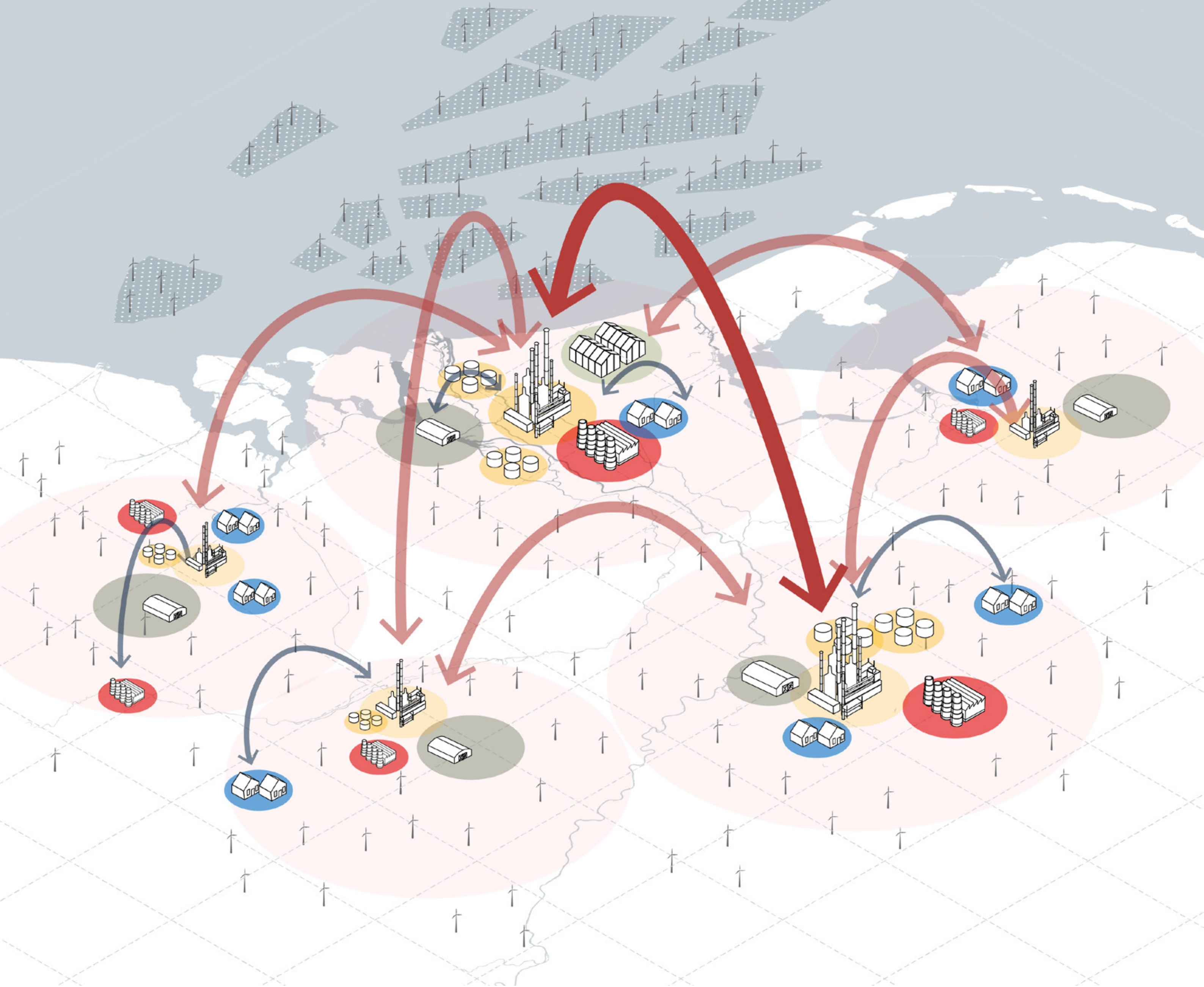

RETURN OF THE INDUSTRIES AS NEW GREEN HUBS

Introducing Circular Hydrogen Landscapes for Energy Systems in Northwest Europe

Delft University of Technology - MSc. Urbanism
(Architecture, Urbanism and the Building Sciences)

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Author I Student number I Email

R. Ebbers – 5725607 -
S. Jocker – 5895421 -
P. Rautela – 5784786 -
A. Valcarcel - 5745063 - I

Tutors

dr. N. Katsikis & dr. R. Cardoso

with additional input from

dr. R. Rocco & dr. M. Dabrowski

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Abstract

The Earth is experiencing an increase in global surface temperature due to a significant amount of greenhouse gas emissions, mainly caused by the production of fossil-fuel-based energy using non-renewable resources. The heavy industries, predominantly comprising refineries, are the primary contributors to these emissions. As the primary source of energy for these industries is also fossil-fuel-based, the European Green Deal emphasizes the need for an energy transition. However, renewable energy production requires a large area, and the current energy grids are overloaded due to the lack of energy storage possibilities. A potential solution to the storage issue could be the implementation of green hydrogen. As refineries are expected to be decommissioned soon, hydrogen plants could be established in their locations, repurposing the existing infrastructure of pipelines and storage facilities. These plants would enable circular energy systems, converting hydrogen to energy using the green hydrogen production method of electrolysis, and vice versa, using fuel cells. Moreover, these redevelopments could be implemented on a larger scale, resulting in the creation of a hydrogen backbone in the Eurodelta, connecting the industrial clusters within this area and making the energy system more resilient. For the execution of a hydrogen energy system in the Netherlands, a strategy has been proposed that involves a centralized main hydrogen production and storage zone in the Port of Rotterdam, including new industries with hydrogen input and future high energy-consuming industries. Renewable energy production would be installed using offshore vertical-axis wind turbines and onshore horizontal-axis wind turbines, photovoltaic panels, and biomass. This approach would also allow for the introduction of additional green areas, improving working conditions and air quality for the re-educated industrial workforce. In addition, a second strategy involves the implementation of a decentralized energy system in an agricultural landscape in the Municipality of Zutphen. These exemplary areas can be used as models to implement this idea in similar regions across Northwest Europe. Future research could focus on technological innovations, economic feasibility, and additional limitations of the introduction of hydrogen energy systems, ensuring the return of industries as new green hubs.

Key words: Circularity, Hydrogen, Industries, Refineries, Renewable Energy

CONTENT

01. Introduction: The Energy Transition

Image 1

Image 2

Image 3

1.1 The Problem with Fossil Fuels

These days, the news is flooded with mentions of the increasing global surface temperatures and its foreseeable consequences. The IPCC (2023) mentioned that human activities, mainly through emissions of greenhouse gases like CO_2, have unequivocally caused global warming. As can be seen in figure 2., global surface temperatures have reached 1.1˚ C above the levels between 1850-1900 during the years 2011-2020.

The conclusions regarding the cause of global warming by the IPCC in 2023 are not new. The same panel already made these conclusions in their first assessment report (1992) by mainly criticizing the emissions of greenhouse gases. Despite these findings, global greenhouse gas emissions have continued to increase over 2010-2019 (figure 1.), with unequal historical and proceeding contributions arising from unsustainable energy use, land use, lifestyles and patterns of consumption and production covering regions, between and within countries, and between individuals. (IPCC, 2023)

To keep global surface temperature rise below 1.5˚ C, huge CO_2 and other greenhouse gas emission reductions are needed. Although, keeping it below 1.5˚ C is already a huge task since the reduction in CO_2 is that high. Figure 7 clearly shows that the longer we wait with reducing CO_2 emissions, the steeper the curve to keep global surface temperature rise below 1.5˚ C will be.

The European Commission (2022) states that the production and use of energy account for more than 75% of the overall EU's greenhouse gas emissions. This is mainly caused by using oil, gas, and coal to produce energy which, besides greenhouse gas emissions, have two additional implications.

Image 1. Dependencies on Russia gas. Adapted from Foreign Policy (2022).

Image 2. Coal mines in Germany. Adapted from Verheyen (2016).

Image 3. Burning of fossil fuels. Adapted from National Geographic (2022).

Figure 1. CO_2 emissions in North West Europe
Source: European Environment Agency (2022a)

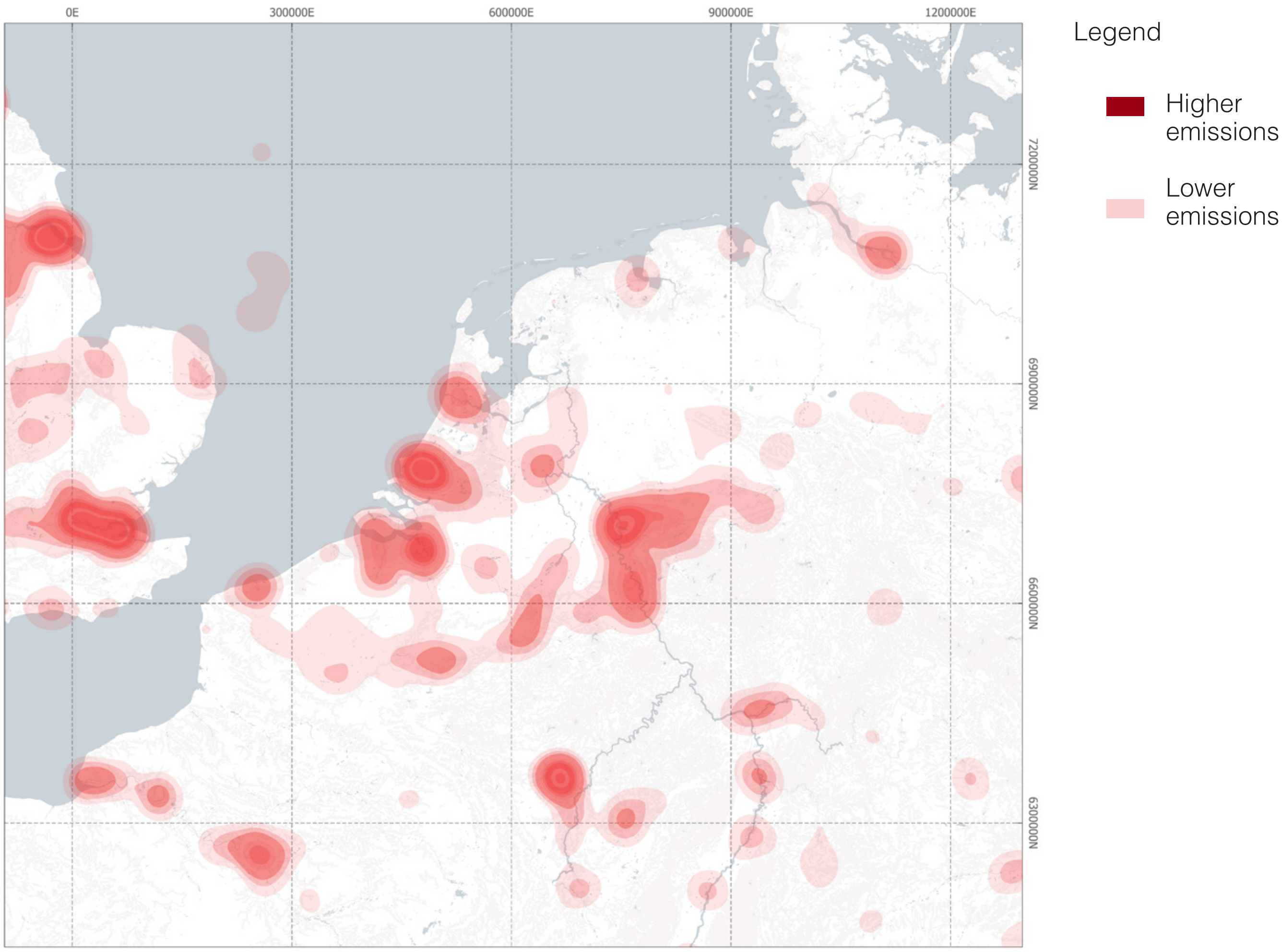
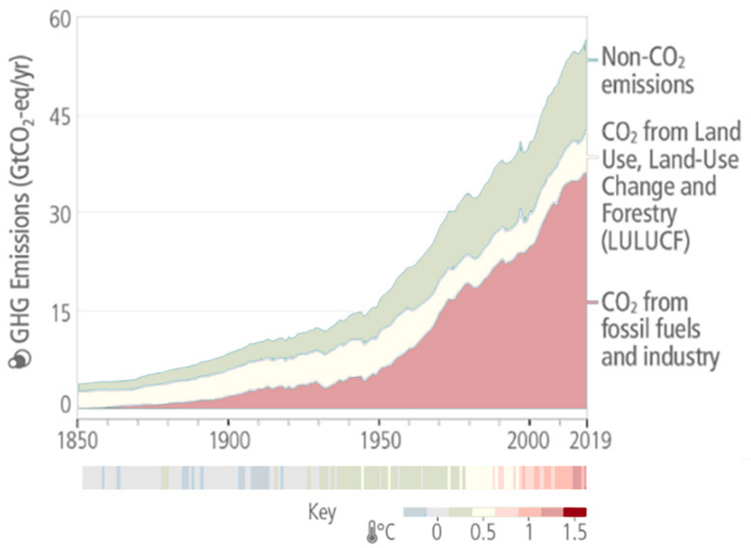


Figure 2. Greenhouse gas emissions resulting from human activities continue to increase
Source: IPCC 2023 (adapted)



First, the use of fossil fuels is finite. The resources are mined in the Earth and will ultimately be depleted in the future. Therefore, we are not able to keep on using these types of fuels and must transition to renewable sources.

Secondly, the origin of these fossil fuels has shifted from being inside the borders of the European Union to other parts of the world. Take for example the Netherlands, since 1990, there energy production has decreased by 55.02% (IEA, 2020) and have since been heavily dependent on gas imports from all around the world and mainly Russia (figure 3.). Since the start of the war by Russia in Ukraine, the import of Russian gas has been boycotted meaning that these imports should come from other countries keeping the worldwide emissions of greenhouse gases high, or to shift the origin of energy to renewables.

Decarbonizing the energy system in the European Union is a critical point on the EU's agenda to reach the 2030 climate objectives and the long-term strategy of achieving carbon neutrality by 2050. The program to achieve this goal has been titled the European Green Deal. Several objectives of the European Commission (2022) part of the energy transition to achieve this are:

- Build interconnected energy systems and better integrated grids to support renewable energy sources.

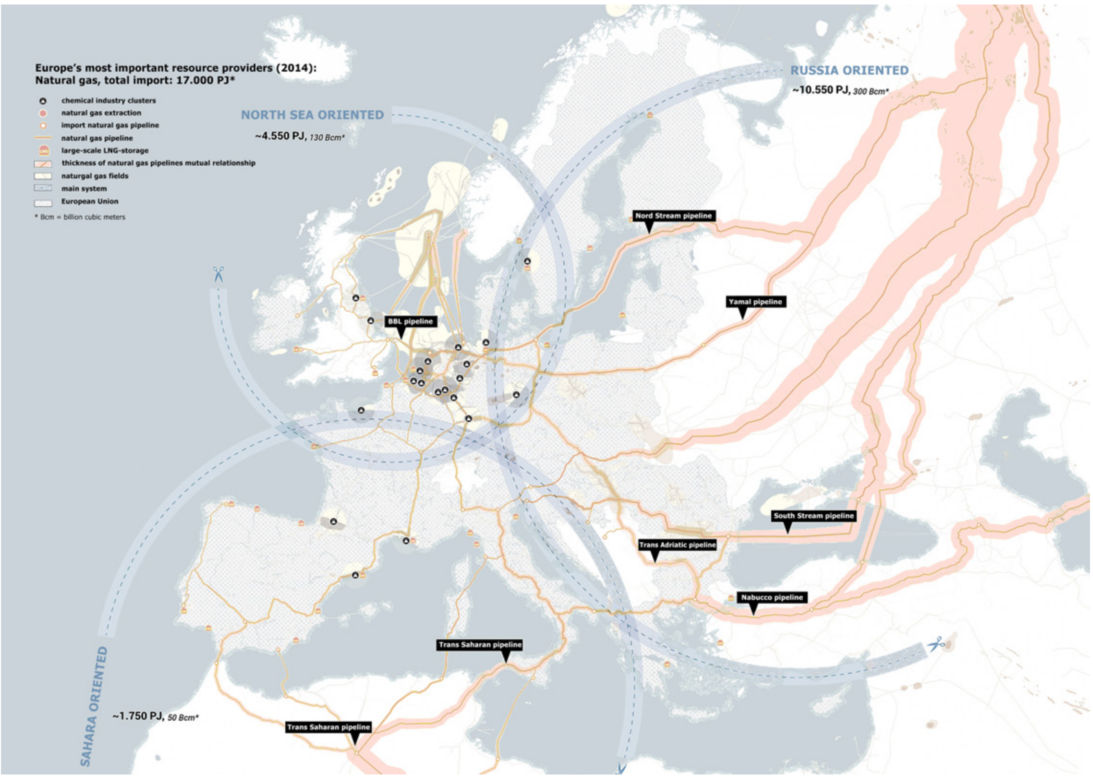
- Decarbonize the gas sector and promote smart integration across sectors.

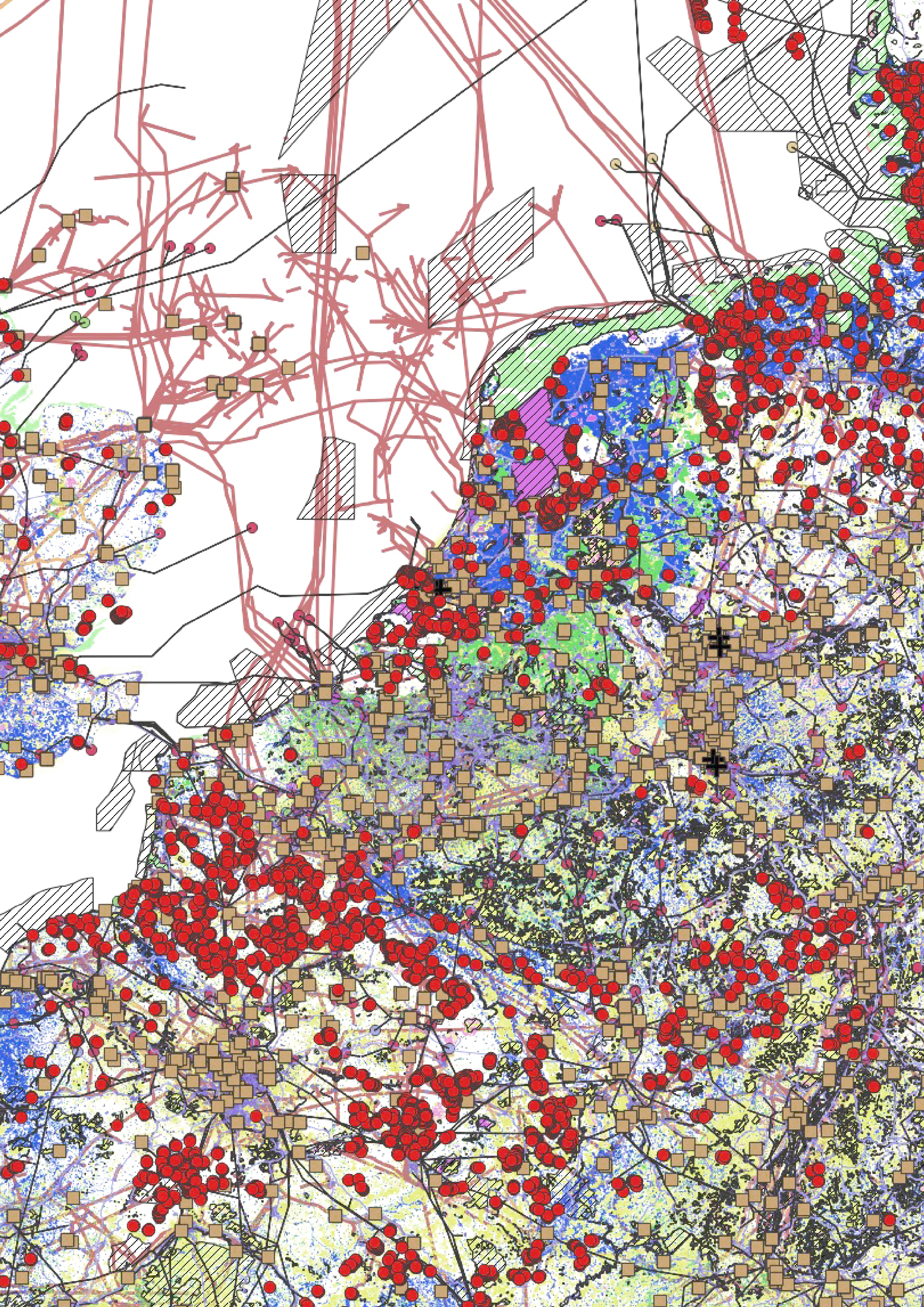
- Empower consumers and help EU countries to tackle energy poverty.

- Promote innovative technologies and modern infrastructure.

- Develop the full potential of Europe's offshore wind energy.

Figure 3. Geopolitical dependencies on natural gas
Source: Studio Marco Vermeulen 2021 (adapted)





1.2 Challenges of Renewable Energy

For the shift from fossil fuel energy to renewable energy several barriers are in place that currently hinder this energy transition. The European Green Deal was approved in 2020 whilst stating that CO_2 reductions should appear as soon as possible. Looking at Europe's biggest sources of electricity per country in figure 5., you can clearly see the northwestern European countries still being heavily reliant on fossil fuels for their energy production. This is also shown in the CO_2 emission clusters for this region in figure 1. All in all, this shows that northwestern European countries still need to invest a lot in the production of renewable energy by installing more photovoltaic panels and wind turbines to change their main energy source.

Unfortunately, renewable energy sources cannot be installed easily due to an overload of the energy grid in e.g., the Netherlands (figure 8.) This means that in certain municipalities, people are not allowed to connect newly placed photovoltaic panels since the energy grid cannot handle additional energy input due to a lack of energy storage possibilities.

The second problem of renewable energy is its volatility. The temporal variation of electricity demand and supply using renewable energy sources can be seen in figure 6. This fundamental problem with renewable energy sources is well known where a future low-carbon energy system will likely face periodic mismatches. To deal with this high volatility of renewable energy sources, a mechanism is needed to be able to make most use of the energy generated, energy storage would therefore be the main solution. (Abrell et al., 2019)

Furthermore, for most European countries, the current energy grid is completely centralized, meaning that all energy consumers are linked together. This can also be linked to the energy grid congestion currently happening in the Netherlands. Due to a centralized grid, energy cannot be transported between regions looking at the supply and demand of energy in a given moment. Decentralized energy systems could be a solution for this problem and the current energy grid congestion.

Figure 4. Visualizing the Spatial Conflict in Northwest Europe

Figure 5. Main energy source per European country
Source: Statista 2022 (adapted)

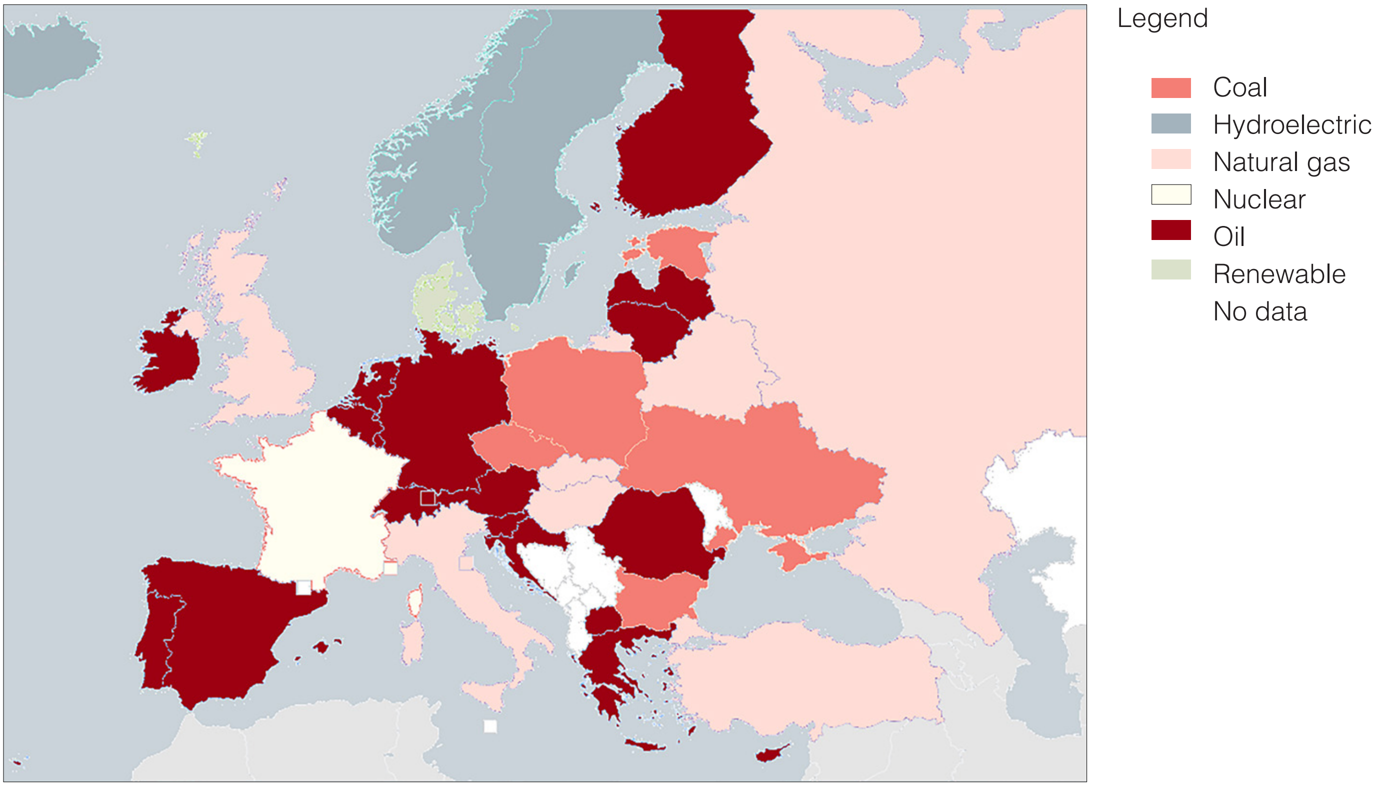


Figure 6. Renewable Energy Volatility
Source: Ebersole 2017 (adapted)

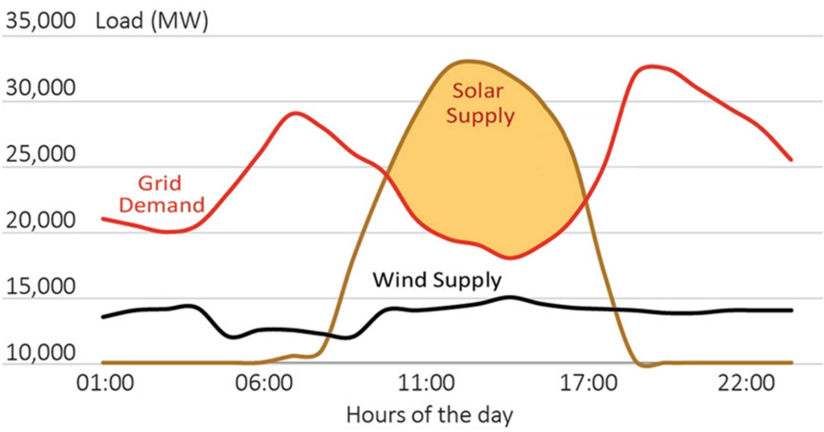
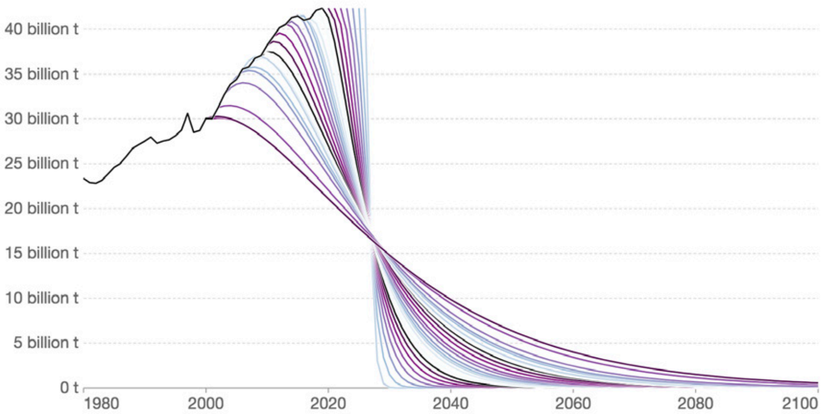


Figure 7. CO_2 reductions to keep temperature rise above 1.5 C
Source: Our World in Data (2022)

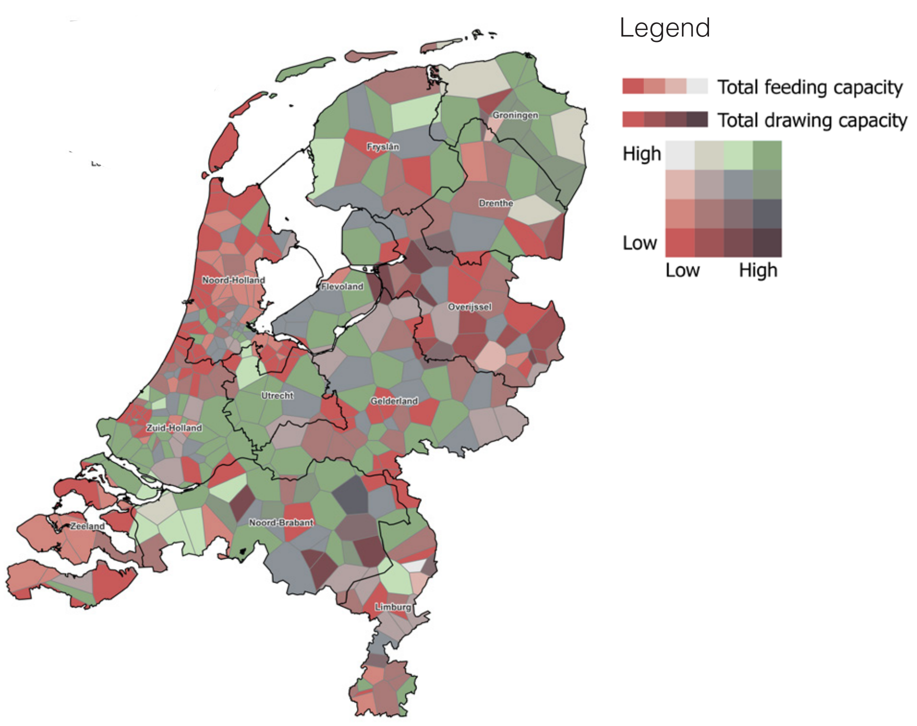


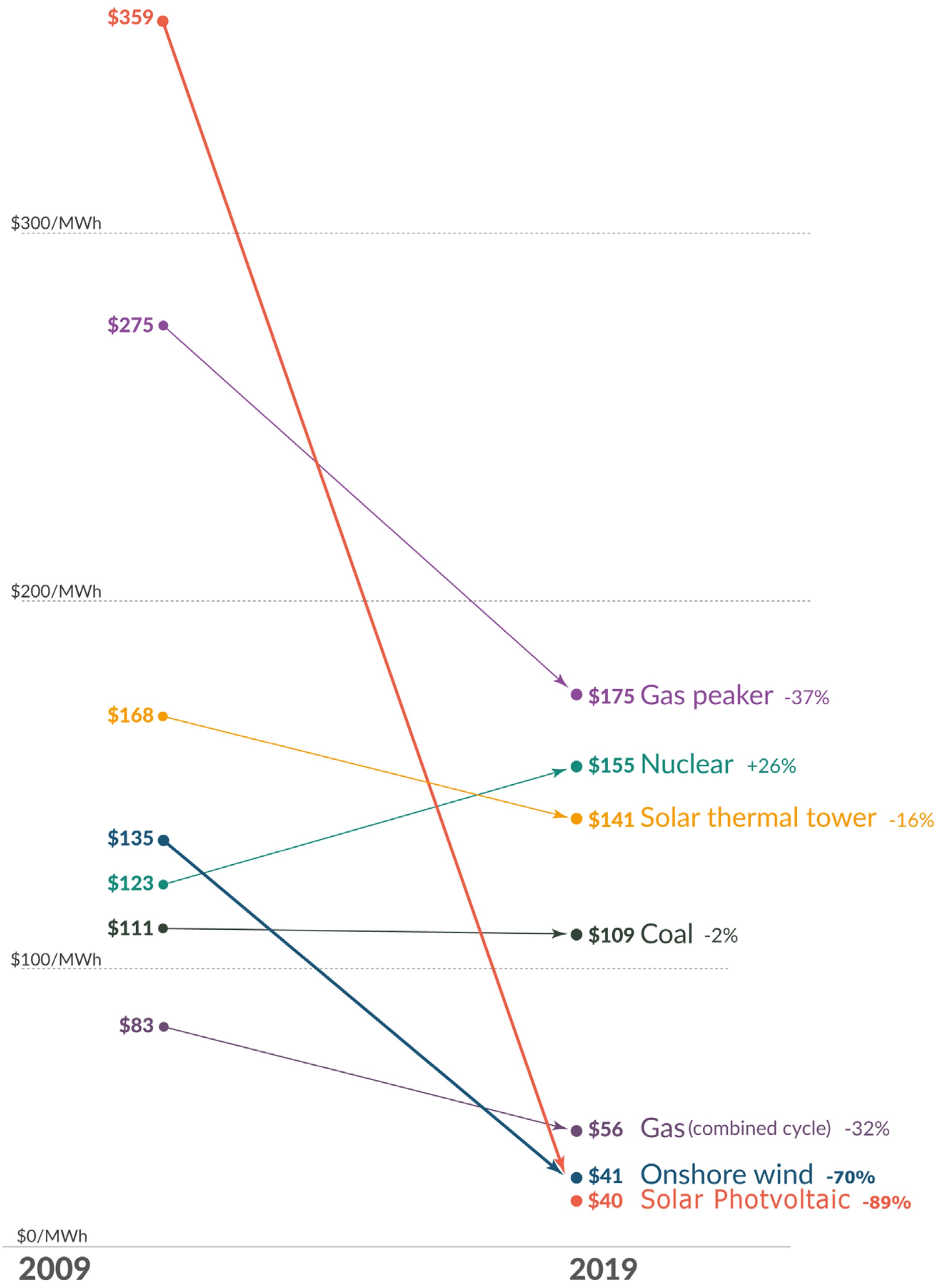
Kaundiya & Ravindranath (2009) researched two different decentralized energy systems:
- Grid-connected systems (GC), an independent decentralized power system connected to the main (existing) energy grid where the operational capacity is determined by the supply source. Connectivity to the main energy grid enables setting up relatively large-scale systems whilst also able to be used as a storage site. Since these systems are being used all year round, the use of renewable energy is less viable due to seasonal change in power output.

- Stand-alone systems (SA), have an operational capacity matched to the demand. This makes these energy systems ideal for remote locations not connected to a main large-scale energy grid. These systems are more usable for seasonal systems using renewable energy. Looking at the earlier mentioned problem with the energy grid in the Netherlands. Grid-connected systems would be more interesting to implement here since the Netherlands are a very dense and small country meaning that remote locations do not exist making stand-alone systems less ideal. Although, using renewable energy in a grid-connected energy system seems less viable according to Kaundiya & Ravindranath (2009), we argue that the use of a very high amount of several types of renewable energy production in the same area should contradict this issue.

Lastly, renewable energy production can be seen as a spatial conflict (figure 4). Renewable energy, compared to fossil fuel-based energy, requires way more space in general (van Zalk & Behrens, 2018). In the fossil fuel-based energy system, oil or gas is exploited far away and transported via pipelines or by ship to incineration plants to turn the raw material into energy. These plants are in industrial areas, far away from residents' sights, meaning that for people living in countries with this system, energy is invisible and therefore a matter of course. In a renewable energy-based system, the photovoltaic panels and wind turbines will be visible to people since they will need to be placed everywhere to be able to produce enough energy for the energy demand. In the Netherlands, being one of the most densely populated areas in the world, space can be a big problem. With high ambitions of becoming carbon-neutral, the question of where to produce energy is getting more important.

Figure 8. Energy grid congestion of the Netherlands
Source: PDOK (2023)




$359
$300/MWh
$275
$200/MWh
$175 Gas peaker -37%
$168
$155 Nuclear +26%
$141 Solar thermal tower -16%
$135
$123
$111
$109 Coal -2%
$100/MWh
$83
$56 Gas (combined cycle) -32%
$41 Onshore wind -70%
$40 Solar Photvoltaic -89%
$0/MWh
2009
2019

1.3 The Just Energy Transition

The consequences of human-caused climate change are already visible in many regions of the world in the form of a higher occurrence of weather and climate extremes, leading to widespread adverse impacts on food and water security. But also, human health, economies and society, and related losses and damages to nature and people. The vulnerable communities which historically contributed the least to current climate change are now disproportionately affected. (IPCC, 2023)

According to the World Health Organization (2023), the major sources of outdoor air pollution include residential energy for cooking and heating, vehicles, power generation, agricultural/waste incineration, and industry. In both cities and rural areas, ambient (outdoor) air pollution causes fine particulate matter resulting in strokes, heart diseases and other respiratory diseases. The combined effects of ambient and household air pollution are associated with 7 million premature deaths annually mainly occurring in the earlier mentioned vulnerable communities. (WHO, 2023)

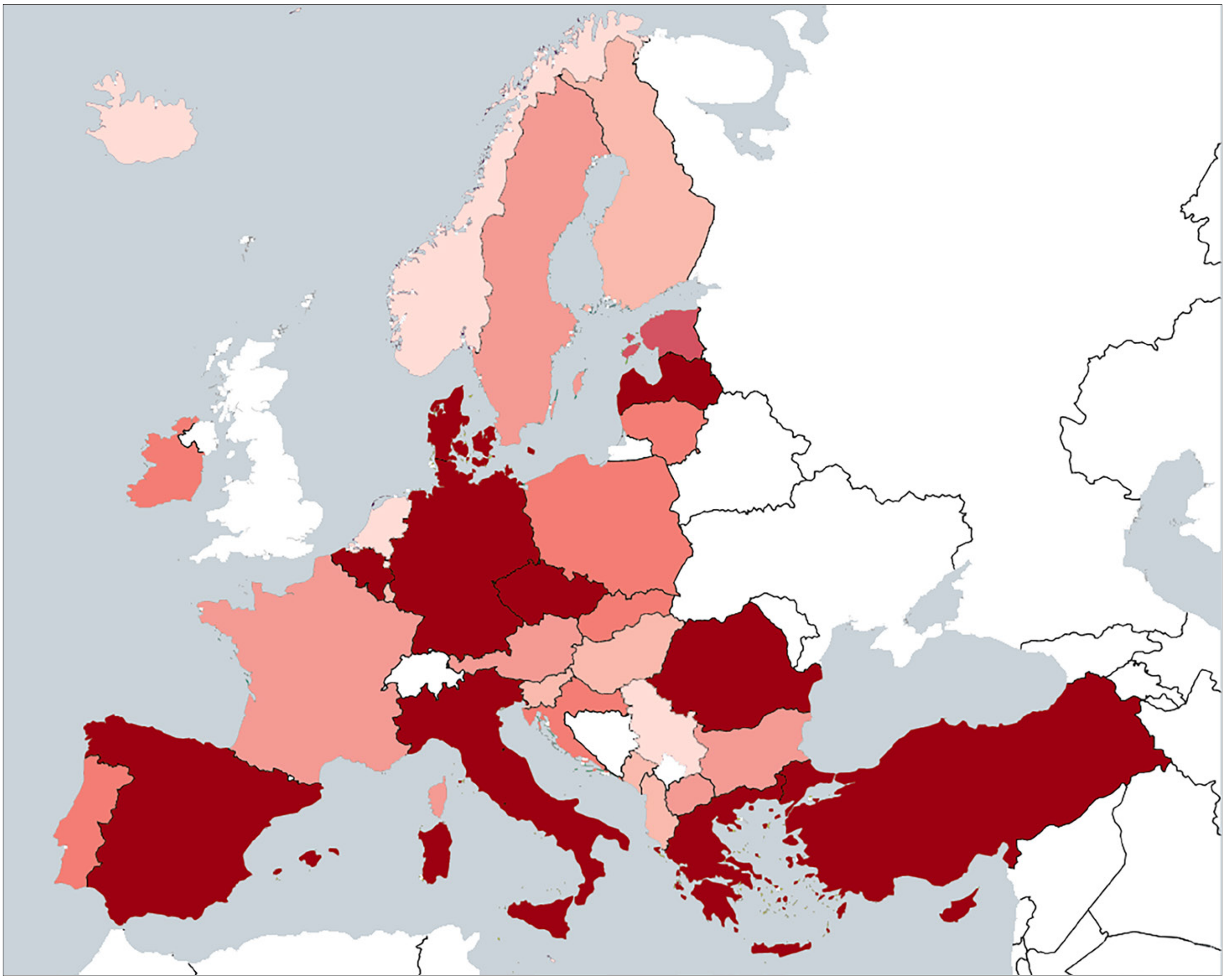
Enforcing the energy transition will be one of humanity's greatest challenges in this century. It will be a complex socio-technological transformation requiring major changes for many communities. Although, the idea of encouraging an energy transition now has widespread support since motivations for change are much stronger than in previous energy crises. The household purchasing power stand (PPS) per 100 kWh for the first half of 2022 can be seen in figure 10., showing a clear division amongst countries. (Miller et al., 2013)

In the words of Vice-President of the European Commission Frans Timmermans:
"We must show solidarity with the most affected regions in Europe, such as coal mining regions and others, to make sure the Green Deal gets everyone's full support and has a chance to become a reality." (European Commission, 2023c)

Miller et al. (2013) mention several more enablers the energy transition will have on society. First, societal concerns have risen on current energy extraction and production, the biggest example here are all the climate protests that are happening all over the world calling for a stop on fossil fuel extraction. Second, an increase in the societal interest in democratic participation in technological change is happening. Furthermore, between 2009 and 2019, the price per MWh of solar energy decreased by 89% in conjunction with the decrease in price of wind energy by 70%. This decrease will enable more lower-income households and companies to invest in their own solar energy. An overview of leveled price per MWh changes for renewable and fossil fuel-based energy can be found in figure 9. Third, opportunities will be created in the development of new infrastructure – like the hydrogen enabled decentralized energy system – incorporating an awareness of social dimensions. For example, people working in the fossil fuel industry can be reschooled to work in the newly created hydrogen system.

Figure 9. Price evolutions of energy sources. Adapted from Ritchie & Roser (2021).

Figure 10. Electricity prices for households consumers 2021
Source: Eurostat 2022a (adapted)



To conduct the energy transition, huge amounts of investments will have to be made in, for example, the (re)development of (existing) infrastructure. Therefore, the European Commission has introduced the Just Transition Mechanism addressing the social and economic effects of the transition. A new Just Transition Fund has been established, investing around 55 billion euros over the period 2021-2027. (European Commission, 2023c)

This support will be available for all Member States of the European Union, focusing on the most carbon-intensive regions where the most people work in the fossil fuel industry. Member States are eligible for this funding by preparing territorial just transition plans in the period up to 2030 by identifying territories that need the most support. The plans should also address social, economic and environmental challenges. (European Commission, 2023c)

The European Commission (2023c) mentioned who will be protected by the Just Transition Mechanism, divided into three groups across three scales. First, they mention the smallest scale of people and citizens who are most vulnerable to the energy transition and will be protected by: Facilitating employment opportunities in new sectors and those in transition, enabled by reschooling and reskilling current workers in the fossil fuel industry. In addition, the investing to fight energy poverty, enabled by giving subsidies to lower the installment cost of solar energy in low-income residential areas.

Second, in a larger scale, companies and sectors in carbon-intensive industries will be protected by: Supporting the transition to low-carbon technologies based on climate-resilient investments and jobs. In addition, creating attractive conditions for public and private investors and providing easier access to loans and financial support accelerating new plans, projects and the emergence of new firms and start-ups. Moreover, investing in research and innovation activities needed for future technologies capabilities and territorial assessments of enablers and limitations.

Third, on the largest scale, Member States and regions with, currently, a high dependence on fossil fuel and carbon-intensive industries, will be protected by: Supporting the transition to low-carbon and climate-resilient activities. In addition, creating new jobs in the green economy due to redevelopment and repurposing of current infrastructure. Moreover, investing in large-scale renewable energy sources like offshore wind parks in the North Sea. Furthermore, improving digital connectivity enabling creation of digital twins of energy infrastructure across regions. Finally, providing affordable loans to local public authorities used to create attractive conditions for companies and sectors to transition and innovate.

Alongside all these mentioned social challenges, the existence of spatial justice in the energy transition shouldn't be neglected. Yenneti, Day & Golubchikov (2016), emphasize land acquisitions for infrastructure development even for 'environmentally progressive' projects, like installing renewable energy sources, can alienate vulnerable communities and flora and fauna from their sources of livelihood.

Most people have heard of the 'NIMBY' – not in my backyard – concept. It entails the problem of finding suitable locations for renewable energy production near residential areas. Residents do not want the wind turbines close to their homes due to visual impacts and noise pollution. Besides the intervention in the human space in the landscape, flora and fauna could also perceive high impacts in their living environment Therefore, whilst analyzing potential locations for offshore wind parks, nature areas with rich biodiversity should be considered. In this sense, the spatial justice of renewable energy production lies hand in hand with the environmental justice.

Legend

PPS

> 26.9

24.8 - < 26.9

20.3 - < 24.8

18.6 - < 20.3

15.3 - < 18.6

< 15.3

No data

During this research and design studio, our goal is to create an Eurodelta wide vision of implementing a hydrogen landscape by replacing future decommissioned refineries with new hydrogen plants located in the heart of northwestern Europe's biggest industrial clusters and thus, reducing fossil fuel (CO_2) emissions.

These research objectives are supported by the following main research question:

What will hydrogen enabled energy landscapes around heavy industries look like in northwest Europe?

Using the following sub questions:

Which industry sectors are the biggest energy consumers and where are they clustered?

How can the future decommissioned heavy polluting industry be repurposed?

What is the role of hydrogen in a decentralized energy grid?

How can a decentralized energy grid improve social and spatial justice?

How can industrial areas become greener, improving air and spatial quality?

1.4 Objectives and research questions

Hydrogen (H_2) is seen as the element of the future and could be an accelerator for the energy transition to renewable energy sources. There are several benefits for the use of hydrogen in the energy transition. First of all, as mentioned before, due to the volatility of renewable energy sources, energy storage has a big role. Energy can be converted into hydrogen with a loss of 15-30% in heat that can be repurposed as well (Saxe & Alvfors, 2007). Besides energy storage, hydrogen can also be used for the transportation of energy and even as an input for green industry sectors creating a fast-growing hydrogen economy. (Kovaĉ, Paranos & Marciuš, 2021)

In the past few years, multiple studies on hydrogens application have been conducted, but the current development of the technology cannot be implemented yet on a large-scale basis. The increasing number of studies and initiated – both public and private - projects show the utilization of hydrogen's immense ecological potential to be expected in the next decades. (Kovaĉ, Paranos & Marciuš, 2021)

During this research and design studio, our goal is to create an Eurodelta wide vision of implementing a Hydrogen Scape by replacing future decommissioned refineries with new Hydrogen plants located in the heart of northwestern Europe's biggest industrial clusters and thus, reducing fossil fuel (CO_2) emissions. This can be partly made circular by reusing the existing storage and infrastructure facilities now in use by the oil and gas industries. Hydrogen plants are implemented as an energy converter from renewable energy production sources to hydrogen storage, meaning that surplus energy can be stored as hydrogen and therefore also reduce the overloading of the power grid. This is mostly applicable to the Port of Rotterdam (main cluster) enabling an additional strategy of redevelopment where there is also room for new green industries to arise in place of the current fossil fuel-based industries which use hydrogen as an input material.

Furthermore, a more in-depth strategy will be shared and designed in the west-central part of the Netherlands showing what the possibilities are for the previously mentioned redevelopment and land-use change. Smaller industrial clusters (subclusters) will be decentralized from the main energy grid as well to be able to create a more robust and lower risk energy system. Additionally, this will benefit the rise of new green industries to be located in these areas as well. However, since the strategy for this area is more geared towards decentralizing the energy grid, these new green industries shouldn't necessarily take hydrogen as an input material.

The rise of new green industries in both proposed strategic redevelopment areas is in line with the EU's Green Deal Industrial Plan published on February 1st, 2023. This plan states that the EU is committed and convinced to be able to speed up net-zero industrial transformation within the EU. The EU desires to be a leading player in the net-zero industries of the future besides the transformation of energy and transport infrastructure and the switch to green hydrogen as a storage medium, fuel and feedstock. The enabling four pillars of the Green Deal Industrial Plan consists of: first, a predictable and simplified regulatory environment; second, faster access to sufficient funding; third, skills and lastly, open trade for resilient supply chains. (European Commission, 2023a)

Renewables
Decentralisation
ENERGY PRODUCTION
DIRECT PRODUCTION
OF LOCAL ENERGY
STORAGE OF
GREEN ENERGY
INDUSTRY 5.0
GREEN
Planet
CIRCULAR ENERGY
LANDSCAPE
Profit
People
HYDROGEN
MANUFACTURING
OF RENEWABLES
Refeneries ->
Hydrogen plants
Housing
TRANSFORMATION
NEW DEVELOPMENT
Nature /
Greenery
Current
industries
New industries
DIRECT USE
OF HYDROGEN
CLUSTERING AS
ECONOMICAL ADVANTAGE

1.6 Methodology

In an attempt to answer the raised research question in this report, a conceptual framework has been created to give an overview of concepts part of the designed vision and strategy (figure 11.) In the middle, the main concept for this research and design studio consists of a circular energy landscape connecting the planet (sustainability), people (justice) and profit (economic growth and stability). This circular energy landscape will be empowered by green hydrogen production solving the problems currently arising in the energy transition with renewable energy and enabling the return of future industries in Europe.

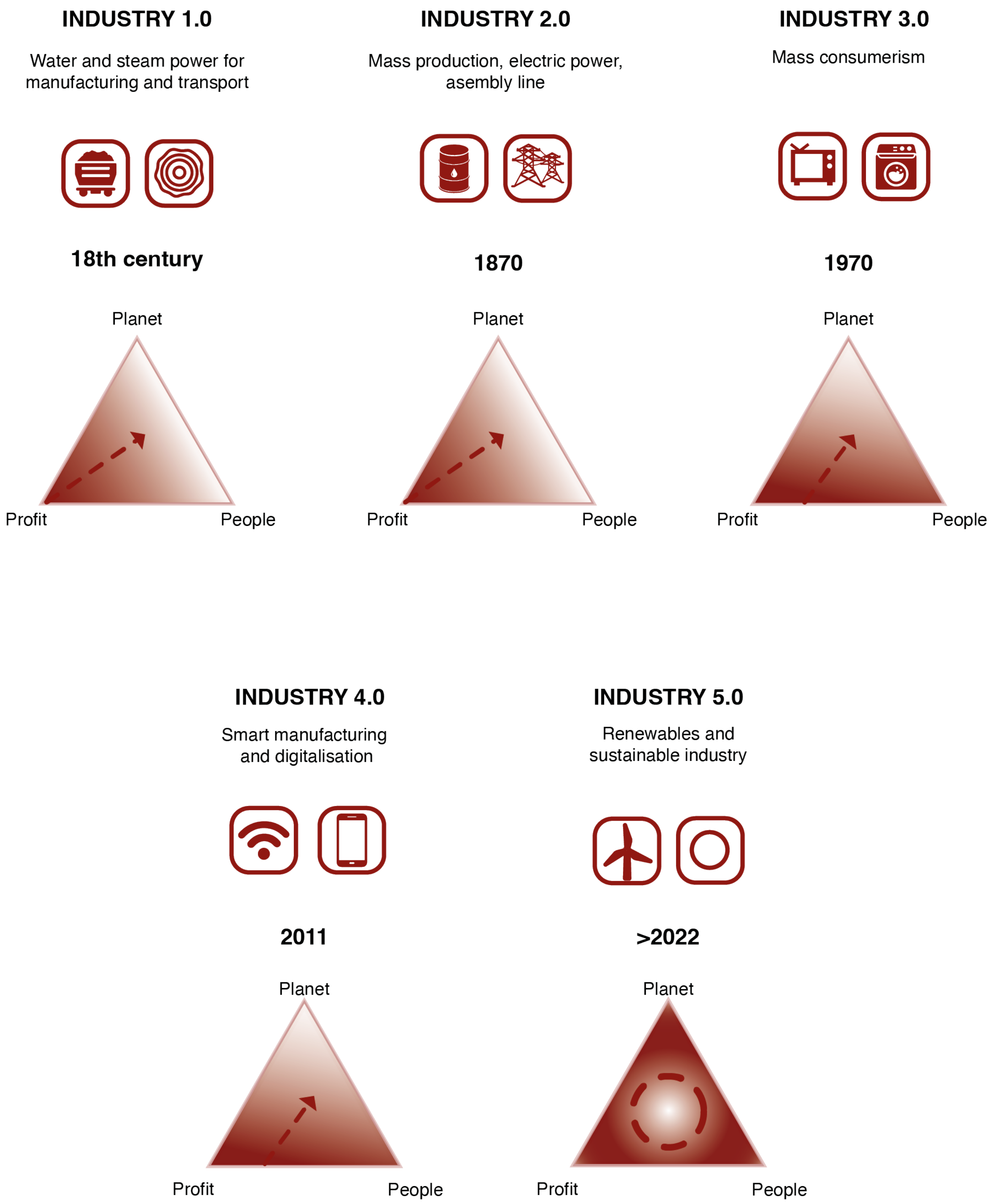
Three pillars exist for the connection between planet, people and profit. First off, the planet requires an energy transition from fossil fuel-based to renewable energy using decentralization to become more circular. This is largely part of the first sub question mentioned in the objectives section on biggest energy consuming sectors.

The second sub question regarding repurposing of refineries can also be identified with this first pillar with the concept of circularity. Secondly, in the profit pillar, conversion of this produced energy into hydrogen will allow the storage of energy, additionally, former fossil fuel-based energy production sites will be repurposed and transformed enabling the rise of hydrogen plants allowing for current industries to adapt and increase economic stability and growth. This generally is in line with the third sub question on the role of hydrogen in a decentralized energy system.

For the last pillar regarding people, new development will be possible in this new circular landscape by introducing more greenery due to lower (and later zero) emissions attracting new housing developments and industries improving job opportunities, working, and living conditions of people. This pillar is predominantly linked to the fourth and fifth research questions regarding social and spatial justice, and improved wellbeing, air quality and overall spatial quality.

Figure 11. Conceptual Framework

02. Analysis: The Heavy Energy Consumers


INDUSTRY 1.0
Water and steam power for manufacturing and transport
18th century
Planet
Profit
People
INDUSTRY 2.0
Mass production, electric power, asembly line
1870
Planet
Profit
People
INDUSTRY 3.0
Mass consumerism
1970
Planet
Profit
People
INDUSTRY 4.0
Smart manufacturing and digitalisation
2011
Planet
Profit
People
INDUSTRY 5.0
Renewables and sustainable industry
>2022
Planet
Profit
People

2.1 The Industrial Revolutions and Energy Production

The daily energy consumption of an average person in the wealthy parts of this world has increased by a hundred-fold since the start of the industrial revolution (Sijmons, 2014). While these revolutions contributed greatly to prosperity, they have led to a society that is heavily dependent on fossil fuels, with far-reaching environmental consequences. This section will examine the link between the industrial revolutions, the energy dependency of society and how this will change with the energy transition and industry 5.0 that has sustainability at its core.

The first industrial revolution started in the 18th century when the steam engine led to the widespread use of water and steam power in factories and transportation. The result was a massive gain in the economy and production power (Maddikunta et al., 2022). Even though it made society dependent on coal and wood, resulting in smog cities while bringing forests almost to extinction in large parts of Europe (Sijmons, 2014).

Moving on in time, the second industrial revolution evolved in the year 1870 with the emergence of electric power and assembly lines that distributed the workload to increase the productivity of manufacturing production, resulting in mass production (Maddikunta et al., 2022). By 1930, oil had surpassed coal as the main fuel for the transportation sector worldwide, during which, it became fashionable to supply energy directly into homes. This industrial revolution democratized energy for the wealthy individual and resulted in an increased dependency of gas and oil consumption. (Sijmons, 2014)

During the third industrial revolution in 1969, the rise of concepts like electronics, programmable logic controllers (PLC's) and communication technologies allowed for a partial automatization of the production process (Maddikunta et al., 2022; Xu et al., 2021). These automated assembly lines were able to mass produce new appliances such as washing machines, ovens and vacuum cleaners which reduced household chores, resulting in more free time for consumption-based activities. By the 1960s privileges like heating, telephones, radio, lighting and owning a car turned into national right in the Netherlands. Since this turnover, room temperatures have been 'standardized' to 20 ˚ C which only changed recently due to the energy crisis. In short, the third industrial revolution made consuming products and energy possible on a wide scale leading to increasing energy consumption in all sectors. (Sijmons, 2014)

Figure 12. History of industrial revolutions. Created using Sijmons (2014).

This diagram gives an overview of the five industrial revolutions. The icons show the main element that increased the energy consumption. The triangle on the bottom indicates where this economic revolution was starting from, industry 5.0 is different since it has sustainability at its core instead of making as much profit as possible.

Industry 4.0 evolved in 2011 and has revolutionized the manufacturing industry by integrating technologies such as artificial intelligence (AI) and the Internet of Things (IoT) making this industry smarter using interconnecting devices able to control each other (Maddikunta et al., 2022). These new technologies enabled efficient production of personalized products leading to an ever-higher rate of energy consumption with new technologies such as digital devices. At the same time, this industrial revolution started addressing challenges such as energy efficiency and society's need to reduce the consumption of energy and resources. (Xu et al., 2021)

Image 4

Image 5

Image 6

The European Commission started discussing industry 5.0 in 2022 from a consensus on industry integrating social and environmental priorities in technological innovation by shifting the focus from individual technologies to a systemic approach. This new industrial revolution should complement the current paradigm 4.0 that is focused on AI driven technologies and digitalization. The new industries enable the transition to a sustainable, people-centric and resilient European industry. (Xu et al., 2021)

Combining the power of man and machine should increase production efficiency and enable mass customization. Discussions have been held around the “age of augmentation”, where men and machines work together in harmony. The European Commission identifies six new technologies that would emerge with this new industrial revolution:

1.Individualized human-machine interaction technologies that connect and combine the strengths of humans and machines.

2. Biologically inspired technologies and smart materials that enable materials with embedded sensors and enhanced functions while being recyclable.

3. Digital twins and simulation to model entire systems.

4. Data transmission, storage and analysis technologies that can handle data and system interoperability.

5.Artificial intelligence to detect causalities in complex, dynamic systems, for example, leading to actionable intelligence.

6. Technologies for energy efficiency, renewables, storage and autonomy.

To end with the future scope of the sixth industrial revolution, Duggal et al. (2022) noted the prime focus of the revolution to be geared towards medical technology with multi-dimensional controlled release of medicines. Automation will develop even further by e.g., automated medical diagnosis, removing this time-consuming process from physicians, allowing them to focus on critical cases. The introduction of automation in the fourth industrial revolution will now be enabled to be implemented as well via capital creation via robotic manufacturing, making it feasible on a mass-production scale. The trend of domestic robots would develop even further, being fully integrated into our lifestyles and taking up most household chores. All these developments will, most likely, require higher energy consumption. Lastly, market borders will change the emphasis on digital business values due to the fusion of ideas providing a fundamental growth catalyst for companies. Choosing appropriate partners, having a comprehensive environmental approach, and implementing an industrial growth strategy focus will enable the success of the cross-industry value experiences. (Dugga et al., 2022)

Image 4. The world’s largest facility for producing hydrogen in Japan. Source: JapanGov, (2021)

Image 5. Refinery in Rotterdam. Source: Exxonmobil, (2022)

Image 6. Wind energy manufacturing in Hull England. Source: Hurriyetdailynews, (2022)

Figure 13. Final consumption by sector for 2019
Source: Enerdata 2021

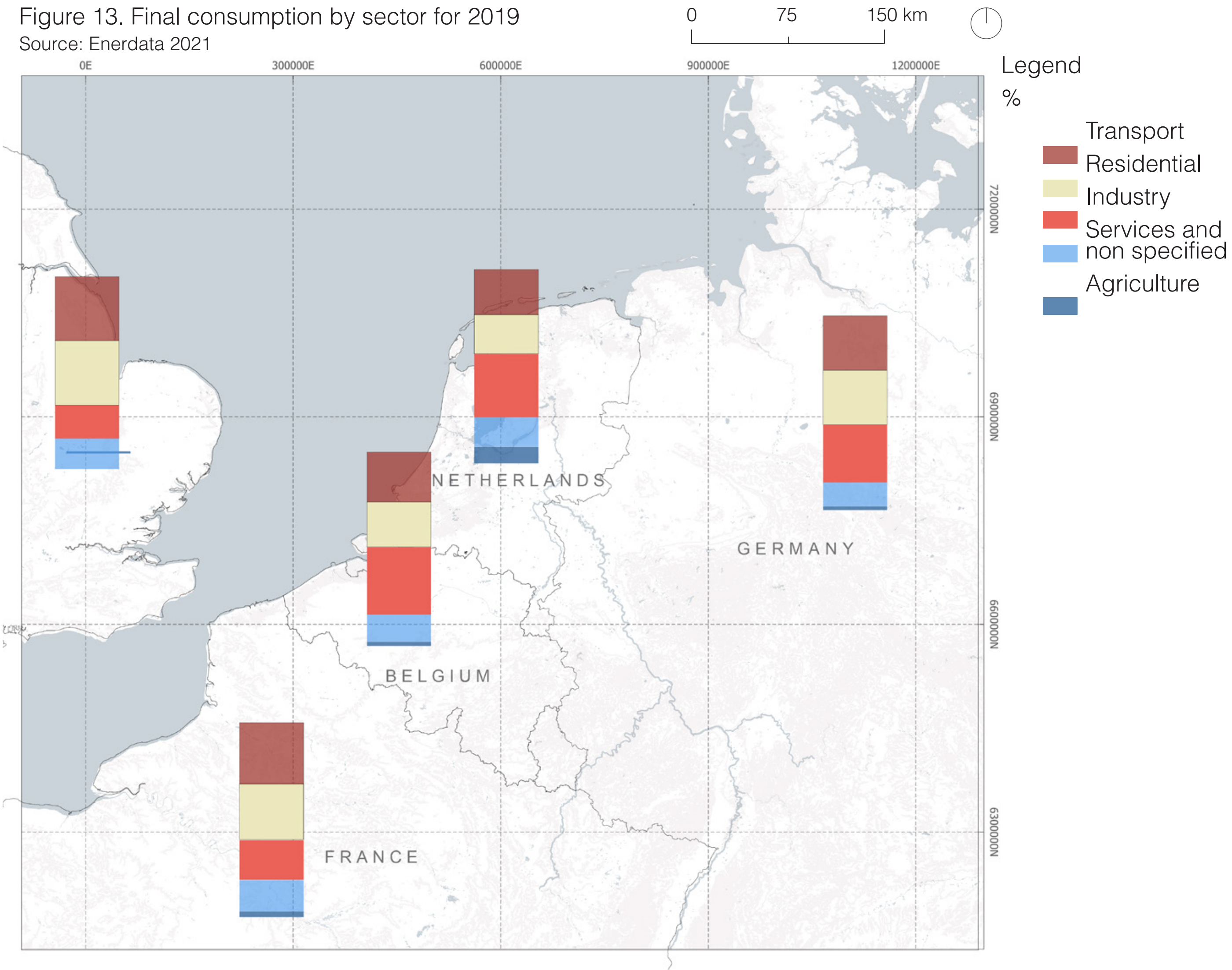


Figure 14. Final energy consumption residential sector by fuel for 2020
Source: Eurostat 2022b

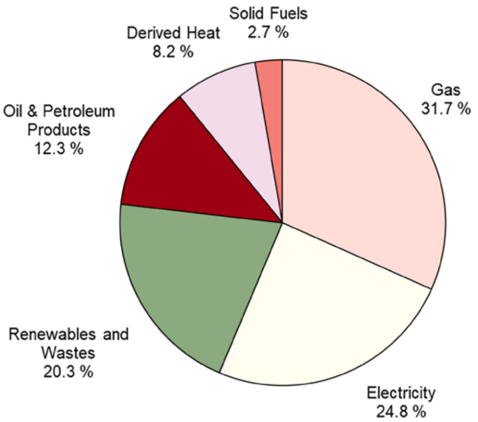
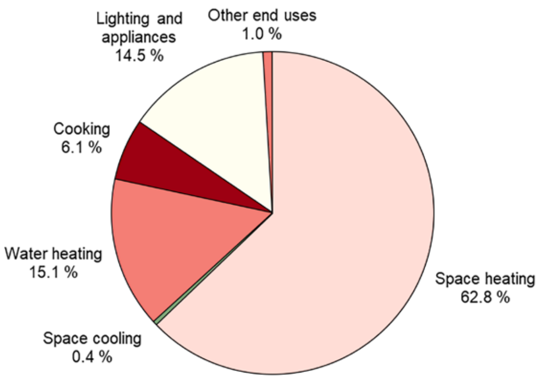


Figure 15. Final energy consumption residential sector by use for 2020
Source: Eurostat 2022b



2.2 Main Energy Consumers in Northwest Europe

Looking at data provided by Enerdata (2021) regarding the energy consumption by sector in the Northwest Europe for the year 2019 (Figure 13), it becomes apparent that the sectors with the biggest energy consumption are transport (28.4%), households (28.0%), and industry (26.1%). The following two subsections will explain why we haven't chosen the transport and household sectors.

The transport sector consists of all transportation options like rail transport, road transport, water transport and air transport. In 2009, the Renewable Energy Directive was set-up by the EU stating that by 2020, at least 10% of all energy used in transport should come from renewable sources in each of the member states. In 2020, 10.2% of the total energy use in the transport sector in the EU came from renewable sources showing a steady increase of around 2% since 2005. This has mainly been made possible by the introduction of more biofuels in this period. (European Environment Agency, 2022b)
In September of 2022, the European Plenary voted to raise the overall renewable energy target to 45% by 2030 by introducing even more large-scale use of advanced biofuels (European Environment Agency, 2022b). These visions and the already seen increase in renewable energy sources in the transport sector show a positive future path of creating a sustainable European transport system in the future.

The residential sector is the second largest energy consumption sector in the EU. The energy consumption in households for 2020 article published by Eurostat (2022a) shows that the biggest purpose of energy consumption in houses is space heating with 62.8%, whilst water heating uses 15.1% and lighting and appliances use 14.5%, with cooking, cooling and others making up the last 7.5% (figure 15).
This article also mentions the main energy products in the final energy consumption in the residential sector for each type of end-use. Zooming in on the purpose of space heating, the biggest energy consumer in the residential sector. Renewable energy and biofuels already make up around 27.5% whilst the majority is still based on natural gas (38%).

Increasing the ratio of renewable energy use is already in full swing. SolarPower Europe's annual 2022 report on the progress of solar power revealed that in 2022, the EU installed 41.4 GW of solar energy in 2022, which is 47% more than the installed 28.1 GW in 2021. The power generation therefore also increased by 25% from 167.5 GW in 2021 to 208.9 GW in 2022. (SolarPower Europe, 2022)

All and all, these numbers show the high increase of photovoltaic panel installments in Europe. These photovoltaic panels can mainly be installed on top of buildings and specifically residential buildings. This would increase the renewable energy source for space heating enormously in the near future. EnergySage (2023) even mentions only 17 – 21 photovoltaic panels being needed to cover 100% of the energy usage of a typical home. This could become even less in the future with more efficient photovoltaic panel innovations. As earlier mentioned, the price of renewable energy has decreased way faster than first expected meaning that people will be able to generate their own solar energy on the roofs of their houses meaning they will be energy independent.

Figure 16. Final energy consumption industry sector for 2020
Source: Eurostat 2022c

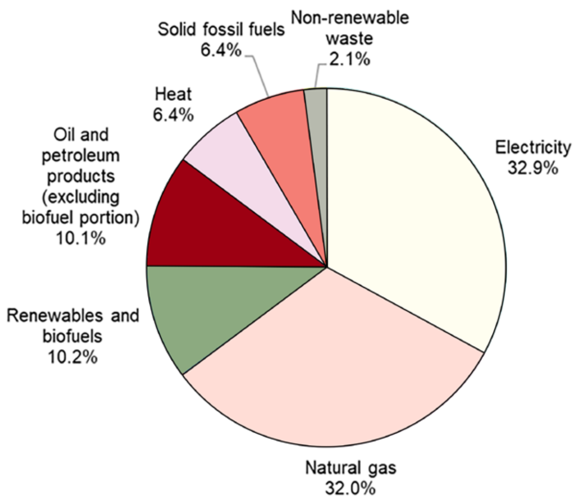
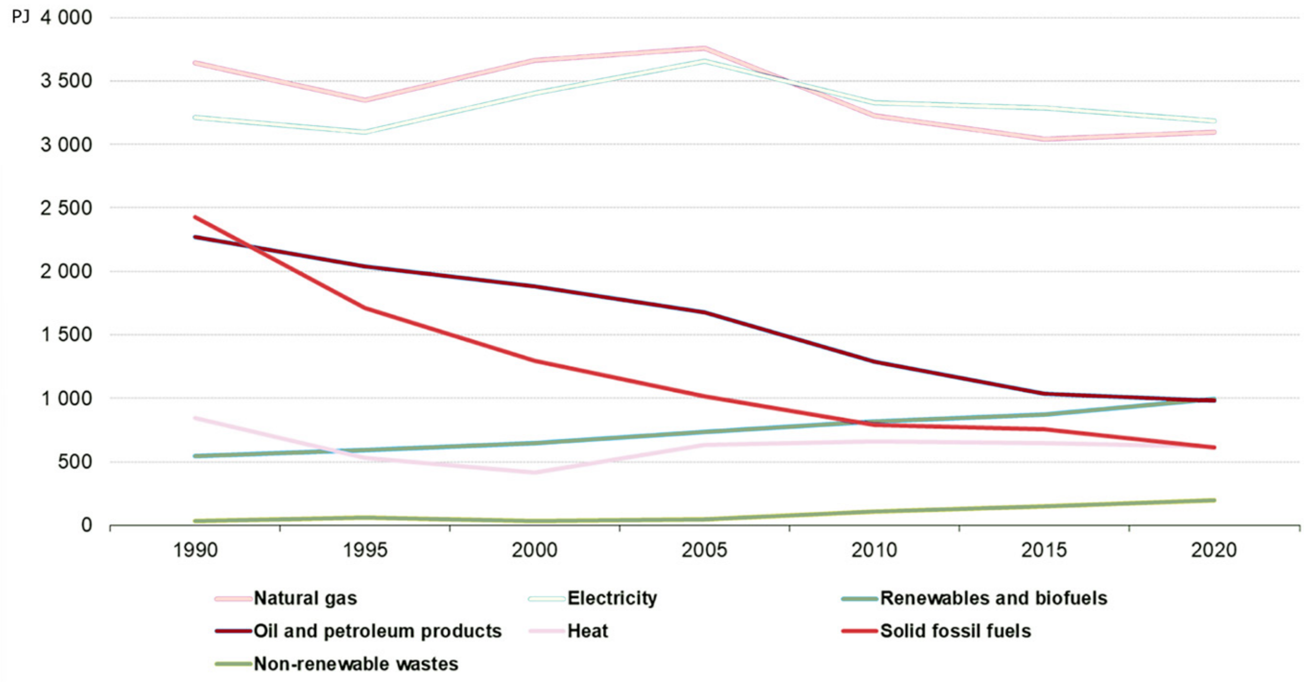


Figure 17. Evolution of final energy consumption in the industry sector per energy source (2020)
Source: Eurostat 2022c



The final main energy consumption sector in Europe to explore is the industry sector. Figure 16 shows the energy consumption of the industry sector by energy product in 2020 part of the report final energy consumption in industry – detailed statistics by Eurostat (2022b). The figure shows natural gas (32.0%) electricity (32.9%) to be the biggest contributor of energy consumption in the industry sector. Eurostat (2022b) mentions one-third of this electricity being produced from fossil fuels. All in all, with this knowledge, around 70% of energy consumption products in the industry sector are using non-renewable energy sources.

Looking at the evolution of the energy consumption of the industry sector by energy product shows even more interesting findings. Figure 17 clearly illustrates a steep decline in use of both solid fossil fuels and oil and petroleum products of respectively 74.7% and 59.9% between 1990 and 2020. An assumption can here be made that the use of these two energy products will decline even more in the following decades. (Eurostat, 2022b)

On the other hand, renewables and biofuel use as energy products show a small but steady increase in the same period of 81.7%. Despite this high relative number, the absolute number shows that this is still a very low amount of the total energy consumption (10.2%, figure 10) from 546 petajoules (PJ) in 1990 to 992 PJ in 2020. The use of natural gas and electricity as an energy product has been relatively stable throughout this time period. The steep decline of fossil fuels and slow increase in renewable energy usage didn't interestingly bring issues in energy supply to the energy sector since the overall energy consumption saw a decrease from 12.988 PJ in 1990 to 9.680 PJ in 2020, a relative decrease of 25.5% (Eurostat, 2022b)

All in all, this data shows that there is still a big need for additional renewable energy production as a source for the energy consumption of industry in Europe. This is the reason why this research and design studio project will focus on the industry sector in Europe. This is supported by a provisional agreement of the European Commission on March 30th, 2023, as part of the European Green Deal titled: EU agrees stronger legislation to accelerate the rollout of renewable energy.

This agreement states the industry sector as a key energy-consuming sector being included for the first time in the Renewable Energy Directive. It establishes an indicative target of an annual increase of renewable energy use of 1.6% and, in addition, a binding target of reaching 42% of renewable hydrogen in total hydrogen consumption in the industry by 2030, supporting the EU's ambitions on renewable hydrogen roll-out. (European Commission, 2023)

Figure 18. Energy demand in industry sector

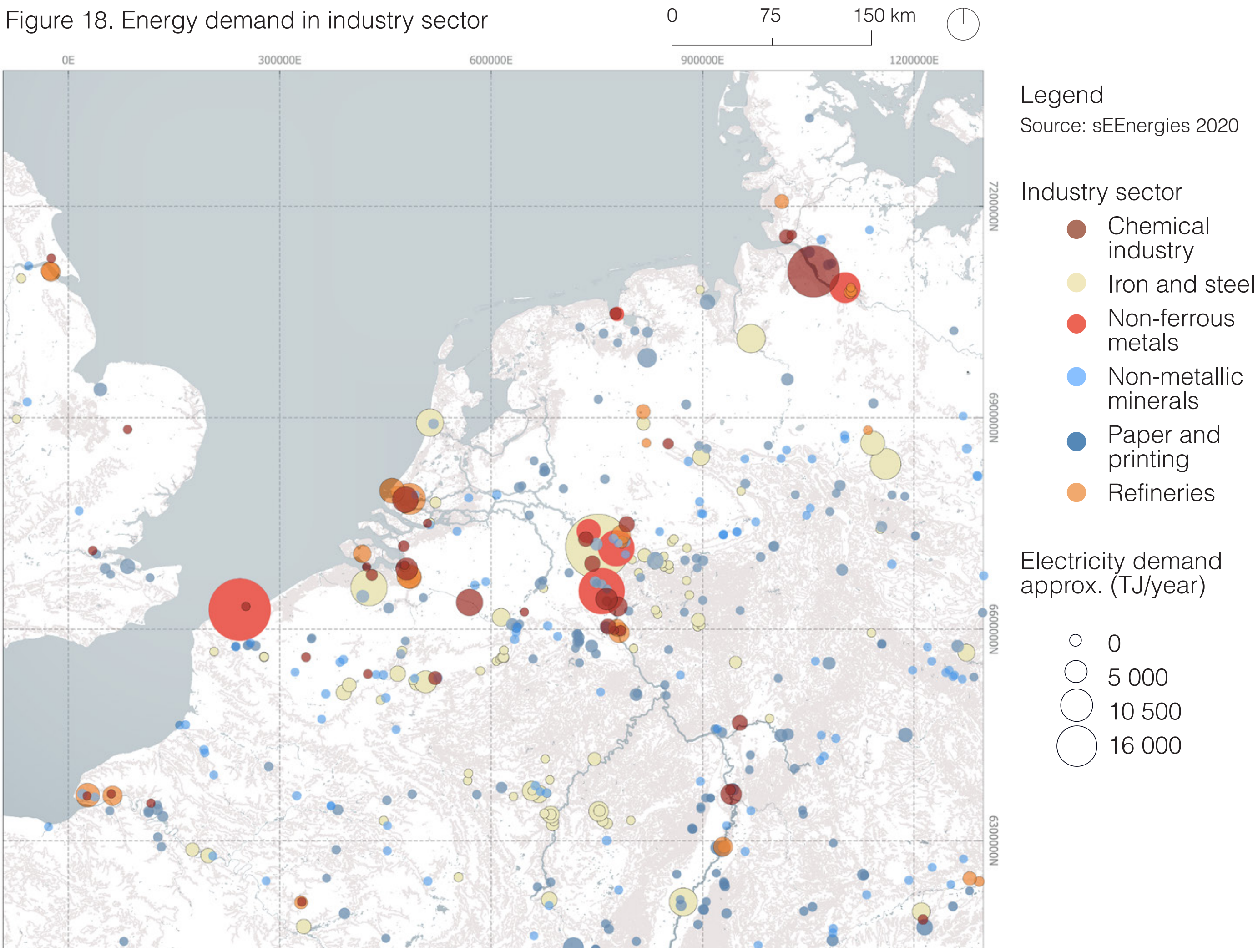
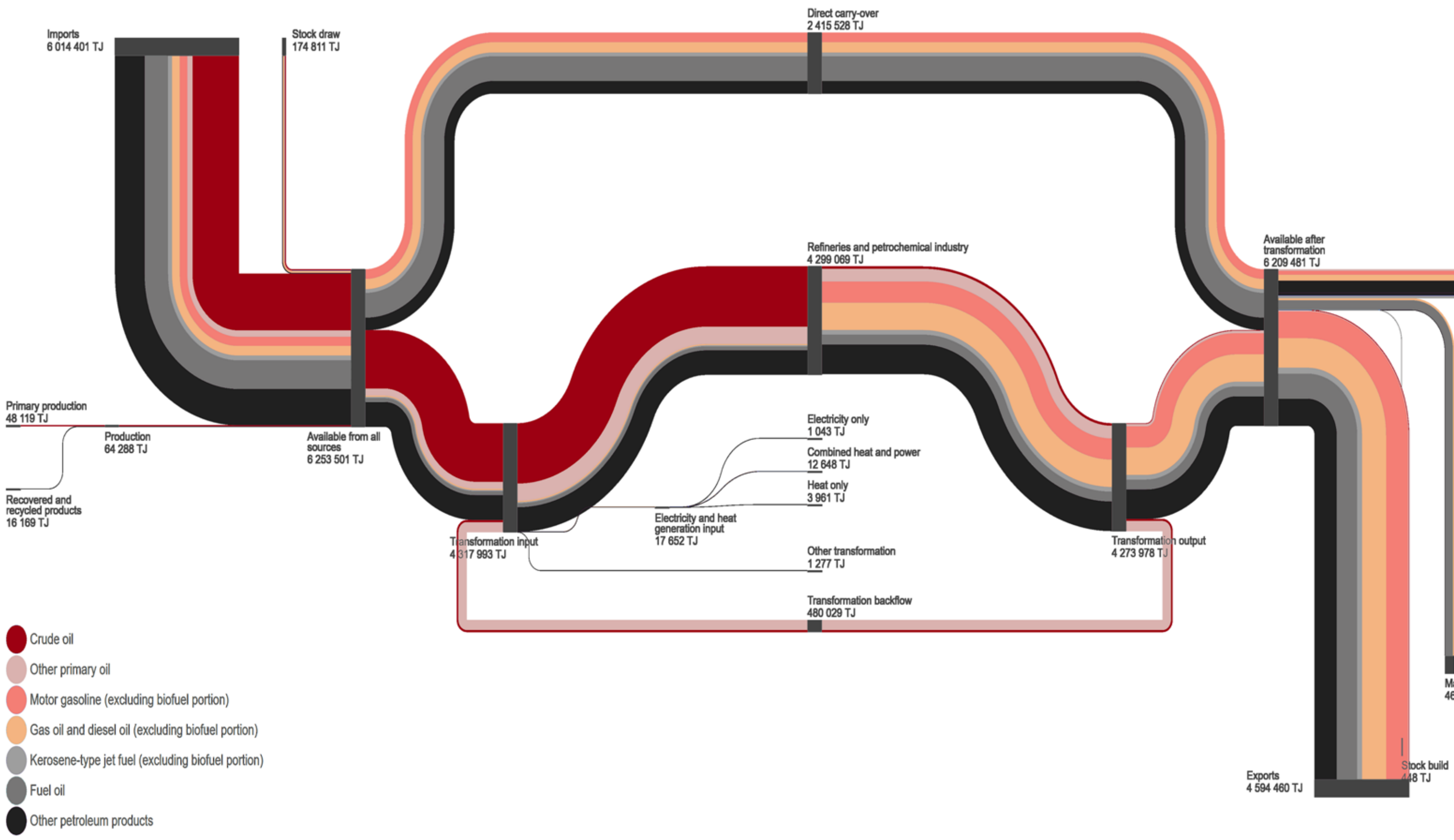


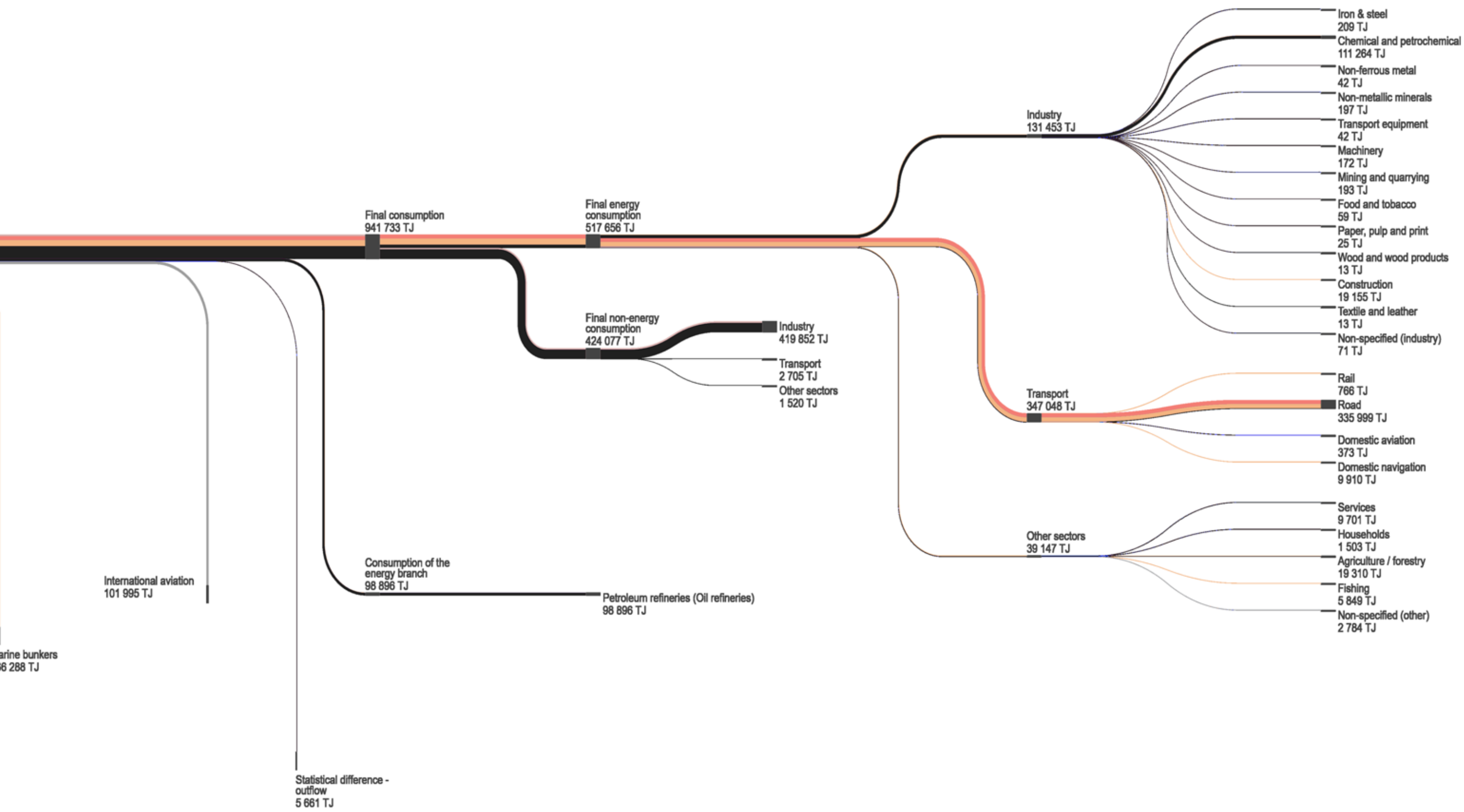
Figure 19. Energy balance flow for the Netherlands in 2021
Source: Eurostat 2023 (adapted)

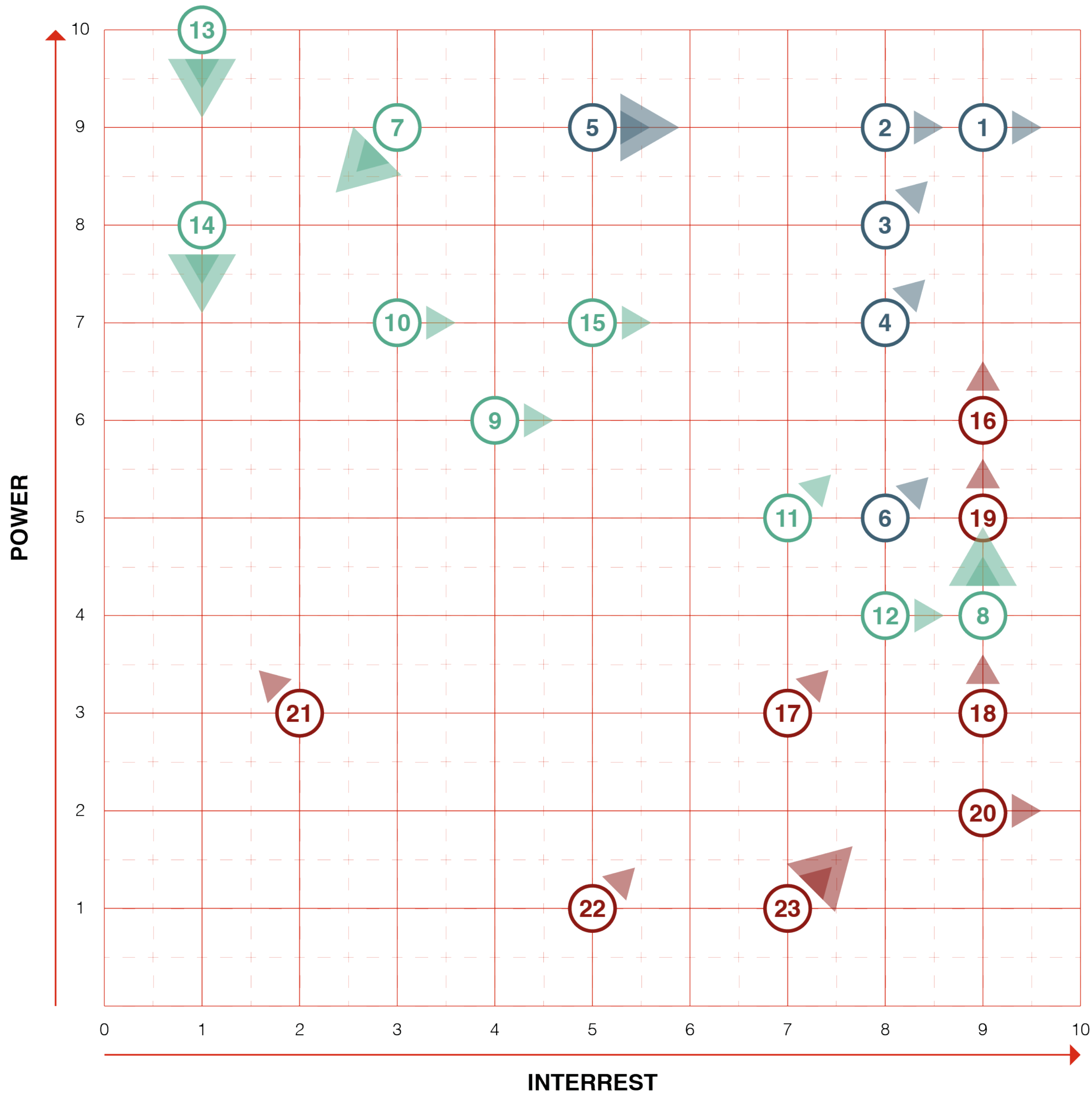


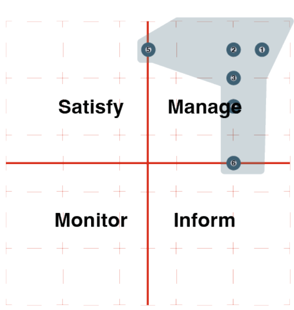
2.3 Refineries in the research area

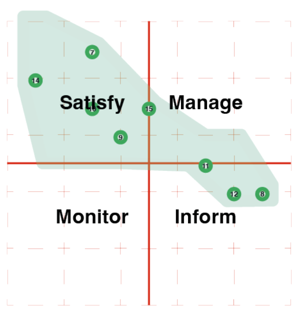
In the previous chapter we have seen that the that the heavy industries are the main consumers in figure 18 the industries are shown with 'the size corresponding to' the 'annual' energy demand by sector. For the port of Rotterdam, we can see that the refineries are the main consumer of energy. When we look at the energy flow diagram figure 19, we see that the refineries use the most oil out of all other industries which is mainly being exported.

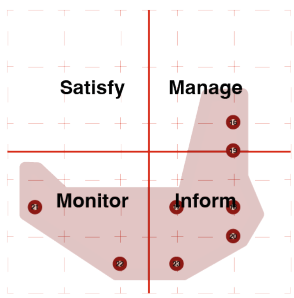
With the energy transition, the refineries will be decommissioned due to their main role as producers of petroleum from raw oil. This is the reason why refineries have been chosen as our industry of interest. The main refineries are clustered in Rotterdam, Antwerp and the Ruhr Area, collectively called the Eurodelta, providing the research area for this report.











public

1. EU
2. Government (NL, GR, BE)
3. Provinces
4. Municipalities
5. Port authority
6. Tennet

Private

7. Fossil energy companies
8. Renewable energy companies
9. Agricultural companies
10. Port related companies
11. Investors (Banks)
12. Industries
13. Refineries
14. Coal companies
15. Transportation companies

Civil

16. Labor associations
17. Housing associations
18. Knowledge institutes
19. Innovation Hubs
20. Environmental organisations
21. Industrial workers (current)
22. Residents close to the clusters
23. Future industrial workers

2.4 Stakeholder Analysis

Making sure that the energy transition will be performed in a just way requires the identification of stakeholders. During strategy making, one of the most important tasks is the management of the interface between many, and most of the time competing, stakeholders in relation to the strategic goals of the proposed project or plan. (Ackermann & Eden, 2011) Creating a power/interest matrix can help with this process. The matrix, in figure 20, shows where the most relevant stakeholders are located with regards to their power and interest in the energy transition. Besides their current location on the grid, the direction they will be headed, as a consequence of our vision and strategy, is also shown using arrows. A more in-depth analysis can be found can be found in tables 1, 2 and 3). (Ackermann & Eden, 2011)

Additionally, the smaller images show the distribution per stakeholder category. The analysis in the following sections has been conducted using Ackermann & Eden (2011). First off, the upper image shows the distribution of the public sector on the power-interest matrix. These are mainly governmental institutions with a high power and interest in the energy transition. In the vision and strategy of this report, they will be the big players who deserve sustained management attention.

Secondly, the middle image visualizes the distribution of the private sector on the power-interest matrix. These mainly consist of companies, industries, and investors. The companies enabling the energy transition will have a higher interest but overall lower power. On the contrary, decommissioned industries and fossil fuel-based companies have the least interest but high power. The first group can be categorized as subjects whose power should be increased to convert them into players, they will need to be informed to be able to adapt to new situations. The second group are the context setters able to influence the overall future context. Awareness in this group should be raised to develop interest. This group will mainly need to be satisfied.

Third, the distribution of the last group of civil society in the lower image is spread out on the power-interest matrix as well. They consist of associations, institutions, organizations, and workers. They can be split into three different groups. The first group have the lowest power and interest and to be monitored since they can be seen as potential rather than stakeholders. The second group has a high interest but low power and needs to be encouraged to become a player. The last group is already starting to become a player and will mainly be managed to increase power.

Figure 20. Power-interest matrix

Table 1.

PUBLIC SECTOR

Stakeholder / Actor	Interest	Power
European Union (EU)	Achieving the goals of the Green Deal and Paris Climate Agreement	Setting European goals and strategies Setting deadlines Handing out fines and restrictions Providing information Providing large-scale funds
Governments (NL, GR, BE)	Enabling the transition on a national scale following the EU's goals and deadlines Additional renewable energy sources Improved national well-being Increased biodiversity	Setting national goals and strategies Formulating laws Providing funds on a national scale Handing out fines and restrictions Setting national visions
Provinces	Implement energy decentralization Improve well-being and living conditions Increase (re)development Increased biodiversity	Formulating provincial goals and strategies Handing out fines and restrictions Planning large-scale (re)development Distributing gathered funds and subsidies Assigning renewable energy production locations
Municipalities	Sustainable industry Increased investment Improved well-being and living conditions	Formulating municipal goals and strategies Handing out fines and restrictions Providing information Coordinating (re)developments Issue (re)development permits
Port Authority	Transition to green industry Improved air quality Conservation of port's global position Ensuring companies existing and new company interests	Implementing governance vision and plans Coordinating with laws Supervising (re)development
Tennet	Improve energy grid robustness Installing additional powerlines	Regulating and coordinating expansion and decentralization of energy grid

Table 2.

PRIVATE SECTOR

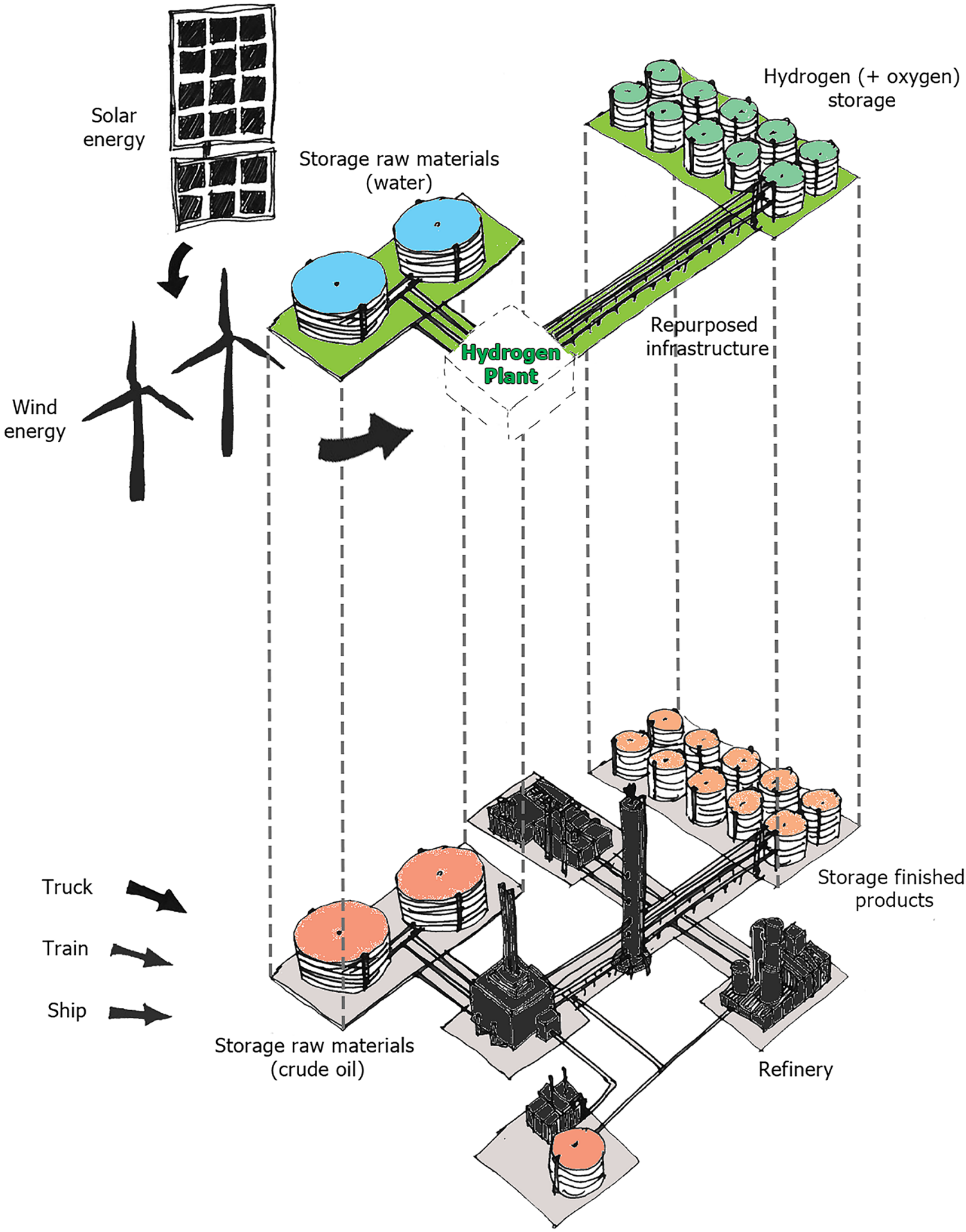
Stakeholder / Actor	Interest	Power
Fossil Energy Companies	Sustainability revolution Economic growth Maintaining position as energy provider	Important for the current energy demand Owns the biggest area of the port Acting as important employer
Renewable Energy Companies	Economic growth Increased power and influence in the sector and region Increased production scale Increased collaboration with knowledge institutions and innovation hubs	Immense grow as future energy provider Very important in the energy transition
Agricultural Companies	Economic growth Mixed land-use	Owning high amounts of land
Port Related Companies	Sustainability revolution Economic growth Increased knowledge and innovation	Driving innovation Key player in supply chain
Investors	Economic growth Enabling innovation, plans and new companies	High influence on realization of plans and developments
Refineries	Sustainability revolution Redevelopment / repurposing opportunities Staying in business	Owning plots of land Key player in supply chains
Coal Companies	Sustainability revolution Redevelopment / repurposing opportunities Staying in business	Owning plots of land Key player in supply chains
Transportation Companies (Electricity, Pipelines, Railway)	Sustainability revolution Economic growth Repurposing of infrastructure Development of new infrastructure	Owning current infrastructure Preserving market position Influencing future development of decentralized energy grid Enabling future new industries

Table 3.

CIVIL SOCIETY

Stakeholder / Actor	Interest	Power
Labor Associations	Improve working conditions Protect worker's rights Maintain availability of jobs	Controlling and monitoring public and private sector on work availability and conditions
Housing Associations	Improved wellbeing and living conditions New housing development	Controlling and monitoring public and private sector on living conditions and new development
Knowledge Institutes	Improved collaboration with public and private sector for researching, experimenting, and innovating	Providing knowledge to policy makers, innovators, industries and society
Innovation Hubs	Improved collaboration with public and private sector and knowledge institutes for experimenting and innovating	Developing future technologies contributing to policy makers, industries and knowledge institutes
Environmental Organizations	Sustainability revolution Decreased greenhouse gas emissions and overall dependency on fossil fuel Responsibility of the private sector regarding its impact on global warming	Influencing future visions and regulations on strategies and developments Controlling potential violations regarding unsustainability Insisting transition to renewable energy sources
Residents close to clusters	Improved well-being and living conditions Lower energy costs and independency	Opposing redevelopment of current living area using housing associations
Industrial Workers (current)	Improved well-being and working conditions Reschooling for more sustainable jobs	Opposing redevelopment or repurposing of employer using labor associations
Industrial Workers (future)	Improved well-being and living conditions Higher wages in new green industry	Opposing redevelopment or repurposing of employer using labor associations

03. The Hydrogen Energy System



Solar energy
Storage raw materials (water)
Hydrogen (+ oxygen) storage
Wind energy
Hydrogen Plant
Repurposed infrastructure
Truck
Train
Ship
Storage finished products
Storage raw materials (crude oil)
Refinery

3.1 Repurposing Decommissioned Refineries

With the energy transition to renewables the refineries that produce mainly petroleum from oil, will lose their purpose. The refinery itself will be decommissioned but the storage facilities and the oil and gas pipelines can be repurposed for the storage and transport of hydrogen that is needed to store the surplus of energy that is produced in peak moments.

Decommissioning the refineries also offers the opportunity to introduce new natural zones in this area since the hydrogen plant is a lot smaller than the existing refineries. Besides this, the space between the storage facilities can be repurposed with additional greenery, creating a more natural environment as well.

Figure 21. Transforming refineries to hydrogen plants

1 **H** Hydrogen 1.008																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

3.2 Hydrogen: The Element of the Future

In the objectives of this research and design project, the importance of hydrogen (H2) has been mentioned as one of the main enablers of the energy transition. Hydrogen is the most abundant element in the universe which on Earth can be mainly found in water and organic compounds. In the periodic table, hydrogen is the first element meaning it being the lightest element (atomic weight of 1.008 atomic mass units) and consists of one electron and one proton. The material has been known for over 200 years and was heavily used in balloons to cross the Atlantic during the 1920s and 1930s. NASA employed hydrogen as fuel and was the world's largest consumer by 1961. Although it has been used in spaceflight a lot in the past century, it has often been synonymous with danger because of its extremely flammable nature and is especially known in the Hindenburg disaster in 1937 killing 35 out of the 97 passengers on the airship. (Dawood, Anda & Shafiullah, 2020)

Getting a bit more in-depth on the safety characteristics of hydrogen, first off, it is not toxic and, therefore, dangerous for human lungs when inhaled. Nonetheless, there is a bigger concern due to its lightness. Hydrogen is lighter than air, meaning that it dissipates quickly when released. This allows for a fast dispersal of the fuel in case of leakages, in for example storage which would make it safer than other fuels. Despite that, the main safety concern arises when a leakage goes unnoticed and the hydrogen, in gas form, collects in a confined space (e.g., in a building) which can eventually easily ignite – due to its low ignition temperature (400 ˚ C) – causing an explosion. (Dawood, Anda & Shafiullah, 2020)

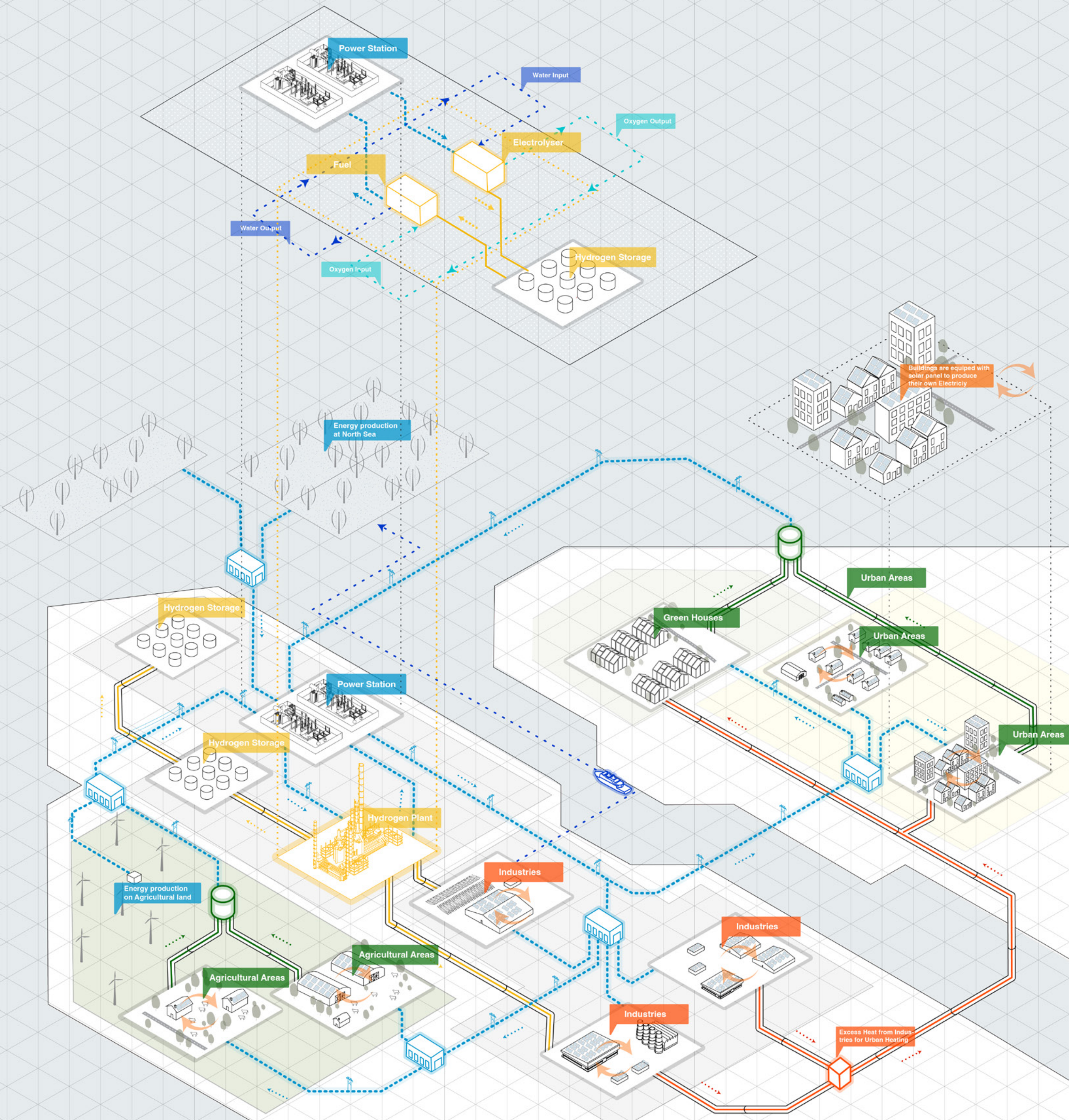
Therefore, it is important to prevent this situation from happening by producing hydrogen in the open air and making sure that leakages in storage are detected in the shortest time possible. Keeping the hydrogen storage away from residential areas will also make sure that the chance of people getting injured or even killed due to an explosion is as low as can be. Hydrogen can be made from different sources, including fossil fuels, nuclear energy, biomass, and renewable resources. Hence, contrasting methods of hydrogen production have gotten different colored names. The most common forms of hydrogen production are grey, blue and green hydrogen.

Currently, grey hydrogen is the most common form of hydrogen production which is generated from natural gas or methane, generating smaller amounts of emissions than black or brown hydrogen. These two forms use either bituminous (black) or lignite (brown) coal in the production process and are the most unsustainable as both CO2 and CO generated during these processes are not captured. (World Economic Forum, 2021)

The second form of hydrogen production has a blue label and gets this name when the carbon generated from the steam reforming is captured and stored underground through carbon capture and storage (CSS). Occasionally, this form of hydrogen production is referred to as carbon neutral since the emissions do not enter the atmosphere. However, "low carbon" is more accurate since 10 to 20 percent of the generated carbon cannot be captured. (World Economic Forum, 2021).

Lastly, green hydrogen, also known as "clean hydrogen", is produced using renewable energy sources, such as solar or wind power, by splitting water into two hydrogen atoms and one oxygen atom. This process is known as electrolysis. Due to the production of renewable energy not being constant each day, green hydrogen production could be used to transform surplus energy in times of low demand and feed back into the energy grid when demand is higher. The utilization of this could be an enabler of decarbonizing chemical, industrial and transportation sectors.

Image 7. Hydrogen as the first element in the periodic table. Adapted from Double sharp (2021) using 8SA (2020).


Power Station
Water Input
Oxygen Output
Electrolyser
Fuel
Water Output
Oxygen Input
Hydrogen Storage
Buildings are equiped with
solar panel to produce
their own Electriciy
Energy production
at North Sea
Urban Areas
Green Houses
Hydrogen Storage
Urban Areas
Power Station
Urban Areas
Hydrogen Storage
Hydrogen Plant
Industries
Energy production
on Agricultural land
Industries
Agricultural Areas
Agricultural Areas
Industries
Excess Heat from Indus-
tries for Urban Heating

3.3 Circularity in Hydrogen Energy Systems

The only sustainable method of producing hydrogen is performed by electrolysis and, for that reason, this green hydrogen production method will be further utilized in the 'Vision' and 'Strategy' of this project. What still needs to be analyzed is the storage possibilities and characteristics of hydrogen.The concept of energy storage from renewable energy production as hydrogen energy is, in essence, quite simple. (Surplus) renewable energy is used to produce hydrogen using electrolysis which is then stored during low energy demand.

When solar or wind energy production is lower but demand is high, the stored hydrogen can be used as fuel in a power plant to generate power for the energy grid with higher demand. Besides energy, electrolysis uses water as input to create hydrogen and additional oxygen as output. This additional oxygen is later on needed in the fuel cell to reverse the process and generate power and water; a circular process otherwise known as the hydrogen cycle. (Breeze, 2018)

A schematic of this hydrogen energy storage system can be found in figure 22., showing how the hydrogen plant operates in the wider region by enabling a ciruclar energy system between industrial, residenital and agricultural areas.

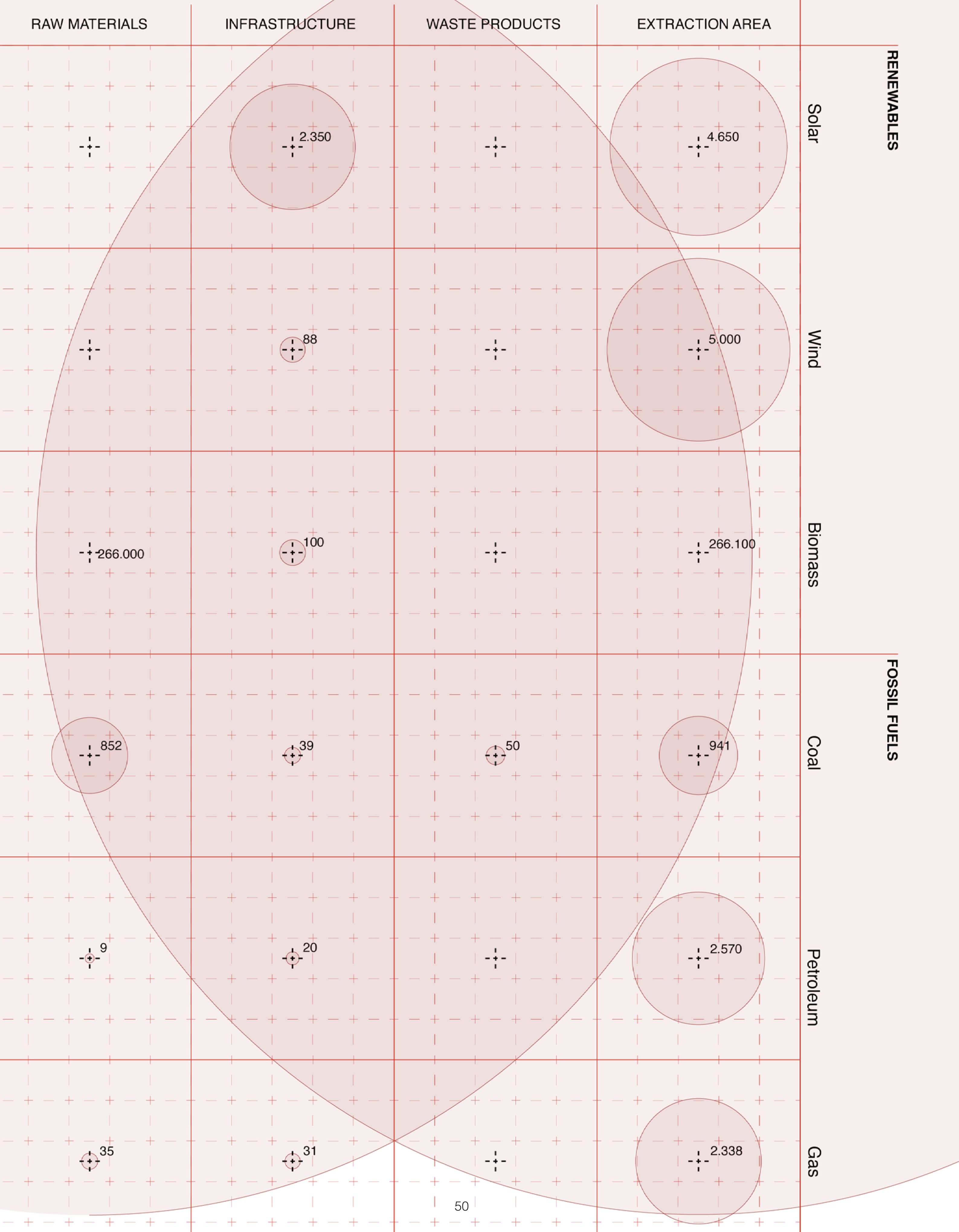
The produced hydrogen must eventually be stored bringing new issues due to the characteristics of hydrogen under ambient conditions. The volumetric energy density of hydrogen in a gaseous state (after electrolysis) at atmospheric pressure is 0.09 kg/m3, meaning that an enormous amount of huge storage tanks is needed to store this hydrogen. But hydrogen can also be stored as a liquid. If the storage temperature stays under -252.9 ˚ C, the boiling point of hydrogen, and is kept under a pressure between 350 – 700 bar, the volumetric energy density is approximately 71,48 kg/m3, almost 800 times as high as being stored under ambient conditions meaning less space needed for the storage of hydrogen and thus energy. (Demaco, 2021)

The issue regarding hydrogen production relates to the energy efficiency of hydrogen and the available renewable energy sources. First off, the energy density of hydrogen is around 33 megawatt hour (MWh) per kilogram (kg) depending on the purity of hydrogen. Electrolysis has a high hydrogen purity of 99.9% but currently requires more energy to be performed with an efficiency of around 70% with the remaining 30% being exhausted as heat (Younas et al., 2022).

Australian company Hysata is working on a future new category of electrolysis with an efficiency of 95% meaning less energy will be lost to heat (Hyasata, 2021). They also mention their system to have a low-cost design, based on earth-abundant materials which links well to the future plans of the European Commission mentioned earlier. The final problem with hydrogen production and storage is the use of renewable energy sources. This co-exists with the spatial conflict of renewable energy production where these green alternatives to fossil-fuel based energy production require way more space. This overall problem for this project will be further elaborated on in the following section.

Figure 22. Circular hydrogen system

SPATIAL FOOTPRINT FOR 1 MILLION HOMES (iN HA.)



3.4 Spatial Footprint of Renewable Energy

One of the most important requirements for the hydrogen energy system to work is the upscaling of renewable energy production to be able to produce hydrogen and end the use of fossil fuel-based energy production. Alas, positioning renewable energy production requires a way bigger area to produce the same amount of energy as fossil fuels, a diagram visualizing this problem can be seen in figure 23.

To elaborate on this problem – and a potential solution – in practice, several calculations have been made using the industrial energy consumption of the province of South Holland and the Netherlands regarding wind and solar power production. An overview of all calculations can be found in table 1 in Appendix A.1.

In 2023, the existing wind turbines in the Netherlands consists of Horizontal-Axis Wind Turbines (HAWT) producing, on average, 5 MWh adding up to an average annual production of 18.000 MWh per HAWT (Nationale EnergieAtlas, 2023). South-Holland's industrial energy consumption in 2018 consisted of approximately 42.196.111,11 MWh (Provincie Zuid Holland, 2019) meaning that a total of 2344 wind turbines would be needed to sustainably produce this amount of annual energy demand. A single HAWT requires an area of 60 hectares meaning that for 2344 of these wind turbines, an area of 140.654 hectares is needed, around 40% of the land area of the province of South Holland.

Comparing this to the use of solar energy, in the Netherlands, the annual production of a photovoltaic panel is around 875 kWh (Utrecht University, 2019). This means that for the annual industrial energy consumption for the province of South Holland, you would need a staggering 48.224.127 photovoltaic panels. With a single photovoltaic panel taking up 1,6335 hectares of space (MetDeZon, 2020), an area of 78.774.111 hectares would be required, an area twenty times larger than the area of the whole Netherlands. Hence, solar energy is not usable as an energy supplier for industry in the province of South Holland and in general requires a lot of space for energy production. Solar energy will still be a big player as a renewable energy source due to the current cheap installment costs and easy process. The power density of solar energy might be higher than wind energy, but the space between wind turbines could be used for other functions as well e.g., agriculture. Off-shore wind energy is a different story.

One of the objectives of the European Commission mentioned earlier in this report was to enable the full potential of offshore wind energy generation as part of the European Green Deal. Besides, after looking at the spatial footprint of both solar and wind energy, wind turbines seem a more logical choice for the production of high amounts of renewable energy for the industry sector.

Figure 23. Spatial footprint of energy sources for 1 million homes. Adapted from Sijmons (2014).

Table 4 Adapted from Islam, Mekhilef & Saidur (2013); Offshore Wind2023); World Wide Wind AS (2023).

Horizontal-Axis Wind Turbine (HAWT)	Vertical-Axis Wind Turbine (VAWT)
Rotating axis of the wind turbine remains horizontal, or parallel to the ground	Rotating axis remains vertical, or perpendicular to the ground
It is able to produce more electricity from a given amount of wind	It produces up to 50% more electricity on an annual basis versus conventional turbines with the same swept area
Comparatively heavier and not suitable for turbulent winds	Lighter and produce well in tumultuous wind conditions
HAWT are only powered with the wind of a specific direction	VAWT are powered by wind coming from all directions, they can even be powered if wind blows from top to bottom
Not suitable to generate electricity from wind speeds below 6 m/s and generally cut out at speeds around 25 m/s	Generates electricity in winds as low as 2 m/s and continuous to generate power in wind speeds up to or even over 60 m/s
Birds are injured or killed by the moving propellers since they are not solid objects making the birds fly into the blades	Does not harm wildlife as birds can detect a solid object and (for human flight) can be seen on aircraft radar
Most are self-starting	Low starting torque and may require energy to start running
Less visibly attractive due to height	Lower height and therefore more aesthetically pleasing and thus improving spatial quality
Difficult to transport and install	Lower construction and transportation costs
Makes more noise	Makes less noise
Maintenance happens at the top of the wind turbine	Maintenance happens at the bottom of the wind turbine
Needs to be constructed on the seabed	Designs can be made floatable making use at deep sea possible
Average area needed per wind turbine around 60 hectares	Average area needed 50% of HAWT meaning on average around 30 hectares
Lower future scalability to around 18 MW	Larger future scalability to more than 40 MW

Image 8

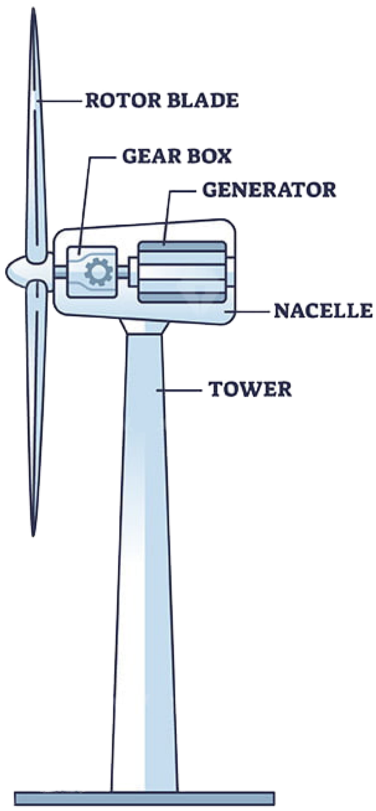
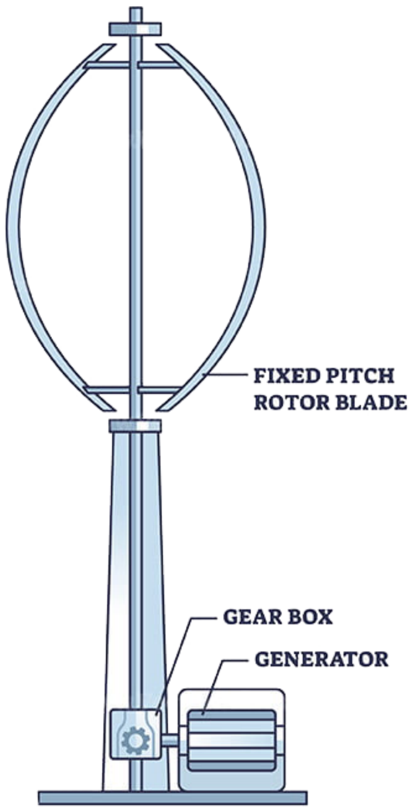


Image 9



Up until now, only HAWT's have been mentioned, but this is not the only wind turbine type in existence. Vertical-Axis Wind Turbines (VAWT) have already been designed in the 1970s and 80s but are still a rare sight in the energy landscape. Studies were carried out concluding that HAWT being more efficient for large-scale wind energy production. Therefore, additional studies on VAWT have sparsely been carried out since. (Islam, Mekhilef & Saidur, 2013)

There has been a change of dialogue since the 2010s. Several companies are now working on future VAWT designs outperforming current and future HAWT designs shown in a comparison between the two summarized in table 4.

SeaTwirl, a Swedish company installed their S1 floating wind turbine with a power output of 30 kWh in 2015. In the following years, they have been working on their S2x model with a pilot installation in 2023 (SeaTwirl, 2023). This VAWT will be able to produce 1 MW and has been used for the next energy footprint calculation. 1 MWh of energy output equals an annual energy production of 3.600 MWh. As mentioned in table 13, VAWT's require 50% less space than HAWT. Using the industrial energy consumption of South-Holland again, the renewable energy production using the S2x would add up to an amount of 11.721 turbines taking up 351.634 hectares of space, equaling the land area of South-Holland.

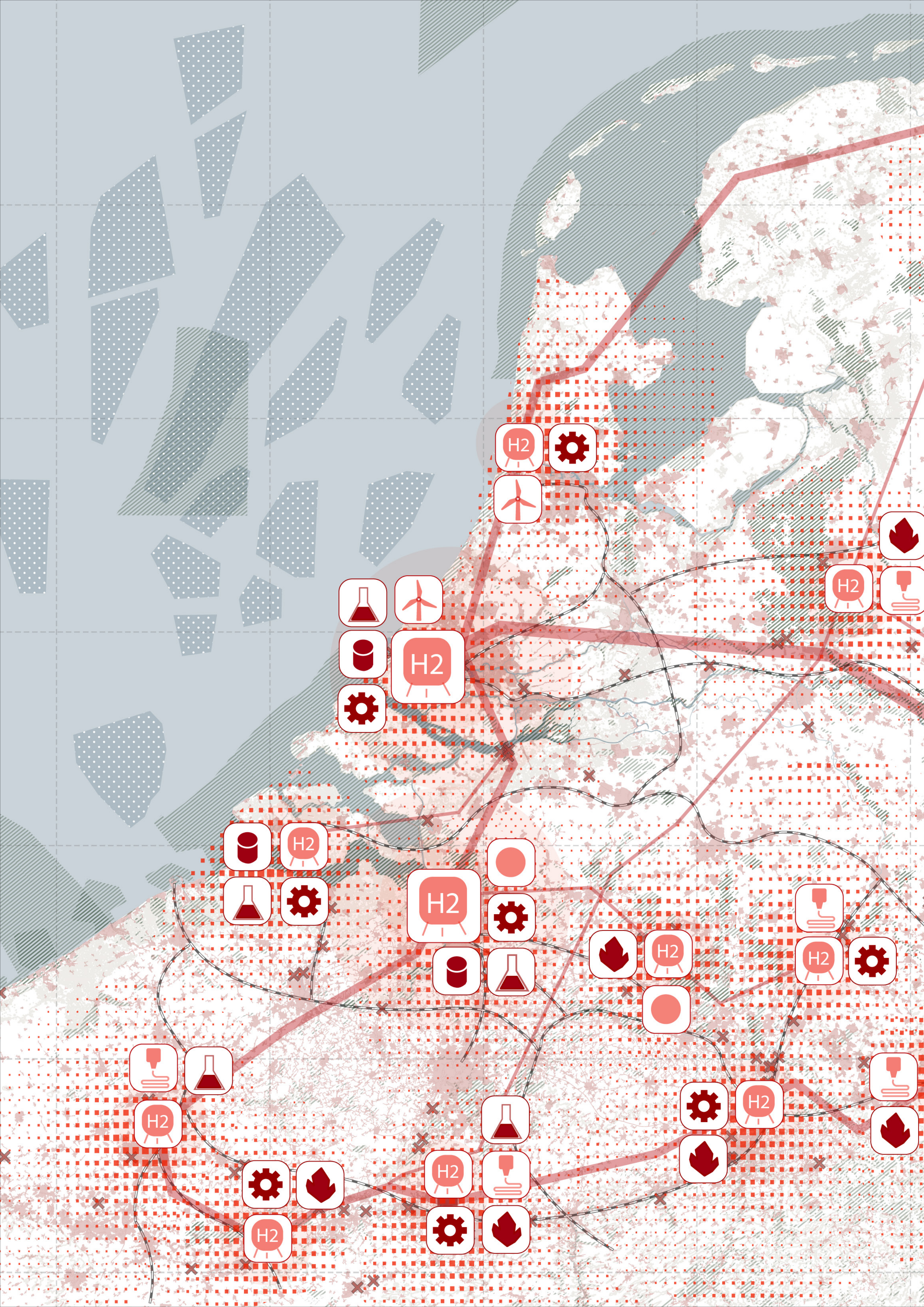
It seems like VAWT are less viable than HAWT looking at the energy output and the overall production area. On the contrary, the Norwegian company called World Wide Wind AS (2023) has a proof of concept consisting of a floatable VAWT able of producing 40 MWh in a few decades. Beyond these already extreme values, Hansen, Mahak & Tzanakis (2021) state positioning VAWT in pairs will increase each other's performance by up to 15% due to the distortion of the air flow field. When three turbines are positioned in a series, the power output will be 3% higher than the pair. This could theoretically mean that three VAWT producing 40 MWh each will have an effective output of 133,2 MWh instead of 120 MWh. (Hansen, Mahak & Tzanakis, 2021)

Assuming VAWT's ability of a power output of 20 MWh in 2030, for the industrial energy consumption of South-Holland, the number of turbines needed is only 586 needing an area of 17.582 hectares. Taking the example of VAWT's power output to be 40 MWh in 2050, the number of turbines need will be even less with 293 pieces using an area of only 8.791 hectares. This would solve the problem with the spatial footprint of wind energy.

Image 8. Horizontal-axis wind turbine.

Image 9. Vertical-axis wind turbine

04.Vision: The Hydrogen Backbone


H2
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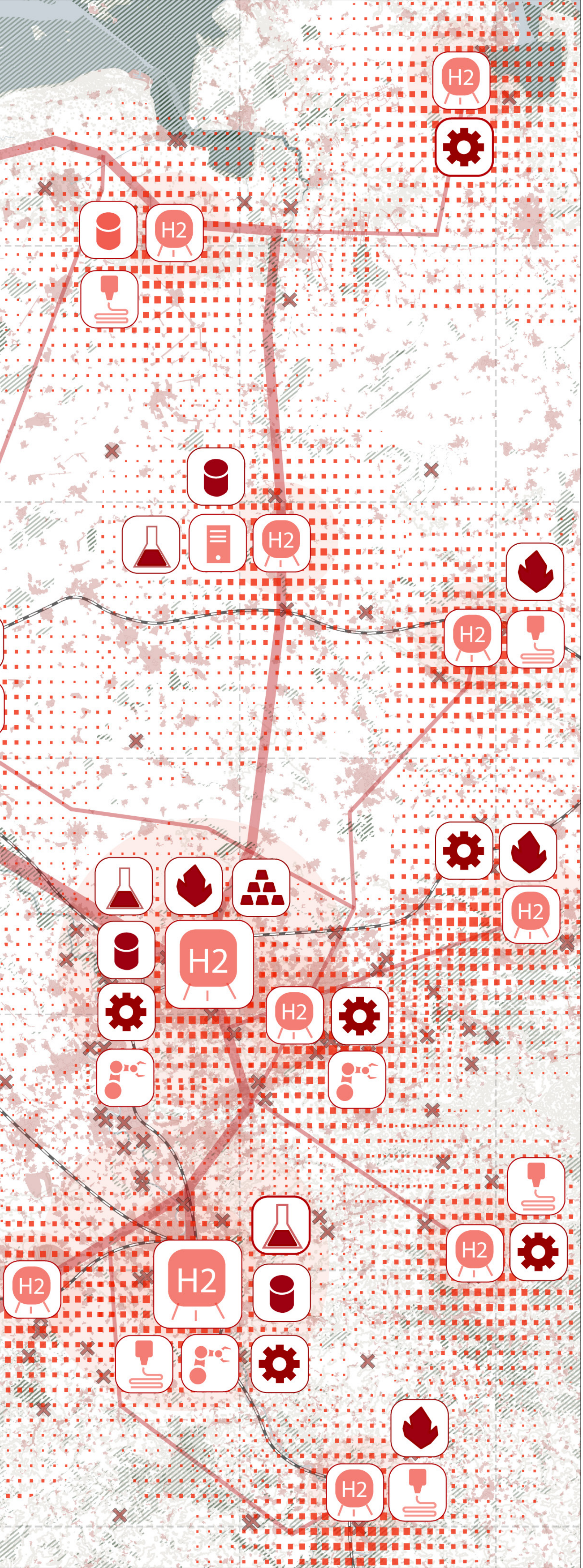


4.1 Vision Overview

0 37.5 km 75 km

Legend

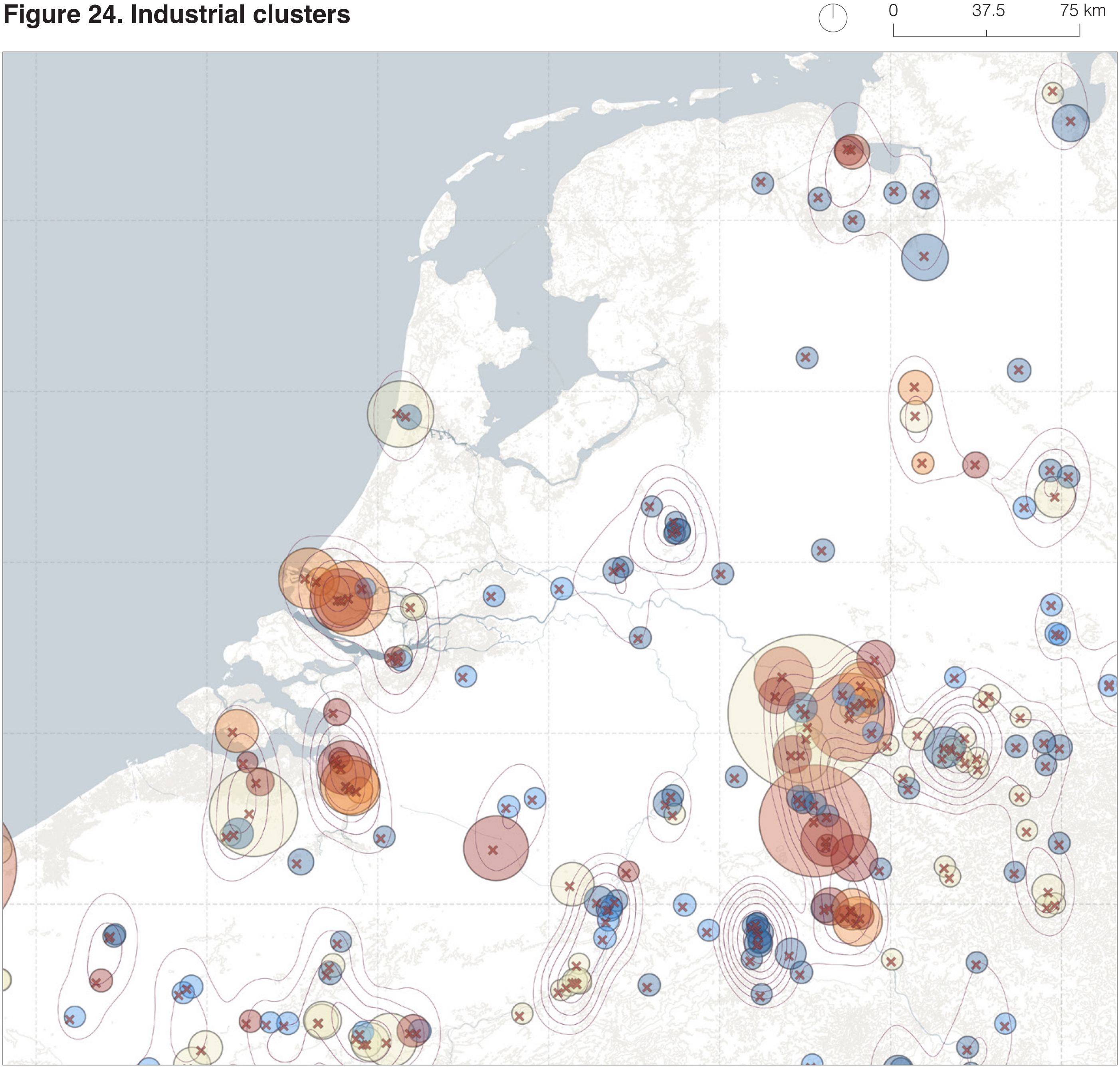
- Proposed hydrogen backbone
- Secondary hydrogen connection
- Proposed hydrogen plants

- Existing storage
- Chemical industry
- Iron and steel
- Non metallic minerals
- Non ferrous metals

- Hydrogen plant
- Wind turbine manufacturing
- Solar panel manufacturing
- Data centers
- 3D printing
- Robotics and automation

In 2030, the assumption can be made that all refineries will have been decommissioned by a sustainability transformation in the industry sector in line with the objectives of the European Commission mentioned in section 2.2. This vision foresees the current location of refineries to be repurposed for the rise of hydrogen plants enabling both a centralized and decentralized energy system, earlier described in section 3.1, which would essentially consist of three main elements: 1. The Industrial Clusters, 2. The Hydrogen Backbone and 3. The Connections.

Figure 24. Industrial clusters



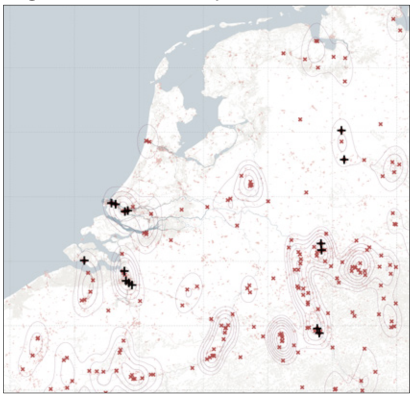


Figure 25. Industry areas

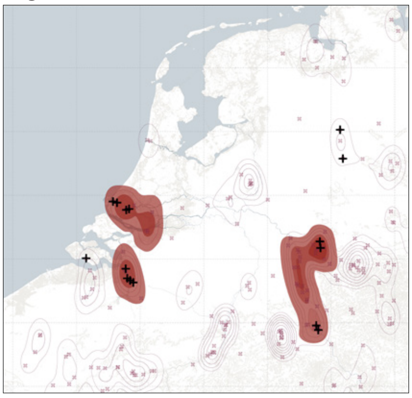


Figure 26. Main industrial clusters

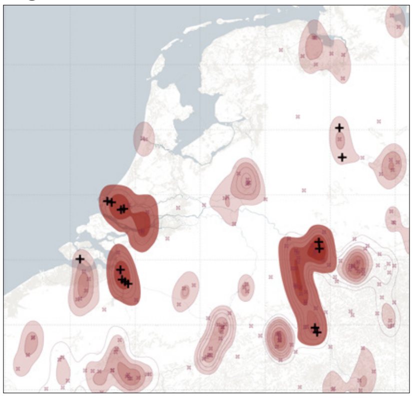
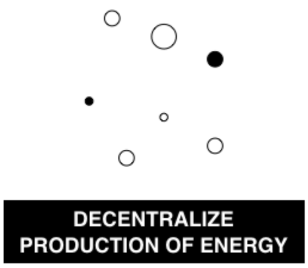


Figure 27. All industrial clusters

4.2 Industrial Hydrogen Energy Systems

4.2.1 The Industrial Clusters



INDUTRIAL CLUSTERS

The first part of creating the vision started with clustering heavy industries into main and subclusters in the research area of the Eurodelta (figure 24 & 25). Performing a point density analysis of heavy industries to cluster the industries, makes it possible to understand the location of the major industries in the region and observe the concentration of heavy industries. Through this, these industries were grouped together to form a node (figure 26)

Since refineries are the heaviest polluters and biggest energy consumers, the main clusters are determined by the presence of refineries that would be converted, when decommissioned, into hydrogen plants since they have the most storage potential for a resilient energy system. These main clusters are connected through a resilient and dynamic connection, forming the vision's backbone. All other clusters would then serve as sub-systems of energy production and storage, dependent on the primary backbone. (figure 27)

Legend

Source: sEEnergies 2020

Industry sector

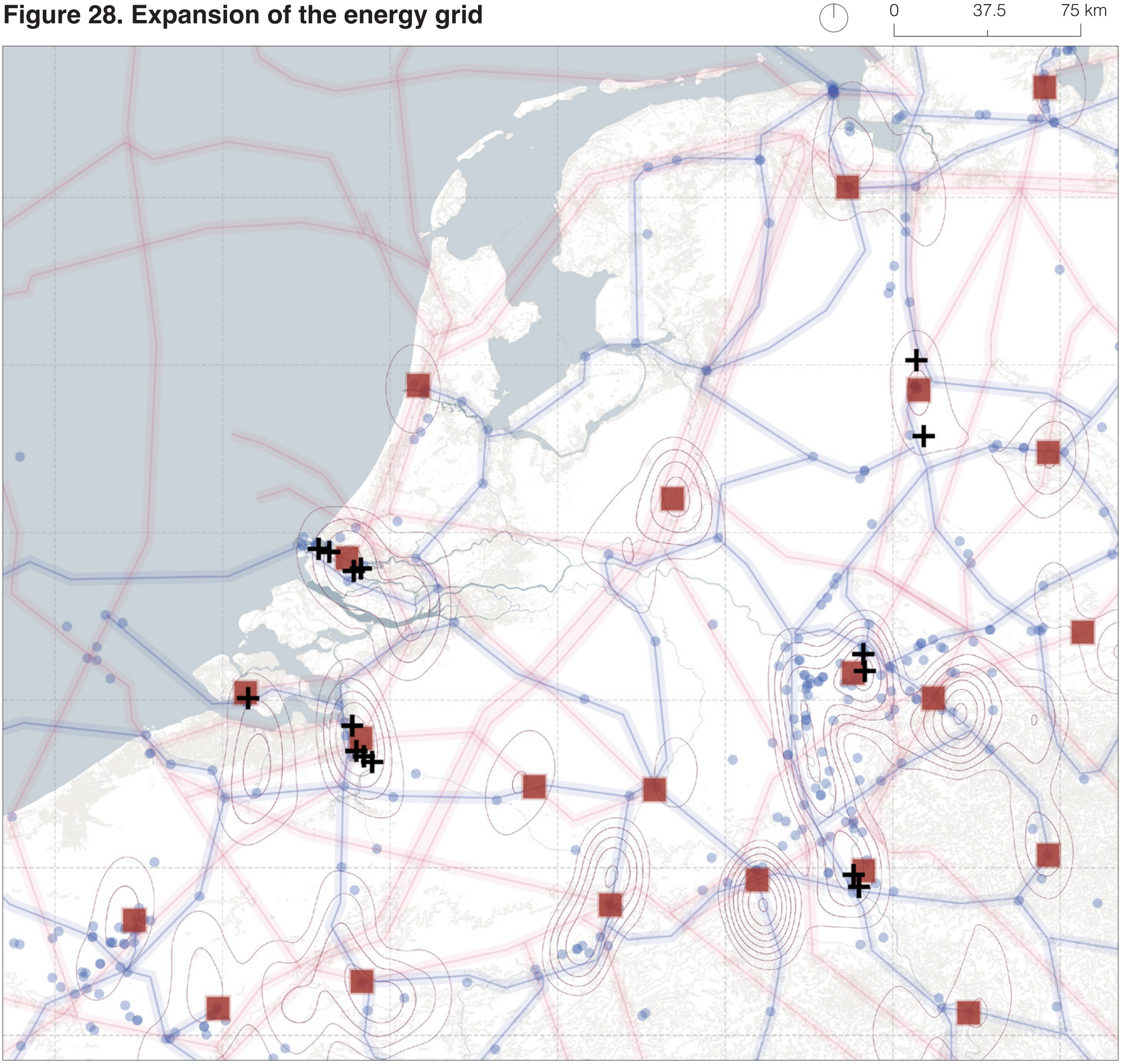
- Chemical industry
- Iron and steel
- Non-ferrous metals
- Non-metallic minerals
- Paper and printing
- Refineries

Electricity demand approx. (TJ/year)

- 0
- 5 000
- 10 500
- 16 000

- Cluster lines
- Industry points
- Industrial areas
- Refineries

Figure 28. Expansion of the energy grid



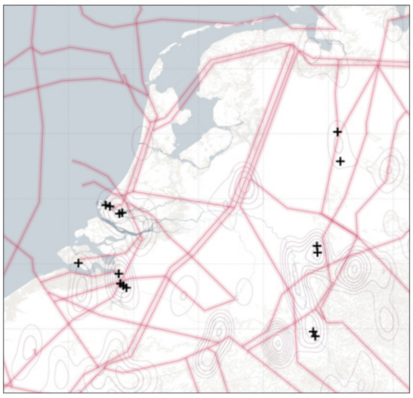
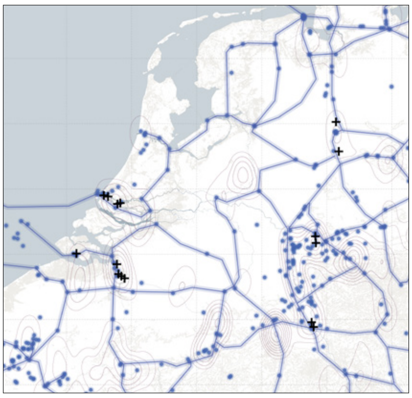


Figure 29. Existing pipelines



F. 30 Existing high tension cables

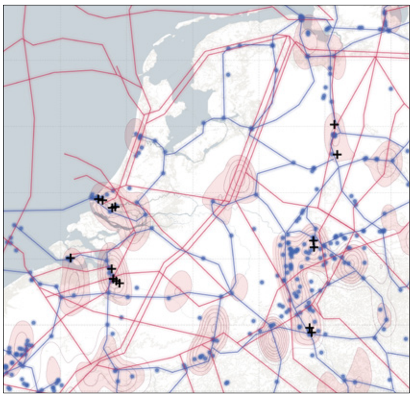
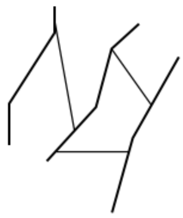


Figure 31. Existing infrastructure

4.2.2The Expansion of Energy grid



CONECTIONS

ENERGY GRID EXPANSION

Secondly, for every cluster to be able to store its own energy a hydrogen plant is needed. The location of these proposed hydrogen plants is determined by existing infrastructure (figure 31). Existing infrastructure, such as oil and gas pipelines, can be adapted to transport hydrogen, which makes it a crucial factor to consider while deciding the location of the plant (figure 29). Another key aspect of determining the location is the proximity to the electricity line and the substation (figure 30). The ideal location for the proposed hydrogen plant would thus be at the intersection of these three elements within the industrial clusters (figure 28).

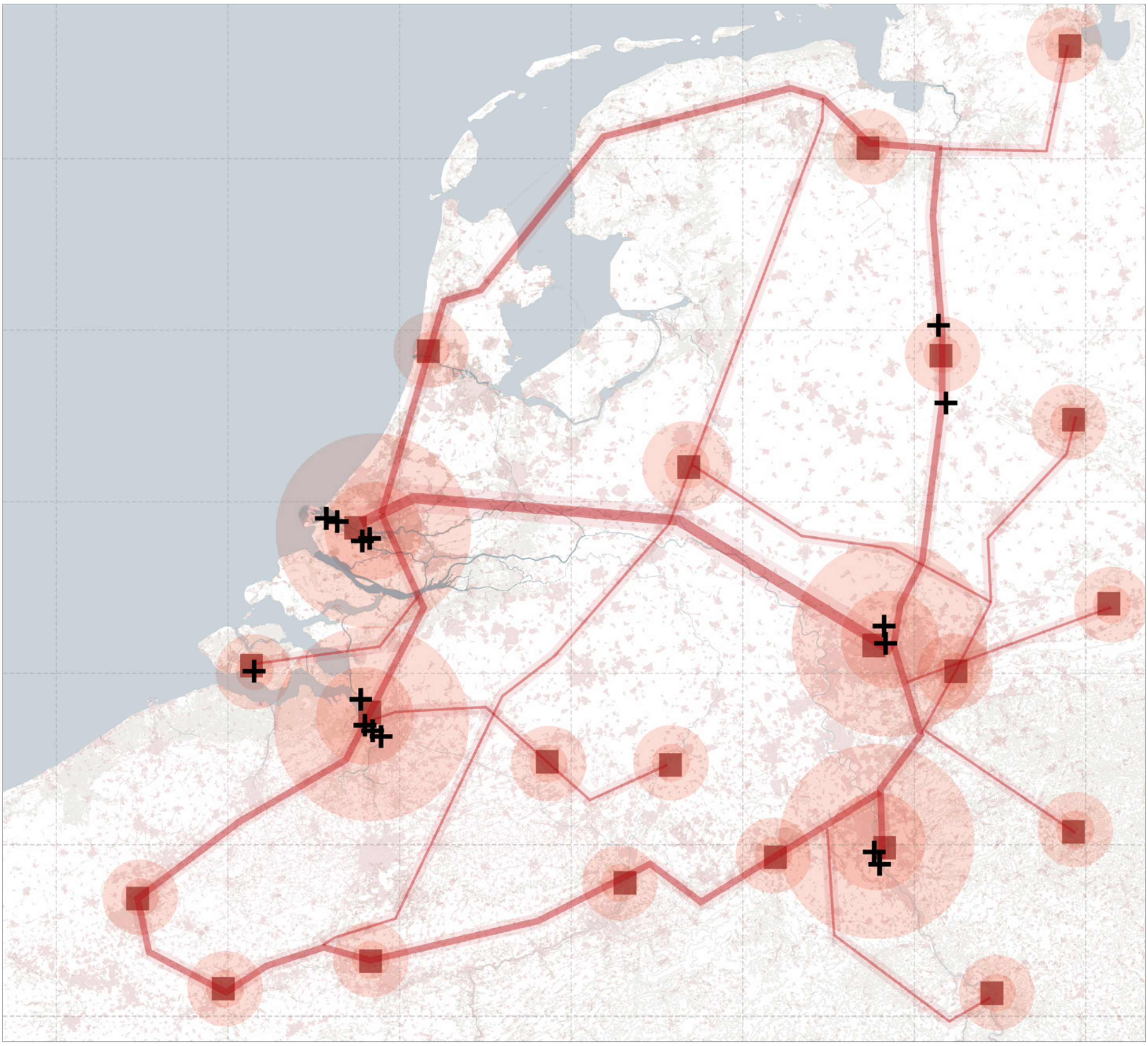
Legend

Source: Garret 2022

- Refineries
- Existing pipelines
- Existing high tension cables
- Existing electricity substations
- Proposed hydrogen plants

Figure 32. Expansion of the electric grid

0 37.5 75 km



F33. Existing pipelines and refineries

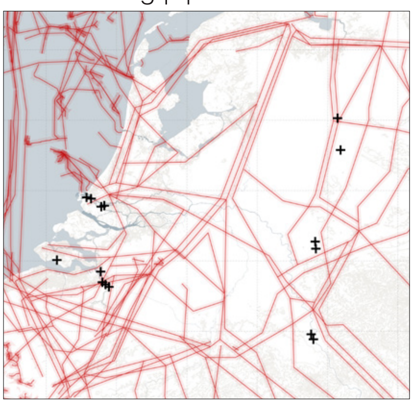


Figure 34. Cluster of pipelines

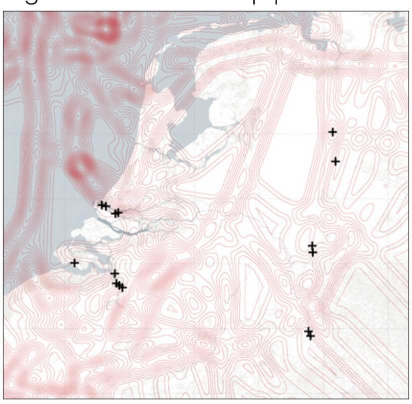
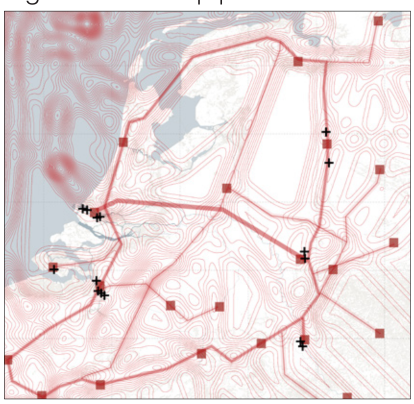
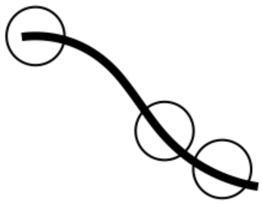


Figure 35. Main pipelines



4.2.3 The Hydrogen Backbone



HYDROGEN BACKBONE

PRODUCTION AREAS AND STORAGE

As a third consequent step, the hydrogen backbone and connections between the hydrogen plants in the subclusters are determined. Existing oil and gas pipelines are used as a basis for forming this connection. As depicted in figure 33, the pipeline network is very cluttered. Therefore, a line density analysis is conducted for the pipelines to create a heatmap to define the most predominant network(figure 34). Through the analysis, a network is formed connecting the subclusters to the main clusters creating a secondary hydrogen loop (figure 35). This depicts the main backbone and the hydrogen loop. Hydrogen clusters play a crucial role in the renewable energy transition due to its capability to store energy. Additionally, these clusters are also essential in determining the location of future industries. Having a high potential of these industrial clusters to become drivers of urban and industrial growth (figure 32).

Legend
Source: Garret 2022

+ Refineries

Proposed hydrogen backbone

Secondary hydrogen connection

Proposed hydrogen plants

Figure 36 Energy Production landscape

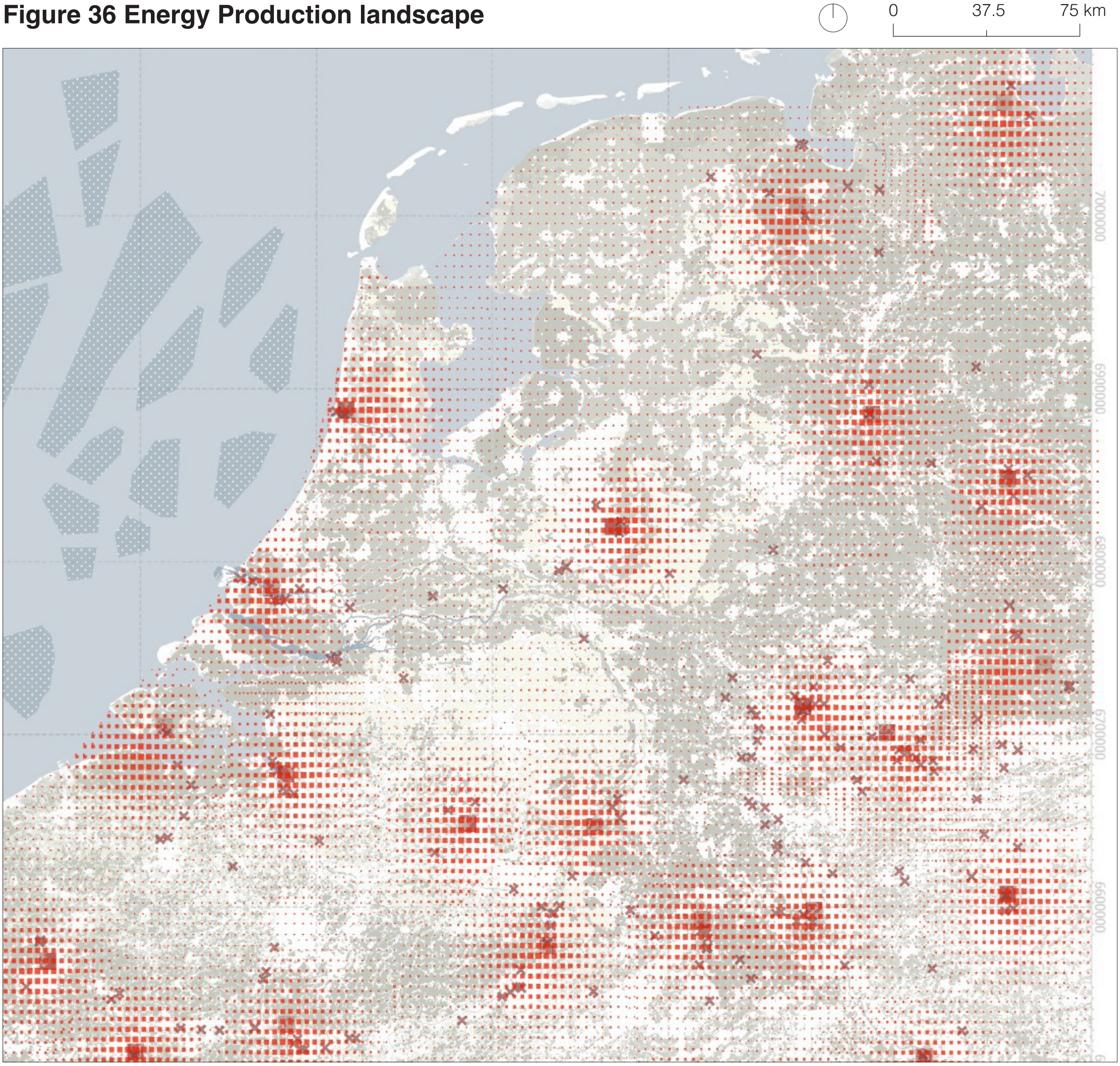


Figure 37. Non production areas

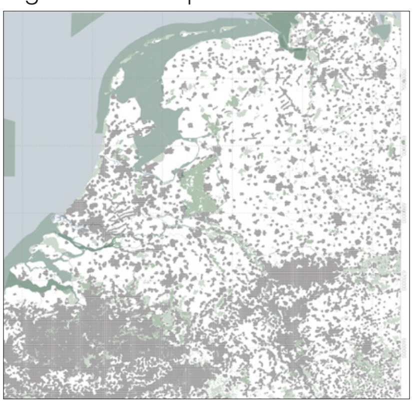
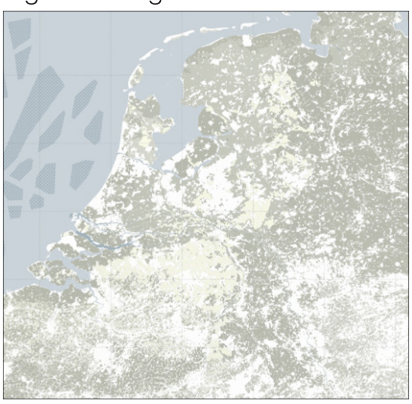
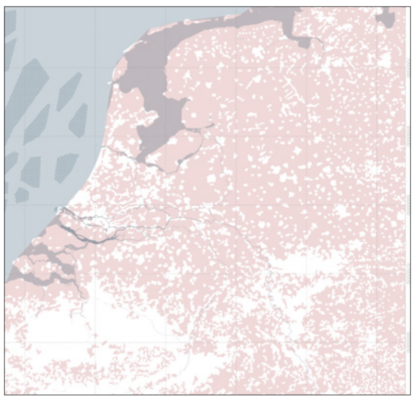


Figure 38. Agriculture areas



F 39. Potential production areas



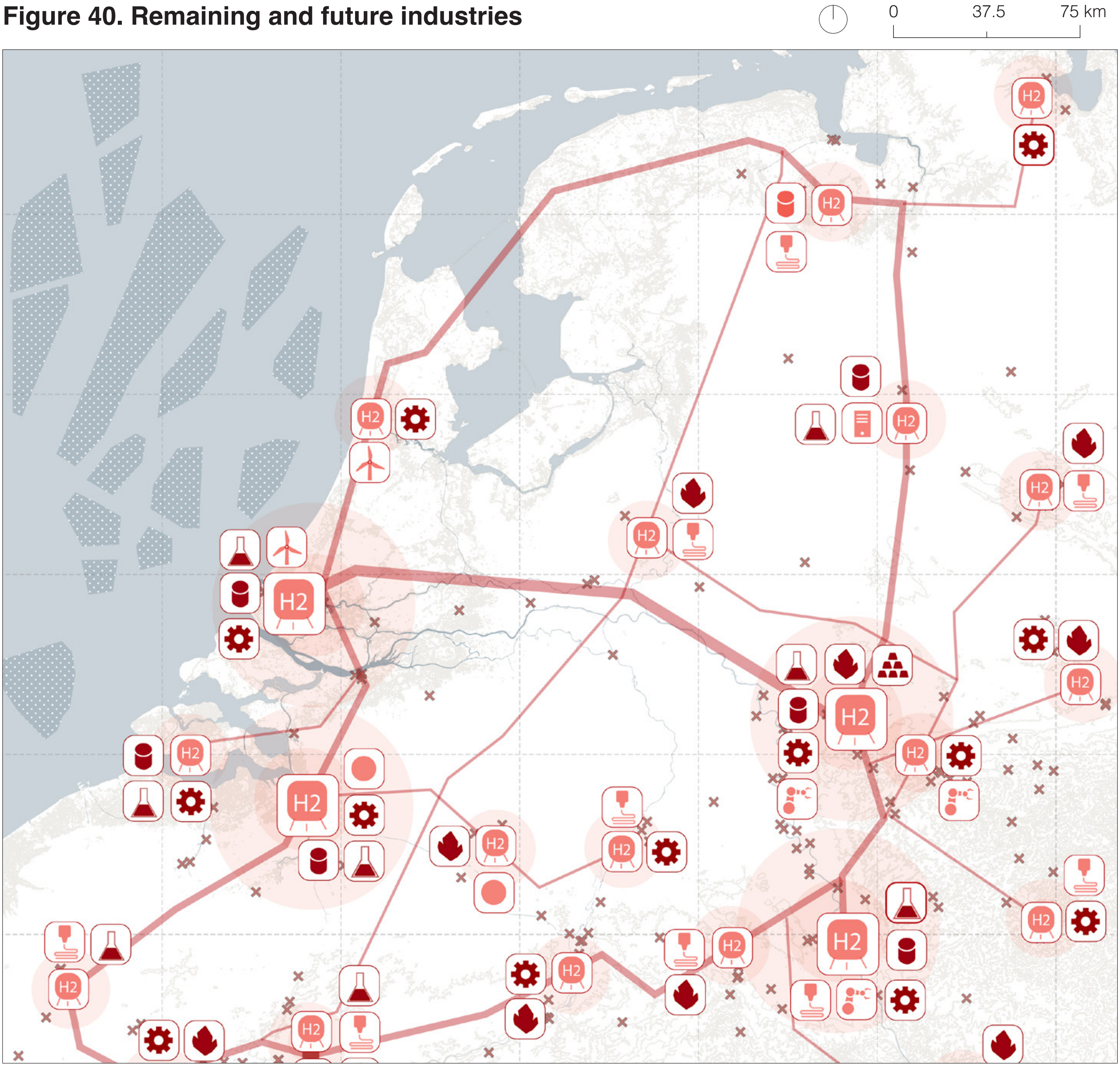
4.2.4 The Energy Production Landscape

Taking a look at the proposal for the energy production landscape. Each subcluster is independently able to produce local energy. The area and amount of production differs for each cluster depending on its energy demand and available land. In urban areas, individual buildings can generate local energy through the installment of photovoltaic panels. Besides, as mentioned in chapter 3.4 on the potential spatial footprint of renewable energy production, large amounts of energy will be generated by wind turbines on the sea. Figure 37 shows the urban area buffers and nature areas where the placement of wind turbines is prohibited. In agricultural areas, different landscapes correspond to different placement arrangements for wind turbines (figure 38). Biomass is also an alternative source of energy production. Production of renewable energy is highest around clusters and decreases as the proximity to the clusters increases(figure 39). In this way, the hydrogen plant serves as a node of energy production density as shown in figure 36).

Legend
Source: Copernicus 2023

- Refineries
- Proposed hydrogen backbone
- Secondary hydrogen connection
- Proposed hydrogen plants
- Agriculture production areas
- Production areas on sea
- Production area density

Figure 40. Remaining and future industries



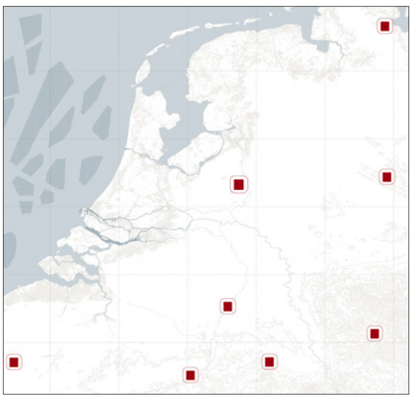


Figure 41. Declining industries

Figure 42. Remaining industries

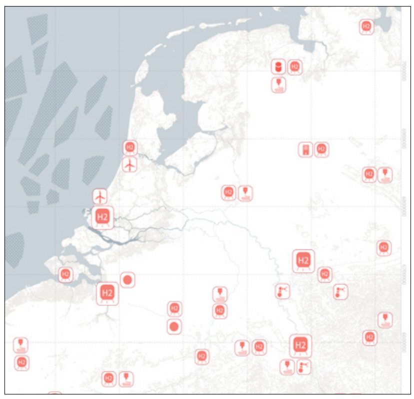


Figure 43. Future industries

4.3 Declining, Remaining and Future Industries

As mentioned before, within the clusters, the predominant heavy industries have been identified although other industries do exist as well. As technology advances and energy transitions occur, these industries will transform to become more sustainable. Besides, new industries will rise relating the the next (6th) industrial revolution. For the declining industries mainly consisting of paper and printing, there is no place in the future due to the big leaps in digitalization (figure 41). Industries that currently produce large amounts of CO_2 emissions, like the steel, iron, and petrochemicals industry would now produce fewer emissions because of using hydrogen as raw material and not petroleum-based products. These industries will remain in the same location like they exist right now (figure 42).

For this vision, an assumption has been made to identify five upcoming industries which consume large amounts of energy – namely – wind turbine production, photovoltaic panel manufacturing, robotics and automation, data centers and 3D printing. Suitable locations of these industries are determined within the sub-hydrogen clusters in accordance with the existing infrastructure and supporting industries (figure 43). For instance, the location of the robotics and automation industry is in proximity to the steel and iron industries since it uses these materials directly.

Robotics and automation are most useful in, e.g., the automotive industry which is why this vision locates those industries in the Ruhr Area in Germany occupying a large automotive industry. Wind turbine production would be most suitable in harbors near the sea since they will be installed offshore whilst transport is also easiest using ships. Assuming the disappearance of the printing industry, 3D printing will be located in these areas replacing the old industry. Due to the digital revolution and increase in data creation, data centers will be needed everywhere which is why these are not positioned in certain locations.

Legend
Source: sEEnergies 2020

- Refineries
- Proposed hydrogen backbone
- Secondary hydrogen connection
- Paper and Printing
- Existing storage
- Chemical industry
- Iron and steel
- Non metallic minerals
- Non ferrous metals
- Hydrogen plant
- Wind turbine manufacturing
- Solar panel manufacturing
- Data centers
- 3D printing
- Robotics and automation

Figure 44. Centralize and decentralize energy systems

Figure 45. Diagram of the centralized energy system

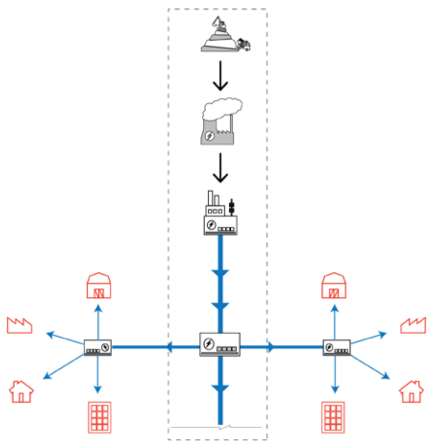
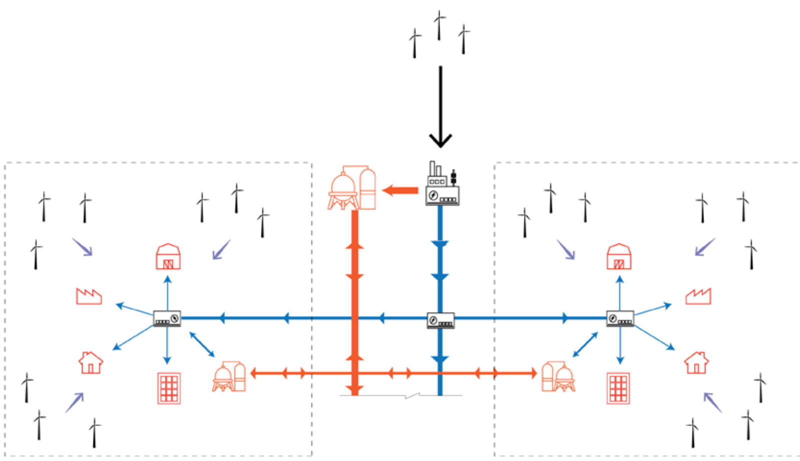


Figure 46. Diagram of the decentralized energy system



4.4 Centralized versus Decentralized Energy Network

One of the most important parts of this vision is the introduction of decentralized energy systems. Currently, as mentioned in section 1.2, most energy systems are completely centralized. Figure 45 shows this current centralized energy system in blue starting at the top with the production of energy by, mainly, fossil fuels. This is further transported using high voltage power lines to transmission stations dividing the energy in lower voltage power lines which in turn go to the industrial, agricultural and residential sectors. In short, all sectors are connected to the main high voltage power line only divided by transmission stations. This way the complete energy system is interconnected like the case is in the Netherlands.

In turn, figure 46 shows the conceptual decentralized energy system using hydrogen storage possibilities. This system, on orange, takes the production of renewable energy and transports it to the main hydrogen plant converting the energy into hydrogen. This will then be transported using the main hydrogen system to decentralized energy systems. These systems are able to produce local renewable energy as well making them self-sufficient energy communities. They will contain a local smaller hydrogen plant with nearby storage able to convert energy to hydrogen in an omnidirectional fashion. This way a surplus of renewable energy production in the decentralized area can be converted into hydrogen and transported to places with a higher energy demand than they can currently supply using the hydrogen system with nearby storage capabilities. The centralized, in blue, energy system is still in use as well.

The overall visionary hydrogen enabled energy system is a combination of both the centralized, in blue, and decentralized, in orange, energy systems to create a more resilient energy system. Combining the two systems will ensure a more safe energy system. In case the hydrogen plant fails, the current centralized energy system is still usable making sure that blackouts don't occur. Besides, the decentralized energy systems are self-sufficient meaning when the centralized energy grid experiences problems, they will not have blackouts as long as they have sufficient renewable energy production or hydrogen storage.

Figure 44 shows how these two systems are interconnected in two parts of the Netherlands. In the western part, a more centralized energy system is envisioned whilst in the eastern part, a more decentralized energy system is visualized. The following chapter regarding the strategy will further elaborate on this energy system vision.

3 GOOD HEALTH AND WELL-BEING

- Improving air quality
- Improving living conditions for residents
- Increase housing availablity
- Improving working conditions for workers

4 QUALITY EDUCATION

- Improving abilities for reschooling for more sustainable jobs
- Improving cooperation between intitutes and the public and private sectors

7 AFFORDABLE AND CLEAN ENERGY

- Introduce centralized energy systems
- Increase renewable energy sources
- Introduce renwebale energy manufacturing

8 DECENT WORK AND ECONOMIC GROWTH

- Economic growth due to new industries
- Improving working conditions due to less emissions
- Hydrogen frontrunner enabling economic growth

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

- Economic growth due to new industries
- Improving working conditions due to less emissions
- Increase research and innovation regarding hyrdogen

10 REDUCED INEQUALITIES

- Reducing price of installing photovoltaic panels
- Increase wellbeing for all
- Centralizing energy grids and renewable energy allow for more democracy

11 SUSTAINABLE CITIES AND COMMUNITIES

- Renewables energy makes cities more sustainable
- Self-sufficiency allows for energy communities

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

- Repurposing existing infrastructure for new hydrogen backbone
- Circularity of hydrogen production creates less waste

13 CLIMATE ACTION

- Reducing polluting emmissions to zero
- Making industries more sustainable
- Energy transition to renewable energy sources

15 LIFE ON LAND

- Placing more trees taking up CO2
- Increase of biodiversity in new greenery areas
- Improving spatial quality in industrial areas

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

- Decreasing geo-political dependencies
- Enabling energy transition through strict regulations
- Bringing justice to heaviest polluting industries

17 PARTNERSHIPS FOR THE GOALS

- Increasing cooperation between:
  - Institutes
  - Innovation hubs
  - Public sector
  - Private sector

4.5 Sustainable Development Goals

As mentioned in the objectives section of the introduction, the most important goal of creating hydrogen enabled decentralized energy systems is to decrease the greenhouse gas emissions to zero reducing global temperature rise and all its consequences. The vision shows a hydrogen backbone implemented in the wider northwest European area. In that context, the United Nations' Sustainable Development Goals (SDGs) are interlinked with strategic interventions involving policies and actions, visualized and explained more thoroughly in the diagram in figure 47.

Link to Planet Pillar

The planet will mainly see improvements by transitioning to renewable energy, reducing fossil fuel use and therefore emissions. Besides, introducing more greenery in industrial areas improves biodiversity and air quality, benefiting this pillar as well. These visionary improvements are linked to the SDGs 7, 9, 11, 12, 13 and 15.

Link to Profit Pillar

The profit pillar will allow existing industries to economic growth in a sustainable way and enable new industries like the manufacturing of renewable energy infrastructure to flourish. Working conditions for workers in current industries will also increase. Increasing partnerships will enable more innovation as well. These benefiting factors are linked to the SDGs 3, 8, 9, 12 and 17.

Link to People Pillar

The last pillar considering people is heavily focused on the fight against inequality, justice and wellbeing. The energy transition will improve air quality and therefore overall wellbeing for everyone. Reschooling opportunities in new industry sectors, new housing developments and cheaper energy will reduce inequality in general. These social enhancements are linked to SDGs 3, 4, 10, and 16.

Figure 47. Sustainable Development Goals linked to this project.

[redacted]

05. Strategy: The Return of Industries as New Green Hubs

Image 10.

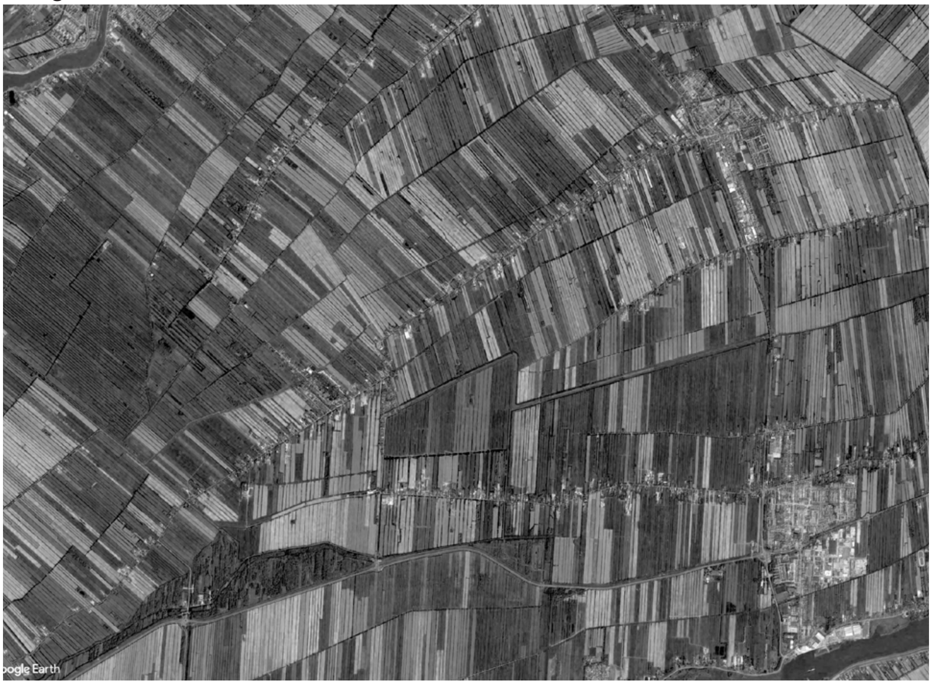


Image 11.

5.1 Energy Production Landscape Typologies

Three types of energy production are considered in the vision and strategy: wind energy, solar energy and biomass-based energy. The production of wind energy will occur in the open spaces such as the sea and the agricultural land. Biomass comes from the agricultural land and the waste of the urban areas. Last, solar energy is produced on the roofs of existing and future buildings. The transition to renewables has a big impact on the landscape and therefore is it important to determine the most suitable locations for these.

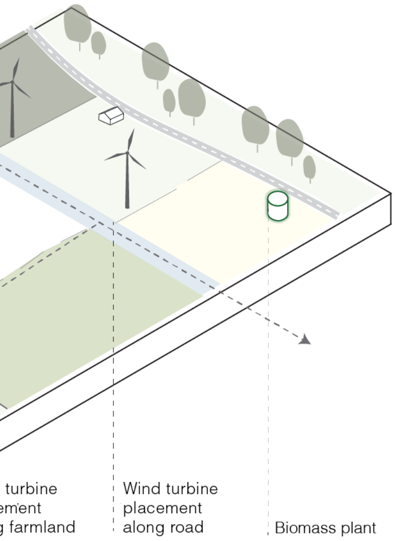
Biomass and solar panels will have less of an impact on the landscape due to a lower availability of the production area but are still important to consider since every bit of energy production is helpful. Wind turbines have the most impact of the three types and, as mentioned in section 1.3, people are often against the placement of wind turbines for fear that they will lead to noise pollution and a loss of spatial quality. A solution can be to give them ownership and profit, but it remains important to place them in the right way within the landscape, so they adjust the best in the landscape. Being part of a self-sufficient energy community will also help in this regard.

Landscapes are in general quite inconsistent due to differences in soil types and land use. What can be seen is that the sand grounds, being older landscapes, are more complex with smaller plots making it very complex to place wind turbines, leaving the only option to place them In the middle of plots to keep distance from houses. Peat, and clay landscapes (non-irrigable arable land and pasture) can be categorized as being more wet land, which made it harder to build houses in these landscapes. The introduction of polders changed this disadvantage. Generally, in these landscapes, positioning wind turbines parallel to waterway gives structure and therefore improves spatial quality compared to an unstructured approach.

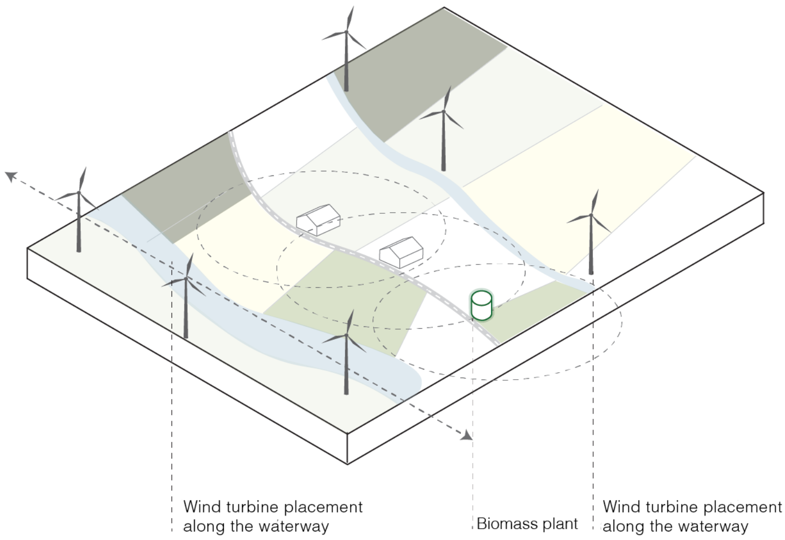
Offshore wind parks will use VAWTs improving overall power output whilst using a smaller production area. Since these wind turbines are less high than HAWT, they will improve the overall spatial quality but are less feasible on land since they will catch wind lower to the ground. The energy production from these wind turbines is shipped to Rotterdam to transport or store it within the main hydrogen cluster and backbone. The typologies of the landscape showing where renewable energy sources can be positioned can be seen in figure 48.

Image 10. Photo taken from Google Earth (2023)
Image 11. Photo taken from Google Earth (2023)

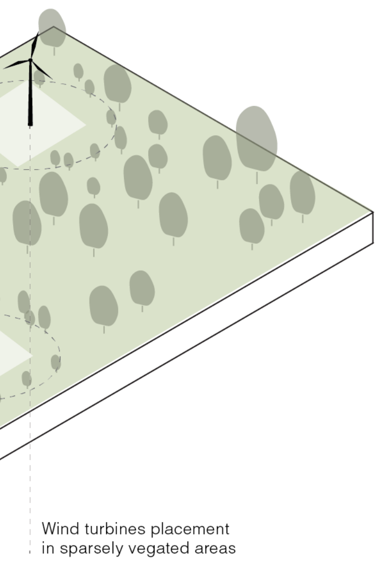
Figure 48. Energy Production Landscape Typologies



Arrable Land



Pastures



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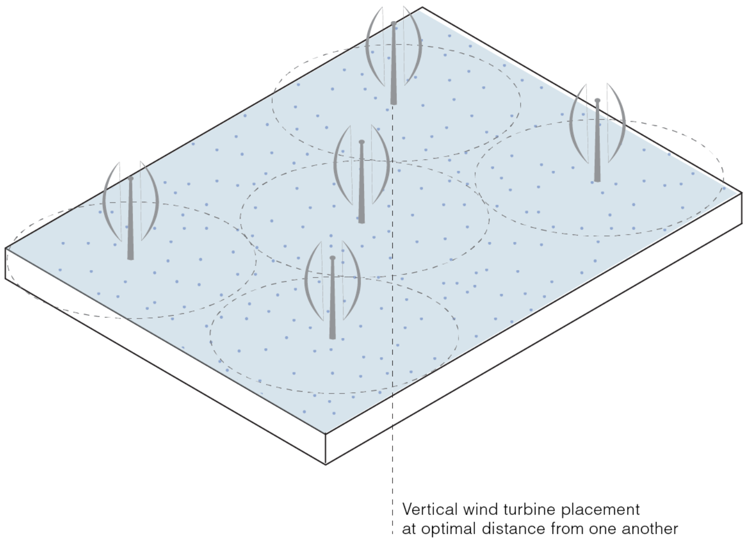
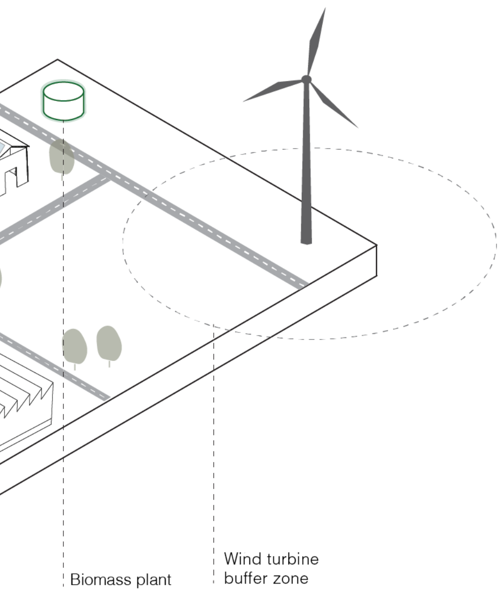
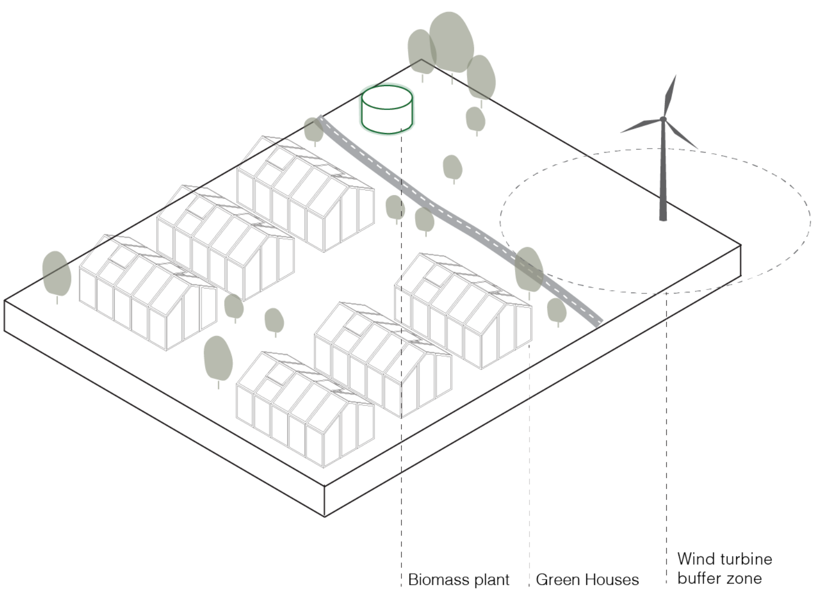


Sea





Green Houses

Image 12.

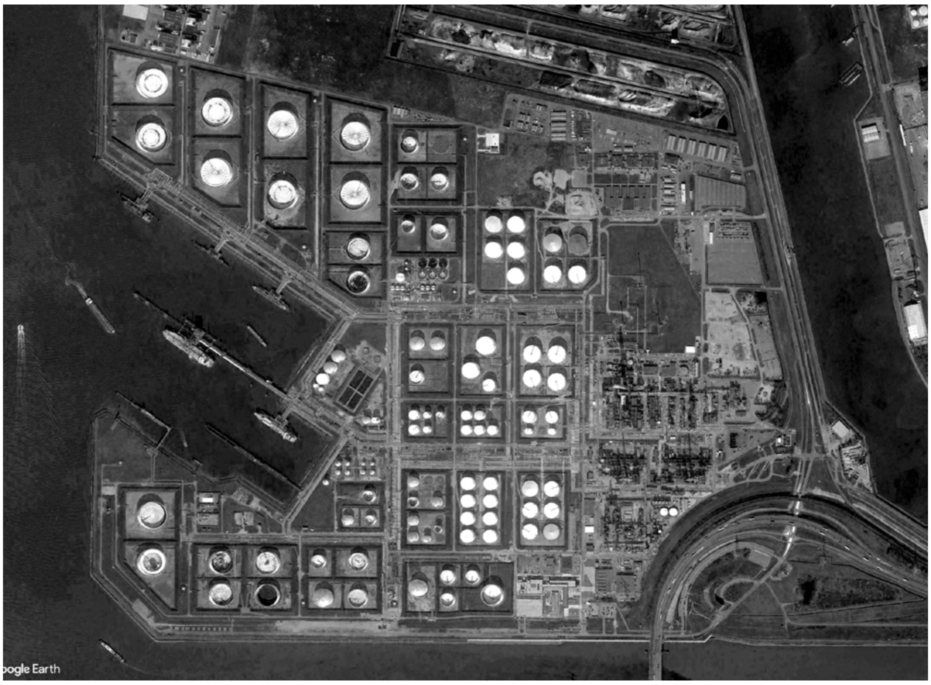


Image 13.

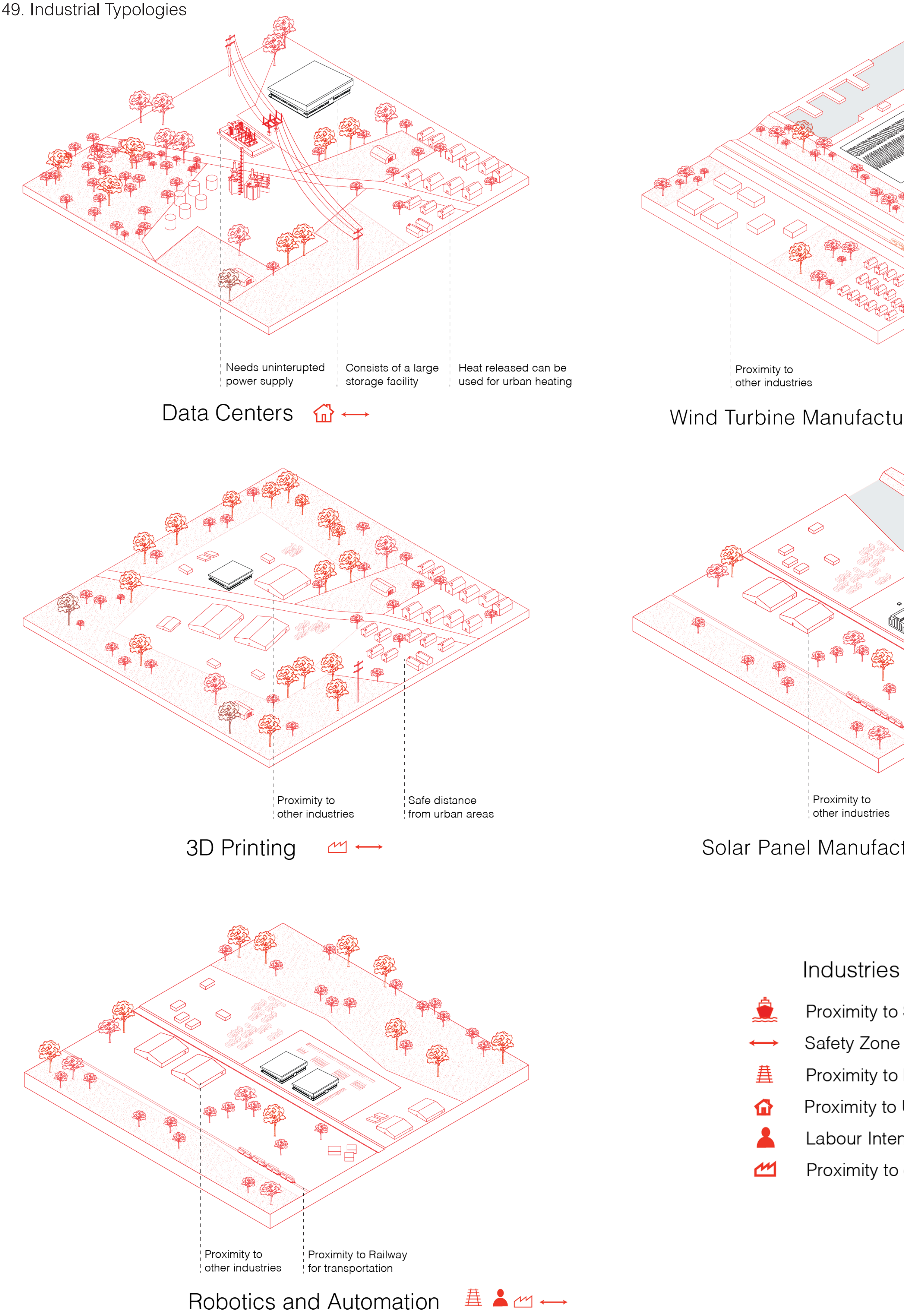
5.2 Industrial Typologies

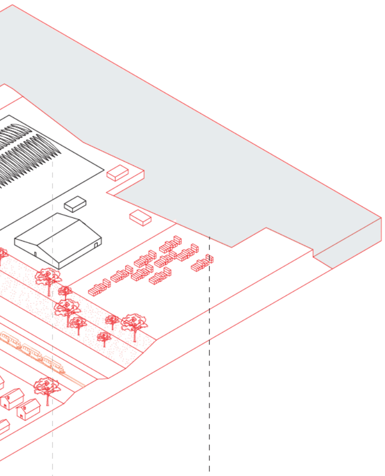
The industrial typologies (figure 49) show the criteria for positioning the new industries within the clusters. For the hydrogen plant in the main clusters, the location is based on proximity to the existing storage to keep transmission infrastructure at a minimum. For secondary clusters, the location of hydrogen plants is based on the location of existing infrastructure like railroads. The ideal location would be at the intersection of the electricity substation, power line and gas pipeline within the industrial cluster.

The location of the five new industries is based on six main criteria, mentioned in the legend of figure 49. For example, some industries produce fumes and emissions and hence they are located outside the urban areas while some can produce heat thus they are located closer to the urban areas. The industry is evaluated on the basis of the criteria and suitable locations are selected.

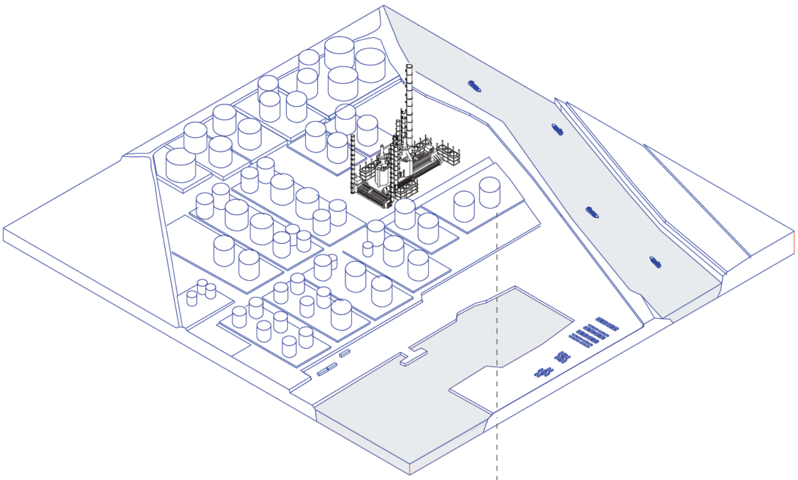
Image 12. Photo taken from Google Earth (2023)
Image 13. Photo taken from Google Earth (2023)

Figure 49. Industrial Typologies

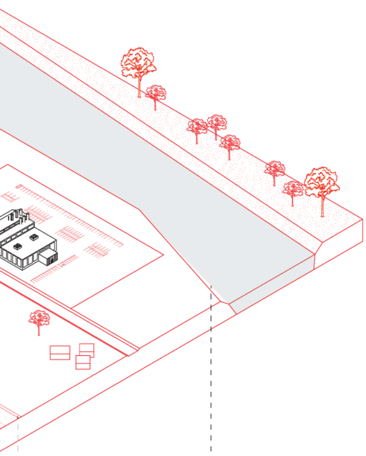




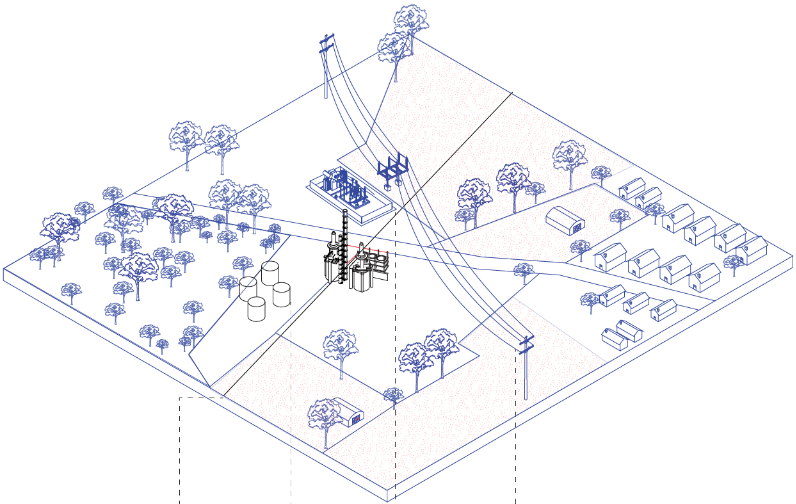
ring



Main Cluster



turing



Subcluster

Shipping Dock

Railway

Urban Areas

sive

other Industries

Clusters

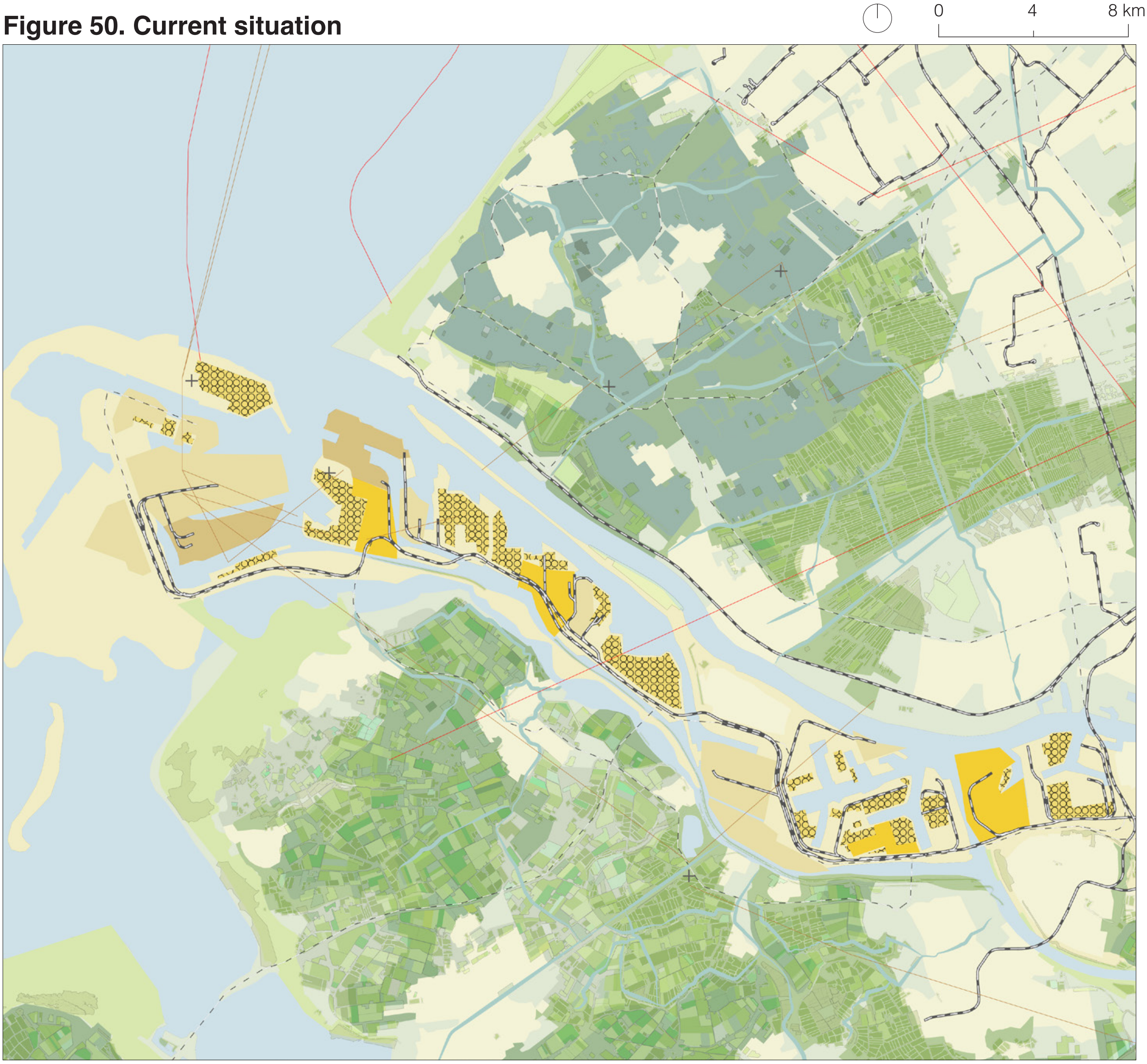
Existing Storage

Electricity line

Electric Power Station

Oil/Gas Pipeline

Figure 50. Current situation



5.3 Centralized Main Cluster: Port of Rotterdam

The port of Rotterdam is one the biggest in the world, currently the port is strongly connected with the bulk oil and chemical industry. With the energy transition the fossil industries will disappear from the harbor, more sustainable industries will be replacing this disappearing industry. This requires not only a spatial change but also the reschooling of the workforce besides developing new residential areas for these people (figure 50).

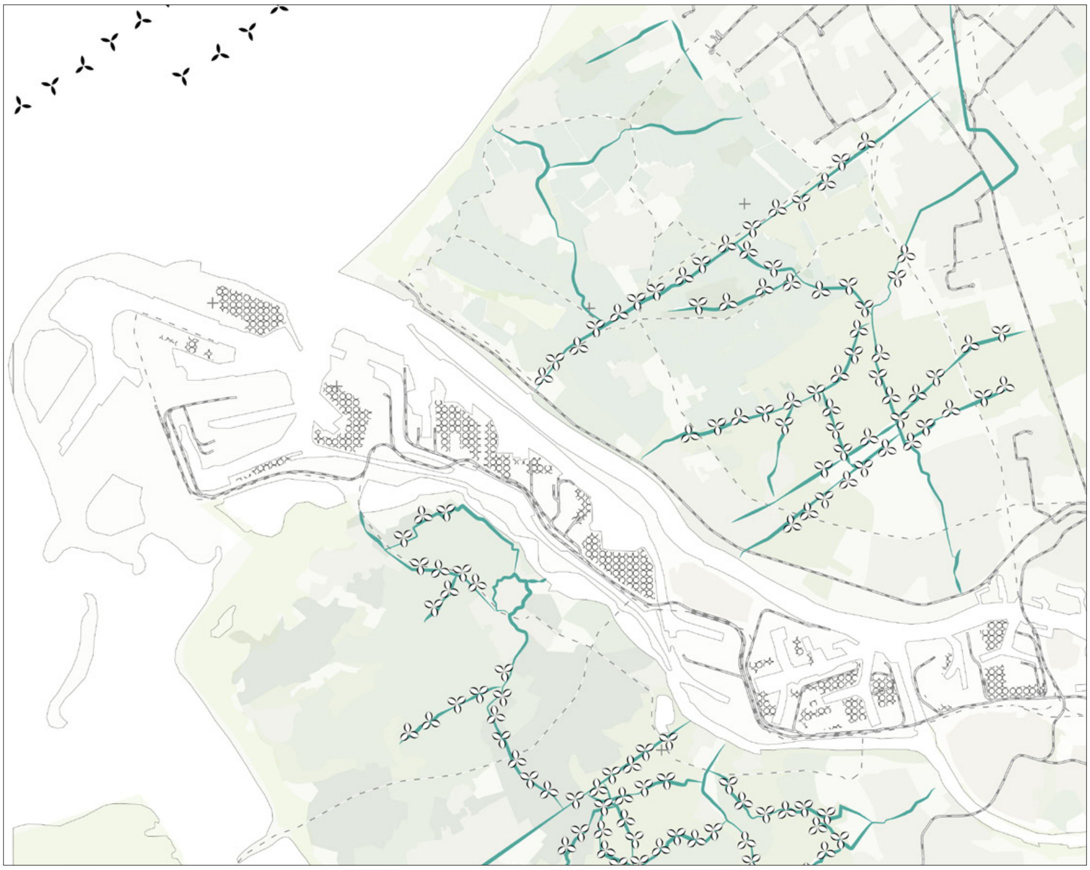
Besides, the production landscape of energy around the city will change. Previously, this system has been centralized, requiring less space since the production area is small and located in other countries. The proposed visionary decentralized energy system will require more space mainly due to the use of renewable energy sources. In the future, renewable energy will be produced locally resulting in multiple changes within the agricultural landscape, sea, glasshouses and urban.

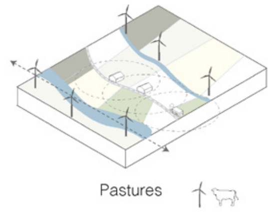
Legend
Source: Copernicus 2023

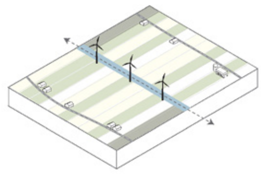
- Pipelines
- Powerlines
- Railways
- Waterways
- Urban areas
- Nature
- Glasshouses
- Non-irrigatable arrable land
- Complex agriculture
- Peat land

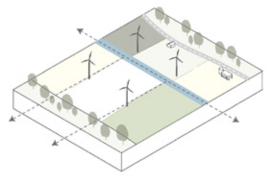
- Refineries
- Oil storage
- Industries
- Storage of raw materials

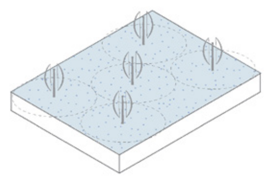
Figure 51. Wind turbines landscape







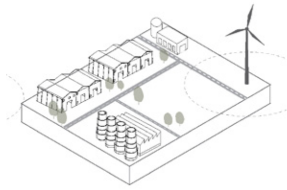


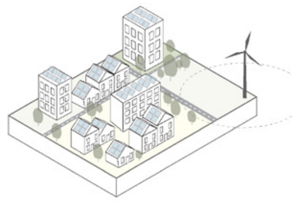


The production area of wind energy near Rotterdam is mainly positioned at the North Sea where massive amounts of energy are produced that can be stored in the harbor of Rotterdam in the form of hydrogen. The energy can either be stored for a longer time, functioning as a storage facility in case of emergencies or can be transported to the other clusters within the network. VAWT will be used for the energy production on sea.

Besides the offshore wind located in the North Sea, the agricultural lands near Rotterdam are used to produce wind energy as well using HAWTs. Both locations can be seen in figure 51. The landscape is a mix of non-irrigatable arable land, glasshouses and pastures. In these types of landscapes, the production of windmills is happening around the waterways. By placing the wind turbines around the waterways, the characteristics of the landscape are used to integrate the wind turbines as best as possible since their visibility will be high.

Figure 52. Solar panels landscape





The metropolitan region of Rotterdam is quite urbanized and therefore has a big amount of solar panels potential. The production will happen on top of roofs in urban areas (figure 52) The production of solar panels is therefore relatively high, but urban areas are also one of the main consumers of energy. Therefore, most of the energy that is produced will be directly used by the city. Occasionally, there can be a surplus of energy production, the left over energy can either be transported to other places close by that are in direct use of energy or can be stored as hydrogen in the harbor to use the energy when there is not enough production to meet the demand.

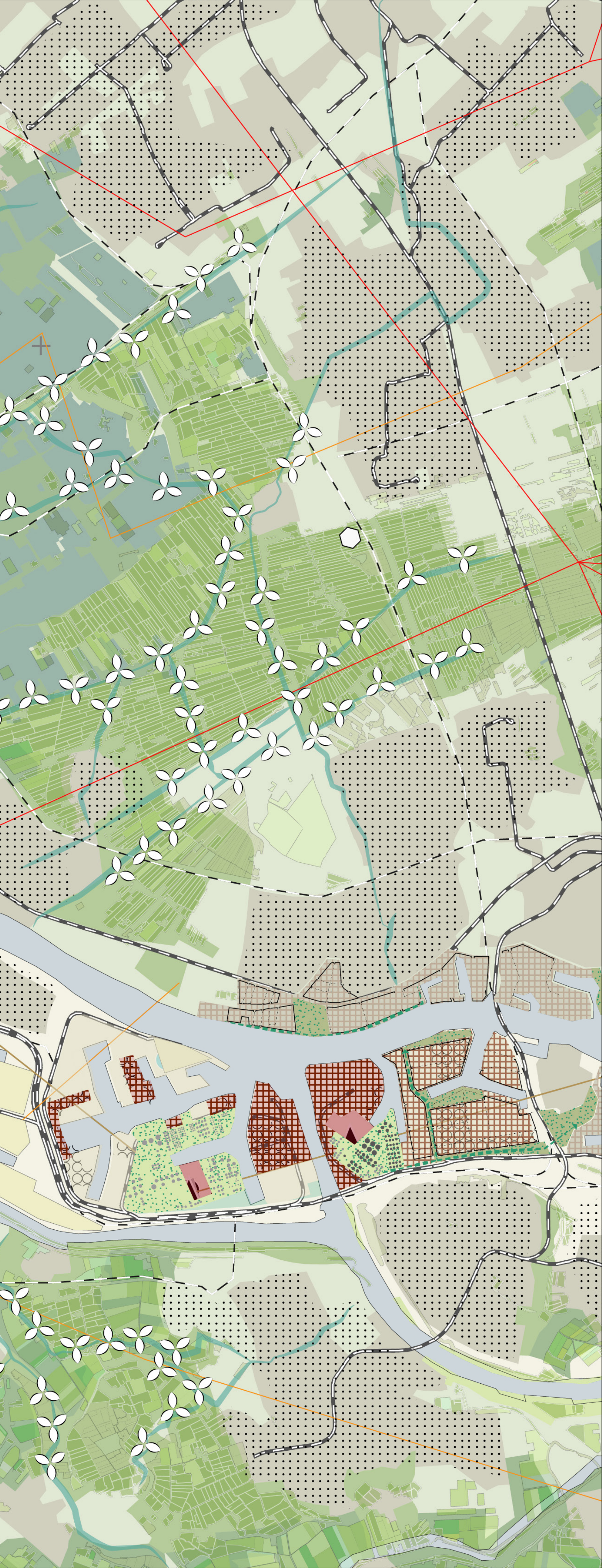
Figure 53. Biomass landscape

Biomass is produced in the agricultural areas, glasshouses and the urban fabric (figure 53) The biomass is produced locally and there are several biomass plants within the region of Rotterdam. By creating multiple biomass plants, the travel distance of the biomass to the plant is low. And the energy produced in the process can be used locally. In the case the supply is higher than the demand it can be stored as biomass.

The glasshouses and urban fabric have a continuous supply of biomass waste, the agricultural parts that are mostly the non-irrigatable land will not have a continuous supply since this landscape has annual crops making biomass the least efficient form of energy production

Figure 54. New industry and hydrogen plants

The industrial landscape of Rotterdam will undergo drastic changes (figure 54). The fossil industries will disappear and the chemical and bulk industries will become sustainable. Consequently, the harbor of Rotterdam will become a main hub of hydrogen storage and the manufacturing of renewables, creating a circular energy manufacturing and production system. By redeveloping the harbor, a smaller amount of storage facilities than currently exist will have to be re-used for hydrogen storage. A more in-depth overview of the redevelopment can be found on the following page.



5.3.2 Proposal Redevelopment Port of Rotterdam

0 2.5 5 km

Current

- Pipelines
- Powerlines
- Railways
- Waterways

- Urban areas
- Natura
- Glass houses
- Non-irregatable land
- Complex agriculture land
- Peat land

- Storage
- Remain Industry
- Storage of raw materials

Proposal:

Energy production

- Wind turbines
- Biomass
- Sun panels
- H2 plant

- Hydrogen plant
- New Industry
- Mixed use area focussed on industry
- Mixed use area focussed on urban
- green arround hydrogen storage
- Green park
- green corridor

- New pipeline

The overall proposal for the redevelopment of the Port of Rotterdam and the location of renewable energy production is shown on the overview here.

The next few pages will go into more depth by zooming in on the western and eastern part of the port. They will be redeveloped differently due to the existing surroundings.

Figure 55. Green Industry: west side of the harbor

Legend
Source: Copernicus (2023)

- Pipelines
- Powerlines
- Railways
- Waterways
- Urban areas
- Nature
- Glasshouses
- Non-irrigatable arrable land
- Complex agriculture
- Peat land

Proposal
- Wind turbines
- Biomass
- Sun panels
- Hydrogen plant
- New industries
- Hydrogen storage
- Nature between storages
- Nature corridos

Zooming in on the west side of the harbor. due to the disappearance of some industries and storage tanks a lot of free space is available The space between the storages can be used to introduce more nature within the area. These nature areas are connected to nature around the coast in the south using a nature corridor. The new industries in this part are the renewable manufacturing industries.

The hydrogen plant itself is a lot smaller compared to the refineries leaving more space for green around the plant shown in the collage above. The industries in this area consist of chemical companies mixed with the new hydrogen plants, storages that are green and additional space for new industries.

Figure 56. Urban area: east side of the harbor

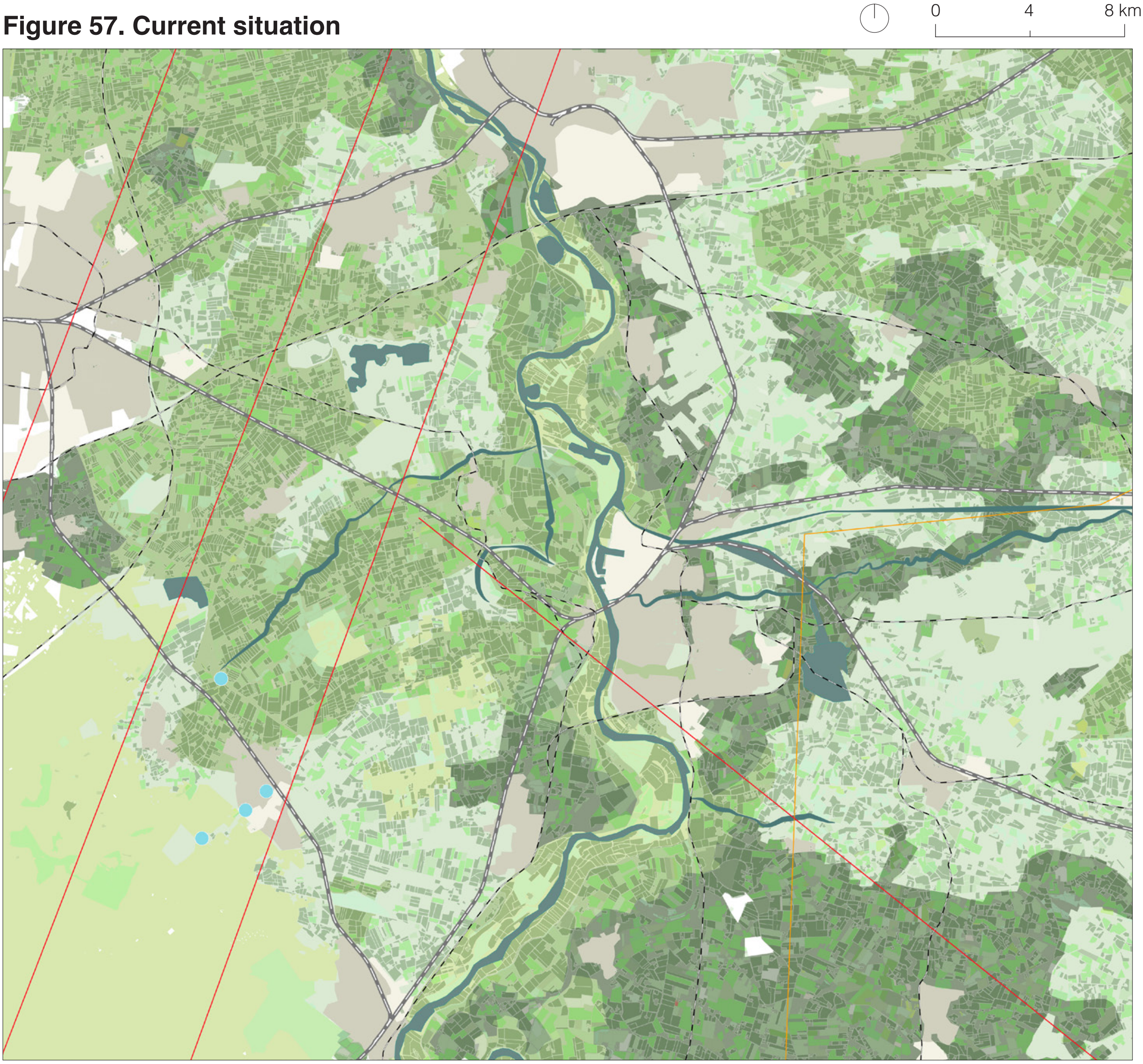
Legend
Source: sEEnergies Open Data

- Pipelines
- Powerlines
- Railways
- Waterways
- Urban areas
- Nature
- Glasshouses
- Non-irrigatable arrable land
- Complex agriculture
- Peat land

Proposal
- Wind turbines
- Biomass
- Sun panels
- Hydrogen plant
- New industries
- Hydrogen storage
- Nature between storages
- Nature corridors

The east side of the harbor will transform by introducing the development of new parks, new urban areas for the new employees and the growth of the city in general. The district will be mixed use, benefiting a good economical business climate for new sustainable companies. Industries will still be able to be located in the south part of this area across the water, away from residential areas. Commercial and recreational areas are also introduced, creating a transition zone between the different types of areas. These changes are visible in figure 56 whilst showing a collage giving an idea on what the area will look like at the top of this page.

Figure 57. Current situation



5.4 Decentralized Subcluster: Municipalty of Zutphen

The focus area of the sub cluster is not very densely populated compared to the main cluster of Rotterdam. In this area there are mostly the paper and printing industries which will not exist in the future. In this landscape there exists a river with mainly pastures and complex cultivated land patterns around it. Besides these areas we see a lot of nature areas that are protected and therefore cannot be used for energy production or the development of new industries or housing. Figure 57 shows the current situation for this area in the Municipality of Zutphen in the province of Gelderland.

Legend
Source: Copernicus 2023

- Pipelines
- Powerlines
- Railways
- Waterways
- Urban areas
- Nature
- Glasshouses
- Non-irrigatable arrable land
- Complex agriculture
- Peat land
- Industries

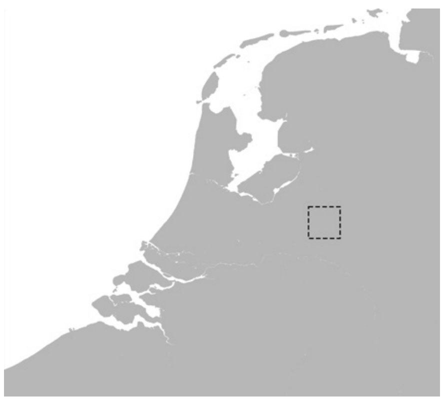
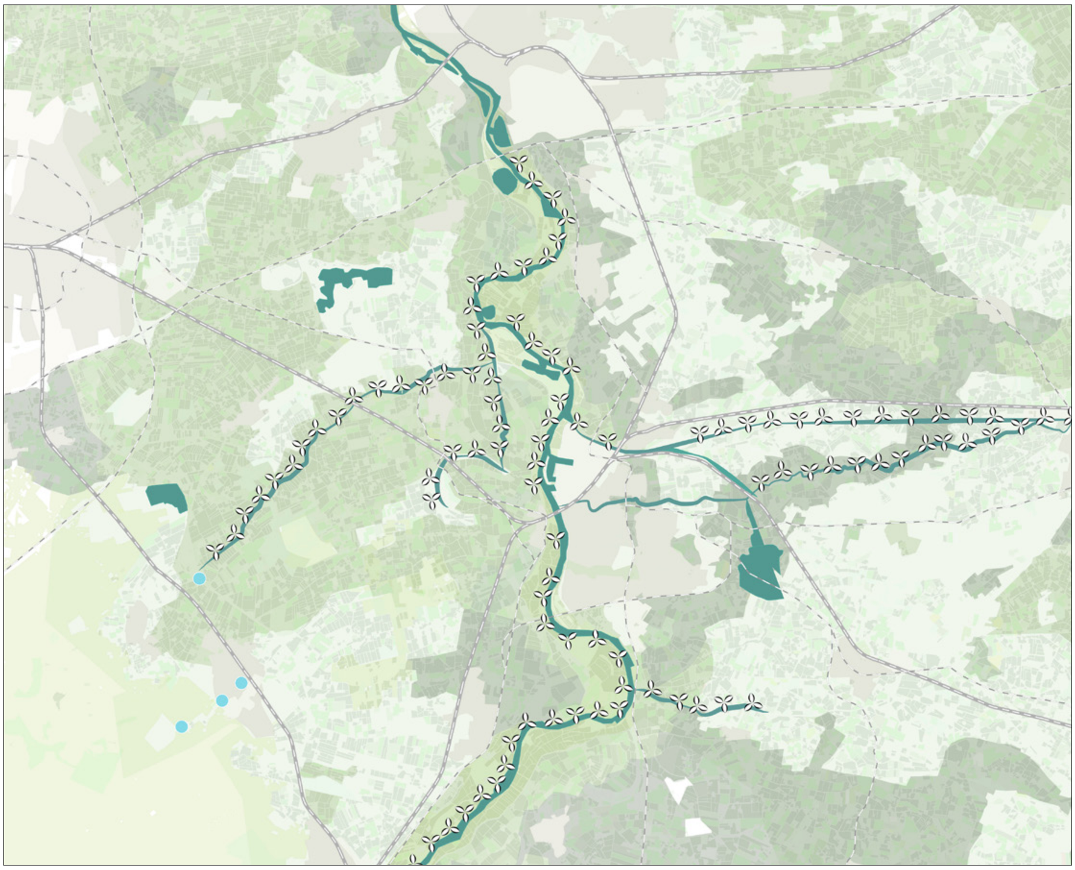
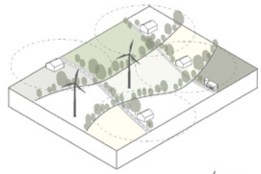
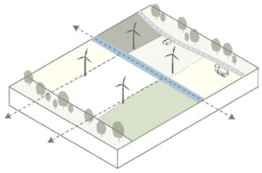


Figure 58. Windturbines

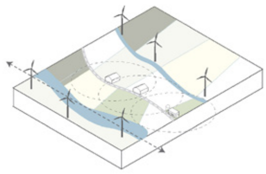




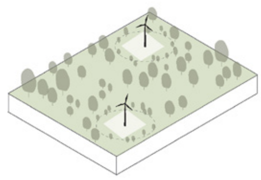
Complex Cultivation Land Patterns



Non Irregatable Arrable Land



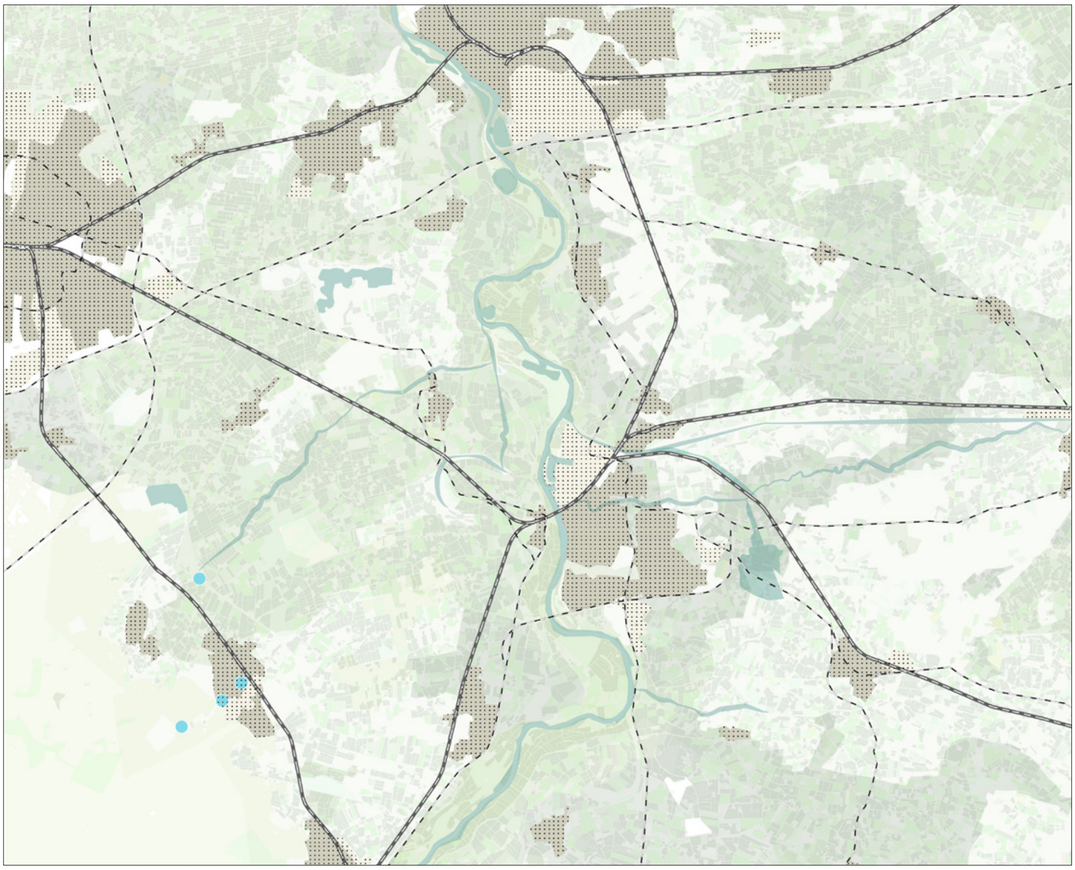
Pastures

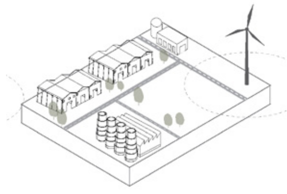


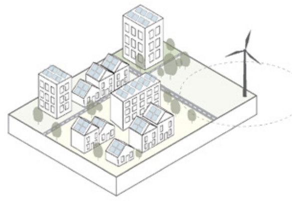
Forests

The production of wind energy is taking place in the agricultural areas and occasionally in the more open areas of the forest (figure 58). The wind turbines follow the logic of the waterways. This gives them the opportunity to blend in as much as possible.

Figure 59. Solar panels landscape

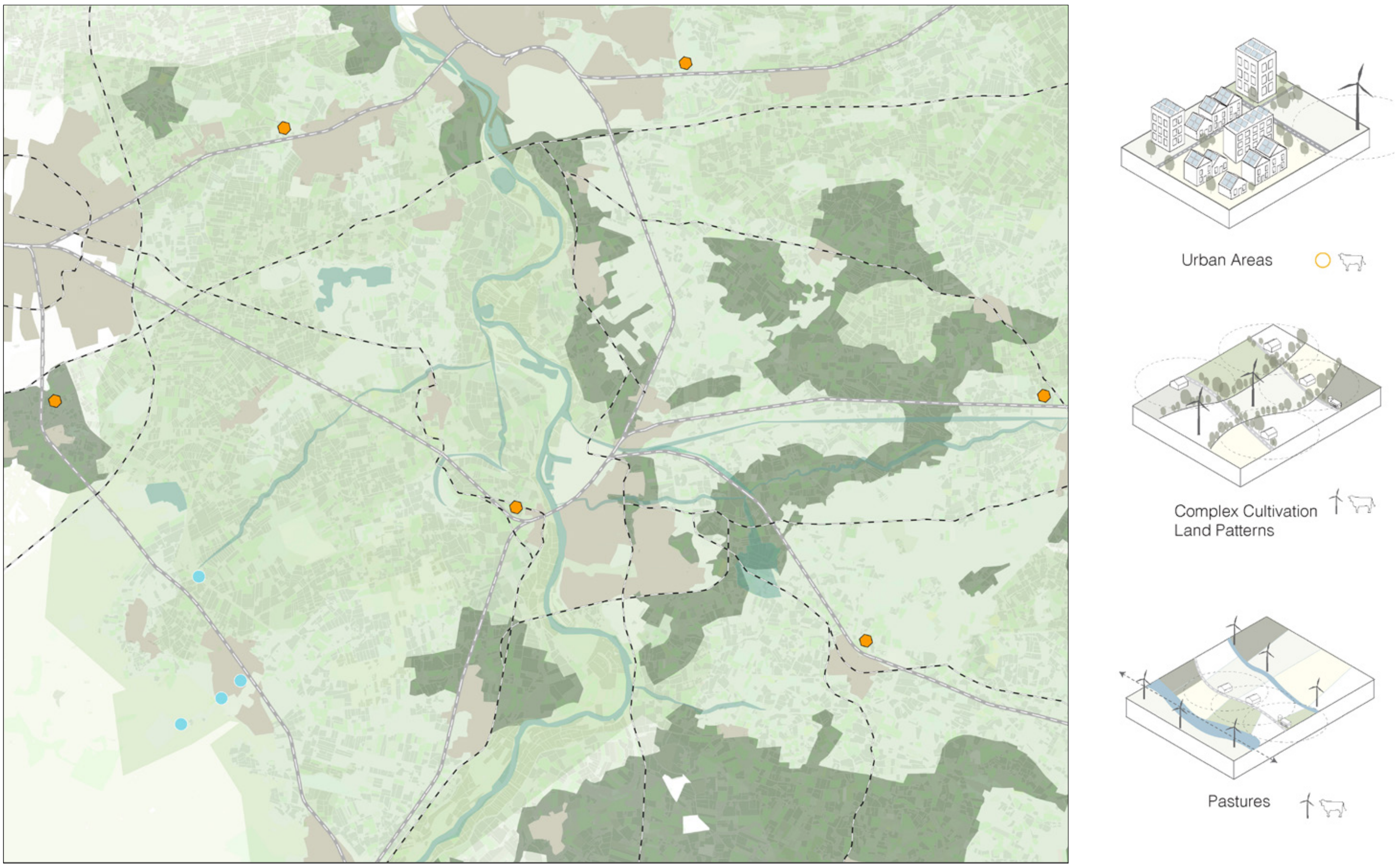






As mentioned before, the subcluster is not densely urbanized. The main production of the solar panels is happening in the urban area (figure 59). The energy is mostly used within the area itself but if there is overproduction this can be stored in the hydrogen plant too use it at a later moment when there is a shortage of local production.

Figure 60. Biomass landscape



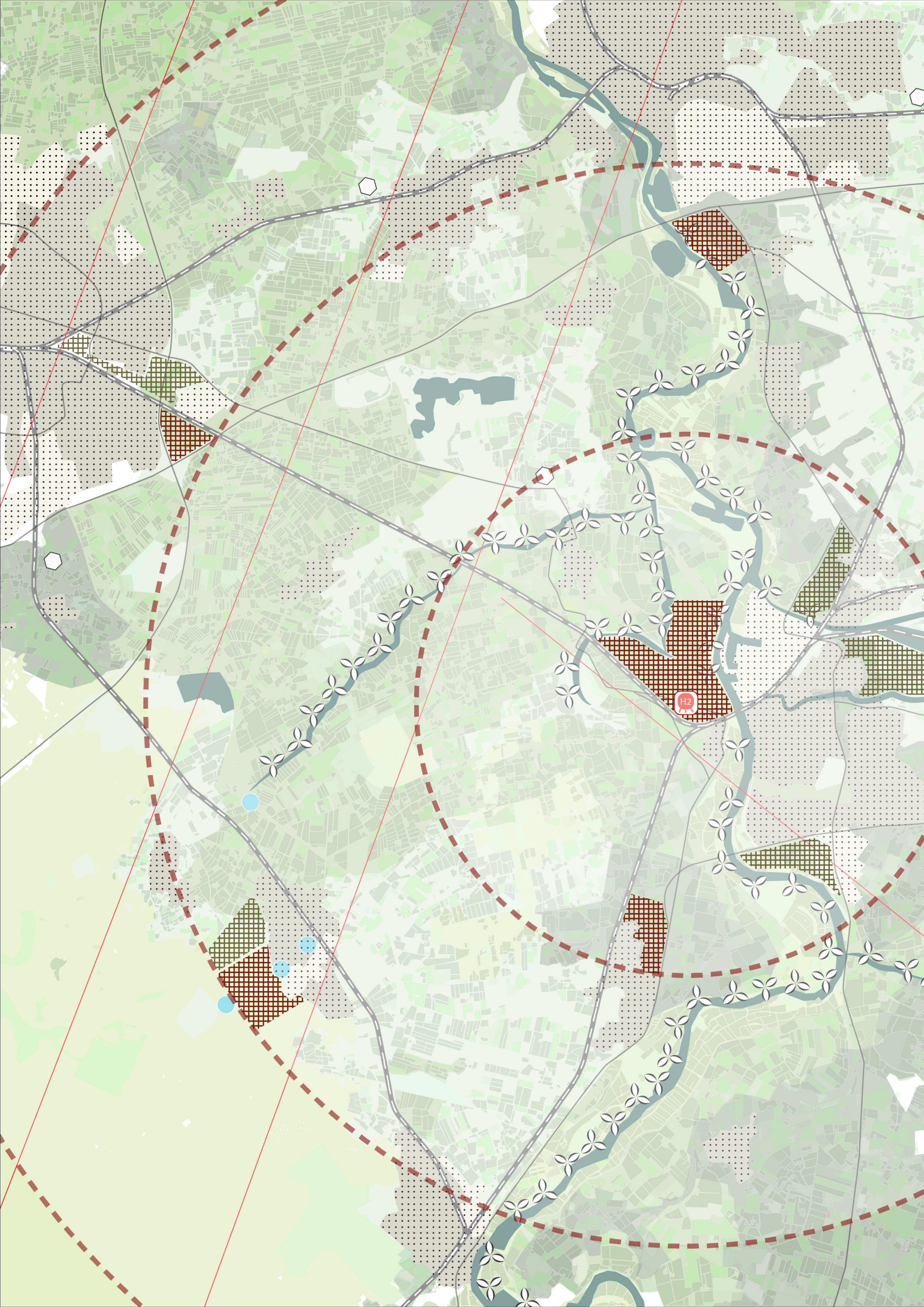
Biomass is produced in the agricultural areas and the urban fabric. There are several biomass plants locally too reduce the travel distance from the producer too the plant. The biomass is mostly throughout the year since the biomass produced form pastures comes from animals and the urban area produces a consistent amount of waste too, the complex cultivated landscape is a mixture of annual crops and animal farms so here will be some differences throughout the year in production (figure 60).

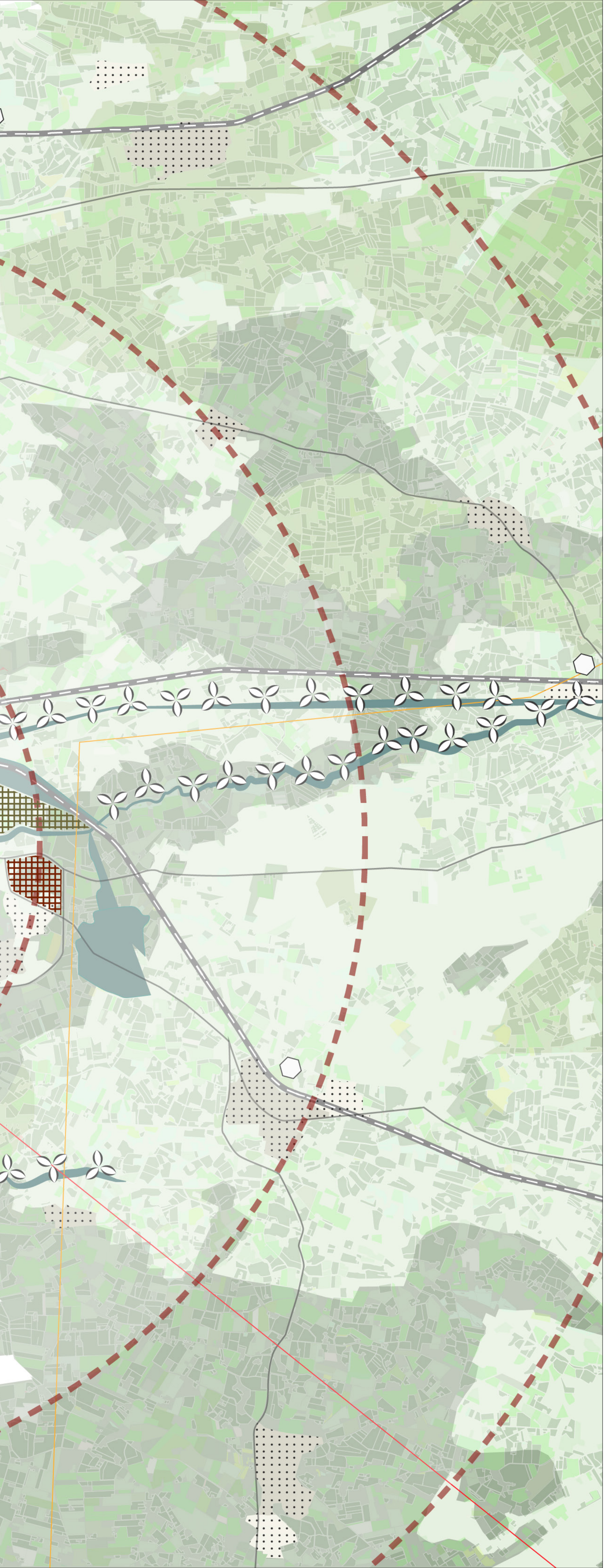
From these plants (in orange) the biomass can be transported to the biomass plants where it is transformed into energy that can be used directly locally or can be transported to the hydrogen storage.

Figure 61. New industry and hydrogen plants

The new industries are mostly clusters around the hydrogen plant itself but since most of the new industries such as 3D printing and data centers are not considered as heavy industry, they can be a bit more spread out (figure 61). Besides, these industries do not use hydrogen as input for the production process.

Areas that are considered need to contain surrounding infrastructure such as roads and train tracks for easy transport of goods and materials. The closer to the hydrogen plant the better to have as little infrastructure introduced to the landscape as possible. Additionally, the growth of industries enables the rise of new urban areas giving workers housing close to their workplace.


H2



5.4.1 Proposal for Industrial Clusters

0 2.5 5 km

Current

- Pipelines
- Powerlines
- Railways
- Waterways

- Urban areas
- Natura
- Glass houses
- Non-irregatable land
- Complex agriculture land
- Peat land

- Industrial areas
- Industries

Proposal:

Energy production

- Wind turbines
- Biomass
- Sun panels

- Hydrogen plant
- Possible industrial zones
- Possible urban zones

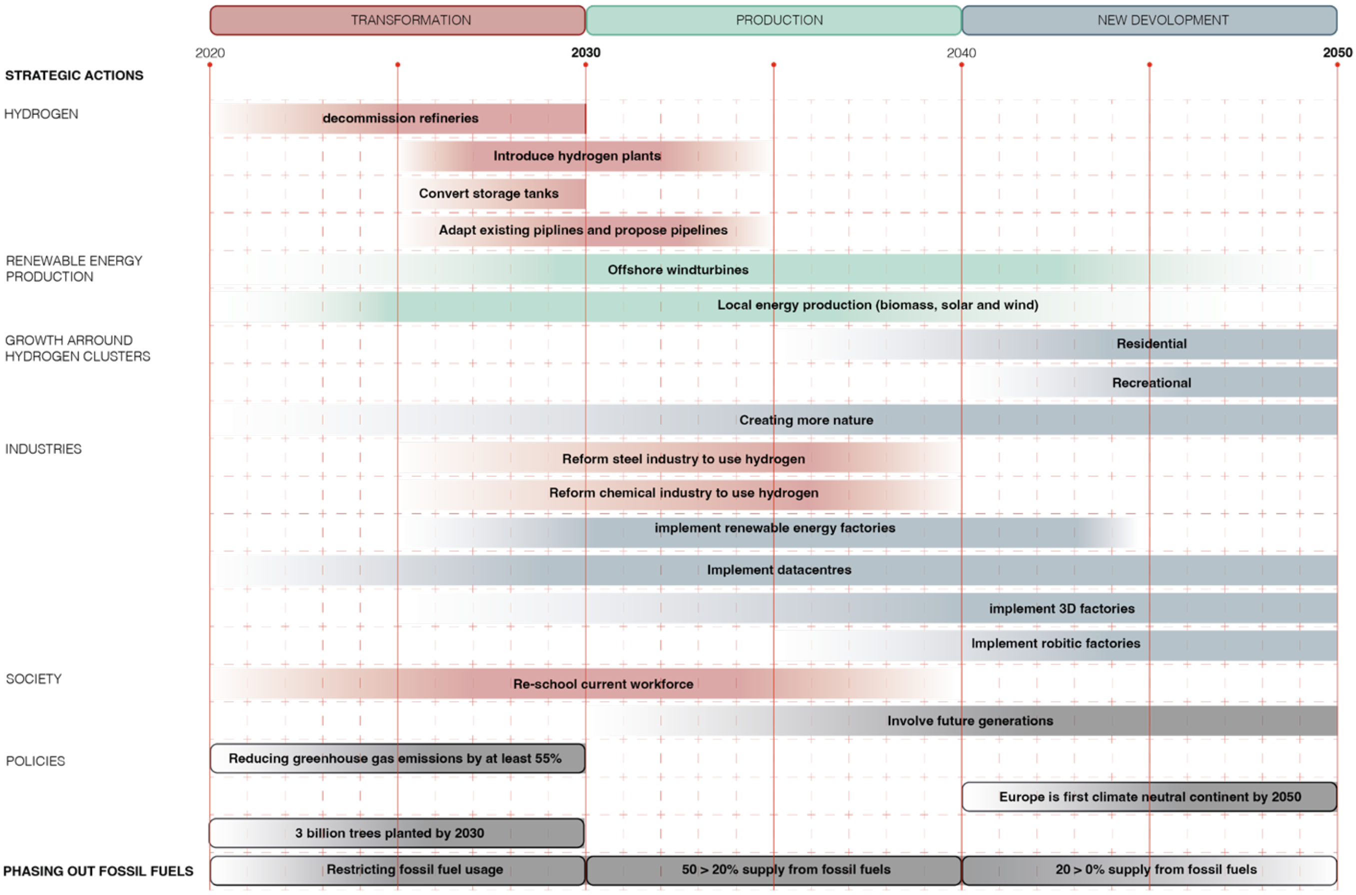
- 5 - 10 - 15 km radius arround hydrogen plant

The hydrogen plant and the storage facilities will make surplus production of renewables possible. The production of the renewable energy is a mixture of wind, solar and biomass energy. The production for this area is fairly high compared to the consumers, the surplus of energy can either be stored of transported to the more energy demanding clusters in the backbone.

The hydrogen plant makes this area a good place were new business can start. Currently there are a lot of printing industries, in the future they will most likely disappear making place for future big industries such as 3D printing. Industries such as nonmetallic minerals will likely stay and will become sustainable.

The radius arround the hydrogen plants show optimal locations for new industries to be developed.

The hydrogen subcluster will be a placed where a lot of new growth in industries and urban areas will be introduced. With local production of renewable energy this will change in a circular energy cluster as a part of the hydrogen backbone.


TRANSFORMATION
PRODUCTION
NEW DEVOLOPMENT
2020
2030
2040
2050
STRATEGIC ACTIONS
HYDROGEN
decommission refineries
Introduce hydrogen plants
Convert storage tanks
Adapt existing piplines and propose pipelines
RENEWABLE ENERGY PRODUCTION
Offshore windturbines
Local energy production (biomass, solar and wind)
GROWTH ARROUND HYDROGEN CLUSTERS
Residential
Recreational
Creating more nature
INDUSTRIES
Reform steel industry to use hydrogen
Reform chemical industry to use hydrogen
implement renewable energy factories
Implement datacentres
implement 3D factories
Implement robitic factories
SOCIETY
Re-school current workforce
Involve future generations
POLICIES
Reducing greenhouse gas emissions by at least 55%
Europe is first climate neutral continent by 2050
3 billion trees planted by 2030
PHASING OUT FOSSIL FUELS
Restricting fossil fuel usage
50 > 20% supply from fossil fuels
20 > 0% supply from fossil fuels

5.5 Timeline

The timeline explains how the hydrogen enabled energy system will be implemented within the Eurodelta region besides mentioning the schedule for redevelopments in the strategy as well. The starting point is the energy transition and the policies that restrict the fuel usage. The refineries should be decommissioned by 2030.

By transforming the refineries into hydrogen plants and re-using the existing infrastructure and storage facilities, the hydrogen network is created. After this transformation other existing industries such as the steel and chemical industry can transform as well into a more sustainable industry. With this transformation a lot of people will lose their jobs within the oil sector, it is essential to re-school these people.

Today the problem is that the grid is overloaded and making it hard to introduce more renewables production within the current grid. With the introduction of hydrogen storage facilities, the production landscape of renewables can be increased drastically, reducing the need for fossil fuels. Additional new development is needed to manufacture our own renewables.

In the last phase of the introduction of the hydrogen scapes new industries such as the manufacturing of renewables, data centers, 3D factories and robotics factories can be implemented. These new industries will require new highly trained workforce that also need a place to live and recreate. In the late phase of the hydrogens scapes new urban areas, parks and recreational areas will be introduced.

Because it is a process that takes a lot of time and will not happen overnight. It is important to involve the future generations and adapt this plan according to new knowledge and insights. This will make sure that the plan is as sustainable as possible while respecting the needs of future generations creating a circular energy system.

06. Conclusion

6.1 Conclusion

Coming back to the research question for this report: What will hydrogen enabled energy landscapes around heavy industries look like in northwest Europe? It is now possible to answer this research question using the posed sub questions.

The first analysis part found out that the biggest industry sectors in Europe are the transport, residential and industrial sectors where the industrial sector is the focus of this report due to this sector having the highest greenhouse gas emissions as well. The clustering of industries defined the research area of the Euro delta leading to the focus on refineries since these will be eventually decommissioned where the vision states to repurpose these sites to introduce green hydrogen plants. The hydrogen plants are implemented to solve the main issues regarding the energy transition.They enable the storage of volatile renewable energy sources and enable the implementation of a decentralized energy system connected to the existing centralized energy system. Hydrogen plants use the concept of electrolysis to convert energy to hydrogen and vice versa creating more resilience regarding energy availability in times of either higher supply or higher demand.

The decentralized energy grid will improve the inequality of residents since they will not be dependent on external energy providers since they are part of a local energy community. Prices of installing renewable energy, e.g. solar panels, are dropping as well, giving more people the opportunity to produce their own energy. The hydrogen plants will bring new types of jobs needed to be filled by the re-schooling of people currently working in the fossil fuel based industry making sure that employment will still be available.

The Eurodelta wide vision is geared towards a region-wide hydrogen backbone giving rise to the sharing and transporting of energy via existing (gas) pipelines. Existing industries making use of hydrogen in their process can be located close to the hydrogen plants whilst new industries needing high amounts of energy are better suitable in decentralized energy system regions.

On a larger scale, offshore wind parks using the future concept of Vertical-Axis Wind Turbines will be able to have a greater energy output whilst using a smaller area making them a viable solution for the problem of the spatial footprint of renewable energy sources. This energy will predominantly be used in the Port of Rotterdam, the first zoom-in of our strategy. The more suitable energy grid is a centralized system since it has a very large production and transport landscape. For the second zoom-in in the municipality of Zutphen, a decentralized energy system is proposed in more detail showing typologies on how energy production could be implemented in inconsistent landscape types.

Due to the sustainability revolution in the industry sector, industrial areas can be redeveloped introducing more natural areas in between hydrogen storage, taking out existing surplus storage availability and redeveloping these areas by introducing more housing and recreational areas geared towards the reschooled workforce. These interventions will make sure that the overall greenhouse gas emissions will decrease and eventually become net-zero.

The three pillars of planet, profit and people have been implemented to achieve this goal whilst simultaneously revolutionizing the industry sector by the return of industries as green hubs.

6.2 Future recommendations

The limitations of this report have mainly to do with uncertainties regarding future innovation and technological advances. The introduction of VAWTs is still in a very early stage and has only been researched more intensely since 2010. Besides, positioning wind turbines on land owned by the agricultural sector could also bring issues when they don't allow the placement of those wind turbines. This would endanger the zoomed-in strategy but also the overall efficiency of the hydrogen backbone in the Eurodelta region.

Further research should therefore be geared towards the feasibility of VAWTs whilst analyzing the willingness of the agricultural sector, but also knowledge institutes and governing bodies, to work together with the industry sector. Additionally, finances have not been taken into account in this report on which analyses should be performed to make sure that the return of industries in Europe as green hubs will take place.

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Appendix

A. Calculations Table

Appendix A. Calculations Table

Table A.1 HAWT	Average (2022)	Annual Production	Area needed	In solar pa
Wind Turbines HAWT				
Energy Production	**5 MWh**	**18.000 MWh**	**60 hectares per HAWT**	6 hectares

Table A.2 Hydrogen	Weight	Efficiency	Energy
Hydrogen		**70%**	
Energy Value	1 ton	Input: 42,9 MWh	Holds: 33 MWh
Input (Water, H20)	9 tons		
(Extra) Output (Oxygen, 02)	8 tons		

Table A.4 VAWT	Average Energy Production	Average Annual MWh	Area needed
Wind Turbines VAWT			
2023	**1 MWh**	**3.600 MWh**	**50% of HAWT**
2030	**20 MWh**	**72.000 MWh**	
2050	**40 MWh**	**144.000 MWh**	

Table A.6 Spatial Footprint 1	Energy Consumption (TJ)	Conversion	Energy Consumption (MWh)	Annual Wi
Industry Energy Consumption	Expected growth: 3,5% / year	*0,0036 Terajoule [TJ]*		
Whole South-Holland (2018)	**151.906 TJ**	=	**42.196.111,11 MWh**	
Whole Netherlands (2018)	547.606 TJ	*1 Megawatt hour [MWh]*	152.112.777,77 MWh	

Table A.7 Spatial Footprint 2	Wind Turbnine Energy Production (MWh)	Area Needed (Hectares)	Energy Demand (2018)	Annual En
HAWT (2022)		60		
Wind Turbnine Energy Production	*5*		**South-Holland**	
Annual Production	*18.000*		The Netherlands	
VAWT (2023)		30		
Wind Turbnine Energy Production	*1*		**South-Holland**	
Annual Production	*3.600*		The Netherlands	
VAWT (2030)		30		
Wind Turbnine Energy Production	*20*		**South-Holland**	
Annual Production	*72.000*		The Netherlands	
VAWT (2050)		30		
Wind Turbnine Energy Production	*40*		**South-Holland**	
Annual Production	*144.000*		The Netherlands	

Table A.8 Electrolysis	Input / Output	Energy use	(Alkaline) Price	Table A.9 S
(Water) Electrolysis				**South-Holl**
Energy demand		4.5–5 kWh/Nm3	~700–800 € / kW	Netherland
Water	9 tonnes			
Oxygen	8 tonnes			**South-Holl**
Formula	**Storage Temp. in C**	**Pressure**	**Density**	Netherlan
H_2O + ElectricalEnergy ↓ $H_2 + \frac{1}{2}O_2$	-235	**350–700 bar**	71,47 kg/m3	
				South-Hol
				Netherlan

nels
s of covered land area

Table A.3 Port of Rotterdam	Oil storage (m3)
Crude Oil	12.000.000
Refined Oil	6.700.000
Mineral Oil	5.500.000
Total	24.200.000

Table A.5 Zutphen	Values
Average Individual Annual Energy:	50 MWh
City of Zutphen:	48.330 residents
Residential & Industry Energy:	4.833.000 MWh
In Hydrogen:	1.915.190 M3

nd Turbines (Amount)	Wind Turbines Area (Hectares)	Annual PV Panels (Amount)	PV Panels Area (Hectares)
± 2.344	**140.640 Hectares**	**± 48.224.127**	**78.774.111 Hectares**
± 8.451	507.060 Hectares	± 173.843.175	283.972.826 Hectares

ergy Consumption (TJ)	Energy Consumption (MWh)	Annual Wind Turbines (Amount)	Wind Turbine Park Area (Hectares)
151.906	**42.196.111,11**	**2344**	**140.654**
547.606	152.112.777,78	8451	507.043
151.906	**42.196.111,11**	**11.721**	**351.634**
547.606	152.112.777,78	42.254	1.267.606
151.906	**42.196.111,11**	**586**	**17.582**
547.606	152.112.777,78	2.113	63.380
151.906	**42.196.111,11**	**293**	**8.791**
547.606	152.112.777,78	1.056	31.690

Storage needs	Energy in Hydrogen Storage (Tonnes)	Hydrogen Storage (m3)	30 days storage Hydrogen (m3)
land	**1.278.670**	**16.721.198**	**1.393.433**
ds	4.609.478	64.495.285	5.374.607
	Water Input (Tonnes)	**Water Input (m3)**	**Water (in)**
land	11508030	13038597,99	1086549,833
ds	41.485.302	47.002.847	3.916.904
	Oxygen Output (Tonnes)	**Oxygen Input (m3)**	**Oxygen (out)**
lland	**10.229.360**	**7.158.279.530**	**596.523.294**
ds	36.875.824	32.304.804.100	2.692.067.008