Radarweg 60
1043 NT Amsterdam
The Netherlands

www.tno.nl

T +31 88 866 50 10

TNO report

TNO 2021 P12401 | Final report

Support for informed decision making on the energy transition of industrial clusters

Deliverable 5.4: Synthesis report based on the ESTRAC case studies

Date	23 December 2021
Author(s)	Wouter Wetzels (TNO), Douwe Truijens (TNO), Pieter Verstraten (TNO), Hans Meerman (University of Groningen), Mirjam Groote Schaarsberg (TNO)
Number of pages	25
Number of appendices	
Sponsor	New Energy Coalition
Project name	ESTRAC - Regional Energy Transition
Project number	060.31042

Acknowledgement

This report is a deliverable of the ESTRAC 'Case Studies Regional Energy Transition' project, commissioned and funded by the research institute Energy Systems Transition Centre (ESTRAC). ESTRAC is a joint initiative of knowledge and research institutes in the Netherlands – including TNO, ECN (since April 2018 part of TNO), University of Groningen, Hanze University of Applied Science, the New Energy Coalition (NEC) and, more recently, PBL – as well as associated partners including Gasunie, Gasterra, EBN and NAM. In addition to funding from the ESTRAC partners, the Case Studies Regional Energy Transition project has benefitted from funding by the Green Deal program of the Dutch government.

Summary

The ESTRAC 'Case Studies Regional Energy Transition' project aims to contribute to informed decision making by providing models, tools and approaches that cover social and techno-economical aspects of the energy transition on the local and regional level.

This synthesis report provides an overview of three ESTRAC case studies that focus on the five large, energy-intensive industrial clusters in the Netherlands. These industrial clusters are characterised by many interdependencies, which provide opportunities for synergy, but can also lead to lock-ins and coordination problems. A comparison of the approaches used in the case studies makes it possible to draw lessons that can be considered in decision processes by stakeholders in industrial clusters.

The greenhouse gas reduction targets for 2030 mean that the Dutch industry must take action to decarbonise rapidly. To realise the EU's target to become climate neutral in 2050, the industry has to undergo a radical transition to large-scale use of renewable energy, non-fossil feedstocks and reuse of carbon. This poses many challenges.

The case studies all focus on the transition of industrial clusters, but use different approaches:

1. The study *Institutional innovation for regional energy transition: from laissez-faire to navigating* uses governance analysis to investigate decision making on energy and CO_2 infrastructure.
2. The study *Multi actor decision models for transformation of industrial clusters* treats the decarbonisation of industrial clusters as a multi actor decision problem.
3. The study *Decarbonisation of industrial clusters - System analysis for screening of mitigation pathways* develops a consistent, transparent methodology to assess the greenhouse gas mitigation potential and the associated costs for decarbonisation of industrial clusters.

The first study starts from the premise that decision making on infrastructure is characterised by strategic uncertainty, complex interdependencies and a polyarchic distribution of power. The study draws the overarching conclusion that the current situation can be described as a *laissez-faire* mode of governance, while there may be benefits from a more *navigating* role of regional and central governments.

The second study recognises that companies in industrial clusters benefit from cooperation and synergies but argues that some characteristics of these clusters complicate decision making. Companies make investment decisions based on individual economic trade-offs, but the costs and benefits of the individually chosen options depend on the other actors' choices as well. Game theory offers an analytical framework for analysing the options of all the different sub coalitions, and for fair allocation of costs and benefits.

The third study uses a techno-economic approach to assess mitigation pathways for industrial clusters. Instead of considering technical decarbonisation options in isolation, the approach takes into account interactions between technological options, pathway dependence and indirect emissions. It also considers the potential synergies of sharing mitigation options between different industrial actors. In this way a more integral overview of costs and benefits is obtained, which can help to avoid lock-ins.

By combining the results of the different approaches that have been used in the case studies, lessons can be drawn that can be considered in decision processes by stakeholders in industrial clusters:

- Analyses based on an actor perspective can be a valuable complement to analyses based on a system perspective.
- Decision makers must look for ways to deal with mutual dependencies, strategic uncertainty and polyarchy.
- As the problem, the context and the available (technological) options are continuously evolving, strategies need to be robust against changes as much as possible.

Contents

Introduction

The energy transition is a complex process that affects many aspects of society. Because major choices need to be made at the regional and local level, decision makers need insights into the implications of interventions and systematic comparisons of alternative options.

The ESTRAC "Case Studies Regional Energy Transition" project aims to contribute to informed decision making by providing models, tools and approaches that cover social and techno-economical aspects of the energy transition on the local and regional level.

The ESTRAC partners have first made an overview of existing models, tools and approaches that are used by different actors, on different scale levels and in different phases of the decision-making process. Subsequently, new approaches have been developed, applied and validated in the various case studies. The project focuses on cases (living labs) in two different settings, namely the industry and the built environment.

This synthesis report provides an overview of three ESTRAC case studies that focus on the five large, energy-intensive industrial clusters in the Netherlands (see Figure 1). These industrial clusters are characterised by many interdependencies, which provide opportunities for synergy, but can also lead to lock-ins and coordination problems. A comparison of the approaches used in the case studies makes it possible to draw lessons that can be considered in decision processes by stakeholders in industrial clusters.

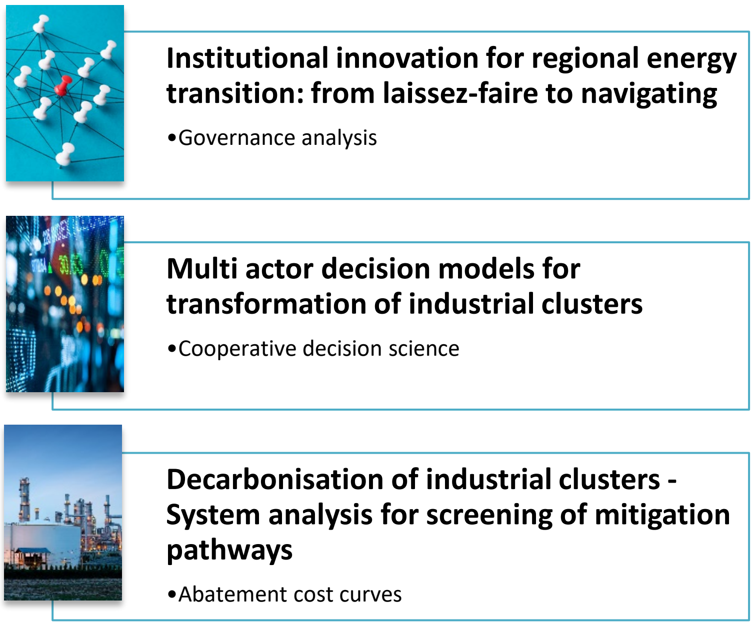

Figure 1 Overview of the ESTRAC case studies and the applied research approaches

Reading guide
Chapter 1 provides an introduction to decision making on the energy transition of industrial clusters, which includes discussions of the current policy targets, some of the main challenges for industrial clusters, and the need for models, tools and approaches that support decision making. Chapter 2 gives an overview of the theoretical frameworks and research approaches that have been used in the case studies that have been carried out in the ESTRAC project. Chapter 3 discusses the three case studies on regional industrial transition. Chapter 4 presents lessons that can be drawn from combining the case studies.

1 Decision making on the energy transition of industrial clusters

This chapter provides an introduction to decision making on the energy transition of industrial clusters, which includes discussions of the current policy targets, some of the main challenges for industrial clusters, and the need for models, tools and approaches that support decision making.

1.1 Policy targets for greenhouse gas emission reduction

At the 2015 UN Climate Change Conference, a global agreement was reached to limit global warming to well below 2 ˚C, preferably to 1.5 ˚C, compared to pre-industrial levels. Since then, there have national and international policy developments that have set more ambitious greenhouse gas reduction targets and introduced new policy instruments (see Figure 2). The current target for 2030 for the Netherlands is to reduce emissions by 49% compared to 1990. The target for 2050 is to reduce emissions by 95%.

The 2030 climate target has been translated into an indicative target for the Dutch industry. The industry's emissions must be reduced from a level of 53.5 megaton in 2020 to 39.9 megaton CO_2-equivalent by 2030 (PBL, TNO, CBS and RIVM, 2021). This means that the Dutch industry must take action to decarbonise rapidly.

The 49% reduction target was the starting point for the negotiations on a national Climate Agreement. The Climate Agreement, which was presented in 2019, announced a new national CO_2 tax for the industry and a subsidy scheme to stimulate emission reduction in the industry (called SDE++). Both policy instruments have been implemented and in combination they offer a strong incentive to reduce industrial greenhouse gas emissions. The Netherlands Climate and Energy Outlook 2021 projects that this will cause a break in the trend in the expected greenhouse gas emissions from industry (PBL, TNO, CBS and RIVM, 2021).

In the near future, new steps will be necessary to align the Dutch climate targets with stricter EU targets (Studiegroep Invulling klimaatopgave Green Deal, 2021). An objective to reduce the EU's greenhouse gas emissions by at least 40% in 2030 was the basis for the EU's contribution to the Paris Agreement. In 2021, the European Climate Law set a binding target of reduction of net greenhouse gas emissions by at least 55% by 2030 compared to 1990, next to the goal to be climate neutral in 2050.

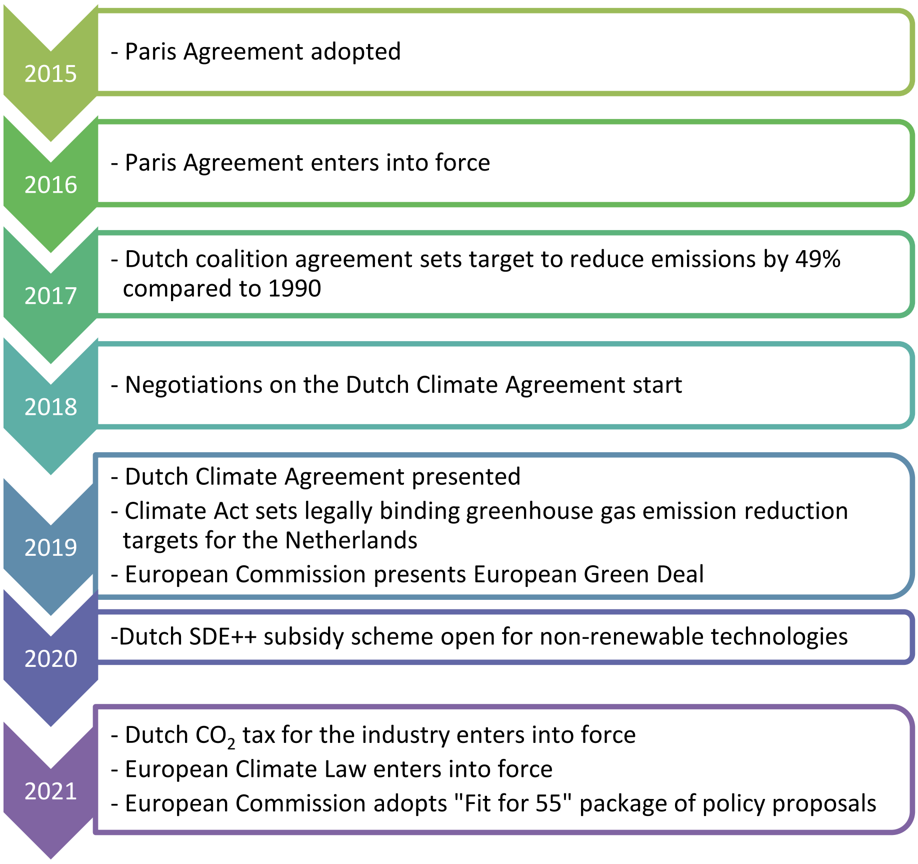

Figure 2 Timeline for national and international policy developments in the period 2015-2021

1.2 Challenges for industrial clusters

To realise the EU's target to become climate neutral in 2050, the industry has to undergo a radical transition to large-scale use of renewable energy, non-fossil feedstocks and reuse of carbon. This poses many challenges.

The energy-intensive industry of the Netherlands is concentrated in five large industrial clusters: Rotterdam-Moerdijk, Chemelot, Zeeland, Noordzeekanaalgebied and Noord-Nederland. These clusters are characterised by many interdependencies, which provide opportunities for synergy but can also lead to lock-ins and coordination problems. The transition requires decisions on a wide range of technological options under large uncertainties. The multi-level decision process requires public coordination and actions by many individual companies.

The ESTRAC report "Decision making on regional energy transition in industrial clusters" (Brunsting, Broecks, Truijens, Hermans, & Wetzels, 2020) has analysed the transition challenges for the clusters and discusses three important factors:

- Sufficient and timely investments in large-scale infrastructure for transport of electricity, hydrogen, heat and CO_2.
- Preserving economic competitiveness of the industry to avoid carbon leakage.

- Securing societal support for decarbonisation investments, which can have important impacts on the use of space and quality of life at the regional level.

Industrial companies, grid operators, energy producers and regional governments have together made Cluster Energy Strategies (CES's) for each of the five large industrial clusters, as well as for the remaining Dutch industry (the 'sixth cluster'). The CES's describe the future demand for energy infrastructure, taking into account the plans of the companies to reduce greenhouse gas emissions, expected production developments and the establishment of new companies.

PBL, RVO and TNO have analysed the CES's (Koelemeijer, Lucassen, & Dervis, 2021) and concluded that the potential emission reduction of the technical measures in the plans is more than sufficient to reach the indicative reduction target for the Dutch industry (see Figure 3). Carrying out the plans would lead to a large increase of the electricity demand. The authors argue that if the Netherlands wants to retain its current industry and wants to support the transition to an emission-free future, the infrastructure that is requested in the CES's is indispensable.

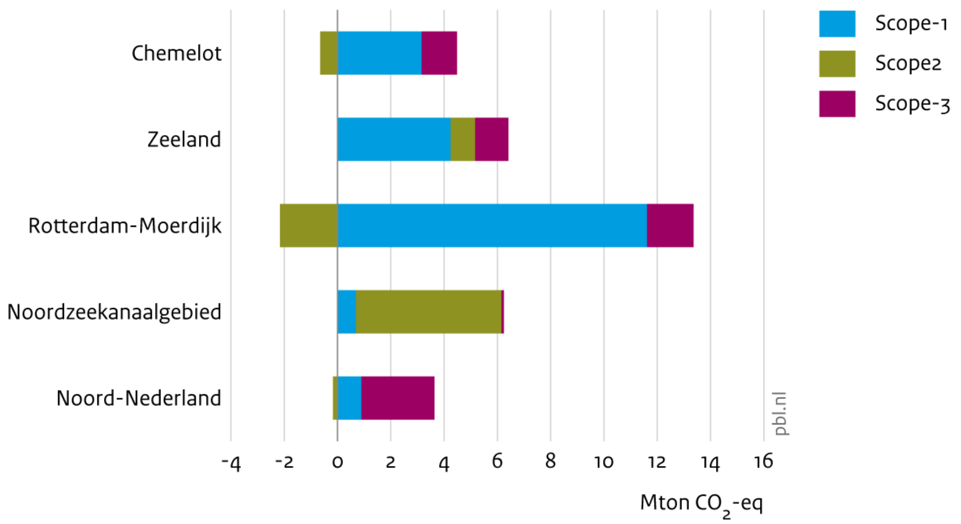

Figure 3 Estimated potential emission reduction per cluster in 2030. Source: (PBL, TNO, CBS and RIVM, 2021)

In the report "*Decision making on regional energy transition; Models, tools and approaches*", the ESTRAC partners have compiled an overview of existing tools, models and approaches that are available to help stakeholders to make well-informed decisions on the energy transition (Wetzels, van Dam, Geerdink, & Meerman, 2019).

In the ESTRAC project, TNO has investigated the need for models, tools and approaches to support decision making on the energy transition in industrial clusters (Brunsting, Broecks, Truijens, Hermans, & Wetzels, 2020). Based on a combination of desk research and expert interviews, the authors conclude that there is a need for approaches that can address multiple project benefits and conflicting stakeholder values. The research also indicates that the industry is interested in

approaches that can make large uncertainties and risks manageable and acceptable.
Techno-economic uncertainties and risks around societal support can be analysed thoroughly but cannot be eliminated. Finally, the study has found that there is interest in methods that can address different values of stakeholders to support a dialogue between the industrial clusters and the surrounding region.

2 Research approaches used in the case studies

Chapter 3 gives on overview of the theoretical frameworks and research approaches that have been used in the three ESTRAC case studies, namely:

- governance analysis
- cooperative decision science, and
- abatement cost curves.

2.1 Governance analysis

The study *Institutional innovation for regional energy transition: from laissez-faire to navigating* (Truijens, 2020) has analysed the governance of energy infrastructure based on a case study for the province of Limburg (Truijens, 2020). This section discusses the theoretical framework and the research approach that were used in this case study.

Theoretical framework

The study starts from the premise that the policy question under study is characterised by strategic uncertainty, complex interdependence and a polyarchic distribution of power:

- *Strategic uncertainty* means that neither policymakers nor private parties know exactly how to set and achieve their (policy) goals, due to the continuous development of both the policy problem and the possible solutions.
- *Complex interdependence* exists between the different relevant local governments as well as between local and central governments, between different private parties and between private and public parties. The complexity of their mutual dependency means that the different parties are both sensitive and vulnerable to actions and decisions of one another.
- *Polyarchy* refers to the situation in which no one single actor can impose their preferred policy option upon others, as there are multiple ‘power centres’ that can each decide on only a part of the problem or solution.

These policymaking conditions can severely hamper policy decisions, especially when those decisions require significant, long-term investments, as is the case with energy infrastructure. A conventional, top-down policymaking and implementation style is therefore not suitable, while a too strong reliance on laissez-faire leads to the risk of stagnation. The institutional organisation of should facilitate and stimulate policy development, decision-making, and implementation.

Woestenburg et al. distinguish three categories – or modes – of government steering contrasted with outsourcing decisions to relevant stakeholders: directing, navigating, and laissez-faire (Woestenburg, et al., 2020):

- *Directing* is the more classical ‘top-down’ variant of government steering, in which the government itself makes concrete and detailed plans and uses decision-making processes to inform involved parties about those plans. In this mode, it is the government that takes initiative and responsibility for execution of the plans, in which deviation from the policy line is generally undesirable. The government furthermore takes responsibility for coordination between transition partners (such as network operators, electricity suppliers, housing corporations, and regional water authorities), for instance regarding the necessary investments.

- In the *laissez-faire* mode, the government plays a significantly smaller role as the responsibility for detailing and execution of the set (broad) policy goals is transferred to the transition partners and stakeholders. In this laissez-faire mode, both the transition pace and the level of innovation are determined by bottom-up initiative. The government merely facilitates and enables information exchange, and 'repairs' possible deficiencies afterwards in case the bottom-up initiative turns out insufficient for achieving the goals.
- In *navigating*, the government's role is somewhere in between the former two modes. The government steers, or coordinates the policy framework, meaning that the broad policy goals, the 'rules of the game', and the pace of transition are determined top-down rather than bottom-up. In navigating, the transition partners and stakeholders take initiative within the framework set by the government. There is however room for reviewing and changing the policy framework along the way based on innovation or insights brought in by stakeholders and transition partners. The role of the government consists of stimulating such initiative, and to monitor it against the set (framework) goals.

Research approach

In order to map out which institutional changes could accelerate the energy transition of heavy industry at the regional level, the province of Limburg with its chemical cluster Chemelot was selected as a case study. On the one hand, Limburg can be seen as a typical case, which makes the findings and insights generalisable to other regions in the Netherlands. On the other hand, the locally initiated Limburg Energy Agreement (LEA partners, 2018) makes Limburg an interesting case to look at, because it shows how collaboration can emerge between top-down and bottom-up initiative. The presence of the Chemelot cluster, one of the five big clusters in the Netherlands, makes realizing the reduction goal in the province difficult, but also means that the potential for emission reduction is large: a high-risk-high-gain situation.

Several interviews with key players in the Limburg region were conducted to determine what strategic uncertainty, complex interdependence and polyarchy look like in practice, and how these conditions constrain progress in the regional energy transition in Limburg. Based on interviews with TenneT, the Province of Limburg, the Royal Association of the Dutch Chemical Industry (VNCI), and Brightlands Chemelot Campus, the case study presents the main obstacles in decision-making on energy infrastructure followed by some lines of thought on where possible solutions for the obstacles may be found. The way in which the stakeholders describe these obstacles and (institutional) solutions are interpreted along the categories described by Woestenburg et al. (Woestenburg, et al., 2020).

2.2 Cooperative decision science

The paper *Multi actor decision models for transformation of industrial clusters* (Verstraten, Groote Schaarsberg, & Stelwagen, 2021) presents a method to include the actor perspective when describing and selecting solutions for the regional industrial cluster decarbonization problem. This section discusses the theoretical framework and the research approach that were used in this case study.

Theoretical framework

Game theory is a mathematical field that describes strategic conflict or cooperative situations. The characteristics of these situations are that:
1) the parties are selfish, i.e., they want to optimise their own profit, and
2) the outcome depends on the parties' actions (Gedai, Koczy, & Zombori, 2012).

This conflict or cooperative situation is called a game. Each player will form a strategy which determines their actions. Given the strategies of the players, a game can be played, and the outcome can be determined. In cooperative game theory, the players can make binding agreements, whereas in non-cooperative game theory they cannot. In a cooperative game, multiple players gain benefit from working together in a coalition. The total benefits of the coalition are divided among the players.

Research approach

In a simplified case, game theory is applied to an existing industrial cluster consisting of three organizations. The players have four options:

- Investing in carbon capture technology, which requires access to CO_2 transport infrastructure.
- Invest in new processes that use hydrogen as feedstock or energy carrier, which requires hydrogen distribution infrastructure.
- Invest in other individually focused measures which do not require significant infrastructure investments, and
- Do nothing.

The costs and effects of the reduction options are clouded by uncertainty, both technical and non-technical. Some of the options require new or adapted energy infrastructure within the cluster and between the cluster and its external environment. This infrastructure is considered to be a shared asset and is a crucial component for a successful transition. Hence, the total costs and benefits of the individually chosen options depend on the other actors' choices as well.

A large coalition can have low fixed costs per company. However, if a company is not satisfied in this coalition, it can step out and choose another option instead. This increases the cost for other companies and can even make their business case negative. Depending on their business strategies companies might differ in their valuation of emission reduction or abatement costs.

2.3 Abatement cost curves

The case study *Decarbonisation of industrial clusters - System analysis for screening of mitigation pathways* (Meerman, 2021) develops a consistent, transparent methodology to assess the greenhouse gas mitigation potential and the corresponding costs for industrial clusters. This section discusses the theoretical framework and the research approach that were used in this case study.

Theoretical framework

Energy systems models allow the analysis of the energy supply and demand. These models are used as a tool to quantify scenarios and to formalise scattered knowledge about complex interactions (Pfenninger, Hawkes, & Keirstead, 2014).

Many energy system models use optimization or simulation techniques:

- *Optimization models* are used to determine a preferred mix of technologies, given certain constraints.
- *Simulation models* attempt to reproduce the operation of an energy system by simulating the behaviour of energy producers and consumers in response to prices and other signals.

Bottom-up (cost) engineering can support decision making at the regional and local level. Other common modelling approaches are based on neural networks, agent-based modelling, complexity science and fuzzy theory (Hall & Buckley, 2016).

Mitigation options for industrial clusters include energy efficiency, CCS and substitution of energy carriers or feedstock. Abatement cost curves show the size and the costs of opportunities to reduce emissions at a given moment in time. Considering mitigation options in isolation, and thereby ignoring the effect that different mitigation options have on each other, can lead to wrong estimations of mitigation potential and CO_2 avoidance costs

Research approach

In the case study, a bottom-up model was developed to assess the potential of greenhouse gas reduction pathways, determine interactions between mitigation options and calculate mitigation costs. The technical analysis provides the relevant mass and energy flows. The greenhouse gas analysis provides direct greenhouse gas emissions as well as energy-related greenhouse emissions and cradle-to-gate greenhouse emissions. The economic analysis provides the cost of the mitigation options. This allows calculation of the CO_2 avoidance cost. This metric can be compared with other industrial sites or with mitigation options in other sectors.

The system boundaries of the model are shown in Figure 5. Although the focus in on the industrial sector, conversion of energy carriers into other energy carriers, e.g., hydrogen, power or steam production, is also included in the analysis.

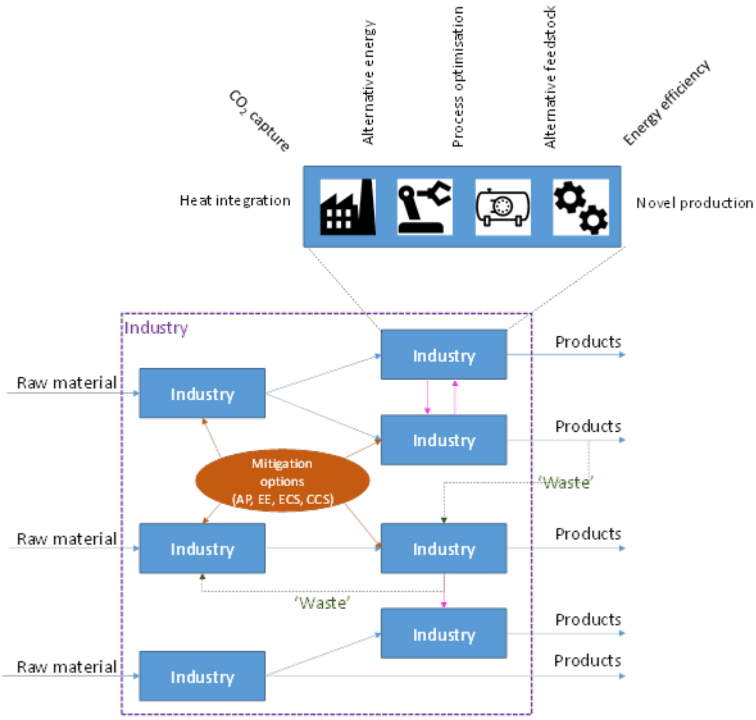

Figure 4 Schematic overview of an industrial area and the mitigation options that are investigated (Ramirez, et al., 2019).

The proposed methodology was applied to a fictional industrial cluster based on the industrial area in the Emmen municipality. The cluster specializes in the production of high-performance specialty polymers, fibres and yarns and the recycling of common plastics. The cluster is home to several industrial companies and a service provider that provides, among others, energy carriers and utilities. The area has a well-developed infrastructure and is connected to the main Dutch electricity and natural gas grids. Nearby are several greenhouses that could be used for CO_2 utilisation. Finally, the site is surrounded by several neighbourhoods, which can potentially consume low-grade waste heat.

Besides describing the current industrial cluster, an important part of the approach is the creation of a transparent, consistent database of mitigation options and determining their effect on the industrial activities (e.g., energy saving, feedstock substitution, CO_2 capture) and their implementation costs.

The model is designed to determine the potential and cost of mitigation options over time. It considers the period 2020-2050. New mitigation options can be implemented in 2030, 2040 or 2050. Implemented options will affect the cost and effectiveness of mitigation options that are implemented at a later stage.

Depending on the scenario, options are selected resulting in the lowest CO_2 avoidance cost, minimum CO_2 mitigation target, or maximum CO_2 reduction. If mitigation options can be shared between industrial activities and the sharing is advantageous, the mitigation option is sized to the combined scale of the relevant industrial activities.

3 Case studies on regional energy transition

This chapter discusses the three case studies on regional industrial transition that have been carried out in the ESTRAC 'Case Studies Regional Energy Transition' project.

3.1 Institutional innovation for regional energy transition

The study *Institutional innovation for regional energy transition: from laissez-faire to navigating* (Truijens, 2020) investigates the governance of energy infrastructure in regional industrial transition. In order to map out which institutional changes could accelerate the energy transition of heavy industry at the regional level, the province of Limburg with its chemical cluster Chemelot was selected as a case study.

The availability of adequate energy infrastructure (such as the electricity grid and hydrogen distribution pipelines) is a necessary condition for the sustainability transition of the heavy industry (Broecks, Truijens, Brunsting, Hermans, & Kooger, 2020). Of central concern for decision making on the construction or expansion of grid infrastructure is the coordination between private and public parties, as well as the interaction between national and local governments. The case study investigates the obstacles that private and public actors face in making these decisions. It also examines what kind of institutional change could accelerate the transition of the heavy industry.

The study starts from the premise that the policy question of energy infrastructure is characterised by strategic uncertainty, complex interdependence and a polyarchic distribution of power. Under these conditions, a conventional, top-down policymaking and implementation style is not suitable. At the same time, a too strong reliance on laissez-faire leads to a risk of standstill and actors waiting for one another to move.

Against this theoretical background and based on several qualitative interviews with experts, transition parties, and stakeholders in the province of Limburg, the study aims to identify what the policy obstacles look like in practice. The study explores what kind of institutional change may be needed and who can take the lead in pursuing that change, based on how the interviewees perceive the policy problem and a reflection on the extent to which the current institutionalisation perpetuates this.

Truijens summarises the obstacles that interviewees experience in the current institutional situation in three core problems:

1. A collective problem perception is lacking: many decisions are being made ad hoc and based on a short-term vision.
2. The required high degree of long-term certainty in order to make investments is at odds with the intrinsic significant uncertainty that characterises the energy transition.
3. The government takes a too small role in coordinating the process, leading to a lack of integral framework for all the smaller decisions to be made.

A high degree of uncertainty about the preferred sustainable alternative and a high degree of polyarchy combined with a low (perceived) degree of interdependence, result in a situation in which the willingness for collective action is low. The most important conclusion in this regard is that most (but not all) of the policy obstacles are kept in place by, if not result from, the current institutional setup. The good news is that some of the central obstacles exist *de jure* and can thus be resolved by changing the governance framework.

The interviews furthermore make clear that in order to move forward with the transition, the relevant parties involved require a mode of government that does not manage all details of the decisions but does shape the scope and frame of the transition in the region. Remarks from both experts, public parties and private companies show a demand for navigation by the government, where bottom-up initiatives are stimulated and facilitated, but are validated within an overarching, coherent policy framework. In this situation, which looks most like a laissez-faire mode of governance, such an overarching framework is lacking. As a result, the combination of strategic uncertainty, interdependence and polyarchy tends to maintain the infrastructural status quo. The multiannual programme infrastructure energy and climate (MIEK) might provide the overarching framework that is needed.

3.2 Multi actor decision models for transformation of industrial clusters

The paper *Multi actor decision models for transformation of industrial clusters* considers the decarbonisation of regional industrial clusters as a multi actor decision problem (Verstraten, Groote Schaarsberg, & Stelwagen, 2021), (Stelwagen, 2021).

The companies in the industrial clusters in the Netherlands profit from cooperation and synergies. The reasons that industry is often organised in regional clusters can be found in spatial characteristics (e.g., presence of a harbour), use of each other's products (e.g., intermediates) or sharing facilities (e.g., a steam network). In addition, industrial companies often have the same group of suppliers and customers and can benefit from regional access to employees with appropriate skills and knowledge. Companies experience that (pre-competitive) cooperation can boost productivity, innovation and 'new business'. This is also referred to as the cluster effect (Porter, 1990).

But companies also make investment decisions based on individual economic trade-offs. Policy instruments and measures can influence the decisions of the industry directly or indirectly, but the actual transition is the result of multiple individual decisions on company level (SER, 2019).

Studies on decarbonisation of the industry often use a system perspective. Because an industrial cluster consists of multiple actors (with different objectives, value creation processes and dependencies), an actor perspective is much needed as well. Decarbonization of industrial clusters is not only an optimization problem, but it is also a multi actor decision problem. The individual pay-off of options can strongly depend on the decisions of other actors in the cluster. Not considering the actor perspective in finding and analysing decarbonization options can result in suboptimal choices, non-robust choices or no chosen option at all.

From an actor perspective, a choice can be suboptimal if the chosen option would result in lower total value creation than another option. A choice is not robust if a subgroup of the actors can split off and achieve better individual or subgroup results when not participating in the system solution. Decarbonisation options may only be feasible if a group decision is made.

Some characteristics of industrial clusters, such as cross-company process optimization, can make decisions more difficult. An in-depth study of multiple regional industrial clusters (Janipour, de Nooij, Scholten, Huijbregts, & de Coninck, 2020) describes this as *heavy system integration* and considers this to be a main source of carbon lock-in of clusters.

Game theory offers an analytical framework for analysing situations for creating and allocating shared costs and benefits: cooperative transferable utility (TU) games (see (Ferguson, 2020), (Gedai, Koczy, & Zombori, 2012) and (Gedai, Koczy, & Zombori, 2015)). In a TU game one considers all options of all different sub coalitions. These coalitional values can be used as reference points for defining allocation rules of the total group benefit. In a TU game there exists a mechanism for the transfer of utility between the players besides the game itself (Ferguson, 2020).

In addition to studying single point solutions, game theory can help to reveal sets of potential allocations that satisfy one or multiple properties of fairness. For example, the requirement of individual rationality can be extended to coalitional rationality or stability. Coalitional rationality implies that no subgroup of players would be able to create more value as a subgroup.

3.3 Screening of mitigation pathways

The case study *Decarbonisation of industrial clusters - System analysis for screening of mitigation pathways* (Meerman, 2021) develops a consistent, transparent methodology to assess the greenhouse gas mitigation potential and the corresponding costs for industrial clusters.

The effectiveness and costs of mitigation options for industrial clusters - especially those resulting in deep emission reduction - often depend strongly on developments in the energy system. However, there is large uncertainty on what the future energy system will look like. Investments in the mitigation options should be taken before there is certainty on how the energy system evolves if the 2030 or even 2050 emission targets are to be met.

Complicating matters further is that deep emission reduction options often negatively impact each other or are even mutually exclusive. For example, suppose a company can apply electrification and carbon capture and storage (CCS). Both options have the potential to significantly reduce greenhouse gas emissions. If the company first applies CCS and then applies electrification, the additional emission reduction will be far less than the reduction potential of electrification alone. The combined mitigation cost, however, will be close to the sum of the individual options. The result is a much lower cost-effectiveness than would have been expected by the analysis of the mitigation options in isolation.

Therefore, uncertainties in the energy system create uncertainties in what the best mitigation strategy is (see Figure 6 for an illustration). Assessing these uncertainties - and therefore risks - requires that the effectiveness and costs of portfolios of mitigation options are considered under various potential future energy systems.

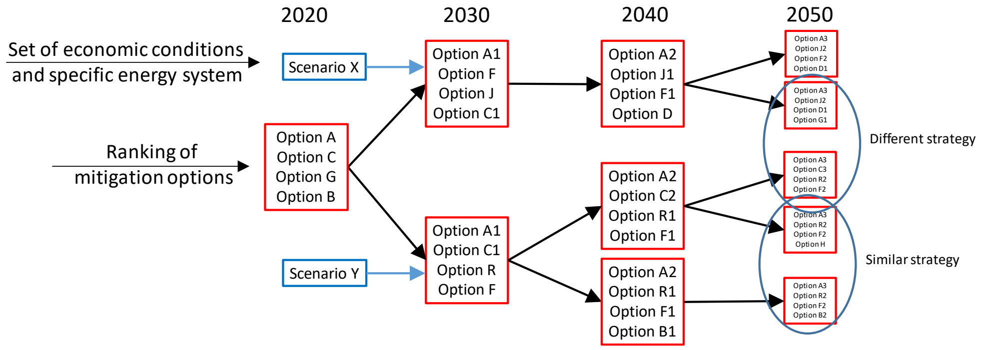

Figure 5 Illustrative representation of the effect of different macro-economic-energetic scenarios on the cost-effectiveness of mitigation options.[1]

The methodology that has been developed in the case study takes local circumstances into account and allows for a variety of scenario assumptions on the energy system. The methodology has been applied to a fictitious industrial cluster based on the one in the Dutch municipality of Emmen. When the methodology is applied to other industrial clusters, this can provide consistent insights into the mitigation potential of the industrial sector as a whole and on the conditions that need to be fulfilled to realise that potential. In addition, the methodology gives insights in the risks of choosing the wrong mitigation strategy.

[1] Option X is a specific mitigation measure. X1, X2, etc. indicate improved versions of that measure.

4 Lessons based on the case studies

This chapter provides an overview of the ESTRAC case studies and presents lessons that can be drawn from combining them.

4.1 Overview of the case studies

The three case studies all focus on the transition of industrial clusters, but use different approaches:

1. The study *Institutional innovation for regional energy transition: from laissez-faire to navigating* uses governance analysis to investigate decision making on energy and CO_2 infrastructure.
2. The study *Multi actor decision models for transformation of industrial clusters* treats the decarbonisation of industrial clusters as a multi actor decision problem.
3. The study *Decarbonisation of industrial clusters - System analysis for screening of mitigation pathways* develops a consistent, transparent methodology to assess the greenhouse gas mitigation potential and the associated costs for decarbonisation of industrial clusters.

The first study starts from the premise that decision making on infrastructure is characterised by strategic uncertainty, complex interdependencies and a polyarchic distribution of power. The study draws the overarching conclusion that the current situation can be described as a *laissez-faire* mode of governance, while there may be benefits from a more *navigating* role of regional and central governments.

The second study recognises that companies in industrial clusters benefit from cooperation and synergies but argues that some characteristics of these clusters complicate decision making. Companies make investment decisions based on individual economic trade-offs, but the costs and benefits of the individually chosen options depend on the other actors' choices as well. Game theory offers an analytical framework for analysing the options of all the different sub coalitions, and for fair allocation of costs and benefits.

The third study uses a techno-economic approach to assess mitigation pathways for industrial clusters. Instead of considering technical decarbonisation options in isolation, the approach takes into account interactions between technological options, pathway dependence and indirect emissions. It also considers the potential synergies of sharing mitigation options between different industrial actors. In this way a more integral overview of costs and benefits is obtained, which can help to avoid lock-ins.

4.2 Lessons based on the combined case studies

By combining the results of the different approaches that have been used in the case studies, lessons can be drawn that can be considered in decision processes by stakeholders in industrial clusters:

- Analyses based an actor perspective can be a valuable complement to analyses based on a system perspective.

- Decision makers must look for ways to deal with mutual dependencies, strategic uncertainty and polyarchy.
- As the problem, the context and the available (technological) options are continuously evolving, strategies need to be robust against changes as much as possible.

A first lesson that can be drawn from the case studies is that analyses from an actor perspective can complement analyses based on a system perspective. Studies on decarbonisation of the industry often use a system perspective. Because an industrial cluster consists of multiple actors (with different objectives, value creation processes and dependencies), an actor perspective is much needed as well. How to decarbonise industrial clusters should not just be viewed as a techno-economic optimization problem.

Cooperative decision science can provide optimal solutions from a different perspective. It can be applied in situations in which actors depend on each other, in which they can make agreements and in which there are actual benefits from these agreements. A game-theoretical approach can help to identify beneficial collaborations of stable coalitions and to allocate costs and benefits in ways that are considered fair. The results of such analyses can be useful to initiate discussions on principles and to define a framework in which negotiations can take place. The results do not provide definitive solutions; many uncertainties remain and what is considered fair allocation is subjective.

A second lesson is that decision makers must look for ways to deal with mutual dependencies, strategic uncertainty and polyarchy. All three case studies focus on and recognise the important role of dependencies at different levels: within clusters and between clusters and the outside world. Neither policy makers, nor private parties know exactly how targets can be best formulated and reached. This strategic uncertainty can be reduced, but not eliminated. Actors lack insights in the effects of their decisions. Information can be either not available, or not shared. The problem is also characterised by polyarchy, which means that no one single actor can impose their preferred policy upon others.

This means, in turn, that institutions, processes and strategies should take these conditions into account. Different approaches can be combined and supplement each other by looking at the same problem with different perspectives, possibly in different phases of an iterative decision-making process. Institutional innovation can help to steer the transition on the right direction. It is likely that is easier to deal with mutual dependencies, polyarchy and strategic uncertainty when the governance method is based on *navigating*.

A third lesson is that strategies need to be robust against changes as much as possible. The energy transition is a complex process that affects many aspects of society. Both the problem and the (technological) options are continuously changing. Decisions that are made now influence the decisions that can be made in the future. This makes it difficult to settle on permanent solutions.

The method to screen mitigation pathways can be helpful, because it makes it possible to consider pathway dependencies under widely varying scenario assumptions.

A game-theoretical approach can help to identify profitable collaborations within stable coalitions. Regulations and policies should create room for new best practices and innovations. This allows to make use of new technologies and options when these become available.

References

Broecks, K., Truijens, D., Brunsting, S., Hermans, L., & Kooger, R. (2020). *The adoption of decarbonization innovations by companies in Dutch industry: obstacles, problem owners and ways forward.*

Brunsting, S., Broecks, K., Truijens, D., Hermans, L., & Wetzels, W. (2020). *Decision making on regional energy transition in industrial clusters.* Amsterdam: TNO.

Carpenter, M., Bauer, T., & Erdogan, B. (2009). *Principles of management.* Boston: FlatWorld.

Ferguson, T. (2020). *A course in game theory.* WSPC.

Gedai, E., Koczy, L., & Zombori, Z. (2012). *Cluster games: A novel, game theory-based approach to better understand incentives and stability in clusters.* University Library of Munich, Germany.

Gedai, E., Koczy, L., & Zombori, Z. (2015). *Cluster games ii: About cooperation, selfishness and joint risks in clusters.* University Library of Munich, Germany.

Hall, L., & Buckley, A. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy*, 607-628.

Janipour, Z., de Nooij, R., Scholten, P., Huijbregts, M., & de Coninck, H. (2020). What are sources of carbon lock-in in energy-intensive industry? a case study into dutch chemicals production. *Energy Research & Social Science*, 60:1–9.

Koelemeijer, R., Lucassen, T., & Dervis, F. (2021). *Reflectie op Cluster Energiestrategieën (CES 1.0).* Den Haag: PBL, RVO en TNO.

LEA partners. (2018). *Limburgs Energie Akkoord: samenwerking tussen Limburgse energie-intensieve bedrijven en de overheid.*

Meerman, J. (2021). *Decarbonisation of industrial clusters - System analysis for screening of mitigation pathways (to be published).*

PBL, TNO, CBS and RIVM. (2021). *Netherlands Climate and Energy Outlook 2021 – Summary.* The Hague: PBL Netherlands Environmental Assessment Agency.

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, 33; 74-86.

Porter, M. (1990). *The competitive advantage of nations.* New York: Free Press.

Ramirez, A., Blok, K., Faaij, A., Meerman, H., Worrell, E., Kramer, G., & van der Broek, M. (2019). *System approach for a sustainable industry.*

SER. (2019). *Nationale klimaataanpak voor regionale industriële koplopers.* Den Haag.

Stelwagen, M. (2021). *Sustainable Industrial Cluster Games.* Rotterdam: Erasmus University Rotterdam.

Studiegroep Invulling klimaatopgave Green Deal. (2021). *Bestemming Parijs; Wegwijzer voor klimaatkeuzes 2030, 2050; Eindrapportage studiegroep Invulling klimaatopgave Green Deal.*

Truijens, D. (2020). *Institutionele innovatie voor de regionale energietransitie: van laveren naar navigeren.* Amsterdam: TNO.

Verstraten, P., Groote Schaarsberg, M., & Stelwagen, M. (2021). *Multi actor decision models for transformation of industrial clusters (to be published).*

Wetzels, W., van Dam, K., Geerdink, T., & Meerman, H. (2019). *Decision making on regional energy transition; Models, tools and approaches.* Amsterdam: TNO, Hanzehogeschool Groningen, Rijksuniversiteit Groningen.

Woestenburg, A., Puts, H., Diran, D., Maas, N., Buitelaar, S., Heeger, A., & van den Akker, D. (2020). *Innovatie in besluitvorming richting aardgasvrije wijken: eindpublicatie van kennisontwikkeling binnen de strategische samenwerking tussen G4/TNO/Platform3.* Den Haag: G4-steden, TNO en Platform31.