Visualising Local Power-to-X Value Chains

A Smart Energy Approach to the Spatial Planning of Power-To-X System Integration in Aabenraa Municipality

Daniel Schubert

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Daniel Schubert

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Abstract:

This thesis investigates how spatial planning can enhance the techno-economic feasibility of Power-to-X (PtX) development in Aabenraa Municipality, with a focus on utilising local value chains through sector integration. PtX technologies are increasingly seen as key enablers for decarbonising hard-to-abate sectors, yet high electricity prices, fragmented infrastructure, and insufficient coordination between local resources often constrain their implementation. By combining a GIS-based spatial suitability analysis, dynamic energy system modelling, and techno-economic assessment, this study identifies optimal locations for PtX facilities. It evaluates the impact of different system configurations. The GIS analysis reveals high-suitability areas near Kassø and Ensted port, characterised by proximity to wastewater treatment, biogenic CO_2 sources, and district heating networks. Four PtX scenarios are modelled, ranging from standalone hydrogen production to integrated e-methanol synthesis. Results show that value-chain integration, particularly waste heat utilisation and local CO_2 sourcing, significantly improves Net Present Value (NPV), Internal Rate of Return (IRR), and Levelised Cost of Methanol (LCoM), with the integrated methanol scenario performing best economically. The findings highlight the importance of localised spatial planning and sector coupling in developing cost-effective and sustainable PtX projects. Municipalities play a critical role in enabling such integration by aligning energy planning with resource availability and infrastructure. This study concludes that energy system integration, rooted in spatial data and cross-sector coordination, is essential for realising the full potential of PtX in Denmarks energy transition by improving business-cases.

Preface

This master's thesis was written as part of the fourth semester master's program on Sustainable Energy Planning and Management at Aalborg University.

The time frame of this thesis spans from February 1, 2025, to May 28, 2025, with the intention of exploring the link between spatial planning methods and economic feasibility assessment.

This semester has taught me many things about myself, work-life balance, and, most importantly, a range of interesting subjects within the novel field of Power-to-X. I would like to extend my gratitude to my supervisor, Jakob Zinck Thellufsen, for his excellent guidance and insightful discussions. Also to Hanne Klintøe from Aabenraa Municipality for supplying interesting aspects and actors, as well as all undisclosed informants for their valuable insights, both within and outside of this thesis.

DSchubert

Daniel Schubert
Dschub20student.aau.dk

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1 | Introduction

Global warming has been repeatedly shown to have a direct correlation with human activities, stemming from centuries of energy-intensive processes derived from fossil fuels and unsustainable land use [1]. Current estimates from the Intergovernmental Panel on Climate Change (IPCC) call for a 42% emission reduction by 2030 to reach the Paris Agreement goal of limiting the global temperature rise to 1.5° and 28% for the 2° pathway [1]. Since the Paris Agreement in 2015, more than 130 countries have submitted proposals for achieving "carbon neutrality." Known links have been demonstrated many times over the years between high energy intensity (carbon emissions) and economic growth [2]. Studies indicate that carbon neutrality is becoming more difficult than anticipated, as countries have yet to find models to achieve true decoupling rather than economic decline [3, 4]. So-called hard-to-abate sectors play a large role in the issue of decarbonising industry and, thereby, the overall economy. In conjunction with the development of an increasingly renewable energy system for heating and electricity, power-to-X pathways are being discussed as a possible solution for sectors that cannot achieve decarbonization through direct electrification [5]. To address this issue in Denmark, the Danish Energy Agency introduced its "Strategy for Power-to-X" in 2021, setting ambitious goals and advancing the Danish political agenda to promote hydrogen infrastructure and production as an international leader [6].

The Danish Government has set its goal of achieving between 4 and 6 GW of electrolyser capacity by 2030. This expansion is assumed to occur at market terms to the extent possible, with a government proposal to invest DKK 1.15 billion in PtX tenders [6]. However, expansion of PtX and electrolyser capacity has shown increasing difficulty in recent years, with projects demonstrating infeasibility caused by higher capital costs and electricity prices than anticipated [7]. Furthermore, the lack of electrolyser capacity in the southern region of Denmark has led to the postponement of the planned hydrogen pipeline infrastructure from Esbjerg to the German border until 2030, and the lowering of the capacity booking requirement [8]. Barriers to developing feasible PtX projects can be countered by applying concepts such as sector integration and "smart energy systems" [9], which look at PtX development from a holistic perspective. This calls for methods and tools to improve spatial planning and advance the utilisation of PtX value chains. Therefore, this thesis will explore GIS-based methods that allow for better decision-making regarding the placement of future PtX facilities. Aabenraa Municipality, located in the southern part of Denmark, has been selected as a critical case for the development of business-economically feasible PtX projects in the future.

2 | National and international energy policy

Climate change, resulting from global greenhouse gas emissions from the burning of fossil fuels, has had problematic effects since the Industrial Revolution and the rise of globalisation. Even though the energy intensity in especially developed countries has led to significant economic growth, these effects include events such as climate hazards and increasing exposure to violent climate from floods and heat exposure. Effects from energy used in cooler parts of the world, developed countries, therefore, have direct consequences for countries located in warmer regions, continually creating economic and societal gaps and inequality [10]. To counteract the adverse effects of climate change, 196 parties signed the Paris Agreement at COP21 in 2015 [11]. This agreement commits the parties to a legally binding treaty to *"hold the increase in the global average temperature to well below 2 ° above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 ° above pre-industrial levels."* [11] The rest of this chapter will present the relation of these endeavours to the European Union (EU) and Danish climate goals, as national and local anchoring will play a significant role in transitioning our society as a whole.

2.1 EU climate goals

The European Union has set ambitious targets for its member states, along with legal and methodological frameworks, to help decarbonise all sectors of society, with a focus on a just transition. Where the Paris Agreement does not set concrete national targets for carbon neutrality, emission reduction should be aimed for sooner rather than later. As of 2025, 139 countries are at least discussing setting carbon neutrality goals by 2070 at the latest. Currently, 33 countries have enacted laws to achieve carbon neutrality, with most aiming to meet their goals by 2050 [12]. The EU has instead opted to mandate minimal reduction goals for all member states, with the end objective of EU carbon neutrality by 2050. Furthermore, the EU has introduced intermediate goals for 2030 and 2040 to ensure objectives are met along the way.

EU 2030 targets

The EU has set its short-term target on a 55% emission reduction for the union. This target goal is accompanied by a set of proposals to update EU policies with new initiatives, ensuring the policy is aligned with the target goal. The Fit for 55 package focuses on just and fair transitioning while strengthening innovation and industry competitiveness [13]. Each area strengthens the aforementioned focus on industry transitioning and innovation. This includes a shift from fossil to renewable fuels, low-carbon transportation, and a revision of the EU Emissions Trading System (ETS). The EU ETS is the primary tool for maintaining and addressing emission reduction through financial means and covers 40% of European emissions [13]. The trading system is a carbon market-based cap-and-trade system, meaning that each polluter has a cap to allow emissions. These "allowances" or "permits" can be exchanged between actors on the ETS, creating incentives for companies to reduce their emissions. However, market prices for CO_2 allowances have historically been relatively

Figure 2.1: EU ETS carbon permit prices per ton emitted from 2016 to 2025 [14]

low, leading to discussions on the actual effect of the EU ETS [15]. This has led to the 2023 reform of the EU ETS, where the allowances cap is reduced yearly by a current 4.3%. As a result, carbon allowance pricing surged in recent years, with supply decreasing and demand remaining constant due to a lack of emission reductions [16]. As a result of "carbon leakage", where some sectors are more exposed to carbon pricing, affecting their competitiveness, the ETS provides free carbon allowances to prevent companies from relocating outside the EU. Finally, the EU aims to promote innovative alternatives to heavy fuels used in aviation, maritime, and road transport, while reducing methane usage, a potent greenhouse gas used for combustion and industry [13].

EU 2040 and long-term target

The EU's 2040 climate goal serves as an intermediate target for integrating renewable energy sources on a large scale into the European energy system. While this objective is relatively far into the future, it will play a crucial role in setting the stage for further decarbonisation after the 2030 targets are met. Reducing net emissions by 90% in 2040 will ensure that resources invested in the next 25 years are compatible with economic and societal goals, thereby reducing unnecessary sunk cost investments into the fossil fuel economy. By doing so, the EU will create possibilities to future-proof jobs, thereby boosting European business competitiveness [17]. Lastly, the world is facing increasing geopolitical turmoil with the continuous Russian invasion of Ukraine and the United States' exit from the Paris Agreement once again. These factors create economic and energy security-related uncertainties, calling for the improvement of resilience and the strengthening of European energy autonomy.

2.2 Hard to abate sectors

As the EU moves closer to decarbonising the economy, some sectors are lagging, with doubts and questions about how these critical sectors can reduce their emissions in the future. The term "hard-to-abate" originates from the widely acknowledged challenges of reducing or mitigating emissions within these sectors. The sectors include industry and subcategories in transportation, particularly aviation, maritime and heavy road transport, and account for 50% of global emissions [18]. One of the means to reduce emissions from industry and transportation is green hydrogen. Hydrogen is used as a feedstock for energy-intensive processes and in the production of chemicals. Still, it mainly originates from a very carbon -and heat-intensive method: steam methane reforming, which splits carbon and hydrogen molecules through high-temperature water vapors[19]. Green Hydrogen, produced through the use of green electricity, has the potential to substitute "grey hydrogen" and "blue hydrogen" derived from fossil fuels with attached carbon capture. Still, the present consensus is that direct electrification should be the first solution when aiming for a 100% renewable energy system [20]. Furthermore, bioenergy sourced from biogas, biomass, and waste may be necessary to reduce the use of coal, natural gas, or oil in high-temperature processes and household heating. Nevertheless, it is essential to consider the ethical implications and sustainability aspects of biomass use, particularly as a solution for hard-to-abate sectors. For the Danish context, the IDA Energy Vision 2050, a coalition report between the Danish Engineering Association and the Planning and Development department at Aalborg University, argues for limiting usage to 40 GJ per capita or 200 PJ for the whole country [21]. In a later

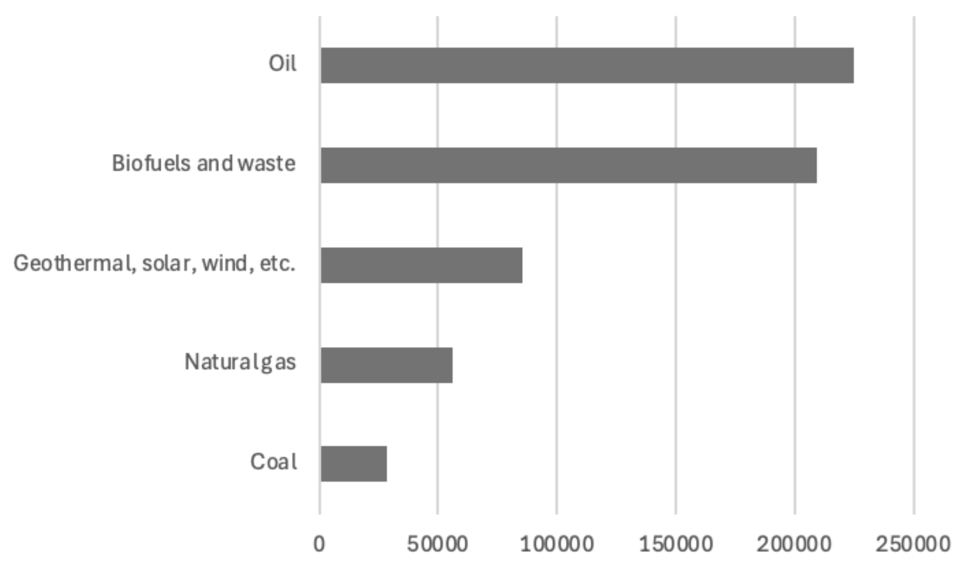

Figure 2.2: Danish primary energy supply in 2023 (TJ) [22]

version of this report from 2021, it is even assumed that biomass availability may be as low as half of what was initially estimated (23 Pj per capita). As indicated by Figure 2.2, the Danish primary energy supply (PES) still consists of a large amount of oil and natural gas. This demonstrates the significant dependence on fossil fuels, which are predominantly derived from hard-to-abate sector demand, such as refining and process heating. Energy from biofuels and waste has already reached the national limitations for available biofuels of 200 PJ in 2023, underscoring the importance of finding alternatives to reduce fossil fuel usage where electrification is not feasible. As demonstrated by Figure 2.3, the development of primary fuels used

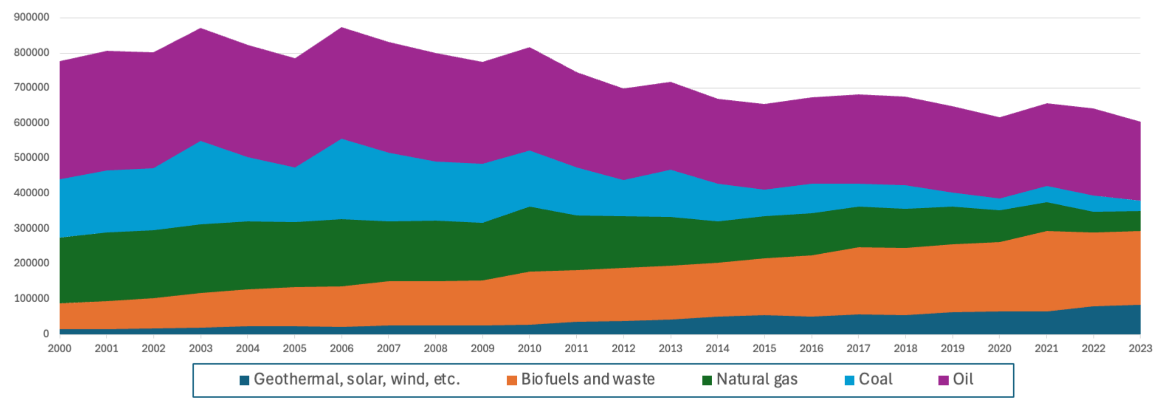

Figure 2.3: Development in the Danish primary energy supply from 2000 to 2023 [22]

in the Danish energy system shows a reasonable reduction in fossil fuel sources. However, there appears to be an underlying trend in which biofuels are becoming a substitute for traditional fossil fuels. Although biofuels will continue to play a crucial role in transitioning to greener energy solutions now and in the future, it is equally imperative that their production remains within sustainable limits in the future as well.

2.3 Danish climate mitigations

As part of the European Union, Denmark's climate goals must align with the EU's reduction targets for 2030, 2040, and 2050. The Danish Government have, instead, chosen to adopt more ambitious reduction goals. The Danish Climate Law entered into force in 2020, stating central mechanisms to reach 70% emission reductions and actively work towards the Paris Agreement by releasing transparent reports along the way with the Climate Council as its council for recommendations [23]. Danish carbon reductions have, until now, primarily been made through transitioning the electricity sector, as illustrated by Figure 2.4. According to estimations from the Danish 2024 climate projection report, the transport and industrial sectors are expected to undergo the least transformation by 2035, alongside the agricultural and fishing sectors [24]. As a result of significant estimated emissions related to hard-to-abate sectors, the Danish Government released its Power-To-X Strategy 2021 to promote alternative fuels produced from renewable electricity [6]. The report targets a build-out of 4-6 GW of electrolyser capacity before 2030 and an ambitious expansion, quadrupling land-based renewable electricity by 2030, to keep prices low [25]. Nevertheless, PtX projects have proven to be a more complex endeavour than initially anticipated, with challenges related to the development of sustainable business cases in the current landscape.

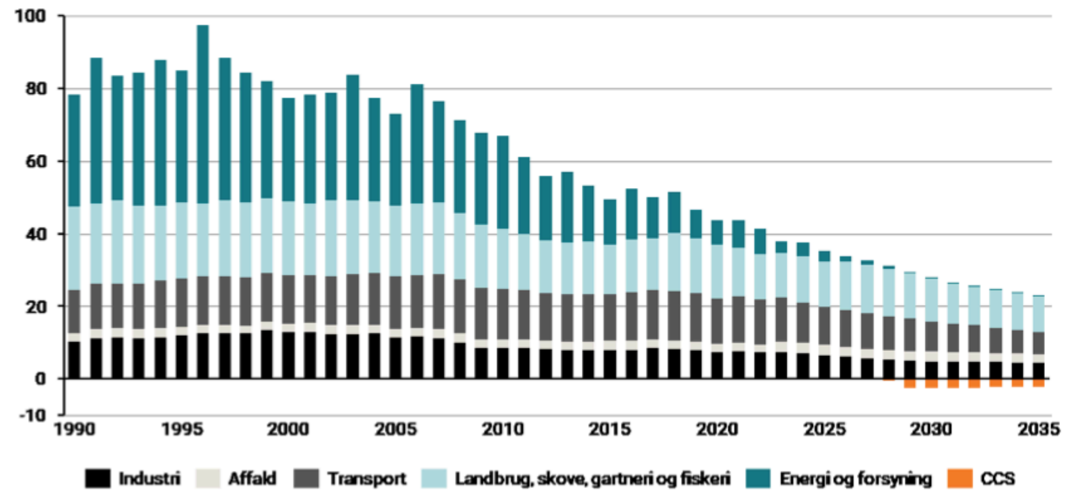

Figure 2.4: Danish emissions from 1990 to 2035 in percent from 100 to -10. It includes industry, garbage, transport, agriculture, forestry, fishery, energy and supply, and carbon capture and storage (CCS) [24]

This situation is likely due to electricity prices still being too high in Denmark, as they account for 75% of the levelized cost of hydrogen (LCoH) [26]. Land-based wind power has almost halted in recent years, barely expanding beyond 2021 capacities due to local opposition, slow administrative processing times, and low earnings resulting from low consumer prices for many hours of the year. While solar power has shown immense capacity increases, going from 2 to almost 4.2 GW, there are indications of market saturation [25, 27]. Furthermore, a substantial part of the electricity price originates from strain and losses in the grid, leading to transport consisting of upwards of 25% of the cost [28], likely only to go up with further electrification. In response to unfavourable electricity prices for producing green fuels, the Danish Energy Agency explored the possibility of using differentiated geographical tariffs and direct lines [29]. The idea is to incentivise consumption and production actors to place their facilities in production-dominated or consumption-dominated zones, reducing strain on the grid. This framework was introduced in 2023 in the form of a new "producer tariff" with feed-in tariffs and a one-time connection payment dependent on geographical location [30]. Direct lines on the same plot have already been utilised in high-consumption PtX plants to reduce the operational costs of producing electrofuels. These frameworks have transformed the landscape for developers, both in production and consumption, leading to a greater emphasis on the spatial aspects of effective business cases. Local anchoring may play a more significant role in achieving national decarbonisation goals, with energy planning transitioning from a centralised, fossil fuel-based system to a decentralised planning system where municipalities determine their local focus in strategic energy planning. Municipalities have already been shown to have a significant focus on the local energy supply [31], but how the energy system is made renewable and how resources are distributed as a result may be unique to each municipality.

2.3.1 The role of municipal planning

Municipal planning is crucial for collaborating with local actors and developers to ensure that national climate goals are achieved. DK2020 is a compulsory cooperation between the 98 Danish municipalities to reach net-zero emissions through collaboration and guidance in the international standard of the "Climate Action Planning Framework" (CAPF) [32].

Table 2.1: Query for the six highest solar and wind power producing municipalities in Denmark [27]

Municipality	**Capacity solar power (MW)**	**Capacity onshore wind power(MW)**
Ringkøbing-Skjern	162	516
Lolland	152	270
Randers	134	248
Aabenraa	355	85
Vejle	222	54
Viborg	183	74

Municipalities have many areas to cover, such as providing social services, creating jobs, protecting the climate, and mitigating climate change, etc. This leads to different pathways and focuses, especially depending on geographical location, when planning for net-zero emissions municipal climate plans. The municipal amount of land-based renewable producers is often based on less populated areas, meaning municipalities with large areas without population will have a more straightforward process during projects. The production of renewable power is primarily reflected in consumer zones located in the western part of Denmark and Lolland-Falster, with the largest municipal producers in solar and wind energy represented by Table 2.1. The engagement of the local population and politicians, a well-founded process for evaluating projects, and a mapping of energy resources will be central to the future possibilities of producing green fuels, thereby reducing emissions in hard-to-abate sectors.

3 | PtX value chains

The ever-increasing energy use on Earth has led to numerous possibilities for economic growth and human capital development. The richest countries are also among the most energy-consuming, which is problematic given that most energy is sourced from Greenhouse Gas-Emitting fossil fuels. Power-to-X (PtX)

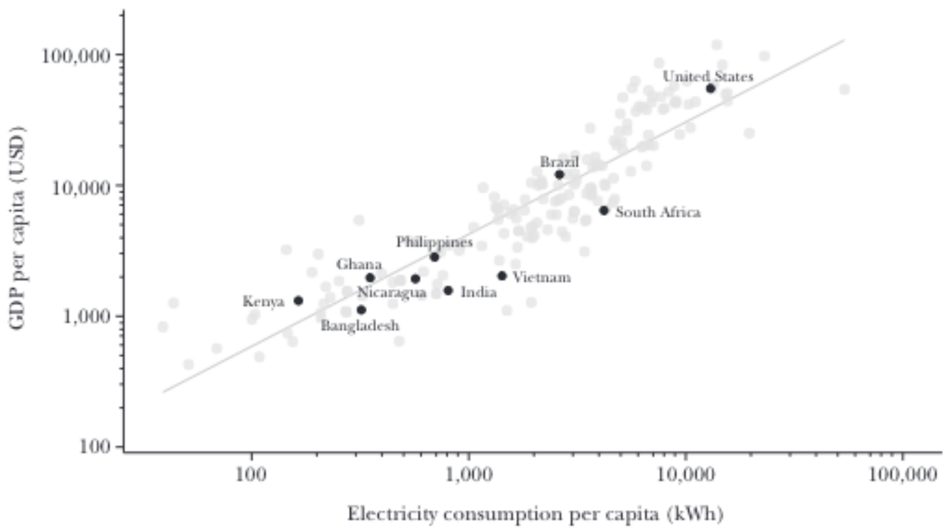

Figure 3.1: Correlation between electricity consumption and GDP per capita [33]

is one method among many discussed ways to reduce emissions from traditional energy usage in energy-intensive sectors, such as transportation and industry. However, as previously shown, PtX fuels have difficulties reaching market-competitive prices compared to hydrogen from fossil fuels due to high electricity prices. Examining the entire PtX value chain, from water, CO_2, and electricity sourcing to by-products such as oxygen and heat, may enhance the business case of PtX products. This section presents the most relevant factors in producing PtX fuels, also known as e-fuels, and describes how we can assess value from different parts of the PtX value chain.

3.1 Power-to-X

Power-to-X is often used as an umbrella term for storing energy from electricity through conversion to different electro-fuel pathways. All sustainable e-fuels from PtX pathways originate from green hydrogen produced through electrolysis using renewable electricity. Different colours have named other types of hydrogen depending on their source of production, whether from fossil fuels, nuclear, or fossil fuels with carbon capture. Today, only 0.04% of all hydrogen is produced from water electrolysis or "green hydrogen", whereas "grey hydrogen" is derived from steam methane reforming (SMR) [34]. This process is widely used to produce various types of synthetic products, primarily fertilisers in the form of ammonia. SMR is responsible for almost 2% of all global emissions, with ammonia being produced from most of it [19]. The figure below presents the most common pathways for electrofuels and biofuels, along with their corresponding chemical or biological processes.

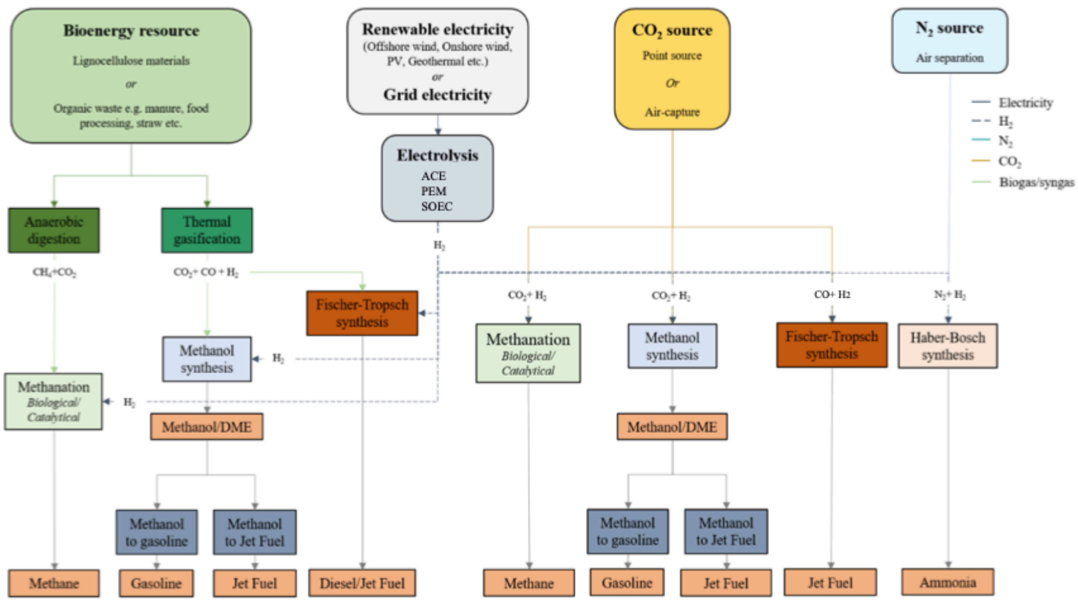

Figure 3.2: A flow chart of PtX pathways going from the main feedstocks needed at the top to end-products at the bottom [35]

Hydrogen has numerous use cases, including hydrogen gas turbines, fuel cells, upgrading biogas through methanisation, and industrial process heat [36]. Besides producing sustainable ammonia for fertilisers, green hydrogen can also be essential in producing methanol as fuel for the maritime sector and a highly used product for industrial purposes. Furthermore, methanol can be further reacted into hydrocarbons such as diesel, gasoline, or kerosene for aviation use through the Fischer-Tropsch synthesis [35]. This means that some sustainable fuels can be integrated into existing technologies and infrastructure, thereby reducing costs associated with retrofitting.

3.2 The EU delegated act for renewable fuels

Renewable fuel is a broadly used term for fuels that reduce carbon emissions by a certain amount compared to traditional fossil fuels. As indicated by Figure 3.2, these include hydrogen, biofuels, and e-fuels with carbon or nitrogen bindings to increase energy density compared to hydrogen at atmospheric pressure. Hence, they are also commonly referred to as energy carriers. Biofuels have numerous applications in the transportation sector, as well as in combined heat and power production, with net-zero carbon emissions during combustion. However, with sustainably sourced biofuels being limited [37], there is a need to define how sustainable fuels, which are not biofuels, should be produced while delivering sufficient reductions to climate change. To improve on terminology used for synthetically produced fuels, the EU released the Renewable Fuels of Non-biological Origin (RFNBO) standard in 2023 under the EU Renewable Energy Directive. The RFNBO standard defines hydrogen as renewable when its method of production ensures at least 70% reductions in GHG emissions, achieved when using grid electricity with at least 90% renewable power in a given bidding zone [38]. Furthermore, renewable hydrogen must meet the criteria of additionally as well as temporal and geographic correlation. Therefore, RFNBO-approved hydrogen must ensure new renewable electricity generation capacity by concluding power purchase agreements or producing it behind the meter, while ensuring that hydrogen is produced when and where renewable electricity is located and available, to avoid incentivising fossil fuel power generation demand [39].

Fuels containing CO_2 are distinguished between carbon originating from fossil or biological sources. Biogenic CO_2, from for instance biogas production or combustion, is accounted as carbon neutral [40], and will likely play an important role in the production of novel sustainable e-fuels. The distinction between fossil and biogenic origin determines whether or not certain fuels will be admissible for RFNBO certification, as CO_2 from fossil origin will only circulate once more in the carbon loop but still emit the same amount. This rule is only excused if the carbon is sourced from an ETS-registered emission source (only until 2036) as biogenic CO_2 is expected to be of inadequate amounts in the coming years to cover demand [40]. This may, however, become problematic as the prices of biogenic $CO2$ will rise with increasing demand, incentivising liquefaction for storage or methanisation as the most cost-efficient solution. Furthermore, it may lead to increasing prices for e-methanol, making it harder to compete with fossil alternatives [26].

3.3 Water electrolysis

Electrolysis is a key component in the production of e-fuel. Requiring large quantities of renewable electricity, constituting the primary part of operational costs related to e-fuels, particularly with high-capacity factors running many load hours [41]. Water electrolysis is an endothermic chemical process that requires heat to produce hydrogen by splitting water into hydrogen and oxygen. Hydrogen is vital as an energy storage solution, particularly for excess energy generated from renewable sources, making load management particularly important. Hydrogen storage acts as an alternative to battery storage, helping to align energy production with utilisation by storing large amounts of energy in either gaseous or liquid forms while ensuring the availability of hydrogen for further use, such as methanol, in hours of high electricity prices. The primary techniques for storing hydrogen in its pure form include compressed gaseous hydrogen and cryogenic liquid hydrogen, where storage density is primarily determined by pressure and temperature [6].

The electrolyser process involves the production of hydrogen and oxygen using water as an input. In contrast, a fuel cell is based on the same technical concept but with the opposite effect of producing electricity and water from hydrogen and oxygen. The chemical reactions occur on two sides of the electrolyser, known as the anode and cathode, through a conductive electrolyte. A separator is placed in the middle of the reactions to prevent the oxygen and hydrogen from mixing once again [42]. The basis for electrolyser inputs and outputs can be described by the equation below:

$$\mathbf{8.8}\ \text{kg}\ \mathbf{H_2O} \xrightarrow{\text{55 KWh}} \mathbf{1}\ \text{kg}\ \mathbf{H_2} + \mathbf{7.8}\ \text{kg}\ \mathbf{O_2}$$

As indicated, the water requirement is a factor of 9:1, meaning that one kilogram of hydrogen produced requires almost nine kilograms of water. Furthermore, this specific case requires an additional 55 kWh of electricity. Given the lower heating value (LHV) of hydrogen at 120 MJ/kg (33.3 KWh), this particular production of one kilogram of hydrogen reaches an efficiency of about 60% [5], which is pretty indicative for most electrolysers today according to the Danish Technology Catalogue for green fuels [42]. The theoretical maximum efficiency representing the total electricity-to-hydrogen is expected at 85% with unavoidable heat losses. However, high-temperature electrolysis can achieve higher overall efficiencies if waste heat is used as an energy input [9]. The three main electrolyser types are the two low-temperature alkaline electrolysis cell (AEC) and proton exchange membrane electrolysis cell (PEMEC), with the high-temperature process being the solid oxide electrolysis cell (SOEC) [42]. The basis for each type of electrolysis is the same. Still, they have different reactions on each electrode side, meaning they also have various properties, use cases, and costs related to the precious metals used.

Alkaline electrolysis cell

AEC is the most established electrolysis technology and utilises a liquid electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). AEC normally operates at temperature ranges between 40-90°C at atmospheric (ATM) pressure [43], leaving it more challenging to control dynamic operation and ramp times. Pressurised AEC technology, capable of up to 30 bar, enables both large stacks and electrolyser systems. Stacks can reach up to 5 MW and produce a hydrogen flow rate of 100 kg/h, while systems exceeding 500 MW are also possible. These systems have a stack lifetime of approximately 80,000 hours, making it the most reliable in terms of stack lifetime [42].

Regarding materials, AEC commonly uses pure nickel (Ni) and Ni-plated carbon steel. More expensive rare-earth metals like ruthenium (Ru) or iridium (Ir) are sometimes incorporated into certain market solutions. The balance of system components, such as electrolyte tanks and gas separators, is primarily made from Ni-plated carbon steel. However, due to the corrosion characteristics of the electrolyte, some stainless steel components may also be required. The chemical reactions for AEC happen as follows:

Reduction reaction at the cathode

$$\mathbf{2OH^-} \longrightarrow \frac{\mathbf{1}}{\mathbf{2}}\mathbf{O_2} + \mathbf{H_2O} + \mathbf{2e^-}$$

Oxidation reaction at the anode:

$$\mathbf{2H_2O + 2e^- \longrightarrow 2OH^- + H_2}$$

While AEC is currently the most cost-effective type of electrolysis due to its technological readiness level (TRL) and long-term durability, the AEC diaphragm has some disadvantages with the crossover of gas, which can slightly lower efficiency and the purity degree of hydrogen outputs [43]. Lastly, the unit footprint for AEC electrolysers remains quite extensive at 25 m^2/MW, necessitating consideration of physical restraints in terms of space for larger projects exceeding 100 MW [42]. Table 3.1 below provides a general indication of the technical specifications for 100 MW AEC, as well as expectations for 2030.

Table 3.1: Central data regarding production of hydrogen from AEC in 2025 and 2030 [42]

	2025	2030
Input		
Electricity (input) % total input (MWh/MWh)	100	100
Ultrapure Water for electrolysis kg/MWh input_e	175	185
Electricity consumption, kWh/kgH2	51.4	48.6
Output		
Hydrogen output (kg/MWh input_e)	19.4	20.6
Heat loss (% total input_e MWh/MWh)	29.4	25.3
- hereof recoverable for district heating (%-points of heat loss)	26.4	22.3

Proton exchange membrane electrolysis

Proton exchange membrane electrolysis cells (PEMEC) are distinguished by their use of a solid electrolyte and their ability to operate at much higher current densities, which results in a significantly smaller electrolyser system footprint of 10 m^2/MW. With an output pressure of approximately 30 bar, PEMEC produces high-purity hydrogen (99.999%) [42]. PEMEC systems can achieve slightly smaller stack sizes compared to AEC, with current typical outputs around 1 MW. Compared to AEC, PEMEC offers a smaller footprint. These large hydrogen output stacks, with compact designs, enable PEMEC manufacturers to scale their systems to over 100 MW. However, with slightly higher electricity consumption on average (56 kWh/kg) and a shorter stack lifetime of 65,500 hours as of 2025 [42].

In terms of materials, PEMEC technology is more demanding in terms of raw materials, requiring substantial quantities of titanium (Ti), platinum (Pt), and iridium (Ir). These metals are relatively scarce, which could pose challenges for the long-term operation of commercially available PEMEC systems and large-scale projects. Ti is used in various stack components, such as bipolar plates and porous transport layers (PTLs), due to its strong performance and stability under high potentials in acidic media. Pt and Ir serve as catalysts for the demanding electrocatalytic reaction in an acidic environment [42]. The chemical reaction for PEMEC happens as follows: Reduction reaction at the cathode

$$\mathbf{4H^+ + 4e^- \longrightarrow 2H_2}$$

Oxidation reaction at the anode:

$$\mathbf{2H_2O \longrightarrow O_2 + 4H^+ + 4e^-}$$

PEMEC has higher investment costs due to the use of more noble materials and a lower level of commercial maturity at present. PEMEC does, however, have more flexibility when it comes to partial load ranges (20-100 °C) and system response, meaning it has fast adaptive capabilities in response to increasingly shifting power availability in second intervals [43]. The main technical characteristics of the PEMEC technology are summarised in Table 3.2

Table 3.2: Central data regarding production of hydrogen from PEMEC in 2025 and 2030 [42]

	2025	2030
Input		
Electricity (input) % total input (MWh/MWh)	100	100
Ultrapure Water for electrolysis kg/MWh input_e	167	178
Electricity consumption, kWh/kgH2	53.9	50.6
Output		
Hydrogen output (kg/MWh input_e)	18.6	19.7
Heat loss (% total input_e MWh/MWh)	33.7	29.5
- hereof recoverable for district heating (%-points of heat loss)	18.6	19.7

Solid oxide electrolysis cell

Solid oxide electrolysis cells (SOECs) are distinguished by their ability to operate at high temperatures (550 to 850 °C), which makes them the most efficient technology among the three electrolysis types. Additionally, they are constructed from inexpensive and abundant materials, such as ceramic oxides. Compared to PEMEC and AEC, SOECs use smaller stacks due to current challenges in scaling up high-quality, reliable ceramic technologies. However, SOEC electrolyser systems are already capable of achieving MW scale, enabling their commercial deployment and supporting ongoing development [42]. The leading developer for this relatively niche electrolyser type in Denmark is Topsoe. The company expects to operate its new factory in 2025 and will then be able to manufacture 500 MW of SOEC capacity annually [44]. This will likely boost development and commercial reach while reducing investment costs. The primary advantage of SOECs over other electrolysis technologies is their significantly higher efficiency. Operating at the thermoneutral point, SOECs achieve stack efficiencies close to 100%. The average electricity consumption for SOECs, when using steam water at 150°C, is 40 kWh/kg. The stack lifetime, however, is the shortest of the three technologies, at 34,500 hours as of 2025.

SOECs are made from low-cost, abundant materials, particularly ceramic oxides. Also, the current usage of Ni and Co in SOECs is relatively low 200 kg/MW for Ni and 25 kg/MW for Co approximately four times less than in AEC technologies for Ni [42]. Considering its high thermal neutral efficiency, SOEC has excellent potential for reducing the operational costs of hydrogen production. However, it is crucial to keep in mind that this type of electrolysis uses steam on both electrode sides at constant high temperatures. As a result, SOEC cannot provide waste heat to district heating or industry as indicated by Table 3.3. Instead, it needs a 20% supply of heat, supplementing electricity input, for its operation to stay efficient, which should preferably be high-temperature waste heat from nearby sources. The chemical reaction for SOEC happens as follows:

Reduction reaction at the cathode

$$\mathbf{2H_2O + 4e^- \longrightarrow 2H_2 + 2O^{2-}}$$

Oxidation reaction at the anode:

$$\mathbf{2O^{2-} \longrightarrow O_2 + 4e^-}$$

Value chains will play an increasing role in industry symbiosis in the future if we are to decarbonise these parts of society. One must, therefore, be aware of the advantages and disadvantages of each type of electrolysis, depending on the use case and placement.

Waste heat utilisation

Denmark has a history of efficiently utilising the co-production of heat and power in district heating for private households and small companies. Assessments from the *IDA: 2045 climate response* conclude that a district heating expansion to 63% is needed to decarbonise the Danish heat demand by 2045. This included higher efficiencies in the district heating grid and lower forward and return temperatures of 55-65°C and 25°C respectively, compared to 80°C forward temperatures previously [45, 46]. Lower forward temperatures enable the utilisation of more waste heat sources, such as data centres and PtX technologies, in combination with heat storage. This concept has been introduced as the 4th Generation District Heating (4GDH) to boost waste heat streams and renewable electricity sources in electric boilers and heat pumps, aiming to eliminate

Table 3.3: Central data regarding production of hydrogen from SOEC in 2025 and 2030 [42]

	2025	2030
Input		
Electricity (input) % total input (MWh/MWh)	79.5	80.5
Heat (% total input ([MWh/MWh)	20.5	19.5
Ultrapure Water for electrolysis kg/MWh input_e	228	237
Electricity consumption, kWh/kgH2	39.4	38.0
Output		
Hydrogen output (kg/MWh input_e)	25.4	26.3
Heat loss (% total input_e MWh/MWh)	17.1	14.4
- hereof recoverable for district heating (%-points of heat loss)	0	0

fossil fuels from the heating sector altogether. Furthermore, 4GDH is part of a paradigm shift from single-sector thinking to sector integration among all energy-using industries and sectors that may be synergistic [47].

Water availability and usage

Water treatment and usage are central aspects of hydrogen production from electrolysis. Substantial amounts of water are used in PtX processes, sparking discussions on water management and its sources. The concept of managing the relationship between energy and water is widely recognised in many scientific communities worldwide, often referred to as the water-energy nexus [48]. Water for electrolysis can be sourced from various sources, including surface water, groundwater, wastewater, and rainwater. Sea water can also be used, but it requires extensive desalination and general treatment. Hence, it is often not feasible. Water treatment requires a significant amount of energy, depending on the number of steps the water undergoes. Consequently, costs related to water treatment become substantial due to the high demand for ultra-pure water [49].

Table 3.4: Power requirements for four of the main water treatment processes. Reverse Osmosis and electro-dialysis are commonly used at PtX facilities to achieve ultra-pure water [50]

Advanced treatment technologies	Process	Typical power use (KWh per 10,000 l)
UV disinfection	Lamps	0.13 - 0.40
Ozonation	Process includes feed-gas preparation, ozone generation, ozone contacting, and off-gas treatment	1.59
Reverse Osmosis	Feed pumps	20.08 - 34.34
Electro-dialysis	Electrified membrane plates	15.85 - 34.34

Most importantly, water demand from PtX facilities cannot compete with local water resources for drinking, agriculture, etc. [51] To ensure coherence in the value chain while guaranteeing sustainability of water use, it has been suggested to locate waste water facilities in close vicinity to PtX production [48].

4 | Research design

Based on the previously presented sections, it is deemed relevant to explore the topic of value chains specifically in terms of the techno-economic benefits of resource utilisation in PtX projects. Firstly, EU and Danish climate policies underscore an urgent need to decarbonise hard-to-abate sectors such as industry and heavy transport, which account for a significant share of emissions. PtX pathways are essential to this transition, especially in sectors where direct electrification is not feasible. Secondly, the complexity of PtX value chains highlights the need for a coherent planning method to evaluate and determine the spatial aspects of PtX projects. The viability of these systems depends on efficient access to renewable electricity, CO_2 sources, access to water, and grid infrastructure. Electrolysis, as the core process of PtX, is capital- and energy-intensive, and its efficiency and economics may be sensitive to site-specific factors. These insights provide an apparent reason for investigating how spatial planning can optimise PtX facility placement by aligning them with existing value-chain resources. Aabenraa Municipality has been chosen as the underlying case for this thesis, as the municipality is already notable for its renewable energy capacity and emerging PtX interest. Researching subjects within the previous sections has led to the following research question:

How can spatial planning in the case of Aabenraa Municipality advance PtX value-chain utilisation from a techno-economic perspective?

In order to answer the research question, it was considered relevant to develop three sub-questions:

- How can Graphical Information Systems (GIS) be used to determine optimal positioning of future PtX facilities that support resource value-chains through sector coupling?
- Which power-to-x scenarios will be beneficial within Aabenraa municipality, considering the location of existing value-chain resources in the area?
- How do these scenarios affect possible business economic gains for investing companies, and to what extent do PtX value chains affect the economic feasibility of pathways in comparison?

The connection between the three questions and the three parts of the analysis is displayed below in Figure 4.1. The first question, related to the first partial-analysis, provides a GIS-based methodology for assessing the suitability of PtX locations. The second part of the analysis is based on scenarios developed in extension to the resources included as part of the spatial analysis. Finally, these scenarios will be compared in a techno-economic assessment, which will be the base for concluding on both parts of the analysis before this.

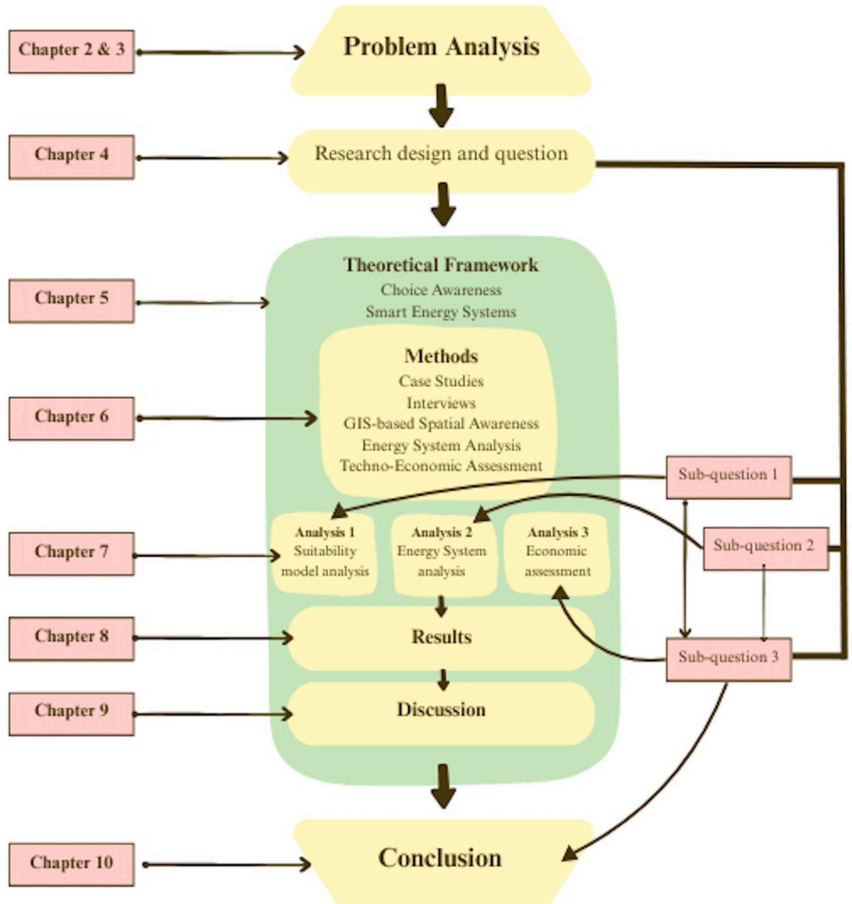

Figure 4.1: Presentation on the chronology of each section of this thesis

4.1 Case description

Aabenraa Municipality is located in the southern part of Denmark, bordering Germany. Like most other municipalities, Aabenraa has participated in the DK2020 program to develop green climate plans for Danish municipalities, aiming to create their plans by 2035. This development strategy, known as "the good life," encompasses a comprehensive plan for social sustainability and business development within the municipality. The strategy emphasises access to transport infrastructure by sea and road, as well as clean energy, while highlighting a lack of recruitment and workforce development. Furthermore, the strategy includes a commitment to renewable energy projects, particularly by promoting PtX projects, sector integrations, industrial synergies, and decarbonising the heating sector. The city council has demonstrated its commitment to this goal by appointing a head of PtX development at the same organisational level as other administrative directors. Furthermore, they have pointed out four specific areas, particularly suitable for business, industrial, or PtX purposes. These areas are marked as Kassoe, Ensted, Kliplev, and Padborg business area in Figure 4.2

below. As of May 2025, the Kassoe e-methanol plant had its official inauguration. The plant, constructed and

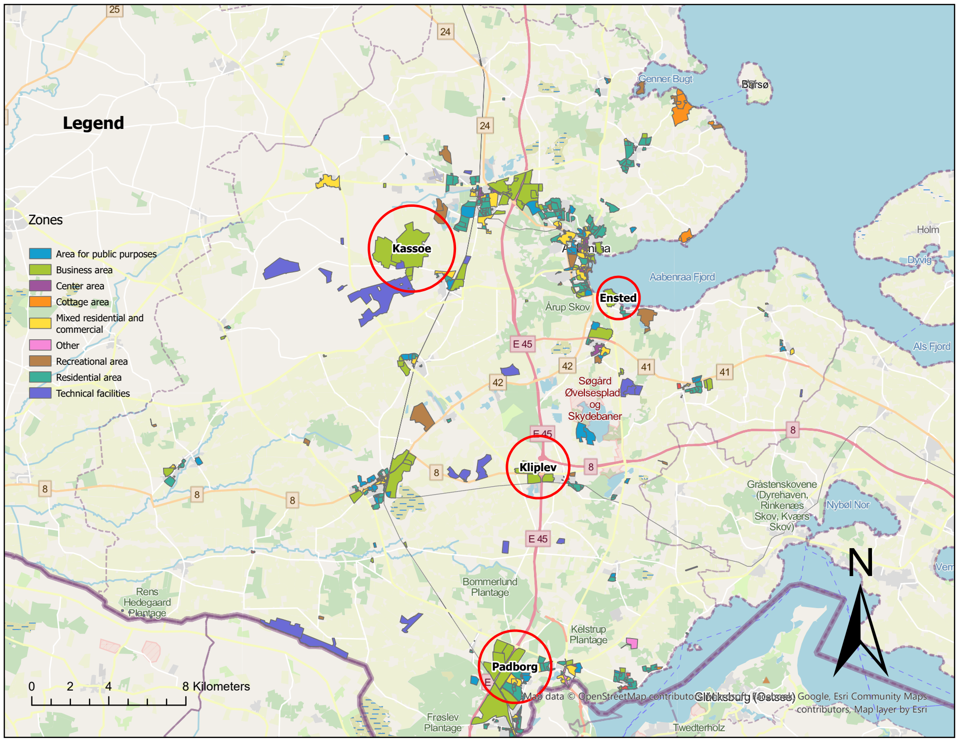

Figure 4.2: The four areas pointed out as suitable for industrial or PtX purposes by Aabenraa Municipality

operated by European Energy, consists of 54 MW of PEM electrolysers, connected to their 300 MW solar farm located next to the methanol plant. Municipal and corporate plans may include an expansion of the plant, as real-world experiences on operations are gained.

5 | Theoretical framework

This section presents the theoretical framework within which the analysis of this thesis is based, including aspects related to choice awareness theory and smart energy systems. However, it is noteworthy to mention that drawing the exact line between theory and methods can be challenging, as they are more or less interlinked. Theories usually present some fact or problem, whereas methods propose tools for solving the issue or disproving the given fact. Therefore, all methods are somewhat rooted in several theories, making it difficult to distinguish between them. Choice awareness theory builds on the ability to raise public awareness to support informed choices within the energy system transition, by providing empirically based concepts to overcome barriers to renewable energy adoption. Smart energy systems advocate for the integration of complex sectors and energy systems to achieve the most efficient routes to a carbon-neutral society.

5.0.1 Choice awareness theory

Choice awareness theory examines how to facilitate radical technological transitions, such as the shift from fossil fuels to renewable energy, by emphasising the societal perception of available choices. Lund argues that significant organisational and institutional changes are necessary for such transitions, yet existing institutions often resist these due to vested interests and power structures. To overcome institutional barriers, radical technological change is essential. Such change involves transformative shifts in several of the following elements: techniques, knowledge, organisational structures, and products to disrupt the status quo [52]. Hvelplund later added *profit* as an additional required element for radical technological change [53], which is a highly relevant factor to PtX projects today, especially as they try to reach a feasible solution on a "free market" basis. Furthermore, transitioning to renewable energy systems necessitates the development of new infrastructure, institutional arrangements, and specialised skill sets. Therefore, these dimensions are interlinked, and thus by modifying one domain often necessitates changes in others. This interdependency is particularly relevant in the context of emerging green fuel technologies, which in addition to a difficulties reaching financial feasibility, also face challenges such as lack of standardisation, limited expertise, and safety concerns.

Central to the theory is the distinction between true choices, where viable alternatives are identified and evaluated, and false choices, in which alternatives are deliberately excluded to create a lack of options. These false narratives are typically constructed by dominant organisations seeking to preserve their interests, often by suppressing or discrediting alternatives during public decision-making processes. Therefore, Lund argues for methodologies to assess technologies, financial feasibility, and public regulation for evaluating alternative green technologies [54]. This theoretical approach therefore aligns very well with the goals of this thesis: to assess scenarios of innovative technological alternatives that are capable of substituting for fossil fuel uses in hard-to-abate sectors.

5.1 Smart energy systems

The concept of a "smart energy system", as described by Lund [55], is included to provide a basis for understanding the complexities and improvements in utilising sector integration. Smart energy systems and sector integration are crucial for ensuring technical stability and economic efficiency during the transition to climate-neutral energy systems. The energy system is often considered several individual closed systems to be optimised. Smart energy system breaks with this understanding to conceptualise the energy system as a whole. For instance, Lund et al. (2025) [56] demonstrate that focusing solely on electricity (smart grid) misses critical synergies that can only be obtained by coordinating electricity, heating, cooling, transport, industry, and materials into a single holistic framework. The study quantifies the least-cost solutions by progressively integrating these sectors through the coupling of surplus heat, flexible demands, and storage options.

Furthermore, 4th-generation district heating may exploit lowtemperature waste heat and integrate large-scale heat pumps. The gas grid can incorporate PtX pathways, using electrolysis to convert surplus renewable electricity into hydrogen or other fuels, acting as a storage technology. By ingraining PtX within a smart energy system, hydrogen and e-fuels become system services rather than standalone commodities. Electrolysers can provide balancing services during hours of abundant renewable output, as they can ramp loads at rapid frequencies, earning revenue from grid support.

Thus, it is essential to understand the importance of utilising smart energy systems to provide solid solutions in an increasingly flexible energy system. The production of different grids must complement each other for optimal operation and performance. Along with other technologies, such as heat pumps, PtX is an essential part of providing a stable electricity grid, while also offering solutions for decarbonising other sectors, including transport and industry.

6 | Methods

6.1 Case study

With the research question centred on a secluded concrete case area, it is relevant to reflect on the strengths and weaknesses of working with this type of case and what the case is actually about. The case study is an excellent way to explore and contextualise the research problem. This is particularly useful when applying several methods to better understand what the case, and thereby the issue of this thesis, is an indication of. Flyvbjerg emphasises that learning and expertise develop through immersion in specific, real-life examples, an argument especially relevant to the field of PtX, which is still emerging and lacks standardised planning frameworks [57]. Because of this, and the fact that PtX projects often come with many uncertainties related to real-world operation and planning, it was relevant to question actors with experience within these fields. Furthermore, both Yin [58] and Flyvbjerg [57] discuss the generalisation of case studies in a scientific context, particularly in single case studies. Yin makes the distinction between single units of analysis (holistic) and multiple units of analysis (embedded) as illustrated in Figure 6.1, where this study explores a single municipal case.

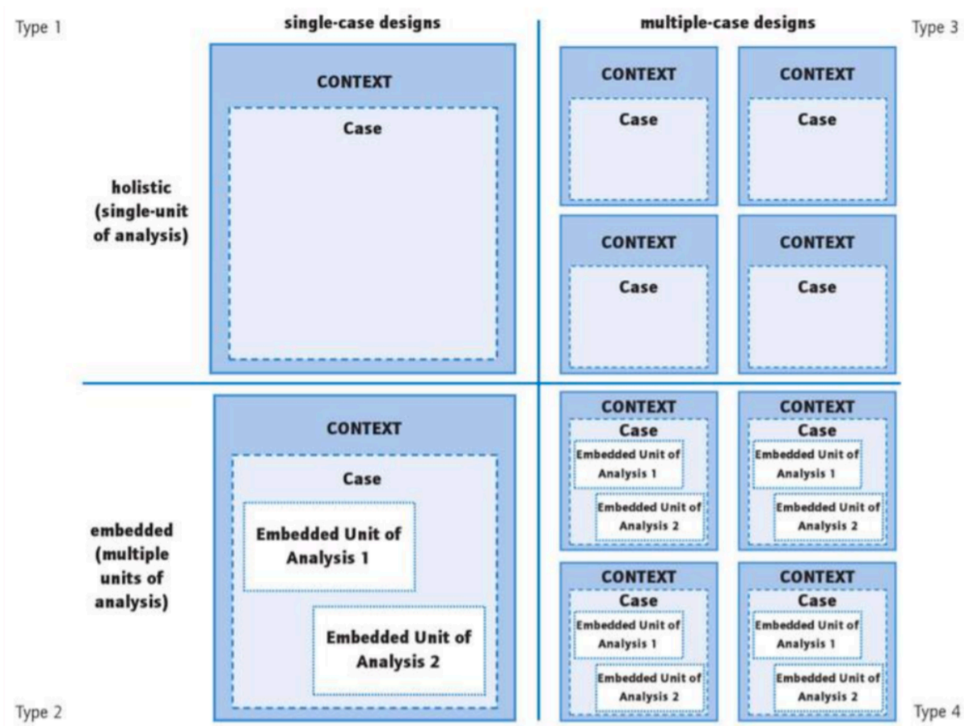

Figure 6.1: Types of case studies and their relationship as single or multiple case studies [59]

"Holistic" cases may also involve more cases within a broader context, for instance, if this study were to research the integration of PtX value chains in the southern region of Denmark, with each municipality as a single case. The inability to generalise case studies is often attributed to the argument that there are too few sample studies to demonstrate recurrences. Flyvbjerg instead argues for information-oriented selection when selecting cases. This emphasises that cases are "*selected on the basis of expectations about their information content*", while differentiating between four types of single cases:

- Extreme/deviant cases: To gather information on atypical cases that are either particularly problematic or exceptionally favourable in a more precisely defined context.
- Maximum variation cases: To understand how different circumstances, such as size, organisational structure, location, or budget, affect the case process and outcome, by examining three to four cases that vary significantly along one of these dimensions.
- Critical case: To obtain information that enables logical inferences such as, "if this holds (or does not hold) true for this case, then it is valid for all (or no) cases".
- Paradigmatic cases: To develop a metaphor or lay the foundation for a theoretical framework within the domain addressed by the case. An example of this is the existing fossil fuel industry cases used by Lund [52] to develop and argue for his thesis on choice awareness theory.

Incorporating additional methods into the research process may enhance a case study's scientific argument. In this context, a mixed-methods approach that integrates diverse qualitative and quantitative techniques can benefit the case study. Hence, the interview method was used to attain real-world knowledge of the context in which the case is situated.

6.2 Interviews

Interviewing can be used as a constructive ethnographic method to collect qualitative information regarding specific subjects within the problem field. For this thesis, contributing actors were chosen based on their organisational roles related to the PtX field in Aabenraa Municipality. Hence, the local wastewater treatment company (Arwos), Aabenraa District heating, and the administration responsible for the Kassø facility in Aabenraa Municipality were contacted. Arwos pointed out through a mail correspondence that they have yet to deliver wastewater, but have started looking into the structure of doing so, making an interview unnecessary. From the two interviews conducted, both informants wished to stay anonymous. However, key insights and valuable information from the interviews have been actively used to provide context for this thesis's data and research design.

6.3 Geographical Information System (GIS)

A Geographic Information System (GIS) is a computer-based tool that creates, manages, analyses, and maps data linked to specific geographic locations. It enables users to capture, store, manipulate, analyse, and present spatial or geographic data. The location-based information and associated attributes form the foundation for mapping and analysis used across virtually every field, from urban planning and environmental science to public health and logistics [60]. GIS enables the overlay of diverse types of data on a single or multiple maps for illustration and analysis, linking spatial data from relevant sources or self-generated data with descriptive information. This integration enables the comparison of geospatial data to examine how different variables interact or relate to one another. Depending on the data inputs, GIS can generate various customised maps to support analysis and decision-making processes [61].

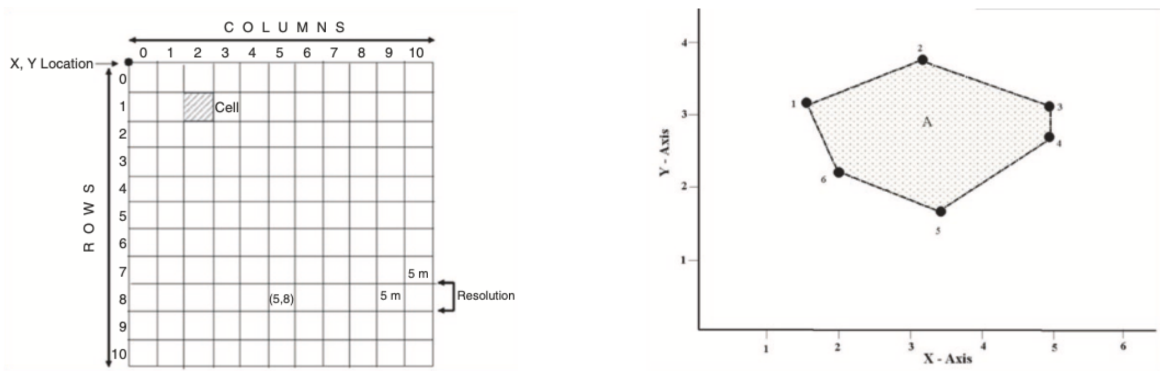

Figure 6.2: Illustrations on the basis of vector and raster functions in GIS software [60]

Spatial data forms the foundation of any GIS environment, representing the world as a collection of features. Specific attributes or properties characterise each feature, and its geographic position can be mapped using a spatial reference system. Landscape is most commonly represented by two types of spatial data models: discrete data (vector models) and continuous data (raster models). These models offer a structured framework for describing and representing real-world features within GIS software. The vector data model represents the world as a collection of distinct features with defined boundaries, identities, and shapes, using points, lines, and polygons. Vector data is structured using x- and y-coordinate systems to precisely display lines, points, or polygons as in Figure 6.2. Vector values are well-suited for representing data with discrete boundaries, such as groundwater wells, streams, and lakes, which are more difficult to represent by pixels. Each feature has a specific dimension, boundary, and geographic location. For instance, a wind turbine can be described by its capacities, construction data, and location, while being accurately positioned using a coordinate system. The raster data model represents an area or region as a surface divided into a grid of cells. It is particularly effective for storing data that varies continuously across space, such as aerial photographs, satellite imagery, humidity levels, or digital elevation models (DEMs). Each cell in the grid contains a value representing a specific attribute, enabling detailed spatial analysis of continuous phenomena. [60]

6.4 Energy system analysis

The modelling and design of energy systems have been applied in various contexts, including planning for future energy systems and optimising existing systems or plants. The mathematical design of all models attempts to replicate the operation of an energy system to some extent based on deterministic algorithms with reproducible outputs, with a given solver and set of inputs [62].

The objective of the modelling in energy modelling tools must be clearly defined, as different goals require different model designs, input data, and analytical approaches. Relevant data must be gathered to support the validity and relevance of the model output in a given analysis. This data is the foundation for analysis, from which insights can be drawn and conclusions formulated. Energy system models also vary in scale, scope, and availability, with certain models limiting the use case to district heating systems or the electricity grid only. Conversely, some modelling tools are designed for national-level analysis of the whole energy and industrial sector, while others focus on regional or local contexts, such as single plants [63, 64]. Literature on energy system tools distinguishes between optimisation and simulation when designing energy system models. The term optimisation is commonly used to describe a modelling approach in which various decision variables are calculated in order to either maximise or minimise an objective function, subject to a defined set of constraints. The overarching goal of an optimisation approach is to identify a single, optimal solution within the boundaries of the defined system. Depending on the chosen objective function, the optimisation may focus on minimising energy consumption, CO_2 emissions, economic costs, or a combination of these and other factors. In contrast, the simulation approach is used to model and assess the behaviour of an energy system under specific conditions. The primary aim of simulation models is to explore and evaluate how variations in key parameters, such as cost, emissions, and energy supply, impact the system. These models typically generate a range of scenarios, rather than a single optimal outcome. In conclusion, optimisation models are designed to identify the most effective solution based on specific objectives and a set of defined assumptions, constraints, and values, often economic in nature. In contrast, simulation models evaluate system performance across different scenarios based on multiple criteria. [65]

6.5 Evaluating techno-economic benchmarks in energy projects

Techno-Economic Assessment (TEA) is an approach used to evaluate the economic viability of various technological options. This method serves multiple purposes, including determining the economic feasibility of energy projects while quantifying associated uncertainties and risks. This is achieved by identifying and analysing key economic parameters. Often, techno-economic assessments involve comparative analysis of alternatives and external factors to enhance decision-making. Traditionally, TEA is used to analyse economic indicators such as payback period (PBP), internal rate of return (IRR), return on investment (ROI), capital costs, general operating costs, revenue, and overall profitability [66].

While this thesis will use these metrics to support the financial indications for each scenario developed, the most commonly used metrics in TEA are Net Present Value (NPV) and the Levelised Cost of Energy (LCoE). These indicators provide quantitative insights into investment performance and cost-effectiveness, which are elaborated on below.

6.5.1 Levelised Cost of Energy (LCoE)

The Levelised Cost of Energy (LCoE) is a widely used metric for calculating the average cost per unit of energy, typically electricity, generated over the lifetime of a system. It incorporates all capital, operational, and fuel-related expenditures, offering a standardised basis for comparing energy generation technologies [67].

LCoE is calculated as:

$$\mathbf{LCoE} = \frac{\sum_{t=1}^{n} \frac{\mathbf{I_t} + \mathbf{M_t} + \mathbf{F_t}}{(\mathbf{1} + \mathbf{r})^{\mathbf{t}}}}{\sum_{t=1}^{n} \frac{\mathbf{E_t}}{(\mathbf{1} + \mathbf{r})^{\mathbf{t}}}}$$

Where:

- I_t: Capital investment in a given year t
- M_t: Operation and maintenance costs in year t
- F_t: Fuel costs in year t
- E_t: Energy generated in year t
- r: Discount rate or interest rate
- n: System lifetime (years)

LCoE reflects the minimum price per unit of energy that must be charged to recover the full cost of the system over its lifetime. It is often benchmarked against market electricity prices to evaluate economic competitiveness. LCoE is frequently adapted in the literature to fit the field of the evaluated energy production, such as Li et al. (2019) [68], who researches the effects of dynamic price models on the levelised cost of producing heat. In the context of PtX systems, the concept can be adapted to evaluate the cost of producing methanol over the lifetime of the technologies in question, leading to the Levelised Cost of Methanol (LCoM), which can also be altered for hydrogen:

$$\mathbf{LCoE} = \frac{\sum_{t=1}^{n} \frac{\mathbf{I_t + M_t + F_t - B_t}}{\mathbf{(1+r)^t}}}{\sum_{t=1}^{n} \frac{\mathbf{M_t}}{\mathbf{(1+r)^t}}}$$

Where:

- M_t: Methanol produced in year t
- B_t: Earnings from the by-production of oxygen and heat

The adaptation of LCoM represents a metric to compare different production pathways of methanol. As earnings from by-products are not the desired product of assessment, it is found reasonable to adapt the formula to include earnings from these. This will, in turn, improve the levelised costs, representing a lower minimum cost of methanol, and hopefully bring it closer to a competitive price point compared to methanol produced from fossil fuels.

6.5.2 Net Present Value (NPV)

NPV is a financial metric used to assess the profitability of investment opportunities by evaluating projected future cash flows. It calculates the present value of all expected revenues and expenses associated with an investment, discounting them to todays value. The result is expressed as a single figure representing the net gain or loss.

The NPV formula is given as:

$$\mathbf{NPV} = \sum_{t=1}^{n} \frac{\mathbf{(R_t - C_t)}}{\mathbf{(1+r)^t}} - \mathbf{I_0}$$

Where:

- R_t: Revenue in year t
- C_t: Cost or expenditure in year t
- r: Discount rate
- n: Investment lifespan (years)
- I_0: Initial capital investment

A positive NPV indicates that the investment is expected to be profitable within its operational lifespan, equivalent to the value calculated. Furthermore, the NPV is highly dependent on the discounting of cash flows, reflecting the importance of deciding on a realistic discount rate [69]. For public companies, the discount rate is typically decided by the "socio-economic discount rate" from the Danish Ministry of Finance [70]. This rate is chosen depending on the length of a given project, with projects below 35 years currently set to 3.5%. While this is mainly based on the real interest rate, company discount rates are often more complex and related to both internal and external factors. The Weighted Average of Capital (WACC) describes the costs of owning equity and debt. It is therefore often used as a discount rate, as it becomes the minimum required return on any investment worth pursuing. The discount rate can also incorporate uncertainties, such as economic crises or untested markets, like green fuels, or be used as a risk mitigation tool when assessing projects.

6.5.3 EBITDA, IRR, ROI

EBITDA, or *Earnings before interest, taxes, depreciation and amortisation*, is often used as a comparative measure for the correlation between income and costs in a cash flow. This is not a particularly useful metric for a business itself. Still, as companies are affected by different taxes, interest rates, and depreciation estimates, EBITDA may be used to compare cash flows before these factors are taken into account. Though interest rates are not used in this case, as no money will be borrowed, EBITDA can be used to calculate a profit after tax. This measure is subject to an assumed yearly taxation after a given depreciation rate has been subtracted, as this amount is not taxable. The internal rate of return (IRR) does not set a predefined discount rate, as does the NPV, but instead considers the discount rate that would be required to produce an NPV of zero in a given project. Thus, the IRR can determine the lowest discount rate required to achieve a positive NPV by calculating the lowest discount rate for each year's cash flows. Furthermore, the IRR describes the risks associated with a project by illustrating how much cash flow can be discounted while still achieving a positive return on investment: The higher the IRR, the better the investment. Finally, like the discount rate, the IRR should exceed the cost of owning capital to a company, which the WACC can traditionally describe. The return on Investment (ROI) describes a percentage measurement of the value of an investment compared to the cost of the investment, expressed as follows:

$$\text{ROI} = \frac{\text{Current investment value in a given year or period} - \text{Investment cost}}{\text{Summed cost of the investment at a given time}} * 100$$

Unlike other discountable financial metrics, such as the NPV and IRR, the ROI does not discount its returned value.

6.6 The use of Excel in technical and economic assessment

With Excel used extensively during the writing of this thesis, for both small and large tasks, some parts of the spreadsheet may not be easily understood at first glance. Therefore, this section will serve as a brief guide to the rationales behind the spreadsheet model. Firstly, an initial technical assessment is created, displayed in the "outputs" tab in appendix (A.0.1), based on linear inputs from the technology catalogue on renewable fuels. Outputs presented in this tab are based on a yearly electricity input, the project evaluation, and conversion values on CO_2, hydrogen, and methanol. Each output is thus a representation of the maximum annual production, helping to decide on dimensional inputs for energy system analysis, which can calculate variable operation based on the given inputs. Following this, an economic assessment is conducted for each chosen scenario, encompassing earnings and cost factors, tax payments, cash flows, production, and a levelized cost presentation over the 25 years.

7 | Analysis

This chapter presents a contextualised methodology for each analysis conducted to conclude on the research question. The steps for each analysis will be presented systematically, along with the data and assumptions used to reach the results, by investigating the particular case of the Aabenraa municipality. As mentioned in the previous chapter, this case aims to provide a framework that can be replicated in the planning and decision-making processes for dedicated PtX areas in other municipalities. However, it is important to mention that the analysis contains many aspects from the "maximum variation case", meaning design outcomes in planning processes are particularly sensitive to size, municipal location, budget, etc. which is also reflected in chosen scenarios and sensitivity analysis later on. The following analysis consists of three steps, each represented by the subquestions in section 4 to answer the main research question. The methodological approach is described chronologically to provide context and coherence to the overarching framework. The steps to answer each subset of the research question are as follows:

- **Step 1:** Identifying the suitability of PtX locations weighted based on decided production
- **Step 2:** Developing PtX system scenarios based on value chain resources within the municipal area
- **Step 3:** Business-economic analysis based on best case system scenarios

7.1 Process of identifying future suitable PtX locations

The suitability of particular municipal areas may become increasingly important depending on the strategic decarbonisation plan. This methodology for finding the most suitable locations is conducted through a geographical information system (GIS) analysis. Selecting these locations will depend on several factors, including data aggregation and the process used in the GIS analysis. This analysis is based on the suitability analysis function in ArcGIS Pro, which is presented in this section, along with the data used to determine an optimal location within the municipality of Aabenraa.

7.1.1 Description of data origin and usage

The ArcGIS Pro suitability analysis is based on five data layers deemed relevant to the PtX value chain specific to Aabenraa Municipality. The five layers are comprised of biogas point sources for PtX pathways that require carbon molecules to increase energy density, wastewater facilities, the location of the Danish hydrogen backbone, the existing distinct heat network, and, finally, high and medium-voltage transformers within the municipal borders. Suitability analysis for other municipalities may require further exploration of other data layers, such as elevation and slopes. Oxygen from electrolysis can only be classified as industrial oxygen; it has food-related uses, but is not applicable for medical uses in hospitals [71]. Nevertheless, bi-product oxygen has seen applications in wastewater treatment and fish production [72, 73], further enhancing the utilisation of PtX value chain. Infrastructural aspects, such as access to the road network or ports, may also be relevant to deciding suitable locations for PtX. Finally, it could be applicable for developers to gather information on sites for renewable energy production in the same decision process as PtX locations, utilising data for solar radiation, suitable areas for wind turbines, nature-protected regions, etc.

As hinted above, certain assumptions are made on the data needed to provide a solid basis for a decision-making tool for PtX suitability. These assumptions relate to the relevance of PtX value chain-associated factors, such as distance intervals, available quantities needed, and the nature of the layers, including direct access to every part of the district heat network. In reality, certain parts may not be feasible due to the lack of consumer demand, especially during the summer.

Biogas and waste water point sources

Biogas is important as a CO_2 feedstock for e-fuels containing any amount of hydrocarbons. However, there is ongoing discussion about where easily accessible biogenic CO_2, such as from biogas, will be used in the future. This is partly due to the Danish Government's policy to achieve immediate results from abating biogenic CO_2 through long-term storage, referred to as "negative emission reduction." Furthermore, the price of biogenic CO_2 remains uncertain with few real-world projects as precedent. Biogas is likely the only current suitable source for CO_2 with high concentrations at approximately 40% CO_2 and 60% methane [74]. Furthermore, biogas facilities require physical or chemical separation methods to reach the required quality for biogas in the gas grid. The chemical solvent monoethanolamine is used in most facilities included in this analysis. The Danish government is currently investing 38 billion DKK. into carbon capture storage through public tenders, with one of the current three tenders focusing only on storage of biogenic CO_2 [75]. This indicates a public policy prioritising instant effect when reducing national carbon emissions, whereas CO_2 utilisation seems less emphasised. This may complicate future cases where CO_2 is needed, as the business case for storing carbon can become more feasible when accounting for both public subsidies and certificates for negative emissions.

Available biogas point sources for the southern region of Denmark are displayed in Table 7.1, showing capacity production in upgraded biogas (Nm^3/h). Biomethane production is found manually on Google and converted to hourly CO_2 flow by assuming a conservative 90% production and 60/40% relationship in biomethane/CO_2.

Table 7.1: Biogas production and emissions in the southern region of Denmark

Biogas facility	Biomethane Production Capacity [Nm^3/h]	CO2 Flow [Nm^3/h]	CO2-emission 2025 [ton/year]
SBS Kliplev	6000	3600	62347
Biogas Taagholm P/S (Rødekro)	700	420	7274
Storde biogas	2300	1370	23724
Toender biogas	4550	1369	47448
Sønderjysk Biogas Bevtoft A/S	5600	3360	58190
Naturbiogas Sode A/S	2200	1320	22860
Nature Energy Glansager	2500	1500	25978

The placement of biogas facilities in various CO_2 increments is illustrated below in Figure 7.1, along with the location of different wastewater capacities within the municipal borders and the Danish hydrogen transmission line, known as the "hydrogen backbone". The hydrogen backbone was initially projected to be operational by 2028 but has recently been confirmed by 2030 instead [8].

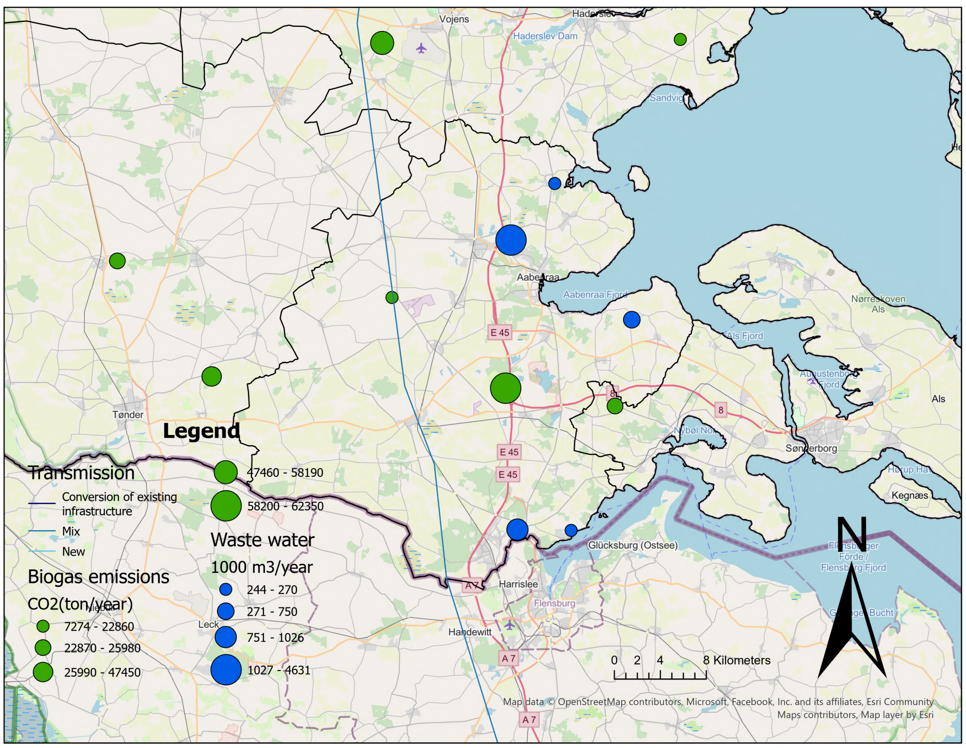

Figure 7.1: Location and capacities of biogas and wastewater facilities

With the water-energy nexus becoming increasingly relevant in the energy sector, this thesis assumes that water consumption for PtX facilities cannot compete with water types suitable for drinking, as groundwater may not be as plentiful if the model were recreated in drier locations. Yearly wastewater capacities processed are displayed for each facility in Table 7.2. The facility type indicates the number of purification processes the wastewater undergoes. Wastewater is first cleaned mechanically (M) by passing through screens that remove solid objects. Next, it goes through biological cleaning (B) in tanks with air. The water passes through filters

Table 7.2: Waste water treatment plants within Aabenraa Municipality with data from ref[76]

Waste water treatment	Amount(1000m^3/year)	Facility type
Stegholdt	4631	MBNDC
Genner	244	MBN
Stenneskær	750	MBNDC
Bov	1026	MBNDC
Kollund Østerskov	270	MBC

filled with stones and helpful bacteria. These bacteria break down the waste in the water. Nitrification (N) is the process by which ammonium in water is converted into nitrate using oxygen. Denitrification (D) occurs when bacteria convert nitrate into nitrogen gas, which is released into the air. Finally, chemical cleaning (C) is done by adding chemicals like iron or aluminum. This causes leftover particles to clump together into a heavy substance that sinks and is removed from the water. Currently, wastewater from treatment plants is let out into the fjord. While slightly higher costs may be associated with purifying wastewater, it is essential to maintain sustainable practices for obtaining water for green hydrogen production, which is why it should be considered to the greatest possible extent when locating suitable sites for PtX. According to Aabenraa Municipality's business administration, the Kassoe facility was granted an exemption for limited access to boreholes for groundwater, as these are located within the solar farm area owned by European Energy. It was, however, emphasised that this will not be the case for future PtX facilities, which will require easy access to water. There is not enough water to meet the demand for PtX. Thus, developers will have to look into wastewater, or perhaps even saltwater, if they see fit.

District heating and power capacity

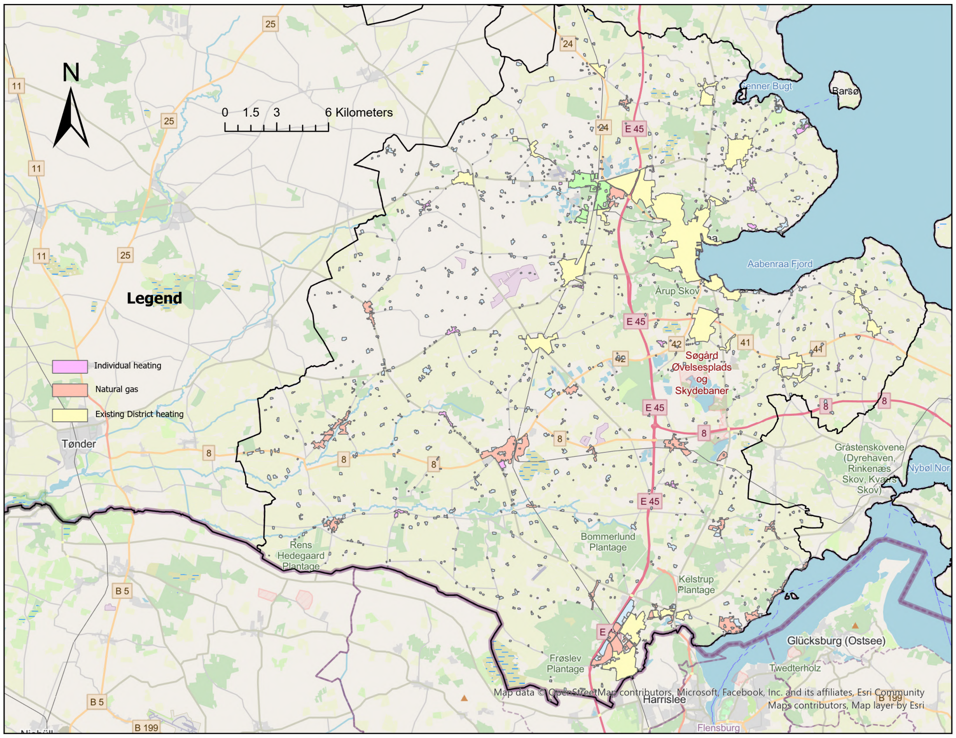

Figure 7.2: Heating types in Aabenraa Municipality ref[77]

Providing waste heat from PtX processes is an excellent way to supply local district heating companies with a cheaper energy source, provided that processes with excess heat, such as electrolysis and methanol synthesis, can meet demand and deliver the required temperature. In some cases, it can also reduce the electricity and capital costs required for cooling. Aabenraa Municipality currently has five district heating companies, with Aabenraa District Heating being the largest. The total heating demand within the municipality is 700,000 MWh, of which 310,000 MWh is district heating. The rest is based on individual heat sources, mainly natural gas and oil, but with some amounts of biomass and heat pumps [78]. Aabenraa Municipality is actively working towards phasing out natural gas and oil for space heating by 2030, with biogas usable until 2035 as a part of the sustainability goal to be carbon neutral by 2030 [79]. This results in a more significant focus on implementing district heating to substitute individual use of oil or natural gas-run district heating companies. Figure 7.2 shows the distribution of individual, natural gas, and district heating zones in Aabenraa. Only existing district heating areas have been included in the suitability analysis. It is, nevertheless, important to mention that these areas may expand in the future, becoming relevant subjects for waste heat sources if demand in the given area is adequate.

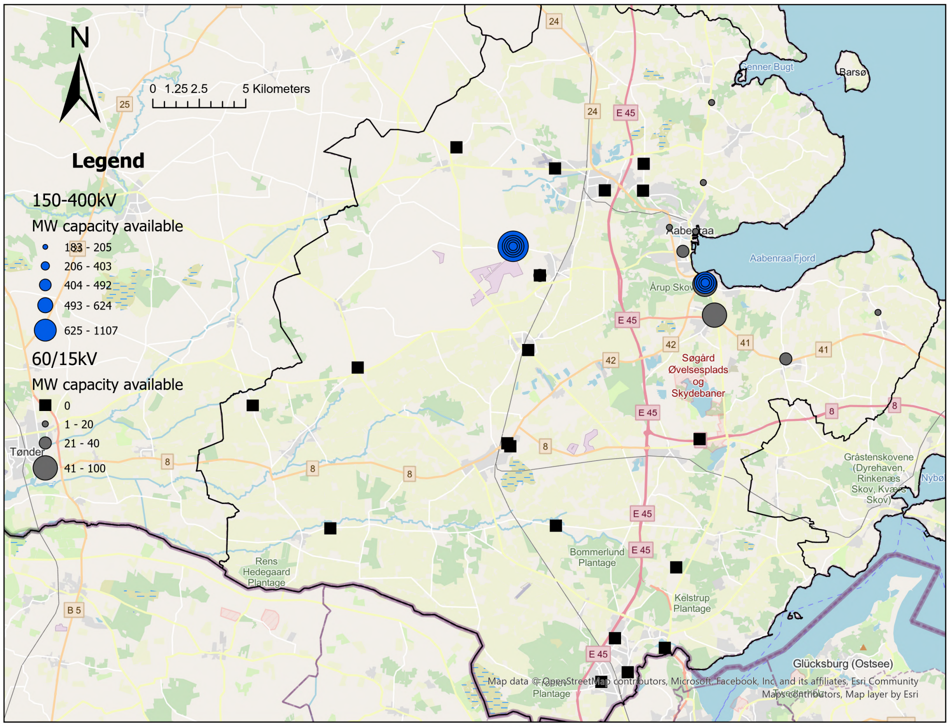

Figure 7.3: Location of 400 and 60 kV transformer stations within the borders of Aabenraa Municipality. Data from ref [80]

Like the importance of water availability for the electrolysis process, electricity is necessary for producing green hydrogen. As previously stated, the qualifications of an e-fuel's ability to be carbon neutral depend on the CO_2 reduction within the output of the fuel itself. Grid-connected productions require at least 90% renewable electricity production yearly to meet this requirement. To circumvent this, the power-purchase agreement can be used to ensure the development of renewable power production in accordance with the capacity needed for hydrogen production, or power can be produced "behind the meter". Figure 7.3 shows the two high-voltage, 400 kV transformers located in Aabenraa, as well as several 60 kV transformers. The figure indicates a lack of capacity available on the 60 kV transformers, as private households and smaller commercial users are most likely to use them already. These have hence been excluded, limiting the suitability analysis to the two 400 kV transformer locations.

7.1.2 Data treatment using suitability analysis in ArcGIS Pro

The treatment of the presented data will be done using the suitability analysis tool in ArcGIS Pro. The suitability analysis is only able to process raster layers; therefore, all vector data, including data fields from these, must first be converted to rasters using the "Feature to Raster" conversion tool. The distance from each data point must be calculated in every raster tile. This is achieved by processing the individual raster data sets using the spatial processing tool "distance accumulation", which assigns a value to each raster tile based on the Euclidean distance measured from all data points. Lastly, all five data sets can be inserted into the suitability model tool, where the value attributed to each layer can be reclassified based on either linear or non-linear functions or as a range of classes. Raster layers may also vary in size; therefore, the maximum distance to the data point is a consideration, which is why a certain logic must be applied to the real-world application of these distances. For this type of data, it was found most suitable to range the classes based on costs related to the transport of the resource type.

Table 7.3: Costs related to electricity, hydrogen and district heating water transport. The newest data available up to 2025 is used [81]

Single power line, 100-250 MW [EUR/MW/m]	Single NG line, 50-100 MW [EUR/MW/m]	Single DH line, 0-50 MW [EUR/MW/m]
3.3	4 but likely 10-20 for H2	63.19

The power distribution is reasonable at 60 kV, as the capacities required for PtX are between 100 and 250 MW, and the distances will never exceed 25 kilometres. However, it may be argued that resistive losses will be high at lower voltages, meaning that at least 150 kV is needed. This instead entails substantial transformer costs to step down the voltage to the 11-33 kV required by many electrolysers. A comparison has been made between hydrogen distribution and existing knowledge on natural gas construction. The cost is likely to increase significantly if newly constructed pipelines are used to mitigate embrittlement and hydrogen leaks by employing more expensive materials. Still, it can be reduced if repurposed natural gas pipelines are used. The cost for one kilometre of a hydrogen pipeline at 59 MW, assuming the flow required for a typical 100 MW electrolyser at full load, amounts to 590,000 EUR. Compared to this, one kilometre of power lines results in a slightly lower cost of 490,500 EUR, not accounting for grid losses. The district heating pipeline will likely need shorter distances to the nearest grid connection. Still, it could become costly at a kilometre price of 630,000 EUR at a 10 MW capacity if not within reach. The inputs for distance intervals based on transport pricing and raster size are displayed below in Table 7.4.

Table 7.4: Distance intervals for data layers. Geometric intervals mean that each interval is multiplied by a fixed factor, which leads to the widths of intervals increasing exponentially. This helps emphasise differences in the lower range, while still covering the full spectrum of distance values. The fixed intervals mean that distances above 10,000 meters and 18,000 meters to the hydrogen backbone and transformers, respectively, become unsuitable

Layer	Classified interval distances
District heat	Geometric intervals
High voltage transformers	2000 meters
Waste water	Geometric intervals
Biogas point sources	Geometric intervals
Hydrogen backbone	1000 meters

After determining these inputs, the suitability model creates a new layer by combining the classified raster layers on top of each other. The suitability modeller is now able to determine the most suitable area based on the input data and restrictions set for public and residential areas in the municipal plan. The locate function can evaluate the best possible position based on different methods, such as the highest average value, which will be used for this analysis. The suitability analysis can pinpoint the best location based on certain applied

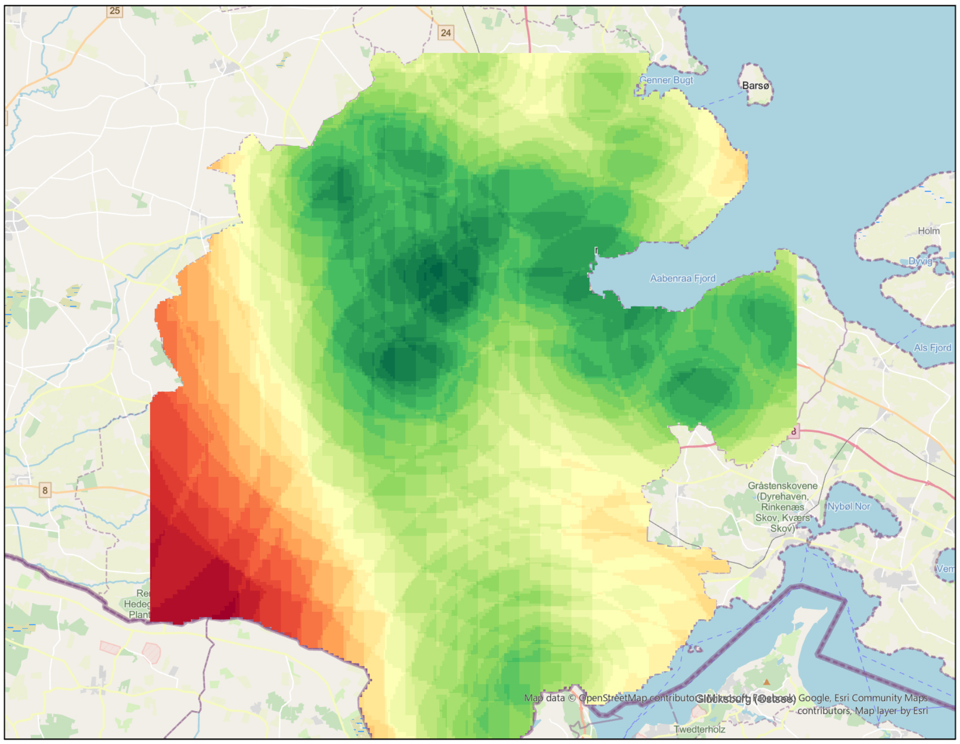

Figure 7.4: Suitability model output layer

weights to each layer. For this analysis, the non-weighted location and four alternatives will be presented, each weighted to provide a specific focus on a possible PtX production. The four focuses are as follows:

1. Focus on hydrogen production and sale while utilising waste heat for district heating. This entails weighting towards wastewater, district heating, and power availability.
2. Focus on hydrogen production and sale, without value chain utilisation, focusing on wastewater and power.
3. Focus on methanol production and sale by truck or ship, while improving on value chain locations by weighting towards CO_2 point sources and district heating.
4. Focus on methanol production and sale by truck or ship without value chain utilisation, only focusing on distance to water, power, and CO_2 point sources.

7.2 Developing PtX scenarios using energy system analysis

Building on the focus of previous sections, this section will present the data and methodology of two PtX scenarios for producing methanol and hydrogen. At the same time, the effects of not utilising the value chain are illustrated through alternatives, as the alternative is to invest heavily in cooling capacity.

7.2.1 Choosing a PtX scenario modelling tool

Given the defined work area and the objective of integrating value chains from Power-to-X (PtX) processes, a suitable energy system modelling tool has been selected. The reviews included by [63, 82, 83] provide comprehensive overviews of various available modelling tools. Based on these reviews, energyPRO (5.0) was chosen as the modelling software for this task. The decision is primarily due to its ability to perform combined techno-economic analyses and optimise complex energy systems comprising diverse energy-producing units, including PtX technologies. EnergyPRO has its roots in the optimisation of combined heat and power (CHP) and district heating systems, but has since developed to provide the possibility of in-depth analysis on heat-pump and electric boiler operations as well as production chains related to electrolysis [82]. The software supports broad energy system analyses and detailed single-plant assessments [63]. This versatility is particularly beneficial for modelling PtX integration with fuel production and using waste heat. While not limited when it comes to including externalities, EnergyPRO focuses inherently on optimising economic gains to improve on investments in renewable energy systems, whereas models like EnergyPLAN have a broader scope for estimating externalities in all sectors [82].

7.2.2 Scenario presentation

The EnergyPRO scenarios are based on techno-economic considerations, data from the technology catalogue for renewable fuels from the Danish Energy Agency (DEA) [42], and assumptions such as heating and cooling prices from interviews with Aabenraa District Heating. Investment costs are not included in the models, as they are assumed to be already accounted for and therefore do not affect the models' operation. Fixed operation and management (O&M) costs also do not influence model operations, but act as a fixed yearly cost in the economic assessment.

Each scenario consists of a fictitious 200 MW photovoltaic farm. This is to improve the realism of the production profile. This is done to illustrate the complexity of reaching a feasible price point for e-fuels, as EnergyPRO will always choose the pathway that maximises profit. As a result, electricity export does not have a revenue price, as the model will export electricity in most hours if the fuel cost is not high enough. On the contrary, EnergyPRO will not produce either if the variable costs from cooling, electricity, and water are too high compared to the e-fuel price.

Hydrogen production scenarios

The first two scenarios are designed to illustrate the differences in economic performance when utilising waste streams and sector integrations. The electrolyser chosen for these scenarios is the alkaline 100 MW stacks due to its commercial maturity, as also presented in section 3.3. Alkaline electrolysers are highly reliable due to their low frequency of stack replacement, have low electrolyte costs, as this is often an abundant material such as lye, and have the highest hydrogen output (% total input [MWh / MWh el]). Technical inputs are based on DEA data for 2025 100 MW alkaline electrolysers as shown in Table 7.5.

Table 7.5: AEC 100 MW inputs for EnergyPRO modelling [42]

	Input	Unit
Electric capacity	100	MW
Hydrogen output	58.7	%/MW-el
Water consumption	9	kg/kg H2
Heat temp. heat usable for DH	8	MW
Low temp. heat unusable for DH	22	MW

Electricity prices are based on time series data for the western Danish price zone in 2024, with tariffs included and excluded to illustrate differences in key performance indicators related to electricity costs. The heat sale technical input shown in Figure 7.5 is based on the usable heat at temperatures required for district heating, which depends on the electrical input in the electrolyser shown in Table 7.5. The effect of output heat at maximum load has been determined based on a theoretical heat amount produced annually from a linear load across the year, converted to an hourly value. This is done to simplify the model; hence, it does not consider peak productions, which could be higher. The cooling requirement is assumed to be represented by the heat produced, while the cost is related to the investment and variable costs for cooling. The efficiency curve and water input are predefined by the EnergyPRO energy conversion unit for alkaline electrolysers with water set to 9 kg per kg of hydrogen output, which depends on the electrolyser efficiency. The electrolyser runs at a minimum load of 10 MW, as indicated by the efficiency curve in appendix (A.0.1). This is required for most electrolysers to maintain voltage when turned on, while changes in load will take longer if turned off.

Table 7.6: Financial inputs for assessing the hydrogen scenarios

	Costs [EUR]
CAPEX	87,500,000
Fixed O&M/year	3,500,000
Stack replacement cost	30,000,000
Depreciation/year	3,500,000

While EnergyPRO can calculate the optimal operation dependent on the cost assumptions, fixed costs such as CAPEX, stack replacements, and O&M are based on the DEA technology catalogue [42]. The number

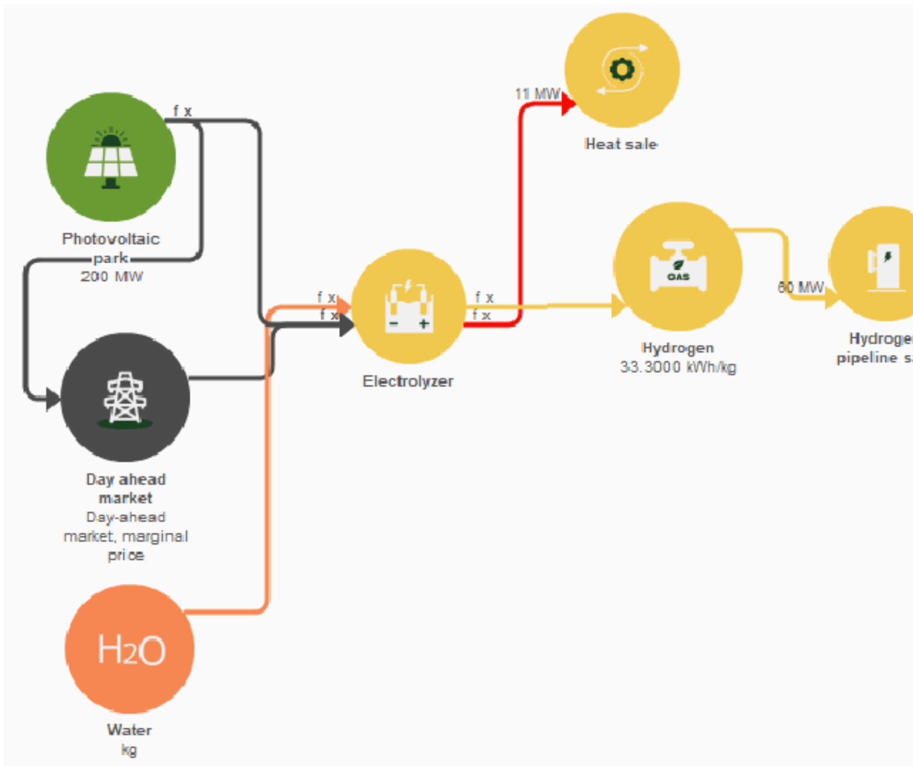

Figure 7.5: Illustration of the EnergyPRO hydrogen scenarios overview

of stack replacements is determined based on the AEC's need for replacement every 80,000 hours. EnergyPRO operates the electrolyser for 7,000 hours annually, resulting in two replacements during its 25-year technical lifespan. While all expenses and revenues are based on a one-year operation of the EnergyPRO simulation, all payments and revenue accounts for a 2% inflation each year.

Methanol production scenarios

The third and fourth scenarios utilise biogenic CO_2 from biogas upgrading to produce green methanol, a more energy-dense product in liquid form, which is usable in many existing products or as a fuel. Methanol synthesis is a chemical endothermic reaction between hydrogen and carbon dioxide, requiring heat in the form of steam to uphold the reaction. One part methanol requires three parts hydrogen and one part CO_2, while the reaction also produces one part water as follows:

$$\mathbf{3H_2 + CO_2 \rightarrow CH_3OH + H_2O}$$

The synthesis produces a raw version of methanol, from which the water has to be distilled. This process, however, is not included in the model. An illustration of the EnergyPRO overview is included in Figure 7.6.

Distilling of methanol must undergo a somewhat constant reaction, requiring no less than 40% load with relatively slow ramp speeds on an hourly basis. This is, however, estimated to progress towards as low as

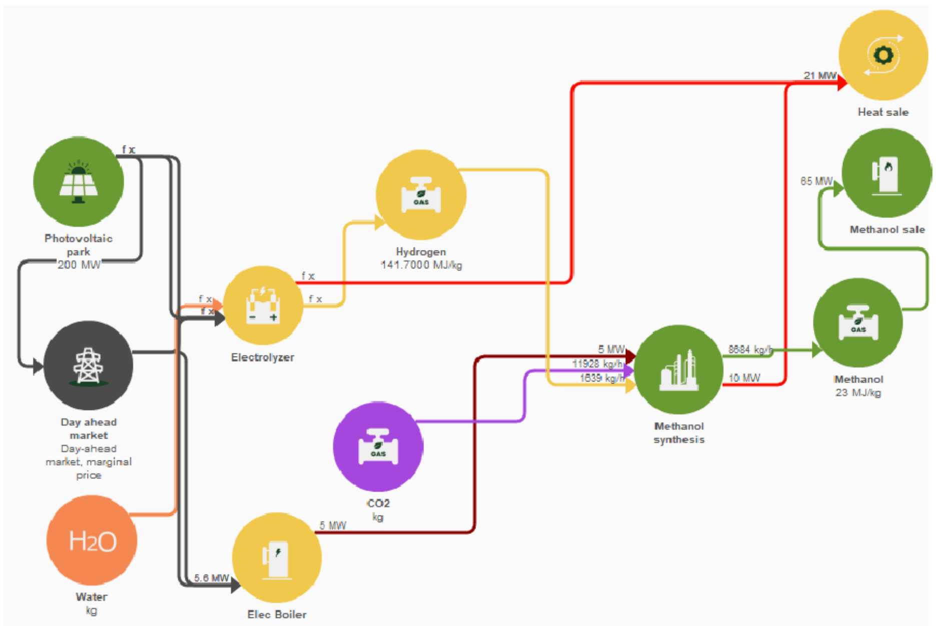

Figure 7.6: EnergyPRO overview of the methanol scenarios. The waste heat input is again represented as cooling in the fourth scenario without a heat sale. The model can be seen in further detail in appendix (A.0.1)

10% load, as industrial methanol synthesis reactors improve [84]. Therefore, the modelling decision stood between the inclusion of hydrogen storage and an even more flexible electrolyser solution to compensate for the less flexible methanol reaction, while still allowing for the ramping of hydrogen production in response to electricity spot prices. Storage buffer solutions, capable of meeting the sufficient hourly demand for hydrogen in methanol production, have been evaluated based on costs related to increased methanol sales, spatial requirements, and technological relevance and readiness. Firstly, hydrogen can be stored in roughly four states other than its original unpressurised state, which lacks energy density and requires too much space to store: compressed, cryogenic compressed, liquid, and as liquid organic hydrogen carriers (LOHC). Hydrogen becomes liquid below its boiling point of -253 °C, significantly increasing its energy density, reducing the footprint required for the storage tanks, and limiting the dangers of high pressures. Cryogenic liquid hydrogen storage partly pressurises the gas to lower the temperature to -233°C thus reaching a supercritical cryogenic gaseous state to achieve even higher storage density than liquid hydrogen [85]. Nevertheless, both solutions require significant energy, resulting in high maintenance with expensive equipment. LOHCs are chemical absorbents that store and release hydrogen, particularly useful over extended periods, as absorption requires substantial energy. This solution may arguably become feasible for mobile hydrogen transport, showing promising economic results over 200 kilometres distances [86]. This leaves the final solution of compressed hydrogen, a cost-effective solution, limited mainly by its spatial requirements at larger storage capacities. A 12-hour storage at 200 bar has been evaluated based on its income advantages in EnergyPRO compared to no storage. This storage decision is based on the hydrogen density at 200 bar and 20 řC, requiring 15 g/L or kg/m^3, as indicated by the phase curve in appendix A. The 12-hour hydrogen storage of about

825 kg requires 55 m^3 of space. Capital costs, estimated based on data from [87] and compression costs of 3 kWh/kg [88] at an average electricity price of 0.4 eur/kWh. Both are subtracted from the operational income, resulting in a negative investment of 680,000 EUR yearly (appendix A.0.1); hence, the slightly more expensive than AEC, but more flexible PEM electrolysis was chosen. Electrolyser data are illustrated in Table 7.7 below.

Table 7.7: PEM electrolyser and methanol synthesis input data are based on [42]

	Input	Unit
Electric capacity	100	MW
Hydrogen output	55	%/MW-el
Water consumption	9	kg/kg H2
Heat temp. heat usable for DH	10.35	MW
Low temp. heat unusable for DH	23.3	MW
Methanol capacity	48	MW
CO2 consumption	11928	kg/h
Hydrogen consumption	1639	kg/h
Process heat [steam] consumption	5	MW
Waste heat for DH	10	MW

The methanol synthesis input values are based on the capacity needed to process the hourly full load of the 100MW electrolyser. Mass balances on an hourly basis are then based on the DEA technology catalogue on renewable fuels, and afterwards checked for correct mass flows in Appendix (A.0.1). Since the chemical process is endothermic, process heat will be supplied in the form of steam by an electric boiler at a 90% efficiency. Due to the temperature of the process, the methanol synthesis can also provide a substantial amount of waste heat for district heating.

Table 7.8: Financial inputs for assessing the e-methanol scenarios

	Electrolysis Costs [EUR]	Methanol synthesis costs [EUR]
CAPEX	97,500,000	64,805,921
Fixed O&M/year	1,950,000	1,872,171
Stack replacement cost	38,400,000	
Depreciation/year	3,900,000	2,160,197

As with the hydrogen production scenarios, the full CAPEX price is paid in year 0, with payments and earnings adjusted for inflation. The number of stack replacements needed for the methanol scenarios increases to three during their lifetime due to lower hours until stack replacement for the PEM stacks and increased hours of operation resulting from the methanol synthesis minimum load. If three stack replacements are needed, a storage solution may once again become feasible, allowing the electrolyser to be shut off and extending the stack lifetime.

7.2.3 Techno-economic assessment of PtX scenarios

This section provides an economic assessment of the four technical scenarios, based on specific financial assumptions regarding fuel prices used in the Energypro models. The assessment aims to provide comparative financial benchmarks from section 6.5 dependent on the assumptions presented. It is therefore essential to emphasise the reliance of these assumptions on the results, as even small changes in fuel prices, production efficiencies, or the discount rate can drastically alter the outcome. Since price points on sales and fuel costs are central to the operation of EnergyPRO, the rationales for these are presented in the following section and listed below in Table 7.9.

Table 7.9: A listing of the cost and sale prices used in - and outside of EnergyPRO

	Price	Unit
Heat sale	13	EUR/MWh
Cooling costs	26	EUR/MWh
Water costs	0.01	EUR/kg
CO2 costs	0.15	EUR/kg
Sale of oxygen	0.09	EUR/kg
Sale of hydrogen	5	EUR/kg
Sale of methanol	1.2	EUR/kg

The cooling and waste heat prices are based on discussions with Aabenraa District Heating, which used their own calculations to determine the further utilisation of waste heat from electrolysis units at the Kassø facility. These price estimates for cooling requirements include full OPEX and CAPEX costs for equipment, as well as electricity costs, etc. The waste heat price is estimated based on the price Kassø would pay Aabenraa District Heating, assuming they put down a long-term investment in the infrastructure needed to deliver the heat to accumulation tanks and consumers. Considering the heat price for consumers connected to the DH grid is 68 EUR per MWh, including VAT [89], which is the average production cost of the company, 13 EUR per MWh and a substantial long-term investment is reasonable to substitute heat production from biomass if grid demands are sufficient.

In the context of water electrolysis, wastewater can serve as a valuable resource, offering an alternative to using drinking water for hydrogen production. As the demand for green hydrogen increases, the integration of wastewater is essential to electrolysis. Wastewater requires more energy for treatment and infrastructure, resulting in substantially higher costs compared to drinking water. Few projects use wastewater in existing PtX facilities, making an assessment difficult. The price point of 0.01 EUR/kg was determined, based on a slightly higher wastewater treatment cost compared to consumer costs associated with Arwos utility in Aabenraa Municipality [90]. Carbon dioxide plays a pivotal role in both the production process and the economic evaluation of the PtX projects. The integration of CO_2 is essential to green, heavy fuel alternatives, closing the carbon loop and enabling carbon-neutral options such as for process heat, maritime fuels, and aviation fuels. However, the costs associated with sourcing, capturing, and utilising CO_2 are critical considerations in the overall financial viability of PtX projects due to the sheer amount required. In reality, the price of CO_2 is highly dependent on whether the buyer has to capture, compress, and transport the gas. With uncertainties related to the demand for biogenic CO_2, prices may also be influenced by this, as biogas plants may hold back on committing to long-term off-take agreements if prices were to rise. A reasonable price point without a point of reference was set at 0.15 EUR/kg of CO_2. This is substantially above the current EU-ETS price point, which would normally indicate the demand for emission quotas. These assumptions account for transport and storage, but not capture, which is assumed to happen by amine or water scrubbers in the biogas upgrading process. The sales price of oxygen is set to 0.09 EUR/kg, which is validated through the two Danish gas producers, Air Liquid and Strandmøllen, as a market competitive price point compared to market prices on oxygen applicable in the food industry. Furthermore, only a third of the produced oxygen is assumed possible to off-set. Oxygen is relatively cheap to produce from direct air capture, and oxygen from electrolysis has relatively few use-cases. Thus making a third of production off-take an optimistic assumption. Hydrogen and methanol costs have to account for the sum of investments and operational costs, while still returning on these investments in a foreseeable period. Green hydrogen has a history of difficult competition compared to hydrogen derived from fossil fuels using steam methane reforming, with estimated prices around 3.5 EUR/kg. The price settled on for both hydrogen projects is 5 EUR/kg due to references of other direct line, or partially direct line projects, limiting electricity tariffs, reaching just above the 4 EUR/kg mark [91]. As a reference for e-methanol, IRENA estimates somewhere between 0.84-1.66 EUR/kg [92], with fossil-fuel derived methanol between 0.4-0.5 EUR/kg and bio-methanol in the 0.34 EUR/kg to 0.79 EUR/kg price range [93]. As a result, the decided price set was 1.2 EUR/kg for both methanol scenarios. Lastly, 2025 tariffs for reduced transmission access and system tariff at 26 and 74 EUR/MWh respectively [94] has been added to the time series function for 2024 electricity prices.

8 | Synthesis of results

This section will present the results from all three analysis's with the aim of showing the business-economic effects of planning PtX projects based on the utilisation of value chains. The structure of this section will follow the same form as the analysis chapter, beginning with a presentation of the five layouts from the ArcGIS Pro suitability analysis. Following this, the results from the link between these four locations in the EnergyPRO analysis will be presented. Finally, a comparison on the financial performance of the four scenarios will be presented.

8.1 Suitability analysis results

Following the input of five chosen data layers relevant to the value chain of PtX projects, this section will present the location results within the boundaries of Aabenraa Municipality. Each presentation of the optimal location, according to the analysis, will involve a 5 km^2 area. The decision to apply this specific size is not based on the size of PtX facilities, but instead proposes a larger area to inspect in further detail. Comparatively, Kassø e-methanol plant has a footprint of 0.05 km^2 and the connected solar park at 3.27 km^2. Arguably, any new larger facility, would require similar capacities to substitute the need for grid electricity at high costs.

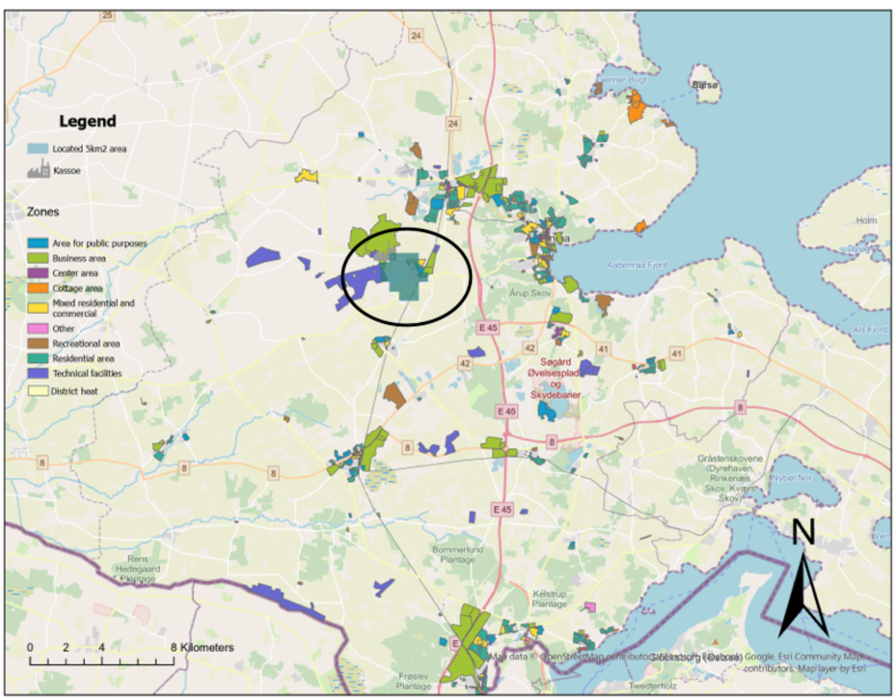

Figure 8.1: Optimal estimated location without any change in weights applied to the layers of the ArcGIS Pro suitability modeller

This is particularly the case for e-methanol, as the methanol synthesis is required to run at a constant minimum load, limiting the dynamic capabilities of the electrolysis, especially without storage. Hence, this type of production facilities will likely have to evaluate area suitable for wind or solar power. With no layer weightings, the suitability modeller has located the first suitable area shown in Figure 8.1. Interestingly, the result of this placement is on top of the existing Kassø plant.

For the first hydrogen scenario, the suitability weights are focusing on distance to the district heating grid, hydrogen pipeline, wastewater, and transformer stations. The result is displayed by Figure 8.2, indicating that the area north-west is more suitable, compared to the original area.

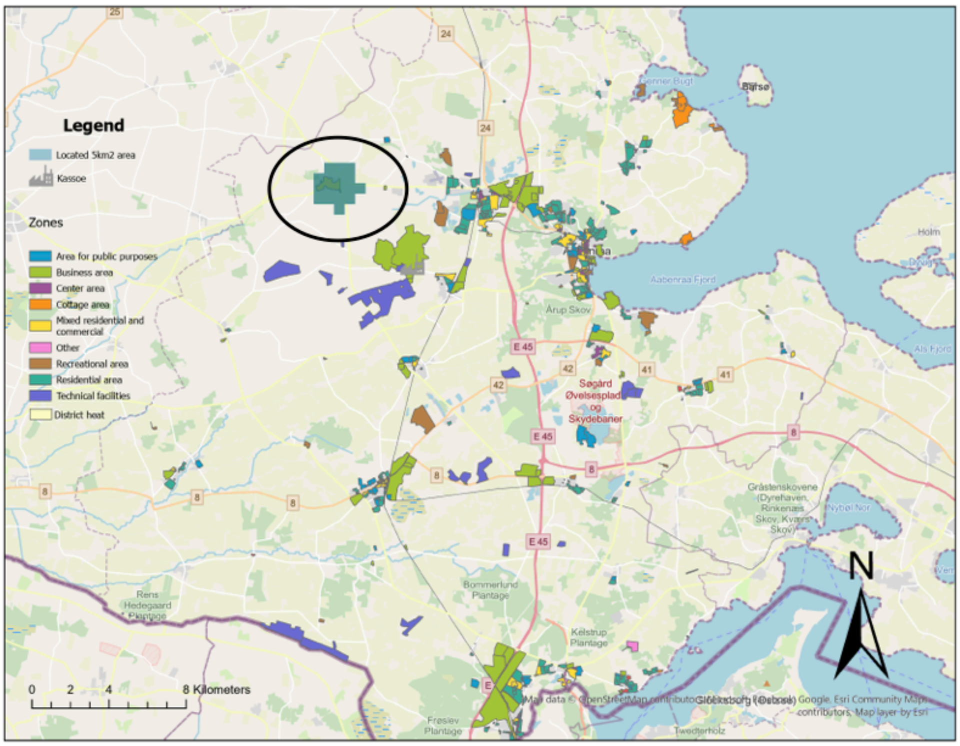

Figure 8.2: Scenario 1: Optimal estimated location with changes in weights applied to wastewater, power, pipeline transport, and district heating of the ArcGIS Pro suitability modeller

For the second scenario, not focusing on utilising waste heat for district heating, the placement in Figure 8.3 moves towards the area outside of Kassø. This is due to the weighting focusing on a location as close as possible to high voltage and capacity power, while the distance to the future hydrogen pipeline is minimised. If a new hydrogen production plant were to be placed in this area, it would likely become part of a larger area designated for industrial purposes now that Kassø is already situated here.

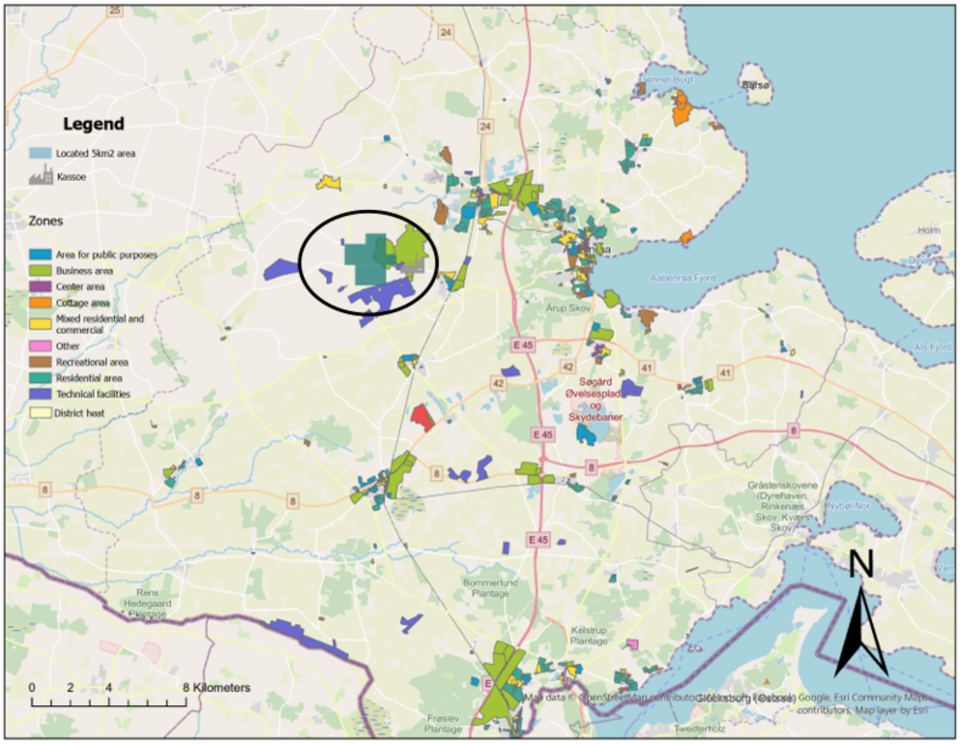

Figure 8.3: Scenario 2: Optimal estimated location with changes in weights applied to wastewater, power, and pipeline transport in the ArcGIS Pro suitability modeller

The third suitable location is based on the requirements for producing methanol from CO_2 located in the southern part of Jutland. Compared to the first scenario location, this area is based on CO_2 instead of its distance to the hydrogen pipeline, while still focusing on wastewater sources and distance to the district heating grid. The result illustrated in Figure 8.4 is situated close to the port of Aabenraa, where the municipality and the port itself have previously tried to attract commercial PtX projects. This is because one of the two high voltage transformers are placed here from when "Enstedværket", a decommissioned coal and oil CHP plant, was in operation, and the industrial synergies can be reached by placing PtX plants here. Since then, the port started bunkering coal due to Russia's invasion of Ukraine, but has expressed interest in looking into PtX projects again [95]. The final location assessment for the fourth scenario removes district heating weighting, resulting in a location further east than in the third scenario. This placement has advantages in terms of distances to populated areas, with Stenneskaer wastewater treatment plant close by.

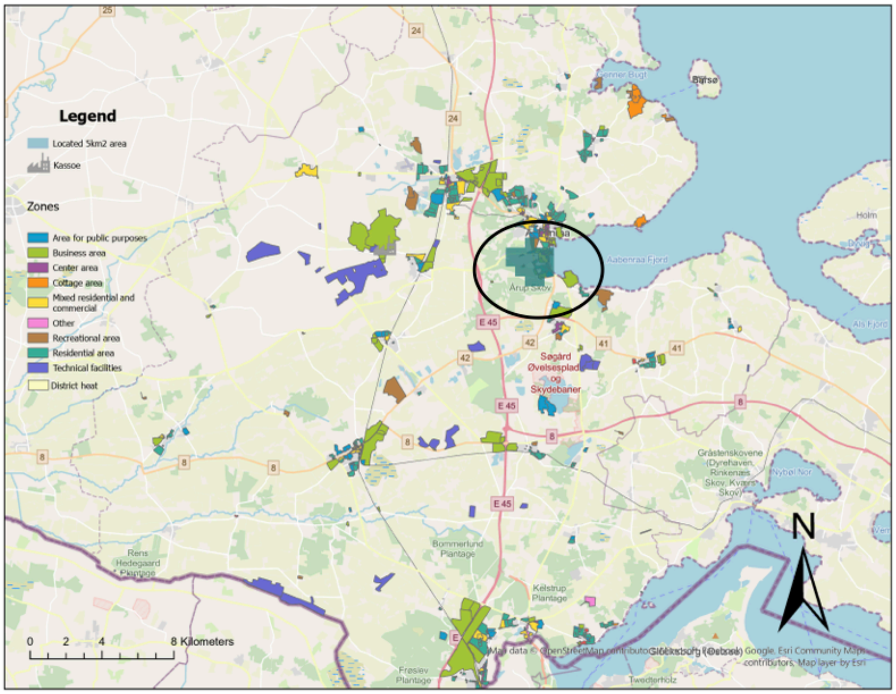

Figure 8.4: Scenario 3: Optimal estimated location with changes in weights applied to wastewater, power, district heating and CO_2 source distances in the ArcGIS Pro suitability modeller

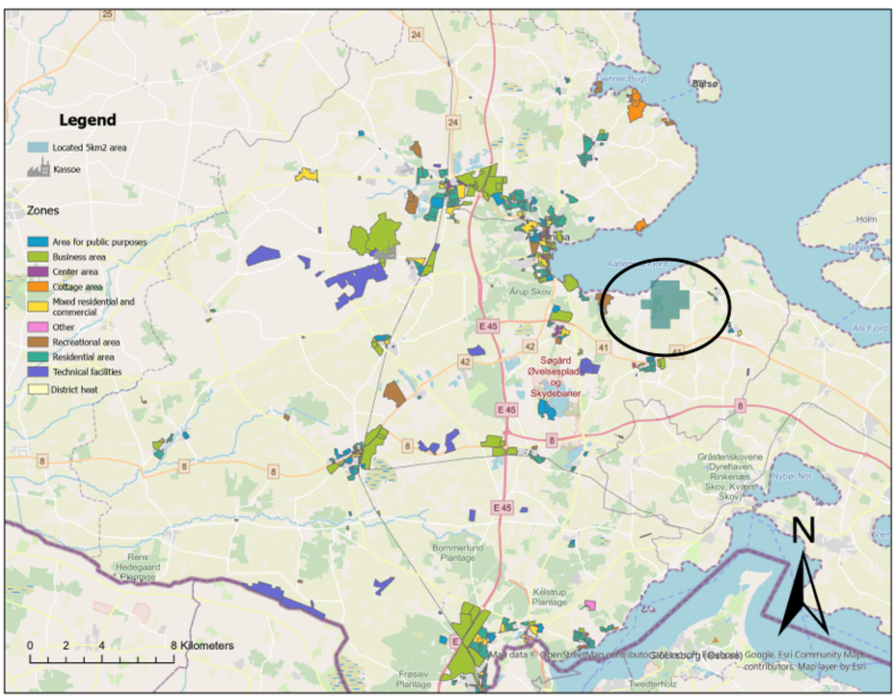

Figure 8.5: Scenario 4: Optimal estimated location with changes in weights applied to wastewater, power, and CO_2 source distances in the ArcGIS Pro suitability modeller

8.2 Energy system modelling results

The following section presents the results of variable production in the four EnergyPRO models designed to represent system differences when utilising PtX value chains. Common for all scenarios was the added 200 MW solar production, which is deemed the minimum capacity to support a flexible electrolyser load profile to result in feasible electricity prices. Electricity grid prices have been found to be detrimental to the feasible of the produced end-product, as Danish grid prices are not near low enough to reach competitive production costs, especially when it comes to e-methanol. Average electricity prices hovered between 64 and 75 EUR/MWh included tariffs, with around 190,000 MWh of the total electricity consumption for each scenario delivered from the photovoltaic park. Table 8.1 below shows key figures from each scenario from the optimised production done by EnergyPRO.

Table 8.1: Consumption and production amounts for the four PtX scenarios

	Scen1	Scen2	Scen3	Scen4
Water consumption [kg]	94,608,423	81,657,594	76,094,379	71,433,819
CO_2 consumption [kg]			61,531,682	57,763,045
Electricity consumption [MWh]	600,269	520,378	621,909	581,045
Heat production [MWh]	47,751		88,381	
Cooling requirement [MWh]		45,856		79,228

These results will provide a better foundation for economic analysis, which can be used to indicate the cumulative production costs of hydrogen and e-methanol compared to the price points assumed in the previous section. At this production capacity, it is noteworthy to point out the required CO_2 for e-methanol production. The third scenario reaches the limit on yearly CO_2 capacity of the single largest biogas producer and biogenic CO_2 point source in Denmark, SBS Kliplev. This capacity hence shows a natural limit to sourcing biogenic CO_2 from one actor alone.

8.3 Applying techno-economic assessment

Techno-economic assessment can be accomplished in many ways and is an excellent method of assessing economic feasibility as a part of providing scenario development to strengthen knowledge on pathways to zero-emission alternatives. This section will present key points and findings from a feasibility assessment based on the variable and fixed costs and earnings. The results can be found in greater detail in appendix (A.0.1).

Firstly, a cost comparison was made to show the impacts of cost factors on each scenario. Costs, in itself, is not an accurate indication of financial performance, as the variable costs grow with the amount of hours EnergyPRO finds feasible in the system. As indicated by Figure 8.6, electricity is a significant expenditure in all production scenarios. This either requires substantial increases in the fuel price to make up for these costs, or electricity prices can be mitigated through measures, such as limiting tariffs by producing "behind the meter". However, this will require an extensive energy production nearby, for many hours of the day. Renewable energy production can also be increased to capacities requiring fewer hours of grid electricity exchange. Finally, the grid electricity price deemed feasible for production can be lowered, to decrease production and the overall electricity price. However, e-methanol production can prove challenging with the methanol synthesis reaction currently requiring a steady minimum load of around 40%. Similarly, expenses

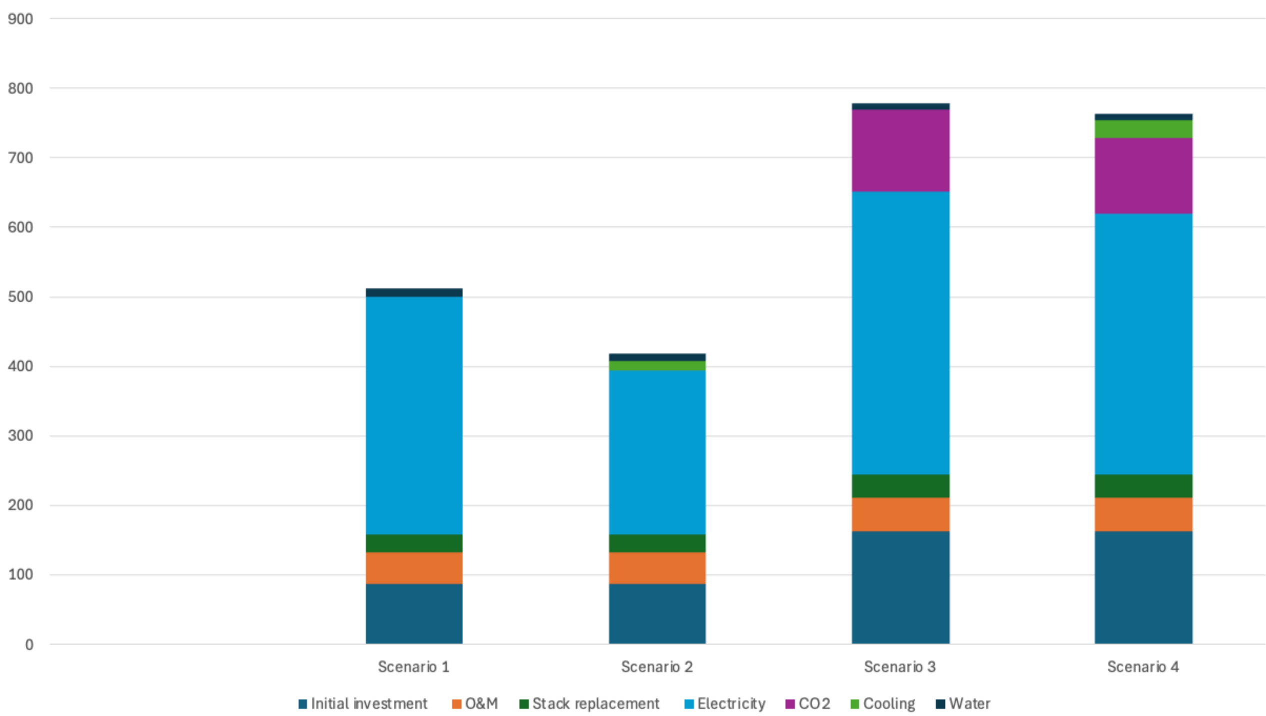

Figure 8.6: Scenario cost breakdown [MEUR]. Scenario costs increases with earnings, thus not an indication of the best performing scenarios.

related to biogeneric CO_2 increase the total production cost of e-methanol compared to hydrogen by a considerable margin. At the assumed price point discussed in section 7.2.3 of 0.15 EUR/kg, payments on biogenic CO_2 may become a limiting factor to the technological and financial development of e-fuels and synthetic hydrocarbons containing biogenic CO_2.

The cost for every scenario can be used to illustrate the development of the levelised cost of both fuel types over the 25-year evaluation, which is displayed below in Figure 8.7. The outcome of the levelised cost results from the accumulated discounted costs minus earnings from oxygen and sales per kilogram of fuel produced.

Significantly, earnings from fuel sales do not affect the LCoE. Hence, LCoE does not indicate investment performance, with variable costs in some scenarios being lower due to EnergyPRO finding fewer viable hours to produce and operate. Interestingly, the compound effect on costs compared hydrogen from discounting 8% yearly, shows the LCoE of scenario 1 overtaking scenario 2 around year 5 due to the effect of the discounting being stronger on the hydrogen output.

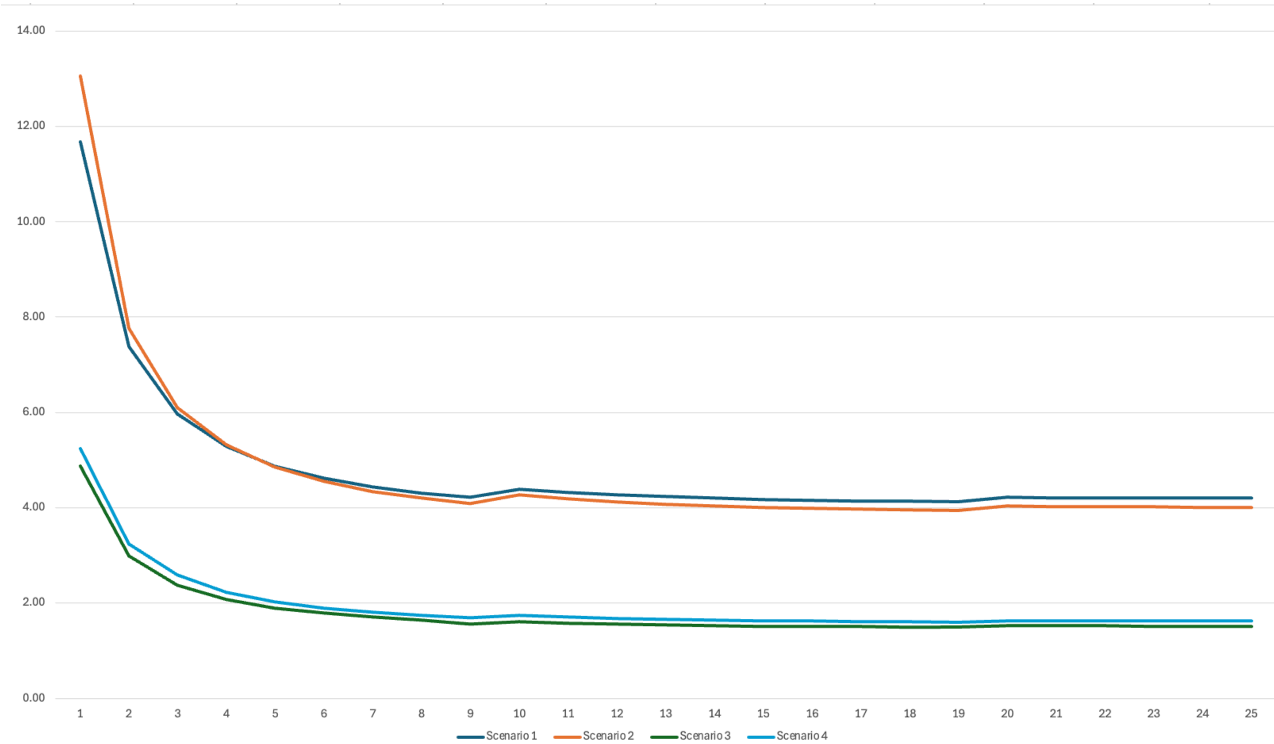

Figure 8.7: Yearly development of the levelised cost of each scenario product [EUR/kg]

The income differences due to the operational expenditure of cooling and income from heat sales can be seen in Table 8.2. The table shows central numbers in the first year of operation, as well as the 25-year evaluation period, where each yearly expense and earnings are adjusted to inflation. In the first year, scenario one outperforms the other scenarios, showing a small profit margin compared to the second scenario as a consequence of utilising value chain sales. The two scenarios based on e-methanol production show profitable earnings, with a considerable outperformance when the sale of by-products is possible. Over the entire period, scenarios 1-3 are able to produce positive returns on investments before discounting, with the fourth scenario unable to achieve this with a net negative 100 MEUR profit after tax or discounted to a -125 MEUR NPV. Both hydrogen scenarios show a very reasonable IRR, indicating a relatively low-risk investment. Additionally, the payback time on the hydrogen scenarios is satisfactory, considering an assumed reasonable payback time of 8-10 years for large energy projects. It is, however, worth discussing whether companies would accept this time frame without long-term off-take agreements to secure investment returns. As for the two e-methanol scenarios, the setup of this analysis has proven to be an unfeasible business-economic investment. With no discounted payback times, due to negative NPV's, and simple payback times within unrealistic time frames, measures must be taken to improve the business case to a more sustainable investment.

Table 8.2: Key comparative metrics to asses differences in economic performance in between the four scenarios

Economic feasibility in year 1				
Benchmarks	Scen1	Scen2	Scen3	Scen4
Income	55,674,379	45,902,796	56,914,500	50,464,216
Costs	31,373,680	24,026,035	45,952,360	44,794,277
EBITDA	24,300,699	21,876,761	10,962,140	5,669,939
Profit after tax	19,724,545	17,833,874	9,883,712	5,302,607
Economic feasibility over the 25 years				
Income	1,783,267,058	1,470,280,314	1,822,988,481	1,616,383,964
Costs	1,173,556,636	938,209,355	1,738,043,546	1,634,969,029
EBITDA	609,710,422	532,070,959	84,944,935	-18,585,065
Profit after tax	470,358,999	408,386,046	44,758,516	-37,880,641
ROI	51.95%	56.71%	4.89%	-4.97%
IRR %	28.71%	25.74%	3.46%	-5.06%
LCoE	4.21	4.01	1.52	1.70
Simple payback time	4.44	4.91	16.42	30.61
Dynamic payback	4.26	4.81		
NPV	**193,984,803**	**163,263,725**	**-57,295,374**	**-124,368,919**

8.4 Summary

This section presents the outcomes from the spatial suitability analysis, energy system modelling, and techno-economic assessment applied to the Aabenraa Municipality PtX case. The goal is to explore the advantages of spatial analysis of PtX value chains and their correlation to the financial viability of PtX scenarios in Denmark. The suitability analysis was conducted using ArcGIS Pro and includes weighted criteria such as proximity to wastewater treatment plants, biogas facilities, the district heating network, high-voltage transformers, and the planned hydrogen backbone. Areas with higher suitability scores are concentrated in the western and central parts of the municipality, aligning spatially with existing infrastructure and key value chain resources. Notably, the Kassø site is shown to be highly suitable, consistent with its selection by existing developers. The analysis does, however, not indicate suitable locations for the appointed areas for industrial synergies by Aabenraa Municipality in Kliplev and Padborg. This is particularly because these areas lack transmission infrastructure needed for the substantial power requirements of electrolysers, which would otherwise lead to significant power-transport costs at lower voltages. Energy system modelling was performed using predefined PtX scenarios based on variable inputs. Four primary scenarios were considered based on inputs from the spatial analysis: Optimised system operation for hydrogen and e-methanol production with and without the utilisation of value chain products. At first, hydrogen storage was deemed spatially demanding and costly, but storage integration to manage load fluctuation may be needed to counter electricity price volatility further. The techno-economic analysis evaluates financial metrics for each scenario to demonstrate the influence of sector integration. All metrics fall below typical investor thresholds for producing e-methanol, but the sector-integrated scenario shows increased promise with a 117% increase in NPV and almost halved payback time. At the sales price of 5 EUR/kg, both hydrogen scenarios show promising financial indicators with a 20% increase to NPV over a 25-year period when emphasis is laid on value chain utilisation.

9 | Discussion

9.1 Modelling and data limitations

One of the limitations to the realism of heat offset to the district heating grid is related to the flexibility of cooling and heating demand, as it increases the complexity and time requirements needed for the model. Demands can be established by modelling either one aggregated demand or by simulating the production units of the district heating system. This can then estimate the hours when it is cheaper and demands allow for the supply of waste heat, compared to production units operating on biomass or natural gas.

Another important limitation of the EnergyPRO output is the ability to simulate the degradation rate effect on electrolysis production. The model is only run for a single year estimate, resulting in yearly identical hydrogen output. Stack change evaluations for this model are based on a data prerequisite for a given frequency of hours an electrolyser type can operate before stack replacement is required. However, the degradation rate describes a percentage loss of efficiency. For instance, an alkaline electrolyser will degrade by 0.13% per 1000 hours, resulting in a 9% decrease in efficiency for the first 10 years, also before the stack replacement period used for this evaluation. Further research should therefore be conducted on simulating and examining the real-life implications of stack degradation rates to determine the optimal cut-off point between production/-efficiency losses and stack replacement costs.

A general limitation of the study lies in the uncertainties associated with the data and information sources, which are primarily derived from secondary literature and articles. While such sources are easily accessible, applying them to the specific municipal context has necessitated a degree of interpretation and assumption. Although not ideal, these steps are accepted as necessary for the analytical process. As the study analyses scenarios for future potential PtX projects, key inputs, particularly cost-related data, are subject to uncertainty. Some variables, such as prices for water and oxygen, are based on current market conditions and may not reflect future developments, which is also the case for fuel prices. Although investments in today's setting can be assumed to be somewhat accurate, operational costs, such as electrolyser stacks and electricity prices, must be reduced dramatically in the coming years to lower prices on renewable fuels designated for hard-to-abate sectors. Data input limitations are addressed through a sensitivity analysis, which evaluates the influence of individual cost components on the overall economic performance. The documentation of data interpretation and modelling assumptions contributes to the transparency and reliability of the outcomes. Additional methodological approaches, such as interviews with key stakeholders, have strengthened the empirical foundation of the study and reduced uncertainty about certain assumptions.

9.2 Sensitivity analysis

Due to the relatively simplistic nature of the techno-economic analysis's result, sensitivity analysis can be used to create context around the results by investigating interactions between input and output parameters. This section will thus present the effects of tariffs on the financial assessments, and the sensitivity of central factors of the analysis to the result of the NPV.

The sensitivity of the CAPEX, O&M, discount rate, electricity price, value chain benefits, and fuel earnings has been evaluated to understand the shifts in scenario NPV when these key inputs change. Each input has been manually adjusted in the Excel spreadsheet in increments of +/-5-20%. The resulting outcome is depicted in Figure 9.1 below with the effects of percent changes to each input on the NPV value. Each parameter is varied independently, allowing for an assessment of the most financially influential factors in the model. The first figure illustrates the hydrogen-based PtX scenario, including value chain utilisation, while the second depicts the e-methanol-focused scenario, which also includes waste heat and oxygen sales.

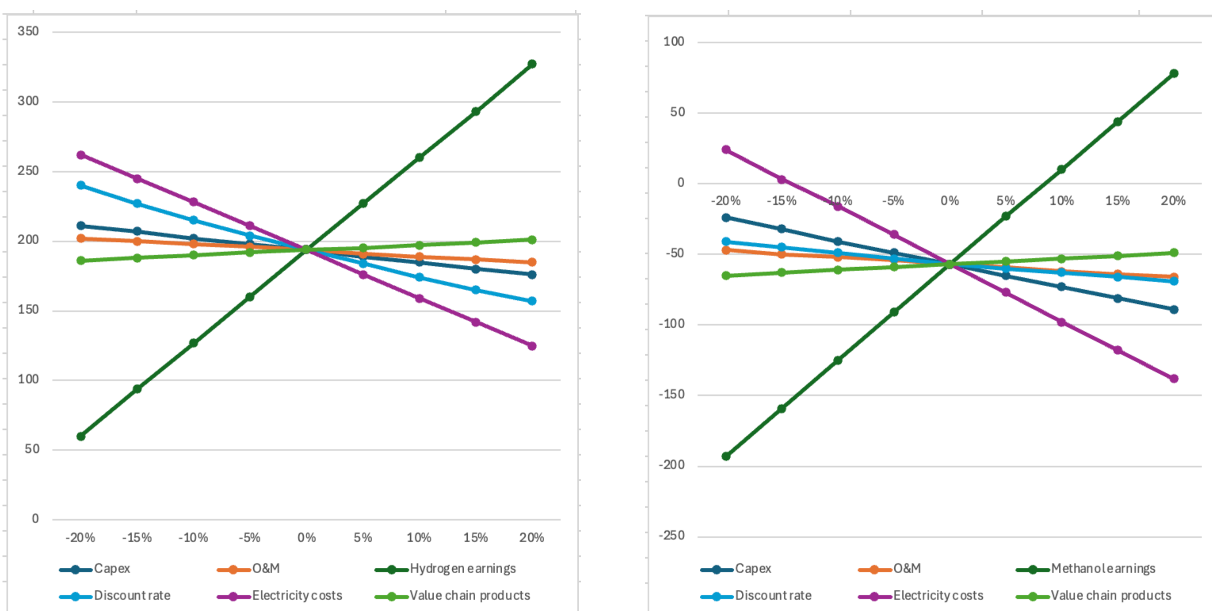

Figure 9.1: Sensitivity of key financial input to scenario one and three. The X-axis show the percentage increments from -20 to +20, and the Y-axis the NPV in MEUR with that percentage input change

In both cases, electricity costs and fuel earnings are the most influential variables. The steep slope of these lines indicates that small variations in either direction have a significant impact on project viability. For the methanol scenario, a 20% decrease in electricity costs results in an NPV increase of approximately 75 MEUR, while a 20% increase leads to an NPV drop of similar magnitude. The analysis shows that a break-even in NPV is possible for the e-methanol scenario when electricity prices are lowered by around 15%, or methanol prices are increased by around 7.5%. Capex, O&M, and discount rate have a moderate impact on NPV. While changes in these parameters affect project performance, the inclination of their respective lines suggests a lesser influence on financial viability. This suggests that while lowering CAPEX and O&M costs is important, these are not currently the primary effects on project success, but still exert a significant impact on the short-term risk mitigation and financial viability of PtX projects in today's markets.

With the initial sensitivity analysis showing noticeable consequences of high electricity prices on economic feasibility, it seems relevant to explore the aspect of electricity prices in further detail. While it is known that electricity prices are highly influenced by the amount of produced cheap electricity in a given hour, it is practically impossible to estimate the changes to electricity prices, as these depend on external and internal factor, such as oil and gas prices, the expansion of renewable energy, demands from the shift to electric heating units, and PtX plant power demands. This is also the main conclusion from a study by Lund et al. (2018) [96], showing the prognosis made over the years, compared to historical oil and electricity prices. Instead, the effect of removing tariffs on the EnergyPRO model was evaluated by excluding them from the hourly electricity values. With the average electricity price of 70.5 EUR/MWh in 2024, the cumulative tariffs cost of 10 EUR/MWh results in a 10% increase on average. Furthermore, these tariffs only include the lowest net tariff as restricted actors on the transmission grid, meaning tariffs on other projects could easily consist of higher prices. Though this tariff is already the 2025 net and system tariff, Energinet has stated that even higher tariffs may become a reality in the coming year, followed by a downward trend as new connections and build-out slow down [94].

Table 9.1: Key comparative metrics to asses differences in economic performance in between the four scenarios including the exclusion of tariffs on the electricity price

Benchmarks	Scen1	Scen2	Scen3	Scen4
Income	1,797,550,341	1,633,860,080	1,996,160,402	1,774,711,689
Costs	1,170,661,456	1,081,591,515	1,708,510,898	1,604,074,388
EBITDA	626,888,885	552,268,564	287,649,504	170,637,301
Profit after tax	484,071,099	424,508,070	206,560,260	113,159,413
ROI	53.55%	51.06%	16.84%	5.53%
IRR %	29.36%	26.52%	9.57%	3.75%
LCoE	3.73	4.51	1.36	1.47
Payback time	3.48	4.77	10.95	17.00
Dynamic payback	3.23	4.65	16.80	
NPV	**281,535,289**	**171,255,694**	**22,912,585**	**-54,109,929**

The results from EnergyPRO have been analysed with the altered variable input to the spreadsheet model, resulting in the outputs presented in Table 9.1. In the base case with tariffs, only the first and second scenarios yield positive financial indicators, with NPVs of approximately 194 million MEUR and 163 million MEUR, respectively. Scenarios 3 and 4 perform considerably worse, both exhibiting negative NPVs, with Scenario

4 reaching a deficit of over 124 MEUR. When tariffs are removed, financial performance improves across all scenarios. Scenario 1 sees its NPV increase to over 280 MEUR and IRR to 29.36%. Similarly, Scenario 2s NPV rises to 171 million MEUR. Most notably, Scenario 3 shifts from a negative to a positive NPV, indicating a marginal feasibility, however, still with unreasonable simple and dynamic payback times. Scenario 4 also improves substantially but fails to reach profitability, with an NPV of 54 MEUR, again highlighting the benefits of adding earnings and limiting expenses from PtX by-products. The analysis demonstrates that removing electricity tariffs significantly improves project feasibility, especially for complex and less financially sound projects, such as e-methanol. While Scenarios 1 and 2 remain the most attractive options in both cases, tariff removal can potentially create viability for e-methanol production price points of around 1.2 EUR/kg and shorten simple payback times by up to 6 years. It does, however, seem unlikely that projects of this size will be able to eliminate tariff costs on grid electricity, as operation during periods lacking solar and wind power is not feasible due to the need for a constant methanol synthesis load. This may, nevertheless, to some extent, be counteracted by scaling up storage capabilities and limiting production.

As a final part of this sensitivity analysis, the effects of fuel price on payback time have been investigated. This has been achieved through an iterative method of price inputs in EnergyPRO, until a reasonable payback period was determined for all scenarios in the Excel spreadsheet.

Benchmarks	Scen1	Scen2	Scen3	Scen4
Income	1,186,796,537	1,033,882,599	2,401,494,023	2,167,893,452
Costs	885,601,559	854,353,745	1,947,432,185	1,832,953,069
EBITDA	301,194,978	179,528,854	454,061,838	334,940,383
Profit after tax	224,097,469	126,981,794	339,393,013	244,308,530
ROI	34.01%	21.01%	23.32%	13.33%
IRR %	16.49%	11.05%	13.68%	8.70%
LCoE	3.97	3.59	1.52	1.63
Payback time	7.17	11.03	7.64	10.36
Dynamic payback	7.76	23.88	8.41	15.08
NPV	**71,908,649**	**2,423,542**	**127,247,546**	**46,007,652**

A reasonable price decrease for hydrogen turned out to be 20% from 5 to 4 EUR/kg. The concluded price for e-methanol was around 22%, with a price increase from 1.2 to 1.5 EUR/kg. Payback times for scenarios one and three now show dynamic payback periods of around 7-9 years, which in some projects could be considered valid, but with some associated risks. The hydrogen scenarios present significantly lower turnover, resulting from EnergyPRO finding less feasible hours of production at the electricity price. This highlights the underlying problem associated with hydrogen production operating based on grid prices, as well as the limitations in reaching competitive prices compared to fossil-derived hydrogen, which is around

1.5-2.5 EUR/kg [97]. Not surprisingly, the opposite is the case when the prices of e-methanol are raised. Now EnergyPRO is able to produce 66% of the theoretical maximum production based on the capacity of e-methanol, compared to only 59% in the original scenarios.

9.3 Carbon dioxide as a market commodity

With the introduction of RFNBO fuels as part of the European Commission's Renewable Energy Directive, green hydrogen plays an essential role in decarbonising hard-to-abate sectors. But since RFNBO certification also includes using CO_2 as a feedstock in fuels such as methane, methanol, or synthetic hydrocarbons, it is worth discussing the role of carbon sources as an enabler of the green transition. Though the source of carbon plays no actual difference in the greenhouse effect, this directive distinguishes between CO_2 sourced from biogenic and fossil processes. The logic is to incentivise the use of biogenic feedstock, as part of the "carbon loop", instead of burning fossil sources by assessing biogenic CO_2 as carbon neutral. This has resulted in the "commodification" of biogenic carbon. This is particularly the case with offsetting fossil CO_2 taxes against carbon credits from the abatement of biogenic carbon. Since biogas plants are the primary, and only financially realistic, source of biogenic carbon in Denmark today (and likely biowaste incineration in the future), it is worth discussing the future pricing of this feedstock. The opening of carbon storage, notably biogenic carbon, such as the governmental NECCS subsidy scheme in Table 9.2 below, presents substantial concerns regarding carbon pricing in the near future.

Table 9.2: The companies involved in the NECCS subsidy scheme [98]

Company	CO2 subsidy price (EUR/kg)	Yearly captured CO2 (ton)	Total subsidy paid (MEUR/year)
BioCirc CO2	0.13	130,700	17
Bioman	0.15	25,000	3.75
The carbon removers	0.35	4,650	1.6

The carbon subsidy price allocated to parties involved in the NECCS subsidy scheme reflects the lowest possible costs for capturing, transporting, and storing biogenic CO2. However, this presents a problem: an increase in carbon prices as a market based on government subsidies is created, which competes with PtX projects requiring biogenic CO_2 as a feedstock. The consequences may include increased costs related to the sourcing of carbon, which, as previously shown, has a substantial effect on the financial feasibility at the price of 0.15 EUR/kg. Although the NECCS subsidy scheme is only in effect for 8 years, regulatory efforts should be made to ensure competitive biogenic carbon pricing, which may otherwise hinder the development of alternative green fuels to decarbonise the heavy transport and industrial sectors.

10 | Conclusion

This thesis has explored how spatial planning can enhance the techno-economic viability of Power-to-X (PtX) projects in Aabenraa Municipality by incorporating methods, including Geographic Information Systems (GIS), energy system modelling, and techno-economic assessment. First, a GIS suitability analysis identified optimal facility locations by combining five key resource layersbiogenic CO_2 from biogas plants, wastewater treatment capacity, existing high-voltage grid nodes, district-heating networks, and the planned hydrogen pipeline. By adjusting the weightings for each criterion, the analysis revealed optimal locations for four types of PtX use-cases. The suitability model found optimal placement near Kassø, Ensted, and, in general, the northern part of Aabenraa Municipality; interestingly, this was not in the designated areas around Kliplev and Padborg.

Next, energy-system scenarios based on 100 MW PEM and AEC electrolysers were developed in EnergyPRO to evaluate four configurations: hydrogen production alone with and without heat sales, and e-methanol synthesis utilising waste heat and local CO_2. Dynamic simulations over a typical year demonstrated that coupling hydrogen electrolysis to district heating significantly improves capacity factors and yields lower production costs, while full PtX value-chain integration achieves the most favourable Levelised fuel cost.

Finally, a techno-economic assessment was conducted to compare Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCoE) across various scenarios. The analysis revealed that hydrogen-only projects have suitable net present values (NPVs) under current electricity prices. At a sales price of 5 EUR/kg, the return on investment is reasonable for hydrogen projects in their current state. Therefore, a sensitivity analysis was conducted to find the lowest possible LCoH and production price compared to traditional fossil-based hydrogen. Conclusively, hydrogen costs are susceptible to high electricity prices, resulting in lower LCoH when the utilisation of electrolysis goes down. Furthermore, the scenarios show a significant increase in financial performance when selling waste heat and oxygen. Producing e-methanol within the reasonable assumptions made does not result in useful payback times. With operation exempt from grid tariffs, however, e-methanol projects utilising value chains to their full extent achieve IRRs above the discount rate set for risk-related energy projects.

In summary, the combined methodology demonstrates that spatially informed siting can provide a basis for decision-making that aligns with local resources, leading to more efficient placement. Sector-coupled energy modelling captures synergies between electricity, heat and CO_2 markets, while full PtX value-chain integration delivers the most solid techno-economic outcomes. These findings suggest that planning processes and methodologies used by municipalities can play a key role in de-risking PtX investments to a great extent by aligning local resource infrastructures, especially biogenic CO_2 streams and district-heating networks, with targeted spatial planning.

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A | Appendix

Appendix A:

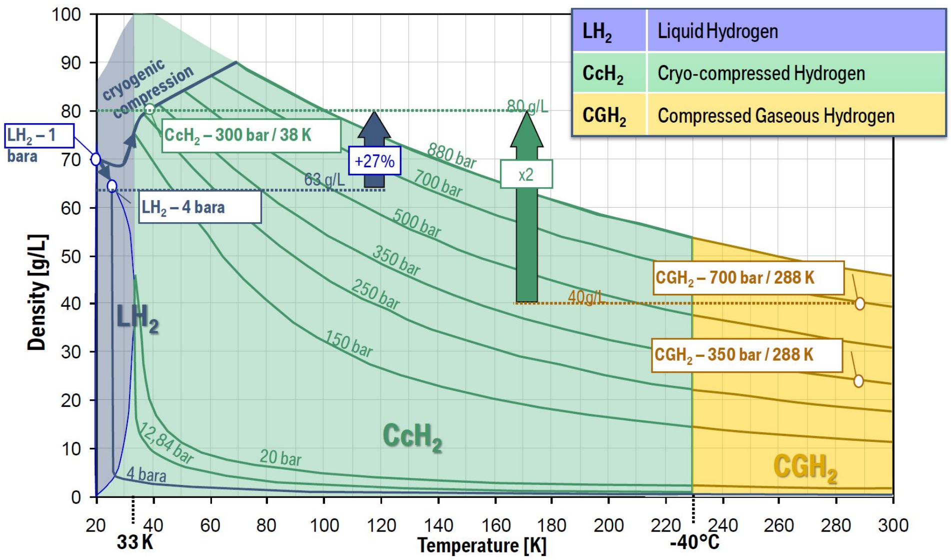

Figure A.1: A phase curve of hydrogen states at different pressure and temperatures [99]

A.0.1 External appendices

Appendix B

See attached: Scenario_1_and_2.eppx

Appendix C

See attached: Scenario_3_and_4.eppx

Appendix D

See attached: Aabenraa_PtX_scenarios.xlsx