New Routes for the Energy Transition

Exploratorive research on three underexposed themes for a new research agenda

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1 Introduction

The energy transition is taking place already with the wide acknowledgement of the climate crisis and the need to move our economies away from fossil fuels. However, such systemic change is quite complex and touches upon many aspects of our lives where several disciplines intersect. Thus, in order to manage the transition successfully, we need to improve our understanding of the anticipated changes from different perspectives. This need was the initial motivation for this report, which aims to determine the research areas that need further investigation. In that regard, three new themes were identified where different disciplines need to collaborate closer to speed up the transition to a renewable energy powered society. These are: the challenge of the energy multi-carrier mix of the future integrated energy system; the spatial challenge of the energy transition; the business challenges for industrial and energy transitions.

This report was commissioned by The Dutch research council (NWO) under the Small Projects for NWA routes 2020. More precisely, the motivation of this report is driven by the recent acceleration of the energy transition and the fact that the NWA Route Energy Transition dates to 2016 (i.e. before the Klimaatakkoord, mission driven policies and the formulation of the MMIP's, etc.), which highlight the necessity for an update of some parts of the route.

Each of the three identified research themes described in this report address very topical questions that we currently face in the energy transition within the Netherlands. This is illustrated by the societal debates on the windmills in Drenthe (spatial planning), the phasing out of the natural gas from Groningen by 2030 (infrastructure), and the Dutch Groeifonds or the EU Recovery Fund (business models). They bring together the original 10 challenges of the Route Energy Transition, provide new crosscuttings through them, and thereby open new routes through the underlying NWA questions. Next to the high societal relevance, these three projects also provide for new and exciting fields of research. It combines the social sciences behind complex multi-actor decision making and legislation with the technical sciences behind the future systems for energy generation, storage, conversion, and transport.

Noting that the aim of the three research projects is not to answer questions or provide solutions, rather, it is to identify the challenges that require more investigation. That is, within these three research themes, we build an inventory of all relevant scientific and societal stakeholders, build the research framework, validate this with selected experts from relevant governmental bodies, NGO's, and industry, and finally disseminate the first findings and further research recommendations. Which means that the research agenda is stakeholder/expert driven. It is based on societal needs rather than academic needs where we start from a dialog with practice to identify the transition challenges under each theme and translate these to an academic research agenda.

Firstly, the theme of the energy multi-carrier mix of the future integrated energy system concerns the question of how to plan the infrastructure of our future energy system while it is yet unknown what the mix of energy carriers therein is going to be. For example, is it wise to maintain the natural gas infrastructure in the built environment until hydrogen or synthetic gas might become available, or should we invest in fortifying the electricity grid or the rolling out of heat networks? To gain more insights into the current and future Dutch energy system, four desk research questions are investigated. They concern which current and future energy carriers and infrastructure are possible, what scenario studies say on the possible energy systems, how the decision-making processes that are involved in this system are structured and what potential frameworks can guide the transition to a more integral energy system. The analyses show that it is likely that the future energy system will consist of a broad set of energy carriers, with the electricity grid as backbone connected to heat networks, gas networks, a hydrogen backbone and smaller heat networks. For specific energy consumption types, many alternatives are available, where for other types only a few possibilities remain. The research into the scenario studies support this by finding broad consensus for certain energy carriers, while for other consumption types, the range of possibilities remains large. However, decisions on which pathway to take haven't been taken in many cases. This can be explained by the shattered energy policy and complicated decision making. A clear roadmap indicating the larger programs and their coherence on how to tackle the energy transition towards 2050 can help to structure the decision-making for the energy system. To come towards a more detailed planning of the energy system, designing a system architecture could help to integrate the different carriers into one energy system. The holon framework is one of the examples that support the creation of such an integrated system architecture.

Secondly, the spatial challenges of the energy transition in the Dutch living environment are analysed. The chapter focuses on the following two questions: Within the context of growing scarcity of available land in the Netherlands, what are the spatial challenges current and future renewable energy technologies have, based on their (technical or legal) spatial claims? In relation to spatial policies, rules and regulations of the current renewable energy technologies, the main challenges the chapter lists are: many public authorities (at the same and different level of governance), with each their own spatial policies, rules and regulations connected to the energy transition; the need for cross-sectoral collaboration for a successful spatial planning of energy projects in the Netherlands; and the public resistance, which can substantially slow down the translation of energy plans into practice. Concerning the technical requirements of the current renewable energy installations, the main challenges are: the availability of renewable sources near energy demand; the availability (also capacity) of supporting infrastructure system to connect technologies to, the distance between supply and demand of heat related technologies; and the 'first come, first served' situation with respect to available space and the spatial demands from other sectors. Future challenges of renewable energy technologies are: reducing the spatial claim of the energy transition through innovative solutions, increasing social acceptance for future energy technologies, creating synergies with other spatial uses and transitions; and implementing the paradigm shift of the Dutch Environment and Planning Act from no, unless to yes, provided that, for the spatial integration of the energy transition in the Dutch living environment.

Thirdly, the theme of the business challenges for industrial and energy transitions is investigated. The chapter focuses on answering the following research questions with a focus on Energy Intensive Industries (EII) because that is where the transition is most challenging: What are the existing non-technical challenges for the Dutch industrial transition with a focus on EII? What are the underexplored research areas on the factors affecting (dis)investment in the industrial and energy transitions? The chapter translates the discussions, the observations, and the insights from the dialogues between relevant Dutch stakeholders into six overarching non-technical challenges. The first challenge concerns the bounding uncertainty of establishing an aspired portfolio, which raises the problem that we simply do not know what the portfolio of activities in the future will be. This creates a risk of wasting valuable resources by investing in projects that do not fit with the future portfolio. The second challenge focuses on the management of the evolution from our legacy towards our aspired portfolio. Like any evolutionary process, this pathway is unpredictable in its details. The third challenge questions the adequacy of market mechanisms to achieve an optimal outcome from the transition perspective. The fourth challenge emphasizes the need for the Dutch transition process to be put in a wider international context. The fifth challenge underlines the essential role of coordination to avoid lock-in and solve any potential bottlenecks in time to move forward. Finally, the sixth challenge spotlights the essential role of finance to boost and steer the transition process. We identify the most urgent research directions under each of these challenges.

The report contains four remaining chapters. Chapters 2 till 4 lay down the themes of the energy multi-carrier mix of the future integrated energy system, the spatial challenge for the energy transition, and the business challenge for the industrial and energy transitions, respectively. For each of the identified challenges under these overarching themes, we start with a background around the challenge followed by the state of the art and ending with an eye on the future by identifying the research areas that benefit from further investigation. Although each chapter had its own specific focus, when comparing the insights gained under these three themes, four overlapping topics could be identified namely: uncertainty, lock-in, scarcity, and coordination. The insights under these themes are gathered as a mutual conclusion in Chapter 5.

2 The challenge of the energy multi-carrier mix of the future integrated energy system

2.1 Introduction

As part of the Dutch energy transition, society is currently creating the energy system of the future. In 2050, the energy system as we know it today will not exist in its current form. Traditional institutions and actors will have either disappeared or changed their (business) model. It is not clear how this system will look like, and the need for a long-term vision is widely acknowledged, among others by the regional grid operators and the Expertteam Energiesysteem 2050, that has recently been appointed by the Dutch Minister for Climate (NVDE, 2021) (VEMW, 2021) (Klimaatcoalitie van bedrijven, 2021) (Expertteam Energiesysteem 2050, 2022).

Today the energy system is linear with wasteful flows of energy and materials. It is also most unidirectional: from the (re-)source to the user. In 2020 the European Commission has drawn a strategy for a future EU integrated energy system with bi-directional flows between users and producers (consumer/prosumer), reducing wasted resources, shown in Figure 1. In addition, the future system will be more efficient and circular, where excess energy and materials are captured and re-used (European Commission, 2020). It will have a cleaner power generation system, less central and more decentralized, utilizing solar and wind, leading to more direct electrification of end-use sectors such as industry, built environment and transport sectors. But also, it will be more dynamic and intermittency and regional variation make the need for storage and energy conversion essential. Next to clean fuels and electricity also heat, both low temperature (for the built environment) as well as high temperature (for the industry) from sustainable sources will be needed. For the hard-to-electrify sectors like heavy industry and transport (long haul, marine and aviation) there will be a need for clean synthetic CO2 neutral fuels (e.g. hydrogen, ammonia, synthetic kerosene) produced from renewable electricity and sustainable resources (such as water, air captured nitrogen and carbon dioxide) (KIVI, 2020) . Therefore, the future energy system will be transformed towards a multi-carrier energy system that can be defined as “energy systems having strong coordination in operation and planning across multiple energy vectors and/or sectors to deliver reliable, cost-effective energy services with minimal impact on the environment” (O’Malley et al., 2020).

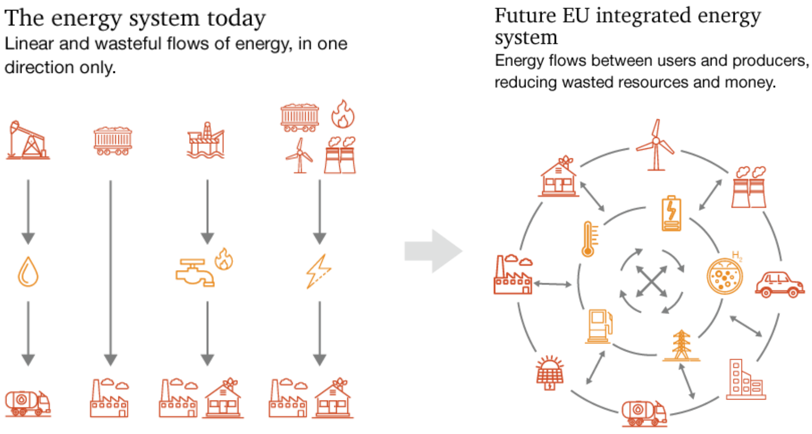

Figure 1. European Commission's EU Strategy for Energy System Integration, 2020

Before diving into further details, it is key to learn more about the multi-carrier energy system. The complete mix of energy-carriers of the future circular energy system is to a large extent unknown. Renewable electricity is evident, but what is the role of e.g., synthetic gas going to be an important energy carrier? If synthetic gas becomes economically viable and available on a large scale, it might implicate important no-regret options for heating the built environment (especially for the older houses and buildings), i.e., not switching to a heat grid or heat pump but instead use the high-quality infrastructure of the present natural gas system. Therefore, the multi-energy carrier character of the future circular energy system leads to important requirements for the system infrastructure - requirements which ultimately determine the design of the system architecture. As this topic is large, complex and could lead to major decisions on the energy system in The Netherlands, a research agenda is required to investigate the future system in more detail. To shape this research agenda, this chapter first discusses the different options for a clear multi-carrier energy system; When are the different energy carriers expected to become available and on which scale? Moreover, it also focuses on the processes and procedures that should guide the implementation of a system architecture for the future integrated energy system.

In order to enable the characteristics of a multi-carrier energy system, drastic changes are required, and sooner than we expected. The rapid growth of solar and wind power on the supply side and the fast electrification on the demand side are causing large capacity problems for the electricity grid, significantly delaying the energy transition[1], economic growth and social stability. Reinforcing the electricity grid requires large societal investments and material use, while renewable electricity production will not be sufficient in wintertime to cover the national energy demand. Electricity as energy carrier is therefore not the holy grail for a sustainable energy system, but we could look at an integrated multi-carrier energy system that is flexible to cope with disbalances between demand and intermittent, unpredictable supply.

Next to that, the war in Ukraine has taught us (again) that the energy system heavily relies on the international (fossil) energy market and geopolitical developments. This results in swift policy changes such as the phase out of Russian gas and the REPowerEU plan. However, the question arises how dependent we want and must be on other (EU) countries or on local energy production that requires energy flexibility (Faaij and Van der Linde, 2022).

This chapter will further elaborate the dilemmas and complexity of the energy system. In order to draft the research agenda, four questions are investigated that lead to new research questions:

1. What are the different **current and potential future energy carriers** and what **underlying infrastructure** do we need for that?
2. What are the **decision-making processes and relevant actors** regarding the deployment of the future energy infrastructure (e.g., policy makers and grid operators)?
3. What future **energy system scenarios** are described and what connects them? Is it possible to identify no-regret options?
4. How could the **decision-making process** regarding our **future energy infrastructure** should look like?

[1] https://energeia.nl/energeia-artikel/40102918/weinig-voortgang-res-en-door-netcongestie-en-gemeenteraadsverkiezingen

2.2 Methodology

As the goal of the research is to come to a new research agenda, the four questions are reviewed exploratively and without direct conclusions, mainly to discover knowledge gaps and points of attention. Per question a review is done by providing schematic overviews of the current situation and projected futures, based on scientific, applied or advisory reports, public meetings, news articles and policy documents. For every question, a different type of overview is found appropriate.

For the first question on the **different current and future energy carriers and their underlying infrastructure**, the energy system is categorized by different types of energy consumption in The Netherland per sector (built environment, mobility, industry and agriculture). Per energy consumption a start is made by looking into the current energy carriers in the Netherlands, based on national energy reports, e.g., for the heating of homes natural gas is the most common energy carrier, followed by electricity for electric heating and water for geothermal energy. Energy outlooks, both general and sector specific, are used to provide an understanding of the prospected energy carriers. Next to the energy carriers, the possibilities for the required underlying infrastructure are added.

To investigate the second question on the **decision-making processes and relevant actors** the aim was to create an overview of the most actual, national programs that support the energy transition. In first instance, the search started with looking into a national action plan or roadmap published by the national government that should explain the different steps, processes and instruments that are used to guide the country through the energy transition. Very recently, the Dutch approach for the future energy system has been published containing the different programs and plans that should lead to the transformation of the energy system (RVO, 2022). However, as the transition approach is not yet systematic and more complex than one program, the different goals, agendas, regulations and instruments are investigated separately. A start is made with more general, national policies such as the National Climate Agreement, while continuing with the policies that are referred to in these documents. In order to create an overview, the different policies are placed on two axes. The energy sector is placed central on the horizontal axis with on the left side the other sectors and on the right side the different energy carriers. Vertically, the projects are divided between a general project (sector and carrier transcendental), a national, regional or local project. Only projects that are consistent for the entire country are included in the regional and local scale, thus all regional and local initiatives are excluded, for means of simplicity. A further classification can be made between the different types of projects indicated with colors, e.g., an agreement, a vision document, a strategy, a plan or agenda, and projects that are more focused on the implementation, for example, regulations, programs, subsidies, or other financing. However, the terminologies do not have a clear definition and their use is not consistent, resulting in scattered information and therefore it is not clear where to find what. The blocks that do not have a color yet are projects that were difficult to classify.

Besides the organizational processes and plans, **scenario studies and projections on the energy system** itself are analyzed in order to know where the policies are aiming for. First, an inventory is made which studies will be included in the study. Criteria for the selection were that the studies are not older than around 5 years as a lot have changed since the Paris agreement (2015) and the National Climate agreement (2019). Secondly, the studies should be focused on national scale in order to reflect on national policies and should include multiple energy carriers and multiple sectors in order to analyze the entire energy system without diving into too many details. With these criteria, the following studies are selected:

- NetbeheerNederland (2021) *Het Energiesysteem van de Toekomst – Integrale Infrastructuurverkenning 2030-2050* with scenarios constructed by Kalavasta & Berenschot (2020), referred to as **II3050 scenarios**.
- Kalavasta & Urgenda (2020) *Een CO2 neutraal energiesysteem met en zonder biomassa* which assumes the same scenarios as II3050 but without biomass, referred to as **Urgenda scenarios**.
- TNO (2020) *Scenario's voor een klimaatneutraal energiesysteem*, referred to as **TNO scenarios**.
- KIVI (2020) The Design of a Dutch carbon-free Energy System, which actually only describes one pathway but in large detail and referred to as **KIVI scenario**.
- TKI Energie & Industrie (2021) *Routekaart Elektrificatie in de Industrie*, referred to as **TKI Industry scenario**. Although this report does not really describe a scenario but only focuses on the electrification of the industry, it does cover a large part of the Dutch energy system and provides some detailed calculations. Therefore, it is also evaluated for some of the parameters.

A comparison between the studies is made structured by the same energy consumption types used for the first question. The use of the sector definitions mobility, built environment, industry and agriculture are common and therefore reflected in all studies, however, the level of detail differs. When analyzing the scenarios, it appears that for some energy parameters it is difficult to make comparisons as in some cases the metrics differ, or the assessed parameter includes or excludes certain energy uses, but where possible, their findings are placed next to each other.

The last question is in essence a summary of the earlier questions; can we make certain recommendations? To be more precise, it is targeted more towards the **decision-making on energy infrastructure**. First, a small overview is given of the current topology of the major energy infrastructure networks, after which literature is used to find new theories and models to deal with a multi-carrier energy system.

2.3 Energy system overviews

In this section, an overview of the energy system and its transition is given by investigating the four research questions one by one. Each question starts with a small introduction, followed by the current status and concludes with the newly identified research questions, directions and knowledge gaps (Köhler et al., 2019).

2.3.1 Current and potential future energy carriers and the required infrastructure

For different energy consumption types, various energy carriers can fulfill the requirements. The conventional energy system consists only of several energy carriers. Over time, the most appropriate energy carrier(s) for a certain consumption type becomes the standard. In The Netherlands the system mainly consists of natural gas, oil and electricity, that is mostly produced from natural gas or coal.

With the transition to renewable energy sources, alternatives to fossil fuel-based energy carriers for the different energy consumption types are being sought. For example, many sectors are trying to electrify their demand, enabling them to make direct use of renewable energy sources like solar or wind energy.

However, electrification brings its challenges; some sectors are difficult to electrify, and increased electricity use also requires larger electricity transport capacity and large upfront investments. For some sectors the alternatives are clear, for other sectors new energy carriers are researched and developed. Different factors can determine if a new carrier or a combination of carriers will become the new standard such as policy, financial aspects, market developments, location, societal acceptance, the required infrastructure and environmental side-effects.

2.3.1.1 *Current status*

The past several years, many developments to transform our energy system to a more sustainable system have taken place. Some originated from bottom-up initiatives, for example the recent investment of Shell into a large-scale electrolyzer, others have been initiated by the government, for example the decision on the hydrogen backbone and subsidies for electric vehicles. After a first phase of separate initiatives, some structures in and aligning of initiatives is taking place, for example with the new plan for the Energysystem 2050 (RVO, 2022). However, in many cases, there is no new standard yet and the search for appropriate solutions is ongoing. To get an overview of the different current and potential energy carriers per type of consumption and the infrastructure they would require, tables are made listing the energy consumption and matching energy carriers. The energy consumption is categorized sectorally by the mobility, built environment, agriculture and industry sector. A distinction is made between the current energy carriers and the potential energy carriers. Next to that, as we are directing towards a more interconnected energy system, the energy output of an energy consumption type and its required infrastructure is also included in the analysis.

What we can learn from doing this analysis is that for some consumption types, only a few carriers remain as possible future options, while for others, there are still plenty of possibilities for alternative energy carriers. For example, looking at aviation, most reports indicate that synthetic fuels are the most feasible option towards green aviation (IRENA, 2019).

For other consumption types, new fuel types like metal fuels or Liquid Organic Hydrogen Carrier (LOHCs) such as hydrozine are mentioned. Both are developed to ease the transportation of hydrogen, either in solid or liquid state. However, with every conversion of hydrogen, losses are associated. Moreover, many of these carriers are still in the development stage and it remains unknown how large their role will be.

For each energy carrier different types of infrastructure are required. Some of these types require an interconnection between different carriers. To visualize these interconnections and the different infrastructure characteristics, a visual overview is made for each energy carrier and its interconnections.

Based on the number of interconnections and the sustainable potential, it is recognized that the electricity infrastructure layer forms the basis of our energy system, which is currently built up by a high voltage network to transport electricity over long distances, medium voltage network to connect different regions with each other and for some industrial sites, and a low voltage network in the capillaries of the network for final use and consumption. Electricity can conveniently be used to generate heat (e.g., with a heat pump or electric heating) or hydrogen by means of electrolysis, and therefore, its network should have many interconnections with other networks. Moreover, as electricity is difficult to store long term, other carriers are sought to store electricity in for flexibility purposes, resulting in more interconnections with other energy carriers and their infrastructure.

The same counts for the natural gas network: at some spots it is currently connected to the electricity or heat network to produce electricity or heat. However, due to the phasing out of the natural gas use, the current gas network, which is still of high quality, is planned to be reused for other gaseous energy carriers (HyWay27, 2021). The first plan is to realize a hydrogen backbone in around 2030 that should connect the larger industrial clusters and storage facilities. This plan mainly involves larger capacity tubes and not the local capillaries of the gas network. It remains the question if hydrogen will be used on large scale in the built environment and smaller industrial sites, and therefore, the destination of the current capillaries network remains uncertain. Another option could be to transport green gas, if available (e.g., biogas) or synthetic gas in parts of the natural gas network, for example on or between industrial and agricultural sites.

Regarding heat (and cold) networks, there is a wide agreement that these networks will only exist locally due to the large transport losses. These networks will often be connected to other energy carriers that can function as heat source. Besides the coupling between carriers, the coupling between sectors is very relevant here. Waste heat of one sector could be coupled to heat networks, e.g., waste heat from industry or from electrolysis for hydrogen production. Important boundary condition is the spatial planning and locations of these assets if they want to strengthen each other.

2.3.1.2 Research directions

To conclude, the (technical) challenges are not found in the reconversion of the old gas network or fortification of the electricity network. There is a lot of knowledge available on how to make more efficient infrastructure, as well subsurface as above surface. Most questions arise where to use which carrier and where to convert one carrier into each other. Where will the important intersections – nodes – between the carriers be situated? In order to add flexibility to our new energy system, these nodes are of great importance and should be researched more intensively. Second, for some energy consumption types it would help to decide in which energy carriers should be used. This will stimulate investments and speed up the energy transition. Simulation models can help to support decisions on which carriers are interesting to be used for each energy consumption type.

2.3.2 Decision-making processes and relevant actors

To analyze the decision-making processes around the energy transition and its required infrastructure, the challenge lies in finding coherence between the different initiatives that arose the past decades. As the urgency to act against climate change has been slowly increasing and gained more momentum the recent years, there is no clear point in time when decision-making on this topic started and there is not one clear responsible organization or acting party. Over time, various initiatives have been started, both bottom-up and top-down, resulting in many advisory reports and programs to support local and national initiatives.

During the analysis it was hard to find an overarching program or structure between the projects to bring coherence into all separate initiatives. This is in line with the urgent call of the last year for more steering from the government especially on the topic of energy infrastructure (NVDE, 2021) (VEMW, 2021) (Klimaatcoalitie van bedrijven, 2021).

2.3.2.1 Current status

Looking to the outlines of the policies, the Climate Agreement execution, the RES-program and the current PIDI-process seem to be projects with a large, national impact and a clear structure. The execution of the Climate agreement is done by the Uitvoeringsoverleggen and the Voortgangsoverleg. The NPRES is coordinating the RES programs, with plenty of participation projects and a clear timeline. The 'Nationaal Programma Infrastructuur Duurzame Industrie' (PIDI) tries to translate the CES and the RES into the MIEK, however there are close relations to the PEH and Programma Energiesysteem (PES), but what the exact relations are, is still unclear. In the latest communications the PES seems to have an overarching role by creating the National Plan Energiesysteem including a long-term planning where other plans and programs will be part of (RVO, 2022). In the contrary, the RES and the PIDI both only have detailed timelines until 2025 but not beyond. Furthermore, as there are many projects divided into certain sectors or a carrier, the use of an integral approach is not stimulated.

To answer the question who the relevant stakeholders are, we could look at the owners of each project. As mentioned before, there is not one or multiple organizations that are in the lead. Multiple ministries, taskforces and working groups are involved, with the Ministry for Economic affairs and Climate as most important. Multiple actors like grid operators, energy suppliers, regional and local governments are waiting for national decisions and each other on energy generation and distribution before acting.

With the RES program, a large part of the responsibility was shifted towards regional governments and municipalities, as the idea is that the energy transition often requires local solutions. However, it appears that these projects are delayed due to their dependence on nationally coordinated infrastructure and international circumstances (Energeia, 2022). With these large and complex societal transitions, it cannot be expected that the transition is as simple as making a plan and executing it as planned. However, comparisons[2] are being made with the (rather successful) Deltaplan and Ruimte voor de rivier (Room for the river) that should assure the protection of the country against water. These plans were made by a committee of experts from industry, science, residents and government and did include a timeline, locations and expected costs, see figure 2. Although for some elements the initial plans were changed, it helped to have a long-term approach where the approach was to learn from easier, smaller project before executing larger, more complicated projects. This shows that the roadmap does not have to include every detail of the energy transition, but it should at least indicate when plans are made for what and when they will be executed by who.

[2] "Het Deltaplan had een duidelijk totaalontwerp, inclusief alle projecten, hun onderlinge samenhang en een tijdslijn. Het is te vergelijken met een legpuzzel waarvan alle stukjes aanwezig zijn, met een helder plaatje op de voorkant van de doos, in elkaar gezet door kundige puzzelaars. Het huidige energiebeleid daarentegen is te vergelijken met een legpuzzel waarvan de doos met het plaatje kwijt is en ongeveer de helft van alle stukjes. We weten alleen niet welke helft en we missen een kundige puzzelaar." - Ernst de Bruijn, Hans van Doesburg, Jaap Hoogcarspel and Theo Spek (Trouw, 2021).

Figure 2. The national plan for the Deltawerken

2.3.2.2 Research directions

It could help to make one clear, national roadmap for the coming 30 years just like many companies and local governments have made for their energy transition. This should include the coherency between existing and potential new projects, the responsible parties and a timeline. The national climate agreement sets the dot on the horizon in terms of the targets we want to achieve with the energy transition, however it does not elaborate what the vision is for the energy system and how this vision can become reality. Research into the energy system as an integral and multi-carrier energy system can support the creation of such a vision. Next, there is little understanding of the main process how to reach such a vision and who is in the lead. Investigating the following questions can help to steer the energy transition: Can we create a more integral approach and roadmap for the energy system in the Netherland? How can we design a system architecture that connects the physical energy assets and policy and societal developments? And who should take which responsibilities, how do we decide this? What governance structures and processes are required to create a more integral energy system? More coordination and involvement of the government is required and has recently been acknowledged (Ministry of Economics and Climate, 2022).

2.3.3 Scenario studies

To get a better grip on the future, scenario studies are a helpful tool to gain more insights into and prepare for possible futures of the Dutch energy system (WRR, 2022). There are different energy system studies that describe one or more scenarios for the situation in The Netherlands. It should be kept in mind that scenario studies describe possible future pathways, while reality will often lie in the middle of extreme projections.

2.3.3.1 Current status

To see where scenarios overlap and where consensus is reached or where projections vary, an overview is shown in Appendix 1. In some way, consensus between scenarios could be seen as a no-regret option as we currently do not foresee any other, more feasible option given the information we have at hand. Some comparisons are highlighted in this section.

The first comparison regards passenger mobility since there is a large consensus that at least 50% will be electric mobility, though it is expected that this number will end up higher as electric mobility has the least energy losses in the drivetrain compared to e.g., biofuel or hydrogen vehicles. Reasons not to electrify our entire passenger fleet is to lower the load on the electricity grid and the scarcity of materials and end-of-life of batteries, though in many cases they outweigh the disadvantages of the alternatives. Moreover, smart charging and temporarily energy storage in the batteries are becoming realistic solutions to solve their (self-caused) grid capacity shortage, however, this should then also be translated to complementary guidelines for grid operators. Next to electric cars, hydrogen cars are a feasible alternative. However, as long as a large hydrogen network is not in place, hydrogen cars will not take off and electric mobility will become more standard, perhaps even locked in in society. Hydrogen infrastructure will be set in place the coming decade, but the industry and heavier transportation will most probably precede as it is more difficult to electrify their energy demands.

Hydrogen fuel cells or combustion will therefore play a larger role in the freight transport sector, especially for longer distances and heavier transport. For short distances, electric trucks can still provide large part of the mobility demand. Green gas can also provide a small part of the mobility demand, but this is not most desirable due to conflicting claims on the biomass and land use (Netbeheer Nederland, 2021).

Concerning inland shipping, II3050 is very determined that bio-LNG will be the most feasible option, whereas KIVI and Urgenda propose hydrogen-based solutions. Recently, many efforts are taking place on development of green shipping, however, we cannot expect large changes soon. Note that for inland shipping only a limited energy infrastructure is required with only a few concentrated charging or fueling points. Therefore, when considering the infrastructure challenges, inland shipping will not be the most complex challenge.

Similar reasoning counts for international shipping and aviation. Based on the physical properties of synthetic fuels (e.g. ammonia, synthetic kerosine, etc.), they seem to be most feasible for international shipping and aviation. Experiments are also done on aviation on hydrogen.

It is very likely that the fuels for aviation and international shipping departing from the Netherlands, and other sectors with a high capacity energy demand, will probably be imported due to lower costs for renewable energy generation in other countries with more wind or solar, and therefore lower synthetic fuel production costs.

When looking into the built environment, there is little consensus on how to provide heating. There are multiple options that all require intensive use of our current infrastructure or the construction on new infrastructure. It is very likely that every street in the very densely populated country will have to be opened in one way or another. What we could conclude from the reports is that around 25-55% of the heating will be provided with an all-electric or hybrid heat pump. Both technologies enable to make a smart use of the electricity grid by smart control of the heat pumps using thermal mass or storage tanks as buffer technology. In addition, around 40% of the built environment will be heated using a district heating network, see Appendix 1. Many heat networks require the use of a large heat pump, that will require a large amount of electricity. However, the benefit in this case is that this large amount of electricity is only required at one location, preventing the enforcement of the entire electricity grid of the neighborhood. Furthermore, the electricity load is to some extent controllable as the case with smaller heat pumps. The source for district heating networks determines how sustainable the heating is, however, there is not one preferred source, and the available sources are often location bound. Note that some (industrial) heat sources will not exist anymore in 2050 due to their reduction of heat losses. However, with the increasing interest in hydrogen a large new heat source can arise – alkaline electrolysers convert around 40 to 50% of their input electricity into heat.

The role of biomass remains heavily debated. Though calculations tell that biomass will not be necessary in 2050, it is still an easy to use and clean energy source to be used in the meanwhile. However, due to land use constraints and relative low energy yields, biomass use is only recommended from waste streams and for applications with little to no alternatives until 2050.

Other energy use in the built environment is caused by cooking and running of appliances such as lighting and electronic equipment. Not much is said about these demands by the reports. It is estimated that the demand will remain equal, being around 50 TWh. Only for cooking, different energy carrier alternatives exist, e.g., electricity, green gas or hydrogen. However, as the electricity network is already in place, it is very likely that all cooking will be on electricity.

When considering the output of the built environment, the estimates for 2050 can be compared to the current installed capacity in order to assess what scenario is realistic. At the end of 2020, 10.2 GWp of solar panels was installed. Estimates of 13 or 17 GW are therefore on the low side and 30 to 40 GW peak seem feasible.

Next, for the Dutch industry, most studies considered low and high temperature heat demand together, although different sources can be interesting for different temperature requirements. Based on the TKI Industry scenario, 80 TWh electricity will be the electricity demand that can replace many fossil energy carriers. This includes the electricity that is required to produce hydrogen, that will play a large role in the industry. In some scenarios biomass-based carriers are used, however this will not be required on a large scale. How much more energy we will need beyond the 80 TWh, is unclear yet. This heavily depends on the question if the energy intensive industry will remain in The Netherlands or not. Especially for this energy intensive industry, fossil fuel source in combination with CCS can remain a transition solution until 2050, while waiting for lower hydrogen prices.

A separate industry sector that is worth mentioning are the data centers. They will require around 11-15 TWh of electricity. Notable is that currently, 6,3 PJ (1,75 TWh) of usable heat output is generated (Berenschot, 2018), and this number will further grow. Strategically localizing the data centers will be a complex, but worthy challenge.

Not much attention is given in the studies to the energy demand of the agriculture sector, except of its thermal energy demand. It is likely that electrification will play a large role as there the heat demand is mostly of low temperatures that can be fulfilled by heat pumps. Geothermal heat could potentially also play a role as there is more space available, however its costs should decrease on forehand. In contrast to the other sectors, a larger role for biomass (10-43%) is also prognosed, probably due to the possibility of direct biomass use. And due to the available space at agricultural sites, there is room for solar panels and wind turbines, however often only small connections to the electricity grid were installed. Therefore, multiple initiatives are experimenting with local, small scale hydrogen production on agricultural sites (Farm of the Future, 2020).

Overarching the demand of the different sectors, most studies also provide more details on the national energy supply. Solar panels and wind turbines are likely to provide a large part of required energy. For offshore wind, the estimates lie between 35 and 95 GW installed capacity. Currently, the schedules installed capacity for 2030 is 11 GW offshore. Therefore, more than 60 GW in 2050 seems unrealistic. Considering onshore wind energy, the reports estimate between 6 to 20 GW installed capacity. Comparing to the current installed onshore capacity of 4,2 GW, 10 GW is realistic. Though, lately there is more and more debate on the placement of onshore wind turbines and, therefore, we should be careful with high estimates.

To fulfill the hydrogen demand, hydrogen can be produced locally or can be imported. Therefore, the required capacity varies between 3 and 45 GW, depending on the chosen strategy. As the industry already requires at least around 40 GW, a high installed capacity will not be unimaginable, especially as The Netherlands already has a large hydrogen production capacity and expertise in place for the chemical industry. To store hydrogen for longer terms, there is 15GW storage capacity in the current salt caverns (Gessel S. v., Dalman, Juez-Larré, & Huijskes, 2021), which is not enough when all reports assume at least a required capacity of 16 GW.

To store electricity, electrical batteries are included in the scenarios. As is the case with hydrogen, its storage capacity depends a lot on the chosen strategy, from 18 to 55 TWh. If the strategy puts a larger emphasis on electricity, larger batteries are required. In most cases it is not specified if these will be large, central batteries or smaller, decentral batteries. It is mentioned that old batteries from electric vehicles can be recycled to be used as buffer capacity.

Besides storage and buffering, peak power plant will also be a part of the energy system. These are assumed to run on gas, green gas or hydrogen. Capacities ranging from 15 to 33 GW are required.

In case of higher renewable energy production than the demand plus the storage capacities, curtailment seems inevitable. Depending on the installed capacity of renewable electricity production, simulations show 1 to 7 TWh curtailment per year.

2.3.3.2 Research directions

The available scenario studies are a found basis for the sketch of the energy system of the future. The presented analyses give a detailed overview of the gross of the energy consumption and supply. However, some missing links have been identified.

First, the analyses are done segmented per sector, while it can be interesting to look cross-sectoral and search for interconnections between sectors. For example, the waste streams from industry, often in the form of heat or cold, can be connected to the energy demand of the built environment. Or the mobility sector, which is expected to have a large electricity demand, but also a large storage potential for grid balancing.

Besides this cross-sectoral link, it was found surprising that the analysis for the agricultural sector was less detailed. A reason behind this could be that the energy demand of the agricultural sector is lower than the other sectors, however the agricultural sector provides interesting opportunities (Wageningen University and Research, 2022). Agricultural sites offer for large scale renewable energy production, where space is a scarce good in The Netherlands, and there are multiple possibilities for the use of their biomass waste streams. However, the business models, the matching of supply and demand & the infrastructures are not designed for this yet.

One of the research directions could be to review the case of a small-scale hydrogen electrolyser to produce and use hydrogen onsite or to distribute it to neighboring demand.

Another observation concerns the flexibility and buffer analysis. All studies recognize the important need to add buffer and flexibility assets to the energy system in order to be able to match supply and demand. The amount of energy production based on intermittent sources in the different scenarios influence how much of these flexible assets will be needed. However, in most cases no further details are provided about these flexibility assets for example, which storage technologies, the locations, the sectors, the capacity sizes, storage durations, while it is recognized as an essential part of the future energy system. More research can take place in detailing flexibility scenarios and creating models on the impact of widespread storage and flexibility involvement in the energy system. Questions like where do we want to store renewable energy and with which capacity? For how long do we want to storage energy in which sector?

In general, the different scenarios are projecting the different possibilities and outcomes of our choices for the future energy system. As explained the scenarios show overlap and reach consensus at certain levels. This can allow policy makers and investors to take decisions for the long term. Further elaboration of the scenarios and comparison of the models can be facilitated in cooperation with the decision makers to enable rapid and transparent process.

2.3.4 Recommended decision-making process regarding our future energy infrastructure

In order to accelerate the energy transition, create a future-proof energy system and stimulate decision-making on energy infrastructure, we investigate how we can improve the decision-making process. Some recommendations and research suggestions have already been made on the process of the energy transition in general, where in this section the focus will lie on the physical energy infrastructure and its assets

2.3.4.1 Current status

In The Netherlands, the energy infrastructure topology has been developed over the century. The governance differs per energy carrier.

In case of the electricity network, TenneT operated the national, high voltage connections. With the advent of large renewable energy parks, TenneT is also appointed as responsible for the connection of these sources to the grid, e.g., wind farms in the North Sea. For the medium and low voltage network, different regional operators oversee the network. They are also responsible for the local connections to smaller renewable energy generation and additional connections for, for example, larger heat pumps and electric vehicles.

A similar structure holds for the natural gas network. The national, high-volume network is operated by GasUnie, while the same regional operators as the electricity network are responsible for the local natural gas networks. These operators are also responsible for the removal of disregarded gas connections, however, for re-destination of the pipelines, it is yet unknown who will be in charge.

Heat networks are often only found on local scale and have therefore only local operators. A difference with the gas and electricity networks is that the operation of the heat network and the generation and delivery of the heat source fall under the same organization.

These structure as mentioned are mostly organized in silos. With this traditional topology can challenging to innovate and redesign our energy system. The desired integral approach requires an adequate form of governance (Topsector Energie, 2020). One recent development, which we want to mention here is the concept of holarchy, where holons represent a semi-autonomous entity that acknowledges being coordinated by a larger system while also being connected with other holons. When possible, a holon manages his energy system completely independently, however, when needed it collaborates with neighboring or higher holons. This concept aims to optimally use the locally generated energy and flexibility by using local strengths and sector coupling.

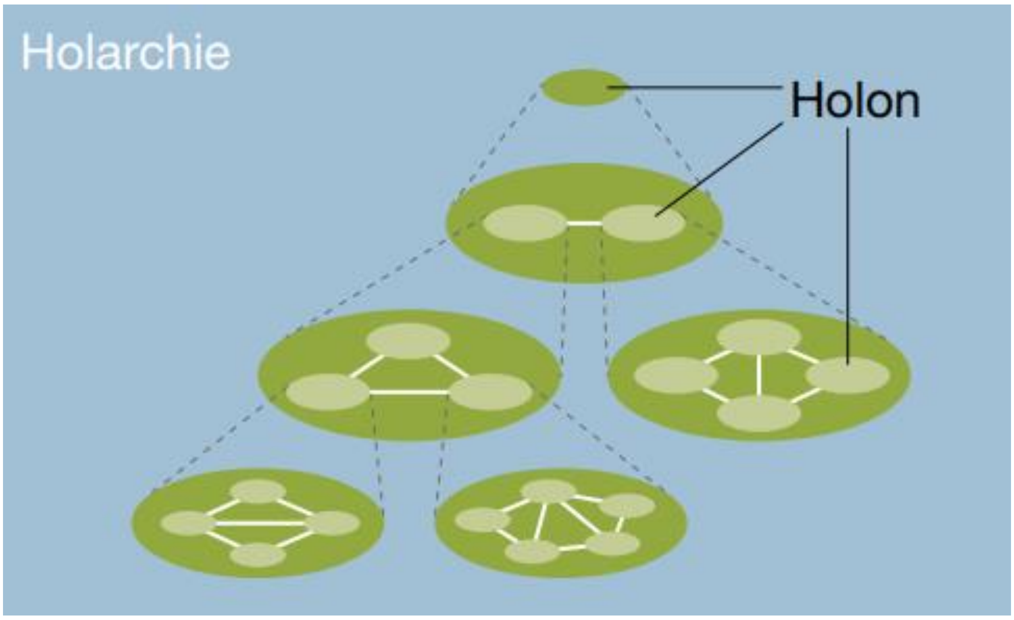

Figure 3. Schematic of the holarchy concept. Source: Topsector Energie, 2020

2.3.4.2 Research directions

The holon-concept is rather new and has not been applied on large scale yet. Therefore, it is still the question if it can truly allow for an optimal coordination of our (local) energy system. To investigate the holarchy in more detail, we distinguish two different research directions: one focusing on more spatial aspects and one on more temporal aspects. Research questions that are linked to spatial aspects can be as follows:

- How do we define the boundaries and different levels of holons?
- What are the connections with other holons?
- On what level do we want to strive for self-sufficiency?
- Where will we place energy storage solutions?
- Who is coordinating a holon and its assets?
- What energy consumption do we currently have within the holon and what do we expect for the future?

Regarding the temporal aspects, we can think of research questions like:

- How much seasonal storage and how much short daily storage do we need within a holon?
- Where do we need seasonal storage and where do we need shorter term storage?
- When will holons depend on each other and when can they operate autonomously?
- How do to the day-to-day optimized operations of the future multi-energy system from the scale of a week down to real time?

2.4 Conclusion

The energy transition has become a complex process with many stakeholders and uncertainty about our future energy system. As explained in this chapter there is no clear scenario path or roadmap that guides us through the energy transition. It seems that the complexity is currently too large to fit this challenge into an organized transition. One of the biggest reasons for this seems the uncertainty which companies, policy makers and individuals have to deal with. A way should be found to deal with uncertainty without hopping from one problem into another. A more detailed vision for the future energy system with a system architecture and possible pathways can help with that.

However, the creation of such a system architecture will include many stakeholders and more extensive research. Many questions must be asked on different spatial and temporal levels. In this chapter, a first effort is made to structure the questions. In general, it should be possible to ask those questions on different spatial levels, locations and on different timeframes or moments in time. When using the multi-carrier energy system as a starting point, the focus should lie on the interconnection between the different energy carriers. Therefore, new research questions are often not directed towards one type of energy carrier but to the energy system.

The research directions proposed in this chapter are pointing towards investigating the design of a system architecture for the long-term energy system using the holon concept, a roadmap to reach that energy system with clear coordination and further investigation on the existing scenario studies to stimulate faster decision-making.

3 The spatial challenges of the Dutch energy transition.

3.1 Introduction

Due to increasing greenhouse gases to the atmosphere, the global average temperature is rising and the climate is changing. In order to limit the adverse effects of climate change, 195 countries, including the Netherlands, signed the Paris Agreement in 2015 (United Nations, 2015). It aims to limit the global average temperature rise by 2050 to well under 2 degrees Celsius. In order to reach this goal, a swift transition from a fossil-based energy system towards a clean, low-carbon energy system is required. In addition, Russia's recent invasion of Ukraine has been a wake-up call concerning our dependence on fossil fuels and increased the EU political will to make Europe independent from Russian fossil fuels well before 2030. Next to diversifying the EU gas supplies, the European REPowerEU plan (European Comission, 2022) aims to speed up the roll-out of renewable gases and replace gas in heating and power generation. Specifically in the Netherlands, the phase out of natural gas extraction in Groningen by 2023, motivated in part by the negative societal impacts in the North of the Netherlands, has been an earlier driver to move away from natural gas use in the built environment and in industry (Rijksoverheid, 2022a). The Dutch Climate Agreement, presented in June of 2019, lays the foundations and measures to realize the necessary energy transition in the Netherlands in all sectors (Rijksoverheid, 2019).

So far the Dutch society, which is still largely dependent on fossil fuels, is not used to an energy system that is visible in our daily living environment. Although, the fossil energy production takes place in large scale power plants, its spatial claim has become spatially efficient over the decades. It is located in only a few locations and its infrastructure is located below ground out of sight, except for the high voltage cables which are the most visible elements of the fossil-based energy system. In contrast, the renewable energy system claims more land to produce the same amount of energy as fossil fuel installation and will be more visible (Kuijers, et al., 2018).

Prior to formulating the paper's research questions, goal, scope and structure, the main spatial differences between a fossil and a renewable energy system are listed and the different spatial claims of energy technologies, which will be used in this paper, are defined.

3.1.1 The energy transition in the Dutch living environment

One of the biggest differences between fossil (coal, oil, natural gas) and renewable energy sources is their spatial power density, or the amount of power they produce per square meter. For example, wind turbines and solar panels have a much lower power density than coal - therefore they require more land area to yield the same amount of power. Additionally, in order to avoid congestion on the existing network, renewable energy sources are more spatially distributed, and together with the supporting infrastructure, renewable energy system will therefore increasingly claim space at new locations. Finally, using renewable energy sources will demand intermediaries between energy systems, for instance electrolysers to convert electricity into hydrogen fuel. In contrast to a fossil-based energy system, the renewable energy system will thus become much more visible in the daily living environment. The energy transition is therefore a spatial transition of our daily living environment, as well as technical transition.

Next to the energy transition, other large and complex challenges such as climate adaptation, circular economy, accessibility and increased housing require space in the Netherlands. At the same time, the availability of land is finite in the Dutch densely populated country and therefore space is a valuable and scarce resource (Ministerie van BZK, 2020). Due to the competing spatial claims of the listed complex challenges, the spatial challenges of the energy transition are becoming increasingly part of the Dutch public debate.

3.1.2 *Spatial claims of energy technologies*

The spatial challenges of the energy transition are related to the spatial claims of the new energy technologies. Therefore, before proceeding to examine the spatial challenges of the energy transition, it is important to first define these spatial claims. These claims can be direct or indirect.

The **direct spatial claim** of an energy technology is defined by the area required for the installation and its enclosure. For example, for a solar park, the direct space is dictated by the solar panels and the required electrical works.

The **indirect spatial claim** is defined by the space around the installation, which forms a constraint for other spatial uses. In this study, this definition is further subdivided by the distinction between the legal and technical indirect spatial claim. The **legal indirect spatial claim** concerns the space determined by rules and regulations with respect to other uses, often with the aim of securing safety or avoiding hinder to people. In the example of a wind turbine, the legal indirect spatial claim is determined by safety zones between the turbine and vulnerable objects (housing, buildings, infrastructure), as well as noise, reflection and shadow cast of the turbine. **The technical indirect spatial claim** is the claim that is needed for the installation to function efficiently, resulting from the technical properties of the installation. For an aquifer thermal energy storage , this would be the space required between multiple aquifers, to ensure the hot and cold sources don't interfere, which causes a reduction in efficiency. The different types of spatial claim and corresponding examples are visualized in Figure 4.

Table 1 displays the definitions of the different types of spatial claim used in this study, which are based on the report accompanying the 'Ruimte voor Energie' tool, developed by the three offices for spatial research (Generation.Energy, Bright, Groen Licht, 2021), as well as documentation used for the development of Regional Energy Strategies (APPM, CE Delft, Decisio, Generation.Energy, Tauw, 2019)

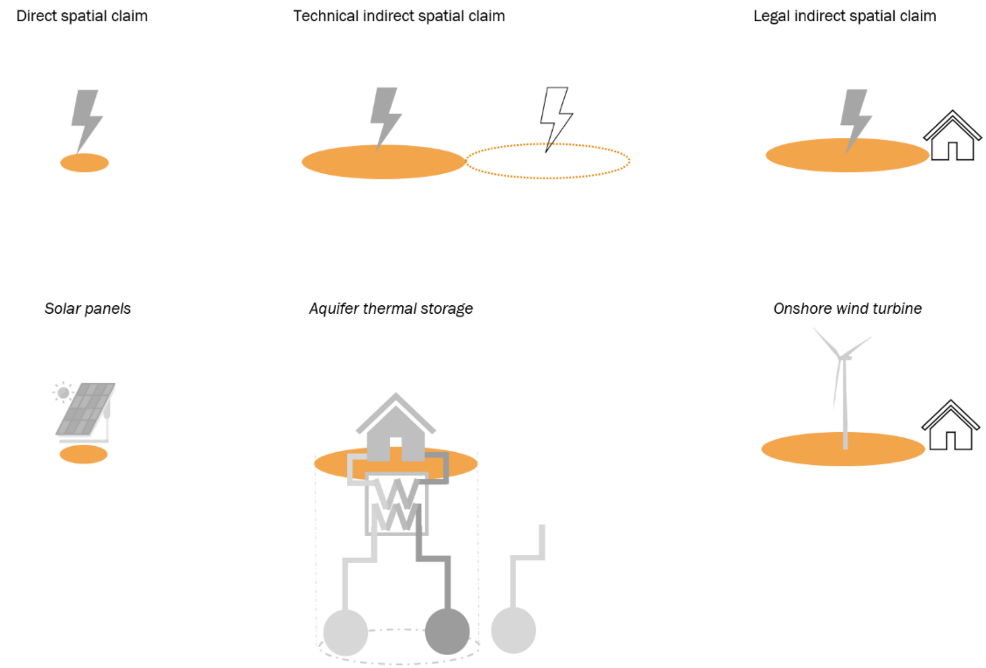

Figure 4. Top row: Illustration of different types spatial claims (in orange) of a generic energy technology (illustrated by the lightning bolt). Bottom row: examples of the direct spatial claim of a solar panel, the technical indirect spatial claim of an aquifer

Table 1. Definitions used for direct and technical or legal indirect spatial claim.

Concept	Definition	
Direct spatial claim	Area claimed by a single energy installation and its enclosure.	
	Legal	*Technical*
Indirect spatial claim	Spatial claim that is determined by rules and regulations with respect to other spatial uses, often with the aim of securing safety or avoiding hinder.	Spatial claim that is needed for the installation to function efficiently, resulting from the technical properties of the installation.

These definitions are useful to assess the spatial consequences of different energy technologies or to compare different technologies to one another. Challenging these definitions from practice, we want to highlight a few discussion points on the concept of spatial claims. Firstly, all of the aforementioned spatial claims can be viewed in different dimensions: as the horizontal surface area on land, the vertical length of an object in the air or the volume of space required below the ground surface. For different energy technologies, different dimensions of the spatial claims are relevant, but often only the horizontal effect is used in comparisons of spatial claims.

Secondly, although the spatial claims have been introduced separately, decisions taken for one, have an influence on the other claims. For instance, one could prefer a wind turbine above a solar field as the direct spatial claim is lower to produce a similar amount of energy. However, the indirect spatial claim of a turbine will be much larger, due to, among others, safety rules and regulation. On the other hand, the indirect space around the wind turbine offers different opportunities for co-use, than the indirect space around a solar panel.

Thirdly, as the energy transition progresses in the Netherlands, the development of renewable energy technologies pushes forward both technical and legal demands. Therefore, we can expect that the technical and legal demands of an energy technology will also change over time, potentially resulting in other direct or indirect spatial claims. Consequently, this paper will look at the spatial claims of the current (section three) and future (section four) renewable energy technologies.

Finally, it is important to clarify the distinction between spatial claims and location. The spatial claim of an installation is more generic and gives an indication on how much area is needed. The location of an installation describes where to implement an installation, as it will have an effect on the (existing or needed) infrastructure in terms of connectivity, capacity and others.

3.1.3 *Goal and scope of the study*

Based on the insights of these previous sections we formulated the following question:

> *Within the context of a growing scarcity of available land in the Netherlands, what are the spatial challenges current and future renewable energy technologies face, based on their spatial claims?*

Our focus is on spatial challenges related to technical or legal spatial claims of renewable energy technologies. The effect of the expanding spatial claim of the energy system on other spatial developments is therefore not in the scope of this report. Using energy technologies as the starting point to identify spatial challenges was a deliberate choice of scope to arrive at concrete challenges and potential solutions within this report.

By translating these challenges to broader, technology independent conclusions, the paper results in a knowledge agenda (for both the current and future renewable energy technologies) for future NWO research questions on the topic of the spatial challenges of the energy transition.

3.1.4 *Structure of this paper*

As this paper results in a knowledge agenda, this study is exploratory and interpretative in nature. The paper is structured as follows. Section two provides an overview of the methodology used and of the selection criteria for the energy technologies we used as cases to better understand their different spatial claims. The third section describes the spatial challenges of the selected current renewable energy technologies and the fourth sections looks at the spatial challenges of the selected future renewable energy technologies. As the fourth section is more explorative, four strategies that aim to reduce the spatial claims of future energy technologies were defined to examine the spatial challenges. Both the third and fourth sections start with a state of the art, followed by challenges and result in a knowledge agenda. The final section brings together conclusions of the spatial challenges of both the current and future renewable energy technologies.

3.2 Methodology

Our methodology to answer the central research question (see section 1.3), consisted of three steps.

Firstly, the current spatial challenges were analyzed from a policy and legal perspective, by conducting a literature review of relevant spatial policy developments, categorized by the level of government: national, regional and municipal. The reviewed policy documents include National Strategy on Spatial Planning and the Environment (NOVI), the National Plan for the Energy System (PES), Main Infrastructure Programme (PEH), as well as documentation of the RES and the Environmental Planning Act. Additionally, input from sector specific roadmaps was used to find current challenges (National Programme for the North Sea, Structural Vision for the Subsurface, II3050).

Secondly, the current spatial challenges related to the technical aspects of renewable energy technologies were analyzed by conducting a literature review on the spatial claims of different renewable energy technologies. For this, both the work of Vaclav Smil (2015) and the ‘Ruimte voor Energie’ tool (Generation.Energy, Bright, Groen Licht, 2021) were used. Additionally, an overview of major spatial developments related to the energy transition in the Netherlands was made, including offshore wind, electricity and gas infrastructure.

Thirdly, to obtain insight into the future challenges of the energy transition, we conducted expert interviews with various technological experts at TNO and a legal expert at Tilburg University. As such we gathered the most important developments in their field that influence the spatial claims of renewable energy technologies into the Dutch living environment in the coming 20 years. The 20 year time period was chosen, based on the Dutch ambitions for a climate neutral society by 2050 (Rijksoverheid, 2019). To reach that goal, the energy and the electricity system must be climate neutral by 2045 and 2035 respectively. Thus, the energy technologies that will be operational within the next 20 years will be used to reach the 2050 ambition.

Based on the different definitions of spatial claims, we distinguished four strategies that each aim to reduce the spatial claim of an energy installation. This provided a useful preliminary framework to categorize and discuss potential technological developments and solutions for different energy sources, but are not necessarily the only strategies that exist for reducing the spatial claim of the future energy system.

For the technical interviews, a short list was made of the energy technologies for which to conduct the interviews. A selection was made that encompassed both heat, electricity and storage technologies and address challenges on land, sea and the subsurface. This resulted in the following selection of technologies:

- On- and offshore wind
- Solar PV
- Solar thermal energy
- Subsurface energy storage (included: hot & cold storage, gas storage, CCS)
- Geothermal energy
- Energy from water (wave, tidal, blue energy and hydropower).

The questions used for the interviews can be found in Appendix 2.

3.3 Spatial challenges of current energy technologies

This section starts with an overview of the state-of-the-art of Dutch policy. By combining the insights from the desk research, overarching challenges related to governance, spatial policies, rules and regulations, and technical feasibility were distinguished. These challenges resulted in a knowledge agenda. Since these policy developments are currently taking place in rapid succession, the state-of-the-art is a snapshot at the time of writing this study, but might already be partly superseded at the moment of publishing this report.

3.3.1 *State of the art: spatial policy, rules and regulations*

3.3.1.1 *National policy*

The most notable legal development on spatial planning concerns the Dutch Environment and Planning Act ('Omgevingswet') (Rijksoverheid, 2014), which is expected to enter into force by July of 2023. The new act embodies 26 existing acts around built environment, housing, infrastructure, environment, nature and water and integrates them into one legal framework. It aims to simplify the rules and regulations for the physical environment, by bundling the many different laws. The point of departure of this act shifts from *no, unless* to *yes, provided that.* There is thus a shift from a situation in which citizens and businesses need to prove that is allowed, to a situation in which the public authority needs to prove that it is not allowed. This new approach should allow for faster and more effective decision making in spatial planning processes and to make it easier for citizens and businesses to initiate and develop projects (Rijksoverheid, 2014). In the Climate Agreement, the government decided that the new Environment and Planning Act should facilitate the energy transition, as much as possible (Rijksoverheid, 2019). The choices made for the energy transition need to be anchored into the instruments of the new act.

Under the new act, the national, provincial and municipal governments must develop their own environmental strategies ('Omgevingsvisies'). In 2020, the first National Strategy on Spatial Planning and the Environment ('Nationale omgevingsvisie', or NOVI for short) was published (Ministerie van BZK, 2020), which provides a long term vision on the future development of the living environment in the Netherlands. In this strategy, one of the four main priorities is the space necessary for climate adaptation and the energy transition. Multiple policy objectives were formulated to aid the careful integration of renewable energy in the living environment of the Netherlands, which include focusing on the development of offshore wind, reserving space for the expansion of our energy infrastructure, combining renewable energy generation with other functions as much as possible and keeping spatial quality in mind. Moreover, the government has determined that there is a preference for large scale clustering of renewable energy production, above scattered distribution across the country. For solar PV, building applied (on rooftops) and integrated solutions are preferred over ground mounted solar panels in either urban or rural areas.

To coordinate the transition towards a reliable, safe, affordable and CO_2-free energy system by 2050, the Ministry of Economic Affairs and Climate is developing the National Plan for the Energy System ('Programma Energiesysteem', PES) (Ministerie van EZK, 2022). Because the energy system spans across multiple sectors and levels of governance, the PES aims to facilitate cross-sectoral and cross-governmental collaboration. An important product within the PES, is the Main Energy Structure Programme ('Programma Energiehoofdstructuur', PEH) (RVO, 2020), which aims to ensure sufficient space for the required energy infrastructures of the future energy system. Within the PEH, the government develops spatial plans for energy infrastructure of national importance for the generation, transport, conversion and storage of energy (electricity, heat) and materials towards 2030 and 2050 (Pondera, CE Delft, 2021). The PEH includes all onshore infrastructure in the

Netherlands, but aligns its plans to the development of offshore electricity infrastructure, pipelines and CO_2 storage (which is covered by the National Program for the North Sea (Ministerie van IenW, 2022)) and international energy infrastructure plans. Additionally, policy relating to the soil and subsurface of the Netherlands, which is the responsibility of the Ministry of Infrastructure and Water Management, provides important input to the PEH. The Structural Vision for the Subsurface (Ministerie van IenW en EZK, 2018) lays down the foundation for spatial policy in the subsurface, with a focus on functions of national importance: drinking water and renewable energy supply.

3.3.1.2 *Regional policy*

In the Netherlands, the national agreements on emissions reduction and energy transition are translated into practice at the regional level, in the National Program Regional Energy Strategies (NPRES). This program aims to support the 30 appointed energy regions (see Figure 5) to develop a Regional Energy Strategy (RES), which describes how and where each region can best generate renewable electricity (with wind and solar energy projects), as well as which heat sources to use in order to reduce the use of natural gas in the built environment. Together, the plans of the regions must add up to at least 35 TWh of renewable electricity on land by 2030. Each region develops its own regional energy strategy with a focus on 2030, in collaboration with provincial and municipal governments, businesses and non-governmental organizations, and where possible with the local citizens. The aim of this regional approach is to make choices for spatial integration of renewable energy generation, heat sources and infrastructure, that are supported by the local stakeholders (NPRES, 2022). For electricity infrastructure developments, the search areas for solar and wind in the RES form an important input for the PEH.

Figure 5. The 30 energy regions in the Netherlands, that need develop a Regional Energy Strategy (RES).

In 2021, the RES 1.0 was published by all regions. The Dutch Environmental Assessment agency (PBL) analyzed these first RESs of the 30 allocated regions (PBL, 2021) and stated that current plans and pipelines will already lead to at least 30 TWh of solar and wind production on land. However, in the implementation of the projects, there are still many uncertainties, related to three main challenges: competition with other spatial uses and interests, electricity grid capacity constraints and uncertainty in the public opinion. All these challenges can hamper the implementation of renewable energy projects in the different regions. Next to renewable electricity, the RES 1.0 also deals with renewable heat generation for applications in the built environment, in the Regional Structure for Heat ('Regionale Structuur Warmte', RSW). In the RSW, the 30 energy regions have determined the heat demand, available heat sources, as well as existing and expected heat infrastructure in the region. The results of the municipal heat transition visions and the RSW are taken into account by the PEH.

Going from RES1.0 towards the next milestone, RES2.0 in 2023, the plans for new renewable energy projects must be translated into practice. The first energy projects will start to be implemented, while alignment with other spatial and societal challenges must be made. Additionally, the search areas will be legally anchored into the instruments of the Environment and Planning Act. At the latest, the environmental permits for the planned wind and solar projects, as well as infrastructure must be granted by January of 2025 (NPRES, 2021a). That process requires participation of local stakeholders, governance, spatial planning and legal embedding into spatial policy documents in the different regions. Therefore, energy professionals, environmental planners, area developers and decision makers need to work closer together and develop a common language, new forms of collaboration and clear agreements (Janssen, Agterbosch, & Koomen, 2022).

An important aspect for successful spatial integration renewable energy technologies is to achieve societal acceptance of the energy transition in the Netherlands. Therefore participation, the active involvement of citizens in the development of renewable energy projects, is an integral part of the NPRES. Participation can take on multiple forms, such as policy-, project- and financial participation (NPRES, 2021b). In the Dutch Climate Agreement of 2019, a target (but not an obligation) of 50% local ownership was set, which is translated into the RES-processes (NPRES, 2021a). Local ownerships means that local citizens and businesses can unite in investing in, developing and operating renewable energy installations by means of community-ownership models. A study by TNO on the experience of local residents of wind farms (Peuchen, Kox, Klosters, & Straver, 2022) showed that financial participation alone is insufficient to realize a positive experience for local residents. When they are not sufficiently involved during the preparation and realization phase of the wind farm, financial participation cannot 'set it right'. Therefore, local ownership should not only mean financial ownership, but also having a say in decision-making right from the inception of the project, in the distribution method of the benefits and bearing part of the risks.

The Dutch provinces are not only involved in the RES-processes, but also develop their own environmental strategy, plan and ordinance, which needs to be aligned with the different RES plans within its borders. In the provincial environmental ordinance ('omgevingsverordening'), energy plans are weighed against other important uses of space such as housing, mobility and nature. The provinces are the competent authority for specific forms of energy generations, such a wind energy projects with capacities between 5 and 100 MW and subsurface energy technologies.

3.3.1.3 Municipal policy

Engrained in the new Environment and Planning Act, is the idea that decisions should be made on a decentral level as much as possible. Therefore, municipalities play an important role in determining spatial integration of (amongst others) solar and wind parks within their own area, by translating the results of the RES into the municipal environmental strategy ('omgevingsvisie') and environmental plan ('omgevingsplan') (Bouma & de Jonge, 2020). The environmental strategy consists of a general description of the quality of the physical living environment, the intended development, use, management and protection of space, and the environmental policy to be implemented within the municipality. It determines the long-term ambitions of the region and considers all facets if the physical living environment, including energy and infrastructure. The environmental plan contains all rules and regulations with respect to activities that impact the physical living environment. By law, the environmental strategy and plan must be developed through involvement of local stakeholders, however the Environmental Planning Act does not stipulate *how* the participation process must be organized (VNG, 2019).

In the climate agreement, it is stipulated that the phase out of natural gas in the built environment must be realized through a 'neighborhood-oriented' approach. Hence, the municipality has the directing role for the implementation of the heat transition in housing an. Each municipal governments must draw up a 'Transition vision for heat' ('Transitie Visie Warmte', TVW) which contains the plans on which neighborhoods within the municipality will be made independent from natural gas before 2030. In March of 2022, more than 300 Dutch municipalities have finalized their TVW. The next step is to draw up concrete implementation plans for every neighborhood. The TVW forms important input for the RSW, in which the different municipal plans for heat use, heat sources and infrastructure are aligned on a supra-municipal level.

3.3.2 Challenges and knowledge agenda: spatial policies, rules and regulations

The state of art showed that several levels of governance are involved in the energy transition and therefore several spatial policies, rules or regulations are made, each with their own focus. Although the current rules and regulations are in many cases a challenge for renewable energy technologies to find suitable locations, the challenges listed in the section look further than these rules or regulations as such. The following three challenges focus on governance and their spatial policies.

The first challenge is the alignment of the many public authorities (at the same and different level of governance), with each their spatial policy, rules and regulations connected to the energy transition. The state of the art has shown that the energy transition is coordinated through different levels of governance in the Netherlands. Additionally, energy projects and energy infrastructure can exceed municipal, RES-regional and provincial borders. Even at the same level of governance, the energy transition is subdivided among public authorities. For instance, the overview of current policies (e.g. Programma Noordzee (Ministerie van IenW, 2022), Programma Energiehoofdstructuur (RVO, 2020), Structuurvisie Ondergrond (Ministerie van IenW en EZK, 2018)) has shown that governments see the surface and subsurface as two separate spaces to arrange functions into, similar for the sea and land side of the Netherlands. Generally, functions above ground are better aligned than below ground. However, multiple energy technologies have spatial effects below and above the ground surface. There is a clear need for both inter- and cross-governmental alignment and collaboration to coordinate a swift and successful energy transition in the Netherlands.

A second challenge is the lack of cross-sectoral collaboration. A successful spatial planning of energy projects in the Netherlands requires taking into account the developments and transitions in different sectors that require space as well, such as nature, existing and new mobility and housing, the transition in agriculture or climate adaptation. It is important that during spatial planning processes, the energy transition is coupled to other spatial developments and that they are taken into account in conjunction instead of separately. Therefore, energy planning must become an integral part of spatial planning, which increases the need for collaboration between energy professionals and spatial planners (Janssen, Agterbosch, & Koomen, 2022).

A third challenge for the spatial developments of the energy transition is the existence of public resistance, which can substantially slow down the translation of energy plans into practice. To achieve societal support for the energy transition, it is important that stakeholders whose physical living environment is impacted and who are expected to change their consumption behavior are not only properly informed, but also involved in decision making and equally share in the profits and risks of renewable energy projects (Rijksoverheid, 2019). One way to achieve this is by means of local ownership. Although targets have been laid down within the Climate agreement, they are not legally binding. Additionally, since different levels of government (national, regional, municipal) are involved in different types of renewable energy development, different forms of participation are applicable. Going forward, the challenge will be to find the right balance between investing time to properly shape participation processes, while accelerating the energy transition.

Knowledge agenda in regard to governance and spatial policy, rules and regulations related to the energy transition

- Next to land surface, the sea or subterrain levels play a vital role in the energy transition. How can current sectoral policies be better aligned or even, if needed, combined? In addition, what type of organisational structures and instruments are needed to coordinate between the public authorities (at the same and different level of governance) involved and push forward decision making that combines the spatial planning of renewable energy technologies below, on or above the surface, and on land and sea?
- Vision forming on the future energy system and decision making on spatial planning currently takes place at different levels of governance (national, provincial, regional, municipal) via Regional energy strategies or environmental strategies within the new Environment and Planning Act. Each of these levels also have to work on other sectors and transitions that require space as well, such as nature, mobility, existing and new housing, the transition in agriculture or climate adaptation. Which organizational structures and instruments could improve the coordination between the different governance levels and sectors and their decision-making regarding locations for energy projects?
- How will participation processes look under the new Environment and Planning act? How can local ownership become an integral part of the development of renewable energy projects?

3.3.3 *State of the art: spatial claims of renewable energy technology.*

3.3.3.1 *Power density of renewable energy technologies*

A useful measure to compare the spatial claims of different types of energy sources is power density. This physical quantity has no single, universal definition, as it is used across different branches of engineering and science. In the context of spatial claims, power density is the energy flux per unit of the Earth's horizontal surface, expressed in W/m^2 (Smil, 2015; Mackay, 2008). The advantage of this measure is that it can be used to systematically compare the spatial claims of all types of energy fluxes. Furthermore, it can be used to assess the potentials of different energy technologies, given an available area. An important factor to take into account when calculating the power density of renewable energy sources is the 'capacity factor' or 'load factor' (Zalk & Behrens, 2018). This is the ratio of the average power to the peak power. Since many renewable energy technologies such as wind and solar PV don't continually run at peak power, the capacity factor is lower than 1. When comparing the power densities of renewable and conventional energy sources (see Figure 6), it becomes clear that renewable energy technologies have a significantly lower power density than their fossil counterparts. This implies that increasing the renewable energy portfolio in a country will also increase land-use of the energy system (Zalk & Behrens, 2018).

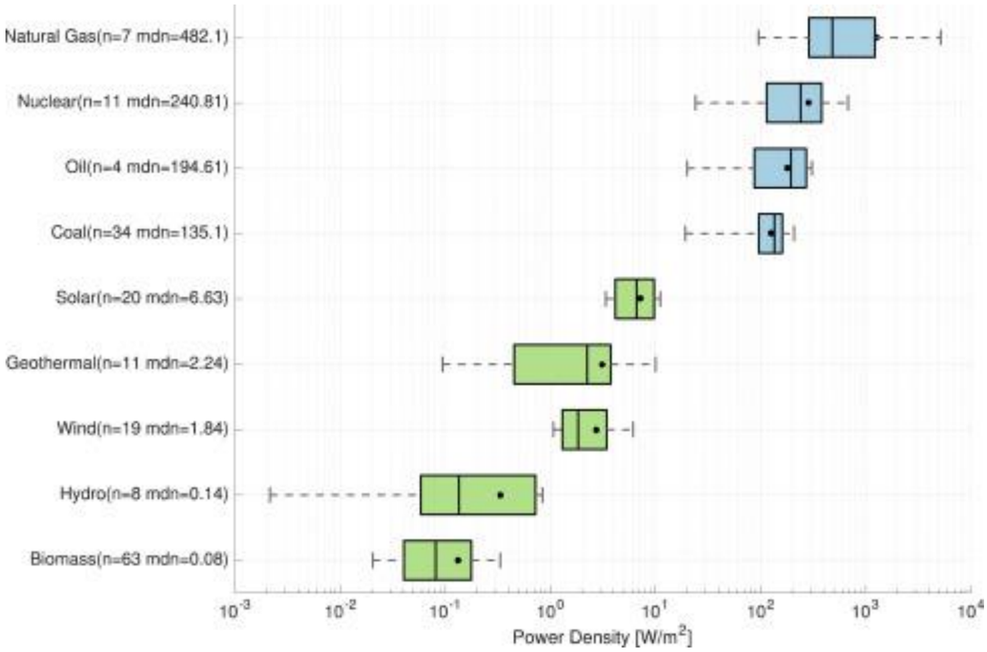

Figure 6. Box plots of power densities for different renewable and non-renewable energy sources, on a logarithmic scale. (n is the number of values found for each energy type; mdn is the median power density). Source: Zalk & Behrens, 2018.

However, as with many quantitative analyses, it is important to make the hidden qualitative aspects and complexities of the energy technologies explicit. Firstly, the measure of power density does not account for differences in the energy quality, for example the environmental consequences (e.g. CO_2 emissions) or the possible applications of the energy technology. Secondly, the spatial quality of the area used by energy technologies varies significantly. The spatial impact can vary from extreme disturbance of the natural surface of the land to complete retention of the initial surface qualities and functions. The required land use for a technology, can also range from fertile soils (e.g. for biofuel production) to unproductive surfaces, hence the competing uses or functions of the claimed area are not reflected in the measure either (Smil, 2015). Additionally, the potential to have multiple uses on the land used by the energy source is not reflected in the measure of power density.

Furthermore, the spatial impact of renewable energy technologies is more than just the direct space required for the installation of wind- or solar parks. Indirectly, energy technologies for electricity or heat also have indirect spatial claims due to technical and legal aspects of the technology (see Section 1.2). For the values displayed in Figure 3, the technical indirect claim is taken into account, but the legal indirect claim is not. Additionally, the choice for a specific type of technology for electricity or heat has spatial consequences with respect to the necessary transport and storage infrastructure. A useful tool that provides insights into these spatial consequences is the interactive webtool 'Ruimte voor Energie', which was developed by Generation.Energy, Bright and Groen Licht, commissioned by Ministry of Interior and Kingdom Relations (Generation.Energy, Bright, Groen Licht, 2021).

Therefore, although power density is a powerful explanatory variable to compare the spatial claim of a certain technology, one should analyze the power densities of energy technologies together with other qualitative factors to determine and compare the spatial effects that different renewable energy technologies have on the physical living environment.

3.3.3.2 *Spatial claims of expected renewable energy developments in the Netherlands*

The Dutch National Strategy on Spatial Planning and the Environment (Ministerie van BZK, 2020) stated that the largest part of renewable energy production needed to achieve the national climate goals for 2030 will come from offshore wind farms on the North Sea. Figure 7 shows these offshore areas and gives an indication of these locations' size. In the North Sea Programme 2022-2027, wind energy areas at sea are determined (Ministerie van IenW, 2022). With the announcement of three new wind energy areas at the start of 2022, 10 additional GW will be installed before 2030, bringing the total installed capacity to 21 GW by 2030 (Rijksoverheid, 2022c). The spatial claim of all offshore wind farms that are realized by 2030 will be around 2600 square kilometer, which translates to approximately 4,5% of the Dutch North Sea area. This value includes the direct and technical indirect claim of the offshore wind parks. In comparison, natural protection areas currently claim around 20% (Rijksoverheid, 2022b).

Figure 7. Map of new offshore wind energy areas on the North Sea. Source: (Rijksoverheid, 2022c)

Ambitions from the RES will need to be translated to implementation towards 2030. The development of the different solar and wind projects that are planned in the RES will have a significant spatial claim. Together, solar and wind projects on land must generate 35 TWh of renewable energy by 2030. Since the RES-regions are free to decide themselves how to reach renewable energy targets, the share of onshore solar and wind generation are still unknown.

Another important spatial development is the expansion of the required infrastructure for the future energy system. In 2021, all Dutch electricity and gas grid operators published a scenario study for the energy system of 2030-2050 (Netbeheer Nederland, 2021). The analysis shows the necessary developments of energy infrastructure in the Netherlands in different scenarios. As a result of the energy transition and the growing demand for electricity in industry and transport, the electricity grid needs to be expanded and reinforced substantially. Additionally, more flexible capacity and storage technologies are needed to maintain balance in the electricity grid. The necessary expansion of infrastructure and flexible technologies will require space. According to the scenario study, the expected spatial claim required for the expansion of the transmission grid above ground will amount to somewhere between 50-80 square kilometers, depending on the scenario. Additionally, the spatial claim below surface for the distribution grid was calculated to be between 220-290 square kilometers. To quote the study: "*An initial estimation of the distribution grid operators shows that one out of every three streets will have to be broken open for this - a figure that illustrates the enormous social task involved in the energy transition*." The spatial claim of flexibility technologies is expected to be limited, but will be located close to site of onshore renewable energy generation, as well as coastal locations where offshore wind energy enters the electricity grid.

Another example of infrastructural development is the hydrogen backbone, which was announced in June of 2022 by the Minister for Climate and Energy. The Dutch grid operator for natural gas, Gasunie, will build and operate this national transport network for hydrogen, shown in Figure 8. This is planned to be developed in three phases (Gasunie, 2022a). First, industrial clusters on the Dutch sea shore where offshore electricity will reach the land, will be connected to each other, as well as the first hydrogen storage facility. Second, the connections to Germany and Belgium will be further developed. Third, the 'ring' will be closed, connecting the south of the Netherlands to the rest of the network. Since this network mostly reuses existing pipelines, the spatial claim of the gas infrastructure is expected to remain approximately the same.

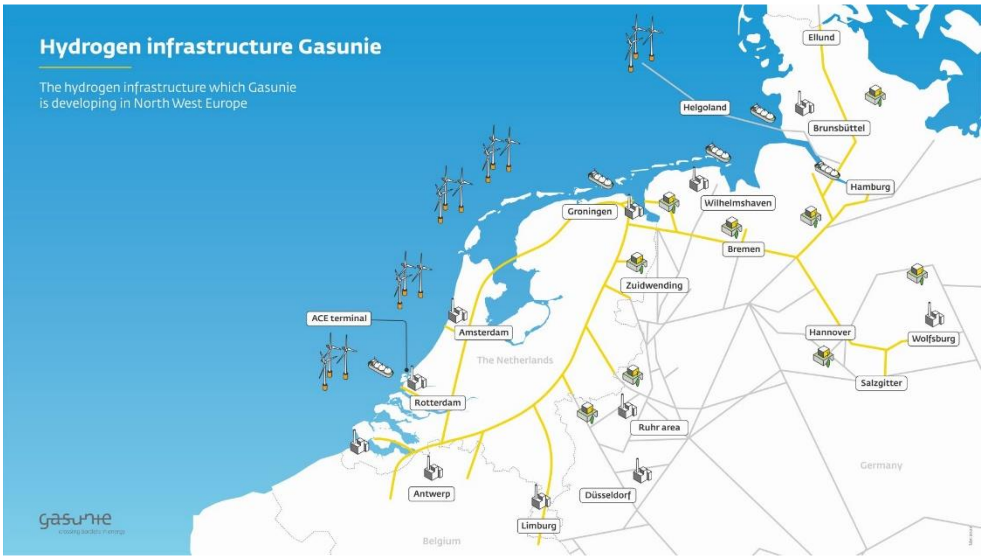

Figure 8. Hydrogen infrastructure which will be developed by Gasunie, across the Netherlands, Germany and Belgium (Gasunie, 2022b).

3.3.4 *Challenges and knowledge agenda, connected to the technical requirements of a renewable energy installation.*

Historically, fossil fuel energy production nodes were developed in parallel with a supporting infrastructure for the supply of oil, gas or coals and the transport of resulting energy across the Netherlands. Due to this expansive network, fossil fuel energy production nodes are not dependent on their surroundings. Furthermore, due to the high power density of fossil fuels, production nodes are compact. In contrast, renewable energy production installations are more dependent on their surrounding (e.g. availability of geothermal heat, sun, wind) and have a lower power density to become compact nodes. The technical requirements of renewable installations leads to four challenges related to space: the presence of available renewable sources to convert into usable electricity or heat, the network capacity of the connecting infrastructure, the nearby demand for energy and a ‘first come, first served’ situation.

The first challenge is the availability of renewable resources. Examples of challenges from a technical requirements perspective are the depth of useful geothermal layers and the permeability of the ground for geothermal energy, a minimum flowrate and depth of water for tidal energy, the presence of salt and fresh water for blue energy, surface water for thermal energy, and caverns for storage of gases. The potential of these technologies is therefore dependent on the locations, amount of available energy sources and efficiency of the technology to convert these resources to usable electricity at the competing market price. However, the potentials of these technologies can overlap. To illustrate, in their study of the national potential of aquathermic energy (CE Delft, Deltares, 2018), CE Delft explained that the potentials of thermal energy from surface water, waste water and drinking water are not additional, but show overlaps with one another. To obtain a realistic estimation of the potential, the analysis should be supplemented by the market potential, and should be compared to alternative, competitive techniques. Additionally, there is the risk that the energy potential of these resources or infrastructures will not materialize, due to the current allocation of these areas.

The second challenge links to the connection of some technologies to an infrastructure system. Most importantly, the electricity grid currently faces congestion issues. This is due to the increase in electricity demand, as a result of economic growth and the electrification of the built environment, mobility and industry, as well as an increase in renewable energy projects. The grid operators cannot keep up the pace for grid reinforcements and new grids, due to shortage of resources. Therefore, many energy projects cannot be connected to the grid and face long waiting times. This influences the possible locations for energy projects in the Netherlands. This challenge is likely of a temporary nature and will not persist during the entire transition period, as the root causes of the problem will be probably be addressed in the short term.

As a third challenge, the distance between supply and demand of heat related technologies. As heat cannot be transported over long distances, due to energy losses, the demand for heat might not be near the offered renewable heat supply. Technologies, such as solar water heaters, are more flexible and it can be expected that technologies that extract heat out of sewage will already be located in an area that has a potential demand for heat.

The fact that the technologies can be realized in a finite number of suitable locations due to the required renewable resource, demand and infrastructure connections, brings us to the fourth challenge: a 'first come, first served' situation with respect to available space. For example, an aquifer thermal energy storage needs a 100 meters minimal distance to other installation between the source for heat or cold to avoid interference. Such an installation is mostly only used for one building and thus once such an installation is installed, neighboring buildings cannot use a similar solution.

Knowledge agenda concerning the spatial challenges connected to the technical requirements of a renewable energy installation:

- Due to recent congestion issues, the possible locations of energy projects are inextricably linked to the availability of electrical infrastructure. Therefore interaction between spatial planners and grid operators is crucial in the short term. How can infrastructure planning be better aligned with the spatial integration of energy technologies and how can this process be formalized?
- There are knowledge gaps about the future potential of different types of energy technologies. The potential is determined by overlapping the availability of the required renewable energy resource with exclusion areas, the availability of required infrastructure and the connection to suitable demand. How can the knowledge on the potentials for different energy technologies, then be translated into plans? How can space be reserved for specific energy projects, to ensure the energy potential of these resources will not get lost due to other spatial uses?

3.4 Spatial challenges of future energy technologies

In this section, we look at the opportunities and challenges that will arise as energy technology progresses. As the energy transition continues, so is the development of renewable energy technologies and the demands for governance posed to these technologies.

According to the Trias Energetica (RVO, 2013) the first step is decreasing the demand for energy, for instance via better isolation of housing. This step also reduces the need of space for renewable energy technologies. As a second step the use of renewables is put forward. As indicated in the NOVI (Ministerie van BZK, 2020), a challenge for the energy transition in the future is the scarcity of space in the Netherlands, which is also needed for climate adaptation, circular economy, accessibility and increased housing. How to deal with this scarcity of space will be leading driver for future developments in renewable energy technologies. Therefore, multiple technology experts were interviewed to provide an overview of the expected technological developments in the coming 20 years, that could potentially help integrate renewable energy technologies into our physical living environment and reduce the overall spatial claims of the energy transition. We distinguished four strategies that each aim to reduce the spatial claim of an energy installation, which are based on the different definitions of spatial claims discussed in Section 1.2:

1. Maximize the direct power density
2. Multiple usage of direct space
3. Decrease the technical indirect spatial claim
4. Decrease the legal indirect spatial claim

These four strategies are illustrated in Figure 9. Before delving into the four strategies separately, we mention some overall lessons we learned from discussing these strategies with the experts. Firstly, the four strategies are not necessarily the only strategies that exist to reduce the spatial claim of renewable energy technologies. However, they provide a preliminary framework for categorizing different solutions. Secondly, they cannot be viewed as independent strategies, as they are often related to one another. For instance, increasing the capacity of a single wind turbine increases the direct power density, but could also increase the hinder caused and thus increase the legal indirect spatial claim. Thirdly, one installation could also use several strategies to decrease their spatial claims in the future.

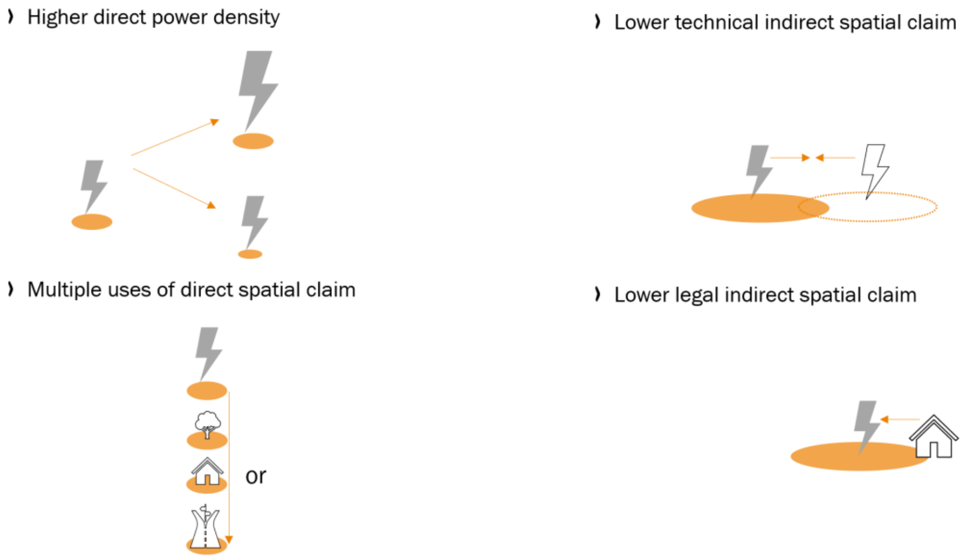

Figure 9. Visualization of four strategies to reduce the spatial claim of renewable energy technologies.

3.4.1 Maximize the direct power density

The first strategy *maximizes the direct power density of a renewable energy technology* would reduce the amount of land area needed to produce a certain amount of power. The direct power density is defined by the following equation:

$$\textit{Direct power density} = \frac{\textit{power generated by the technology}}{\textit{the direct surface area required by the installations to produce that power}}$$

By reducing the direct area required or by increasing the amount of power generated by one installation, the power density increases and the land is used more efficiently from an energy point of view. During the interviews it became clear that, the increase in power density is an important driver for development for most technical research fields. Table 2 gives an overview of the expected technological developments, related to this strategy.

Table 2. Expected technological developments related to the strategy: Maximize the direct power density.

Technology	**Developments**
Solar PV	• Solar PV efficiency is expected to improve by about 2% relatively per year, primarily driven by developments at the solar cell level. • The development of multi-junction solar cells. • Innovations on module level, such as increasing the active area and improved interconnections to reduce electrical losses. • The development of bifacial modules results in a higher yield per square meter.
Solar PT	• Concentrating solar thermal technology in development. Potential is larger in Southern Europe, compared to the Netherlands, because a higher percentage of direct radiation is required.
Onshore wind	• Growth in size and output power per turbine. Limitations in size are mainly due to permits and logistics.
Offshore wind	• Offshore wind turbines are increasingly getting bigger with larger rated power, mainly to reduce costs (more power, still one structure to install and maintain). There are some recent studies that say that a plateau will be reached (at around 2030) after which it might not be cost-effective anymore to grow even larger. • Another strategy to increase power output is to include floating solar parks, wave- or tidal converters between offshore wind turbines. This also allows for optimization of the required electrical infrastructure to integrate large amounts of wind power into our grid.
Ocean energy technologies	• Technologies have not yet reached commercial deployment. Still strong efficiency gains expected. E.g. for blue energy, membrane improvement is crucial. • Technologies themselves are still undergoing changes and have not yet converged to an optimal design. • Wave- and tidal converters could be placed between offshore wind turbines or in the exclusion zone around oil and gas platforms.
Water electrolysis	• Technology choice between polymer-electrolyte membrane and alkaline electrolysers has a small effect on the power density of an installation. • Re-using oxygen and heat by-products to replace other oxygen and heat producing installations for industrial processes.
Geothermal heat	• Development of more efficient heat exchangers. • Drilling wells with a larger diameter, which result in a higher heat yield per well.

	• Expected efficiency improvement in pumps combined with energy savings due to the use of composite materials for pipes (instead of steel), which reduce resistance in the pipe. • Theoretically possible to extract heat from heat sources that are stacked on top of each other underground.

3.4.2 Multiple usage of direct space

The second strategy for the reduction of the overall spatial claim of the energy transition is by combining space needed for energy generation with other (non-energetic) uses, such as agricultural land, transport infrastructure, urban areas or ecological reserves.

In a few different technical fields, there is a focus on the ecological effects of these technologies. If technological developments could reduce the negative ecological effects, or even enable a positive symbiosis with natural ecosystems, they could enable the use of more natural areas for renewable energy generation. Table 3 gives an overview of the expected technological developments, related to this strategy.

Table 3. Expected technological developments related to the strategy: Multiple usage of direct space.

Technology	Development
Solar PV	• PV applied on agricultural land. Research efforts are focused on maintaining biodiversity and enhancing agricultural growth between and underneath the modules. Potential solutions include vertical and bifacial modules, panels that also water the land in the shadow preventing evaporation and panels that disperse light on the land underneath. • PV applied to infrastructure, such as dikes and crash barriers along sides of roads. • PV integrated into buildings, such as building facades, roof tiles, windows or window shades. Main challenge lies in improving lifetime of components, since building components have a longer lifetime than PV modules. Another challenge is the compliance with building codes, which vary from country to country. Also, there are safety risks due to electrical connections of PV integrated building components. • Developments to decrease the weight of PV installations, so large commercial roofs can be used for energy generation. • PV integrated in the roofs of vehicles (passenger cars, trucks, vans, buses) as an on-board power source. Technological developments: more efficient vehicles, higher power density of PV and batteries could improve range and reliability. • Floating solar is being developed near-offshore, and potentially far-offshore.
Solar thermal	• PT could be combined with agricultural land. • PVT systems, or hybrid panels, which produce both heat and electricity for housing applications. A specific benefit is the possibility to combine PVT systems with water-water heat pumps, which are more efficient and

	produce less noise than the more usual air-water heat pumps.
Offshore wind	• Development of offshore energy hubs in the North Sea, where offshore wind is combined with offshore hydrogen production and potentially CCS. • Ecological inclusivity is becoming more important to win tender bids. • Research into using turbine foundations as artificial reefs. • Re-use of oil and gas platforms.
Ocean energy technologies	• Research into effects on marine ecosystems.
Hydropower	• Fish-friendly turbines
Subsurface heat storage	• Possibility to build a parking area above a heat storage site.

3.4.3 Decrease the technical indirect spatial claim

The technical indirect spatial claim relates to the spacing required between multiple installations to ensure that they don't interfere with one another and thereby reduce their performance. By decreasing the required technical indirect claim, more units could be spaced closer together and thus produce more power per total area.

This strategy is mostly relevant for geothermal energy. Although the technical indirect spatial claim is a relevant design parameter for wind and solar farms, there were no noteworthy technological developments related to this strategy in those fields. For newer technologies, such as wave- and tidal energy, there is still a lot of optimization possible in the design of multiple converters and their distances to each other. Table 4 gives an overview of the expected technological developments, related to this strategy.

Table 4. Expected technological developments related to the strategy: Decrease the technical indirect spatial claim

Technology	**Development**
Offshore wind	• Spacing of wind turbines is an optimization process, of energy yield from the turbines and cost of electrical cables. • Research into interference between multiple wind parks. Regeneration of the wind is an issue.
Ocean energy technologies	• Because the technologies are still under development, the spacing between multiple wave- and tidal units is still being optimized.
Geothermal heat	• Increased interest in less deep geothermal wells, because of the increasing demand for low temperature heating for houses with heat pumps. These wells have a smaller indirect spatial claim

	underground, therefore they can be spaced closer together.

3.4.4 Decrease the legal indirect spatial claim

The last strategy concerns developments that could impact the necessary distance of energy technologies to other spatial objects, such as houses and roads. Technological developments could drive changes to rules and regulations that decrease the legal indirect spatial claim, for example by improving the safety of the installation. Table 5 gives an overview of the expected technological developments, related to this strategy.

Table 5. Expected technological developments related to the strategy: Decrease the legal indirect spatial claim

Technology	**Development**
Onshore wind	• More silent design could enable a shorter distance to houses.
Offshore wind	• Combining multiple energetic uses into one offshore energy hub also leads to a reduced legal indirect claim.
Geothermal energy	• Rules and regulations with respect to drinking water reserves are under discussion. Both drinking water and renewable energy supply are of national importance.
Water electrolysis	• The future choice of hydrogen carriers will impact the legal indirect spatial claim. For instance, ammonia poses a relatively high health hazard, compared to other carriers.

When combining multiple energetic functions in one area (strategy 1), often the legal indirect spatial claims overlap as well, leading to an overall reduction of the legal indirect area. This would be the case for offshore energy hubs, where the safety zones around the wind turbines and the electrolyser platform where no shipping and fishing is allowed, would overlap.

3.4.5 Challenges and knowledge agenda, connected to future renewable energy technologies

The first challenge for technological innovation in the coming years is reducing the spatial claim of the energy transition. Earlier, Tables 2 to 5 illustrated creative solutions to combine multiple energetic or non-energetic functions. However, these examples also indicated that a specific set of engineering thought is required to decrease spatial claims. Most interviewed experts could identify technology specific research directions for NWO to pursue in future, which can be found in Appendix 3.

A second challenge most of the interviewed experts have put forward is social acceptance for current and future energy technologies. According to the interviewees, this acceptance can only be partly solved through technological developments. For example, a more silent design could potentially decrease the hinder of wind turbines, or use of different colors could make PV modules more aesthetically pleasing. However, more important is the measure in which people are allowed to participate in decision making regarding the spatial planning of energy projects and to which extent they receive benefits from installations in their vicinity.

A third challenge are the spatial claims of other large and complex challenges. How can future renewable technologies increase synergies with other challenges and as such decrease their spatial claim? Aside from simply combining multiple functions in the same space, energy technologies can also form synergies with spatial claims of other large and complex challenges, by sharing or reinforcing a common goal. Potential synergies include those with existing infrastructure (e.g. PV on noise protection walls), land use synergy (PV on agricultural land), environmental synergy (offshore wind farms functioning as artificial reefs to improve marine ecosystems).

Knowledge agenda in regard to the spatial challenges of future energy technologies:

- The research has put forward four strategies to decrease the spatial claim of the energy transition. Which other spatial strategies can be developed to decrease this claim?
- How can technological developments improve the social acceptability of future renewable energy technologies?
- How to stimulate synergies between the spatial claims of the energy transition with the spatial claims of other large and complex challenges? Next to solely spatial synergies, also local economic synergy are interesting options to explore, examples that were mentioned in the interviews were: community benefit sharing agreements or stimulating collective energy project and shareholding. More research is needed into the nature of these synergies and into the quantitative potential of these solutions in the Netherlands. Where are potential areas for synergy located and which innovations, instruments, policy and legal developments are needed to facilitate their implementation?

3.5 Conclusion

Within the context of a growing scarcity of available land in the Netherlands, the aim of this paper is to examine what are the spatial challenges current and future renewable energy technologies have, based on their spatial claims?

With regard to the spatial challenges of the current renewable energy technologies, we looked at the challenges of different groups of energy technologies (heat, electricity and storage) in regard to organization, policies, rules and regulations, and technological requirements. Even though the current rules and regulations are challenging for renewable energy technologies to find suitable locations, the three challenges we focused on were: how to deal with the many public authorities with each their spatial policy, rules and regulations connected to the energy transition; how to organize cross-sectoral collaboration to avoid future spatial conflicts that will hinder the development of energy projects; and how to develop specific legal spatial instruments or policies that can support the development of energy projects. Concerning the technological requirements, the four resulting challenges for renewable technologies from spatial perspective, were the availability of renewable sources in the surrounding, the connection of some technologies to an already congested infrastructure system, the distance between supply and demand of heat related technologies and the current ‘first come, first served’ situation with respect to available space.

Concerning the spatial challenges of future renewable energy technologies, we conducted eight in-depth interviews with energy technology and legal experts. As a basis for these interviews, we grouped the most important technical and legal expected developments according to four strategies, developed during this project, that could be applied to reduce the spatial claims of energy transition. The four challenges for future renewable energy technologies we found were: how to reduce the spatial claims, how to increase the social acceptance for current and future energy technologies, how can future renewable technologies increase synergies with other challenges and as such decrease their spatial claim, and can spatial policies, rules and regulations concerning energy technologies be based on qualitative goals?

Limitations of this study have been that documents on the spatial impact of selected technologies, especially for the indirect legal space, are extensive and at the same time very specific per technology. Therefore, to improve understanding of specific rules and regulations and their spatial implications would require a deeper dive into these technology specific documents. Furthermore, several of the selected technologies are still in full development and therefore their future expected technical and legal spatial claim is unknown. Another limitation is that the four strategies that were distinguished for reducing the spatial integration of renewable energy technologies are not necessarily the only strategies that exist. An example of another strategy is the use smart methods for balancing supply and demand of electricity. This could enable the use of as little energy generation, transportation and storage technologies, thereby reducing the overall spatial claim of the system. This was not included in the knowledge agenda.

Regardless of these limitations, this study has identified key research questions for the knowledge agenda. For both spatial challenges of current and future renewable energy technologies, the focus has been on questions that look at governance, policy or technical developments to reduce the spatial claims of renewable energy installations.

4 The business challenge for the energy transition

4.1 Introduction

The systemic change in the structure of our economy by moving from a fossil-based economy to a ‘green’ renewable based economy involves many challenges. Whereas the technical challenges have received ample attention, the economic and financial challenges are not clearly articulated, let alone well understood.

The first step in any transition is to know what we want to achieve. In the context of the energy transition, this is outlined in terms of greenhouse gas emission reductions in the coming three decades. The next, more challenging, step is to identify where these reductions should take place in our economies. This task is country-specific and involves decreasing our use of fossil fuels, which is achieved by switching to renewables in the power sector along with efficiency improvements, electrification, and the replacement of fossil carbon feedstocks with renewable alternatives in other sectors.

The transition involves both public and private stakeholders. Within the broad business domain, our focus in this chapter is on the industrial sector since the transition in this sector is not yet well understood and is in most cases industry specific. Furthermore, this sector is critically important to any climate plan with 26.6% share of emissions attributed to Dutch industry in 2018 (OECD, 2021). Accordingly, we distinguish in this chapter between the energy and industrial transitions. The energy transition is defined as a systemic change in the supply and demand of energy that involves the substitution of fossil-based energy sources with low-carbon energy sources. The industrial transition on the other hand reflects the process of reducing industrial carbon emissions through the means of electrification, efficiency improvements, or carbon capture and storage. These definitions illustrate the link between the two transitions where the industrial transition is part of the change in the demand side of the energy system, while the outcome of the energy transition represents a change in the supply side for any industrial process. Therefore, the challenges identified in this chapter affect the two transitions in a direct or indirect way.

Transformation comes about by investment in new processes, new factories, new products and new (energy) infrastructure, along with divestment from unprofitable and fossil-based processes or businesses. Although the technical scope of these (dis)investments is clear, non-technical and economic uncertainties may hold back the transition. Since (dis)investment sets the pace for industrial transformation, we focus on the identification of non-technical transition challenges. By clarifying what these challenges are and how they impact decision making, we arrive at a research agenda that will identify the conditions for an investment climate that will support the transition in Dutch industry. Accordingly, our aim in this chapter is to outline a research agenda that addresses the business-economic challenges of the Dutch industrial transformation.

Note that the obtained research agenda is stakeholder/expert driven. That is, it is based on societal needs rather than academic needs because we start from a dialog with practitioners to identify the drivers and barriers of the Dutch industrial transition and translate these to academic research directions for future investigation. We focus here on Energy Intensive Industries (EII) mainly because that is where the energy transition is most challenging, and a better understanding of the barriers to transition is most urgent. This chapter aims to answer the following research questions:

- *What are the non-technical challenges for the energy and industrial transition in Dutch EII?*
- *What are the underexplored research areas on the factors affecting (dis)investment in the industrial and energy transitions?*

This chapter is structured as follows: we outline the methodology in section two. In section three, six transition challenges are outlined and put in scope followed by a problem analysis and description of the state of the art. Finally, research directions for each challenge are discussed and possible new research questions are proposed. Section 4 concludes this chapter.

4.2 Methodology

The research agenda is inspired by conversations with several stakeholders in the Dutch heavy industry sector and the agenda is constructed over three steps. In the first step, data was collected through interviews with different stakeholders within the framework of Sustainable Industry Lab (SIL)1 under the social earning capacity theme. The interviews involved conversations with academics, government representatives, investors, and representatives of existing Dutch industrial corporations. The interviews were exploratory and non-structured. They aimed at identifying the impediments and enablers for a successful transition of the Dutch industry. The insights from these interviews were coded under five overarching themes which formed a basis for discussion in a workshop that gathered all interviewees and other stakeholders. The workshop aimed to identify and discuss essential choices and the associated consequences for the transition to a sustainable industry by 2050, along with the future economic role of the Dutch industry in the wider economy. The themes and further discussions during the workshop formulated a base to identify the lines of needed research of non-technical challenges associated to the Dutch industrial transition.

The second step involves desk research on the identified themes. This involved surveying the relevant literature for each theme, along with constructing a framework that maps the research questions which need to be addressed from the perspective of relevant stakeholders forming a draft for the research agenda.

The third step entails an expert revision to gather feedback on the proposed research agenda and addressing any missing aspects or potential improvements.

4.3 Transition Challenges

The process explained above resulted in six transition challenges that will be developed in this section:

1. Bounding uncertainty by establishing an aspired portfolio.
2. Managing evolution: the movement from our legacy towards an aspired portfolio.
3. The adequacy of market mechanisms to achieve the needed transition: the roles and responsibilities of different stakeholders.
4. The national aspects within an international context
5. The need for coordination.
6. Financing the transition.

For each of these challenges, we give a short introduction and consult the state of the art of the related academic literature and ends with an eye on the future by identifying the research areas that would benefit from further investigation. Note that given the wide scope of the theme of this chapter, this section is not meant to be exhaustive neither in the identified challenges nor in the related literature or the proposed research directions, rather it should be considered as start for all these aspects.

4.3.1 Bounding uncertainty by establishing an aspired portfolio

Production of final goods and services needs to alter its processes to adapt to a new energy mix. However, the transition in industry does not only entail a change in its energy inputs but will very likely also involve a (very) significant change in the portfolio of industrial products. Thus, we posit that the final systemic change is a product of the interaction between the two transitions. That is, the new energy mix will affect the direction of the industrial mix and vice versa. For example: the availability of clean power drives investments for electrification, while at the same time investing in electrified industrial processes drives investments in renewables. Moreover, there is a 'chicken and egg' dilemma related to the two transitions. For example, an industry will not invest in electrification if they don't have certainty of a sufficient grid connection, while grid operators will not invest in grid reinforcements if there is no demand. Note that the strength of the interaction will be different across industrial sectors. It may be comparatively weak in light industry, but critically important in heavy industry (steel, petrochemicals).

The problem is that we have rather little a priori knowledge about the future portfolio of needed products of the future. Such uncertainty entails a risk of wasting valuable resources by investing in projects that do not fit in the future aspired portfolio (our vision). Furthermore, there is also associated uncertainty about the potential role of the current industrial/energy system assets (our legacy) in the transition. This calls for an analysis of the rationales that were behind the present portfolio and to check whether such rationales are still valid for our vision given the socio-economic and political conditions.

Deep decarbonization of energy intensive industries faces different barriers. For example: the complex value chain of these industries; the immaturity of technologies; the long-term investment cycles which could hinder the breakthrough of new technologies (Wesseling and Van der Vooren, 2017); high technology risk that could induce a lock-in effect (Wesseling et al., 2017); high global competition in these industries with low profit margins which makes it hard to handle extra costs by these companies; risks associated to the development (high unit investment costs, nonstandard design and high required level of integration in the system (Löfgren and Rootzén, 2021)) and deployment of new technologies (Johansson et al., 2021).

Even though the aspired portfolio is a product of a complex interaction between many transition aspects, Busch et al., 2018 identify criteria that could be considered when investing in technologies or sectors. Such criteria could help sketching some guidelines for the aspired portfolio. Those are related to potential scale of contribution of: reaching carbon reductions; achieving national economic goals; creating other 'co-benefits'; drawing on existing skills and expertise while achieving growth and development at the same time.

Accordingly, we can identify the following research questions that link to the future aspired portfolio:

- What would the future entail for Dutch Energy Intensive Industries? How would the future (in 2030 and 2050) products look like given the current technical and non-technical information we have around these industries?
- Given the geographic limits to the renewable energy generation in the Netherlands and the price level of domestic renewable energy, will the fossil-era rationale for the Dutch EII remain valid in the renewable era? If so, what are the key arguments for that? What are the social, political, economic aspects that govern the interactions between the Dutch energy and the industrial transitions over time?
- How does the emission reduction goal in industry translate to a goal for economic activities? what will the contribution of individual parties towards the aspired portfolio?
- What is the role of existing assets (the current legacy) in the transition? To what extent will our legacy be valuable during the transition process? Could our legacy be needed to buffer unexpected transition risks (For example, coal and nuclear power plants in times of natural gas price shocks)?

Note that these questions related to economic aspects of an aspired portfolio are intimately related to a technical analysis, in particular of renewable energy prospects nationally and globally. The subsequent challenge looks at the movement from the legacy we have to our aspired vision.

4.3.2 Managing evolution: the movement from our legacy towards an aspired portfolio

A transition is, by definition, a movement from one state to another over time. The time dimension entails many possible paths that could materialize. The materialized path is a critical matter and has a direct impact on the success of the transition process. Noting that the prevailing pathway depends on the interaction of many interdependent factors such as innovations, policies, and preferences, which in turn is non-linear, complex, uncertain, and hard to predict. Moreover, there are also political and socio-economic processes that increase transition uncertainty (Köhler et al., 2019). Transitions research aims at understanding the interaction and multidimensionality between radical change and stability factors from a multidisciplinary approach. Markarda et al., 2012 argue that the transition in socio-technical systems will be incremental rather than radical. This is because of the complexity of transitions incorporating the changes in many related variables that depend on each other. For example: established technologies are highly intertwined with user practices and lifestyles, complementary technologies, business models, value chains, organizational structures, regulations, institutional structures, and even political structures (e.g., Rip and Kemp, 1998). Therefore, it should be emphasized that the transition process is an exploratory one which entails that the adaptiveness of all parties is essential for a successful transition, mistakes should be communicated, risks should be accommodated rather than avoided, and efficiency should not be a target by itself, otherwise, it may induce inflexibility that may hinder the transition.

Grublera et al., 2016 acknowledges different sources for a slow transition such as the time needed for the development of multiple technologies, infrastructure, and governance settings, along with the development and adoption of new concepts.

They further investigated how the transition speed differ across markets based on spillover learnings and the growth speed of the technology. Therefore, the speed of the transition is another important aspect that needs to be considered under different transition paths.

Lock-in of certain technologies would affect undergoing transition and alter the materialize transition path. Possible reasons for locking-in certain high carbon technologies is the increasing returns of adoption which leads to path dependency. This is because once interests are established in a sector or technology, while having at the same time the support from the system, the cost of changing/reversing the path become quite high and lock-in is most likely to materialize even with the existence of superior alternatives (Janipour et al., 2020).

Based on the discussed aspects, several research areas associated to the path of the transition process still need further investigation:

- There is a need to have better understanding on how transitions could be governed and materialize across different sectors (Wesseling et al., 2017). Accordingly, the empirics of demonstration effects of previous or pilot transitions should be revisited to investigate the possible impacts of putting up transition examples in different sectors and to determine the similarities, differences, and the degree of adaptiveness of transition processes across sectors.
- Transition speed and understanding how it could be influenced is an important topic to explore. How much time will the Dutch energy and the low carbon industrial transition take? What circumstances can accelerate or slow down these transitions? What are the possible sectoral transition bottlenecks that if solved would speed up the transition? (Köhler et al., 2019, Bento and Wilson, 2016). How to reach the Dutch climate goals in time? What is needed from the business perspective to reach it?
- More research is needed to better understand lock-in mechanisms and strengths over time and across sectors. This understanding is essential to anticipate the degree of path dependency and the materialized transition path (Köhler et al., 2019). Moreover, to understand the slow decarbonization transition, it would be fruitful to assess if and how interdependent systemic problems form closed feedback loops that constitute systemic lock-in (Wesseling et al., 2017).

The focus under this challenge was on the pathway to a fully decarbonized system. The subsequent challenge focuses on the policies and tools needed to steer the transition to a specific direction.

4.3.3 The adequacy of market mechanism to achieve the needed transitions: the roles and responsibilities of different stakeholders

The energy transition is a systematic change, which involves many stakeholders, both public and private. Each of these parties has a role to play in the prospective transition. We distinguish between market driven and non-market driven transition with larger role of the government. The arguments for more government involvement in the transition would be to create transparency and certainty and to provide clarity on the policy in both the short and the long-term targeting what can be called ‘transition failures’. A transition failure is a term that reflects a situation where the government does not act in time to address new emerging market failures, or account for transition originated scarcities, which would result in hindering or slowing down the transition. The necessary intervention to correct for these transition failures is absent because of the lack of understanding of the problem, its complexity, and the time aspect of the process. Moreover, carbon taxes have limits in achieving transition goals as they fail to address the lock-in of fossil fuel industries or steering the needed finance and to move innovations from the demonstration to market diffusion (Busch et al. 2018; Gallagher et al., 2011). For example, as we are in process of building the capacity of renewable power, a temporarily scarcity emerges since there is limited capacity that can be built in the short term. This capacity could be considered as 'transition scarcity' in the short run. The question is then: how do we allocate this capacity in the way that is most effective to help the transition move forward? A market-based outcome could result in allocating this (temporary) scarce resource to activities that are not in line with the transition agenda or inducing a lock-in effect to existing activities. For example, allocating scarce renewable capacity to existing well-established activities (like steel and cement) may hinder, or at least postpone, investments in green hydrogen that mainly rely on renewable power. This is practically a horizon problem. The market outcome is short term which does not necessary fits the long termism of transition goals.

We are used to think in the context of 'optimal transitions', yet such thinking does not properly take into account the fact that there are a lot of uncertainties surrounding the effectiveness of policies. When coordination/multiple equilibria is/are no major issue, this problem is perhaps fine to neglect. But when policy failure becomes real failure, a case might be made for a 'better safe than sorry' type of approach. One needs to keep in mind that the energy transition is unprecedented, and attention is needed for the design of policies and the role of the government to achieve the targeted transition.

There have been many proposals on the extent of governments intervention in the transition and the tools used to fulfill their role. Köhler et al., 2019 call for normative statements on the goals and achievements of transitions arguing for a central role of the public policy in shaping the directionality of transitions. Loorbach, 2010 proposes a four steps framework to formulate and manage transitions by policy makers identifying four types of activities: strategic, tactical, operational, and reflexive. Those activities incorporate developing a vision and possible pathways, developing plans and agendas with potential commitments, executing experiments and implementation of plans, performing periodic evaluations that lead to vision amendment and pinpointing of best practices (Köhler et al., 2019). Johansson et al., 2021 argue for the independent treatment of risks in the design of policy leading the transition of investments and technologies. Busch et al., 2018 proposes a strategic objective for policy interventions for a low carbon industrial strategy. In their proposed transition management strategy, they highlight the need for an initial policy commitment followed by sectoral and national stakeholder commitments that stem from a pathway led process, along with GHG pricing and carbon leakage and competitiveness protection. In a more proactive direction, Mazzucato, 2018 calls for societal relevant missions where industrial and innovation policies work systematically on both horizontal and vertical policies. She calls for the government to go beyond the correction of market failures and to play a more active role in industrial policy by creating and shaping markets and identifying the needed industry and sectors for the transition. Her mission-oriented framework promotes an adaptive innovation policy process that employs an active and continuous monitoring and evaluation. Finally, creating markets for low fossil-based carbon commodities is essential for their development and would help boosting the transition. Such a policy along with the long-term commitment to climate policy and innovation support would reduce the associated regulatory risks and provide assurance that is needed to boost the transition in these industries (Löfgren and Rootzén, 2021).

After having consulted some related literature, we identify several research directions related to the limits of the market and steering the transition of the Dutch EII to net zero fossil carbon:

- What are the risks associated to the industrial transition? depending on the risk that we are dealing with, is the risk (from some point onwards) mainly a public or a private responsibility? what should be left to the market in terms of risks and where should the government step in? what is the role division between the government and other parties in the transition? How do we translate what is needed to be done (high level insights) into tangible actionable items (actionable insights) that help the transition?
- Acknowledging that there is no such thing as ‘failure-free’ policy (in the sense of perfect efficiency and effectiveness), it is unproductive to think in terms of policy ‘failure’. Rather, the challenge is to learn fast from mistakes and to correct them. The question is then: how can the government be adaptive in policy making (Bataille et al., 2018), while maintaining policy cohesion and predictability over longer horizons? Alternatively, how to design more ‘robust’ policies (i.e., policies that even if they are not perfectly optimized still deliver a decent result)? What are the incentives/tools that could/should be provided by the government to achieve the identified transition ambitions and goals? What are the potential and effective industry-specific policy instruments that can be used to deal with locking-in high carbon technologies (Janipour et al, 2020)? How can the government be more predictable and reliable such that companies and investors have some certainty about their future investments?
- What are the unexpected newly emerging transition scarcities, risks, and opportunities? How to introduce these scarcities in time to the attention of the policy maker? What can authorities do to create needed markets for low carbon commodities and support associated infrastructure?

We focus in the subsequent challenge on the international facet of the industrial and energy transitions and dive into some aspects that need to be considered from a national perspective.

4.3.4 The national aspects in an international context

We live in an interconnected globalized world where each country has certain comparative advantages based on its geographical location and available resources. Accordingly, the supply and value chains for many goods are scattered all over the world, highlighting at the same time the inter-sectoral dependency of our economies. Therefore, the national nature of the energy transition should be examined in a global and international context which identify any potential feedback loops or spillovers between regions and sectors.

The global and complex value chains for energy intensive industries hinder the transition of these industries mainly because of the involvement of different countries along the value chain, which makes tracking the emissions and the use of inputs very hard in practice. Moreover, the markets for these inputs are global with high competition and low profit margins which makes the market position of companies very sensitive to any increase in costs, hindering the adoption of new, low carbon technologies (Oberthür et al. 2021; Fischedick et al. 2014). Issues arise due to different rules/laws across countries (e.g. Belgium, NL), e.g. export/import, waste management which makes industrial circularity difficult. Therefore, another determinant to the future energy and industrial mix is the position of the Dutch industry in the international industry map (global value chains and trade flows, ...etc.), which has a direct impact on the future portfolio of the Dutch industry and could give investors some clarity on the associated transition risks and opportunities.

There are several proposals that give guidance for the industrial transition in a global context. Oberthür et al. 2021 argue for an international decarbonization vision that aligns future orientation for basic material industries. They emphasize the role of having international rules in addressing the competition worries (ie, decrease in international competitiveness), along with incentivizing investments in new technologies and boosting circularity across global value chains. Bataille et al., 2018 call for each nation's climate policy to reflect the development of a decarbonized EII as a priority. Once this is established and communicated, each region needs to specify a pathway effort that is focused on the existing capabilities and the competitive (dis)advantages and potential markets. They further emphasize that trade routes and flows would change in volume and directions following a relocation of globally competitive industries towards places where renewable energy sources are available as these resources will become the main source of energy[2]. Respectively, they call for the development of ameliorated methodologies that incorporate dynamic trade in global and national modelling.

One should pay attention to the potential transition feedback loops that could emerge between regions or across sectors. For example, efficiency improvements in the production processes of final products might make the business case for investing in low carbon technologies of basic materials producers not feasible and thus hinder the transition of these industries (Löfgren and Rootzén, 2021).

The wide scope of this challenge induces many research questions/directions that require further investigation:

- What would be the possible range of possibilities for the Dutch industry in the new global industrial map and global value chains given the capabilities, resources, skills, political support, the present and post-transition comparative advantage, and the Dutch transition plans? Which activities will not have a competitive fit with the Netherlands and which ones will? How will the Dutch and international competitiveness shift as a result of the energy and industrial transitions? are there first-mover effects to 'claim' for certain industries? what are the anticipated changes in future value chains and – concomitantly – the changes in trade flows? how would global trade flows look like with the global change in energy sources, as well as materials and products?
- What are the spillover effects of different regional and sectoral transitions? what are the expected inter-regional, inter-sectoral, and intra-sectoral feedback loops that could emerge during the energy and industrial transitions? How should these loops be accounted for to achieve the transition for the Dutch economy?
- Which role do foreign investments play in the industrial/energy transition of the Netherlands? How can we attract low carbon investments to the

Netherlands? What is the role of multinational companies in shaping the path of the industrial transition of the Netherlands? How much control do we actually have over the transition of our industry, when the board rooms of companies are located abroad and have potentially different transition agenda's than those of the Netherlands?

- Learning from each other and exchange expertise: How are different countries dealing with the energy and industrial transitions? Where is the transition going well and why? What are the best transition practices from other countries and how they could be applied to the Dutch context?
- Acknowledging that our global dependencies will persist, how can we make use of those dependencies in the transition on a national and global levels? What are the existing vulnerabilities of the Dutch industry to different energy sources and suppliers? What is the effect of the energy transition on the geopolitical global balances and the other way around?

The subsequent challenge spotlights the coordination aspect of the industrial and energy transitions. It overlaps with some of the preceding challenges since coordination is needed on multiple levels.

4.3.5 The need for coordination

The energy transition is an unprecedented change with divergent views among involved stakeholders. The coordination between these stakeholders is needed to achieve a smooth and timely transition. Furthermore, the nature and urgency of the transition require immediate investments, even in the presence of uncertainties. Coordination is essential to determine the roles and risks each party needs to take to avoid lock-ins or any potential bottlenecks. Coordination could take place on multiple levels both between and within countries in a vertical (public-private) and horizontal (public-public[3] or private-private) direction. Moreover, we need cooperation across the supply chain, or different agreements on sharing risks and liabilities (Löfgren and Rootzén, 2021).

Coordination between economic actors does not evolve naturally through market dynamics even with the presence of carbon pricing or R&D subsidies because of the collective action nature of the problem. Rather, policies that are targeted towards cooperative arrangements are needed (Johansson et al., 2021). In line with this idea, Löfgren and Rootzén, 2021 argue that an effective policy to induce investments in abatement technologies could be through a combination of carbon pricing and other effective policies that overcome these barriers and bridge the gaps between different actors.

One of the important tools for coordination is to create a vision that is feasible and endorsed by involved stakeholders. One example of such a vision is Moore's law. This law is based on the empirical observation in the semiconductor industry which states that the number of transistors in a dense integrated circuit doubles about every two years. Everyone in Silicon Valley anticipated that every 24 months their capacity must be twice as good otherwise they will be outperformed and dropped off the market. Accordingly, Moore's law aligned expectation among market players and thereby the law acted as a coordination device for a long time. It formulated some sort of a vision and fortunately the industry could confirm and deliver to that vision. Thus, the vision was feasible, and it reduced uncertainty in expected outcome along with providing a planning horizon for at least 24 months to different stakeholders. However, the interesting aspect about this vision inspired by Moore's law is that it was not focused on the end state or goal, but rather the driving mechanism of progress through the years, which could be a useful one for the industrial and energy transitions.

In the literature, one of the effective transition pathways that help to create a common shared vision for different stakeholders from the public (government) and private domain (industry and society) would be a stakeholder-oriented pathway. Such pathway should be consistently revised, which help relevant stakeholders building a mutual strategy, cooperate, coordinate, manage and reassess the transition process as more information becomes available along the transition horizon (Battaille et al., 2018; Lechtenbohmer et al., 2015). Once this vision is created and collectively owned (i.e., is believed to be achievable), uncertainty is reduced and short- and long-term planning and decision making become more reliable, which help smoothing and speeding up the transition process. In the same direction, Mazzucato's mission-oriented framework reflects the need for a vision (Mazzucato, 2018). In her framework, setting the direction of a solution without specifying how to achieve success will stimulate and encourage different stakeholders to develop paths and solutions to achieve the objective.

The transition in some sectors could be governed on a national level, while other sectors, like heavy industry (which is exposed to international competition, has low profit margins and high costs for low-carbon investments that do not yet have a market), necessitate an international coordination to manage their transition (Bataille et al., 2018). Such coordination could materialize in the form of communication of regional visions and roadmaps for decarbonization of industries based on comparative (dis)advantages, regional and national capabilities (Colozza et al., 2021), future markets and products (aspired portfolio) (Bataille et al., 2018; Bataille et al., 2016; Williams et al., 2012). In this regard, there is a role for international organizations, like UN agencies, the World Bank, the World Trade Organization (WTO) and others, to address international coordination (Oberthür et al. 2021)[4].

Creating markets for new low carbon technologies or products could be achieved through a policy of public procurement. However, such policy could be less effective in risky projects where coordination is needed (Johansson et al., 2021). Accordingly, one could differentiate between process-based coordination and investment-based coordination. Process-based coordination includes coordination along the supply chain, where the adoption of new technologies is not always simple and straightforward, therefore, it requires coordination with suppliers and producers across the value chain. Furthermore, it could require adaptation and development for all these actors, along with the development of supporting infrastructure and appropriate skills and competences (Löfgren and Rootzén, 2021). Investment-based coordination refers to coordination of transition investments in a certain sector. For example, investing in electrolyzers might be hindered by the lack of supporting infrastructure, policies to correct incentives or create markets, or supporting technologies along the supply chain (Johansson et al., 2021). A first step would be to draw up a pathway which can then identify where cooperation or coordination is required, along with the prioritization of funding for R&D and piloting (Bataille et al., 2018).

Note that technologies differ across industries which could require a tailored policies/solutions for the industrial transition. Moreover, there might be a conflict with some laws (for example, coordination between stakeholders could conflict with the competition law) that needs to be taken into consideration. The focus should be on the articulation of the problem. Having a carbon tax only, there is a mismatch between the coordination problem and the intervention. Possible interventions could be to provide information along with signaling. Attention is needed for the fairness of solutions/interventions.

Johansson et al., 2021 argue that barriers related to collective action and coordination between different actors could be addressed through collaborative arrangements. These arrangements could evolve between private parties without or with small government intervention. Such intervention could be through enabling or initiating such cooperation whether on a central or regional level. An example for a successful coordination model that is largely based on cultural attitude is the Rhineland model. This model is rely on strong interactions between government and companies. Such a social contract between the government and companies would work as long as it induces benefits for all parties involved. In the same direction, Löfgren and Rootzén, 2021 identify four main coordination barriers that need to be addressed for smoother transition: timely deployment of supporting infrastructure; cross and within supply chain collaboration; international coordination; mobilizing and matching financing.

In the Dutch context, several initiatives and programs have been established to coordinate different aspects of the industrial and energy transitions. For example, the Dutch Ministry of Economic Affairs and Climate is developing the “Programma Energie Systemen” (PES), the “Nationaal Plan Energiesysteem” (NPE), and commissioned the “Expertteam Energiesysteem 2050” (ETES2050). The NPE looks at the 2050 horizon taking into account the energy system in a very broad sense, including people, behavior, justice, society, economy, industry, built environment, other sectors, the technical system (energy carriers, demand, supply). Within the ETES2050 a group of independent experts is developing an outlook on the future energy system for the Dutch government. Both, NPE and ETES2050, also include possible views on the future economy/industry and possible pathways. The PES on the other hand aims to facilitate cross-sectoral and cross-governmental collaboration. Furthermore, the Dutch ministry for Economic Affairs and Climate appointed in October 2019 the “Taskforce Infrastructuur Klimaatakkoord Industrie” (TIKI) with the task of identifying the bottlenecks in the energy infrastructure that hinder the industry from complying with the agreements in the climate agreement and coming up with solutions. The TIKI advised the cabinet to develop a “Meerjarenprogramma Infrastructuur Energie en Klimaat” (MIEK) for this purpose. The MIEK aims to accelerate the decision-making processes regarding large infrastructure projects that are of “national importance” and takes long time to be implemented. The Dutch Ministry of Economic Affairs and Climate supports the acceleration of MIEK projects, such that industrial clusters will have the right infrastructure in time to become more sustainable. MIEK projects are based on the “Cluster Energiestrategie” (CES), which are created by each of the industrial clusters. These contain their infrastructure needs (e.g. high voltage cables, 380 kV). One note is that the MIEK programmes are not transformative as they are made for existing industry with a goal to make these industries more sustainable instead of looking at the comparative advantages of the Netherlands and the position in the world.

Some of the Dutch initiatives and programs could be considered to form a vision for the Dutch industrial and energy transitions (NPE and PES). At the same time some of these programs adopt the mission-oriented framework in their setup (MIEK, CES).

Taking all the mentioned coordination aspects into consideration, we can formulate the following research questions/directions related to the coordination of the industrial and energy transition:

- How can we calibrate a national vision and the associated policies against the global process of industrial transformation? In that regard, further investigation on the barriers for international institutions to play their potential role in addressing international coordination is needed.
- There is a need for research that identifies policies and initiatives to develop new ways of cooperating, coordinating, and sharing information among actors in the supply chain and across sectors (Löfgren and Rootzén, 2021).
- We need a collectively owned vision that reflect a future image which is believable and feasible to all stakeholders. Are there different levels for such a vision? Would a vision on the driving mechanism of progress through the years be more suitable for the transition than a vision focusing on an end goal? How can such a vision be formulated? Who is responsible for forming it?
- The energy transition is a big coordination and lock-in problem which means that we could benefit from some years of direction by the government followed by an entrepreneurial state. What is the timeframe for such role of the state? What is the role of the government as a regulator and as a user/customer in the coordination exercise? What are the coordination problems that need to be solved on the public level so that the conditions for firms are set and adequate?
- Further research on how to overcome barriers to coordination across sectors and between industries is needed. One uncertainty related to sectoral transition is the induced cross-sectoral feedback loops (spillover effects). How will the transition in one sector affect the speed and direction of transition in other sectors? How to coordinate the transition across sectors and industries in a way that minimizes the adverse feedback loops?
- How to coordinate the transition without quantity targets? That is, further insights on the coordination of the different impacts of the transition: social, economic, environmental, and even political are needed.

The final subsequent challenge focuses on the impediments and drivers for an effective role of finance in the industrial and energy transitions.

4.3.6 Financing the transition

Finance has an essential role to play in boosting the transition by steering the needed funds towards low carbon innovations and investments (Löfgren and Rootzén, 2021). In this regard, there is a role for public and private finances. Moreover, Busch et al., 2018 highlight that finance is one of the main drivers for a well-functioning innovation system both from public (R&D subsidies, tax relieves for early-stage projects/markets, et cetera) and private sources (finance for market diffusion).

So far financing the transition is not at the required levels as there is still a mismatch between the potentially available funds and the needed level of climate investments (Egli et al., 2022). DNB, 2021 highlights several reasons for this inadequacy of funds. The first reason is the underpricing of negative externalities which weakens the business case for sustainable low carbon projects vis a vis carbon intensive project.

The uncertainty of government policy is the second reason that affects the sustainability business case adversely through the lagging share of sustainable finance in overall finance stream. A third reason would be the high risk for climate investments due to immaturity of sustainable technologies and businesses which mismatch the risk profile of private financiers and results in insufficient funding. That is, the business case for innovative investments which involve inevitable financial uncertainty (van Tilburg, 2016) is not competitive in the current market. Thus, private finance for the innovative transition investments is in limited supply. Additionally, other traditional ways of finance (banks) do not have an appetite for such kind of finance. Moreover, the wideness of needed adaptiveness along several chains of products and processes necessitates the coordination between different investors and financiers in certain sectors. Another issue that faces financiers is the information asymmetry on the sustainability and climate related risks position of companies which holds back the flow of funds for the transition and hold back on new financing (DNB, 2021).

Governments can play a role in addressing the impediments that hamper the optimal role of finance in the transition. Polzin, 2017 calls for an adaptive policy design where policy makers obtain the necessary skills and knowledge to overcome the impediments to low carbon innovation. Such policy design would entail (innovation) stage-specific policy instruments that help reducing uncertainty and help redirecting private finance towards low carbon technologies. Polzin, 2017 further suggests connecting public support with private finance in an effective and efficient way to help the technological transition. For example, a consultation process between policy makers and private stakeholders to jointly determine and specify future finance needs will deliver reliability, and result in a calculable risk and returns, which in turn help maximizing private finance in the needed direction. Regarding the instruments that trigger and mobilize private investments in renewable energy sources, Polzin et al. 2019 argue that the type of the instrument has a partial role in affecting private finance, emphasizing at the same time the role of policy design characteristics and implementation which induce an impact on risks. In the same direction, DNB, 2021 suggests a stronger role of the government in addressing the coordination problems between investors and financiers in sectors that face such obstacles, along with promoting investments in new innovations and its financing to reduce uncertainty for private investors. This can be done by promoting the market for equity finance and financial innovations without affecting the stability of public finances. DNB, 2021 further emphasizes that for investors to assess whether innovative projects are transition enhancing, climate reporting should be forward-looking. Egli et al, 2022 mention that direct market activity of state organizations can be one of the potentially effective policy instruments to boost socio-technical transitions. Not to mention that financing innovation needs to be long term and patient over the lifecycle of innovation (Mazzucato and Penna, 2015).

Several research questions/directions related to the challenge of financing the industrial and energy transition need further investigation:

- The financial sector is linked directly or indirectly to almost every aspect of our economies. Climate related transition risks to the financial sector originate when an abrupt sudden transition towards a low carbon economy take place, which induce assets to become stranded and could initiate a cascading effect on the financial institutions with an exposure to these assets. Quantitative measures for climate related financial risk are not yet well-established. Modelling and predicting climate risk require novel tools that combine climate and financial modelling. Scenario analysis and stress-testing is one of the methods that been promoted to use in the absence of needed data. Stress-testing studies increase our understanding on the effect of different shocks on firms and the stability the financial system. Stress-testing studies so far focused on one kind of shocks at the time. However, recent developments highlighted the need for investigating the impacts of combining acute shocks (such like COVID or the current Ukrainian war), conventionally studied shocks (i.e. supply shocks), and policy driven shocks (for example, carbon taxes) on the transition and the stability of the financing system as a whole. On a different related issue, the quality of models used by policy makers should be ameliorated by incorporating better finance modules that embody an understanding on how to match the available funds in different assets with the dynamics of demand of the transition (Egli et al, 2022).

- What are the socio-economic impacts of supporting different kinds of investors especially regarding inequality, energy justice or social acceptance? (Polzin et al., 2019).
- From the lens of the transition, it is important to understand where finance could form bottlenecks that could hinder the transition and identify the potential instruments/interventions to avoid such bottlenecks in time. To that end, data and more research is needed on the impacts of different types of finance for the energy transition, with an emphasis on riskier non-traded type of assets (Egli et al, 2022).
- Research is needed on understanding and quantifying the link between different instruments at the disposal of central banks and the government and the real asset cost of capital. This would help in a better designing an effective policy intervention for less mature low-carbon technologies in different sectors, which help the transition further. Also, the link between financial markets and the cost of capital of real assets should be conceptualized to better understand how the maturity of the technology, the structure of the financial market and the available types of finance could determine the cost of capital of different assets. (Egli et al, 2022).
- There is a need for financial innovation that link the supply of different types of finance to the needed demand for green investments. Such innovation would help spreading additional transition related credit risks among multiple financiers and scale up sustainable investments (DNB, 2021).

Finally, we emphasize that the proposed list of challenges or research directions is not exhaustive as it was inspired by conversations with relevant stakeholders within the Dutch industrial sector. However, these challenges and research directions are of generic nature which make them relevant to industrial and energy transitions in countries beyond the Netherlands.

4.4 Conclusion

This chapter identified six challenges for the industrial and energy transition. These challenges were inspired by conversations and meetings with relevant stakeholders (academics, industry and government representatives, experts, and others), along with desk research that highlighted part of the related state of art of the identified challenges. The chapter concluded each challenge with a list of future research questions/directions that require further investigation to understand and help the industrial and energy transition further.

The first challenge relates to the ambiguity of the aspired Dutch portfolio for future products. More precisely, this challenge emphasized that the rational for the Dutch EII should be revisited given the scarcity of the renewable energy sources in the Netherlands. Furthermore, under this challenge research is needed on the role of existing assets in the transition.

The second identified challenge is focused on the pathway to a fully decarbonized system highlighting the need for investigating the empirics of demonstration effects of previous transitions to determine the similarities, differences, and the degree of adaptiveness of transition processes across sectors. Also, the challenge accentuates the importance of understanding the transition speed and its drivers. There is also a need to better understand the mechanisms by which lock-ins emerge and evolve overtime and across sectors which will help in expecting and evaluating the degree of path dependency and the materialized transition path.

The subsequent third challenge focuses on the tools that can used to steer the transition to a specific direction and questioned the adequacy of market mechanism to drive the transition. This challenge concluded with a research agenda that help identifying the roles of public and private stakeholders in the transition and the tools that could be used to address transition scarcities, risks or opportunities in a timely manner.

The fourth challenge took an international perspective for the transition process. Needed research directions incorporated the future possible position of the Dutch industry in the newly global industry map and global value chains given the different aspects of the Dutch economy, and the current and future competitiveness of the Dutch industries. Furthermore, there a need for further investigation on the role of foreign direct investments, multinational companies, global dependencies and Dutch vulnerabilities to energy sources and suppliers in forming and affecting the Dutch transition process/plans.

Coordination on multiple levels is being identified as the fifth challenge to avoid lock-in and solve any potential bottlenecks in time which help the transition to move forward. The challenge emphasized the role of having a vision to coordinate the actions of involved stakeholders towards a mutual transition goal. Such vision could also provide a driving mechanism of progress through the years. Moreover, the challenge recognizes the international position of certain industries to require a coordination on an international level to manage the transition of such industries. The challenge is concluded with several future research directions linked to coordinating the transition across sectors and across the social, economic, environmental, and even political aspects of the transition in order to address any possible unintended feedback loops.

Finally, the role of finance in the transition process constituted the sixth challenge for the industrial and energy transitions. Acquiring more data on the impacts of different types of finance for the energy transition is important for understanding where finance could form bottlenecks that could burden the transition. Additionally, the challenge displayed a need for new modelling techniques that incorporate new financial modules, along with the requirement for financial innovation linking available funds and the demand for climate investments would help spreading additional transition related credit risks among multiple financiers and scale up sustainable investments.

This chapter could be used as a base for an industrial and energy transition program for NWO. Such a program would envision six lines of research that correspond to the six identified challenges. Multiple research projects inspired by the future research directions under each challenge could be commissioned.

5 Concluding remarks

This report consisted of three chapters, each focusing on a different challenge within the energy transition: the infrastructural challenges of a multi-carrier energy mix, the spatial challenge and the business challenge of the industrial and energy transition. The joint aim of the papers was to distinguish the most important questions and challenges related to those three perspectives on the energy transition within the context of the Netherlands and to propose a research agenda for further investigation, to be used for future research funded by the Dutch Research Council (NWO). Although each chapter had its own specific focus, four mutual themes could be identified: scarcity, uncertainty, lock-in and governance. Challenges and questions from the multi-carrier energy system, spatial and business perspective relating to these common themes are discussed in the following paragraphs. Consequently, a comparison is made with an overview that has been published by the Expert team for the energy system of 2050 in parallel to this work (Expertteam Energiesysteem 2050, 2022).

The first common challenge identified by the three papers is **scarcity**. For instance, material scarcity can influence the choice for one specific energy carrier over another. This is an important challenge for the scale up of specific assets needed in the energy transition, such as batteries and electrolysers. The development of renewable energy projects also requires expansion of electricity infrastructure, which is hindered mainly by the scarcity of technical personnel, materials and space in the Netherlands. Additionally, the use of biomass or green gas in mobility is deemed less desirable due to the scarcity of agricultural land and the resulting competition with food production. Furthermore, the scarcity of available space in the Netherlands was identified as one of the main challenges for the energy transition in the future, especially considering the lower power density of renewable energy technologies compared to their fossil-based counterparts and the fact that the available land is also needed for climate adaptation, circular economy, accessibility and housing. As a result, dealing with this scarcity of space is expected to be a leading driver for future innovations of renewable energy technologies, allowing for more efficient use of space and synergies with other spatial functions. As both material and spatial scarcity can slow down the development of renewable energy projects, renewable energy sources themselves could become a temporarily scarce resource within the energy transition, which can cause transition failure, where the government fails to act in time to address the emerging short-term transition scarcities. Therefore, questions were raised about which transition scarcities can be expected and how can they be addressed in time. Further, the inadequacy of market mechanisms to allocate such scarcities in an optimal manner from the transition perspective was emphasized and the need for further investigation on the roles of different stakeholders in the transition process was highlighted.

The second common challenge is **uncertainty** - the most important uncertainty being what the energy system of 2030 and 2050 will look like, which causes challenges from all three perspectives in this report. This uncertainty is partly a result of the uncertainty of the aspired portfolio of products needed in the future, the optimal path for the transition, the role the government to direct the transition to the aspired direction and the effectiveness of policy measures. As a result, uncertainties about which energy carrier to use in different applications and locations lead to uncertainties about the required development and placement of infrastructure and the necessary intersections between multiple infrastructure networks. Moreover, uncertainty in demand, supply and infrastructure development also leads to uncertainty in the spatial embedding of energy projects, which is amplified by challenges related to competition with other spatial uses and interests, electricity grid capacity constraints and uncertainty in the public debate. Ultimately, the sum of uncertainties may translate into lower public and private investment levels than are required to meet the targets. Hence addressing uncertainty and coming to grips with investment under uncertainty is a key task.

The third common challenge identified is **lock-in**. This concept, specifically ‘carbon lock-in', has been extensively used to explain the persistent global use of fossil fuels, despite the well-known fact that the associated green-house gas emissions contribute to climate change (Klitkou, 2015). In this work, the concept of lock-in of high-carbon technologies is addressed and how this affects the path of the energy transition. The need to better understand the mechanisms by which lock-ins emerge and evolve over time and across sectors was emphasized. Such understanding will help foresee and evaluate the degree of path dependency as well as determine the roles and risks different stakeholders need to take to avoid further carbon lock-ins from occurring. Looking towards the future energy transition, other types of technological lock-ins and path-dependencies were distinguished, such as the lock-in of electric vehicles, due to the faster development of charging infrastructure compared to the lack of hydrogen infrastructure for hydrogen powered vehicles. Furthermore, in contrast to the example of vehicles, the announced large-scale hydrogen infrastructure in the Netherlands can cause a long-term lock-in in the industry, forcing them to use hydrogen as energy carrier while it could be the case that another carrier better fits their energy demand. Next to technological lock-in, the concept of spatial lock-in was introduced. A renewable energy installation lays claim on available space in a specific location, as well as the available resources and available infrastructure capacity. Therefore, this choice can limit further possibilities of using that same space and resource for other purposes. Furthermore, safety and hinder regulations result in exclusion zones around energy assets, which limit other uses in the areas surrounding energy projects, e.g. housing near wind turbines.

The final common theme is **governance**. Firstly, all perspectives show that cross-governmental alignment and cooperation is needed for a successful energy transition, both through different levels of governance within the Netherlands as well as with governments from countries. For instance, there is a need for international cooperation to manage the industrial transition, due to the international position of many energy-intensive industries. Secondly, the importance of an integral approach in the energy system was underlined, which calls for cross-sectoral cooperation. A specific challenge related to the multi-carrier energy system is that different infrastructure networks are currently organized in silos. Furthermore, only looking at the energy transition ‘sectorally’ could risk potential spatial conflicts with other spatial uses in future, posing a barrier to the development of energy projects. Therefore, the importance of social acceptance of energy technologies and the need to increase synergies between the energy transition and other societal challenges was highlighted. Several future research directions were recommended linked to coordinating the transition across sectors and across the social, economic, environmental, and even political aspects of the transition to address any possible unintended feedback loops.

While conducting this NWA research, the Dutch minister of Climate and Energy appointed an independent interdisciplinary expert team on the energy system of 2050 in April of 2022. Their task is to describe what the energy system of 2050 should look like, which is needed to achieve the climate goals defined in the Climate Agreement.

In May 2022, the expert team published the starting points which form the basis of the Outlook of the Energy System of 2050 that will be published in 2023. This outlook will be used as input to the National Plan for the Energy System. Interestingly, certain parallels can be drawn between the leading principles, enabling conditions and questions posed by the expert team and the knowledge agenda from our three papers. To deal with the uncertainty of the future energy system, the expert team has identified leading principles which should guide the decisions made on the road towards 2050. These address amongst others quality of the living environment and public engagement, efficient use of scarce resources and spatially justifiable choices. Similar to our work, the expert team underlines that for a successful transition an integral approach is required, which necessitates collaboration between different governmental departments and levels of governance, as well as between different sectors and actors. Important enabling conditions which facilitate the realization of the transition include governance, innovation, financial systems change and governmental instruments. Compared to this work, the expert team put a stronger emphasis on public values, such as security of supply, affordability, safety and public engagement. Additionally, citizens' assemblies ('burgerberaad') are mentioned as an important tool to engage and consider the wishes of the public in the energy transition.

In conclusion, this work identified a wide range of challenges that we face in the process of transitioning from a fossil-fuelled system towards a sustainable, renewable energy system in the future. These challenges together shaped a comprehensive research agenda that should help focus future research efforts into the energy transition in the Netherlands, thereby accelerating our transition to a clean energy system.

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Appendix 1. Overview of multiple energy scenarios for The Netherlands

	Energy function	KIVI: Design for a Dutch Carbon free energy system (2020)	II3050 Regional	II3050 National	II3050 European	II3050 International	Kalavasta/Urgenda report	Industrie: Routekaart industriële elektrificatie	TNO ADAPT	TNO TRANSFORM	Conclusions
Mobility	Passenger cars	100% electric: 28 TWh	100% electric	95% electric, 5% hydrogen	70% electric, 30% hydrogen	50% electric, 40% hydrogen, 10%	biobased replaced by				At least 50% electric, probably not biobased.
	Freight transport	Hydrogen fuel cell EV: 30 TWh + 5TWh for compression	75% electric, 15% hydrogen, 10% green gas	50% electric, 25% hydrogen, 25% biofuels	25% electric, 25% hydrogen, 25% biofuels, 25% green gas	50% biofuels, 25% electric, 25% hydrogen	biobased replaced by electric		Hydrogen, 9,81 PJ biomass for all inland transport	Hydrogen, 85,6 PJ biomass for all inland transport	Mainly electricity and hydrogen as energy carriers in 2050
	Inland shipping	Hydrogen fuel cell EV: 14 TWh	100% bio-LNG	100% bio-LNG	100% bio-LNG	100% bio-LNG					
	International shipping		1% decrease - Synthetic fuels made by 12 GW offshore (=113PJ) and 391 PJ import	Equal demand - Synthetic fuels made by 21 GW offshore (=188PJ) and 495 PJ import	1% growth - Synthetic fuels made by 12 GW (=110PJ) offshore and 844 PJ import	1% growth - Synthetic fuels made by 11 GW offshore (=100PJ) and 938 PJ import			304 PJ biofuels and 164 PJ synthetic fuels from hydrogen and CO2, 310 PJ fossil fuels	215 PJ synthetic fuels and 215 PJ imported biomass	Large part synthetic fuels, perhaps ome imported biomass
	Inland Aviation or international	100% synthetic fuels: 3,2 TWh				2% growth					100% synthetic fuels, at least 77% of energy imported. Together with shipping a minimum of 500PJ
	Total		*143 PJ*	*225 PJ*	*350 PJ*	*377 PJ*					
Built environment	Heating	heat nets: 20 TWh excess heat, electricity heat pump: 25 TWh x COP 4 = 100 TWh	heat nets: 45% geothermal/greeng as/biomass, heat pump: 35% elec & 20% hybrid HP green gass = 203 PJ	heat nets: 25% geothermal/greenga s/biomass, heat pump: 55% heat pump & 20% hybrid green gas = 189 PJ	heat pump: 40% hybrid green gas & 20% hybrid hydrogen & 25 elec, heat net: 15% waste heat/green gas/biomass = 213 PJ	heat pump: 60% hybrid hydrogen, 25% elec, heat net: 15% waste heat/green gas/biomass = 215 PJ	Green gas & biomass replaced by electricity or hydrogen		10% natural gas, 1% hydrogen, 10% biomass (49,5 PJ), 16% ambient heat, 10% electricity, 1% other, 50% external heat	9% natural gas, 1% hydrogen, 10% biomass (56,4 PJ), 18% ambient heat, 11% electricity, 1% other, 49% external heat	Around 25% - 55% of built environment will have a all-electric or hybrid heat pump. Probably around 40% heat nets. Difficult to electrify or heat net: around 10% green gas (or hydrogen). Note for heat networks that some waste heat sources will not exist in 2050.
	Cooking	included in 127 TWh for appliences	50,6 TWh	50,4 TWh	50,9 TWh	50,9 TWh					Not often included in analyses. According to II3050 around 50 TWh
	Appliences	included in 127 TWh for appliences									
	Output	47 GW PV, max. 65 % of roofspce used for solar panels	42 GW pv, 38 PJ solar thermal energy	35 GW PV, 18 PJ solar thermal	17 GW PV, 16 PJ solar thermal	13 GW PV, 12 PJ solar thermal					Total current PV capacity is 10,2 GWp, so at least 30 GWp in 2050 will not be strange. Thermal heat also has potential to grow to at least 30 PJ
Industry	High temperature heating processes (> 100°C)	electricity: 26 TWh electricity, hydrogen: 27 TWh for ammonia production & 13 TWh for heat, 20 TWh for steel production	Electricity and green gas	Electricity and hydrogen	Electricity and hydrogen	Electricity, hydrogen and fossil + CCS	Green gas replaced by electricity or hydrogen	Minimal 80 TWh electricity in 2050 for electrification of industry and its required hydrogen	471 PJ biomass, 141 PJ hydrogen	152 PJ biomass, 146 PJ hydrogen	Electricity will play the largest role, together with hydrogen and green gas. Likely that fossil + CCS and biomass are transition solutions that have to wait for lower hydrogen prices. At least 80 TWh for direct electricity use and indirect electricity use (hydrogen production) is realistic.
	Medium temperature heating (< 100°C)							Minimal 80 TWh electricity in 2050 for electrification of industry and its			
	Other manufacturing	included in 127 TWh for appliences	Circular feedstock	Circular feedstock	Fossil feedstock	Fossil feedstock		Minimal 80 TWh electricity in 2050 for electrification of industry and its			
	Datacenters		41,6 PJ, 100% electri	41,6 PJ, 100% electrici	41,6 PJ, 100% electricity	41,6 PJ, 100% electricity		Additional 15 TWh			Around 15 TWh electricity only. Currently, heat output of 6,3 PJ (Berenschot, 2018).
	Total exl feedstock?	*86 TWh*	*414 PJ = 115 TWh*	*545 PJ = 151 TWh*	*718 PJ = 199 TWh*	*760 PJ = 211 TWh*					

Appendix 2. Interview guide for technology experts

During the expert interviews in step three, the following questions were asked (where X is the technology in question):

1. What are the spatial aspects (direct, indirect) of the X?
2. Which forms of multiple space use are now (or conditionally) possible with X?
3. Which forms of multiple space use with X are conceivable in the future?
4. Which challenges do you foresee for the spatial integration of X?
5. Which other spatial claims currently and in the future compete with X?
6. What are the most important technological developments in the next 20 years that will affect the energy or power density (energy generation/direct area) of X?
7. What are the most important technological developments in the next 20 years that will affect the technical indirect spatial claim of X?
8. What are the most important technological developments in the next 20 years that will affect the legal indirect spatial claim of X?
9. What are the most important technological developments in the next 20 years that will affect the opportunities for multiple land-use of X?
10. What spatial integration issues of X should be further explored (through a future NWO route)?

For the legal interview, the following questions were asked:

1. Which future legal developments (20-year time horizon) do you foresee that will increase or decrease the spatial claim of the energy transition?
2. Wat are the implications of the new Environment Act (on e.g. spatial procedures for energy projects)?
3. What is the link between technological developments of energy technologies and their legal claim on space?
4. What are the most important knowledge questions you see, around the spatial integration of renewable energy technologies?

Appendix 3. Technology specific research directions

In the interviews the TNO experts identify technology specific research directions related to space, an overview sorted by technology.

1. Hydrogen

The main uncertainty to determine the future space claimed by hydrogen production, is to what extent we will need hydrogen. How much will be produced in the Netherlands and how much will be imported, also considering the energy security and costs?

Concerning the related technologies, what will be the spatial implications of:

- the use of hydrogen for the production of synthetic fuels?
- the choice of hydrogen carrier (methanol, ammonia, …)?
- electrolysers on land or at sea?

Finally, to what extent will the national hydrogen backbone become a structuring element for spatial developments?

2. PV

What will be the expected social acceptance of PV, integrated into the environment (cars, buildings, etc.) and how can this acceptance be increased?

There is a need for more funding to look at floating PV aspects or infrastructure projects, as it requires a lot of money to make these projects happen.

3. PT

Which strategies will we choose for natural gas-free neighborhoods and the heat transition? Are we going for solar heat? Will we use solar heat for heat networks or building integrated applications?

Concerning heat networks:

- How can the temperature level of these networks go down (50-30 C)?
- How will we store heat and what is the spatial impact of such a storage?

4. Offshore wind

Concerning offshore wind, the following questions arise:

- How to integrate it with other systems and thus reduce the spatial claim?
- Will the technologies interfere with each other at offshore energy hubs? There are no studies yet on how to optimally integrate the technologies in spatial terms (such as floating sun and offshore wind).
- How can offshore wind coexist with nature, both in the air (birds, bats) and in the sea (marine life)?
- How will regulations regarding shipping and fishing develop along with technological developments?

5. Onshore wind

More research needs to be done on:

- Social acceptability
- Ecological effects
- Regulations/policy regarding the technical aspects of cast shadow and noise.

6. Underground energy storage

Can a better characterization of underground potentials be made (storage, detailed screening of offshore domain for empty gas fields, storage) so that you can include the subsurface in the above-ground plans?

Inspired by the North Sea Energy Atlas, can layered maps of the Netherlands be developed for people who are working with the new environmental planning act, coupling spatial and technical requirements?

More research and awareness is needed for the possibilities of underground energy storage, as this could move current space claims on land to the subsurface.

7. Ocean energy and hydropower

Most of these technologies (wave energy, blue energy, tidal- and hydropower) are still in full development.

Concerning wave energy, pivotal space related questions are:

- Where can they be located and how much energy will these locations provide?
- How can the technology be optimized by combining it with other spatial uses?
- How much space is needed per converter?

For blue energy, the following main questions were brought forward:

- What are the environmental effects?
- What scale we're going to do it, as the scale of the technology will determine whether we need to build additional dams?