunbound	4600	4600	3400
	STibound10	4400	3400	3400
STbount100	STibound15	4400	3400	3400
	STiBound30	4400	4600	3400
	STiunbound	4400	4600	3400
	STibound10	4400	3400	3400

subsidy costs [k€]		SHunbound	SHbound20	SHbound10
STunbound	STibound15	150	0	0
	STiBound30	250	50	0
	STiunbound	490	92	0
	STibound10	100	0	0
STbound200	STibound15	150	0	0
	STiBound30	200	50	0
	STiunbound	200	92	0
	STibound10	100	0	0
STbount100	STibound15	100	0	0
	STiBound30	100	50	0
	STiunbound	100	92	0
	STibound10	100	0	0

Figure 38: The results of the verification runs of the size variables. More money leads to more hydrogen usage.

E.3.1 Results of size variables

In figures 38 and 39 the outcomes of the size attributes of the subsidy module are presented. Using colour schemes, the conclusion is visualized as well. It can be concluded that the model behaviour is as expected as higher subsidy costs lead to more hydrogen usage. It can also be concluded that the subsidy height is a determining factor in whether the time span or the total subsidy is limiting. This can be specifically noticed in the subsidy height of 20 €/ton and the bound vs. unbound subsidy total. From figure 39 can be concluded that under the basic model assumptions, the subsidy height of 20€/ton and a subsidy time of 30 years is most efficient (i.e. has the highest effect with respect to the costs).



Efficiency [Ton/k€]		SHunbound	SHbound20	SHbound10
STunbound	**STibound15**	30.67	0	0
	STiBound30	18.4	92	0
	STiunbound	10	50	0
	STibound10	44	0	0
STbound200	**STibound15**	30.67	0	0
	STiBound30	23	92	0
	STiunbound	23	50	0
	STibound10	44	0	0
STbount100	**STibound15**	44	0	0
	STiBound30	44	92	0
	STiunbound	44	50	0
	STibound10	44	0	0

Figure 39: The efficiency results of the verification runs. 92 tons per k€ can be reached in combination of a subsidy height of 20 €/ton and a subsidy time of 30 years.

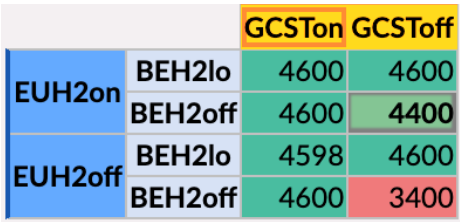
E.3.2 Verification of the offering time

To verify the offering time, the same model is used but different subsidies are included. This way different offering times can be used simultaneously and the effect can be determined. Also the effect of a varying offering time of one subsidy is verified. It is expected that if the subsidy is high enough to compensate for the losses of early switching to hydrogen (in the simplified test model), the outcome will be that the switch is made at the latest moment of the offering time except in the case that the time span of the subsidy is longer than the time horizon minus the offer time. In this case it would be profitable to switch before the latest moment of the offer time.

If subsidy schemes are combined, the shortest offer time is leading in the switching decision. Off course the combined subsidy incomes have to be taken into account. If many subsidies are combined/available, it is expected that the running time increases due to the inclusion of more binary values in linear optimization (Murray & Ming Ng, 2010).

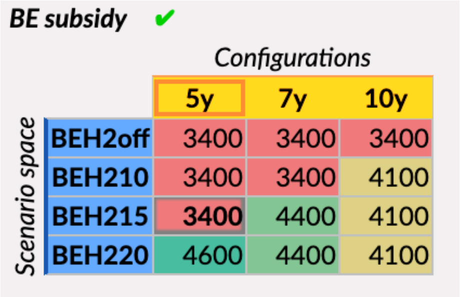
In the verification experiment, three subsidies are taken into account. These consist of a Belgium (BE), European (EU) and a general (GC) subsidy that are all focused at stimulating a switch to hydrogen. The Belgium and general subsidy both have an offer time of five years, the EU subsidy has an offer time of seven.

In the figure below (40), an overview is presented of the hydrogen consumption in the scenario of different subsidies that are enabled or disabled. It can be concluded that all subsidies are high enough to compensate for the losses of switching early as the more hydrogen is consumed in every case except if the subsidies are all off. It can also be concluded that if only the EU subsidy is enabled, less hydrogen is consumed than if other subsidies are enabled. This is because of the two years longer offering time.



		GCSTon	GCSToff
EUH2on	**BEH2lo**	4600	4600
	BEH2off	4600	**4400**
EUH2off	**BEH2lo**	4598	4600
	BEH2off	4600	3400

Figure 40: An overview of the cumulative hydrogen production with different subsidies and varying offer times.



BE subsidy ✔

Configurations

Scenario space		5y	7y	10y
	BEH2off	3400	3400	3400
	BEH210	3400	3400	4100
	BEH215	**3400**	4400	4100
	BEH220	4600	4400	4100

Figure 41: An overview of the cumulative hydrogen production with different subsidy heights and varying offer times.

In the next verification experiment, one subsidy module is used and the offering time is varied between five, seven and ten years. Combined with a specific subsidy height and a subsidy time span of 30 years, the effect of the offering time is tested. The maximum subsidy per year is not limited and the full (100 tons) can be subsidized.

From the results in the following figure (41), is becomes clear that there is an interplay between the offering time and the height of the subsidy. As described as hypothesis earlier in this sub chapter, if the switch can be postponed long enough (a higher offering time), a lower subsidy is needed. It can thus be concluded that the module behaves as expected.