BORNHOLM

A POWER-TO-X ISLAND

Title Page

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Summary in Danish

Dette speciale undersøger muligheden for at implementere et Power-to-X anlæg på Bornholm i forbindelse med Energiø Bornholm, hvor det er planlagt at bygge Danmarks hidtil største havvindmøllepark frem mod 2030 sydvest for Bornholm. Havvindmøllerne skal tilkobles en transformerstation placeret tæt ved Åkirkeby. Formålet med dette speciale er at undersøge, hvordan Bornholms lokalmiljø, både de fysiske omgivelser og samfundet, vil blive påvirket ved implementeringen af et Power-to-X anlæg med elektricitet fra Energiø Bornholm.

I specialet undersøges muligheden for at integrere Power-to-X i den eksisterende energi- og vandinfrastruktur på Bornholm, ved at undersøge de potentielle risici og miljøpåvirkninger, der er forbundet med at implementere et sådant anlæg på øen. Anlæggets påvirkninger vil ligeledes afhænge af anlæggets størrelse, beliggenhed og potentielle slutprodukt, som i dette tilfælde enten kan være Power-to-Hydrogen, Power-to-Methanol og Power-to-Ammoniak. Gennem dialog med de involverede aktører er der generelt en positiv indstilling til implementeringen af Power-to-X på øen. Muligheden anses for at kunne bidrage til øens fremtidige udvikling samt gøre Bornholm til en vigtig del af den grønne omstilling i Danmark, dog er private lokale aktører skeptiske omkring implementeringen.

Det kan konkluderes, at implementering af Power-to-X på Bornholm vil resultere i nye interaktioner mellem involverede aktører, da anlægget forventes at skabe nye muligheder for sektorkobling og synergier mellem el-, vand-, varme- og transportsektoren på Bornholm. Yderligere konkluderes det, at den mest fordelagtige placering af Power-to-X anlægget vil være sammen med transformerstationen, samt at det mest fordelagtige vil være enten at producere Power-to-Hydrogen eller Power-to-Ammoniak afhængigt af brændslets formål.

Preface

This thesis was conducted as part of the master’s program Sustainable Cities at Aalborg University in Copenhagen. The project was completed between 01/02/2023 and 01/06/2023. The thesis deals with the possibility of implementing a Power-to-X plant on Bornholm in the future, and how it eventually will impact the local area and community. We, therefore, want to express our gratitude to the involved interviewees, since this study would not have been possible without the help from our interviewees who took time off to share their valuable knowledge essential for this thesis.

We would like to show our gratitude towards our interviewees. **Rasmus Zink Sørensen** from the Danish Energy Agency for sharing knowledge about the agency's work with Energy Island Bornholm and Power-to-X. **Jesper Sjørvad** and **Jorge Ivan Contreras-Cardeno** from Danish Institute of Fire and Security Technology for insightful information about their work with safety and risks related to Power-to-X. **Mads Boss**, **Svend Bilo Høegh Stigsen**, **Lillian Rasch Madsen** and the Mayor **Jacob Trøst** from Regional Municipality of Bornholm for valuable local information about their work and the citizens' conception towards becoming an energy island and potentially producing Power-to-X. **Klaus Vesløv** from Bornholms Energi & Forsyning for giving us invaluable insight into the energy, drinking water and wastewater infrastructure. **Maja Felicia Bendtsen** from Port of Rønne for sharing her work on making Power-to-X a reality on Bornholm. **Mikkel Mortensen** from Port of Rønne for sharing the port’s role in the construction phase of offshore wind turbine farms and showing us the site where offshore wind turbines are assembled. **Kim Fønss-Lundberg** from Baltic Energy Island for giving us an understanding of how collaborations contribute to the potential implementation of Power-to-X. **David Dupont-Mouritzen** from HØST PtX Esbjerg and Ulrik Torp Svendsen from Everfuel for sharing their experiences on planning and implementing a Power-to-X plant. A special thanks to Svendsen for guidance in the final phase of our thesis. **João A. B. R. Møller** from the Technical University of Denmark for sharing his knowledge about companies, politicians, and other actors' relationships and how they work together.

Last but not least we want to show our gratitude towards our supervisor **Iva Ridjan Skov** for guiding our research and giving us constructive feedback throughout our semester.

The referencing method in this study is Harvard style, meaning references begin with [Surname, year] and they are listed alphabetically in the reference list.

Appendices referenced in the study are handed in in DigitalExam separately from the report.

The Thesis Contributions

Academic literature on Power-to-X generally concerns the benefits for the energy system and how it can contribute to the green transition. However, literature covering the impact Power-to-X can have on the local community and surrounding environment is minimal which has been the starting point for this thesis.

It has been decided by the government that Bornholm is going to be an energy island in 2030 and energy technologies are therefore being implemented around and on the island in the coming years. This is a pioneer project since implementing wind turbine farms on such a large scale has not been seen before in Denmark. Experiences of how to incorporate this in a local community are limited, but nevertheless important for ensuring positive impacts on the surroundings. Energy technologies take up a significant amount of space and differ from the present characteristic of the landscape on the island. Implementing Energy Island Bornholm and potentially Power-to-X will influence the existing community, however, Bornholm has the possibility of benefitting from it.

This thesis seeks to emphasise the importance of understanding the impacts of an implementation of a Power-to-X plant on the local area. The aim is that knowledge about the impacts can have a contribution to better inclusion and integration of the local area and community in the long term. It is not a matter of course that the local community and local area will benefit from Power-to-X, since apart from taking up space, the implementation of Power-to-X can overall happen independently of the community. However, if the local community is actively integrated, synergies can be strengthened resulting in benefits for the community, such as obtaining environmental benefits, securing more job opportunities, and improving the local economy.

As Sustainable City planners a holistic approach has been adopted when defining and investigating the subject of this thesis. The educational background and large focus on sustainability have therefore ensured a holistic approach considering both citizens, economy, sector coupling, water resources, and other relevant factors as integral to the implementation of Power-to-X. The holistic approach has contributed to identifying potential sector coupling opportunities and benefits going across the different actors of this study, securing integration of several different interests. Thereby, the holistic approach has addressed the complexity of Power-to-X implementation by recognising the interdependencies between social, economic, and environmental aspects and acknowledging that they cannot be examined in isolation.

Summary

This thesis investigates the possibility of implementing a Power-to-X plant on Bornholm in connection to Energy Island Bornholm. The project of Energy Island Bornholm is planned to be developed by the end of 2030, consisting of 3.2-3.8 GW electricity from offshore wind with a possibility of expanding with 3.0 GW offshore wind by Copenhagen Infrastructure Partners and Ørsted. The offshore wind turbines will be connected to the island with a large onshore transformer station. The focus within this thesis is to investigate the following problem statement: *What effect will a Power-to-X plant have on the local community and area on Bornholm?*

The critical hermeneutic theory has been used as a theory of science, using an iterative process when developing knowledge. The empirical data is gathered by semi-structured interviews with relevant identified actors related to Power-to-X implementation on Bornholm. The hermeneutic spiral is combined with Actor-Network Theory as an interpretive tool and analytic framework to understand the socio-technical system. Using Actor-Network Theory the focus is on the different interests of the involved actors, the various benefits and challenges identified by the actors, and ultimately investigating how the implementation of Power-to-X will affect the local community and area on Bornholm.

The thesis uncovers the possibility of integrating Power-to-X in the existing energy and water infrastructure at Bornholm, by investigating the potential risks and environmental impacts of implementing such a plant, depending on size, location, and potential end-product; Power-to-Hydrogen, Power-to-Methanol, and Power-to-Ammonia. The study finds that the method used when investigating the subject, impacts the results as well as the researcher's background. Overall, the implementation of Power-to-X on Bornholm is identified as a great opportunity for Bornholm to become important in the green transition of Denmark.

To achieve the most positive effect from implementing Power-to-X on Bornholm, it is concluded that the most beneficial location is to place the plant next to the transformer station and produce either Power-to-Hydrogen or Power-to-Ammonia. The thesis concludes implementing Power-to-X on Bornholm will result in a translation process of the existing system by creating new interactions between human and non-human actors. This will result in sector coupling opportunities and synergies between water, electricity, heat, and transport sector on Bornholm. It can therefore be concluded from this thesis that implementing Power-to-X on Bornholm will both bring positive and negative effects to the local community and area on Bornholm.

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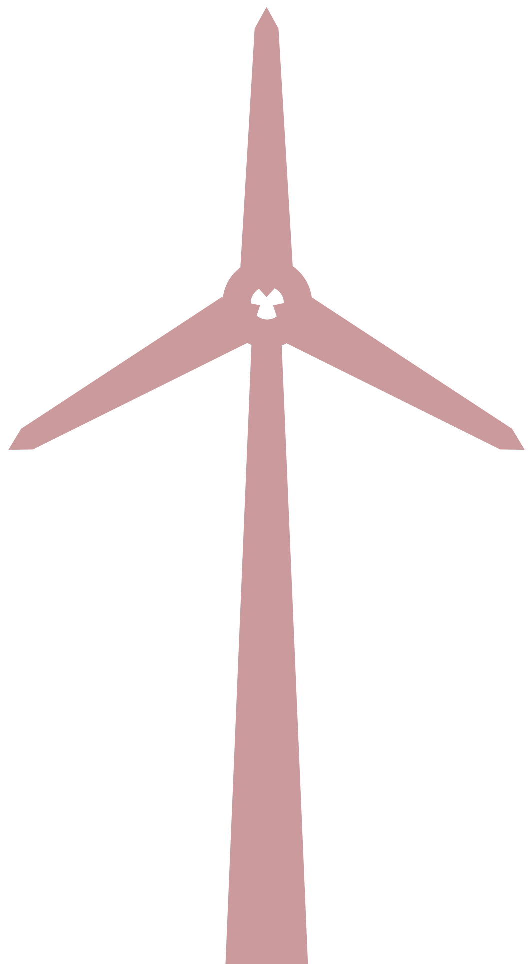
1 Introduction



In the debate on the green transition of the energy system, challenges regarding the transport sector have been much discussed since Green House Gas (GHG) emissions are increasing despite the awareness of how negatively it impacts climate change. Whereas other sectors of the energy system have managed to transition to greener solutions and decrease GHG emissions, the transport sector is dependent on the implementation of more technologies to store renewable energy before it is possible to see significant reductions in emissions (Kany et al., 2022).

Today the flexibility of the energy system is secured by the use of fossil fuels making it possible to balance the energy system regardless of the renewable energy supply. The same flexibility does not occur in a fluctuating renewable energy system if fossil fuels are not used (Lund, 2014; Skov et al., 2021). Lund (2014) therefore introduced the smart energy system approach, where a 100% renewable energy system is modelled using a holistic approach instead of the traditional silo thinking approach (Skov et al., 2021; Lund, 2014). The purpose of the smart energy system is to find another solution for how to generate flexibility in the future energy system, and it can potentially be achieved by coupling the electricity, heating, and transport sector to utilise energy storage (Lund, 2014; Mathiesen et al., 2015). The energy system will therefore transform into working with a cross-sectoral approach with the goal of integrating sectors to cover the energy demand at all times (Lund, 2014; Mathiesen et al., 2015). It is within this sector coupling Power-to-X technology becomes essential (Skov et al., 2021; Mathiesen et al., 2015; Salgi et al., 2007; Hedegaard et al., 2012) since it potentially can clear the way to transition parts of the transport sector which to this day still are highly dependent on fossil fuels.

1.1 A New Technology in Denmark

Power-to-X is still a relatively new technology, meaning there is only limited experience in the implementation of the technology and most projects in Denmark are in the research and planning phase and thereby not yet implemented (HØST, n.d; Everfuel, n.d.B). However, both the government and private companies view Power-to-X as a promising technology and believe it will play a significant role in the future. This can be seen in the political agenda in Denmark as the government has initiated several initiatives to implement Power-to-X. First of all, a Power-to-X strategy was published in 2022 in which it was agreed to aim for an electrolysis capacity of 4-6 GW in 2030. Further, the government decided to invest 1.25 billion DDK for a Power-to-X tender as a market-based competitive bid to upscale and support Power-to-X in Denmark (Regeringen, 2022). Also, the government is focussing on implementing more green energy and is aiming to implement 9 GW of offshore wind energy before the exit of 2030 (Energistyrelsen, n.d.G). The latest governmental initiative on green hydrogen is an agreement from March 2023 on implementing a large-scale transmission interconnector infrastructure in 2028 between Denmark and Germany enabling hydrogen export (Ministry for Economic Affairs and Climate Action of the Federal Republic of Germany & Ministry of Climate, Energy and Utilities of Denmark, 2023).

Alongside this, several companies have initiated projects across Denmark, hereunder HØST (HØST, n.d) and Everfuel (Everfuel, n.d.B), that both are planning large-scale Power-to-X plants in Jutland which potentially can be the starting point for transitioning the hard-to-abate sectors - the heavy transport and the industry sector (Løvstad, 2021; CSR.dk, 2021). Furthermore, a Power-to-X strategy for ports has been formulated with ambitious visions of becoming a leading nation in providing e-fuels (Green Power Denmark, 2021). Not only is there potential for Power-to-X within Denmark but it is expected to have great potential for export that creates business opportunities, which has made it appealing for several companies to invest in Power-to-X projects (Regeringen, 2022).

1.2 The Concept of Power-to-X

Power-to-X is a process where electrolysis is used to produce hydrogen to hereafter convert the produced hydrogen into other end-products or function as an energy carrier (Skov et al., 2021; Wulf et al., 2020; Foit et al., 2017). This makes it possible to store renewable energy which can be used for heavy transport such as aviation, trucks and ships allowing a transition of the heavy transport sector (Skov et al., 2021), contributing to a decrease in GHG emissions (Kany et al., 2022). This process is illustrated in Figure 1.

Hydrogen is produced by merging water and electricity in an electrolyser. The hydrogen can then be converted into different variations of e-fuels depending on whether it is mixed with a carbon or a nitrogen source. If hydrogen is mixed with a carbon source, either fossil or biogenic, it will transition into methane or methanol and if a nitrogen source is used it will transition into ammonia (Skov et al., 2021; ACS Energy Letters, 2020). After transitioning hydrogen into e-fuels, the e-fuels can be used in heavy transport and industry sectors (Skov et al., 2021; Foit et al., 2017; Wulf et al., 2020; Helgeson & Peter, 2020; ACS Energy Letters, 2020) whereas ammonia also can be used in fertiliser production (Wulf et al., 2020).

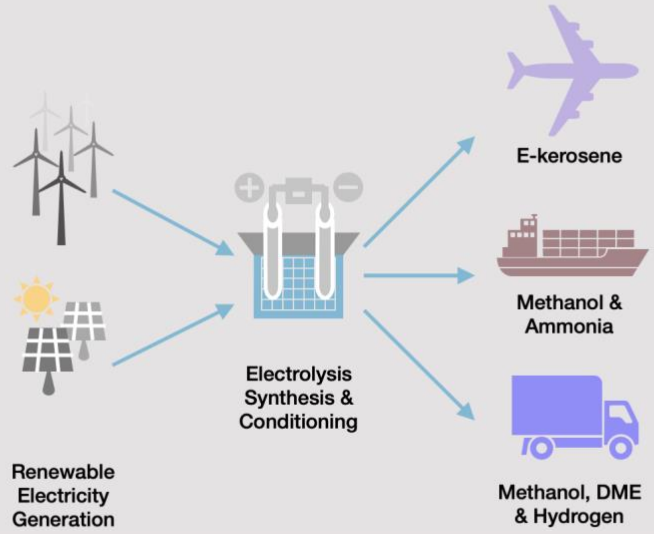


Figure 1 Illustration of converting renewable energy into an e-fuel via electrolysis which can be used in the transport sector. Own production, made in Pages (Kany et al., 2022).

Heavy transport also encompasses maritime transport, where the use of either ammonia or methanol is suitable for shipping (Skov et al., 2021). Whether ammonia or methanol is the most beneficial transition of hydrogen for the shipping industry, relies on ship development, fuel handling clarification, upscaling of infrastructure as well as preparing the ports for Power-to-X products. These are long-term investments which take time to implement but in the long run will be part of transitioning the international shipping industry (Skov & Schneider, 2022). Before Power-to-X can have a significant impact on the green transition there are challenges to be solved which will be elaborated upon in the following chapter.

1.2.1 Challenges of Power-to-X

Even though Power-to-X technology is constantly developing, especially in the last couple of years, the implementation of Power-to-X continuously is challenged by technical and non-technical aspects (Skov et al., 2021). On the technical part, the efficiency of the electrolyser (Danish Energy Agency, 2021), the utilisation of fluctuating renewable energy (Wang et al., 2020; Skov et al., 2021), and the large share of both electricity (ACS Energy Letters, 2020) and water needed in the electrolyser (Koj et al., 2019) are examples of challenges which need to be solved. On the non-technical part, the challenges are related to the current prices and cost of using Power-to-X compared to fossil fuels (Burre et al., 2020), lack of market formation (Decourt, 2019), and complete Life-Cycle Assessment (LCA) (Burre et al., 2020), regulatory framework (Dolci et al. 2019), and social acceptance (Burre et al., 2020; ACS Energy Letters, 2020; Skov et al., 2021).

1.2.1.1 The Lack of Green Energy Supply

The electrolyser in Power-to-X requires a large share of electricity, preferably supplied by renewable energy, in order to achieve green hydrogen and for the end-products to secure storage of renewable energy (ACS Energy Letters, 2020).

To achieve the goal of decarbonising the energy sector by securing a renewable output from the Power-to-X process, it is essential to know how the electricity used in the electrolyser is produced. In 2022, approximately 60% of the electricity in the Danish electricity grid was produced by wind and solar power, meaning 40% of the electricity in the grid is from fossil fuels (Energinet, 2022A). At present time, it is therefore not possible to ensure a 100% renewable energy source for electrolysis in Denmark, due to the share of fossil fuels. However, by supplying the electrolyser with energy in periods where the energy is cheap and the grid thereby mainly is supplied by renewable energy, it is possible to ensure the production is mainly green. This is how the company Everfuel, who is planning on implementing a large-scale Power-to-X plant, is planning to keep the production green (Appendix L). However, Denmark is currently transitioning the energy system, and the electricity in the grid increasingly depends on renewable energy (Danish

Ministry of Climate, Energy and Utilities, 2021B).

1.2.1.2 Clean Water is a Scarce Resource

Besides a large amount of electricity, the electrolyser also needs a large supply of water. The electrolyser is sensitive to the quality of water used when producing Power-to-X (Koj et al, 2019). Drinking water contains too many impurities to be used directly, meaning that it is necessary with water treatments to improve the quality of the water to achieve high enough purities for it to be used in the electrolyser (Koj et al., 2019; State of Green, 2022; Niras, 2022). The preferred quality of water is often mentioned to be deionized water (Koj et al., 2019; Turner et al., 2007; Symes et al., 2012) and the water consumption to produce 1 kg of hydrogen is around 9 kg (Shi et al., 2020). The electrolyser, therefore, requires a large quantity of water input, which can be a challenge due to the limited available water resources depending on the location of the Power-to-X plant (Koj et al., 2019; State of Green, 2022; Niras, 2022). Denmark does have clean water; however, this is not the case in all countries, and clean water is a scarce resource. Increasing pollution is seen in the Danish drinking water from groundwater, which has led to more and more boreholes being closed (Danske Regioner, n.d.; Miljøstyrelsen, n.d.A). The drinking water resource in Denmark is, therefore, no longer seen as being renewable but rather a scarce resource that must be handled with care (Danske Regioner, n.d.; Miljøstyrelsen, n.d.C). With population growth, water consumption is increasing making it even more important to address. Therefore, it is important to look into alternative water sources for purposes where drinking water is not a necessity. For Power-to-X plants, large amounts of water are needed for the electrolysis process. This has made several Power-to-X projects investigate the use of treated wastewater and seawater instead (State of Green, 2022; International Power-to-X hub, 2021; Niras, 2022; ACS Energy Letters, 2020). Using alternatives to drinking water can contribute positively to the environmental and sustainable aspects of Power-to-X projects (State of Green, 2022; Niras, 2022).

1.2.1.3 Energy Efficiency

The technology of the electrolyser only has an energy efficiency of 63-80% to produce hydrogen (Danish Energy Agency, 2021), resulting in a low conversion of hydrogen into e-fuels since not all energy is utilised. To accommodate this, it is possible to utilise the surplus heat in the district heating system by implementing it in the energy infrastructure (Grøn Energi, COWI, TVIS, 2021).

1.2.1.4 Cost

On the non-technical side, Power-to-X technology is an expensive alternative to fossil fuels, since it is difficult to implement, particularly on a larger scale because the electrolysis cells are not sufficient enough for upscaling (Skov et al., 2021; Mathiesen et al., 2015; ACS Energy Letters, 2020). Power-to-X projects are still only developed on a small scale, meaning they are impacted by high capital costs resulting in limited price variations (ACS Energy Letters, 2020). Also, they still require a large share of electricity and in addition, the availability of cheap and excess renewable electricity dictates the cost-competitiveness of Power-to-X projects (ACS Energy Letters, 2020).

1.2.1.5 Market Formation

Besides the economic challenges, lack of market formation is also a weakness within Power-to-X projects (Decourt, 2019, Skov et al., 2021). To secure the successful implementation of Power-to-X projects in the near future, market formation should be stronger both on resource mobilisation and to reinforce guidance of the research (Decourt, 2019).

1.2.1.6 Regulatory Framework

Many authors mention regulatory framework as a weakness, but also as an opportunity to secure changes in the traditional way of planning the energy system and to improve the development of the technology (Skov et al, 2021; Decourt, 2019; Dolci et al., 2019) and thereby be a driver for the transition (Decourt, 2019). A change in regulation could potentially help create a niche market for Power-to-X technology (Decourt, 2019).

The regulatory framework differs from country to country, but a push benefitting Power-to-X implementation is already happening from several governmental sides, such as; Japan, South Korea, European Union, and Australia, where the governments are implementing national roadmaps and strategies for effective decarbonisation by advocating renewable hydrogen (ACS Energy Letters, 2020). An example of an initiative, the Renewable Energy Directive (RED), announced by the European Union in 2018 (Directive (EU) 2018/2001 of the European Parliament and of the Council, 2018), was the first foray into regulation for Power-to-X (Decourt, 2019).

As mentioned, the Danish government also pushes towards this transition through the Power-to-X Strategy from 2022 and the investment of 1.25 billion DDK for a Power-to-X tender (Regeringen, 2022). One of the latest initiatives from the government is a Power-to-X step-by-step guide, which has the purpose of creating transparency for developers in which authorisations are required before a Power-to-X plant can be implemented. The guide presents the required authorisations from before the developer starts applying for implementing a Power-to-X plant and until the permit to operate the plant is given. These authorisations include environmental approval, risk and safety measures, planning permission among other approvals (Energistyrelsen, n.d.D).

1.2.1.7 Environmental Impact

Besides the above-mentioned challenges, more and more literature is focussing on the importance of investigating the environmental impact of a Power-to-X plant (ACS Energy Letters, 2020; Koj et al., 2017; Koj et al., 2019; Decourt, 2019; Helgeson & Peter, 2020; Brynolf et al., 2019; Mehmeti et al., 2018). Looking into the environmental aspects of challenges for the implementation of Power-to-X, both lack of complete Life-Cycle Assessments (LCA), pollution and social acceptance can be mentioned (Skov et al., 2021, ACS Energy Letters, 2020).

The lack of complete LCA has been pointed out by several articles as a challenge which needs to be solved before knowing how effective Power-to-X implementation is regarding carbon reduction (Skov et al., 2021; Mac Dowell et al., 2017; Searle & Christensen 2018). It is still unsure how much Power-to-X will contribute to a carbon reduction, and it is therefore important to make LCA results for different Power-to-X variations to evaluate their impact on carbon emissions and compare their potential reductions with other alternatives (Skov et al., 2021; Koj et al., 2019).

Incorporating investigation of the potential environmental impacts from a Power-to-X plant can contribute to the sustainability value of the project (Mehmeti et al., 2018). Therefore, it is worth mentioning there is a lack of focus on pollution which will be investigated within this study by analysing multiple environmental impacts from the electrolysis process and production of the end-product securing sustainable resource management.

1.2.1.8 Social Acceptance

It is important to be aware of the surroundings and also consider the citizens who will be impacted by the installation of a Power-to-X plant (Koj et al., 2017; Skov et al., 2021; ACS Energy Letters, 2020). Social acceptance of Power-to-X projects can be considered a weakness (Decourt, 2019; Skov et al., 2021). The benefits related to Power-to-X are not as visible to the end-user as clean technology, like wind turbines, because of the many “invisible” technologies and applications used to produce energy. This is expected to decrease the opportunity for using social acceptance as a benefit since it is more difficult for end-users, policymakers, and society to understand. It is therefore important with an educational approach, to learn other relevant stakeholders about the environmental benefits of Power-to-X (Decourt, 2019). However, it is important to mention that parts of society are aware of the Power-to-X technology and a push on the decarbonising of the energy system using e-fuels is also happening from the citizens and society is therefore also part of pushing this agenda forward (Helgeson & Peter, 2020).

1.2.2 Summary

Despite the focus on implementing Power-to-X, the fact is that to this day the first large-scale Power-to-X plants is only about to be implemented, meaning there is a limited experience to learn from (Din Forsyning, 2022). Generally speaking, Power-to-X is viewed as one of the most promising technologies for transitioning the transport sector (Skov & Schneider, 2022), however, the production of Power-to-X is demanding on the surroundings (ACS Energy Letters, 2020). This makes it essential to research how a Power-to-X plant impacts the area it is located in. Power-to-X is mostly viewed from the energy perspective focussing on the potential energy outcome of the product whereas the use of resources, environmental impacts and impacts on the surrounding areas are often overseen but nevertheless important to manage (Grahn et al., 2022). This makes it interesting to investigate further to obtain a better understanding of what impacts can be expected, making it possible to include in the early planning process and potentially minimise them. This research will investigate these impacts based on the potential implementation of Power-to-X on Bornholm. This case will be elaborated upon in the following chapter.

1.3 Bornholm: An Energy Island in the Baltic Sea

As part of the transition of the energy network, the Danish Parliament has in a political agreement decided on two energy islands to be constructed, one being an artificial island in the North Sea and the other being the existing island, Bornholm (Klima-, Energi- og Forsyningsministeriet, 2020). This thesis takes its starting point in Energy Island Bornholm which is expected to be the world's first energy island (Danish Energy Agency, n.d.).

Bornholm has a central location, as the island is located in the Baltic Sea, thus, a hub for shipping, ferries and fishing as well as a great connection to Zealand (Denmark) and other nearby countries (Energiø Bornholm, n.d A; Port of Rønne, n.d.D). In several ways, the island is well-suited to be an energy island of which a Power-to-X plant could be a part of (Danmarks Erhvervsfremme-bestyrelse, n.d). The connected offshore wind turbine farm will be located up to 15 km south and southwest of Bornholm and have a capacity of 3.2-3.8 GW of electricity in 2030, which is equivalent to the electricity consumption of three million households (Energiø Bornholm, n.d A; Energiø Bornholm, n.d.B). 3.2 GW will be connected to the grid, whereas 0.6 GW is the capacity the developer is allowed to overplant (Energistyrelsen, 2022A). Overplanting is the concept of allowing the developer to optimise the power capacity by exceeding the limit of the transmission capacity. Increasing the capacity can either be by installing a larger generator size on the turbines or by increasing the number of turbines on the site (Wolter et al., 2020). The overplanted capacity will not be connected to the grid but potentially can be used for Power-to-X (Energistyrelsen, 2022B).

On Bornholm a transformer station will be implemented receiving the electricity from the offshore wind turbines which will be delivered to other places in Denmark and Germany. As of now, this function will be the function of the island, but it is expected that there will be implemented a Power-to-X plant on the island in the future (Energiø Bornholm, n.d A) which will make it possible to convert electricity into a sustainable e-fuel (Port of Rønne, 2021).

A Power-to-X plant on Bornholm is considered beneficial due to the transport infrastructure of which Bornholm is a part of, but there are interesting aspects in the location of a Power-to-X plant (Singlitico et al., 2020; Appendix M). Bornholm is a much-visited island (Destination Bornholm, n.d) and tourism, therefore, plays a significant role (Appendix M). Thereby, it is interesting to investigate whether a larger Power-to-X plant can have an impact on the tourism of the island. Firstly, the physical construction will take up space, and secondly there can be safety reasons, meaning tourism and the surroundings will be affected if Power-to-X is implemented on Bornholm (Appendix M).

Knowledge about Power-to-X is limited among locals on Bornholm, contributing to an ignorance to what extent a Power-to-X is an advantage for them (Appendix M). In the future, a Power-to-X plant may cause resistance from locals along with people becoming more aware of what it is (Appendix M). The uncertainty about safety and location are aspects that are expected to create a critical stance towards a Power-to-X plant on the island (Appendix M). Concerns can arise about the safety behind a Power-to-X plant which is comparable to the concerns towards nuclear power, and the opposition to the location of the plant can also be compared to the attitude several people have towards wind turbines where the much discussed "not in my backyard" thinking applies (Appendix M). The locals on Bornholm stances on Power-to-X are expected to be a challenge but to what degree is still unknown and not yet investigated making it interesting to investigate as this may have an effect on the implementation of a Power-to-X plant on Bornholm.

Another important aspect is the water supply for Power-to-X, as pointed out earlier, since Power-to-X uses large amounts of water for electrolysis. This is also the case for Bornholm and has brought concern among locals (Bentsen, 2022). The current supply is considered insufficient to cover the future water consumption that a Power-to-X plant will entail (Bentsen, 2022). At present, 3.5 million m^3 of drinking water is pumped up each year to cover the current water demand of Bornholm. The available water resource is estimated to be 5.7 million m^3 annually (Bornholms Regionskommune, n.d.A). If a Power-to-

X plant is implemented, this could challenge the drinking water resource on Bornholm, making it interesting to investigate as well as look into alternative water resources (Bentsen, 2022).

It can be concluded that there are a number of challenges that implementation of Power-to-X faces, as well as a greater uncertainty about Power-to-X in Denmark both nationally and locally. The following introduction and scope will present the problem statement that has been carried out to examine some of the challenges that a Power-to-X plant at Bornholm can face.

2 Introduction to Problem Statement

Based on this report's preliminary research a knowledge gap in the academic literature has been identified regarding how Power-to-X plants impact a local community and the surrounding area. The existing literature primarily focuses on the energy outcomes and the transitioning of the energy system whereof only limited literature has been found concerning environmental and local community potential benefits and challenges of implementing Power-to-X which has led to the problem statement of this report. The report studies the physical framework of the infrastructure and area as well as the actor-network regarding Power-to-X, meaning the research is defined by the use of methodology and theory.

This report takes its starting point in the current plans and visions of green energy on Bornholm. Towards 2030 Bornholm will become an energy island that is going to produce electricity for Zealand and Germany and potentially Power-to-X (Energiø Bornholm, n.d A). Also, investors see a potential of producing Power-to-X and have started the permitting process (Copenhagen Infrastructure Partners, 2022A). Since the Power-to-X plants are in the planning phase it has not yet been decided which end-product potentially is going to be produced, however, most actors consider hydrogen, methanol or ammonia as the potential fuel wherefore this research is limited to study these fuels (*1.2 The Concept of Power-to-X*). It has to be acknowledged that the regulatory framework and economy can be a barrier for implementing Power-to-X on Bornholm, however, this is not included in the scope of this report as it is estimated of low importance for researching the problem statement.

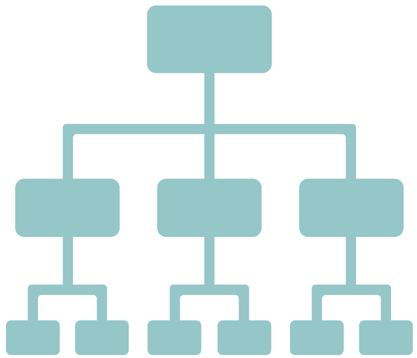
The scope of the local community and area in this report is defined as the onshore land area and the existing community of Bornholm. It is acknowledged that the surrounding sea is impacted by the offshore wind turbines but limited to solely concern the onshore area and how the community and environment is affected. This research investigates the environment and safety concerns of an implementation of Power-to-X. The environment is limited to concern noise and air pollution, conservation areas and visual impact and safety is limited to concern risks of producing hydrogen, methanol and ammonia and recognises the need for safety zones but leaves out the specific sizes for safety zones since this has to be evaluated based on the specific project. Followed by this scope, this report will investigate the following problem statement by answering three supplementary questions:

Problem Statement

What effect will a Power-to-X plant have on the local community and area on Bornholm?

1. *How will a potential Power-to-X plant impact the energy system and the local area's environment, safety and water supply?*
2. *Which translation process and interactions can be identified in the implementation of a Power-to-X plant and how will these affect the local actors?*
3. *How could different perspectives have impacted the findings?*

3 Research Design



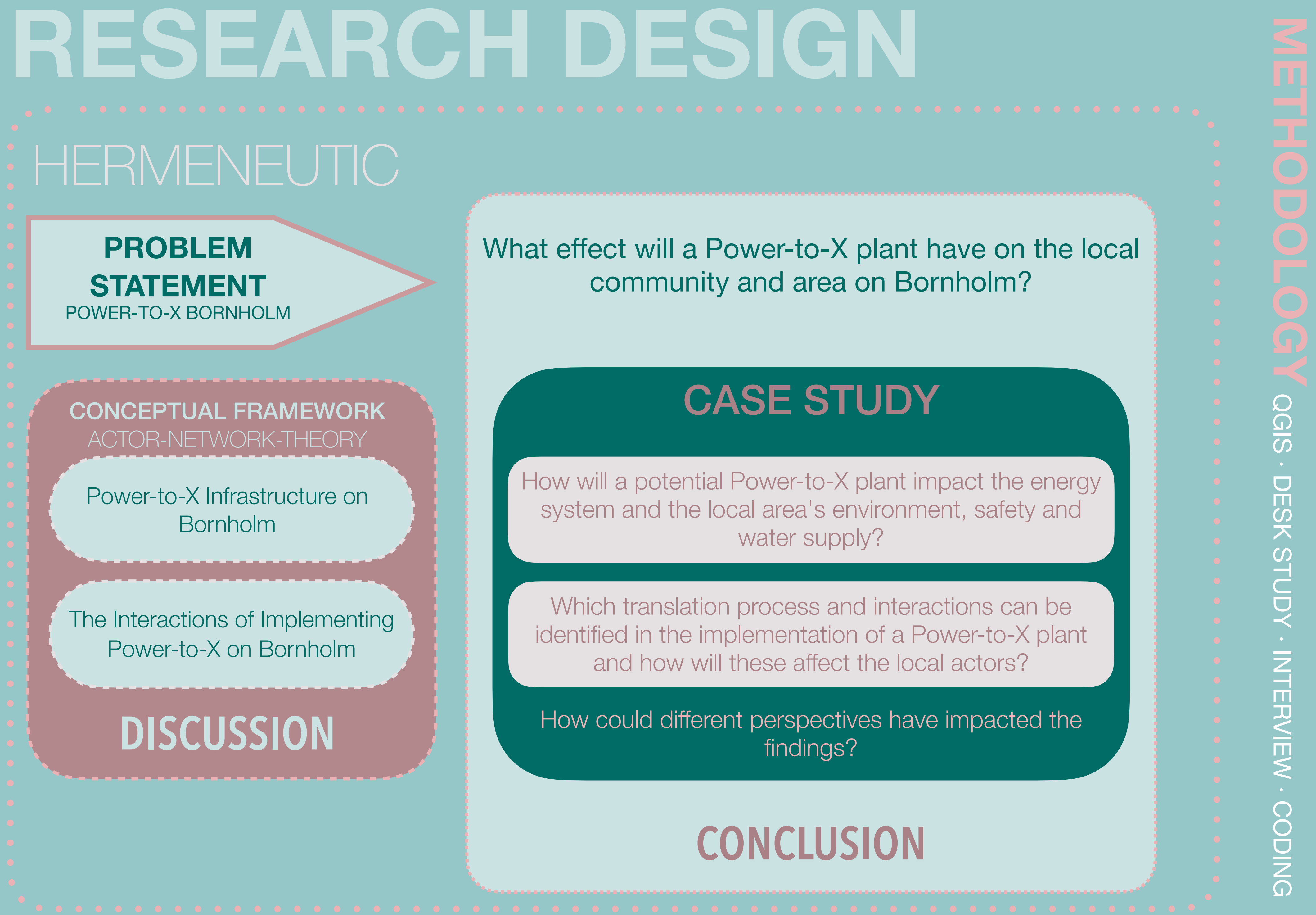


Figure 2 Research design visualising the setup of this report. Own production, made in Pages.

This chapter presents the research design to visualise the theoretical framework and methodology for answering the problem statement and the supplementing subquestions.

The problem statement (*2. Introduction to Problem Statement*) is answered by formulating three subquestions (*2. Introduction to Problem Statement*) to structure the analysis of the thesis. The development of this thesis is guided by critical hermeneutics. This is illustrated in Figure 2, which represents the overarching framework for the study, encompassing the chapters of the thesis. Moreover this study is a case study, investigating a specific case concerning Power-to-X on Bornholm, which serves as the foundation for the conducted analyses. Additionally, Actor-Network Theory serves as the conceptual framework, consistently informing the investigations and shaping the understanding of the findings. The *1. Introduction* serves as the foundation for the development of the thesis' problem statement. In the search for a worthwhile challenge to investigate within Power-to-X desk study has been used. Additionally, an informative interview has been conducted, providing knowledge about the Power-to-X plans on Bornholm.

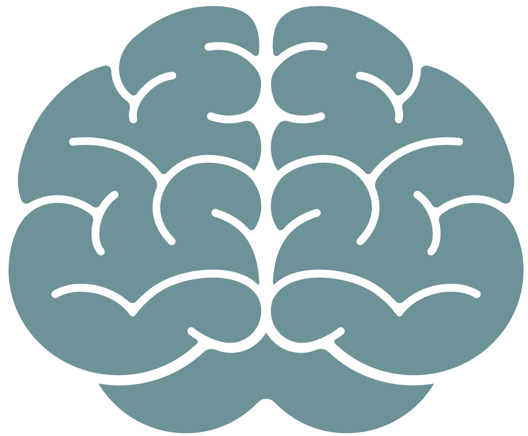
The first subquestion serves as the basis for addressing the environmental impacts of a Power-to-X plant. This analysis examines the necessary changes in the existing infrastructure to accommodate the resources required for Power-to-X. The knowledge obtained from this analysis is further utilised to assess potential locations for a Power-to-X plant. To answer the first subquestion, desk study, and interviews have been conducted as the research method. Additionally, Geographic Information System (GIS) is used to map the current infrastructure and determine how a future facility can be situated in relation to the existing infrastructure. The second subquestion has been formulated to analyse how a Power-to-X plant will impact the community and the local area. This research primarily relies on conducted interviews and findings from the previous chapter which have been analysed by the use of Actor-Network Theory.

In addition to the analyses, a discussion has been developed based on the findings from *6. Power-to-X Infrastructure on Bornholm* and *7. The Interactions of Implementing Power-to-X on Bornholm*. In this discussion, alternative choices of theories have been discussed, along with an exploration of how they can contribute differently. Furthermore, the discussion interprets the varying impacts different Power-to-X end-products will have on the environment, the area, and the community on Bornholm. Finally, perspectives from other Power-to-X plants in other locations are considered to assess what they can contribute with in relation to a Power-to-X plant on Bornholm.

Lastly, a conclusion has been formulated based on the findings from the analyses and the discussion, providing an answer to the problem statement of this thesis.

4 Theoretical Framework

Critical Hermeneutic Theory



To ensure reliability of this study, the theory of science is stated from the beginning since it is used to establish the direction of scientific research and knowledge production. Throughout this study, applying critical hermeneutic theory has been crucial for knowledge production. Critical hermeneutics is based on an iterative process investigating the entirety of the subject matter and specific elements, securing enhanced interpretations and a deeper understanding of the investigated object. According to hermeneutic theory, implementation is only achievable through interactions between comprehensive and partial understandings, as advocated by the hermeneutic circle (Juul & Pedersen, 2012), meaning there is not only one interpretation or universal truth.

It is acknowledged by critical hermeneutics that the researchers have knowledge and preconceptions gained depending on diverse backgrounds, studies, professional fields, and history, making complete objectivity unattainable. Furthermore, the historical circumstances will always influence the understanding and interpretation of the world (Juul & Pedersen, 2012). In this study, the subject of Power-to-X implementation in a local context is approached based on individual knowledge and personal experience from the researchers. These experiences and preconceptions have impacted the formulation of the problem statement and supplementary questions which have been subject for investigation and have thereby influenced the outcome of this study. Since the hermeneutic circle builds upon a foundation of continually generating new insights and knowledge, it is important to remain receptive to new interpretations and also acknowledging the iterative process within hermeneutics (Juul & Pedersen, 2012). Within this study, the hermeneutic circle is actively employed, particularly during the interviews, since the prior interviews have influenced the new knowledge.

In this research a critical hermeneutic perspective is adapted, emphasising that social science needs an emancipatory aim and critical perspective (Juul & Pedersen, 2012). The motivation behind this study is a curiosity about the possibilities and challenges related to implementation of Power-to-X in a local context regarding environmental impacts, since a knowledge gap is experienced within existing literature. This served as the starting point of this research. A critical approach to the development and planning of Power-to-X on Bornholm is therefore taken within this study, without predefined ideals. In this study, the critical perspective draws on Doganova et al. (2014), where the critical hermeneutic illuminates the subject matter from several angles, meaning previously unseen elements are identified. Based on this new understanding of the topic new knowledge, conversations, and decision-making is enabled. Even though Doganova et al. (2014) applies this approach in the context of valuation theory, the critical hermeneutic within this study is expanded to increase the understanding of the social, environmental and technical system regarding Power-to-X planning on Bornholm.

Since hermeneutics generates knowledge based on interpretations, it is acknowledged that the truth is subjective, meaning the findings within this study depend on findings from the interviews and the researcher's ability to analyse and interpret the subject matter. A single universal truth is not claimed within this study about potentials and challenges related to implementation of Power-to-X on Bornholm. The goal of this research is on the other hand to identify different translation processes, interactions and interrelations of the object from different perspectives involving several actors who will be impacted by the implementation of Power-to-X. By identifying perspectives on the subject-matter the goal is to increase awareness, secure knowledge sharing and a common understanding of the impacts from implementing the Power-to-X plant.

In this study, Actor-Network Theory (ANT) is applied as an analytic framework to understand the socio-technical system. To investigate the subject matter from a specific perspective the hermeneutic spiral is combined with the use of Actor-Network Theory as an interpretive tool. Actor-Network Theory is explained further in the following chapter.

4.1 Actor-Network Theory

To understand the impact of implementing Power-to-X on Bornholm Actor-Network theory has been used. The Actor-Network theory and how it is used will be presented in the following chapter.

Actor-Network Theory (ANT) was developed by Latour, Callon, and Law in the 1980-90s and is a descriptive social theory and socio-anthropological approach used to study the impact of technologies in society (Jolivet & Heiskanen, 2010; Latour, 2007). The main focus of Actor-Network Theory is to examine how a network is shaped through the actors' interactions with each other, and how the actors are defined by the relationships in the network. Using Actor-Network Theory can thereby help understand existing planning practices on Bornholm, and also give alternative planning practice perspectives to improve the existing planning (Boelens, 2010).

4.1.1 Actors

When implementing new technologies an understanding of the existing settings and local framework is required. It is important to identify the different actors and their relations to map and understand the interrelations of the framework. The affected actors can be human and non-human, and they all take part in the interactions, reasoning why they are seen with an equal footing and importance (Rydin, 2013; Callon & Blackwell, 2007). Thereby, the theory seeks to understand the interrelations between social and material elements (Rydin, 2013) and how they impact each other. It should be recognised that actors have different values and interests in a given project, which have to be considered (Boelens, 2010). Actors are defined as an object whose action occurs on the basis of relations with other actors. Since the action occurs on the basis of relationships, it can be difficult to define where the actual action starts (Rydin, 2013).

In this report, the human actors span a wide range of actors, including; the permanent citizens of Bornholm, local associations, local politicians, cottage owners, local companies, developers, tourists, and visitors, among others. The non-human actors in this project are the available infrastructure and resources on Bornholm, such as regulatory framework, the future Energy Island Bornholm, Port of Rønne, the district heating network, the future transformer plant, the electricity grid, the shipping industry which sails through the Baltic Sea, and the future Power-to-X plant in the energy system. The actors within this project are visualised in Figure 22.

4.1.2 Network

A network is defined based on the actors and their relationships and interactions with each other. The network is a process that constantly is redefined, meaning the network can also be defined as infinite, thus cannot be defined in its perfection. Thereby, the network is a tool where the actions of actors and the influence of other actors are analysed through observation of these (Rydin, 2013). The involved parties will have to agree on what the actual problem is and how to solve it. The network of interactions will change when either new useful knowledge is produced or cast aside, this will change the positions of already-known actors and incorporate new actors. By understanding the relationships between the actors, it is possible to identify the translation process, and new potential relationships can arise from changes. The network thereby includes a high level of uncertainty and complexity when taking all values and actors into account, and it will vary based on the local context.

In relation to this study, Actor-Network Theory can provide guidance and tools for how to implement a Power-to-X plant suitable for the local context of Bornholm, and through compromises, arguments, negotiation, and conflicts all actors, human and non-human, can be brought on board (Jolivet & Heiskanen, 2010). Furthermore the Actor-Network Theory, through mapping, can contribute to keeping track of decision-making and power dynamics between actors.

5 Methodology

The effect on the local area of a potential Power-to-X plant implemented on Bornholm is analysed using different methods to gather information and knowledge about the subject. The purpose of this chapter is to present the methods used to answer the problem formulation, describing the methods, how it has been applied, and the limitations.

5.1 Desk Study

The purpose of using desk research was to expand the knowledge about the chosen subject in order to receive more context of the research problem (Van Thiel 2014, p. 106). Different scientific articles and reports have been used to investigate the subject. Nevertheless, it is important to be critical when using literature, since it is influenced by the author, recipient, and publisher.

In this study, literature and desk research has been useful when closing knowledge gaps. However, the knowledge gaps of the researcher can also be a limitation of the study, since the researcher's existing knowledge will impact the starting point in the search for new knowledge. The starting point varies from researcher to researcher, meaning that finding a shared understanding of the subject affects the start-up process of the research.

5.2 Participant Selection

To understand how a Power-to-X plant will impact the actor-network on Bornholm and the translation process of the energy system in the future, different stakeholders have been interviewed. The selected participants have a crucial role to gain an understanding of the current situation on Bornholm regarding the energy system, water infrastructure, and political agenda. The knowledge and perspective gathered from the participants have been used throughout the report, and have in particular had a central role in the analysis *7. The Interactions of Implementation Power-to-X on Bornholm.*

Reaching out to different respondents was essential to gather knowledge and get an understanding of the current situation on Bornholm, which goals they have for the future development of the island as well as gaining knowledge and experience from other Power-to-X projects in Denmark.
The following respondents were interviewed in the given order:

- Port of Rønne: Maja Felicia Bendtsen, Business Manager at Port of Rønne (Referred to as Bendtsen).

- Danish Energy Agency (DEA): Rasmus Zink Sørensen, Deputy Head of Division - Centre for Energy Islands (Referred to as Sørensen).

- Danish Institute of Fire and Security Technology (DBI): Jesper Sjørvad, Business Developer within Green Fuels & Jorge Ivan Contreras-Cardeno part of the Power-to-X team (Referred to as Sjørvad and Contreras-Cardeno).

- The Regional Municipality of Bornholm (BRK): Mads Boss, Head of Development and Planning at Bornholm's Regional Municipality (Referred to as Boss).

- Bornholms Energi & Forsyning (BEOF): Klaus Vesløv, VP, Public Affairs, Communication, and ESG (Referred to as Vesløv).

- The Regional Municipality of Bornholm (BRK): Svend Bilo Høegh Stigsen, Architect and Planner in Bornholm's Regional Municipality (Referred to as Bilo).

- Port of Rønne: Mikkel Mortensen, Deputy Manager Port Service in Port of Rønne (Referred to as Mortensen).

- Baltic Energy Island: Kim Fønss-Lundberg, Senior Business Development Manager Baltic Energy Island at Copenhagen Capacity (Referred to as Fønns-Lundberg).

- The Regional Municipality of Bornholm (BRK): Lillian Rasch Madsen, Director at Bornholm’s Regional Municipality (Referred to as Madsen).

- Technical University of Denmark (DTU): João A. B. R. Møller, Developer for Residential College on Bornholm (Referred to as Møller).

- The Regional Municipality of Bornholm (BRK): Jacob Trøst, Mayor at Bornholm’s Regional Municipality (Referred to as Trøst).

- HØST: David Dupont-Mouritzen, Project Director (Referred to as Dupont-Mouritzen).

- Everfuel: Ulrik Torp Svendsen, Director Power-to-X Development (Referred to as Svendsen).

The included participants are only a small representation of the actual network, meaning other angles and a broader perspective could have been achieved if other or more participants were included. Within this study, mainly actors with a direct interest in a Power-to-X plant have been interviewed, however, involving actors such as farmers or someone from the tourism industry could contribute with other relevant interests and perspectives. Implementation of

Power-to-X on Bornholm is still not decided, however, if the project becomes a reality, the investor and developer would be important to involve.
Furthermore, the inclusion of local organisations, actors, and citizens in the area has been limited. This is a limitation of this study, even though the involved actors contribute with essential knowledge and information about the subject. However, the involved participants have been decided with care, based on the limited time and size of the project.

The roles of the different participants are described in Chapter *5.3 Interviews.*

Furthermore, we also participated in a citizen meeting on Bornholm, where different relevant representatives spoke and presented their opinion about Energy Island Bornholm. At the end of the meeting, we got the opportunity to speak with several citizens, who enriched us with inputs and opinions. The minutes from the citizen's meeting can be found in Appendix O.

5.3 Interviews

Qualitative interviews have been central for this study. A total of 13 interviews have been conducted with the previous-listed participants. Qualitative interviews can be executed in different ways which impacts the gathered knowledge from the interviews. Besides the preliminary informant interview conducted in the early stages of our data collection, semi-structured interviews have been the main interview method. An interview guide has been made prior to the semi-structured interviews, which has ensured relevant questions to be asked (Andersen, 2008). However, the interviewer was not obligated to follow the interview guide (Andersen, 2008) and the respondent was allowed to elaborate on their answers, which makes the interview more of a dialog (Brinkmann & Tanggaard, 2010) with space for curiosity (Andersen, 2008). Since the semi-structured interview allows for shifting between understanding of the object and engagement, the hermeneutic spiral became effective. The Actor-Network Theory and critical hermeneutics has been crucial for the development of the interview guides, meaning gathered knowledge from previous interviews impacted the development of the following interview guides since our understanding and knowledge within the subject has been constantly developed and expanded.
The interview guides were built on an initial understanding of Power-to-X and which impacts it could have for Bornholm.

All conducted interviews, besides the ones with representatives from Port of Rønne, were recorded and transcribed. The interviews varied in length from 30-60 minutes. The process and purpose of the interviews will briefly be elaborated upon in the following chapters, followed by methodological reflections.

5.3.1 Preliminary Informant Interview

In the initial phase, an informant interview was completed with Maja Felicia Bendtsen, Business Manager at Port of Rønne. Bendtsen has a background in chemical engineering and has previously been the project manager of a Feasibility Study for Power-to-X on Bornholm. Currently, Bendtsen works with the mission of getting Power-to-X implemented on Bornholm. One of her main tasks is to break down barriers related to Power-to-X by sharing knowledge and information about the technology with citizens and local actors. Since Bendtsen is experienced in the field she was assumed to have an extended understanding and knowledge about the current state and political agenda on Bornholm, the interview had an explorative approach. The focus during the interview was to let the respondent take the lead, be open-minded, and not bias the answers.

Because the interview with Bendtsen was conducted in an early stage of the project work, the preliminary interview was used to get an insight and understanding of the current energy system planning on Bornholm, and which goal the island has for the future.

Minutes from the interview can be viewed in Appendix M.

5.3.2 Interview with the Danish Energy Agency

Rasmus Zink Sørensen, Deputy Head of Division, Centre for Energy Islands at the Danish Energy Agency (DEA), was interviewed to get a common understanding of the energy island project at Power-to-X development in Denmark. Furthermore, was the interview used to gain an understanding of which role the Danish Energy Agency has in the implementation of a potential Power-to-X plant on Bornholm, which environmental impacts could be expected, and how the Danish Energy Agency works with those. The interview was also used to gain knowledge about how the Danish Energy Agency works with Energy Island Bornholm, how much overplanting is expected, which actors they collaborated with in the project, and how far the development of a potential Power-to-X plant on Bornholm is.

The transcription of the interview can be found in Appendix A.

5.3.3 Interview with Danish Institute of Fire and Security Technology

Danish Institute of Fire and Security Technology (DBI) are specialists within fire and safety risks and offer different services in fire engineering, security, and fire prevention. Furthermore, DBI has an extensive course business, educating customers within fire and security regarding different materials, industries, technologies, businesses, etc. (Danske Brand- og Sikringsteknisk

Institut, n.d.A). One main goal for DBI is to give holistic solutions based on years of experience and professional knowledge. DBI constantly develops new knowledge following the development in society to achieve the best possible security solutions (Danske Brand- og Sikringsteknisk Institut, n.d.A).

Jesper Sjørvad, Business Developer within green fuels, and Jorge Ivan Contreras-Cardeno, part of the Power-to-X team, were interviewed together, to get insight information about safety measures related to implementations of Power-to-X. Furthermore, the interviews were used to gain knowledge about safety, fire, and explosion risks related to Power-to-X, depending on which end-fuel the plant produces.

The transcription of the interview can be found in Appendix B.

5.3.4 Interviews with Regional Municipality of Bornholm

In total, four different respondents from the Regional Municipality of Bornholm were interviewed; Mads Boss, Head of Development and Planning, Svend Bilo Høegh Stigsen, Architect and Planner, Lillian Rasch Madsen, Director, and Jacob Trøst, Mayor. The respondents from the municipality were interviewed to get an understanding of the political agenda and the priorities of the development of Bornholm. The four actors were placed at different positions making them represent different interests in the municipality.

The purpose of the interviews was to investigate the opinion of the municipality regarding Power-to-X on Bornholm and to gain an idea about which opinion they experience regarding the subject. Furthermore, were the interviews used to get insights of how far the development of Power-to-X on Bornholm is at the current stage, and which size, location, capacity, consumption, production, supply, and end-product from the Power-to-X plant the municipality currently is aiming for.

The transcriptions of the four interviews can be found in Appendix C, D, F, G.

5.3.5 Interview with Bornholms Energi & Forsyning

The Vice President, Klaus Vesløv, working with Public Affairs, Communication, and ESG in Bornholms Energi & Forsyning (BEOF) was interviewed to get an understanding of the current energy system at Bornholm and how Power-to-X could be implemented. The interview contributed with knowledge about the water, electricity, and heat infrastructure on Bornholm. Furthermore, the interview contributed with knowledge about potential size, location, capacity, supply, distribution, and potential end-product productions from the Power-to-X plant.

The transcription of the interview can be found in Appendix H.

5.3.6 Interview with Port of Rønne

Besides Bendtsen from Port of Rønne, Mikkel Mortensen, Deputy Manager of Port Service in Port of Rønne was interviewed. The interview was used to get information about how they are building wind turbines at the port for offshore wind turbine projects. The port has been through an expansion, to make it possible to assemble wind turbines for the future wind turbine project at the port.

The interview with Mortensen varied from the other interviews since it was more of a dialog while we were given a tour at the port to see the large expansion and turbine components.

The summary of the interview can be found in Appendix N.

5.3.7 Interview with Baltic Energy Island

Baltic Energy Island is a business fund aiming to promote development of new energy technology solutions, green fuels, and education focused on Energy Island technologies on Bornholm. The fund functions as a hub creating interactions in the energy sector between stakeholders, innovations, and entrepreneurship with the ultimate goal of fostering local business and economic growth on Bornholm (Baltic Energy Island, n.d.).

Kim Fønss-Lundberg, Senior Business Development Manager Baltic Energy Island at Copenhagen Capacity, was interviewed to get an understanding of how the initiatives from Baltic Energy Island can reduce Bornholm's reliance on fossil fuels and promote a more sustainable energy system.

Furthermore, the purpose of the interview was to gain information about how Baltic Energy Island expect Power-to-X can be implemented on Bornholm, which actors they collaborate with, and which potentials a Power-to-X plant on Bornholm can contribute with.

The transcription of the interview can be found in Appendix I.

5.3.8 Interview with the Technical University of Denmark

João Møller, Developer for Residential College on Bornholm, the Technical University of Denmark (DTU), establishes relationships between actors and organisations on Bornholm. Furthermore, Møller focuses on the development by attracting knowledge to the island in the form of students and innovative projects. Møller was interviewed to collect information about the current relationships between companies, politicians, and citizens on Bornholm, and his take on the opinions about a potential Power-to-X plant on Bornholm.

The transcription of the interview can be found in Appendix J.

5.3.9 Interview with HØST PtX Esbjerg

HØST PtX Esbjerg is one of the leading Power-to-X projects in Denmark, using solar and wind energy for green ammonia production. The produced ammonia is stored and used for artificial fertilisers and fuels in shipping. David Dupont-Mouritzen, Project Director in HØST, was interviewed to gain insight into their experiences and learnings from the project in Esbjerg. Dupont-Mouritzen contributed with knowledge about how HØST works with the implementation of Power-to-X, regarding involvement of actors, size, consumption, capacity of the plant, water supply, production of ammonia, safety, and the impact on the environment.

The transcription of the interview can be found in Appendix K.

5.3.10 Interview with Everfuel

The purpose of interviewing Ulrik Torp Svendsen, Director of Power-to-X Development at Everfuel, was similar to interviewing Dupont-Mouritzen. The mission of Everfuel is to enable European-wide production, distribution, and refuelling of green hydrogen and offer hydrogen supply as a substitute for traditional diesel and gasoline within heavy-duty vehicles and industrial stakeholders (Everfuel, n.d.A). Everfuel currently work targeted towards establishing facilities for hydrogen production and distribution across Europe and creating key partnerships. (Everfuel, n.d.A). Interviewing Svendsen, contributed with knowledge, experiences, and learnings from their ongoing projects, mainly focusing on their current project in Fredericia.

The transcription of the interview can be found in Appendix L.

5.3.11 Reflections of the Interview Method

The majority of the interviews were made in one week on a trip to Bornholm, and all interviews were completed within a month, meaning that the previous interviews were fresh in mind when interviewing. At most of the interviews, all three group members were present, one as an interviewer, one as a notetaker, and one as a secondary interviewer. Having all group members participate, allowed time for reflection during the interviews, follow-up questions to be asked, and improved the basis of knowledge for all group members.

It is important to acknowledge that the participants represent large bureaucratic organisations, and their statements, observations, and point of views may not fully represent the official positions of their respective organisations. Including interviews with other employees could have yielded variations in the data, providing additional perspectives. However, the study encompasses thirteen representatives from different organisations and positions, which enabled different statements and diverse perspectives, resulting in robust and comprehensive empirical data.

The interviews were conducted in either Danish or English, which were decided by the primary language of the interviewees. This choice was made to minimise potential misunderstandings and limitations in expression, aiming to achieve the best possible outcomes. Quotes from the Danish interviews, used in this report, have been translated, striving for concise translations. Even though interviews have had a crucial role in data collection for this study, it is important to acknowledge that there is a risk of misinterpreting the interviewees and given statements (Brinkmann & Tanggaard, 2010).

5.4 Coding of Interviews

After conducting the interviews, they have been coded in twelve different categories. The categories are made based on the consistent topics touched upon during the interviews (Bryman, 2012), the problem statement, and research questions. The codes used to process the interviews are:

1. Water (qualities) required in a Power-to-X plant
2. Security in and around a Power-to-X plant
3. Location (potential) of the Power-to-X plant
4. Size (Ha, GW, etc) of the Power-to-X plant
5. Political opinions about Power-to-X on Bornholm
6. Citizen attitudes about Power-to-X on Bornholm
7. Possibilities / Potentials for the future (jobs, more people moving in) when implementing Power-to-X on Bornholm
8. Technical challenges and potentials (surplus heat, energy waste, etc.) when implementing Power-to-X plant on Bornholm
9. Environmental impacts from a Power-to-X plant
10. Local planning
11. Energy Island Bornholm
12. CIP/Ørsted Project

The division helped structure the gathered information, and hindered prejudices and personal understandings to impact the results (Bryman, 2012) which are used throughout the two analyses of this thesis.

5.5 Geographical Information System

This chapter outlines the methodology used to investigate the potential effects of implementing a large-scale Power-to-X plant on the local community, environment, and area of Bornholm. The study employs a mapping method to analyse suitable locations for the Power-to-X plant and assess its impact. The rationale for using mapping methods, and the mapping used in the research will be described. The method has been used to make maps of the current locations of water technologies and energy infrastructure on Bornholm. Furthermore, the method has been used to map the location of the transformer station and visualising the surrounding nature and protected areas used to recommend a location for a Power-to-X plant in the future. The maps are used in the first analysis of this report (*6. Power-to-X Infrastructure on Bornholm*).

Mapping methods provide a visual representation of spatial data, enabling researchers to analyse key regulatory areas, water sources, and infrastructure related to the Power-to-X plant (National Geographic, n.d.). By using mapping techniques, the study aims to evaluate the suitability and impact of different implementation sites on the local community, environment, and area of

Bornholm (National Geographic, n.d). Maps help visualise spatial relationships and understand the potential implications of the Power-to-X plant in a geographic manner (National Geographic, n.d).
Geographical Information System (GIS) is a tool for spatial analysis and visualisation. It integrates various data layers, such as regulatory zones, water sources, and existing infrastructure, into a comprehensive map (National Geographic, n.d). GIS software, QGIS, is used to create thematic maps displaying relevant spatial information (National Geographic, n.d). These maps provide insights into suitable areas for the Power-to-X plant and help identify potential conflicts or synergies with existing features.

5.6 Case Study

The selection of the case study research method stems from its ability to facilitate a thorough and in-depth analysis of a specific case, allowing for the potential to draw conclusions which can be generalised (Flyvbjerg, 2010). The objective is to comprehensively investigate all pertinent aspects that may influence a study or research focused on understanding the effects of Power-to-X implementation on Bornholm.

In this study, the investigation of the impact of a large-scale Power-to-X plant on Bornholm on the local community and area is approached using the theory of a critical case. Drawing from Flyvbjerg's (2010) definition of a critical, which can be defined as a case of strategic importance in relation to a general question that needs to be answered (Flyvbjerg, 2010), the large-scale Power-to-X plant at Bornholm is treated as a critical case due to its strategic importance in addressing a general question related to the impact of a Power-to-X implementation.

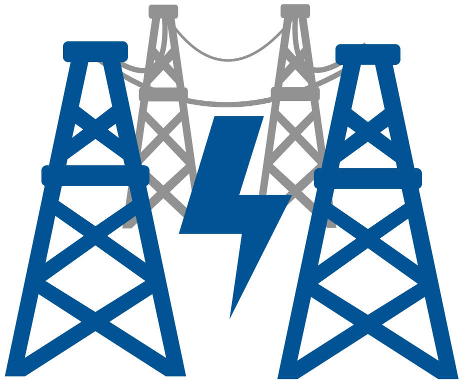
By considering the Power-to-X implementation on Bornholm as a point of departure, the study assumes that if it proves this specific case, it can also be applicable to other similar cases. This aligns with the concept of a critical case, which aims to illustrate questions critical to the general issue (Flyvbjerg, 2010). By studying the specific dynamics and outcomes of the implementation of a large-scale Power-to-X plant on Bornholm, the study seeks to provide insights that can be valuable for understanding and addressing similar cases in the future.

Implementing a large-scale Power-to-X plant can have significant implications for the local community (*7. The Interactions of Implementing Power-to-X on Bornholm*). Studying the impact of such a project on the community allows researchers to understand the social, economic, and cultural factors that influence community acceptance, engagement, and participation. This case study can provide insights into the strategies and mechanisms needed to foster community support and address any concerns or challenges that may arise.

Case study is in this research used to provide insights into the environmental benefits and trade-offs associated with Power-to-X plants, identify ways to mitigate any negative social or cultural effects, and enhance the positive aspects of the project.

By using the theory of a critical case, this study acknowledges the importance of examining the large-scale Power-to-X plant on Bornholm as a strategic and illustrative case that can contribute to the broader understanding of the impact of large-scale Power-to-X projects on local communities and areas. The findings from this critical case study can help inform decision-making, policy development, and the sustainable implementation of Power-to-X technologies in various contexts.

6 Power-to-X Infrastructure on Bornholm



Within this report, environmental and safety challenges regarding the implementation of Power-to-X have been pointed out as a problematic knowledge gap that needs to be investigated further to understand the impact a Power-to-X plant has on the surrounding area. This analysis will elaborate upon environmental and safety challenges of implementing Power-to-X in the local context of Bornholm, by answering the following question: *How will a potential Power-to-X plant impact the energy system and the local area's environment, safety and water supply?*

However, to answer the above question, it is essential to understand how the energy system, water infrastructure and environment at Bornholm is at the current stage. The first part of this analysis will therefore investigate the current infrastructure at Bornholm related to a potential Power-to-X plant, including the current energy system and water infrastructure. Hereafter will the impacts of the implementation of the Energy Island Bornholm and the related transformer station be analysed.
After having developed an understanding of the current stage on Bornholm, the analysis digs into which impacts the Power-to-X plant will have on the local community. The plant has the potential to contribute with surplus heat and production of either hydrogen, ammonia, or methanol. Although the implementation of a Power-to-X plant has several unknowns, several benefits appear which will be elaborated upon.

Furthermore, the plant is expected to impact the surrounding environment, which also is investigated within this analysis regarding safety measures, potential risks, air, and noise pollution.

The last part of the analysis sums up the identified potentials, contributions, and challenges of implementing Power-to-X at Bornholm, to develop recommendations of a suitable location for a Power-to-X plant on Bornholm as well as what end-product is most beneficial for the island to produce.

6.1 Current Infrastructure on Bornholm

To understand the impact of a potential Power-to-X plant on Bornholm, the current infrastructure on Bornholm related for Power-to-X implementation and involved actors are investigated. The chapter identifies how the current energy system works, which resources and technologies Bornholm uses, and how the energy is distributed between consumers. Furthermore, the current water supply, distribution, use, and wastewater are identified to understand the current situation at Bornholm. The different technologies within the current energy infrastructure are visualised in Figure 3.

Currently, all electricity, heat, water, and wastewater are managed and distributed around Bornholm by the multi-utility company Bornholms Energi & Forsyning (BEOF) (Bornholms Energi og Forsyning, n.d.A; Bornholms

Energi og Forsyning, n.d.B). BEOF is in principle owned by the citizens of Bornholm through the Regional Municipality of Bornholm and is one of the biggest supply companies on the island, meaning they have large impact on the security of supply, welfare, growth, development, and the green transition (Bornholms Energi og Forsyning, n.d.B). One of their main focuses is to create an intelligent green transition and growth through efficient supply. BEOF's role as a multi-utility company also results in a large responsibility in Bornholm's target of achieving net zero in 2040 and a sustainable society with renewable energy (Bornholms Energi og Forsyning, n.d.B).

6.1.1 Energy System

To ensure a common understanding of the energy system at Bornholm, the purpose of this chapter is to present how the energy system currently distributes energy sources. The energy system of Bornholm is visualised in Figure 4.

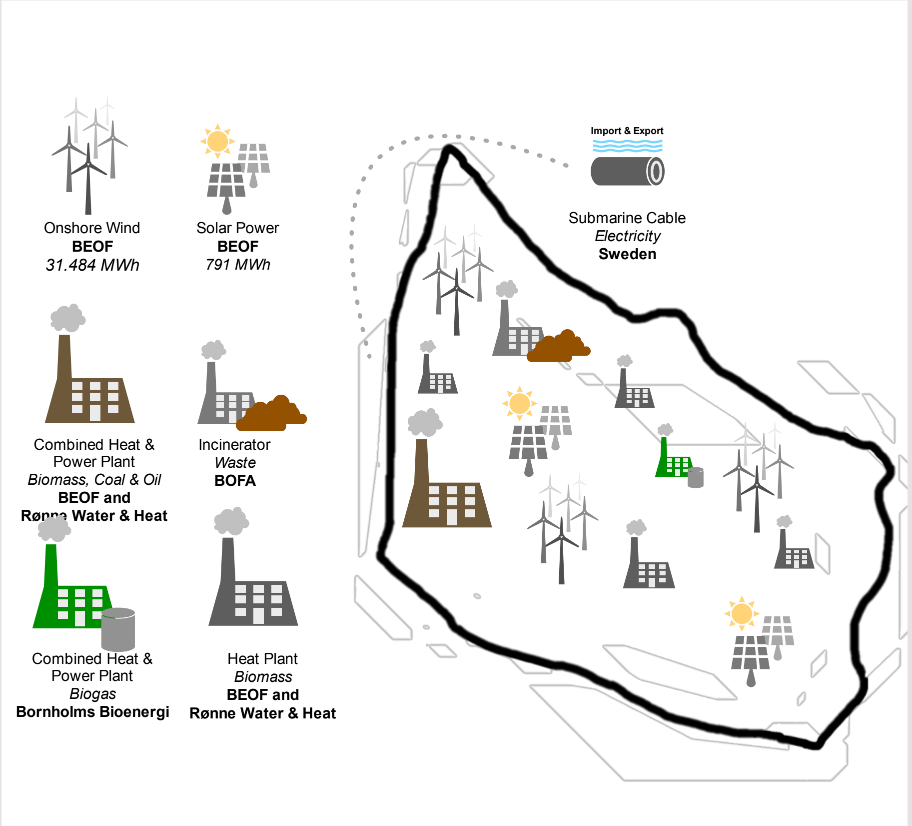


Figure 3 Illustration of Bornholm's energy suppliers. Own Production, made in Pages (Energistyrelsen, 2019).

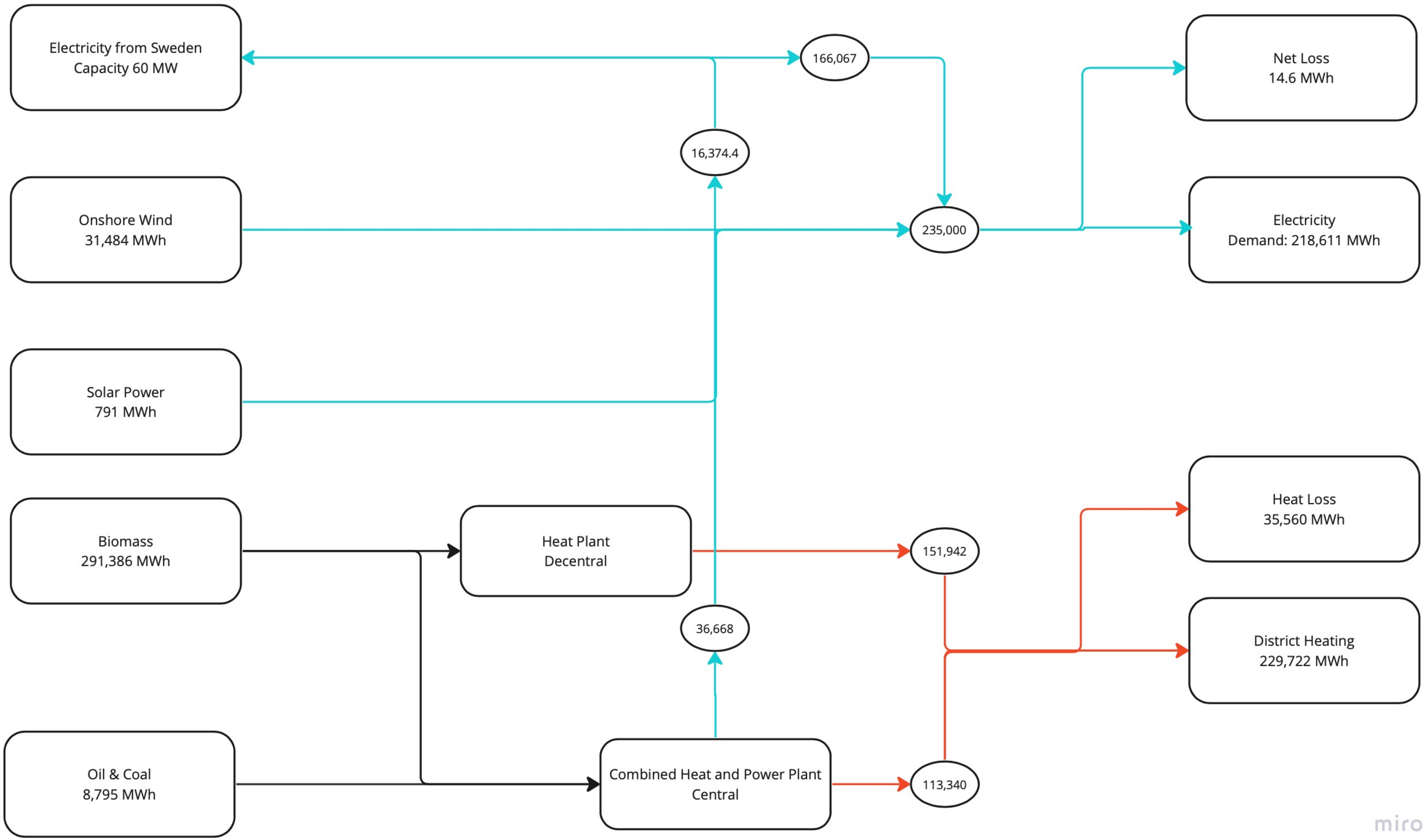


Figure 4 Input-output model of Bornholm's current energy system. Own production, made in Miro (Kristensen, 2022; Energistyrelsen, 2019; Bornholms Energi og Forsyning, n.d.E; Rønne Varme A/S, 2019; Klima-, Energi- og Forsyningsministeriet, n.d.)

6.1.1.1 Electricity on Bornholm

Currently, Bornholm is dependent on electricity from local wind turbines, solar power, a combined heat, and power plant (CHP) fuelled by biomass, oil, and coal, and electricity from Sweden (Bornholms Energi og Forsyning, n.d.B) received through three submarine cables (Figure 6; Energinet, 2022B). The electricity input and output of the energy system is visualised with blue lines in Figure 4.

The submarine cables to Sweden create a connection from Bornholm's electricity grid to the Nordic energy system securing Bornholm is connected to power when Bornholm is not able to produce enough electricity to meet the electricity demand (Bornholms Energi og Forsyning, n.d.B). At Bornholm, BEOF is responsible for distributing the electricity to the grid, which is owned by the Energy Group Ewii, and the grid is referred to as TREFOR EL-NET Øst (Bornholms Energi og Forsyning, n.d.B; EWII, 2021).

Even though BEOF is responsible for the security of supply at Bornholm, they work together with Energinet, responsible for the security of supply in Denmark and ensure equal market access to the electricity and gas grid (Energinet, n.d.C), hereby also on Bornholm. However, the collaboration with Energinet means that in certain cases BEOF has to contribute to producing electricity to the Danish and Nordic electricity grid for the rest of Denmark and other Nordic countries in cases of power shortage (Bornholms Energi og Forsyning, n.d.B). When BEOF is producing electricity for the Danish and Nordic electricity grid, biomass and fossil fuels are used in the combined heat and power plant. In 2021 it resulted in higher use of fossil fuels than anticipated due to the energy crisis (Bornholms Energi og Forsyning, n.d.B). The use of fossil fuels for electricity production was therefore higher in 2021 compared to previous years (Bornholms Energi og Forsyning, n.d.B). In 2021, 7,688 MWh of electricity was produced by coal and oil from BEOF's combined heat and power plant, which is 11.7% of the total electricity production (Bornholms Energi og Forsyning, n.d.B).

6.1.1.1.1 Combined Heat and Power

Most of the electricity on Bornholm is produced from the combined heat and power plant located in Port of Rønne and owned by BEOF. In 2021 56.7% of the electricity produced on Bornholm was produced by the plant. From this, 45% stemmed from biomass (mainly wood chips) and 11.7% stemmed from oil and coal (Bornholms Energi og Forsyning, n.d.B).
BEOF expects the use of wood chips for electricity production in the combined heat and power plant to decrease, since they account biomass as a transitional fuel, which BEOF predict to be substituted by new technologies in the future, for example, developed as part of the Energy Island Bornholm (Bornholms Energi og Forsyning, n.d.B).

The combined heat and power plant also delivers heat for the district heating network at Bornholm, which will be elaborated upon in Chapter *6.1.1.2.1 District Heating*.

6.1.1.1.2 Renewable Energy - Wind Turbines, Solar Power, Biogas, and Biomass

As mentioned, the combined heat and power plant in Rønne, among other fuels, uses biomass, and biomass is also used by other decentralised heat plants on Bornholm to supply district heating (*6.1.1.2.2 District Heating*). BEOF is the largest customer of biomass on Bornholm and considers biomass as an important tool to reduce the use of fossil fuels, but the supply of biomass in the energy system is seen as a temporary step to become CO_2-neutral. Biomass consumption at Bornholm contains straw (22.4%), wood chips (77.2%), and wood pellets (0.3%), and 86% of the used biomass is locally produced (Bornholms Energi og Forsyning, n.d.B). As illustrated in Figure 5, biomass on Bornholm was used to generate 29,564 MWh of electricity and 282,563 MWh of heat in district heating (Bornholms Energi og Forsyning, n.d.B), which is enough energy to supply 6,570 households annually (two adults and two kids) with electricity (Bornholms Energi og Forsyning, n.d.D; Bolius, 2023) and 15,611 households (130 m^2) with heat through district heating in 2021 (Bolius, 2023).

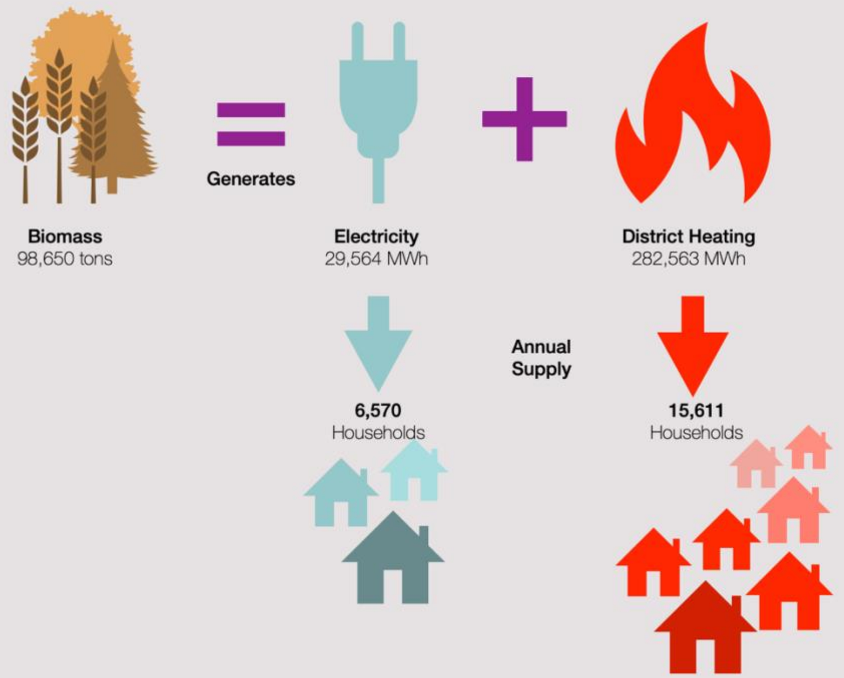


Figure 5 Illustration of annual electricity and heat production in relation to the number of households it can supply. Own production, made in Pages (Bornholms Energi og Forsyning, n.d.B; Bolius, 2023).

To secure only sustainable biomass is used, the target from BEOF is to achieve 98% use of sustainable certified wood chips and pellets (Bornholms Energi og Forsyning, n.d.B).

Bornholm also has a biogas plant, operated by Bornholms Bioenergi, with a capacity of 135,000 tons/year (Bornholms Landbrug & Fødevarer, 2023), located close to Aakirkeby. The plant generates both electricity and heat for district heating using animal manure and slaughterhouse waste from local farmers as biomass sources (Bornholms Landbrug & Fødevarer, 2023). The main purpose of installing this plant in 2007 was to improve the environmental consequences of the use of manure (Bornholms Landbrug & Fødevarer, 2023). In March 2023, a new plan for biogas on Bornholm was published with a vision of a significant increase in biogas production on the island, with a capacity up to 600,000 tons/year. The plan is built upon a target of using local biomass resources to produce biogas and green fuels (Bornholms Landbrug & Fødevarer, 2023).

Bornholm also produces electricity from locally installed onshore wind turbines and solar power. In total, Bornholm produced 31.484 MWh of electricity from onshore wind and 791 MWh of electricity from solar power in 2019 which is directly used in the electricity grid (Figure 4; Energistyrelsen, 2019). The total wind and solar power accounted for 85.4% of Bornholm's electricity production in 2019 (Energistyrelsen, 2019).

6.1.1.1.3 Electricity Emergency Supply

When the renewably produced energy from Bornholm is not able to cover the demand on the island, submarine cables from Sweden are used to cover the demand. In total the three submarine cables from Sweden have a capacity of 60 MW and are connected to Hasle on Bornholm with Borreby in Sweden, see Figure 6 (Klima-, Energi- og Forsyningsministeriet, n.d.; Energinet, 2023). Multiple times, Bornholm has been affected by failed power supply caused by damage from ships sailing into the submarine cable, leaving the citizens of Bornholm in the dark until the local power supply system is up and running. When the connection to Sweden fails, Bornholm has an emergency power plant located in Port of Rønne enabling a full power supply within six hours. The emergency power plant runs on oil and coal, meaning every time Bornholm turns on the emergency power plant it has a negative impact on the CO_2-emissions of Bornholm (Bornholms Energi og Forsyning, n.d.B). Therefore, it is crucial for Bornholm to acquire an energy source that makes them independent of the electricity supplied by Sweden, thus obviating the need to activate the emergency power facility which potentially could be Energy Island Bornholm (Appendix F; Appendix H).

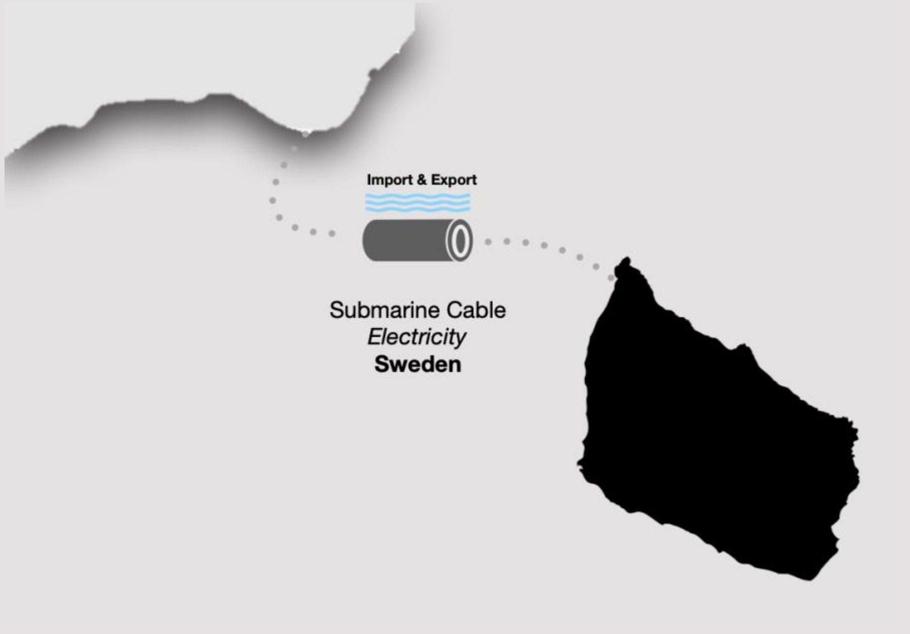


Figure 6 Illustration of the submarine cables to Sweden. Own production, made in Pages (Energinet, 2023).

6.1.1.2 Heating on Bornholm

The heat infrastructure at Bornholm is visualised in Figure 4 with red lines and is currently distributed between district heating and individual heating.

6.1.1.2.1 District Heating

Currently 13,351 households, out of 20,320 households, on Bornholm are heated by district heating (Danmarks Statistik, 2023A; Danmarks Statistik, 2023B), whereof BEOF distributes district heating to more than 6,500 customers within the larger cities of Bornholm. They also supply district heating for Rønne Vand og Varme, responsible for the district heating network in Rønne and supply drinking water to parts of Bornholm (Bornholms Energi og Forsyning, n.d.B). The district heating network of Bornholm is visualised in Figure 7.

The district heating plants on Bornholm run by biomass, and as previously mentioned in Chapter *6.1.1.1.2 Renewable Energy - Wind Turbines, Solar Power, Biogas, and Biomass*, Bornholm is aware of using sustainable, renewable, and certified biomass for energy production (Bornholms Energi og Forsyning, n.d.B). Thereby, the district heating grid is almost 100% powered by renewable energy besides the heat from the power plants that occasionally use oil and coal (Bornholms Energi og Forsyning, n.d.B).

Rønne Vand og Varme and their district heating grid in Rønne are supplied with heat from the combined heat and power plant located in Port of Rønne, which also delivers electricity to the island (*6.1.1.1.1 Combined Heat and Power*; Bornholms Energi og Forsyning, n.d.B) and by heat from BOFA's incinerator (BOFA, n.d.). BOFA is the waste treatment company at Bornholm (BOFA, n.d.). The combined heat and power plant is fired with biomass and in 2021 55,762 tons/year of wood chips were used in the plant (Bornholms Energi og Forsyning, n.d., b). BOFA's incinerator receives waste suitable for incineration from the island, which in total is around 20,000 tons/year (BOFA, n.d.). The heat from BOFA’s incinerator currently delivers 25% of the yearly heat consumption in Rønne (BOFA, n.d.). However, BOFA's incinerator is expected to close in 2032 as part of BOFA’s zero-waste project (BOFA, 2019). The vision for BOFA in 2032 is to treat all waste as a resource by recycling, meaning Bornholm will not have any waste and the incinerator will close (BOFA, 2019), resulting in a need for the district heating to be supplied in other ways. Closing the incinerator is not only a benefit for the island, since it will mean a source for carbon is removed, which has the potential to be used in Power-to-Methanol production in the future on Bornholm. How Power-to-Methanol production proceeds is elaborated in Chapter *6.3.2.2.3 Power-to-Methanol*.

Besides the district heating in Rønne, Bornholm has four decentralised district heating plants fired by wood chips, straw, and slurry (Figure 7) and three reserve district heating plants fired by wood pellets and straw (Bornholms Energi og Forsyning, n.d.B).

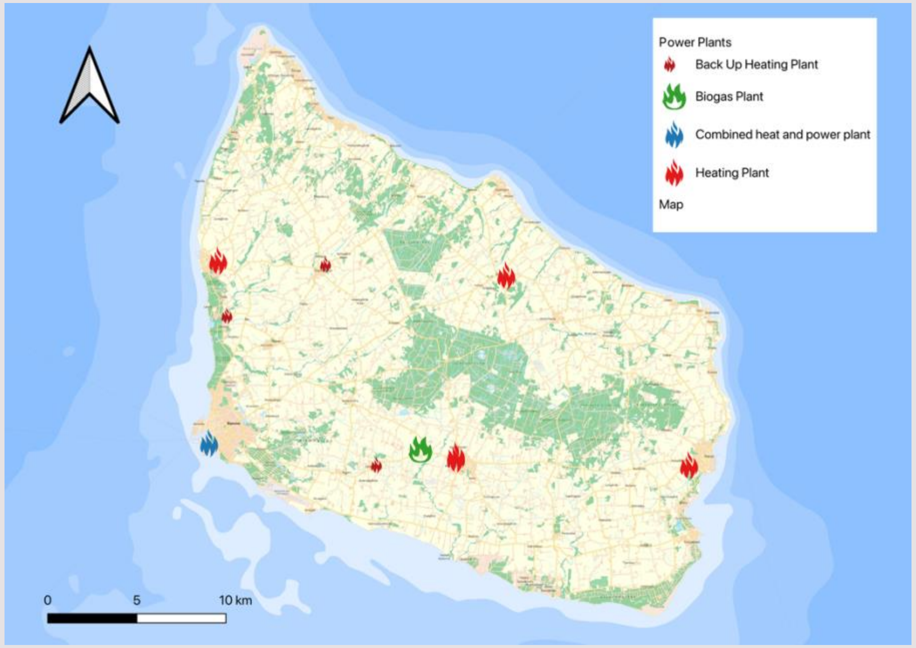


Figure 7 Map showing where plants producing heat are located on Bornholm. Own production, made in QGIS (Appendix R).

The overall heat loss in the district heating network on Bornholm is relatively high, due to long distances. The long distances make the district heating network more vulnerable to impacts from the weather, leaks, and breakdowns. In total in 2021, the heat loss in the district heating network was 25.3% from decentralised district heating plants (Bornholms Energi og Forsyning, n.d.B).

6.1.1.2.2 Individual Heating

Individual heating is mainly used in smaller towns and rural areas on Bornholm. Typically, oil boilers, individual heat pumps, or biomass boilers are used for individual heating (Energistyrelsen, n.d.C).

According to Danmarks Statistik, 2779 households are still heated by oil boilers on Bornholm, which corresponds to 13.7% of the households (Danmarks Statistik, 2023A). However, Bornholm is in the process of phasing out all oil boilers and have stated in their energy strategy [Danish: Bornholms Energistrategi 2040], they are working towards phasing out all oil boilers by 2030 (Bornholms Regionskommune, n.d.C).

The goal is to replace all the oil boilers with green solutions, and either install individual heat pumps, individual biomass boilers, or connect the buildings to the district heating network (Bornholms Regionskommune, n.d.C). Currently, 11.9% of the households on Bornholm, corresponding to 2411 households, are heated by individual heat pumps (Danmarks Statistik, 2023A).

6.1.2 Water Infrastructure

Since Power-to-X technology is water consuming (*1.2.1.2 Clean Water is a Scarce Resource*), the water infrastructure at Bornholm is presented and analysed in the following chapters by investigating the current water supply, distribution, use, and wastewater. The current water cycle on Bornholm is presented in Figure 9.

6.1.2.1 Water Supply

Bornholm has 18 water plants located around the island, supplying the citizens with drinking water (Bornholms Regionskommune, n.d.A, Figure 10). The water plants deliver water to 93% of the citizens, while the last 7% have individual drinking water plants (Bornholms Regionskommune, n.d.A). From Figure 9, it appears that the annual water supply has been around 3.5 million m^3 the last couple of years (Bornholms Regionskommune, n.d.A). However, this is far from the total available water resources being around 5.7 million m^3 (Figure 9; Bornholms Regionskommune, n.d.A). The difference is illustrated in Figure 8.

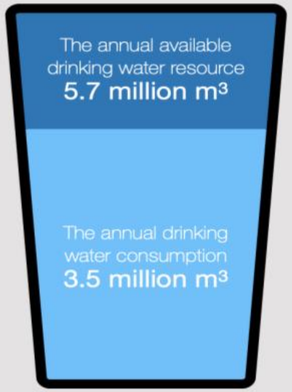


Figure 8 Total available drinking water resources in relation to the annual drinking water consumption. Own production, made in Pages (Bornholms Regionskommune, n.d.A).

Four of the water plants on Bornholm are driven by BEOF, who in total supply 40% of the citizens on Bornholm with drinking water (Bornholms Regionskommune, n.d.A, Bornholms Energi og Forsyning n.d.B). Furthermore, the four water plants supply some of the privately owned water plants (Bornholms Energi og Forsyning, n.d.A). The three water plants in Rønne are owned by the private company Rønne Vand og Varme A/S and are responsible for supplying Rønne with drinking water (Bornholms Regionskommune, n.d.A). The last eleven water plants are owned by private companies (Bornholms Regionskommune, n.d.A).

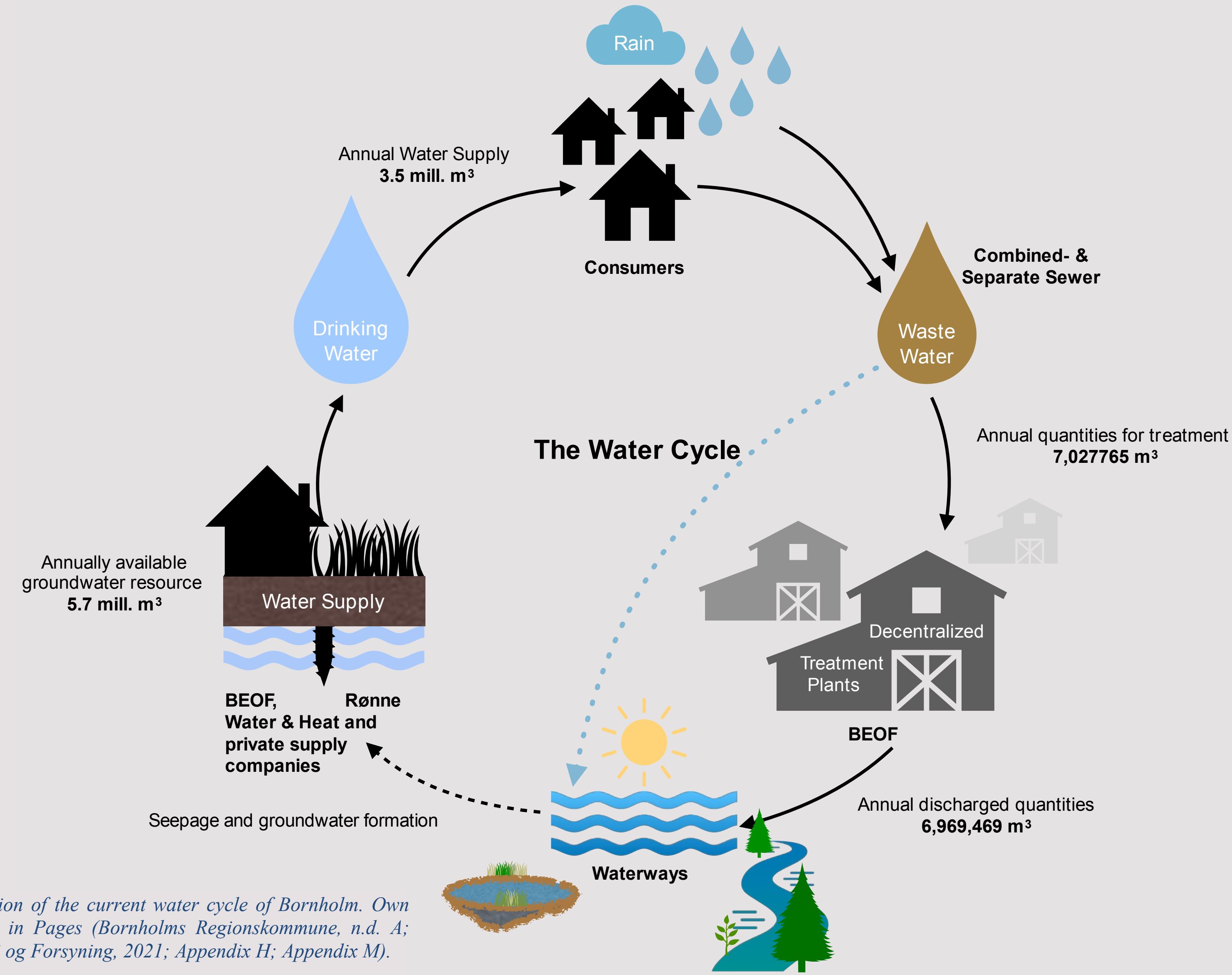


Figure 9 Illustration of the current water cycle of Bornholm. Own production, made in Pages (Bornholms Regionskommune, n.d. A; Bornholms Energi og Forsyning, 2021; Appendix H; Appendix M).

Figure 10 Map showing the location of wastewater treatment plants and water plants. Own production, made in QGIS (Appendix Q).

6.1.2.2 Wastewater

The wastewater on Bornholm is managed by BEOF who has seven wastewater treatment plants located around the island (Figure 10; Bornholms Energi og Forsyning, n.d.C; Bornholms Energi og Forsyning, n.d.B). BEOF is responsible for the wastewater in sewered areas and responsible for emptying schemes in rural areas of the island (Bornholms Energi og Forsyning, n.d.C).

The wastewater is treated through several steps in the treatment plants to become purified and when it fulfils the requirements, decided by the Danish Environmental Protection Agency and the municipality, the treated water is discharged to the sea (Vandetsvej, n.d.). However, within the process of treating the wastewater large amounts of compostable surplus product is removed from the water as part of the purification. This surplus product is also treated, whereafter it either can be used as incinerator or fertiliser in agriculture (Vandetsvej, n.d.).

The Regional Municipality of Bornholm aims to purify the wastewater as much as it is technically and economically possible. However, this ambition is constantly challenged by different factors; the increased amounts of wastewater on Bornholm, more extreme weather with large amounts of rain, increase in social activities, and wastewater treatment from docked ships (Bornholms Energi og Forsyning, n.d.B).

To accommodate the Regional Municipality of Bornholm's policy of managing wastewater optimally, the treatment plant in Port of Rønne is certified with ISO14001 (Environmental management). BEOF operates according to the same principles for their six treatment plants around Bornholm (Bornholms Energi og Forsyning, n.d.B). In total, the treatment plants purify around 7.0 million m^3 of wastewater each year (Figure 9; Bornholms Energi og Forsyning, 2021).

Currently, the wastewater treatment plants on Bornholm are decentralised, see Figure 10. However, Klaus Vesløv, VP, Public Affairs, Communication, and ESG at BEOF, explains BEOF is investigating the possibility of centralising the treatment plants, in particular if the treatment plant is placed near a potential Power-to-X plant (Appendix H).

6.1.3 Summary

Based on the above, it appears Bornholm's current energy and water infrastructure involve stakeholders, and energy and water technologies. Even though some of the technologies combine different functions, such as the combined heat and power plant delivering heat and electricity for the island, most of the current infrastructure and different technologies are decentralised as visualised in Figure 11. Furthermore, Bornholm still relies on fossil fuels (oil, diesel, and coal) and biomass but has a goal of phasing it out of the energy system before 2040 (Bornholms Regionskommune, n.d.C).

For Bornholm to achieve a sustainable energy and water infrastructure, it is essential to consider how they can implement more synergies and sector couplings in their energy system. Therefore, the following chapter will investigate the potential energy system transition on Bornholm.

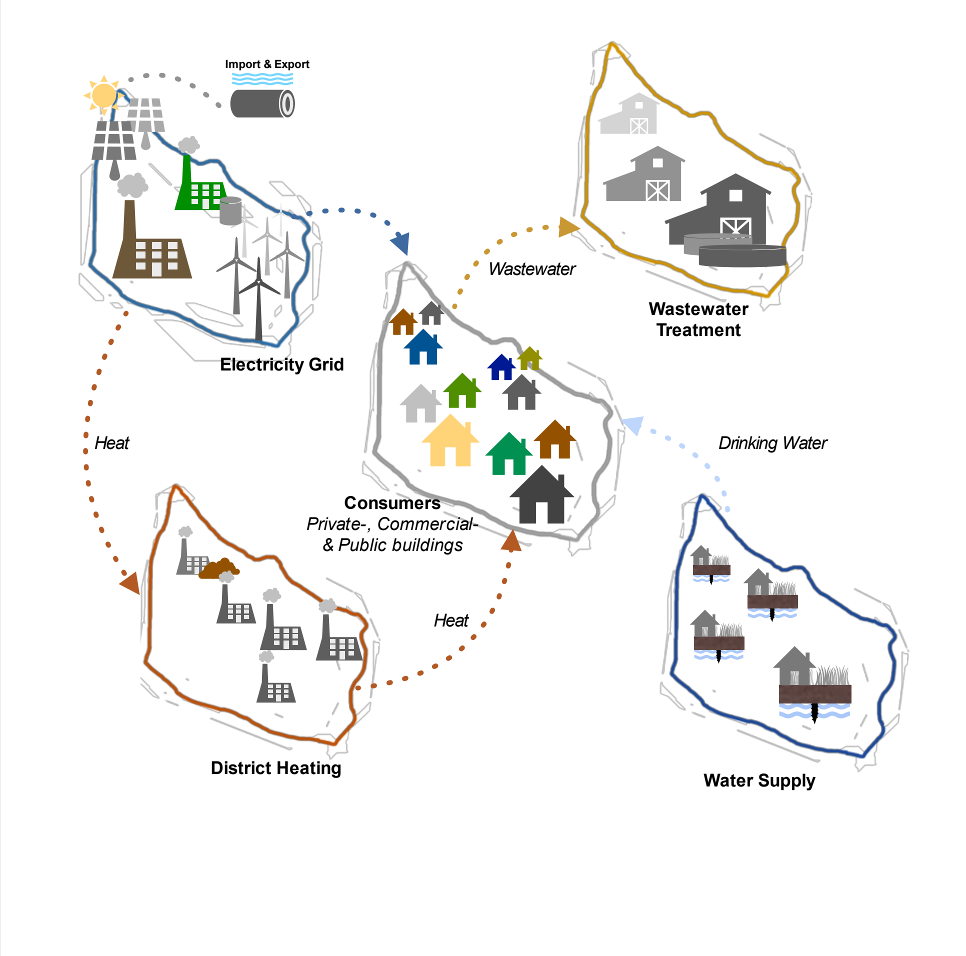


Figure 11 Illustration of current infrastructure systems and consumers on Bornholm showing the interactions between the technologies. Own production, made in Pages.

6.2 Future Energy System Transition on Bornholm

As mentioned in the Chapter *1.3 Bornholm: An Energy Island in the Baltic Sea*, it has been decided to build an offshore wind turbine farm connected to a transformer plant on Bornholm, with a production of 3.2 GW of electricity per year from 2030. The offshore wind turbine will be installed south and southwest of Bornholm. The closest wind turbines to Bornholm will be placed 15 km from the shore and the wind turbines potentially could be over 350 metres tall, meaning the wind turbines will be visible from Bornholm (Bornholms Regionskommune, n.d.B).

Moreover, the developer will have the opportunity to overplant and thereby install a higher capacity wind energy of a maximum of 3.8 GW. Whereby, the 3.2 GW are planned to be connected to the grid, up to 0.6 GW is for overplanting and will not be connected to the grid (*1.3 Bornholm: An Energy Island in the Baltic Sea*) (Energistyrelsen, 2022A), meaning it could potentially be used for Power-to-X. The implementation of Energy Island Bornholm can be seen as a pioneer project since it varies from previous offshore wind turbine farms being significantly larger in scale compared to the 15 existing farms in Denmark that have a total capacity of around 2.298 GW (Energistyrelsen, n.d.B).

Such an implementation takes up space affecting the island. In Figure 12 the energy technologies are visualised after Energy Island Bornholm is implemented.

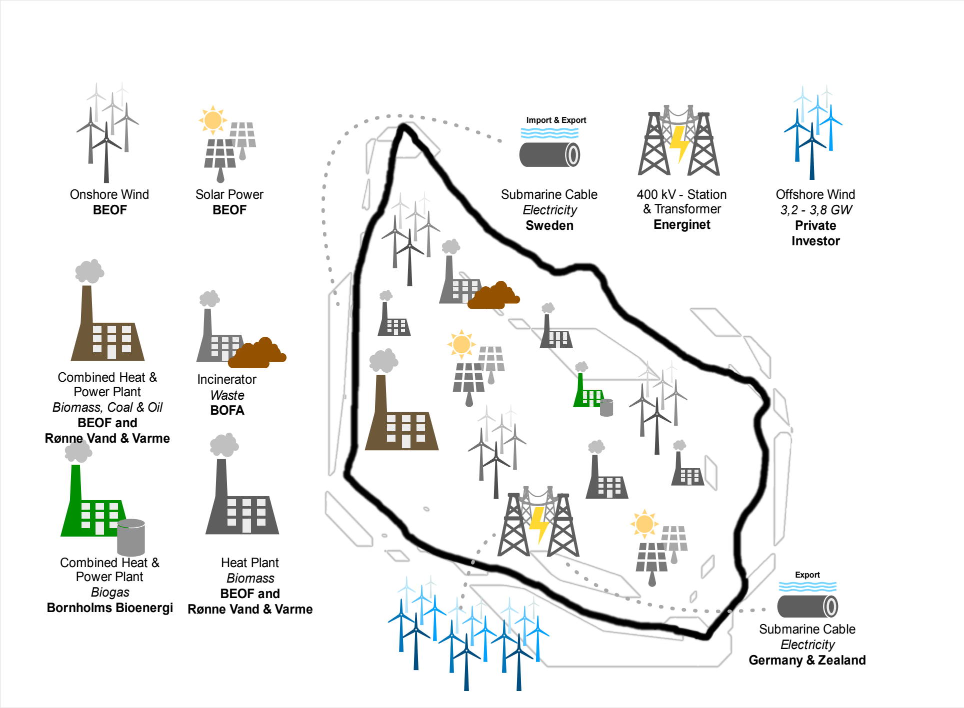


Figure 12 Illustration of energy technologies after Energy Island Bornholm is implemented. Own production, made in Pages (Energistyrelsen, 2022A; Energinet, n.d.A).

The implementation of the energy island will require a transformer station on Bornholm to transform the energy before being sent to Zealand and Germany. This station will affect the surrounding area. It is the Danish National transmission operator, Energinet, that is in charge of designing and placing the transformer station for Energy Island Bornholm (Energinet, n.d.A). The decision-making and designing of the transformer station have been going on for a while (Energinet, n.d.A) and the area can be seen in Figure 13. The technical part of the transformer station takes up 52 hectares but in total with roads, planting, and other matters it will take up around 107 hectares (Energinet, n.d.A). Energinet is aware that the transformer station will affect the area since the construction is large and bulky and have, therefore, been working on including the citizens in the planning to minimise the negative impacts on the area (Energinet, n.d.A). However, it cannot be avoided that such a large construction will mean that some home- and landowners will lose their homes, either by agreeing to sell or by expropriation by the government. Nearby homes will also be affected by the transformer station, since they potentially also will experience the visual and environmental impacts and a decrease in their house and land value (Energiø Bornholm, 2023), which also will be elaborated further in Chapter *7. The Interactions of Implementing Power-to-X on Bornholm*.

Figure 13 Map showing planned location for the transformer station of Energy Island Bornholm. The transformer station takes up 52 hectares, but including roads, planting, etc. it takes up 107 hectares. Own Production. Made in QGIS (Hansen, 2023B).

At the moment, the government's focus is to increase the capacity of offshore wind energy in the Baltic Sea (Hansen, 2023C) speaking in favour of a future with Power-to-X on Bornholm. Investors have also seen the potential of installing offshore wind turbines by Bornholm as the renewable energy investors Copenhagen Infrastructure Partners (CIP) and Ørsted are together applying for two open-door wind turbine projects east of Bornholm with a total capacity of 3 GW. The projects are respectively called Bornholm Bassin Øst and Bornholm Bassin Syd, both with a capacity of 1.5 GW. Copenhagen Infrastructure Partners has described potential cable run in their application and does see potential in connecting the same area as the transformer station for Energy Island Bornholm is placed (Copenhagen Infrastructure Partners, 2022A; Copenhagen Infrastructure Partners, 2022B). The energy from these wind turbine farms could be directly connected to an electrolyser and solely be used for Power-to-X (Ørsted, 2022), as illustrated on Figure 14.

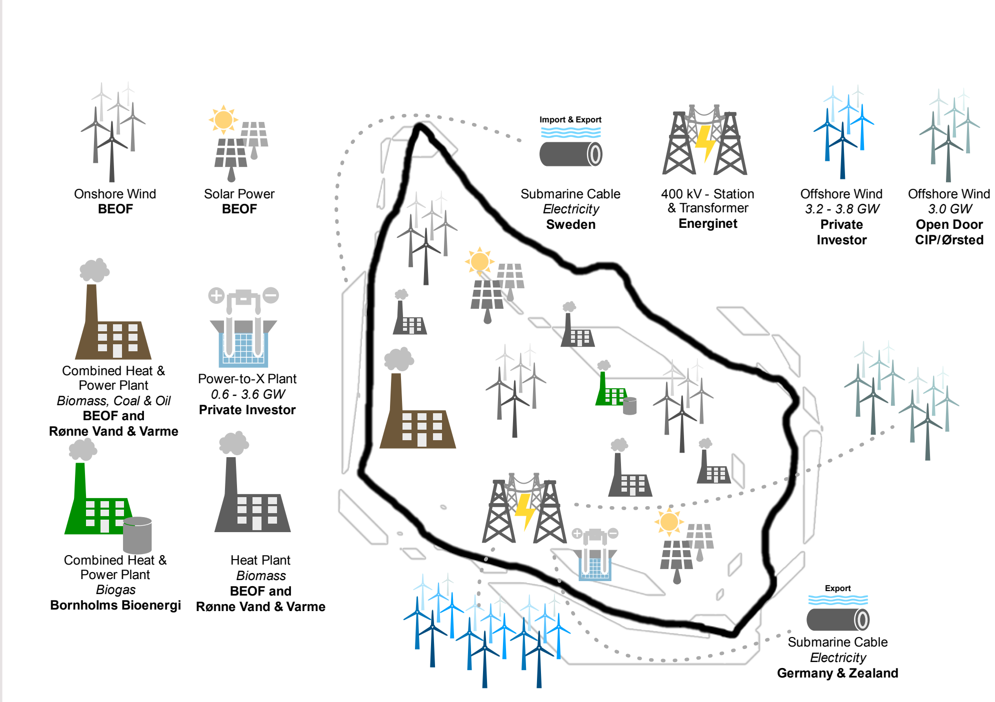


Figure 14 Illustration of energy technologies after implementation of Energy Island Bornholm and if the open door wind project and Power-to-X becomes a reality on Bornholm. Own production, made in Pages (Energistyrelsen, 2022A; Energinet, n.d.A; Copenhagen Infrastructure Partners, 2022A; Copenhagen Infrastructure Partners, 2022B).

From this, there can be identified several scenarios of Power-to-X on Bornholm. If the developer of Energy Island Bornholm Offshore Wind Farm instals the full capacity and thereby overplants 0.6 GW, this could be used for Power-to-X. If both open-door projects are implemented, the capacity for Power-to-X could be up to 3.6 GW and if the energy island is not overplanted but the open-door project is implemented the capacity will be 3 GW. Which capacity is implemented on Bornholm will influence how it will affect the island since it comes with pros and cons. The capacity of the plant will also impact the physical size of the plant, however, when talking to the different respondents from Bornholm, they estimate a maximum size of 90 hectares for the plant (Appendix D, F, M, I). It is therefore assumed in this report that the size of the Power-to-X plant will be 90 hectares.

6.2.1 Estimated Production of Power-to-X

If a Power-to-X plant is to be implemented on Bornholm, it has the possibility to produce different types of end-products (*1.2 The Concept of Power-to-X*). On Bornholm three different types of products have been discussed, namely: hydrogen, methanol, and ammonia (Appendix A, B, C, D, F, G, H, I, K, L, M, N).

Power-to-Ammonia involves electrolysis, to convert electricity and water into hydrogen. The hydrogen gas is then combined with nitrogen gas (N2) using the Haber-Bosch process (Ikäheimo et. al., 2018). The Haber-Bosch process typically involves the use of a catalyst, high pressure, and high temperature to convert the hydrogen and nitrogen gases into ammonia (NH_3) (Ikäheimo et. al., 2018). When producing ammonia, three different compounds are needed, namely electricity, water, and ambient air (polluted air containing Nitrogen and Oxygen) (Smith & Klosek, 2000). Electricity and water are used in the electrolysis to produce hydrogen. Ambient air and electricity are used in an air separator, separating nitrogen from the air (Smith & Klosek, 2000). The Power-to-Ammonia process is illustrated in Figure 15.

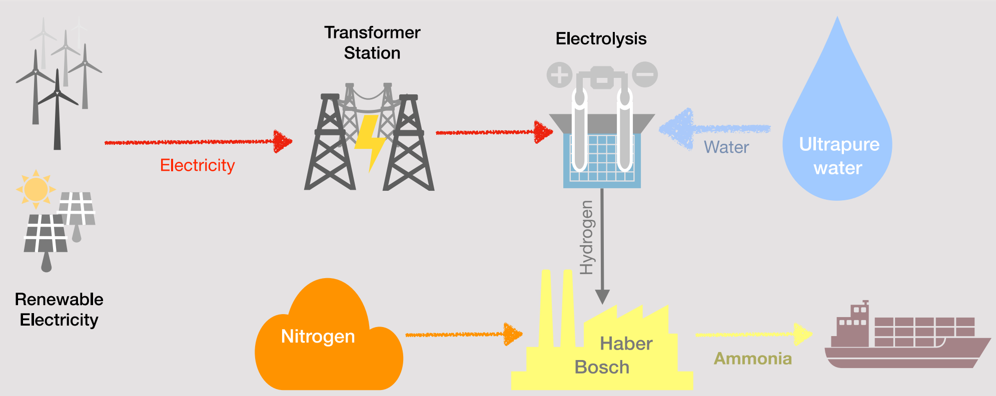


Figure 15 Illustration of the Haber-Bosch Power-to-Ammonia process. Own production, made in Pages (Green Ammonia Working Group, n.d.).

Methanol is produced by converting renewable electricity into hydrogen gas through electrolysis (Danish Ministry of Climate, Energy, and Utilities, 2021C). Hereafter, hydrogen is mixed with carbon dioxide, which can be captured from industrial processes or directly from the air, and passed over a catalyst at high pressure and temperature. This causes a chemical reaction that produces methanol and water vapour (Danish Ministry of Climate, Energy, and Utilities, 2021C). The Power-to-Methanol process is illustrated in Figure 16.

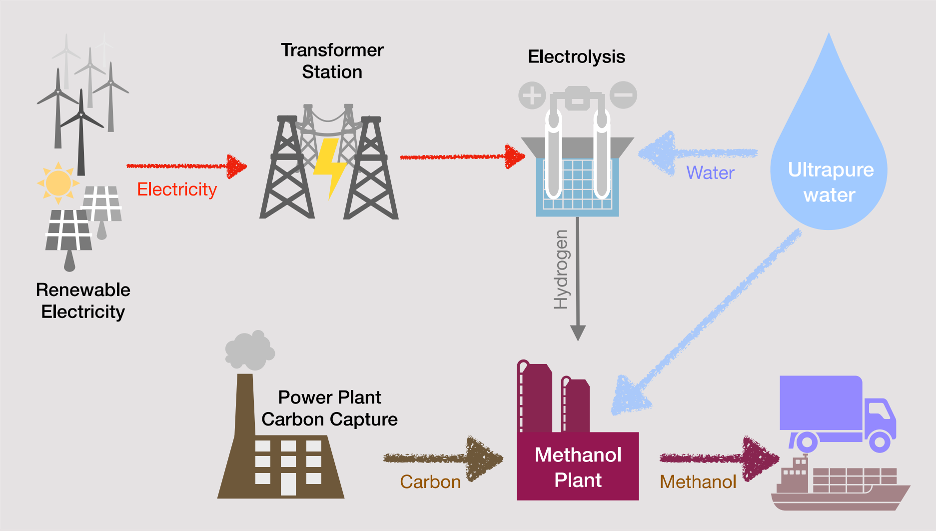


Figure 16 Illustration of the Power-to-Methanol process. Own production, made in Pages (A.spire, n.d.).

The amount of product produced can vary based on the efficiency of the Power-to-X system. Additionally, the choice of product produced also affects the amount produced per unit of renewable electricity. For example, producing methanol through Power-to-X is less efficient than producing hydrogen or ammonia, so a smaller amount of methanol would be produced per unit of renewable electricity (HØST, n.d.; Haldor Topsøe, n.d.; Danish Energy Agency, 2021).

These are important considerations when having to decide what fuel the Power-to-X plant should produce. The energy efficiency varies depending on whether it is hydrogen, methanol, or ammonia. Table 1 shows the energy efficiencies and the amount of energy generated for hydrogen, methanol, and ammonia. Power-to-Hydrogen is the most energy efficient technology with an efficiency of 66.5% (Danish Energy Agency, 2021), however challenging to transport (Bellotti et al., 2022). On Bornholm, it is considered to either produce liquid methanol or ammonia if a Power-to-X plant is implemented. By comparing them, Power-to-Methanol is the most energy efficient technology with an efficiency of 52.7%, whereas the efficiency for Power-to-Ammonia is 51.4% (Bellotti et al., 2022). Also, when investigating the fuels density, methanol scores higher on volumetric energy density being 15.8 MJ/L whereas ammonia has a volumetric energy density of 12.7 MJ/L (Aziz et al., 2022). Despite methanol being the most efficient, ammonia is seen as the solution long term as it does not require a carbon source to be produced and does not emit CO_2 when combusted. This is further elaborated upon in Chapter *8. Discussion*.

Table 1 presents estimated values for the production of hydrogen, methanol, and ammonia, showing the quantity produced by Power-to-X plants with capacities of 0.6 GW, 3.0 GW, and 3.6 GW respectively.

Table 1 *Annual Production of Hydrogen, Methanol, and Ammonia from Power-to-X Technology.*

Scenarios	Capacity of Wind Turbines	Annual Electricity Energy Consumption	Annual Hydrogen production Efficiency 66.5 %	Annual Methanol Production Efficiency 52.7 %	Annual Ammonia production Efficiency 51.4 %
Overplanting (Energy Island)	600 MW	3 TWh	2 TWh	1.6 TWh	1.5 TWh
Open Door (CIP/ Ørsted)	3.0 GW	15 TWh	10 TWh	8 TWh	7.7 TWh
Overplanting + Open Door	3.6 GW	18 TWh	12 TWh	9.5 TWh	9.3 TWh

Table 1 displays the production capacities of different Power-to-X plants in terms of hydrogen, methanol, and ammonia. The values represent the amount of fuel each plant can produce per year in TWh (Energistyrelsen, 2023; Danish Energy Agency, 2021; Bellotti e t al., 2022). Calculations, estimates and assumptions can be found in Appendix P.

In Table 1, it can be seen how the estimated production of the different products varies depending on the size of the Power-to-X plant. The estimated values are based on an assumption that the capacity of the wind turbine farms is the same as the capacity for the electrolysis, and thereby also the Power-to-X plant.

6.2.2 Summary

The above-described implementation of Energy Island Bornholm and a potential Power-to-X plant can be seen as an opportunity for Bornholm to transform their energy system in a more sustainable direction. The implementation of the new technologies on Bornholm is a step towards creating new energy synergies on the island and break with the silo thinking approach that has dominated the former planning of Danish energy infrastructure (Skov et al., 2021; Lund, 2014). Since a Power-to-X plant on Bornholm will result in a need for new technologies and infrastructure to be implemented and since it potentially will eliminate other technologies, it will have a major role in the translation process of the energy system on Bornholm. Therefore, implementing a Power-to-X needs consideration of the surrounding area, however, the impacts from the Power-to-X plant will depend on the type of end-product.

6.3 Impacts of Power-to-X

The following parts of this analysis will investigate the potential impacts on water resources, risks, air and noise pollution, and surrounding nature depending on the produced end-product. Likewise, the end-fuel is important for how the Power-to-X facility can contribute to the energy synergies on Bornholm, both by being able to feed into district heating and produce e-fuels for the transport sector.

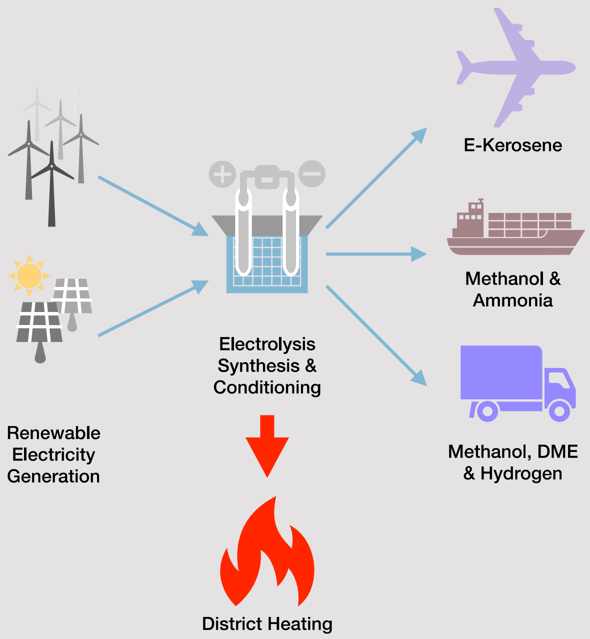


Figure 17 Illustration of the synergies between e-fuels and district heating. Own production, made in Pages.

6.3.1 Water Challenges

As explained in Chapter *1.2.1.2 Clean Water is a Scarce Resource* electrolysis' main resource is water in Power-to-X. It can seem basic that the electrolysis process just needs water, but the amounts and quality of water required makes water supply a challenge. This will be elaborated upon in the following chapter.

Implementation of a large-scale Power-to-X plant on Bornholm would mean an increase in water consumption caused by the high amounts of water needed for electrolysis. The exact amount of water needed varies depending on the electrolyser and its technical performance. To sense the degree of difference between water consumption and the resulting hydrogen outcome, it can be seen from a stoichiometric perspective (Simoes et al., 2021). From this perspective, the electrolysis process consumes circa 9 kg of water to produce 1 kg of hydrogen as visualised in Figure 18 (Shi et al., 2020; Madsen, 2022). However, from a manufacturing point of view, the water consumption is even larger, differing from 10.01 to 22.40 litres pr. kg hydrogen (Simoes et al., 2021).

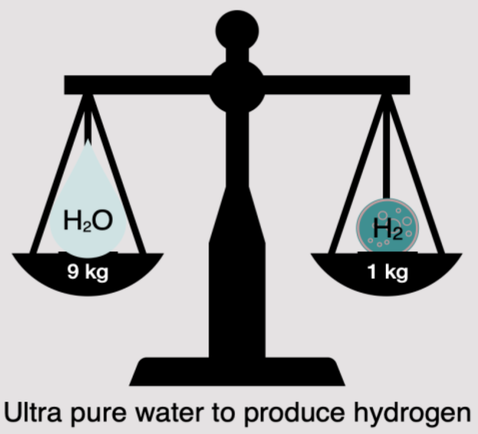


Figure 18 Visualisation showing the consumption of ultrapure water needed to produce 1 kg of hydrogen. Own production, made in Pages (Shi et al., 2020; Madsen, 2022).

Water supply is a challenge on Bornholm, since in recent years drought has become a reality and during summer the highest level on the drought index has been reached (Danmarks Meteorologiske Institut, n.d.). This is a challenge at the present time regardless of the island not having much industry that consumes high levels of water. This makes it quite conceivable that an island already affected by drought (Danmarks Meteorologiske Institut, n.d.) is going to be highly challenged if a Power-to-X plant is implemented. Therefore, it is necessary to find alternative solutions for water supply such as seawater and wastewater (Appendix M). Purifying water is energy-demanding which affects the overall energy efficiency of a Power-to-X plant. However, compared to the energy demand for electrolysis the energy demand for treating water is low (Madsen, 2022). Figure 19 illustrates the energy demand for purifying water is 2-7 kWh depending on whether it is groundwater, treated wastewater, or seawater in comparison to the energy demand needed for electrolysis of the same amount of water. Hence, the need for expanding the capacity of renewable energy is more dependent on the amounts needed for electrolysis rather than what the process of water treatment accounts for.

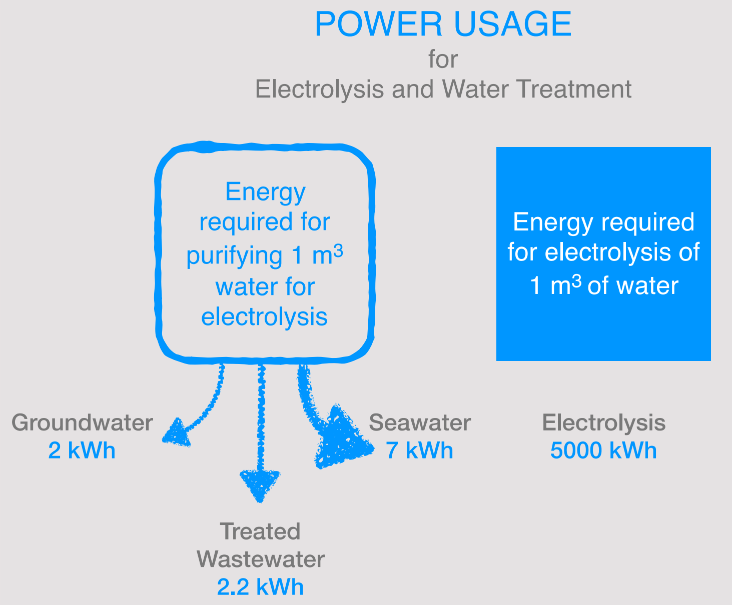


Figure 19 Illustration of the needed energy to purify 1 m³ water for electrolysis in comparison to the needed energy for electrolysis of 1 m³ of water. Own production. Made in Pages (Madsen, 2022).

Furthermore, purifying water also leaves byproducts such as minerals which are highly concentrated making it important to consider how it is managed to avoid environmental impacts onshore as well as offshore (Appendix H).

BEOF is currently responsible for treating wastewater but only to a degree of 85% to 90% pure (Appendix H). However, this does not meet the quality of water needed for Power-to-X meaning it is required to further treat the water before it can be used for electrolysis. This is something BEOF is considering as they see the benefits of purifying the water completely as it becomes easier to control the emissions of byproducts (Appendix H). At present time, the wastewater pollutes to some degree since it contains byproducts. Furthermore, BEOF sees the implementation of Power-to-X as an opportunity to build one combined wastewater treatment facility instead of having several small facilities as it is today (Appendix H). The 7,027,765 m^3/year generated (Bornholms Energi og Forsyning, 2021) wastewater on Bornholm can potentially be purified and used for Power-to-X. As it appears from Table 2, Bornholm has enough wastewater resources available to cover the water consumption in the different Power-to-X plant capacities, if it is assumed that 9 kg of water is used to produce 1 kg of hydrogen (Shi et al., 2020). In cases, where the wastewater resource does not meet the water demand for Power-to-X, it is an option to desalinate seawater or use technical water (Appendix K).

Table 2 *Annual Water Consumption for Power-to-Hydrogen.*

Scenarios	Capacity of Power-to-X	Annual Estimated Water Consumption - for hydrogen production
Overplanting	0.6 GW	544,091 m^3
Open Door	3.0 GW	2,720,455 m^3
Overplanting + Open Door	3.6 GW	3,264,545 m^3

Table 2 displays the consumption of water for a Power-to-Hydrogen with different capacities. The values represent the amount of water each plant consumes per year in m^3 (Shi et al., 2020; Carbon Commentary, 2021). Calculations, estimates, and assumptions can be found in Appendix P)

By implementing Power-to-X, it is possible to create synergies between wastewater treatment and agriculture. When water is treated to the extent and quality needed for Power-to-X, the process will create a compostable byproduct, which has the potential to be used as fertiliser for agriculture. The surplus product can potentially also be used as biogas, and thereby contribute to the district heating (Appendix H, Appendix I).

The wastewater treatment plant can benefit from the Power-to-X plant because within the electrolyser a surplus of oxygen is generated which can be used for wastewater treatment. The treatment plant and Power-to-X plant are therefore beneficial for one another (Appendix H, Appendix I).

6.3.2 Contributions in form of Surplus Heat and E-fuels

Implementing a Power-to-X plant on Bornholm can contribute to the synergies of the energy system within the district heating network because of surplus heat and the production of e-fuels can contribute to the transport sector, agriculture among other things.

6.3.2.1 Surplus Heat

The amount of surplus heat that a Power-to-X plant can produce depends on various factors, including the type of technology used, the capacity of the plant, and the operating conditions (Danish Energy Agency, 2021).

During the electrolysis process in Power-to-X, there is a heat loss, which can be considered surplus heat (Danish Energy Agency, 2021). However, the amount of surplus heat produced can vary depending on the specific process and system used (Danish Energy Agency, 2021).

If a Power-to-X plant was implemented on Bornholm the production of surplus heat would be estimated as it appears from Table 3, depending on the capacity of the plant.
The estimated surplus heat increases depending on the size and has the potential to be used for either district heating or other industrial purposes.

Table 3 *Annual Heat Production and Heat Loss from Power-to-X.*

Scenarios	Capacity of Wind Turbines	Annual Electricity Energy Consumption	Annual Heat Loss 21.4 %	Annual Surplus/ District Heating Production 18.4 %	Annual Unrecoverable heat loss 3 %
Overplanting (Energy Island)	600 MW	3 TWh	0.642 TWh	0.552 TWh	0.09 TWh
Open Door (CIP/ Ørsted)	3.0 GW	15 TWh	3.210 TWh	8 TWh	7.7 TWh
Overplanting + Open Door	3.6 GW	18 TWh	3.852 TWh	2.760 TWh	0.45 TWh

Table 3 displays the annual heat loss, surplus/district heating, and unrecoverable heat loss from a Power-to-X plant with different capacities. The values represent the amount of fuel each plant can produce per year in TWh. The surplus heat numbers are based on the Power-to-X being able to recycle 18.4% of the energy consumption (Danish Energy Agency, 2021). Calculations, estimates and assumptions can be found in Appendix P.

6.3.2.1.1 District Heating

Utilising the surplus heat can provide district heating for Bornholm, leading to a reduction in dependency on fossil fuels and biomass, and increasing the use of renewable energy sources (Appendix C, H, I, L). The three Power-to-X scenarios, outlined in Table 4, generate sufficient surplus heat to meet the district heating demand on Bornholm. For instance, the first scenario with a plant capacity of 600 MW produces 552,000 MWh annually, exceeding the district heating demand of 229.722 MWh (Figure 4). However, as mentioned in Chapter *6.1.1.2.1 District Heating*, heat loss in the district heating grid depends on the location of the Power-to-X plant of which longer distances result in higher heat loss (EnergiTjenesten, n.d.). Therefore, to optimise the use of surplus heat for district heating, it is recommended to place the Power-to-X plant as close as possible to the district heating grid.

Table 4 *Number of Households Power-to-X Can Supply with Heat.*

Scenarios	**Capacity of Wind Turbines**	**Annual surplus/ district Heating Production** 18.4 %	**Number of Households** (Supplied with District Heating and Domestic hot water)
Overplanting (Energy Island)	600 MW	0.552 TWh	30,497 Households
Open Door (CIP/Ørsted)	3.0 GW	8 TWh	152,486 Households
Overplanting + Open Door	3.6 GW	2.760 TWh	182,983 Households

Table 4 displays the number of households a Power-to-X plant can supply with district heating on a yearly basis. The numbers of households are based on an annual average household heat demand (incl. domestic hot water) of 18.1 MWh (Bolius, 2023). Calculations, estimates and assumptions can be found in Appendix P.

Upon conducting an investigation into the potential applications of surplus heat from Power-to-X plants with capacities of 3.0 GW and 3.6 GW, it has been discovered, they have the capacity to provide district heating consumers with a surplus of 11 to 14 times the demand (Table 4). Therefore, it would be wise to redirect the surplus heat towards additional purposes beyond district heating.

6.3.2.1.2 Vertical Farming

The surplus heat can be utilised for greenhouses and vertical farming (Appendix D, F, G, H, I, L, M), which will extend the growing season and boost local food production, ultimately supporting the local economy and reducing the environmental impact of food transportation (Appendix D, F, G, H, I, L, M). Vertical farming presents a promising opportunity for Bornholm to cultivate a diverse range of crops using soil-free techniques in a vertical, multi-level system (Soojin & Chungui, 2023; Beacham et. al., 2019). This innovative approach to farming optimises space utilisation, boosts crop yields, and minimises water consumption (Soojin & Chungui, 2023; Beacham et. al., 2019). The island could grow a variety of crops, including leafy greens, herbs, and fruits, using hydroponic or aeroponic systems that deliver the necessary nutrients to the plants through nutrient-rich water or mist (Soojin & Chungui, 2023; Beacham et. al., 2019). Supplementing natural sunlight with artificial lighting could further enhance plant growth, especially during the darker winter months (Soojin & Chungui, 2023; Beacham et. al., 2019). By selling locally grown produce, Bornholm could provide citizens with fresh, nutritious, and sustainable food while reducing the carbon footprint associated with importing food from the mainland (Soojin & Chungui, 2023; Beacham et. al., 2019; Appendix G).

6.3.2.1.3 Storing Opportunities

The surplus heat can be stored and used as a backup energy source during times of low renewable energy production or high demand (Skov et. al., 2021). To store surplus heat from Power-to-X plants on Bornholm, it can be captured using thermal energy storage systems (Danfoss, n.d.). These systems store the surplus heat in insulated tanks, which can be used to provide backup energy during times of low renewable energy production or high demand (Skov et. al., 2021).

One method of thermal energy storage is using molten salts as the storage medium, as they have a high heat capacity and can retain heat for extended periods (Way, 2008). This method is already used on Bornholm, since BEOF currently collaborates with Hyme Energy, a company working with the acceleration of fossil-free energy solutions of large-scale molten salt energy storage (Hyme, n.d.), on the transformations of an existing combined heat and power plant in Rønne into a storage facility of renewable energy. The storage system is designed to use renewable electricity to heat up molten salt, wherein the energy can be stored for 24 hours or longer with an energy loss of 1% per day. The storage facility in Rønne is expected to be up and running in 2024, with a storage capacity of 20 MWh (Hansen, 2022). The learning and experiences from this work with storage facilities of renewable energy on Bornholm can be used if a Power-to-X plant is implemented with a possibility for energy storage.

Another approach is using Phase Change Materials (PCMs), which can absorb and release heat energy as they change from solid to liquid or vice versa (Danfoss, n.d.). These thermal energy storage systems can be integrated with the district heating network, allowing the surplus heat to be available as a backup energy source when needed (Skov et. al., 2021).

6.3.2.1.4 Industry and Tourism Purposes

The surplus heat generated by renewable energy sources can be utilised for various industrial and tourism purposes, including the creation of new attractions like a "Blue Lagoon" or other innovative ventures (Appendix D, Appendix F, Appendix J). This can result in a significant boost in tourism and increase visitor numbers on the island, leading to the creation of new job opportunities (Appendix D).

6.3.2.2 E-fuels

One of the key benefits of e-fuels is that they can contribute to reducing carbon emissions in the transport and energy sectors (*1.2 The Concept of Power-to-X*). E-fuels produced using renewable energy sources, such as wind or solar power, in a Power-to-X plant are low-carbon alternatives to traditional fuels, especially within sectors such as aviation, heavy-duty transport, and maritime shipping (Skov et al., 2021; Foit et al., 2017; Wulf et al., 2020; Helgeson & Peter, 2020; ACS Energy Letters, 2020). E-fuels are similar to traditional fuels, like gasoline, diesel, and natural gas, but the key difference is, they are produced from renewable energy sources (Technical University of Denmark, n.d.; ACS Energy Letters, 2020). Therefore, Bornholm can benefit from the production of e-fuels produced locally since it can reduce their dependence on imported fossil fuels contributing to a sustainable future and a green transition of the energy system on the island.

Another benefit of the production of e-fuels is the possibility to store renewable energy from solar and wind production on Bornholm. Power-to-X technology can be used to store surplus renewable energy generated during peak production periods, whereafter the energy can be converted into e-fuels (ACS Energy Letters, 2020). The produced e-fuels can hereafter be stored and used during periods of low renewable energy production (ACS Energy Letters, 2020). The local production of e-fuels also contributes to the energy security of supply on Bornholm by reducing their dependency on imported fossil fuels (Appendix I). In addition, e-fuels can be used to power critical infrastructure, such as emergency services, during power outages or other disruptions (Helgeson & Peter, 2020).

Besides the direct benefits for the energy supply on Bornholm, e-fuels contribute to the development of the local economy, education, and society which will be elaborated in Chapter *7. The Interactions of Implementing Power-to-X on Bornholm*.

6.3.2.2.1 Power-to-Hydrogen

Power-to-Hydrogen technology presents an attractive option for energy storage, enabling Bornholm to harness surplus renewable energy and convert it into hydrogen for storage. This stored hydrogen can then be reconverted back to electricity using fuel cells or combustion engines as needed (Escamilla et. al., 2022). Furthermore, hydrogen has the potential to serve as a versatile fuel source for the transport sector. It can be employed directly as a fuel or utilised as a feedstock for the production of other transportation fuels, including synthetic methane or ammonia (McKinlay et. al., 2021). The local production of hydrogen through Power-to-Hydrogen technology at Bornholm presents a promising opportunity to reduce the island's reliance on imported fossil fuels and imported electricity from Sweden, thereby advancing local self-sufficiency in energy production (Appendix I).
However, the transportation and storage of hydrogen necessitate substantial infrastructure, including pipelines and storage facilities. Therefore, large investments need to be made in the development of infrastructure to support the storage and sale of hydrogen (Skov et al., 2021; Mathiesen et al., 2015; ACS Energy Letters, 2020; Appendix L).

6.3.2.2.2 Power-to-Ammonia

Green ammonia produced on Bornholm can be used as a carbon-free fuel for transportation, such as shipping and fishery (*1.2 The Concept of Power-to-X*). Green ammonia can be used for energy storage to balance the intermittent nature of renewable energy sources, such as wind and solar power (Valera-Medina & Banares-Alcantara, 2021). Ammonia can be stored for extended periods and used to generate electricity when renewable energy is not available. It can furthermore be used as a fuel for power generation, either by combusting it directly or by using ammonia-powered fuel cells to produce electricity (Valera-Medina & Banares-Alcantara, 2021), which potentially can benefit Bornholm to be totally independent on the electricity imported from Sweden (Appendix I), and thereby become 100% self-sufficient.

Furthermore, ammonia is a key component in the production of nitrogen fertilisers, widely used in agriculture (Appendix K). Green ammonia can be used to produce sustainable fertilisers for local agriculture (Ghavam et al., 2021; Fertilizers Europe, n.d.), which has a great importance for Bornholm, since it is one of the biggest professions on the island (TrapDanmark, n.d.).

Another benefit from the implementation of green ammonia production on Bornholm, is the potential attraction of new industries or encouraging the expansion of existing ones, which can leverage green ammonia as a sustainable feedstock (Appendix G, H, K, I). This can stimulate economic growth on the island while promoting sustainability (Appendix G) and reducing carbon emissions (Appendix H).

The implementation of Power-to-Ammonia technology on Bornholm presents challenges, including the requirement for extensive infrastructure investments to produce, transport, and store ammonia (Valera-Medina & Banares-Alcantara, 2021). This entails the development of new pipelines, storage tanks, and shipping terminals.

Moreover, due to ammonia's toxic nature, special care is necessary when handling and transporting it to avoid risks (Shi et al., 2023). Additionally, concerns arise regarding the potential environmental impact of using ammonia as a fuel source, including the possibility of contributing to air and water pollution (Appendix A; Appendix M).

6.3.2.2.3 Power-to-Methanol

Similar to Power-to-Hydrogen and Power-to-Ammonia, the implementation of Power-to-Methanol technology has the potential to facilitate the integration of a higher proportion of renewable energy into Bornholm's energy mix (Blue World Technologies, n.d.; Appendix C, Appendix F, Appendix H). This is achieved by enabling excess energy generated by wind turbines or solar panels to be stored as methanol, which can serve as energy storage (Blue World Technologies, n.d.). As a result, Power-to-Methanol can be beneficial for Bornholm to meet the energy demand, even during periods of low renewable energy generation (Eurowind Energy, n.d.). However, one of the main reasons why Power-to-Methanol is challenging for Bornholm, is that it requires carbon (Bos et al., 2020) which is not available in large-scale on Bornholm (Bornholms Regionskommune, n.d.C).

Furthermore, the utilisation of methanol as a fuel source for transport has the potential to assist Bornholm in reducing carbon emissions and achieving climate targets (Eurowind Energy, n.d.; Appendix F, Appendix H). Additionally, Power-to-Methanol technology can reduce Bornholm's dependence on imported fossil fuels, promoting energy independence (Blue World Technologies, n.d.).

Thus, the production of methanol through Power-to-Methanol technology offers a promising opportunity for Bornholm to diversify its renewable energy portfolio, enhance its energy security, and decrease its environmental impact (Eurowind Energy, n.d.).

In contrast to hydrogen and ammonia, methanol is a liquid fuel that can be conveniently transported and stored in pre-existing infrastructure, such as fuel tanks and pipelines (Blue World Technologies, n.d.; Eurowind Energy, n.d.). This renders methanol as a more practical alternative fuel option for certain types of transportation, such as heavy-duty vehicles or shipping (Skov et al., 2021; Foit et al., 2017; Wulf et al., 2020; Helgeson & Peter, 2020; ACS Energy Letters, 2020; Eurowind Energy, n.d.). By blending methanol with gasoline, a fuel blend known as "M85" can be produced, which is suitable for use in certain types of gasoline-powered vehicles (NewQuantum, n.d.). This provides an opportunity for a gradual transition from fossil fuels to renewable energy sources (NewQuantum, n.d.).

6.3.3 Summary

Power-to-Hydrogen, Power-to-Ammonia, and Power-to-Methanol share the common attribute of enabling the integration of renewable energy sources into Bornholm's energy mix. They allow excess energy generated by wind turbines to be stored as a fuel, reducing the island's dependency on imported fossil fuels.

The implementation of Power-to-Hydrogen, Power-to-Ammonia, and Power-to-Methanol technologies can bring various benefits to Bornholm, such as reducing carbon emissions, promoting sustainable development, and creating new economic opportunities. Furthermore, provide a dependable energy source during periods of low renewable energy generation.

However, implementing these technologies presents several challenges. Producing and transporting hydrogen and ammonia necessitate significant infrastructure investments. In contrast, using methanol as a transportation fuel may require new changes in infrastructure and vehicle modifications to enable widespread use. Additionally, Power-to-Methanol technology requires a source of CO_2 (Bos et al., 2020), which needs to be procured from outside the island, since there is not enough carbon available on the island.

6.3.4 Potential Risk Related to Power-to-X Implementation

A Power-to-X plant is chemical industry (Vasconcelos & Lavoie, 2019), meaning it does imply risks to Bornholm. As of now, the island has mainly been characterised by tourism, farming, and small local businesses (Business Center Bornholm, n.d.) but with a potential Power-to-X plant this implies a paradigm shift in the business community since such a plant differs from usual business by handling materials that potentially can be dangerous if not handled with caution (Appendix M; Qi et al., 2023).

In Denmark, safety of hazardous industrial sites is regulated through the Risk Assessment Law [Danish: Risikobekendtgørelsen] which purpose is to prevent accidents and minimise consequences if an accident happened. In appendix 1 in the Risk Assessment Law hydrogen, methanol and ammonia are on the list of hazardous materials (BEK 372 af 25/04/2016). This act regulates all companies handling large amounts of chemical industry and thereby also electrolysis plants. These companies can be categorised either as column 2 or column 3 companies depending on the amount and type of fuel it is producing (Energistyrelsen, n.d.D). If the production exceeds the threshold amount for the produced fuel the company has to follow the regulation in the Risk Assessment Law. If a large-scale Power-to-X plant is implemented the production of the plant manages hazardous materials to an extent that it would be categorised a column 3 company since the production exceeds the threshold amount for hydrogen, methanol, and ammonia. Such companies are obligated to take the necessary measures to minimise risks and complete a safety report where they have assessed the risks and how to manage them (BEK 372 af 25/04/2016). Furthermore, safety precautions for a specific plant are set by the Danish Emergency Management Agency and the municipal rescue service, meaning the final necessary safety precautions are specific for each project (Energistyrelsen, n.d.D).

The location for an electrolysis plant has to be assessed and according to Ulrik Torp Svendsen, Director of Power-to-X Development at Everfuel, when planning a Power-to-X plant, a part of the safety precautions is to consider the current use of the area and plans since it would be most optimal to place a Power-to-X plant in an area which is not too populated or nearby a school or hospital (Appendix L). However, it is worth mentioning that this does not mean that it is a safety issue to be near a Power-to-X facility but rather a precautionary principle since there is no regulatory framework that prevents hospitals or schools to be located nearby but in case of an accident the consequences would be smaller if the area is not to populated (Appendix L). Furthermore, Torp mentions that a Power-to-X plant has a safety distance, which depends on the type of fuel and storage capacity. Since the safety distance

depends on several unknown factors, making it difficult to evaluate for a Power-to-X plant not yet planned, this report does not touch upon the specific safety distance but acknowledges that it is a requirement when managing hazardous materials.

Safety precautions for producing hydrogen, methanol, and ammonia are necessary since they can be dangerous but vary in the degree of risk (Incer-Valverde et al., 2022). Moreover, to produce any X, hydrogen is a step in the process before being able to produce methanol or ammonia, making safety precautions related to the production of hydrogen applicable for any Power-to-X plant.

Hydrogen and methanol are highly flammable and explosive and should be handled with precaution in the production, storage, and transportation phases to avoid incidents impacting citizens or the environment. Ammonia, on the other hand, is highly toxic, meaning it can be dangerous in a situation of leakage (Shi et al., 2023).

However, it is important to weigh which option to choose since the energy efficiency, emissions, transportability, and risks varies depending on the choice of fuel (Shi et al., 2023). Researching and knowledge sharing the different options of fuels can have an important role in the implementation since this can affect the social acceptance of a Power-to-X plant, as well as avoid any misconception of the risks (Incer-Valverde et al., 2022).

6.3.5 Environmental Impacts

When building a Power-to-X plant there is a risk of pollution and visual disturbance of the local area, making it important to consider the location of the plant regarding air pollution, noise pollution, impact on nature (conservation areas), and visual impact.

6.3.5.1 Pollution - Air and Noise

Some factors which are important to investigate are air and noise pollution potentially affecting the surrounding area. Hence, the investigation of these parameters is important for the choice of area to implement a Power-to-X plant.

When comparing ammonia, methanol and hydrogen, the fuel with the least harm to the environment is hydrogen (Shi et al., 2023). However, storing, and transporting hydrogen has a considerably higher cost than ammonia and methanol. Furthermore, methanol is highly explosive which also could harm the environment (Shi et al., 2023). Ammonia, on the other hand, easily can be stored and transported but is highly toxic and a potential slip can pose a threat to human health and environment, making it challenging to handle (Shi et al., 2023). Methanol is also toxic but much less than ammonia and also has less of an impact than heavy fuel oil or diesel if leakage happens (Shi et al., 2023).

A Power-to-X plant can cause noise pollution from the process plant that can disturb the neighbourhood (Appendix I, Appendix K, Appendix L). However, it is possible to minimise noise pollution by soundproofing the buildings, reasoning why noise pollution plays a minimal role in the decision-making of the location of the Power-to-X plant (Appendix L). Furthermore, noise pollution would be assessed in the Environmental Impact Assessment (EIA) before the Power-to-X plant would be implemented (BEK nr 2080 af 15/11/2021). This has been done for the future Power-to-X plant in the Municipality of Aabenraa which has managed to keep the level of noise below the noise limit (Miljøministeriet, n.d.). The role of noise pollution thereby has little effect on the location of the Power-to-X plant.

6.3.5.2 Conservation Areas

Bornholm has multiple conservation areas and some of them are in the location where the transformer station for Energy Island Bornholm is planned, meaning there already has to be made an exemption from the Protection of Nature Act (Naturbeskyttelsesloven, 2022) before it can be built (Hansen, 2023A). Since the location and size of a potential Power-to-X plant is not yet decided, it is unknown if it will impact additional conservation areas.

6.3.5.3 Visual Impact

As mentioned in Chapter *6.2 Future Energy System Transition on Bornholm* there is already planned a 52 hectares transformer station to connect Energy

Island Bornholm Offshore Wind Farm on the south end of Bornholm affecting the local area and community. The 52 hectares only includes the technical transformer plant but with access roads, stormwater reservoirs, and other matters the total area for the transformer station is going to take up 107 hectares (Energinet, n.d.A). The potential Power-to-X plant is not included in the tender but can be a part of the overplanting (Danish Energy Agency, 2022), meaning if Power-to-X ends up being finally decided the Power-to-X plant is going to take up additional acreage. Furthermore, the offshore wind turbines also will affect the area around Bornholm from a visual perspective (Danish Energy Agency, 2022). Cumulatively, these technical plants will stand out and have a visual impact on the area. However, Energinet has been working on making a plan for the transformer station where the citizens have had the possibility of contributing to the architectural image of the station (Energinet, n.d.A). This can also be done for the Power-to-X plant to tailor it to the existing area and architecture with the aim of minimising the visual impact.

6.4 Recommendations for Placing the Power-to-X Plant

Based on the findings, the purpose of this chapter is to recommend where a Power-to-X plant beneficially can be placed on Bornholm. This depends on the overall goal for implementing Power-to-X, and whether the purpose is to ensure storage of energy, security of supply, heat, transport or to station it near the water supply. Furthermore, choosing the location for a Power-to-X plant varies whether it produces hydrogen, methanol, or ammonia.

When the Energy Island Bornholm is implemented, a transformer station will be built on the southern part of Bornholm, close to Aakirkeby, and is going to receive the electricity from offshore wind turbines. Locating the Power-to-X plant near the transformer station allows easy access to the large amounts of electricity needed in the electrolysis process. Placing the two plants close to each other can make Power-to-X more feasible for the developers since this would minimise the necessity of expanding the infrastructure and transport of electricity. Thereby, the area impacted by the implementation is concentrated around the transformer station which also is beneficial for minimising the energy loss (Appendix H). Locating the Power-to-X plant next to the transformer station necessitates an expansion of the infrastructure to transport the end fuels to the consumers, as well as creating synergies for the surplus heat.

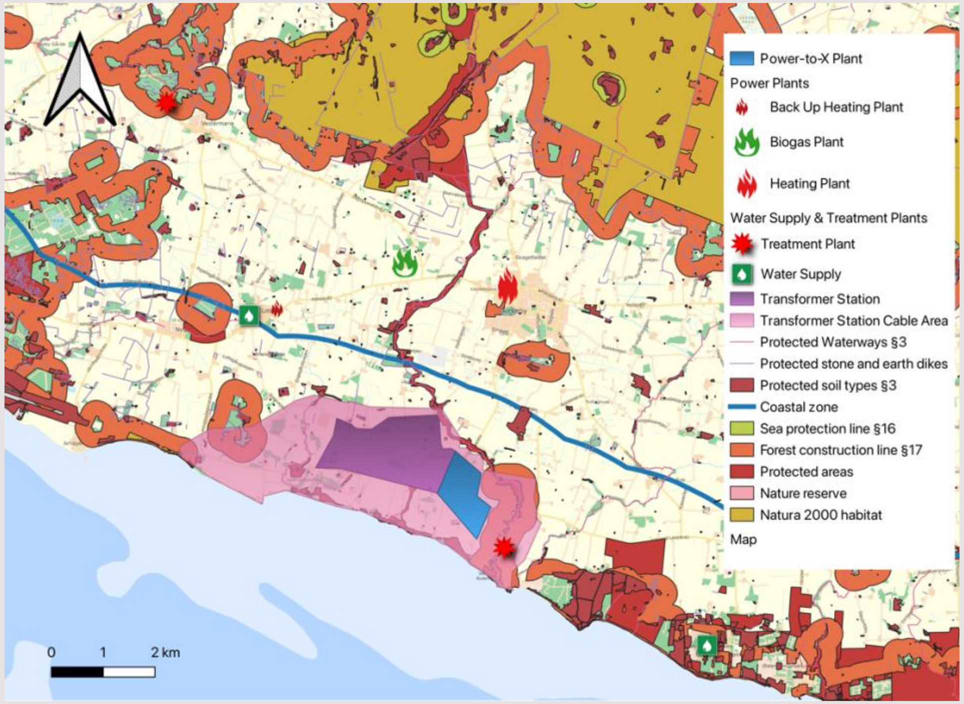


Figure 20 Map showing the recommended location for a Power-to-X besides the transformer station. Furthermore, the map illustrates nearby infrastructure systems and zoned areas. Own production, made in QGIS (Hansen, 2023B; Appendix R; Appendix Q, Dataforsyningen plugin in QGIS).

The electrolysis process within the Power-to-X plant has a large water consumption, making it important to consider proximity to available water resources. Bornholm mainly considers using wastewater as the water source for the electrolyser, meaning it would be optimal to locate the Power-to-X plant near existing wastewater treatment facilities. However, the wastewater on Bornholm is treated on decentralised water treatment plants and none of the separated wastewater treatment plants treats enough wastewater alone to supply a Power-to-X plant. To accommodate this, Vesløv sees it as an option for BEOF to centralise the wastewater treatment facilities, making it possible to supply the Power-to-X plant solely with purified wastewater (Appendix H). Centralising the wastewater treatment will contribute to the expansion of sector coupling and synergies of the current energy system, which is one of the main advantages of implementing Power-to-X. This will be further elaborated upon in Chapter *7.4 The Water System of Bornholm*.

As part of sector coupling, Power-to-X results in surplus heat that can be used for other purposes, such as district heating, vertical farming, or other industrial purposes, see Chapter *6.3.2.1 Surplus Heat*. If the surplus heat is used in district heating the plant should be located near existing district heating or in an area suitable for implementation of a new district heating network. The short distances to the district heating consumers are essential to minimise heat loss.

The district heating network is already supplied with sustainable biomass, mainly locally produced, and it is therefore not necessarily of high importance to replace the biomass with heat from the Power-to-X plant. However, BEOF considers the used biomass as a transitional fuel which should be replaced

(Bornholms Energi og Forsyning, n.d.B), speaking in favour of using the surplus heat from Power-to-X for district heating.
However, the heat production from the Power-to-X plant will exceed the existing district heating demand on Bornholm, reasoning why the surplus heat also should be used for other purposes, such as vertical farming, industrial purposes, or tourist attractions. To avoid heat loss, it is essential to locate industries and businesses that can benefit from the surplus heat close proximity to the Power-to-X plant. This makes it important to consider available space around the plant in order to get the most out of the energy production.

The surrounding environment should be considered when implementing new technology, in this case, chemical industry. This is due to the risks and safety concerns that need to be addressed to ensure safe operation of the plant and protection of the surrounding environment and communities. One of the concerns is the storage capacity and handling of chemical industry, which can be challenging regardless of whether the plant is producing ammonia, methanol, or hydrogen. However, the end fuels can potentially be flammable, explosive, and toxic, and to mitigate these risks, the Power-to-X plant must comply with relevant safety regulations and best practices for the storage, handling, and transport of the respective end fuels, including the use of appropriate safety equipment, monitoring systems, and emergency response plans, see Chapter *6.3.4 Potential Risk Related to Power-to-X Implementation*.

The location of the Power-to-X plant can impact the surrounding environment and communities, meaning the distance to the coastal zone, nature, protected areas, households, businesses, and other industries should be considered. The plant's emissions and noise levels can impact local air and noise pollution levels. To mitigate these impacts, the Power-to-X plant may comply with relevant environmental regulations and best practices, including the use of emission controls and noise mitigation measures.

Bornholm has considered the opportunities to either locate the Power-to-X plant in Port of Rønne or in the countryside, close to the planned transformer station. Placing the Power-to-X plant in Port of Rønne is beneficial since the fuel can be used for the shipping industry. However, since it would require storage of either hydrogen, methanol, or ammonia, placing the plant in Port of Rønne is critical due to safety risks, and close distance to households.

Based on the above findings, it is recommended to locate the Power-to-X plant next to the transformer station since several benefits are related to this location. It will contribute to the overall goals of Bornholm on creating sector couplings and synergies within the energy system. The location will secure easily available electricity for the Power-to-X plant by connecting the plant to the transformer station. Furthermore, the location will make it beneficial to centralise the water treatment facilities on Bornholm, both benefiting the Power-to-X plant and the agricultural sector which can use the byproducts from the water treatment as fertiliser. A location next to the transformer station means the plant will be located within proper distance to cities and neighbours, meaning the plant wants to be associated with any safety concerns and allowing space for storing e-fuels. The recommended location of a 90 hectares Power-to-X plant is visualised in Figure 20. Various protected areas are also marked on this map, ensuring the placement of the Power-to-X facility does not encroach upon these areas. However, the Power-to-X plant is situated within the coastal zone. Due to the already planned location of the transformer station within the same zone, it is assessed that it is energetically advantageous to position the Power-to-X plant and the transformer station adjacent to each other.

Locating the Power-to-X plant next to the transformer station is also in line with the opinion of the Social Democratic Party on Bornholm, who wants to make a green industrial park as part of the transformer station, and therefore prepare the island for a potential Power-to-X plant next to the transformer station (Hansen, 2023B).

6.5 Preliminary Conclusion

How will a potential Power-to-X plant impact the energy system and the local area's environment, safety and water supply?

A Power-to-X plant producing hydrogen, ammonia, or methanol on Bornholm impacts the local area's environment, safety, and water supply, since it takes up space, causes risks and is water demanding. Nevertheless, the implementation can be beneficial for the local community and area which will be further elaborated on in Chapter *7. The Interactions of Implementing Power-to-X on Bornholm*. Power-to-X produces e-fuels making it possible to store green energy reducing carbon emissions which can be used as an e-fuel. Furthermore, it produces surplus heat that can be used for district heating, vertical farming and other industrial purposes, reducing the demand for fossil fuels and lowering carbon emissions. Furthermore, the implementation of Power-to-X can create a synergy between the wastewater treatment and the energy infrastructure by using the surplus oxygen from the Power-to-X plant, and vice versa use treated wastewater in the electrolysis process in the Power-to-X plant. A synergy between heat, water and electricity can be created by implementing Power-to-X on Bornholm, as illustrated on Figure 21.

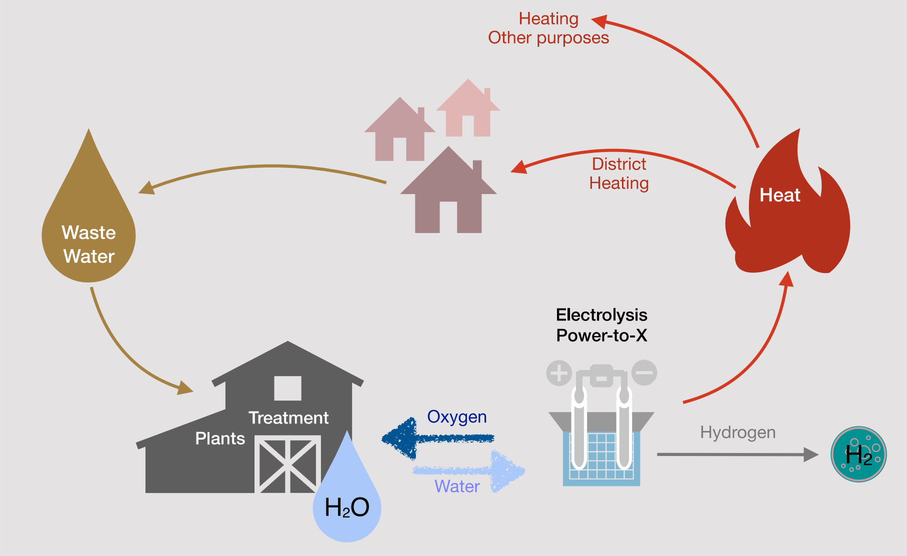


Figure 21 Illustration of sector coupling between water and heat. Own production, made in Pages.

The plant's physical infrastructure, such as buildings, pipelines, and storage will impact the local area, however, this can be handled by designing and considering the location of the plant to minimise its visual impact. Noise pollution is also a concern when implementing Power-to-X, but this can be minimised by soundproofing buildings and assessing noise levels in the Environmental Impact Assessment.

Further, the plant must comply with strict safety regulations to ensure the safety of workers, nearby citizens, and environment. Power-to-X plants handle hazardous materials such as hydrogen and ammonia, which are highly flammable. Proper safety measures must be in place to prevent incidents of fire, explosion and intoxication.

The choice of producing hydrogen, methanol, or ammonia has varying degrees of impact on environment and human health. While hydrogen is least harmful, it also has higher costs for storage and transportation. Methanol has a lower environmental impact than heavy fuel oil or diesel but is highly explosive and still emits carbon dioxide when combusted. Ammonia, on the other hand, is easy to transport and store but highly toxic.

Lastly, Power-to-X plants have a significant water demand for the electrolysis process, depending on the plant's size. This will pressure the local water supply stemming from groundwater but a sustainable solution for this is purified wastewater. However, this will require investments in more advanced water treatment facilities on Bornholm.

Based on the analysis, the recommendation for placing a Power-to-X plant on Bornholm depends on the overall goal for implementing Power-to-X, such as storage of energy, security of supply, or transport. Additionally, the chosen end-product also plays a significant role in choosing the plant's location, depending on the end fuel. The recommendation is to place the Power-to-X plant next to the new transformer station to be built in the southern part of

Bornholm, close to Aakirkeby, as part of Energy Island Bornholm. This placement allows easy access to the large amounts of electricity needed in the electrolysis process of the Power-to-X plant. To achieve sector coupling from Power-to-X, it is important to consider how the surplus heat from the plant can be used most beneficially. If the surplus heat shall be used in district heating, it is essential to locate the plant close to existing district heating or in an area where there is potential for establishing a new district heating network. When placing the Power-to-X plant, the surrounding environment should also be considered, including potential risks and safety concerns that need to be addressed to ensure the safe operation of the plant and the protection of the surrounding environment and communities. The location of the Power-to-X plant can impact the surrounding environment and communities, and it is therefore also important to be aware of the distance to the coastal zone, nature, protected areas, households, businesses, and other industries. Since an implementation of Power-to-X will impact the community and area in several ways, this chapter will be followed by an interpretation of the actor-network.

7 The Interactions of Implementing Power-to-X on Bornholm

In the following analysis the actor-network will be mapped to interpret the existing setting and identify potential translation processes. In the previous analysis, the current situation on Bornholm is elaborated upon, followed by an analysis of the future if Power-to-X is implemented. The findings are used as a baseline for identifying the actor-network, enabling identifying potential translation processes to answer the following subquestion: *Which translation process and interactions can be identified in the implementation of a Power-to-X plant and how will these affect the local actors?*

The actors and interrelations within this study are identified based on findings collected from interviews and the previous analysis. It is known from Actor-Network Theory (*4.1 Actor-Network Theory*) that actor-networks constantly are developing and redefined, however, this study focuses on six identified networks, relevant if Power-to-X is implemented. The six identified actor-networks are illustrated in Figure 22A, consisting of the following networks:

Legislative Power Network consists of regulations, decisions, and political agendas impacting Power-to-X development. **Executive Order** Network includes governmental and municipal actors as well as other regulatory actors who have the main role in executing Energy Island Bornholm. **Energy Island Bornholm** Network, consisting of human and non-human actors, is the catalyst within the whole translation process. **The Water System** Network is identified as local water resources, technologies, and water infrastructure systems. **The Energy System** Network mainly consists of non-human actors, including the energy technologies, sources and plans as well as their correlations. **The Local Influenced** Network includes actors physically located on Bornholm, consisting of human and non-human actors such as private citizens, companies, and local resources.

Based on the identified actor-networks, the purpose of the following analysis is to understand the effect an implementation of Power-to-X has on the identified actor-networks. The analysis will identify barriers and challenges of implementing Power-to-X, as well as opportunities of translation processes.

The following chapters present and describe the actor-networks and the essential actors. This will be supplemented by detailed illustrations of the concerned actor-network visualising correlations and potentials between actors.

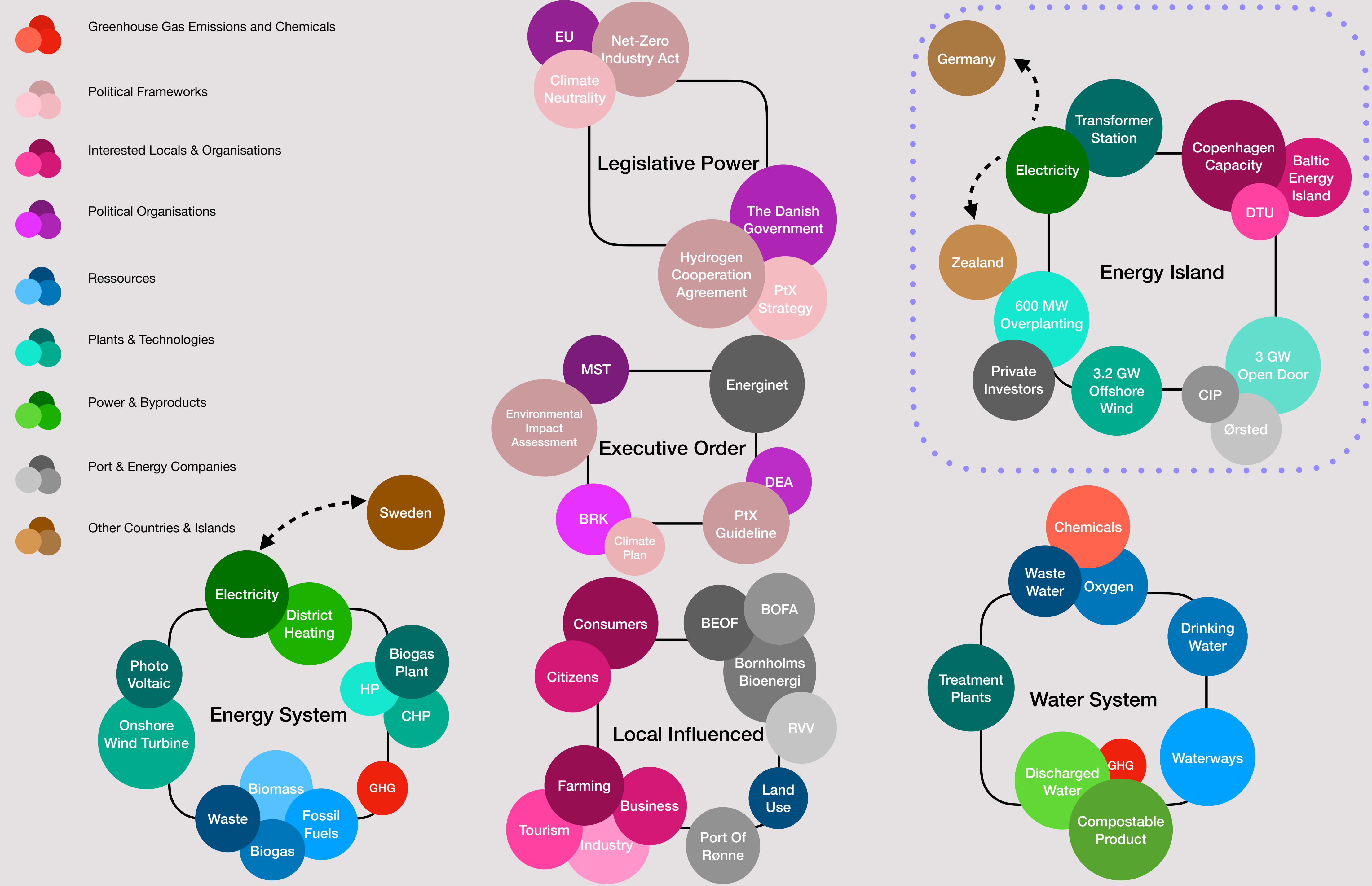


Figure 22 A simplified illustration of the various networks and actors that are part of or are affected by a potential implementation of Power-to-X on Bornholm. Each network is illustrated with a black ring whereas the most important actors are placed in circles. They have different colours depending on which category they belong to. In addition, the Energy Island Network is marked with a dotted line as this is a network in the planning phase. The dotted arrows represent physical connections to other countries and Zealand. The networks are positioned in relation to power. The Legislative Power Network is powerful and is therefore placed at the top of the illustration. The illustration represents the current system of Bornholm and is the reason Power-to-X is not included in the illustration. Own production, made in pages.

7.1 Legislative Power

The Legislative Power Network consists of the Danish government, political agreements, plans for Power-to-X, the European Union hydrogen plans, and climate targets and can be analysed as interconnected actors in a network since they influence each other. This network is named Legislative Power, since it includes actors with legislative and regulatory power on the plans of implementing Energy Island Bornholm and Power-to-X. The network is visualised in Figure 22A.

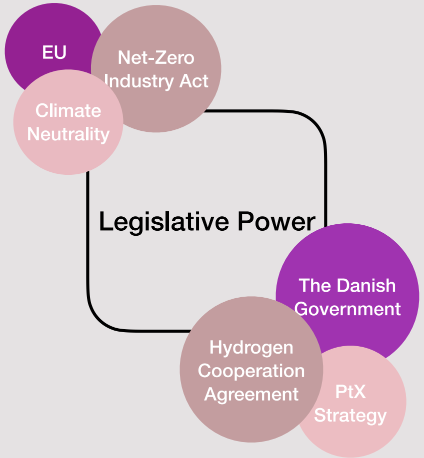


Figure 22A An illustration of the Legislative Power Network and the relevant actors (circles). Own production, made in Pages.

7.1.1 Power-to-X in Focus

Focus on producing Power-to-X has increased rapidly in the past years with the aim of reaching climate goals (Palys & Daoutidis, 2022). The European Union as an actor in the network, and its policies and targets can impact the actions of the Danish government and other actors in the network. The European Union has set a goal of reaching climate neutrality by 2050 but this requires new technologies, such as Power-to-X, to be implemented on a large scale to enable the transition of hard-to-abate sectors (European Commission, 2019).

One of the crucial initiatives is the EU Hydrogen Strategy from July 2020 that sets out a goal of installing 40 GW electrolysis capacity and produce 10 million tons of renewable hydrogen by 2030 (*1.2.1.6 Regulatory Framework*). With this, the aim is to accelerate the implementation of hydrogen-producing plants rapidly in the coming years and back up the development of a hydrogen market in the EU (European Commission, 2020). In other words, this can be seen as a translation process since the Hydrogen Strategy drives the Power-to-X plant to become part of the energy system at Bornholm and the rest of Denmark.

7.1.2 Power-to-X Tender

The Danish government has set targets for accelerating Power-to-X implementation by aiming for a 4-6 GW electrolysis capacity in 2030

(Energistyrelsen, n.d.E). This was decided in the Power-to-X strategy launched in March 2022 in which the government has agreed on initiatives to accelerate and increase the use of Power-to-X in Denmark (Klima-, Energi- og Forsyningsministeriet, 2021). In this context, the government has initiated a Power-to-X tender where it is possible for project developers to apply for subsidies for the implementation of Power-to-X with the purpose of lowering the costs of producing hydrogen. The total sum of subsidies is 1.25 billion DKK, and the aim is to produce as much hydrogen as possible at the cheapest price (Energistyrelsen, n.d.E). Thereby, the government is focussing on developing a framework that makes investments in Power-to-X more attractive for project developers.

These initiatives act as a mediator, shaping interactions between actors, moreover, between the project developers and governmental climate goals, which can enable a translation process at Bornholm that makes the implementation of Power-to-X a reality. However, the current government plans for Energy Island Bornholm do not include the initiative for Power-to-X in the tender material but the concessionaire has the possibility of overplanting up to 600 MW (*1.3 Bornholm: An Energy Island in the Baltic Sea*), meaning this capacity is not going to be connected to the grid and thereby potentially can be used directly for Power-to-X. At this point, the framework of a potential Power-to-X plant on Bornholm is unknown for both the planned Energy Island Bornholm and the two open-door projects, mentioned in *1.3 Bornholm: An Energy Island in the Baltic Sea*, with a total capacity of 3 GW, meaning there are yet no development plans for a Power-to-X plant on Bornholm.

7.1.3 Great Potentials in Exporting Hydrogen

Denmark has great potential for exporting hydrogen and is also a necessity if Denmark is going to produce up to 6 GW of hydrogen since this exceeds the amount Denmark can utilise. In this relation, the Danish Climate, Energy, and Utilities Minister and the German Economics and Climate Minister signed an agreement in March 2023 on a hydrogen pipeline between Denmark and Germany which is planned to be operating in 2028 (Invest in Denmark, 2023; Ministry for Economic Affairs and Climate Action of the Federal Republic of Germany & Ministry of Climate, Energy and Utilities of Denmark, 2023). This initiative is key for the Power-to-X development since this means that investors are ensured that the hydrogen infrastructure will be implemented and makes it more attractive for developers to make investments (Invest in Denmark, 2023), as well as speaking in favour of implementing Power-to-X on Bornholm.

7.1.4 Summary

In the Legislative Power Network, the government has the ability to set policies and regulations related to energy and the environment, but these policies can be influenced by political agreements and targets, and thereby contribute to a translation of the energy system. The hydrogen plan and the EU's targets for reducing greenhouse gas emissions and increasing renewable energy production also have an impact on the government's actions. The government is focusing on developing a framework that makes investments in Power-to-X more attractive for project developers to accelerate the implementation of such plants. The Energy Island Bornholm project does not include Power-to-X in the tender material, but the concessionaire has the possibility of overplanting and potentially using it for Power-to-X. The framework of a potential Power-to-X plant on Bornholm is unknown until the tender process is finished and the concessionaire has been decided. The network of Legislative Power plays a significant role in unfolding the roadmap for Power-to-X implementation in Denmark and ensuring the progress. Establishing the framework and creating conditions to make investments in Power-to-X attractive is an essential step toward increasing Power-to-X.

7.2 Executive Order

Within this study the Executive Order Network has been identified to consist of; the Regional Municipality of Bornholm (BRK), Danish Energy Agency (DEA), Energinet, Danish Environmental Protection Agency (EPA), and DBI. This chapter will elaborate on the actor-network translations regarding these actors, visualised in Figure 22B.

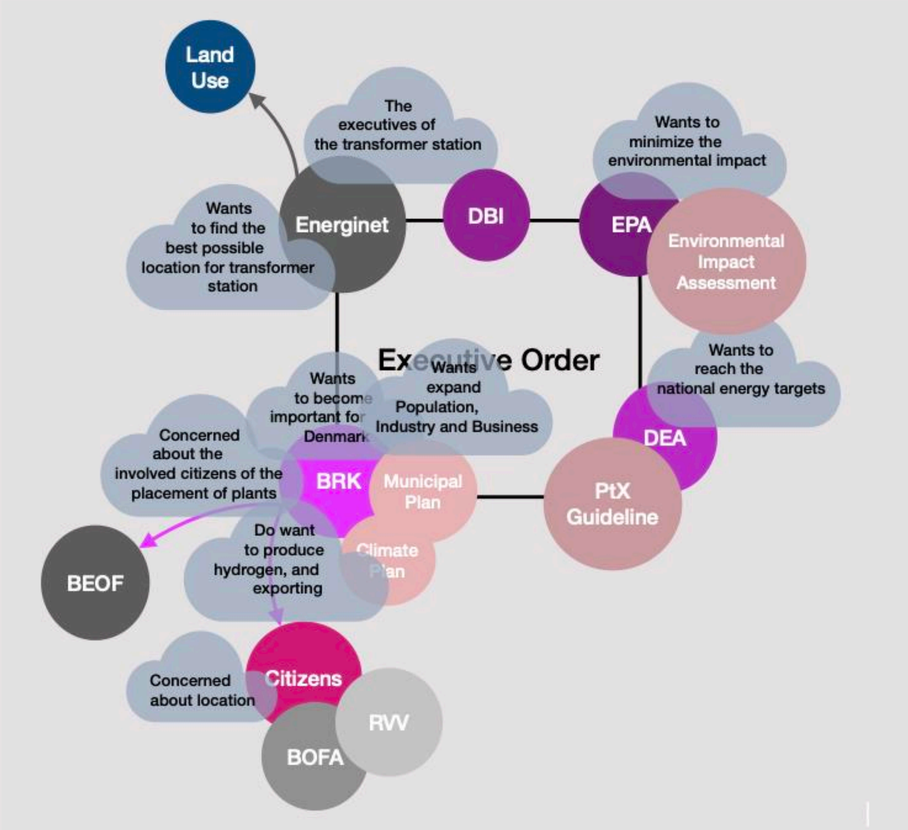


Figure 22B Illustration of the Executive Order Network showing the actors (circles), their matter of concern (clouds), and interactions to actors in other networks (arrows). Own production, made in Pages.

7.2.1 Regional Municipality of Bornholm

The Regional Municipality of Bornholm (BRK) is the only actor physically located on Bornholm within this network of actors. It is composed of both a political and administrative organisation, with the former comprising elected officials, including the municipal council and various committees, and the latter consisting of personnel employed by the Regional Municipality of Bornholm on a daily basis (Bornholms Regionskommune, n.d.E).

7.2.1.1 Ambitious Goals for Sustainability

The Regional Municipality of Bornholm has set ambitious goals for sustainable development and climate, including becoming CO_2-neutral by 2025 and fossil fuel-free by 2040, as outlined in the Municipal Plan 2020 [Danish: Bornholms Kommuneplan 2020]. To achieve these targets, the municipality aims to use its resources wisely and sustainably (Bornholms Regionskommune, 2021). The Bright Green Island's vision, based on the UN's 17 SDGs, outlines eight specific targets for achieving a community without fossil fuels (Bornholms Regionskommune, 2021). Power-to-X technology may play a crucial role in achieving these climate targets by providing a sustainable solution for the municipality.

7.2.1.2 "What's in it for Bornholm?"

Regarding the energy island project and the implementation of a potential Power-to-X plant, the Regional Municipality of Bornholm is involved in the projects to ensure a translation of the energy system and an implementation that is in line with the political agenda on Bornholm. However, like all municipalities in Denmark, the Regional Municipality of Bornholm, depends on decisions made by the Danish government. Therefore, the planning and targets within the Regional Municipality of Bornholm are impacted by decisions made on national level, including Energy Island Bornholm that will be connected directly to Bornholm (Appendix C, Appendix F, Appendix G). From the beginning, the Regional Municipality of Bornholm decided to collaborate with the Danish government on the planning of Energy Island Bornholm. This was to ensure the best possible implementation process of the transformer station since they knew they could not prevent the implementation of the island but possibly could influence how it is going to affect the island (Appendix F). This is expected to be the same case if implementing Power-to-X contributing to a successful implementation without compromising with the local community (Appendix G).

The approach within the Regional Municipality of Bornholm is "*what's in it for Bornholm*" and is an example in dialogue with Energinet, who is responsible for the transformer station for Energy Island Bornholm (Appendix C, D, F, G). By collaborating with Energinet, the municipality attempts to be the voice of the citizens and gain as many benefits from the project as possible (Appendix F).

7.2.1.3 Side Effects

During the interviews and from participating in the citizen's meeting about Energy Island Bornholm, it becomes clear that one of the main targets for

Bornholm is to increase the population on the island which potentially will result in economic growth. Currently, Bornholm has around 39,500 citizens, but the goal is to increase the population to 42,000 (Bornholms Regionskommune, 2021; Appendix F). It is expected implementing Energy Island Bornholm and a Power-to-X plant will contribute to an increase in the population, and economic growth, create permanent households, job opportunities, increase the educational level, and more sustainable and effective land use (Figure 23; Appendix C, D, F, G, H). Therefore, the implementation of Power-to-X can enable a translation process that works to achieve a common goal of different actors, namely increasing the population of Bornholm.

The municipality expects that implementing new technologies will create new job opportunities, both during the construction of the plant and on a more permanent basis when the plants are operating (Appendix C, D, F, G, H). Besides jobs created directly in relation to the plant, it is also expected to create a potential for existing companies on the island since they can take advantage of the new technologies (Appendix C, D, F, G, H, J; Energiø Bornholm, n.d.B).

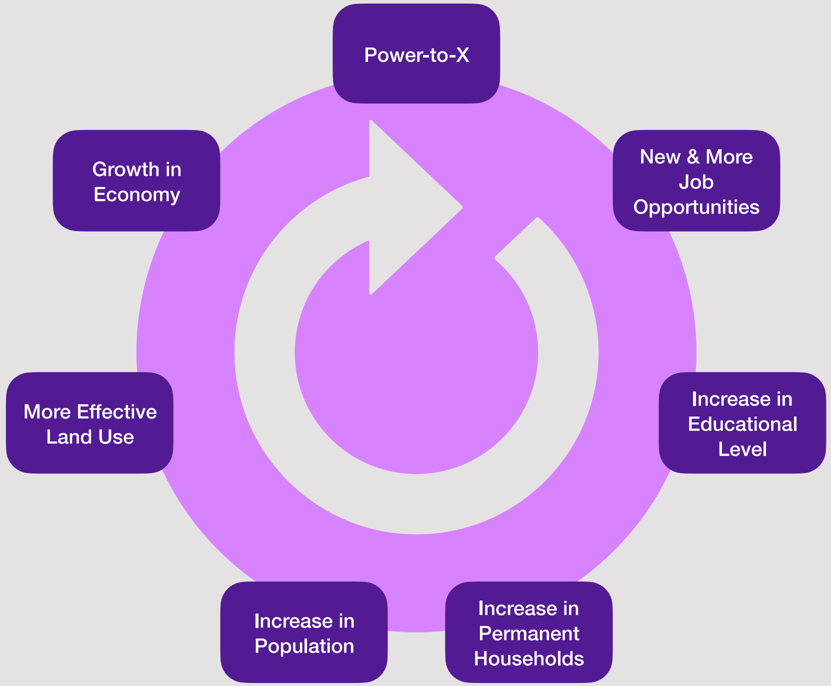


Figure 23 Illustration of how Power-to-X can create growth in the community. Own production, made in Pages.

The new technologies are also expected to attract education of a higher level by giving universities the opportunity to use the technologies as part of education. Thereby, the municipality aims to keep and create knowledge on Bornholm in the long term and can also result in students settling down on the island (Appendix J).

By attracting more workers and students, another side effect of building the new technologies is the possibility to increase permanent households on Bornholm. Currently, there is a housing shortage, meaning it is difficult to find a rental property. The municipality aims at utilising temporary homes built for construction workers during the construction phase of Energy Island Bornholm. These buildings can hereafter be used for permanent housing (Appendix C, D, F, G, O).

In total, the above-mentioned impacts have the potential to result in growth in the economy, because the population will increase and the educational level will become higher, meaning that more taxpayers will be present on the island. The implementation of Power-to-X has the possibility to contribute to a change of Bornholm from being a low-income municipality and instead become a resourceful municipality (Appendix F, Appendix G).
Another side effect of implementing new technologies is to use the land more effectively. Besides, implementing Power-to-X will allow sector coupling and thereby use energy resources more effectively, it is also expected to contribute to the agricultural sector and land use. As mentioned in *6.3.2.1 Surplus Heat*, surplus heat can be used for other industrial purposes than supplying the district heating network. Currently, the thought within the municipality is to compensate some of the impacted farmers by allowing them to use surplus heat from the Power-to-X plant in the farming technologies. This could as mentioned earlier be in vertical farming or greenhouses, allowing the farmers to grow locally produced crops all year round (Appendix D, Appendix F, Appendix G).

7.2.2 Danish Energy Agency and Energinet

The Regional Municipality of Bornholm works closely together with the main drivers behind the energy island project, the Danish Energy Agency, and Energinet.

The Danish Energy Agency is for Energy Island Bornholm responsible for the tender of the offshore wind turbine farms (Energiø Bornholm, n.d.A; Energistyrelsen, n.d.F) and is the authority of the energy island project, while Energinet provides tendering and establishment of the transformer station and cables on Bornholm and securing the connection to Zealand and Germany (Energistyrelsen, n.d.F; Energinet, n.d.B). Therefore, Energinet and the Danish Energy Agency work together in the project regarding the technical parts of the implementation. Furthermore, they collaborate with the Regional Municipality of Bornholm regarding hearings, citizen involvement, and communication of the project (Energistyrelsen, n.d.F). As part of the communication of the project, the Danish Energy Agency has had the responsibility of visualising how the offshore wind turbine farms will look from the coast (Energistyrelsen, 2020). Currently, the Danish Energy Agency is preparing the tenders for the offshore wind turbine farms in the Baltic Sea, collaborating with Germany about how to share green electricity with other

European energy systems, and working on the environmental impact assessment for the offshore farm (Energistyrelsen, n.d.F). Meanwhile, Energinet is collaborating with the Regional Municipality of Bornholm on finding a location for the transformer station where they currently are during preliminary studies of the area and making environmental impact assessments (Energistyrelsen, n.d.F). The overall goal of the Danish Energy Agency is to supply the grid and to transform some of the electricity to other energy sources, such as Power-to-X. However, the developer of the offshore wind turbine farm has the opportunity to establish the Power-to-X development in connection to the energy island project (Energistyrelsen, n.d.F).

7.2.3 Danish Environmental Protection Agency

As mentioned in Chapter *6.3.5 Environmental Impacts*, the environmental impacts can become a barrier for implementing Power-to-X since the plant will impact the surrounding area. Implementing Energy Island Bornholm will therefore require several environmental assessments since the project consists of different elements (Energiø Bornholm n.d.E; Miljøstyrelsen, n.d.B). Danish Energy Agency, Energinet, and the future developers must request the Danish Environmental Protection Agency for different environmental assessments during the project. In 2021/2022 a Strategic Environmental Assessment was made for the overall energy island project and currently, an environmental impact assessment for the transformer station is in preparation by Energinet and Danish Environmental Protection Agency (Energistyrelsen, n.d.H). Furthermore, concessionaire winners of the offshore wind turbine farm must make an environmental impact assessment on the area (Energistyrelsen, n.d.H). The Danish Environmental Protection Agency plays a major role in whether Energy Island Bornholm will be a reality and where it will be implemented (Miljøstyrelsen, n.d.B). If the Power-to-X plant is implemented in the future, a new environmental impact assessment will need to be made (Appendix A), considering pollutants such as noise, air, and visual impacts as mentioned in *6.3.5 Environmental Impacts.*

As part of the environmental impact assessment process, the Danish Environmental Protection Agency has to facilitate public hearings where all interested parties get the opportunity to submit consultation responses (Energistyrelsen, n.d.I).

7.2.4 Danish Institute of Fire and Security Technology

Danish Institute of Fire and Security Technology, DBI's, connection to the actor-network within the project on Bornholm regarding the potential implementation of a Power-to-X plant is associated with their knowledge and experiences regarding safety and risk related to Power-to-X (Danske Brand- og Sikringsteknisk Institut, n.d.B). A collaboration between DBI and other involved actors can become important in order to gain the needed knowledge about Power-to-X (Danish Institute of Fire and Security Technology, 2021). As described in *6.3.4 Potential Risk Related to Power-to-X Implementation,* the safety regulations will depend on which end-product is produced

(Ammonia, Hydrogen, or Methanol), the distance to other industries, workplaces, citizens, and how large the production and plant is going to be. DBI is an important actor when needing guidance and supervision about how the plant can be implemented safely on Bornholm (Appendix B). Power-to-X plant can be viewed as an actor that has the potential to influence DBI's operations and serve as a knowledge producer. DBI can leverage this opportunity to learn from the plant and share its knowledge with other countries. Additionally, DBI can act as an intermediary between different actors, technologies, and knowledge systems to facilitate the translation processes necessary for implementing Power-to-X on Bornholm.

7.2.5 Summary

In this network the actors have interrelations that consist of executive relationships. Similar to the Legislative Power Network, the Executive Order Network comprises actors that possess agency and can shape and impact the network. The Regional Municipality of Bornholm has its own distinct interests and targets concerning the island's economy, energy production, and consumption, which could affect the implementation of Power-to-X on Bornholm. Furthermore, the Danish Energy Agency is an important actor as they are responsible for regulating and developing the offshore wind turbine farms. Energinet is in charge of implementing the grid and transformer station, which is essential for the distribution and transmission of energy on the island, but also decides the location of the transformer station, and hereby interacts with land use.

Danish Environmental Protection Agency and DBI are important actors in the network, as they are responsible for ensuring that energy infrastructure and technologies meet environmental and safety regulations.

7.3 Energy Island Bornholm

This network includes actors that have a role in the planning and preparations prior to implementing Energy Island Bornholm. The actors within this network are visualised in Figure 22C.

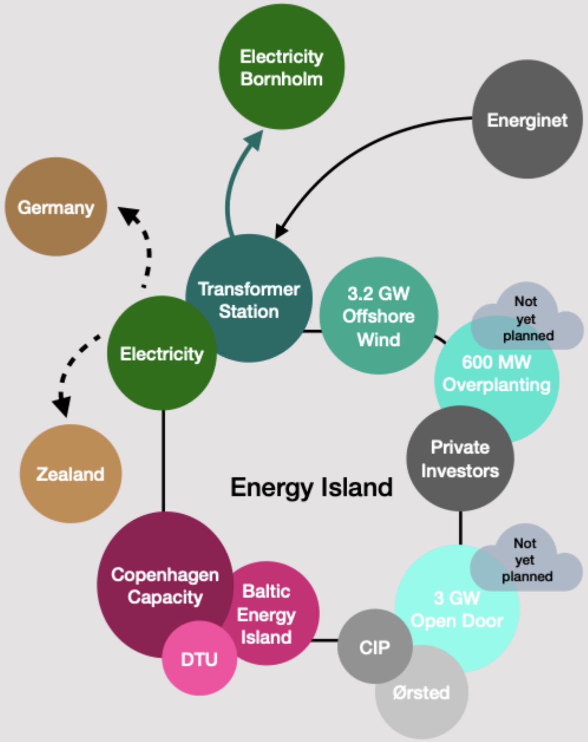


Figure 22C Illustration of Energy Island Network showing the actors (circles), their matter of concern (clouds), interactions to actors in other networks (arrows), and physical interactions (dotted arrow). Own production, made in Pages.

Potentially producing Power-to-X on Bornholm originally started with the concept of implementing Energy Island Bornholm initiated by the government (Appendix O). In the material prior to the tender process, the government has enabled the possibility of overplanting that could be used for Power-to-X (as mentioned in *1.3 Bornholm: An Energy Island in the Baltic Sea*). Since then, investors have seen potential in producing offshore wind energy around Bornholm whereof Copenhagen Infrastructure Partners and Ørsted have applied through the Open-door procedure for two offshore wind projects on the east side of Bornholm that could be used for Power-to-X, see Chapter *1.3 Bornholm: An Energy Island in the Baltic Sea* (Ørsted, 2022).

Energy Island Bornholm is the centre of this network since it is this project that initiated considerations of implementing Power-to-X on Bornholm (Appendix O). Moreover, the capacity of the wind turbine farms is interconnected with the capacity of Power-to-X, and ultimately, with the quantity of hydrogen, methanol, or ammonia that can be produced (Energistyrelsen, 2023). Therefore, it can be concluded that the capacity of the wind turbines has a great impact on other actors in this network.

Furthermore, this network contains actors that pave the way for implementing Energy Island Bornholm such as Baltic Energy Island and the Technical University of Denmark. These actors have a role in combining knowledge and experiences which can be used in the implementation of Power-to-X on Bornholm (Appendix I, Appendix J).

7.3.1 Baltic Energy Island

The Baltic Energy Island aims to develop a network of actors consisting of companies and system operators entailing the green transition, researchers developing and teaching innovative solutions to the Regional Municipality of Bornholm, local companies, and stakeholders who are working towards transforming the future of Bornholm (Baltic Energy Island, n.d.). This stakeholder could have a great influence on the implementation of Power-to-X on Bornholm since it might attract experts and business tourism to Bornholm. This will create a positive translation process enabling the necessary changes needed for the successful implementation of Power-to-X. Furthermore, this provides expertise and knowledge that enables the development of the needed technologies for the implementation of Power-to-X. The Baltic Energy Island is a mediator that connects and mobilises the different actors in the network toward achieving a common goal.

7.3.2 Transformer Station

The transformer station is a crucial actor in the network of Energy Island Bornholm since it distributes the energy generated by offshore wind farms to the grid. Energinet operates the transformer station and has a significant role in the development and implementation of the overall energy infrastructure. There is an interaction between the actors in this network because the capacity of the wind farms impacts the capacity of the transformer station. Additionally, the transformer station has the potential to impact the implementation of the Power-to-X plant on Bornholm and enable Bornholm to be supplied with renewable energy.

Connecting the transformer station directly to the electricity grid of Bornholm is technically challenging as Lillian Rasch Madsen, Director at Bornholm's Regional Municipality stated: "*I understood that technically it is enormously complicated because it is like connecting a small sewing thread into some such huge cable*" (Appendix F, Line 375-376 - translated from Danish). This is a technical barrier since it is complicated to supply such a proportionally small grid with the power generated from the wind turbines.

Madsen, furthermore, reflects upon the opportunity to impact the electricity costs for the citizens of Bornholm which therefore is an interaction with the current system of Bornholm. According to Madsen, could the connection between the transformer station and the electricity grid of Bornholm result in a new price zone called DK3, which would be a bit reduced compared to the already existing price zones DK1 and DK2 (Appendix F). However, the price difference is expected to be minimal. In this context, the implementation of a Power-to-X plant at Bornholm involves various actors such as the citizens, the electricity grid, the transformer station, and potentially new price zones. The

Power-to-X plant introduces a new element into the existing network, which can potentially impact the electricity costs for the citizens, similar to the transformer station.
Lillian's reflection on the opportunity to impact electricity costs suggests an awareness of the potential effects of implementing Power-to-X in the current system. The connection between the transformer station and the electricity grid of Bornholm creates a new interaction within the network.

7.3.3 Summary

Since the transformer station is already being planned it has a significant role in the implementation of a Power-to-X facility on Bornholm. Energy Island Bornholm involves multiple actors and stakeholders, including the government, investors, offshore wind turbine farms, the transformer station, and the Baltic Energy Island. Power-to-X is considered a potential source of renewable energy which is interconnected with the capacity of offshore wind farms and the transformer station. The Baltic Energy Island is a stakeholder that will influence the success of the project by drawing experts and business tourism to Bornholm.

The transformer station is a crucial actor and has the potential to impact the location of Power-to-X on Bornholm, and as recommended in *6.4 Recommendations for Placing the Power-to-X Plant,* it could be beneficial to locate the Power-to-X facilities next to the transformer station. Connecting the transformer station to the electricity grid of Bornholm is a barrier that needs to be solved if Energy Island Bornholm should become a benefit for the green transition of Bornholm.

7.4 The Water System of Bornholm

The Water System of Bornholm will be analysed as an actor-network to gain a better understanding of the potential impact on implementation of a Power-to-X plant. This analysis is necessary due to the water demand that electrolysis requires, elaborated upon in Chapter *6.3.1 Water Challenges*. The goal of this chapter is to gain insights into how the Water System needs to be adapted or optimised to support implementation of a Power-to-X plant.

Figure 22D illustrates the current network of the Water System of Bornholm, which is used to analyse the interactions that will occur if Power-to-X is implemented. The figure also identifies matters of concern on the current state of reality and possibilities for enacting changes in the current water system (Law, 2016).

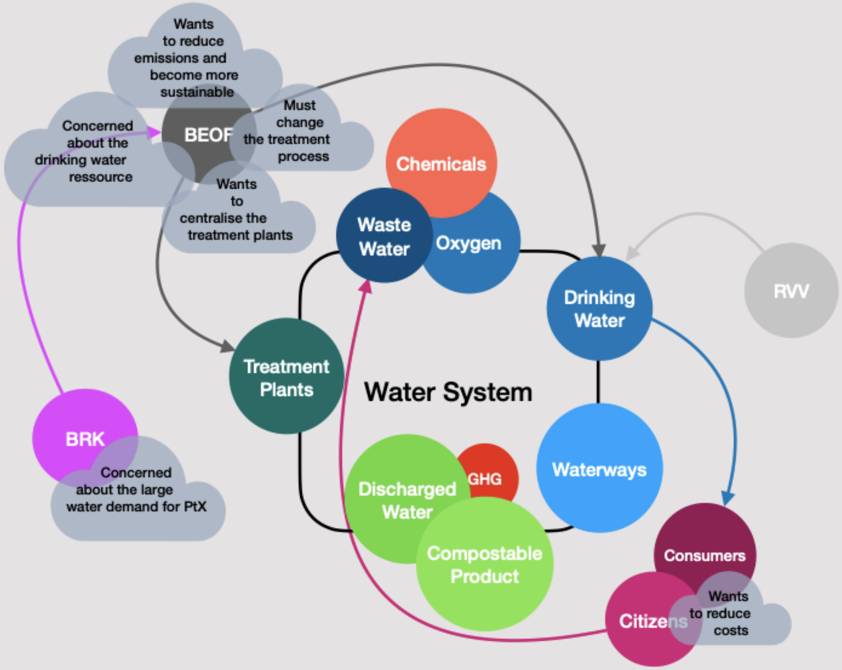


Figure 22D Illustration of the Water System Network showing the actors (circles), their matter of concern (clouds), and interactions to actors in other networks (arrows). Own production, made in Pages.

The water demand is a concern for the Regional Municipality of Bornholm (Appendix D, Appendix F), meaning it is a barrier for the implementation of Power-to-X (*6.3.1 Water Challenges*).

The water challenges add another layer of actors to the network. The Regional Municipality of Bornholm impacts the actor-network by setting policies about drinking water and wastewater and sees a potential in purifying the wastewater as much as possible (Appendix D, F, G, H), making it suitable for electrolysis.

7.4.1 Centralising the Wastewater Treatment Plant

In an actor-network perspective, the actors involved in the water infrastructure on Bornholm includes 18 water plants located around the island supplying the citizens with drinking water (*6.1.2.1 Water Supply*), illustrated on Figure 10. BEOF is responsible for managing the wastewater on the island, meaning they are an actor, playing a major role in the network. They purify the wastewater on Bornholm and supply, together with other private companies, including Rønne Vand & Varme, with drinking water (*6.1.2.1 Water Supply*).

Furthermore, the seven wastewater treatment plants play a role in the network when implementing Power-to-X by being a barrier if they stay decentralised (Appendix H; *6.1.2.1 Water Supply*). To overcome this barrier the wastewater treatment plants can be centralised. Centralising current wastewater infrastructure can become a barrier economically, physically, and environmentally. Additionally, BEOF investigates whether the wastewater treatment plants should be centralised in the future, especially if it is placed near a potential Power-to-X plant (Appendix H).

The interaction between BEOF and the Power-to-X plant has the power to push for changes in the current system by treating wastewater to a quality suitable for electrolysis. This interaction could serve as a driving force for changes in the Water System of Bornholm.

Centralising the treatment plants, mostly placed by the coast, can contribute to interactions between actors in the network. As an example, Madsen states:

> *"I start to think that then you can get some coastal area released for something exciting, right? So, among other things, in Rønne there is, after all, the area that could have been used for something else, for example where the sewage treatment plant is now".* (Appendix F, Line nr. 328-330, translated from Danish).

Thereby, Madsen sees a potential in centralising treatment plants since this would release scenic areas with potential for developing nature, biodiversity or housing (Appendix F).

7.4.2 Water Consumers

Besides the need for available drinking water for citizens, depending on the population, the water system of Bornholm comprises other actors. This includes by-products from the treatment plants consisting of purified wastewater that is discharged into waterways and compostable surplus products as illustrated on Figure 9 and mentioned in Chapter *6.1.2.1 Water Supply*. Although these actors do not have a direct role in implementing Power-to-X, they will be impacted if such implementation takes place (Appendix H). These by-products can enable a synergy between the Energy System Network, Local Influenced, and the Water System Network.

The extended treatment process of wastewater leads to an increase in the amount of compostable surplus products, making it an important actor in the network. The compostable surplus products are extracted from wastewater during the purification process and can be repurposed as biogas, increasing the production of heat and power at the biogas plant, fertiliser in agriculture or for incineration (*6.1.2.2 Wastewater*). However, the farmers may face an ethical dilemma in using fertiliser made from wastewater by-products (Appendix H). Therefore, the implementation of Power-to-X can create new interactions between various actors from different networks.

7.4.3 Surplus Oxygen

As mentioned in *6.3.1 Water Challenges,* there is a surplus product of oxygen from the electrolysis process. The surplus oxygen can be used in the treatment process of wastewater to purify the water to the needed quality for the electrolysis. The treatment plant is an important actor in the Water System network as it uses chemicals and oxygen to purify wastewater. If the treatment plant were to purify wastewater to a quality good enough, it would lead to an extension of the treatment process (Appendix H). The process could result in an increase in emissions from the treatment plant (Appendix H). Therefore, any changes made to the water system must consider the potential impact on the treatment plant and its use of chemicals (Appendix H; Bornholms Energi og Forsyning, 2021).

To make this process work within the existing water system, new actor-networks need to be formed between the water treatment plant, BEOF, and the actors involved in the production and use of renewable fuels. This would require a translation of the existing practices and technologies used in the water treatment plant to incorporate the use of oxygen generated through electrolysis. This is visualised in Figure 24. The water treatment plant would need to be modified to allow for the injection of oxygen from the electrolyser into the wastewater treatment plant. The increased oxygen in the treatment could improve the efficiency of the treatment process and potentially reduce the emissions produced (Appendix H).

The translation process would require involvement of actors from other networks, such as the energy system and private companies involved in the Power-to-X plant. Furthermore, the energy system and private companies would need to collaborate with the Water System through new actor-networks that enable the exchange of resources and knowledge necessary for the implementation of Power-to-X.

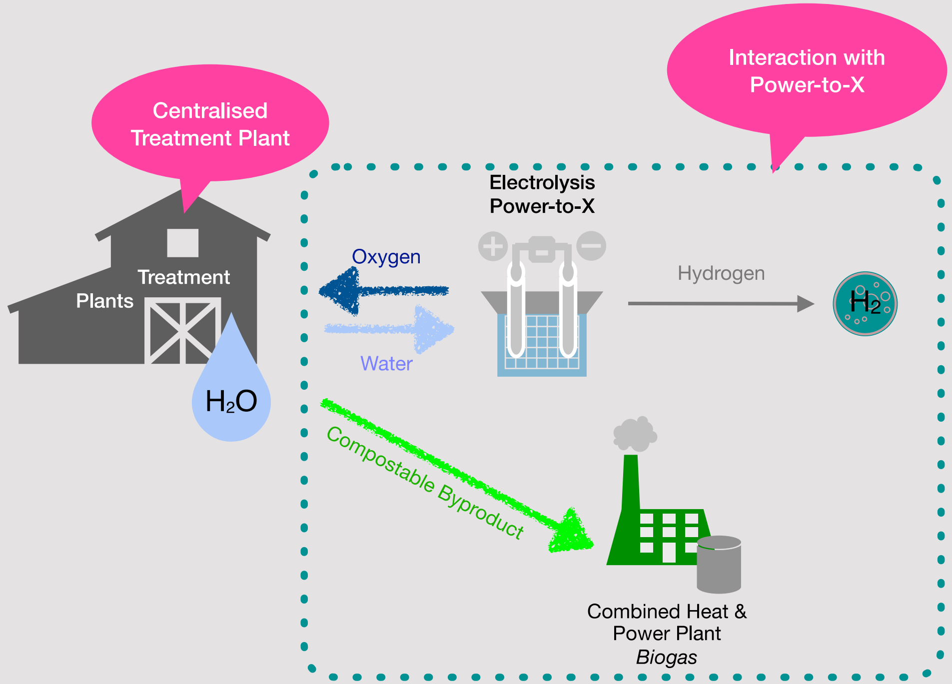


Figure 24 Illustration of the synergies between water treatment plants and Power-to-X processes. Own production, made in Pages.

7.4.4 Summary

The Water System of Bornholm can be seen as a network, due to the interdependencies between above-described actors who have an impact on water supply. Since the water supply is essential for producing Power-to-X it should be considered how to treat and distribute the water resources. Initiatives, such as centralising water treatments, using the surplus oxygen from the treatment process and compostable product, should be part of the sector coupling when implementing Power-to-X.

The network is going to change if a Power-to-X plant is implemented by new actors being involved and technologies introduced. For example, new water treatment technologies are going to be introduced, more advanced treatment processes and a change in water demand, which can have significant impacts on this network.

7.5 Energy System of Bornholm

The Energy System on Bornholm can be seen as a network mainly consisting of non-human actors in the form of different energy technologies. The current Energy System on Bornholm is identified as a network, because of the interrelations between the existing technologies. These interrelations are visualised in Figure 22E. The Energy System is connected with a physical connection since many technologies within the Energy System are connected with physical pipes and wires, making the interactions visible.

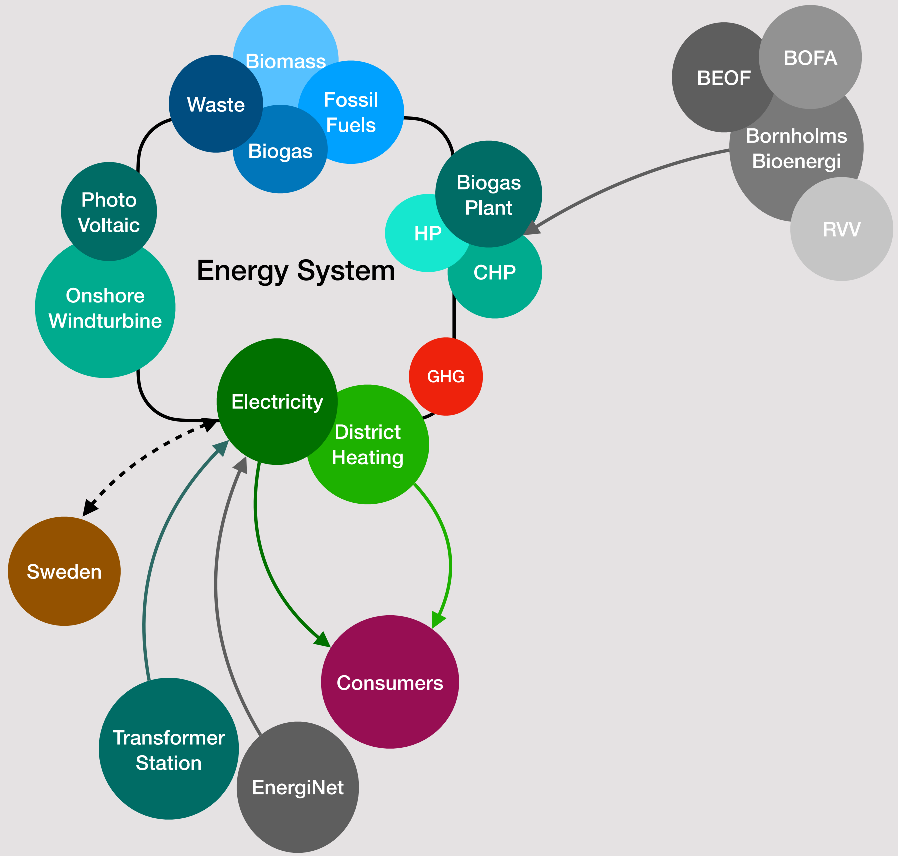


Figure 22E Illustration of the Energy System Network showing the actors (circles), their matter of concern (clouds), interactions to actors in other networks (arrows), and physical interactions (dotted arrows). Own Production, made in Pages.

7.5.1 Actors in the Energy System

As mentioned in *6.1.1.1.1 Combined Heat and Power* a combined heat and power plant located in Rønne produces a large amount of the electricity and district heating consumed on Bornholm (Bornholms Energi og Forsyning, n.d.B). A large share of the energy on Bornholm is today produced by local energy (*6.1 Current Infrastructure on Bornholm*). However, the energy system at Bornholm still depends on imported biomass for district heating, electricity from Sweden, and fossil fuels as energy supply, meaning the network still interacts with actors outside Bornholm.

Furthermore, the newly published plan for biogas on Bornholm, states the possibility of increasing the biogas production on the island, leading to possibilities of creating sector couplings contributing to the green transition on Bornholm (Bornholms Landbrug & Fødevarer, 2023). The biogas production is going to use local resources from the agricultural sector, industry, companies, and households, making interrelations across these sectors. Additionally, the biogas plant will result in CO_2 emissions which potentially can be used for methanol production (Bornholms Landbrug & Fødevarer, 2023), limiting the barriers for production of Power-to-Methanol (*6.3.2.2.3 Power-to-Methanol*).

Besides the technologies of the Energy system, supply companies; Energinet, BEOF, BOFA, Bornholms Bioenergi, Rønne Vand & Varme, influence the energy system and the interrelations. The different supply companies on Bornholm are related and collaborate to secure energy supply for consumers. The supply companies, in the context of the current Energy System Network, act as stabilisers and function as agents that contribute to the stability and coherence of the network.

If Power-to-X is implemented on Bornholm, some of the main goals and benefits of the project is to become self-sufficient and achieve a 100% renewable energy system. If Power-to-X is implemented on Bornholm it will impact the relations in the network of the Energy System which is visualised in Figure 22F.

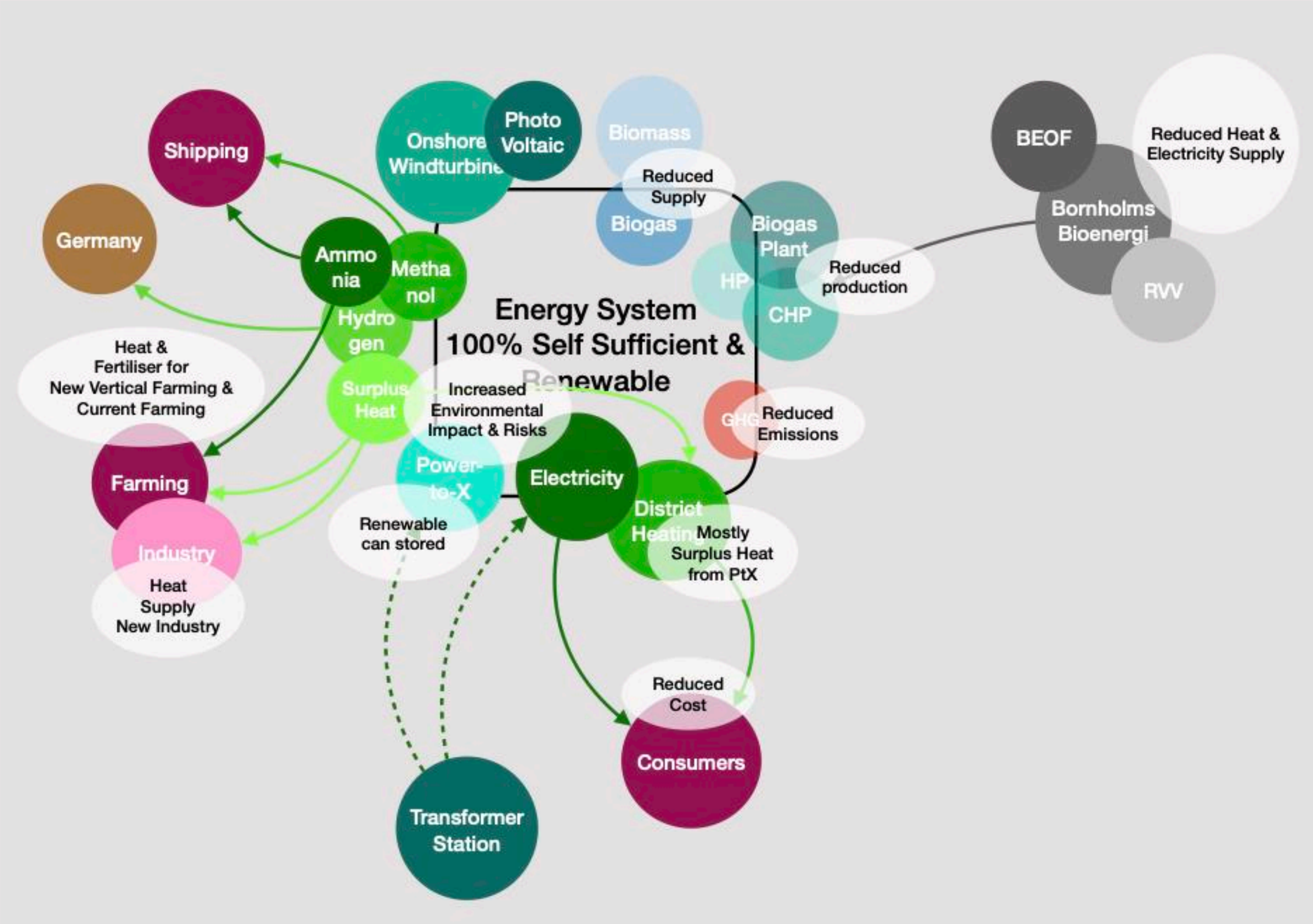


Figure 22F Illustration of the network if Power-to-X is implemented showing the actors (circles), interactions to actors in other networks (arrows), some of the benefits (ovals), and physical interactions (dotted arrows). Own production, made in Pages.

7.5.2 The Impacts from Power-to-X on the Energy System

As analysed throughout the above chapters, implementation of Energy Island Bornholm will impact the overall energy system on the island in several aspects (see Figure 22F). The implementation of the Power-to-X plant on Bornholm next to the new transformer station will introduce new elements into this network and initiate a process of translation. Regardless of how the transformer station is implemented it will be part of Bornholm since it takes up land, however, it is not yet decided whether it is going to be connected to the local grid. Depending on the final decision on the grid connection, it will influence whether the energy system of Bornholm can benefit from Energy Island Bornholm.

Contrary, there can be identified barriers to implementing Power-to-X. One barrier is that it will require installations of new equipment. First of all, it would require electrolysers to convert the electricity into Power-to-X. Depending on which end-product is produced the technologies will vary hereunder would methanol require carbon capture technology. Finally, infrastructure connection to transport the fuel would have to be installed, potentially together with storage technologies. Securing the needed technologies is a translation process which can be difficult to overcome, due to economic and land use barriers.

As mentioned earlier in Chapter *6.1.1.1.2 Renewable Energy - Wind Turbines, Solar Power, Biogas, and Biomass*, BEOF considers biomass as a temporary resource, which only should be used until it can be substituted with other resources for heating. Power-to-X has the potential to become the substitute for biomass, since during the production within the plant, a large share of surplus heat will occur. The surplus heat from the Power-to-X plant has the potential to be used within the district heating network of Bornholm and impact the heating interrelations of the actor-network.
As mentioned earlier in *6.3.2.1 Surplus Heat*, the heat generation from Power-to-X will overcome the heating demand for district heating, meaning that there will be further surplus heat that can be used for other purposes. When talking to several of the respondents, they also mention the opportunity to use some of the surplus heat in either vertical farming or tourism purposes such as concepts like "the blue lagoon" (Appendix D, F, G, H, M). Due to the surplus heat production, implementing Power-to-X will create new interrelations between the Energy System, agricultural sector, and tourism.

7.5.3 Power-to-X as Substitute for Fossil Fuels

Depending on how the Power-to-X plant is made and incorporated into the energy system it also has the potential to contribute with energy storage (*6.3.2.1.3 Storing Opportunities*). This can solve the problem of using fossil fuels for emergency energy generation when the production of renewable energy is impossible and when the connection to Sweden is out of order. Storage of Power-to-X end-products can reduce the need for fossil fuels and for a connection to the Swedish electricity grid (Appendix H).

As mentioned in Chapter *1.3 Bornholm: An Energy Island in the Baltic Sea*, Bornholm can be a hub to produce methanol and ammonia for the shipping industry, which can be seen as a driver for the implementation of Power-to-X. The production of methanol and ammonia could lead to new economic opportunities for the island and help to establish Bornholm as a key player in the transition to a more sustainable Energy System (Appendix M, Appendix O). Therefore, the production of ammonia and methanol can be viewed as actors that have the ability to create a translation process between different networks, connecting the energy and shipping sectors. However, implementing such a system may encounter barriers such as resistance from existing industries, technological limitations, and regulatory hurdles (Appendix M).

7.5.4 Bornholm’s Position on Denmark's Green Transition

Implementing Power-to-X in the energy system of Bornholm can potentially also transform Bornholm's position and status in Denmark. Several of the respondents mention the possibility to increase the status of Bornholm (Appendix C, Appendix H, Appendix O). At the citizens meeting Søren Møller-Christensen, Director of Baltic Energy Island, also highlighted the potential of changing the physical location of Bornholm on a map, where it typically is placed in the upper right corner and instead placing it at the right location on the map (Appendix O). Implementing Power-to-X on Bornholm will make the island front runners in the green transition, and Bornholm will gain an important location in the direct lines of the future planned hydrogen network from Finland through the Baltic Sea and down to Germany or Denmark (Appendix O).

7.5.5 Summary

To achieve a self-sufficient, renewable energy system on Bornholm, the implementation of Power-to-X is necessary. However, introducing new elements into the network can be challenging. The energy island project, which will supply electricity from offshore wind turbines, will act as a catalyst for translating the Energy System on Bornholm.

Creating interactions between existing infrastructure and Power-to-X plants can reduce the use of non-renewable energy sources, such as imported biomass, electricity from Sweden, and fossil fuels. The translation process involves the reconfiguration of existing networks, including the establishment of new connections and the disconnection of others. The outcome will be a self-sufficient, renewable energy system on Bornholm with reduced reliance on non-renewable sources.

7.6 Local Influenced

The network of Local Influenced consists of interconnected actors, including citizens, consumers, supply companies, Port of Rønne, land use, farming, business, tourism, and industry. These will be influenced if Power-to-X is implemented, but in various ways which will be described in the following chapter.

Figure 22G provides a visual representation of the actors in the network, highlighting the importance of the actors and their matter of concerns. However, it is important to note that the influence of the utility companies and consumers has been analysed in previously described networks, emphasising the interconnectedness of the various networks.

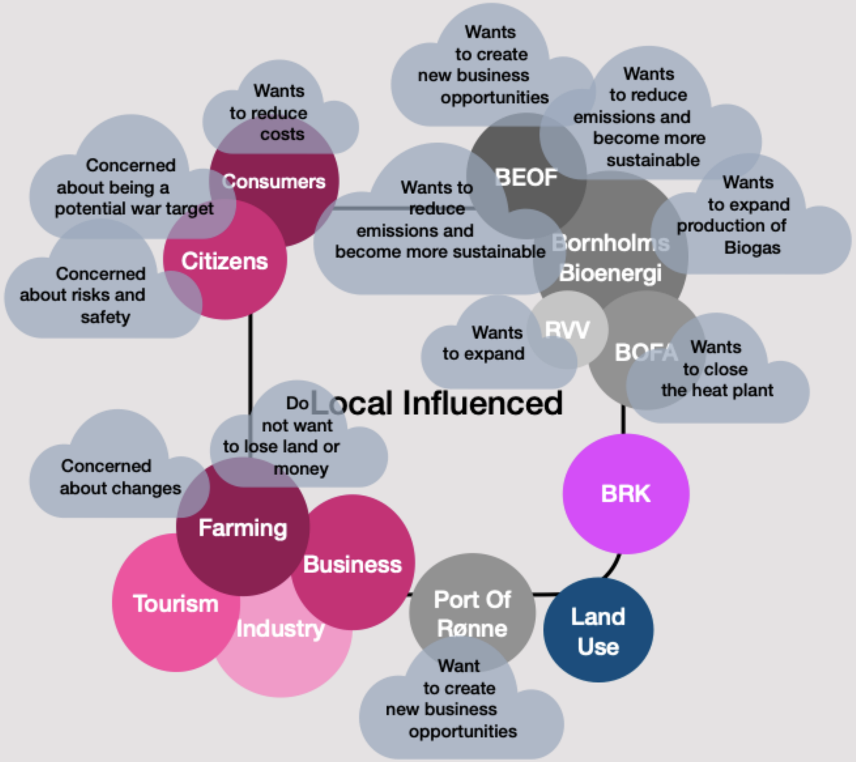


Figure 22G Illustration of the Local Influenced Network showing the important actors (circles) and their matter of concern (clouds). Own production, made in Pages.

7.6.1 Impacts on Local Businesses

The implementation of Energy Island Bornholm and a Power-to-X plant has made locals concerned about how these changes may impact their businesses (Appendix C; Appendix G). Firstly, implementations of energy technologies take up space influencing agriculture and their yields.

Contrarily, the implementation of Power-to-X and the utilisation of surplus heat can promote vertical farming on Bornholm (*6.3.2.1 Surplus Heat*). Vertical farming is a method of growing crops in vertical layers in controlled environments (*6.3.2.1.2 Vertical Farming*). By utilising surplus heat from Power-to-X processes to heat indoor facilities, Bornholm's farmers can grow a wide range of crops (Appendix G, Appendix H). This can lead to new economic opportunities for Bornholm's farmers and reduce the island's dependence on imported fruits and vegetables, reducing transport needs and thereby the use of fossil fuels. Furthermore, the change from traditional farming to vertical farming can reduce the use of fertilisers and water, making farming more sustainable (Soojin & Chungui, 2023; Beacham et. al., 2019). However, there are also some potential challenges associated with vertical farming, since it may require specialised knowledge of indoor farming and technology (Cultivatd, 2022).

It can be concluded that the implementation of Power-to-X technology can result in changes to the agricultural practices of local farmers. The process of adapting to these changes can be hindered by a lack of knowledge and access to appropriate technology. To overcome this barrier, the Regional Municipality of Bornholm attempts to provide education and knowledge resources for the local farmers and make a platform for knowledge sharing (Appendix G; Appendix J). This will function as a translation process, easing the implementation of Power-to-X technology.

7.6.2 Impacts on Tourism

Tourism has a significant role in the economy of Bornholm. From the Regional Municipality of Bornholm's point of view, implementation of Power-to-X will not make tourists avoid going to Bornholm but nevertheless emphasises that it is important to focus on avoiding any loss in tourism (Appendix F). The tourism industry on Bornholm can be seen as a network of interconnected actors, including tourists, local businesses such as restaurants, shops, and tourist attractions. The different kinds of tourist businesses rely on each other to secure best practice, service, and experience within the tourism industry on Bornholm.

By utilising surplus heat from a Power-to-X plant for tourist attractions, such as implementing a "Blue Lagoon" or a ski slope at Bornholm (Appendix D), the network can potentially be expanded. This allows businesses to remain open year-round and for more tourists to be attracted to the island during off-peak seasons. This would lead to a more sustainable tourism industry on Bornholm, with a more stable flow of revenue throughout the year and potentially a better economy for Bornholm (Appendix D).

The implementation of Power-to-X can attract business tourists interested in learning about Energy Island Bornholm (*7.3.1 Baltic Energy Island*), leading to increased interaction between the energy island and local businesses. This results in businesses remaining open in the off-season and hereby, more jobs can be created resulting in economic growth on the island. Additionally, the use of Power-to-X, such as vertical farming for local food production (*6.3.2.1.2 Vertical Farming*), can attract eco-tourists interested in sustainable and locally produced food (Appendix G; Appendix H). This can further enhance tourism on Bornholm and contribute to a reputation as a sustainable, green, and innovative destination.

7.6.3 Job Creations

As mentioned in Chapter *7.2.1.3 Side Effects*, an important interaction in this network is the potential for job creation. In the construction phase, the jobs are temporary but during the operation phase, there is a possibility of creating permanent jobs, essential for attracting people to move to the island. This has previously been seen related to projects on the Port of Rønne (Appendix G). Madsen from the Regional Municipality of Bornholm states:

> *"But I think the Power-to-X plant is going to be the game changer in this. If this is implemented, it will open up to several possibilities that can give permanent jobs which is a condition for making people move."* (Appendix F, Line nr. 120-123 - Translated from Danish).

Job opportunities are essential for attracting people to move to the island which is in the interest of the regional municipality. Furthermore, the regional municipality experiences a housing shortage which could be accommodated by adapting the housing for construction workers to function on a permanent basis, as mentioned in *7.2.1.3 Side Effects*. To secure the interaction between Energy Island, Power-to-X and better economy for the Regional Municipality of Bornholm, the securing of permanent housing plays a significant role. The Mayor of Bornholm, Jacob Trøst, states:

> *"One way to potentially ensure the construction of permanent housing is by incorporating a clause in the contract that obligates the developer to lease a certain number of units for a set period of time. This would provide some level of guaranteed rental income for the developer, incentivizing them to proceed with construction. As a result, it may be possible to secure the necessary funding for the project".* (Appendix G, Line nr. 182-185 - Translated from Danish).

Based on the quote, interaction can be secured by making a clause in the contract with developers of the potential Power-to-X plant. This can entail an economic guarantee for investment in housing at Bornholm.

In general, the Regional Municipality of Bornholm has a history of being economically badly off and sees opportunities of becoming a stronger municipality by the implementation of Energy Island Bornholm since it could create jobs and attract citizens (Energiø Bornholm, n.d.F).

However, it is notable that new jobs, companies, and work synergies related to the implementation of Power-to-X can result in a loss in other jobs and business, meaning a decrease in existing workplaces. Implementation of Power-to-X can create sector couplings, centralise existing energy and water infrastructure and integrate new, advanced technologies, resulting in a need for fewer employees (Appendix F; Appendix M).

7.6.4 Concerns from the Local Citizens

As mentioned in Chapter *6.3.4 Potential Risk Related to Power-to-X Implementation*, hydrogen, methanol and ammonia can be toxic and explosive, meaning they must be handled with caution. However, implementing potentially hazardous energy technologies can be met by concern from local citizens. At the latest, citizens in Aalborg have expressed concern about a Power-to-X project in Aalborg being explosive and a target for terror (Schouenborg, 2023). Similarly, the citizens of Bornholm have the same concerns, affecting the implementation (Appendix O). The citizens of Bornholm are comparing a Power-to-X plant to a nuclear power plant (Appendix M; Appendix N; Appendix O), a comparison that has arisen due to a lack of knowledge about Power-to-X (Appendix M). By providing knowledge about Power-to-X to the citizens of Bornholm, there is a potential of a translation process that could contribute to optimising the implementation of Power-to-X. However, this requires an increase of citizen involvement which as an example could be Baltic Energy Island as they are knowledge-sharing actors. They could be responsible for involving citizens and providing them with the necessary knowledge about Power-to-X, thereby overcoming the citizens' concerns.

Secondly, the citizens are concerned of becoming a war target, especially after Russia's spying activities and search for critical infrastructure targets (Appendix O). This concern arises since the future transformer station will handle large amounts of the electricity that will be distributed to both Zealand and Germany, making Bornholm of great infrastructural importance. However, this is not a concern shared by the Mayor of Bornholm, Trøst, who states:

> "*We have had drilling platforms in the North Sea for many years, and they are relatively easy to blow up if someone has malicious intentions (...) energy infrastructure will always be a target in times of full-scale war. We can see in Ukraine how their energy infrastructure has been targeted. However, this does not necessarily put Bornholm at a greater risk.*"
> (Appendix G, Line nr. 92-97 - Translated from Danish).

The Mayor is not of the belief that the implementation of the Power-to-X will make Bornholm a greater war target, but acknowledges the concerns of the citizens.

Additionally, the citizens' concerns are relevant actors in the implementation of Power-to-X on Bornholm since neighbours to the transformer station and the potential Power-to-X plant are concerned about the impact on their quality of life, which includes noise and visual pollution. To ensure the success of the implementation of Power-to-X, the local government needs to acknowledge these concerns and involve the citizens in the decision-making process. It is important to address these concerns and provide reassurance to the citizens that their well-being is a priority in the implementation of the Power-to-X.

7.6.5 Land Use

The transformer station and Power-to-X plant can impact the land use of Bornholm differently. One is the environmental impact that depends on size and capacity (*6.3.5 Environmental Impacts*). As the location of the transformer station is cultivated land, the implementation of transformer station and Power-to-X does not have a significant impact on biodiversity, as Madsen states:

"The Nature Conservation Association says that there is no biodiversity, so nothing is lost because such cultivated land has no biodiversity. We can also discuss what landscape value this area has because it is already disturbed. Therefore, I am not worried, and there is more space to use for implementation."

Hence, it can be concluded that the regional municipality does not see barriers related to biodiversity using the land adjacent to the transformer station for a Power-to-X plant.

The transformer station and the Power-to-X plant will have a negative visual impact on the nature of Bornholm. It can be difficult for the locals to accept the visual change since it is a change in the landscape (Appendix G).

Therefore, involvement of citizens is important to minimise concerns and make the implementation of Power-to-X successful (Jyllands-Posten, 2022). This is due to a general opposition among citizens that can act as a barrier to the implementation of Power-to-X (Jyllands-Posten, 2023).

Farmers are also concerned about using their land for a Power-to-X plant. The farmers' agricultural land will become less valuable and/or partially or completely acquired for the transformer station and the potential Power-to-X implementation. This resistance is natural (Appendix H) since property value may decrease, or their farmland may need to be shut down or converted. Therefore, it is crucial for the Regional Municipality of Bornholm to take care of the directly affected parties in the best possible way. This includes ensuring the best possible compensation for the involved parties, as there is currently no legislation outlining clear guidelines for compensation (Appendix F; Appendix G; Appendix H). The responsibility of the Regional Municipality of Bornholm is to negotiate any potential compensation for citizens with Energinet (Appendix F). Additionally, the Mayor of the Regional Municipality of Bornholm also states the opportunity for educating the affected farmers about how they can use their land differently, such as implementing vertical farming, and teach them about potential benefits from changing their agriculture (Appendix G). From an Actor-Network perspective, the Regional Municipality can act as a mediator between citizens, Energinet and the implementation of Power-to-X, acting as a translation process to help align these different actors' interests and needs in the negotiation process.

To prevent the strong opposition and resistance towards the implementation of Power-to-X, it is necessary for resistance to get knowledge about the positive aspects of the implementation. According to the mayor, it is the politicians' duty to demonstrate that implementing Power-to-X is not dangerous and provide the necessary knowledge to the citizens. Trøst explains:

"*Politicians have a significant task in demonstrating what it is* (Power-to-X)*, showing green fuels produced by a Power-to-X plant is done under extensive precautionary measures that it does not pose any greater risk than other industries. But the Power-to-X plant can be beneficial, either in the form of providing green energy or in the form of creating job opportunities"*.
(Appendix G, Line nr. 45-48 - Translated from Danish).

From this quote, it can be concluded that politicians act as a bridge between citizens and the implementation of Power-to-X. From an Actor-Network perspective, politicians can act as a translation process. In this case, politicians are translating the concerns and perspectives of citizens into the decision-making process around the implementation of Power-to-X. They are also translating the benefits and potential positive impacts of the Power-to-X back to citizens in order to gain their support. By doing so, they are helping to build a network of actors that can support the successful implementation of Power-to-X on Bornholm.

7.6.6 Port of Rønne

Port of Rønne is working towards sustainability and wants to contribute to the community both economically, socially, and environmentally by contributing to the sustainable translation. As part of this translation, Port of Rønne was the first Danish port to become part UN Global Compact in 2022, by working purposefully with four of the Sustainability goals; Affordable and Clean Energy, Decent Work and Economic Growth, Industry, Innovation and Infrastructure and Responsible Consumption and Production (Port of Rønne, n.d.A). As part of the sustainability work, they also work towards becoming the centre of green energy in the Baltic Sea (Port of Rønne n.d.B). The implementation of Power-to-X at Bornholm has the possibility to contribute to this target, since production of e-fuels can create a bunkering opportunity which can supply passing ships and ferries with sustainable, green fuels (Port of Rønne, n.d.C). The implementation of Power-to-X on Bornholm thereby presents new business opportunities in the field of e-fuels for shipping and ferries (ACS Energy Letters, 2020; Appendix M). As the demand for sustainable transportation fuels increases, there is a growing market for e-fuels that can replace traditional fossil fuels in the maritime sector (*1. Introduction*). Port of Rønne can have a significant role in this transition by facilitating storage, and distribution of e-fuels for ships and ferries operating at Bornholm. By embracing this emerging market and supporting the adoption of cleaner fuel options, the port can create employment opportunities (Appendix C; Appendix F) and contribute to the decarbonization of the maritime industry (Appendix C; Appendix F; Appendix M).

7.6.7 Summary

The implementation of Power-to-X on Bornholm presents a range of challenges and opportunities within the Local Influenced Network. The process involves complex interactions and translation processes among various actors in the network of Local Influences. Efforts are being made by the Regional Municipality of Bornholm to address concerns related to land use, visual impact, and farmer adaptation through education, knowledge sharing, and collaboration with relevant actors from other networks. The Energy Island project and Power-to-X have the potential to positively impact the tourism industry by attracting both private and business tourists throughout the year, benefiting local businesses such as hotels and restaurants. Additionally, Port of Rønne can capitalise on the opportunity to become a leading hub for e-fuels, contributing to the decarbonisation of the maritime sector. By actively considering citizen concerns and engaging in effective translation processes, the Regional Municipality of Bornholm can navigate the implementation of Power-to-X while maximising benefits and minimising drawbacks.

7.7 Preliminary conclusion

The purpose of this analysis is to answer the following question: *Which translation process and interactions can be identified in the implementation of a Power-to-X plant and how will these affect the local actors?*

This analysis emphasises the complexity of the actor-network when implementing Power-to-X on Bornholm, which is presented in Figure 25. The identified networks influence each other crosswise, meaning changes in one network also will affect the other networks. Therefore, the findings and identified networks for this analysis only represent a simplified reflection of reality.

The Legislative Power Network, consisting of governmental institutions, has the power to set policies, regulations, and targets contributing to a translation of the energy system and thereby unfolding the roadmap for Power-to-X implementation in Denmark and ensuring progress in increasing Power-to-X. In this case, the government decided the implementation of Energy Island Bornholm, which is predicted to be a catalyst for a translation process of the energy system on Bornholm. Since Energy Island Bornholm was decided by the government, the Regional Municipality of Bornholm, together with the other identified actors from the Executive Order Network, have to collaborate on how to integrate the project within the society and energy system of Bornholm. The actors within the network of the Executive Order, have different responsibilities such as implementing offshore wind, the transformer station, local utility, and supply, as well as communication and knowledge sharing. One of the main responsibilities of the Regional Municipalities on Bornholm is communicating the impact implementing Power-to-X on Bornholm will have on the local actors such as the citizens, farmers, and industries. The Regional Municipality of Bornholm thereby functions as a translation process by securing the essential knowledge about the object is shared between the involved actors.

Implementing Power-to-X will mean an interaction within the current energy system because the island can become 100% self-sufficient both regarding electricity and heat. The production of hydrogen, methanol, and ammonia create an opportunity for a translation of the heavy transport sector by being a possible substitute for fossil fuels used within shipping.

Implementing Power-to-X on Bornholm would require the local actors to rethink their current way of energy planning. If all the actors collaborate, they have the possibility to become front runners within the green transition of Denmark and change their status within Danish energy planning to have a central role in green fuel production. This is only achievable if actors such as Bornholms Energy & Forsyning, Rønne Vand & Varme, BOFA, Baltic Energy Island, and the Regional Municipality of Bornholm collaborate on a paradigm shift in the silo thinking approach to their energy system and planning and instead are creating synergies and sector couplings within the energy system. Since Bornholm is a small island, the implementation of Power-to-X has the potential to create a closed energy system, making the island 100% self-sufficient. Therefore, implementing Power-to-X on Bornholm is a unique case with unique possibilities.

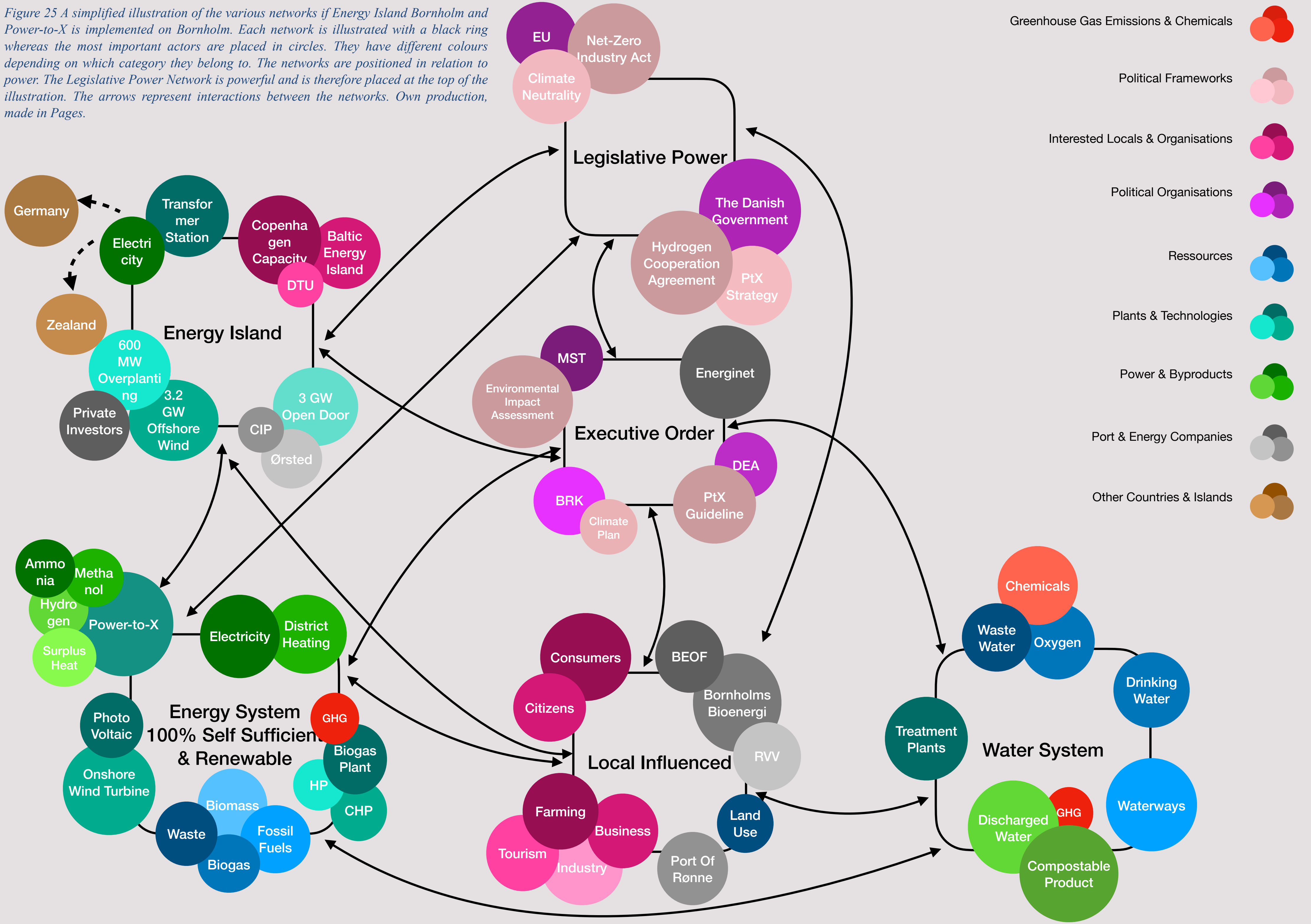
In order to get Power-to-X implemented there must be interactions between the Legislative Power Network and the Local Influenced Network. It can be concluded that the Legislative Power Network plays a crucial role in deciding the implementation of Power-to-X. Once the decision is made, interactions with other networks will follow. Current interactions within the network exist, but further interactions are needed.

It can furthermore be concluded that the translation process between the Regional Municipality of Bornholm, Baltic Energy Island, and the Local Influenced play a major role on a local level when implementing Power-to-X. However, an implementation cannot happen before a translation has been executed on a higher level of the society on governmental level. Therefore, the municipality is an important actor, regarding the communication of the decisions made by the Legislative Power to the local actors. This will both involve local citizens and require engagement from the local utility companies in order to achieve the needed changes of the translation.

On a local level, the translation requires a transformation of the wastewater system and the distribution of land use which will impact the agricultural sector. For the translation to become successful it is important that the regional municipality are available and implement the translation process needed to accommodate the translation processes decided by the Legislative Power,

The implementation of a Power-to-X plant on Bornholm involves various interactions and translation processes within the networks. It presents challenges and opportunities for local businesses, tourism, job creation, land use, and citizen concerns. The Regional Municipality of Bornholm plays a crucial role in addressing these issues through education, knowledge sharing, and collaboration. The implementation of Power-to-X can benefit agriculture through vertical farming, attract tourists year-round, create job opportunities, and support the development of e-fuels in the maritime industry. By considering citizen concerns and engaging in effective translation processes, Bornholm can navigate the implementation of Power-to-X while maximising benefits and minimising drawbacks.

Figure 25 A simplified illustration of the various networks if Energy Island Bornholm and Power-to-X is implemented on Bornholm. Each network is illustrated with a black ring whereas the most important actors are placed in circles. They have different colours depending on which category they belong to. The networks are positioned in relation to power. The Legislative Power Network is powerful and is therefore placed at the top of the illustration. The arrows represent interactions between the networks. Own production, made in Pages.



8 Discussion

This chapter will discuss the following subquestion: *How could different perspectives have impacted the findings?* by considering the choice of end-fuel, followed by a discussion whether Power-to-X is a reality on Bornholm. Lastly, the choice of theoretical framework will be elaborated upon.

8.1 Hydrogen, Ammonia or Methanol

Producing methanol, ammonia, or hydrogen through Power-to-X on Bornholm presents both challenges and opportunities. From a technical standpoint, each fuel has its own considerations, and it is essential to evaluate what would be most beneficial for different stakeholders in terms of societal impact.

Power-to-Hydrogen is advantageous because it is the end product of Power-to-X processes and has multiple applications, including energy storage and transportation fuel (Skov et al., 2021; ACS Energy Letters, 2020). However, hydrogen production may have moderate energy losses during electrolysis and storage and handling can be challenging due to its low density and high reactivity (Terega, n.d.). If the focus is solely on hydrogen production, it might be worth exploring the integration of Power-to-X facilities in the planned offshore wind turbines next to Bornholm (Offshorewind.biz, 2021). However, in this scenario, there would be no local surplus heat production. As a result, Bornholm would gain the same benefits as indicated in previous analyses, where district heating and surplus heat utilisation in agriculture and tourist attractions played a significant role in the island's economy. Many policymakers and employees in the regional municipality view hydrogen as the best solution, anticipating that it would provide the most favourable conditions for themselves and the region (Appendix C, Appendix F).

Power-to-Ammonia has the advantage of supporting sustainable agriculture practices through its use as a fertiliser and can also be used as a fuel in shipping (*6.3.2.2.2 Power-to-Ammonia*) (ACS Energy Letters, 2020). However, the use of ammonia as a fuel in shipping is still in the early stages of development (Gallucci, 2022). Several challenges need to be addressed before its widespread adoption. These challenges include technical modifications to ship engines and fuel systems, ensuring safety in handling and storage (Gallucci, 2022), developing the necessary infrastructure and supply chain, and establishing regulatory frameworks. Converting hydrogen into ammonia or methanol adds an additional step and may require extra technology and infrastructure (Skov et al., 2021; ACS Energy Letters, 2020). Land availability on Bornholm for these purposes can therefore pose a constraint for ammonia or methanol production and storage facilities.

Power-to-Methanol offers the advantage of utilising existing engines in the shipping industry and infrastructure without significant modifications (Blue World Technologies, n.d.; Eurowind Energy, n.d.; Skov & Schneider 2022). However, methanol production requires a carbon source (Skov et al., 2021, p.

2; ACS Energy Letters, 2020), which may not be readily available on Bornholm in the future (Appendix B; Appendix F; Appendix I).

Port of Rønne envisions methanol and ammonia as potential products from a Power-to-X plant, aiming to establish itself as a shipping hub (Appendix M). While methanol serves as a short-term plan, Port of Rønne believes that ammonia holds greater advantages for shipping in the long run (Böck, 2023), making the port more attractive which is also benefiting Bornholm's Regional Municipality (Appendix M). Ammonia's environmental advantages are noteworthy. It is carbon-free, emitting only nitrogen and water when burned, thus minimising greenhouse gas emissions (Shi et al, 2023). In contrast, methanol contains carbon and generates carbon dioxide emissions upon combustion (Shi et al., 2023).

The choice of the end-product within the Power-to-X plant will impact Bornholm differently. Power-to-Hydrogen aligns with Denmark's focus on hydrogen production and export (Klima-, Energi- og Forsyningsministeriet, 2021), potentially benefiting the country economically. However, if it is going to be integrated directly in the offshore wind turbines, it may limit the utilisation of surplus heat and other value-added opportunities on the island (Appendix L). Power-to-Methanol offers easier integration with existing infrastructure, but relies on carbon sources (Skov et al., 2021; ACS Energy Letters, 2020) that may not be available locally (Appendix B; Appendix F; Appendix I). Power-to-Ammonia supports sustainable agriculture and shipping, but the technology is less developed and may require additional land use (Skov et al., 2021; ACS Energy Letters, 2020).

8.2 Power-to-X on Bornholm?

The implementation of Power-to-X on Bornholm is subject to various factors and uncertainties. While many locals and politicians believe that Power-to-X has potentials for Bornholm (Appendix A, C, D, F, G, H, I, M, O), the specific form and scale of implementation may differ from the envisioned onshore Power-to-X plant. To make Power-to-X a reality, active participation from policymakers in the government and private actors is crucial to initiate the planning process and secure the necessary funding (*7.6.3 Job Creations*). The successful implementation of Power-to-X therefore depends on the involvement of multiple stakeholders, with the economic aspect playing a significant role (Skov et al., 2021).

The establishment of a large-scale Power-to-X project capable of receiving electricity from offshore wind turbines with a capacity of 3 GW or 3.6 GW can require a substantial financial investment for the government, similar to the Energy Island Project (Energiwatch, 2023). While such a project can boost the local economy, the high cost of implementation poses a barrier on governmental level that must be considered when evaluating the feasibility of Power-to-X, particularly in the context of these large-scale scenarios.

One positive aspect of implementing a Power-to-X facility is its potential for connectivity with other Power-to-X plants in the Baltic Sea region. Åland, an island in Finland, has plans for a Power-to-X facility on Åland that is also expected to contribute to economic gains in the local area (Flexens, 2021; Offshorewind.biz, 2023). It is believed that such projects can create new job opportunities and attract additional industries to the island, similar to the benefits identified for Bornholm (*7.6.3 Job Creations*; Flexens, 2021; Energiø Bornholm, n.d.F; Nørmark, 2023). The geographical proximity between Bornholm and Åland presents an interesting opportunity when considering the establishment of Power-to-X projects and their potential role in creating bunker hubs for e-fuels for shipping or forming an international network for hydrogen (Nørmark, 2023).

The close proximity of Bornholm and Åland allows for the possibility of synergies and collaboration between their respective Power-to-X facilities (Nørmark, 2023). By leveraging this geographical advantage, Bornholm and Åland can potentially create a regional network that facilitates the production, storage, and distribution of e-fuels or hydrogen (Nørmark, 2023). The establishment of a regional network would attract more attention and investment from stakeholders interested in clean energy solutions for the shipping industry. By combining their efforts, Bornholm and Åland could create a larger and more attractive market for e-fuels or hydrogen, increasing the potential for commercial viability and long-term sustainability (Nørmark, 2023).

Furthermore, collaboration between Bornholm and Åland could extend beyond their immediate geographical proximity. By strategically positioning themselves as key players in the Baltic Sea region, they could attract other neighbouring countries or regions to join their network, further expanding the potential customer base and enhancing the economic viability of the Power-to-X projects (Nørmark, 2023; Appendix O).

While the potential benefits of Power-to-X are evident, the timing of its implementation remains uncertain. However, the desire to be at the forefront of large-scale Power-to-X facilities that convert electricity into hydrogen, ammonia, or methanol is present for Bornholm. The economic viability of such projects does not align perfectly with the local reality and outcomes. While they can boost the local economy, there are costs associated with implementation, as seen elsewhere. The local economy should be carefully considered in the context of Power-to-X projects, alongside projects such as the one in Åland.

8.3 Multi-Level Perspective

In this study of analysing the potential impacts of implementing Power-to-X on Bornholm, Multi-Level Perspective could have offered valuable insights and contributions supplementing the Actor-Network Theory used in this analysis. Multi-Level Perspective is a framework examining technological transitions and interplay between different levels of societal systems. This includes the niche level, where the innovations emerge, the regime level, where the existing dominant systems are established, and the landscape level, a broader socio-technical and cultural context that keeps the regime in place (Geels, 2012).

While Actor-Network Theory focuses on the network of actors and their interactions, the Multi-Level Perspective takes a broader perspective, considering the interplay between different levels of societal systems (Geels, 2012). The following chapter will elaborate upon how the Multi-Level Perspective could have contributed to this study.

The Multi-Level Perspective emphasises the importance of considering the landscape level (Geels, 2012), involving examining the wider socio-technical and cultural context surrounding the implementation of Power-to-X. This includes regional, national, and international sustainability goals, policies, and green energy transition targets. The Multi-Level Perspective provides a more comprehensive understanding of how the implementation of Power-to-X at Bornholm aligns with these broader goals and how it contributes to the larger energy transition on national and international level. Actor-Network Theory, on the other hand, involves examining the local socio-technical and cultural context surrounding the implementation of Power-to-X and thereby investigates local goals and policies. By investigating the landscape, a more comprehensive analysis of the legislation had been possible and could have led to a better understanding of how the current legislation is a barrier for the Power-to-X to become a part of the existing regime of the current energy system of Bornholm. The landscape has a role in maintaining the current system and regime, but it also challenges the system to change, particularly due to climate change concerns (Geels, 2012).

The Multi-Level Perspective allows for the analysis of interactions and dynamics between the niche, the regime, and the landscape level (Geels, 2012). This enables an examination of how the implementation of Power-to-X challenges and interacts with the existing energy regime on Bornholm, including traditional energy sources and practices. The perspective provides a framework to understand the barriers, conflicts, and collaborations that arise during the translation process and how these dynamics influence the local environment and local citizens. By using this perspective, a further analysis of the technical barriers for Power-to-X as a niche could have been executed, including technical challenges related to the different fuels such as hydrogen, ammonia, and methanol, which will be elaborated upon in *6.3.2.2 E-fuels*.

Using the Multi-Level Perspective, enables a thorough analysis of the impacts on local citizens, encompassing their daily lives and socio-economic conditions. This approach allows for a detailed examination of potential economic opportunities that arise from Power-to-X, including job creation, development of local value chains, and emergence of new business models (Laak et al., 2006). In *7. The Interactions of Implementing Power-to-X on Bornholm*, in which Actor-Network Theory is applied, several of these topics have been investigated, making it conceivable that Multi-Level Perspective would have supplemented the analysis. It can therefore be stated that emphasising the socio-economic perspective, the Multi-Level Perspective complements Actor-Network Theory's focus on actor interactions. This results in a holistic understanding of how Power-to-X implementation affects the local community on many levels. If both Multi-Level Perspective and Actor-Network Theory were used as the theoretical framework of this study, it could have brought more perspectives and nuances on the sociotechnical transition of the implementation of Power-to-X on Bornholm.

Multi-Level Perspective incorporates a comprehensive assessment of the environmental impacts of technological transitions (Geels, 2004). It examines how the implementation of Power-to-X affects the local environment, including changes in emissions, resource consumption, and impacts on local ecosystems and biodiversity (Geels et al., 2017). Multi-Level Perspective's focus on sustainability goals and environmental considerations (Smith et al., 2010) allows for a more robust analysis of the environmental implications of Power-to-X implementation on Bornholm. If the Multi-Level Perspective approach had been used throughout the analysis of this report, it could have led to a more in-depth investigation of the impacts on the local environment.

The Actor-Network Theory provides valuable insights of the network of actors and their interactions, whereas the Multi-Level Perspective offers a broader perspective that incorporates the wider context and analyses the dynamics between different levels. While the Multi-Level Perspective also provides valuable insights into technological transitions, Actor-Network Theory offers a more actor-centric and relational approach to understand the local dynamics and interactions related to an implementation of Power-to-X on Bornholm. By focusing on actor-networks and the complexities of translation processes, Actor-Network Theory has provided a detailed understanding of the local impact and the socio-technical dynamics involved in the transition to Power-to-X.

8.4 Hermeneutics & Holistic Approach

As described in Chapter *4. Theoretical Framework - Critical Hermeneutic Theory*, the researcher's background has an influence on the focus areas and challenges deemed important to investigate, similarly the defined networks within this thesis have been chosen based on existing knowledge and the researcher's interpretations. The critical hermeneutic approach, used as the theoretical framework has shaped the investigations and findings within this study.

Water, noise, and air pollution resulting from the interaction with the Power-to-X plant have been crucial challenges that have received significant attention in this thesis since there is existing knowledge and curiosity within this field. If the interviews were executed in another order or at another time period of the thesis development, the results and outcomes from the interviews could have been different or included differently, since the prior knowledge at the interviews impacted the focus of the following interview and which questions were asked.

An alternative and expanded focus could have been the environmental impact of the large offshore wind turbine farms on the local area. Considering the sea surrounding Bornholm as part of the local area, investigating this aspect would have resulted in a fundamentally different study. In such a study, the interrelation between different actor-networks and the local citizens would have played a different role, as the emphasis would shift towards examining environmental impacts such as the maritime environment, biodiversity, and animal protection in the surroundings of the offshore wind turbines.

Within several existing studies, the impact on the maritime environment and bird habitats are highlighted as key challenges and weaknesses regarding the implementation of offshore wind turbines, since the surrounding area is vulnerable to changes in the environment (Bennun, 2021; Vaissiere, 2014; Causon & Gill, 2018; Virtanan et al., 2022). This study could have been further developed by also investigating the environmental impacts of the offshore wind turbines in the Energy Island Bornholm project, by looking into if there were any specific habitats or species which needed to be taken into consideration. Nevertheless, it is not possible to investigate the exact environmental impacts before the developer is found, and hereafter will the impact assessments be essential when deciding the exact location and dimensions of the offshore wind turbine farm (Bornholms Regionskommune, n.d.B). If the environmental impacts of the offshore wind turbines had been investigated, the conclusion would have been different since the offshore environmental impacts are expected to be significant.

However, due to the researcher's background as a sustainable city planner, a more holistic approach is adopted, considering the citizens, economy, sector coupling, water resources, and other relevant factors as integral to the implementation of Power-to-X. The choice of a critical hermeneutic and holistic approach reflects the understanding that addressing the complex challenges of Power-to-X implementation requires considering multiple interconnected dimensions. This perspective recognises the interdependencies between social, economic, and environmental aspects, acknowledging that they cannot be examined in isolation. By taking into account the broader context and interrelationships between various factors, the study aims to provide a comprehensive understanding of the implications of Power-to-X implementation on Bornholm's local area. This approach recognises the need to balance environmental concerns with socio-economic considerations, ensuring a sustainable and inclusive transition. The holistic approach is essential within smart energy system development, where the focus in energy planning is shifting from a silo-thinking approach towards integrating synergies and sector couplings (Lund, 2014).

9 Conclusion

The purpose of this thesis is to answer the following problem statement: *What effect will a Power-to-X plant have on the local community and area on Bornholm?*

In conclusion, implementing Power-to-X on Bornholm can benefit the local development by leading to growth in the economy, create job opportunities during the construction and operation phases, stimulate employment and potentially attract skilled workers to the area. Additionally, the plant requires local resources and services, leading to increased business activity and revenue for the community. Implementing Power-to-X will contribute to technological innovation, research, and development on the island since the plant may attract investments and collaborations with actors working with renewable energy, meaning expansion of local knowledge and advancement in renewable energy technologies on Bornholm.

Even though Power-to-X has the potential to contribute to local development, implementing Power-to-X will require collaboration and engagement with the local community. Stakeholders' consultations, public hearing sessions, and community involvement in decision-making processes can ensure concerns and interests of different actors are considered, which can foster ownership, understanding, and acceptance of the project. In relation, it is important to address concerns related to noise, emissions, or visual impact during the planning of the plant.

For the implementation of Power-to-X to become economical and energy sufficient the Power-to-X plant must be large-scale, which can be challenging to implement on an island with limited space. The specific effects of a Power-to-X plant on Bornholm will depend on factors such as scale, location, design considerations, and community engagement processes. Addressing and assessing potential concerns and maximising the benefits will be crucial for ensuring a successful integration of the plant.

The implementation will lead to positive environmental impacts by reducing greenhouse gas emissions on the island and contributing to the green transition of the energy system. The environmental impacts depend on the renewable energy resources, the extraction and production processes, and the potential release of byproducts or emissions, meaning it is essential with thorough environmental impact assessments to evaluate the environmental impacts and take the necessary precautionary measures.

Furthermore, the implementation of Power-to-X creates sector coupling and synergies between the electricity generated from the offshore wind turbines, heat, and water infrastructure on Bornholm. The Power-to-X plant can allow Bornholm to become energy independent by utilising renewable energy sources available on Bornholm, meaning the island can become independent of imported electricity from the Danish or Swedish electricity grid. In relation, a synergy is identified since a large share of surplus heat from the Power-to-

X plant can be utilised for either district heating, industrial purposes, or for the agriculture sector, and thereby reduce the need of imported biomass.

The water infrastructure is an important actor since electrolysis in Power-to-X requires a large share of water. As of now, Bornholm has a large share of wastewater available, meaning the island has the potential of supplying the plant with treated wastewater if the treatment plants are made more advanced.

Even though a Power-to-X plant will secure sector coupling and synergies, it will require large amounts of renewable energy to produce fuels. The available renewable energy supply can affect the feasibility and sustainability of the Power-to-X implementation. Furthermore, the conversion process in Power-to-X plants results in energy loss, which can decrease the overall efficiency of the energy system. Efficiency varies depending on the specific technologies and processes used. The effect on Bornholm will depend on which fuel is chosen as the end-product in the Power-to-X technology since there are different benefits and challenges related to the production of hydrogen, methanol, and ammonia.

However, whether Power-to-X will be implemented on Bornholm is not yet decided and not a reality before the implementation of Energy Island Bornholm in 2030. The technologies of either hydrogen, methanol, and ammonia production can be further developed and improved before a Power-to-X plant on Bornholm becomes a reality. There is the possibility of wind turbines becoming more advanced in the future where small Power-to-X plants are built directly on the offshore wind turbines, meaning that it would not be necessary to build a large Power-to-X plant onshore. If the technologies are changed to such a degree in the future, some of the synergies and benefits might disappear such as the possibility to use the surplus heat for district heating or other industry purposes. However, building the Power-to-X plants directly on the wind turbines will mean the onshore environmental impacts are limited since it will no longer be necessary to build a large plant onshore.

Within this thesis, a local and case-specific subject has been investigated, however, several of the same impacts, benefits, and challenges can be transformed into other similar projects implementing Power-to-X at other locations and on different scales. The viability of Power-to-X depends on local context, available resources, technological advancements, and policy frameworks. If Bornholm is to implement Power-to-X, it is essential that they evaluate the impacts, consider alternatives, and prioritise sustainability and long-term goals. In relation, the Power-to-X plant can in principle be implemented without including Bornholm, meaning they will not necessarily benefit from the implementation. However, the potential positive effects are significant but requires Bornholm is allowed to be part of the planning and benefit from the end-products and byproducts, such as e-fuels, surplus heat, and oxygen.

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Appendix P - Calculations

Appendix Q - Addresses for Wastewater Treatment Plants and Water Plants

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