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CHALLENGES AND STRATEGIES IN POWER-TO-METHANOL PROJECT DEVELOPMENT: A PROJECT DEVELOPER PERSPECTIVE

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ABSTRACT

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This study investigates the Power to Methanol value chain, identifying challenges and opportunities for project developers, particularly medium sized and small companies leveraging their operational agility. The research examines how developers address difficulties and seize opportunities, aiming to provide effective strategies, with consideration for the Finnish energy market context.

The methodology relies on extensive literature review and analysis of publicly available data. Key challenges emerge in technical, economic, and regulatory areas, including production costs and policy development. Strategies to overcome these involve technological advancements, robust project management, and strategic partnerships. The study also details criteria for selecting suppliers and partners, focusing on expertise, financial stability, and collaborative potential.

The research makes it clear that agility is key for small and medium sized firms and that partner networks are necessity. The use of Power to Methanol will only be successful if it is carefully planned and backed by supporting structures for green energy transition.

Keywords Power-to-Methanol, value chain, zero emission, renewable energy, proton-exchange membrane electrolysis PEM.

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ABBREVIATIONS

AEL	Alkaline Electrolyser
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CAPEX	Capital Expenditure
EPC	Development, Engineering, Procurement, and Construction
EIAs	Comprehensive Environmental Impact Assessments
FEED	Front-End Engineering Design
LCOM	Levelized Cost of Methanol
MeOH	Methanol
OPEX	Operational Expenses
PEM	Polymer electrolyte membrane

PtX	Power-to-X
PtM	Power-to-Methanol
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cells

1 INTRODUCTION

The value chain in Power to Methanol (PtM) is extensive, and its breadth can lead to opportunities remaining hidden and unexplored. Identifying these untapped opportunities and the associated challenges is crucial for enhancing overall efficiency, reducing costs, and accelerating progress toward achieving PtM milestones.

The primary objective of this study is to identify key challenges and opportunities in implementing the PtM value chain from a project developer's perspective and link these opportunities with the specific challenges of the company, while also examine how project developers address these challenges and seize opportunities. Additionally, this study aims to provide effective and practical strategies that developers use to overcome these challenges.

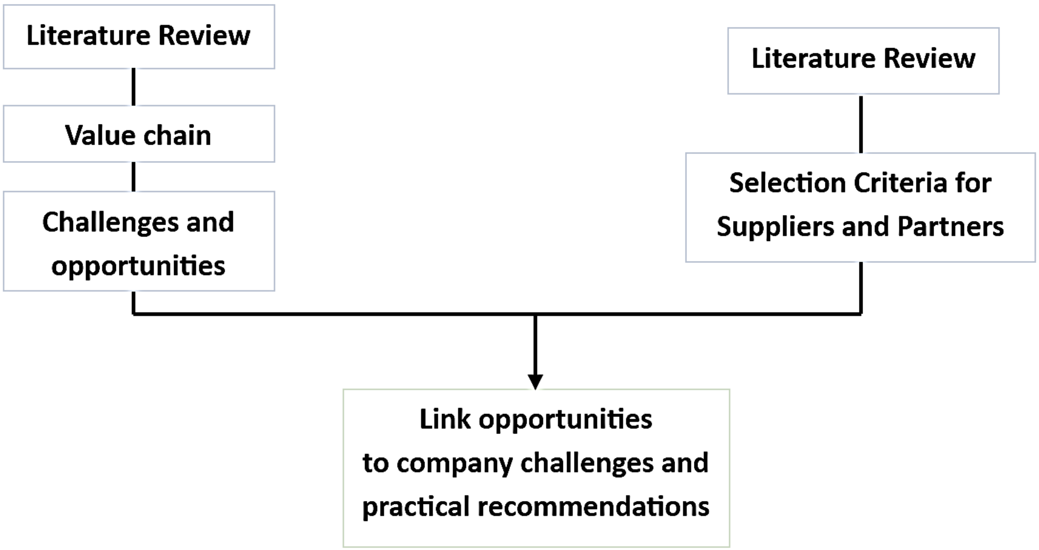

Figure 1. Study flow diagram.

This study emphasizes enterprises with higher operational agility to adopt the proposed investment strategies, including medium-sized and, in some cases, small companies. The rationale behind this focus is that small and medium-sized companies are less constrained by the limitations often faced by larger organizations, such as complex organizational structures and rigid portfolios. This flexibility is considered a valuable opportunity in this context. From another perspective, some small and medium-sized companies already possess the necessary infrastructure to collaborate in the green transition. With minor optimization and alignment, they can actively contribute to achieving the objectives of this chain. It both cuts down costs and raises the effectiveness of the company’s production chain.

A detailed analysis of the PtM chain enables the identification of potential bottlenecks and growth areas, which are crucial for strategic planning. Furthermore, aligning these findings with the company's specific needs ensures that the recommendations are both realistic and impactful. The findings from the analysis, combined with a comprehensive review of relevant literature, will guide the development of strategies to achieve the stated objectives.

1.1 Research questions

Based on the defined objectives and research scope, the following research questions have been formulated and will be addressed in this study:

- **What are the main challenges in implementing the PtM value chain from a project developer's perspective?**
- **How do project developers tackle these challenges and catch the opportunity?**
- **What are the criteria for choosing suppliers and partners for implementing the project?**

1.2 Background

With advancements in technology and emergence of challenges associated with fossil fuels, alongside crises such as geopolitical tensions and conflicts, the importance of energy and its various dimensions has become even more evident. This evidence has further accelerated the movement towards less dependence on fossil fuels and adoption of green energy in Europe (IEA, 2022).The need for sustainable energy carriers and reducing dependency on fossil fuels has proven to be crucial in addressing these challenges. In recent years, Power to X (PtX) has been proposed as an effective approach to achieving decarbonization and net-zero emissions strategies. As one potential application, PtM is considered an effective method for decarbonization within the broader PtX framework. Methanol itself holds a wide array of applications, making PtM a potential solution for both energy storage and the decarbonization of various sectors. Methanol synthesis, the core chemical conversion step in PtM, can be achieved through different process configurations, primarily direct and two-step synthesis(Hren et al., 2024). The primary attraction of Methanol "as a shipping fuel lies in its ability to be stored as a liquid at ambient temperatures and pressures, and its favorable energy-density"(MAN, 2023).

The preference between direct and two-step synthesis in PtM applications is influenced by factors such as the source of CO2, the desired process flexibility, and the specific catalysts employed. While direct synthesis appears more energy-efficient and offers a higher yield based on current research, the potential for heat integration and optimization in the two-step process is also being explored(Hren et al., 2024)

Investors, technical developers, and end users need to have a solid grasp of the interconnected players in the power-to-synthetic methanol value chain in order to successfully navigate and participate in this developing industry. This study makes it easier to understand the opportunities and challenges associated with the scale up of production and commercialization of synthetic methanol by explicitly outlining the roles of each actor.

1.2.1 The relevance of PtM in Finland

Finland argues that new and innovative technologies must be at the forefront of climate action and will also promote the role of carbon markets(Liselotte, 2024). The nation has committed to achieving carbon neutrality by 2035, a goal that places it ahead of many other European countries in its decarbonization efforts(Liselotte Jensen, 2024). This commitment is underpinned by binding national greenhouse gas (GHG) emission reduction objectives for the forthcoming decades, targeting a 60% decrease by 2030, 80% by 2040, and 90-95% by 2050, all relative to 1990 levels. To achieve these objectives, Finland's energy policy emphasizes a significant shift towards renewable energy sources, with a stated goal of increasing the share of renewables in final energy consumption to 62% by 2030 (Liselotte Jensen, 2024).

“Finland aims to account for 10 percent of the EU’s clean hydrogen production and for at least the same percentage of hydrogen use. Promoting the hydrogen economy will be an important part of the new Climate and Energy Strategy, which will focus on the transformation of industry” (Finnish Government Prime Minister’s Office, 2023). The development and implementation of PtM technologies in Finland are placed in a highly relevant strategic context by this proactive policy environment, which is marked by strong climate pledges and an emphasis on hydrogen and renewable energy. The imperative to meet ambitious emission reduction targets and significantly increase the penetration of renewable energy provides a strong rationale for exploring and investing in PtM as a key solution(Liselotte Jensen, 2024). The growth in intermittent renewable energy sources also underscores the increasing need for effective energy storage solutions, where methanol produced through PtM could play a significant role. The expansion of intermittent renewable energy sources highlights the escalating demand for efficient energy storage solutions, in which methanol generated by PtM might be pivotal(Fulham et al., 2024a).

“Koppö Energy Oy, the joint venture established by Prime Green Energy Infrastructure Fund and CPC Finland Oy”(Epressi, 2023), reflects Finland’s commercial potential in advancing PtX initiatives. One noteworthy instance is their major project under development in Kristinestad on the West Coast of Finland, which has reached a major milestone by awarding FEED agreements to several suppliers(Epressi, 2023). This thesis is particularly interested in studying the value chain related to this specific PtM project development. It should be noted that the analysis within this study is based on a literature review, and information regarding this case company and project is drawn solely from publicly available sources. “The plant is part of the Koppö Energy Cluster, which includes the parallel development of up to 500 MW of wind and 100 MW of solar power to supply the PtX plant with new green electricity” (Epressi, 2023). “In 2023, the project was awarded the PtX Innovation Award at the Tamarindo Global Wind Investment Awards ceremony”(CPC Finland, 2023).

1.3 Limitations

This research operates within certain constraints, including restricted access to data due to its confidentiality and extensive scope, limiting availability for publication or analysis. Additionally, a lack of historical data on the value chain development for hydrogen and PtM in Finland poses challenges for comprehensive assessments. The focus on specific value chain conditions may limit the generalizability of findings to other companies, requiring further validation before broader application. Moreover, time constraints may impact the overall comprehensiveness of the study.

Recognizing these constraints, efforts have been made to address them as much as possible to enhance the effectiveness and comprehensiveness of the research.

1.4 Research methodology

A review of related literature was performed to explore the challenges and strategies associated with implementing Power-to-Methanol (PtM) projects from a project developer's perspective. The goal of this review was to pinpoint the main technical, financial, regulatory and project management problems that developers run into and how they solve them. Using combinations of keywords such as "Power-to-Methanol," "Power-to-X," "Project Development," "Renewable Energy Projects," "Project Management Challenges," and "Implementation Strategies," keywords, well-known academic databases such as Scopus, Web of Science, ScienceDirect and Google Scholar, were all considered. Limited to papers, industry reports and case studies published from 2015 to 2025, studies in English were used for this review.

1.5 Outline of the thesis

This thesis is structured into six chapters, commencing with an introduction that defines the research questions, objectives, and limitations. The second chapter is dedicated to a comprehensive literature review, covering the hydrogen market, the application of green hydrogen in PtX processes, and an overview of current strategies relevant to PtM. Subsequently, the third chapter analyzes the PtM value chain and its constituent components. Chapter four then discusses the opportunities and challenges inherent within this value chain. Following this, chapter five examines existing solutions pertaining to regulatory frameworks that impact PtM development. Finally, the sixth chapter presents actionable recommendations and proposes an investment strategy based on the preceding analysis.

1.6 Use of AI in thesis

In this thesis, I have used Chat GPT and Microsoft Copilot for ideation, information retrieval and language checking. I have edited the text several times using AI, to make the text clearer and easier to understand but so that it would convey matters according to my original purpose.

I have ensured the authenticity of the contents and respected copyrights. If AI has produced new ideas for the text, I have always checked them from the original sources and cited them accordingly. I have used all cited sources myself and they are not produced by AI. This can be verified from my notes and from the referencing management software I have used.

2 LITERATURE REVIEW

This chapter provides a comprehensive literature review on the PtM value chain. The scope of this section is to review past research in the technical aspects of the PtM process, such as methanol synthesis, carbon dioxide capture, and green hydrogen production. In addition, it addresses various methanol storage techniques as well as its many applications as a chemical feedstock and fuel. A fundamental part of this assessment is to examine the many stages of the PtM value chain, from renewable energy generation to methanol end-use. The technological maturity, scalability, and efficiency of each stage are highlighted throughout the study, providing important details related to PtM technology investment and project development.

The key references considered for the literature review include case studies and reports, academic papers and articles, online publications, and books.

2.1 Hydrogen in industry and green hydrogen

The green transition is essential due to the unsustainable overconsumption of natural resources, leading to biodiversity loss and climate change, which impose significant economic costs. At the regional level, the EU has set high short-term ambitions related to PtX(Ramboll, 2022), "with policies to ensure 6-gigawatt (GW) electrolysis capacity in 2024. By 2030, the goal is 50 GW inside EU, plus a 40 GW capacity produced outside EU boundaries"(Ramboll, 2022). It also strengthens Finland's economy by boosting competitiveness, fostering well-being within planetary limits, and creating demand for low-carbon solutions. Success in mitigating climate change and biodiversity loss is critical for long-term public finances, future generations well-being, and environmental stability. Additionally, reducing reliance on foreign fossil fuels and expanding clean energy production will enhance national security and supply resilience(Ministry of the Environment, 2024a).The significance of the green transition is highlighted by the considerable consumption of fossil fuels, which directly contribute to climate challenges. This becomes even more apparent when noting that electricity and heating production account for 46% of global emissions, while transportation accounts for 25%. These sectors represent crucial areas where hydrogen can play a transformative role(Akpasi & Isa, 2022). Green hydrogen, made using renewable electricity, looks like a promising solution to decarbonize both the industrial and transportation sectors, which remain heavily reliant on fossil fuels. Figure 2 illustrates the carbon emissions generated by each industry, further emphasizing the need for cleaner alternatives like hydrogen in achieving global emissions reduction targets(IEA, 2022). The projections indicate that global energy demand is expected to increase by 15% by 2050, primarily driven by industrial growth and population expansion. The industrial sector is anticipated to experience a 20% rise in energy consumption, reflecting the higher demand for material production and manufacturing activities (Figure 3-4).

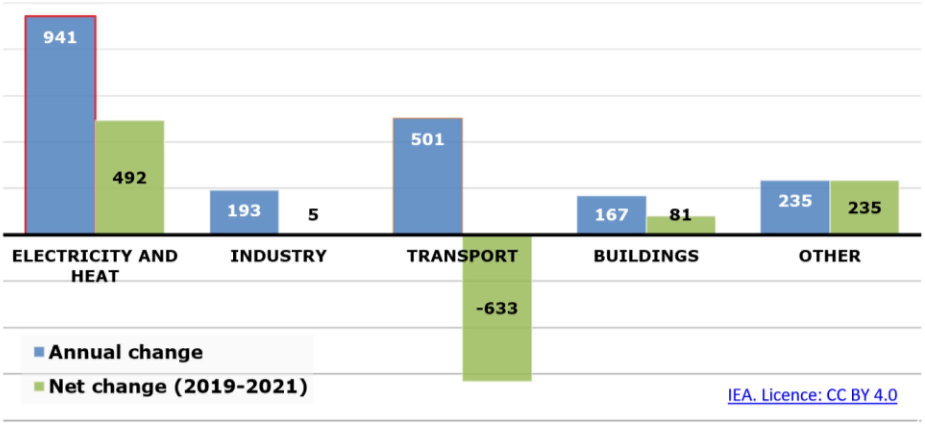

Figure 2. Annual change in CO2 emissions by sector(IEA, 2022).

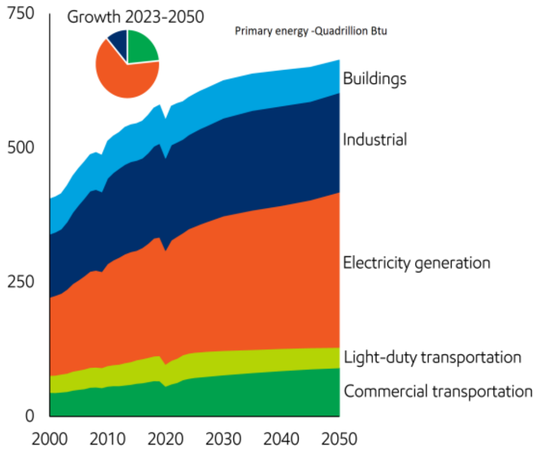

Figure 3. Global energy demand by sector (ExxonMobil , 2024)

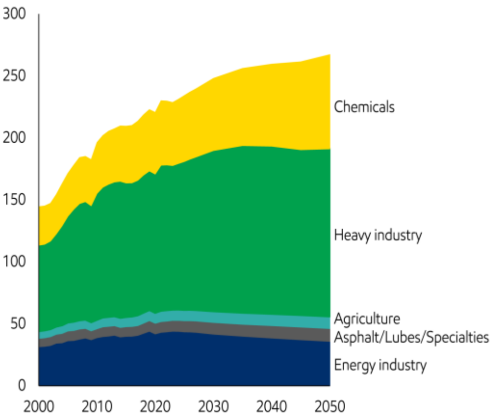

Figure 4. Global industry energy demand (ExxonMobil , 2024)

According to IEA projections, for many years, oil and natural gas are expected to provide the majority of the world’s energy. Low-carbon solutions like carbon capture and storage (CCS), hydrogen, and biofuels are essential for mitigating emissions, but according to industry association the transition to a renewable energy future will need to be gradual, with continued investment in both conventional and emerging energy infrastructures. Compared to other energy outlooks, this projection presents a more gradual shift toward renewables, suggesting that fossil fuels will remain dominant for decades(IEA, 2022). Enhancing efficiency, the development of standardized methods for transitioning to green energy, and the reduction of costs have led to the implementation of policies such that support the development of PtX. Hydrogen plays a critical role in this process, even though it is not inherently a renewable energy source. It may be generated through renewable energy sources such as solar, wind, and biomass, establishing it as a feasible alternative for the future.(Akpasi & Isa, 2022). This synergy significantly reinforces the importance of supply chain and value chain analysis for industries and sectors focused on reducing carbon emissions.

There are various methods for hydrogen production, which differ based on the source of the feedstock and the production techniques employed.

Different types of farming produce vastly different amounts of greenhouse gases when being produced. The differences shown in the figure 5 have been grouped by a conventional classification.

Grey hydrogen "is produced with fossil fuels (i.e. hydrogen produced from methane using SMR or coal gasification). The use of grey hydrogen entails substantial CO2 emissions, which makes these hydrogen technologies unsuitable for a route toward net-zero emissions"(IRENA, 2020).

Blue hydrogen production of hydrogen from fossil fuels with CO2 emissions reduced by the use of (IEA, 2022).

Pink hydrogen meaning "hydrogen produced through electrolysis powered by nuclear energy" (IRENA, 2020).

Brown hydrogen "produced through the process of coal gasification, which involves reacting coal with oxygen and steam under high temperatures to produce synthesis gas"(IEA, 2019).

"Currently, 42% of all hydrogen produced is used in oil refineries, 35% in ammonia production, and 15% in methanol production"(IEA, 2022).

However, besides releasing harmful greenhouse gases to the atmosphere, these methods can only produce low-purity hydrogen(Holladay et al., 2009). "Hydrogen production reached 97 Mt in 2023, of which less than 1% was low emissions"(IEA, 2024). The price of both producing and storing green hydrogen limits its competitiveness. This challenge could present an opportunity for companies with mid and long-term strategies and innovative approaches to overcome such barriers. According to published forecasts, green hydrogen is expected to become more competitive, with production costs for end users projected to decrease by 50% by 2030(McKinsey & Company, 2024).

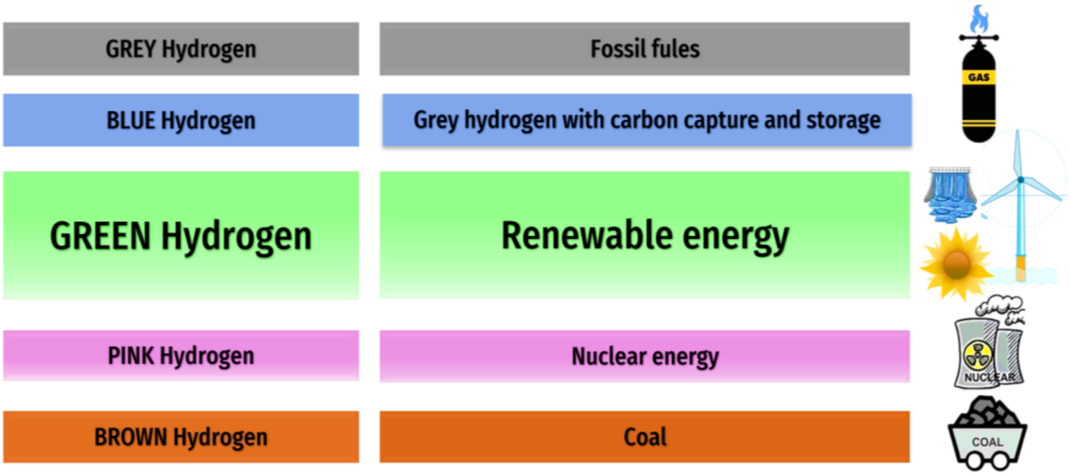

Figure 5. Hydrogen production methods based on the type of resource (IRENA, 2020; Patel et al., 2024)

2.2 PtX technologies

Due to policies and changes in approaches in the last decade, renewable electricity, primarily wind turbines and PV arrays, has increased seven-fold(IEA, 2022). PtX refers to the conversion of renewable energy into chemical products and green fuels(Kober, Tom et al., 2019; Ramboll, 2022), which can be produced, stored, and transported using existing infrastructure and methods. Key classifications for PtX include:

Power-to-Gas (PtG): This process involves converting electricity into gaseous fuels, such as hydrogen or methane(Shojaei et al., 2024). Hydrogen is typically produced through water electrolysis, while methane can be synthesized via methanation processes(Sterner & Specht, 2021).

Nowadays, methanation has garnered attention due to its compatibility with the PtX structure, which is part of the PtG group. The electrolysis-based method in PtX is currently undergoing extensive development(Nemmour et al., 2023).

Power-to-Liquids (PtL): This category utilizes electrical energy to generate liquid fuels such as methanol or synthetic hydrocarbons

(Marques et al., 2024). These fuels are synthesized through chemical reactions involving hydrogen and carbon dioxide(Rego de Vasconcelos & Lavoie, 2019).

Power-to-Chemicals (PtC): This involves the production of chemical commodities, such as ammonia or methanol, using electricity as the primary energy source(Zhai et al., 2024).

Power-to-Heat (PtH): Electricity is instantly transformed into thermal energy, which may be employed for domestic heating or industrial applications(Marques et al., 2024). This approach can enhance energy efficiency and reduce reliance on fossil fuels for heat generation(Edmond Mkaratigwa, 2023; Samuel et al., 2022).

Since storage and transportation are key challenges for PtX technologies, they must be addressed as potential bottlenecks. However, this technology offers competitive advantages compared to other methods of implementing a zero-emission strategy, including:

Batteries vs. PtX: In the comparison between batteries and PtX, batteries provide short-term, high-efficiency storage solutions, making them appropriate for applications requiring a fast response. However, they are constrained by capacity and duration limits. In contrast, PtX offers lower round-trip efficiency but enables large-scale, long-term storage and the production of versatile energy carriers (Daiyan et al., 2020).

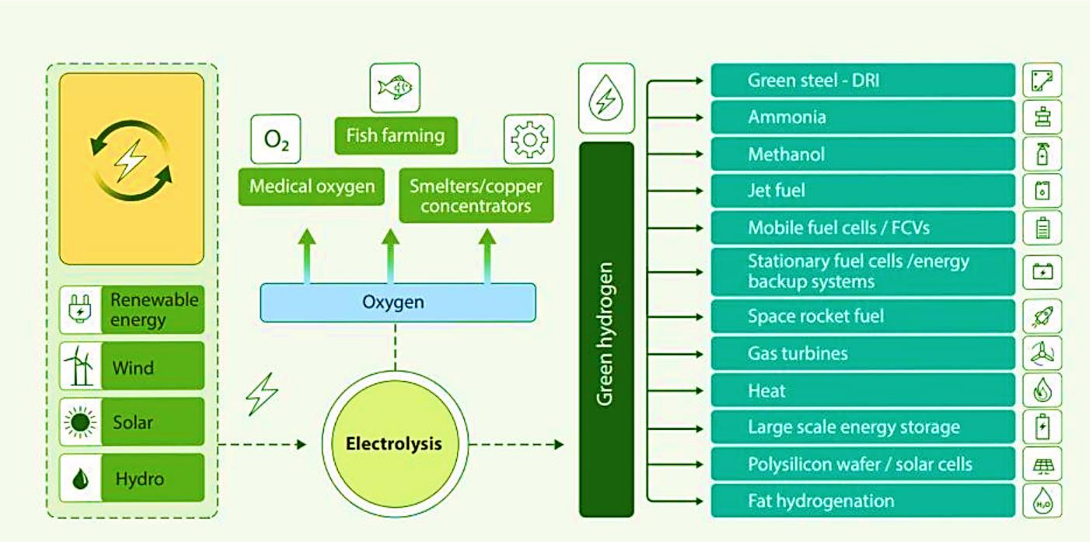

Figure 6. PtX value chain(Marin, & Raimon, 2022).

Pumped Hydro Storage (PHS) vs. PtX: PHS is a well-established method for large-scale energy storage with relatively high efficiency. However, it is geographically constrained and requires significant up-front investment. PtX, while also capital-intensive, is more flexible in terms of location and offers the additional benefit of producing chemical products that can be utilized across various sectors(Daiyan et al., 2020).

Power-to-Heat vs. PtX: One of the main challenges in reducing greenhouse gases is the use of fossil fuels for residential heating. PtX can help address this challenge. While direct conversion of electricity to heat is highly efficient and cost-effective for immediate thermal applications, it does not solve the environmental challenges. PtX, although less efficient in energy conversion, provides solutions for these needs by producing storable and transportable energy carriers(Samuel et al., 2022).

2.2.1 Power to Methanol (PtM)

The main focus of this thesis is to examine the value chain in PtM from the developer's perspective and to identify areas for improvement, as well as hidden and overlooked benefits within this value chain, particularly in the Finnish energy market.

The PtM process involves various technical elements, mainly concentrating on methanol production, its storage, and its later use. Grasping these elements is essential for assessing the viability and possibilities of PtM technology.

Methanol, generally known as CH3OH, methyl alcohol, hydroxymethane, wood alcohol or carbinol, is a commonly used basic raw material. It exists as a neutral polar liquid that is invisible. (Martin Bertau et al., 2014).

Renewable methanol has risen as a clean alternative to fossil fuels, offering a clear pathway to drastically cutting emissions in power generation, overland transportation, shipping and industry(Tammy Klein, 2020).

It is essential to understand that the demand for methanol is ever increasing since it has been widely targeted as a potential candidate to replace gasoline with excellent combustion characteristics and minimal environmental effects(Nguyen & Zondervan, 2019). Methanol will become valuable due to its positive impact on the green transition(IRENA, 2020), power generation, its role in zero-emission processes, and versatility as a feedstock for various industries, including chemicals(Martin Bertau et al., 2014).

An "innovative and efficient way of extracting the energy from methanol is in fuel cells, which are electrochemical devices that use the energy in the chemical bond of fuels to produce electricity. Like batteries, they are composed of electrodes and electrolytes, but unlike batteries instead of storing electricity, they produce it continuously as long as they are fed with a fuel (methanol in this case)"(Samuel et al., 2022).

The unique properties of methanol make it an interesting investment opportunity, leading to significant growth in the global market. “The global methanol market size was USD 27.95 Billion in 2020 and is projected to grow from USD 28.74 billion in 2021 to USD 39.18 billion in 2028 at a CAGR of 4.5% during the 2021-2028 period”(Bulk Chemicals, 2025).

Environmental sustainability will boost the advantages, potential and significance of the value chain. The products and applications of some methanol and its derivative products are outlined in the figure 7 (Simon Araya et al., 2020).

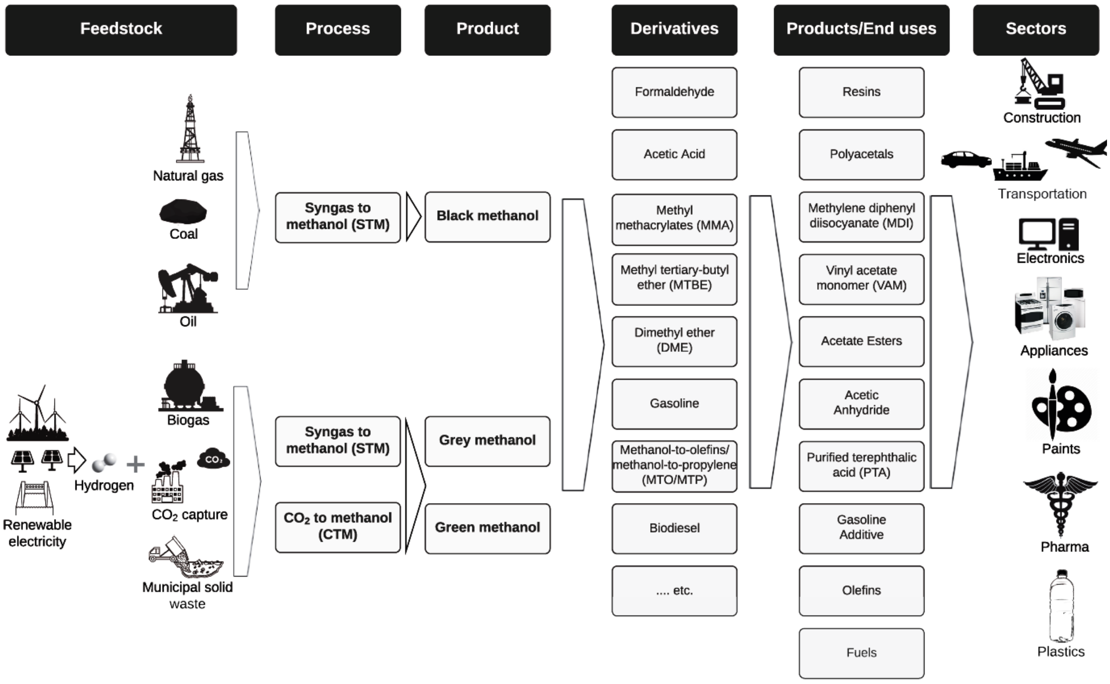

Figure 7. The methanol value chain (Simon Araya & et al., 2020).

2.3 Technical foundations of PtM production

The PtM process fundamentally relies on two key inputs: green hydrogen produced from renewable electricity and a source of carbon dioxide. These are then chemically reacted to form methanol.

The primary mechanism in the context of PtM refers to **the catalytic hydrogenation of carbon dioxide**. In this method, hydrogen generated from renewable energy via water electrolysis reacts with carbon dioxide, which is obtained from sources such as industrial emissions or directly from the atmosphere The reactions typically take place in synthesis reactors operating at temperatures between 200 and 300 °C and pressures around 50 to 100 bar(Marques et al., 2024). Different reactor setups such as fixed bed reactors, adiabatic reactors (which can be arranged in single-stage or multi-stage configurations either in series or parallel), and boiling water reactors, are employed to control the heat produced by exothermic reactions and enhance the conversion rates. It should be noted that the target company of this research, the A main part of the Koppö project is to produce green hydrogen from water electrolysis and then use catalysis to convert CO_2 into e-methanol synthetic fuel.

Biomass gasification: Although it is not exclusively a PtM route, renewable methanol can also be produced through the gasification of biomass(Tabibian & Sharifzadeh, 2023). In this method, organic materials such as wood, agricultural byproducts, and various biomass forms are transformed into syngas, which has mainly carbon monoxide and hydrogen as its main components., through high-temperature, low-oxygen processes. The syngas is subsequently purified to eliminate impurities before being converted into methanol catalytically, utilizing similar catalysts and reaction conditions as in CO2 hydrogenation(es'haghi & Shayesteh, 2025). This approach utilizes existing methanol synthesis infrastructure but relies on the sustainable availability of biomass feedstocks.

Electrochemical production: A developing and possibly transformational technology involves the direct electrochemical synthesis of methanol from CO2 and water using renewable power(Ullah et al., 2023). This approach seeks to integrate the synthesis of methanol and the generation of hydrogen into a single electrochemical procedure.

This method differs from the catalytic hydrogenation of carbon dioxide in terms of the type of process. In catalytic hydrogenation, a thermochemical process is used, along with hydrogen typically produced via electrolysis.

The key characteristics of these several methanol production methods are compared in the following table:

Table 1. Key characteristics of several methanol production methods.

Feature	**Feedstock**	**Energy Efficiency**	**Technological Maturity**	**Estimated Production Cost**
CO2 Hydrogenation	Renewable H2, Captured CO2	50-60% (overall PtM process)(Mbatha et al., 2024)	Commercial (methanol synthesis), Developing (large-scale electrolysis, CO2 capture)	USD 800-1600/tonne (e-methanol current) (IRENA, 2020)
Biomass Gasification	Biomass (wood, agricultural waste, etc.)	40-50% (biomass to methanol) (Harris et al., 2021)	Commercial (gasification and synthesis)(Harris et al., 2021)	USD 320-770/tonne (bio-methanol current) (IRENA, 2020)
Electrochemical Production	Renewable Electricity, CO2, Water	Varies widely, currently lower than other pathways	Early-stage research and development	Highly variable, generally higher than other pathways

2.4 PtM value chain

2.4.1 Definition and components of the PtX value chain in general

A value chain in general encompasses all processes and activities within an industry or company that generate value during production or service delivery. It is typically divided into two categories: primary activities and support activities. Optimizing and enhancing each of these components can strengthen competitive advantage and increase profitability(Porter M.E, 1998). However, it should be kept in mind that in this concept, value is not solely financial. It also includes factors currently observed in various industries, such as improving efficiency and productivity, enhancing quality and improving customer service, as well as addressing critical concerns like environmental sustainability, which are clearly evident in PtM and in PtX value chain in general.

The value chain in PtM consists of three main sections: **production**, **storage and transportation**, and **distribution and utilization**(Akpasi et al., 2025)**.** Each section includes sub-sections that vary depending on the type of final product, the target market, and the technologies used in the processes (Figure 7). The efficient functioning of value chain relies on the active involvement of local infrastructure and enterprises, which play a pivotal role in facilitating these processes. **"Integrating small and medium PtX projects into existing facilities is an attractive approach already taken by several players in the " (S&P Global's, 2020)" due to the revalorization of side streams and potential reduction of the CO_2 footprint of the existing facility"(Marin, & Raimon, 2022)**. An other important aspect is the creation of domestic demand, which means enhancing local value and careful and sustainable use of the territory, together with careful exporting, to reach the overall purpose of the value chain (Carmona et al., 2024).

Production

The production of e-methanol involves several interconnected stages, each with its own technological and economic considerations that project developers must navigate.

Renewable electricity generation

The cornerstone of e-methanol is abundant, low-cost renewable electricity, primarily from solar photovoltaic (PV) and wind power(Siphesihle Mbatha et al., 2019). Developers face the challenge of intermittency from these sources, which directly impacts the operational stability and overall economics of the subsequent PtM processes(Siphesihle Mbatha et al., 2019). For utility-scale solar PV, key components include modules, inverters, and mounting structures, with supply chains significantly concentrated in China for c-Si, while CdTe offers more diversified sourcing(U.S. Department of Energy, 2022b). EIAs are indispensable for large-scale renewable energy projects, addressing land use, water consumption, and biodiversity impacts(Faisal A. Osra, 2024). The cost and carbon intensity of this electricity are paramount for the viability of e-methanol(Siphesihle Mbatha et al., 2019).

Green hydrogen production via electrolysis

Green hydrogen, produced through water electrolysis powered by renewable electricity, serves as a pivotal intermediate(Ramboll, 2022), as discussed in detail in the previous chapters. The cost of green hydrogen, heavily influenced by renewable electricity prices and electrolyzer CAPEX, is a predominant driver of the final e-methanol price(Cameli et al., 2024). "Balance of Plant components, such as power electronics", water purification, and gas conditioning systems, also constitute a significant portion of the total electrolyzer system cost and require careful consideration by developers(Alex Badgett, et al., 2024).

2.4.2 CCU

The carbon feedstock for PtM, CO2, can be sourced from industrial flue gases, biogenic processes, or directly from the atmosphere, each with distinct implications for project developers.

Industrial flue gas: Sources like cement plants, power stations, and steel mills offer CO2 at higher concentrations, which generally reduces capture costs compared to more dilute sources (Homsy & Fout, 2022). However, these streams often contain impurities that must be removed to protect downstream catalysts(Mbatha et al., 2024).

Biogenic sources: CO2 from biomass combustion, biogas upgrading, or bioethanol fermentation is considered renewable or carbon-neutral if the biomass is sustainably sourced (IEA, 2025). This is critical for producing green e-methanol. High-purity streams can reduce purification needs. However, the availability, scale, and logistics of biogenic CO2 can be limiting factors for large-scale projects(BCG & OGC, 2024).

Direct Air Capture (DAC): DAC technologies extract CO2 directly from ambient air (~420 ppm), offering locational flexibility to co-locate PtM plants with abundant renewable energy, independent of point sources(Cameli et al., 2024). When powered by renewables, DAC enables carbon-negative e-methanol. However, DAC is currently more energy-intensive and costly than point source capture, with costs ranging from several hundred USD/tonne CO2, though projections suggest potential future reductions to $40-$100/tonne CO2 (Cameli et al., 2024).

Common CO2 capture technologies relevant to project developers include:

Chemical absorption: A mature technology widely used for post-combustion capture, offering high capture rates (more than90%) and purity (more than 99%)(Thiedemann & Wark, 2025). However, it is energy-intensive due to solvent regeneration and can suffer from solvent degradation.

Membrane separation: Utilizes semi-permeable membranes for CO2 separation. Advantages include modularity and potentially lower energy use, but there's a trade-off between permeability and selectivity(Adhikari et al., 2023)

The purity of the captured CO2 stream is paramount, as impurities like sulfur compounds and chlorine compounds can severely poison the downstream methanol synthesis catalysts, particularly copper-based ones(DJETTENE et al., 2022). This often necessitates additional purification steps, adding to project costs.

2.4.3 Methanol synthesis

The core chemical transformation is the catalytic hydrogenation of CO2 with green hydrogen: $CO2+3H2 \rightleftharpoons CH3OH+H2O$.89 This reaction is exothermic and favored by lower temperatures and higher pressures(Zhong et al., 2020).

Catalysts: The industrial benchmark is the Cu/ZnO/Al2O3 catalyst due to its activity, selectivity, and cost-effectiveness(Berahim et al., 2023). However, these catalysts are susceptible to deactivation by water (and impurities from the feed gas(Mbatha et al., 2024). Dynamic operation due to variable renewable hydrogen supply can also exacerbate deactivation(Mbatha et al., 2024).

Reactor technologies: Reactor design is crucial for heat management, overcoming equilibrium limitations, and enabling dynamic operation with fluctuating hydrogen supply(Mbatha et al., 2024).

2.4.4 Methanol storage technologies and transportation:

Bulk storage: Large quantities of methanol are typically stored in tank farms at production facilities, ports, and distribution terminals. These tank farms consist of above-ground storage tanks, often equipped with floating roofs to minimize vapor losses and the risk of ignition(Methanol

Institute, 2020). Safety features such as emergency shutdown mechanisms and leak detection systems are crucial components of these bulk storage facilities.

Portable storage: Smaller volumes of methanol are stored and transported in portable containers like drums and intermediate bulk containers. Spill containment measures should also be in place wherever methanol is stored, regardless of the container size(Methanol Institute, 2020).

2.4.5 Investment challenges and opportunities in the value chain and key stakeholders

The examination of the sectors and scope of PtM applications highlight its vast complexity, requiring careful consideration from a stakeholder perspective. These stakeholders primarily consist of various sectors and organizations. This part of the study will analyze investment challenges and opportunities within the value chain from the perspective of key stakeholders developers, suppliers, and policymakers.

Developers, at the forefront of implementing all types of PtX projects, encounter significant challenges, including substantial capital expenditures and the requirement for specialized infrastructure to produce, store, and distribute products such as methanol. Additionally, the intermittent nature of renewable energy sources, such as wind and solar, demands the design of flexible and resilient systems, which further contributes to increased costs. However, as technologies mature and economies of scale are achieved, investment opportunities are expected to expand, potentially leading to more cost-effective solutions(Daiyan et al., 2020). Developers meticulously assess the economic viability and potential profitability projects, considering factors such as projected revenues from sales, anticipated operating costs, and the expected return on investment. A key metric in this evaluation is the levelized cost of the final product, in this case methanol (LCOMeOH). The provides an estimate of the average cost to produce one unit of methanol over the project's lifetime(Madi et al., 2025).

Suppliers and manufacturers provide the essential components for PtM systems, thus a developer needs to compare the cost and technological maturity of all of these, such as electrolyzers, catalysts, and storage solutions, which are critical for ensuring reliability and economic feasibility(IEA, 2022). The suppliers of different components can be categorized into several key groups:

Renewable energy equipment suppliers: Investment case strongly depend on a stable supply of renewable electricity from wind, solar, and hydro.

Electrolyzer manufacturers: Electrolyzers are the core technology for hydrogen production in PtM systems. These suppliers provide different types of electrolyzers, including AEL, PEM, and SOEC.

Carbon capture and utilization suppliers: The PtM process of synthetic fuel production requires an outside source of CO2, thus CCU technologies are essential.

Fuel synthesis technology providers: It pertains to sectors engaged in the development of technologies that convert green hydrogen and captured CO_2 into synthetic fuels, including methanol, ammonia, and e-fuels.

Storage and transportation suppliers: Green hydrogen and methanol require safe storage and distribution networks.

2.5 Challenges in PtM implementation

Since PtM is inherently multidimensional and spans multiple industries with distinct technologies, its implementation presents a complex array of challenges. These challenges can be broadly classified into technical barriers, financial and market risks, as well as regulatory and policy constraints(Bailera et al., 2017).

2.5.1 Technical considerations

Infrastructure: Methanol necessitates less infrastructure compared to hydrogen in certain aspects, but it should be noted that methanol requires more safety measures and infrastructure for storage due to its flammability and toxicity(Bram et al., 2024). Establishment of targeted investment funds and regulatory schemes could unlock additional abatement potential(Szarek et al., 2024).

Energy storage and efficiency: One of the key efficiency challenges in hydrogen storage is achieving high-density storage, which remains a significant barrier, particularly in "transportation applications. Existing storage methods often require large-volume systems to store hydrogen in its gaseous" form(Akpasi et al., 2025b), leading to lower efficiency for mobile applications(U.S. Department of Energy, 2022a). As hydrogen is a major building block of PtM technologies, this challenge must be addressed for the PtM system to succeed.

Safety: Additionally, the safety aspects of any PtX project are essential and involve several challenges related to hydrogen, including its high flammability, the difficulty in leak detection due to its colorless and odorless nature, and the necessity for specialized materials to prevent permeation and embrittlement(Hydrogen Safety, 2020).

Technological cost: Another challenge facing E-methanol is the cost of producing renewable methanol, which currently remains high compared to conventional methods due to the technology maturation(Tabibian & Sharifzadeh, 2023).

2.6 Financial consideration and market outlook

As PtM technology advances, its integration with renewable energy sources presents significant economic opportunities, particularly in the context of sustainable energy transitions and carbon reduction strategies. The cost-effectiveness of renewable electricity-based methanol production highlights its potential as an energy storage medium, a versatile platform chemical, and a commercially viable solution(Adnan & Kibria, 2020). Depending on favorable local conditions, early or niche opportunities for bio-methanol and e-methanol production are emerging(IRENA, 2020).

Designing PtM plants requires balancing two key factors: maximizing plant availability to achieve a short investment payback period while ensuring a low cost of renewable electricity in the power supply(Pratschner et al., 2023). In support of renewable methanol production, this study provides a comprehensive statistical and analytical overview of the global methanol value chain.

From a project developer's perspective, the PtM value chain offers significant opportunities for decarbonization by producing a versatile liquid energy carrier and chemical feedstock from renewable resources that already has existing well know technologies for its use(Mbatha et al., 2024). The compatibility of methanol with existing storage, transport, and distribution infrastructure remains a key enabler for its broader adoption (Mbatha et al., 2024).

However, substantial challenges remain, primarily concerning economic viability. The current production cost of e-methanol (e.g.,US$631-US$643/ton in 2023, projected to US$467-US$480/ton by 2030) (Pakdel & Eslamloueyan , 2024) is significantly higher than conventional methanol (US$100-250/ton)(Pakdel & Eslamloueyan, 2024), a green premium driven by the high costs of renewable electricity, green hydrogen (electrolyzer CAPEX and electricity OPEX), and CO2 capture, especially DAC(Cameli et al., 2024).

Finally, policymakers and regulatory bodies shape the legal and financial environment for PtX adoption by providing incentives, carbon pricing mechanisms, and policy frameworks to enhance market attractiveness.

Successful PtM project development hinges on continued R&D for cost reduction, strategic site selection (co-locating with low-cost renewables and CO2 sources), securing off-take agreements, and supportive policies to bridge the economic gap(Cameli et al., 2024).

3 STRATEGIES FOR OVERCOMING CHALLENGES IN PTM PROJECTS

The main objective of reviewing the existing literature in this section is to examine the body of knowledge and identify approaches for overcoming challenges in energy projects, with a specific focus on their relevance and applicability to the development of PtM projects. By examining the challenges commonly encountered in diverse energy infrastructure projects and the risk mitigation strategies and best practices suggested in the academic literature, this study analyzes how these general strategies can be incorporated into the value chain and partner selection, and adapted and applied to PtM project development.

3.1 Landscape of challenges in energy projects

The development of energy infrastructure projects, particularly those involving new technologies and a transition towards sustainability, is often fraught with a multitude of challenges. These challenges can span various aspects of the project lifecycle, from initial planning and financing to technological implementation and operational management.

3.1.1 Common challenges in diverse energy infrastructure projects

Effective project management and planning are foundational to the success of any large-scale endeavor, and energy projects are no exception. Deficiencies in these areas can lead to significant setbacks. Insufficient planning, often characterized by a lack of detailed feasibility studies and risk assessments, can result in unrealistic cost and time estimations.

An unclear project scope, where objectives and deliverables are not well-defined, further exacerbates these issues, leading to scope creep and potential project failure. Inadequate project delivery systems, coupled with a lack of accountability in decision-making processes, can hinder progress and create inefficiencies throughout the project lifecycle(Arwadi et al., 2025).

Challenges in engaging local communities (Stakeholders) effectively and addressing their concerns about potential environmental and social impacts can result in significant resistance, as seen in various renewable energy projects(Ashraf et al., 2024). Financial and economic hurdles represent another crucial category of challenges. Securing adequate financing for energy projects, which are often capital-intensive with long gestation periods, can be a major obstacle and challenge. Moreover, the rapid pace of technological advancements in the energy sector can lead to concerns about potential obsolescence of chosen technologies, creating a risk for long-term investments(Ogunniran et al., 2025). The regulatory, policy environment, and social impacts are increasingly important considerations for energy projects.

Project management in the renewable energy sector faces several unique challenges, including the intermittency and variability of renewable resources, the geographic distribution of these resources often requiring significant transmission infrastructure, and the complex and evolving regulatory environment(Arwadi et al., 2025). Best practices in renewable energy development are specifically designed to address these challenges through sophisticated forecasting and grid management strategies, careful site selection and community engagement, proactive navigation of regulations, and the application of advanced technologies like energy storage(Arwadi et al., 2025).

3.2 Unique development challenges PtM

While PtM projects share many of the general challenges inherent in energy infrastructure development, they also present a unique set of hurdles stemming from the novelty of the technology, its complex integration requirements, and the evolving market landscape for sustainable fuels.

3.2.1 Technological obstacles and operational complexities in PtM implementation

The first stage, hydrogen production via electrolysis, is a critical determinant of the overall efficiency and cost of the PtM project(Dieterich et al., 2020). While various electrolysis technologies exist, such as alkaline, PEM, and SOEC, each has its own trade-offs in terms of efficiency, cost, operating temperature, and flexibility(Dieterich et al., 2020)Ensuring a stable and reliable supply of green hydrogen, produced from intermittent renewable energy sources like wind and solar, poses a significant challenge, requiring either electrolyzers capable of flexible operation or the integration of storage solutions to buffer fluctuations in renewable electricity supply(Akram & Kienberger, 2024).

The second stage entails the sequestration of carbon dioxide, which acts as the carbon feedstock for methanol production. The source and purity of the captured CO2 can significantly impact the sustainability and economics of the PtM project(Akram & Kienberger, 2024) Options range from capturing CO2 from industrial emissions, which offers a more concentrated source but may not align with a fully renewable vision if the emissions are from fossil fuel combustion, to DAC, which captures CO2 directly from the atmosphere and represents a more truly carbon-neutral approach but is currently more energy-intensive and costly(Dieterich et al., 2020) Matching the supply of captured CO2 with the availability of green hydrogen in the required stoichiometric ratio for efficient methanol synthesis is another operational complexity(Akram & Kienberger, 2024).

Methanol synthesis is the end of the technology, in which hydrogen and carbon dioxide combine over a catalyst to become methanol. The efficiency and selectivity of the catalyst used for this CO2 hydrogenation reaction are crucial factors in maximizing methanol yield and minimizing unwanted by-products(Dieterich et al., 2020)Reactor design and optimization are also critical, particularly for PtM plants that need to operate flexibly in response to the variable nature of renewable energy inputs(Dieterich et al., 2020). Managing the heat generated during the exothermic methanol synthesis reaction and dealing with the formation of water as a by-product are additional operational considerations that require careful process design and integration(Dieterich et al., 2020)

Seamless process integration across these three stages: hydrogen production, CO2 capture, and methanol synthesis is essential for achieving optimal efficiency and economic viability in PtM projects(Akram & Kienberger, 2024). Designing the entire system for flexible operation to align with the fluctuating supply of renewable electricity is a significant challenge, often requiring sophisticated control systems and potentially the incorporation of energy storage options for hydrogen and, in some cases, CO2(Mbatha et al., 2024).

The shift in methanol production from traditional syngas-based routes to direct CO2 utilization in PtM processes introduces specific technological challenges(Ouda et al., 2019). The increased formation of water as a byproduct and the lower equilibrium conversion rates associated with direct CO2 hydrogenation necessitate the development of new, more efficient catalysts and innovative reactor designs to overcome these limitations. This ongoing research and development is crucial for enhancing the technological maturity and commercial viability of PtM projects.

3.2.2 Economic and financial viability of PtM projects in the current energy market

The economic and financial viability of PtM projects in the current energy market landscape faces several significant challenges. One of the primary hurdles is the high production costs associated with renewable methanol compared to methanol produced from conventional fossil fuels(IRENA, 2020). Green hydrogen is a significant input for PtM and its cost is high, is currently significantly higher than hydrogen produced from natural gas, largely due to the expense of renewable electricity and the capital investment required for electrolyzers(IRENA, 2020). The cost and energy intensity of CO2 capture technologies, particularly direct air capture, further contribute to the overall production expense(Dieterich et al., 2020). The LCOM from PtM plants is influenced by a combination of capital investment in the plant infrastructure and ongoing operational expenses, including electricity consumption, feedstock costs, and maintenance(Rivera-Tinoco et al., 2016). While the demand for renewable methanol as a sustainable fuel and chemical feedstock is steadily growing, its widespread adoption is contingent upon achieving cost competitiveness with traditional alternatives and securing long-term offtake agreements(IRENA, 2020). The willingness of end consumers, particularly in sectors like shipping and aviation, to pay a premium for green methanol is a key factor in establishing a viable market(P. E. D. Love et al., 2024). PtM also faces competition from other alternative fuels, such as green ammonia and sustainable aviation fuels produced through different pathways, as well as from advancements in direct electrification and other energy storage technologies(Daggash et al., 2018).

The relatively large scale and novelty of PtM technology deployment contribute to the perception of these projects as high-risk investments, creating barriers to securing external financing and long-term financial commitments from investors(Peak and Wind, 2022). To mitigate these risks, project developers often need to engage in risk-sharing through the formation of project consortia and strategic partnerships, where the financial burden and technological risks are distributed among multiple stakeholders(Peak and Wind, 2022).

Numerous techno-economic assessments of PtM plants have been conducted under various scenarios, exploring the sensitivity of production costs to factors like electricity prices, hydrogen costs, and carbon pricing mechanisms(Rivera-Tinoco et al., 2016) These studies generally indicate that while current production costs are significantly higher than those of fossil-based methanol, PtM has the potential to become economically competitive in the future with anticipated declines in renewable energy costs, advancements in electrolysis and CO2 capture technologies, and the implementation of supportive government policies, such as carbon taxes and subsidies(IRENA, 2020). The long-term outlook suggests that the cost of e-methanol could decrease substantially by mid-century, reaching parity with or even becoming more economical than gray methanol(IRENA, 2020).

3.2.3 Policy and regulatory frameworks of PtM development

The regulatory and policy environment has a significant impact on how PtM initiatives are developed and implemented. To overcome the early economic obstacles and hasten the adoption of PtM technology, supportive government regulations and financial incentives are crucial(Falcone, 2023). These can include direct financial support through grants and subsidies, the implementation of feed-in tariffs or power purchase agreements that provide stable revenue streams, and government funding for crucial research, development, and demonstration projects(Falcone, 2023).

Navigating the complicated processes for obtaining environmental approvals and other necessary permits can be a significant hurdle for PtM project developers. The lack of clear and consistent standards and certification schemes for low-carbon fuels, including renewable methanol, can also impede market adoption and create uncertainty for both producers and consumers(PtX Hub, 2022).

The successful integration of PtM into the broader energy system requires alignment with existing energy transition strategies and climate goals(Weinberg, 2021). Policies need to consider the impact of PtM plants on electricity grids, particularly the need for grid balancing services to manage the intermittent nature of renewable power supply(Akram & Kienberger, 2024). The interplay between PtM development and policies related to CCU, as well as mandates for the use of renewable fuels in transportation and industry, will also be critical in shaping the trajectory of PtM(Sankaran, 2023).

Given the prospect for renewable methanol to serve as a sustainable fuel for international maritime and aviation transport, international cooperation and the establishment of harmonized regulatory frameworks will be increasingly important(Bloomberg NEF, 2024). Opportunities for international collaboration on technology transfer and capacity building in developing nations can also help to promote the global adoption of PtM and other PtX technologies (Falcone, 2023). The regulations in the European Union and the goals set by the International Maritime Organization are already creating pressure on the shipping sector to transition to green fuels like methanol, which could significantly drive demand for PtM-produced methanol(Bloomberg NEF, 2024).

Table 2. key challenge categories and their relevance to PtM projects

Challenge Category	**Specific Challenges**	**Relevance to PtM Projects**
Technological(Rego de Vasconcelos & Lavoie, 2019)	Efficiency of conversion processes, scalability of technologies, maturity level of certain PtM pathways, integration with existing energy infrastructure, performance and durability of equipment.	The core of PtM relies on complex chemical and electrochemical processes. Advancements in efficiency and scalability are crucial for economic viability and widespread adoption. Integration with existing grids and infrastructure poses significant engineering challenges.
Economic & Financial(Ullah et al., 2023)	High upfront capital costs, operational expenses (especially electricity costs), market competitiveness against established fossil fuels, access to financing and investment, price volatility of renewable energy and PtM products.	PtM technologies often face high initial investment requirements and operational costs, particularly due to the reliance on renewable electricity. Achieving price parity with conventional fuels is a key hurdle for market penetration.
Regulatory and policy(PtX Hub, 2022)	Lack of clear and specific regulatory frameworks for PtM, complex and lengthy permitting processes, insufficient or inconsistent incentives and subsidies, absence of standardized product	The novelty of PtM technologies often means that existing regulations are not directly applicable or sufficient, creating uncertainty for developers. Supportive policies and

	specifications and certification schemes.	clear standards are essential to de-risk investments and facilitate market growth.
Infrastructure and logistical(Gobbo et al., 2018)	Availability of large-scale renewable energy sources, access to sufficient water resources (for electrolysis), development of CO2 capture and utilization infrastructure, transportation and storage solutions for PtM products (e.g., hydrogen, e-fuels).	PtM projects require substantial inputs like renewable energy and potentially water and CO2. The infrastructure to supply these inputs and distribute the outputs needs to be developed or adapted.
Environmental and sustainability(WORD ECONOMIC FORUM, 2023)	Ensuring a positive life cycle environmental impact, minimizing the carbon footprint of PtM production (considering the electricity source), land use requirements for renewable energy and PtM plants, water consumption and management, potential emissions from PtM processes.	While PtM aims for sustainability, it's crucial to ensure that the entire process, from energy generation to product utilization, yields genuine environmental benefits and avoids unintended negative consequences.

3.3 Established strategies to PtM projects

Given the uncertainties associated with emerging projects and the associated technologies in PtM, adopting flexible and adaptable project management methodologies that allow for adjustments in response to unforeseen challenges and technological advancements is particularly important(Adegboyega et al., 2024).

Effective stakeholder engagement and communication are of paramount importance for PtM projects. A wide variety of stakeholders are frequently involved in the creation of PtM projects, including technology providers specializing in electrolysis, CO2 capture, and methanol synthesis, energy companies, policymakers at various levels, and potential end-users in the transportation and chemical industries (Arwadi et al., 2025). Proactive and transparent communication among these stakeholders is essential for building consensus, securing necessary support, and ensuring the successful implementation of PtM projects. Resolving public perceptions and concerns regarding the deployment of new technologies and associated infrastructure, such as H2 or CO2 pipelines or hydrogen production facilities, is also critical for gaining social acceptance (Ashraf et al., 2024).

Utilizing project finance models, where the project is financed through debt and equity that are repaid from the project's cash flow, can help to mitigate the high capital costs and perceived risks associated with PtM (Suvvari & SAXENA, 2023).Exploring innovative financing mechanisms, such as green bonds and blended finance, and fostering public-private partnerships can help to overcome traditional investment barriers and attract the necessary capital for large-scale PtM deployment(Falcone, 2023). Strategies aimed at optimizing the economic viability of PtM, such as co-locating plants with low-cost renewable energy sources or industrial facilities that can provide a concentrated CO2 stream, and exploring potential revenue streams from by-products like oxygen generated during electrolysis, can enhance the financial attractiveness of these projects (Emanuele Moioli et al., 2022).

Technological and operational strategies employed in other energy projects offer valuable insights for PtM development. In order to guarantee optimal performance, a thorough selection of technology is essential, based on a rigorous examination of factors including cost, scalability, efficiency, and reliability for each PtM process component (electrolyzers, CO2 collecting units, and methanol synthesis reactors). Given the intermittent supply of renewable electricity, implementing strategies to ensure operational flexibility in the PtM plants is essential. This can include incorporating hydrogen storage capabilities to decouple hydrogen production from methanol synthesis, and designing the methanol synthesis process for dynamic operation to match fluctuations in feedstock availability(Mbatha et al., 2024). Implementing robust monitoring and control systems is also critical for optimizing process efficiency, ensuring the safety of PtM plant operations, and minimizing potential environmental impacts(Arwadi et al., 2025).

Navigating the regulatory and policy landscape for PtM projects requires adapting strategies used in other energy sectors. Actively engaging with policymakers and regulatory bodies to advocate for the development of supportive regulations and incentives that specifically address the unique characteristics of PtM technology is crucial for creating a favorable environment for its deployment(Falcone, 2023). Developing comprehensive strategies for navigating the often-complex permitting processes associated with industrial and energy infrastructure projects, and ensuring ongoing compliance with environmental and safety standards relevant to PtM technologies, are also essential(World wide recruitment, 2023). Furthermore, contributing to the development of clear and consistent standards and certification schemes for renewable methanol can help to build market confidence and facilitate wider adoption of PtM-produced fuel(PtX Hub, 2022).

However, the specific nuances of PtM technology and its integration into the broader energy system require a tailored approach to these fundamental project management principles.

3.4 Emerging strategies and solutions for overcoming challenges in PtM projects

A number of innovative strategies and technical developments demonstrate potential as approaches that precisely handle the particular difficulties involved in PtM project development.

Enhancement in electrolysis technologies are crucial for enhancing the efficiency and lowering the costs of green hydrogen generation, a critical element in the economic feasibility of PtM. SOEC and AEM membrane electrolysis are being explored for their potential to offer higher efficiencies and lower costs compared to more established technologies like alkaline and PEM electrolysis(Dieterich et al., 2020). Furthermore, the development of electrolyzers with greater operational flexibility, characterized by faster ramp-up and ramp-down rates, is essential for effectively integrating with the intermittent nature of renewable power sources like wind and solar energy(Akram & Kienberger, 2024).

Significant study and development efforts are focused on boosting the efficiency and at a lower cost of CO2 capture technologies. This includes exploring more energy-efficient solvents and sorbents for post-combustion capture from industrial sources, as well as advancements in DAC technologies aimed at lowering their high energy intensity and cost(Dieterich et al., 2020). Innovative approaches that integrate CO2 capture directly with methanol production processes are also being investigated as a way to improve overall efficiency and potentially reduce costs(Sankaran, 2023).

The efficiency and effectiveness of methanol synthesis in PtM plants are heavily dependent on the performance of the catalysts used. Current research is focused on developing more active, selective, and durable catalysts for the direct hydrogenation of CO2 to methanol, particularly catalysts that can maintain high performance under the dynamic operating conditions expected in PtM plants powered by intermittent renewables(Dieterich et al., 2020) Alongside catalyst development, innovative reactor configurations are being designed to better handle fluctuating feed streams of hydrogen and CO2 and to optimize heat transfer within the reactor, thereby enhancing efficiency and productivity(Dieterich et al., 2020).

Integrating PtM plants with other energy systems offers opportunities for improved efficiency and cost reduction. Co-locating PtM facilities with renewable energy power plants, such as wind farms or solar photovoltaic arrays, allows for a direct supply of electricity, potentially reducing transmission costs and providing grid balancing services(Fulham et al., 2024b). Similarly, integrating PtM plants with industrial facilities that emit large quantities of CO2 provides a readily available carbon source, while the produced methanol can potentially be utilized on-site or in nearby industrial processes(Akram & Kienberger, 2024)

Advanced modeling techniques, such as the combined investment and operational optimization approach using mixed-integer linear programming (MILP), are also emerging as valuable tools for improving the economic viability of PtM plants. These approaches allow for the simultaneous optimization of plant design, component sizing, and operational strategies, taking into account factors like fluctuating renewable energy availability and market prices.

On the other hand, tailored risk management frameworks and best practices are essential for ensuring project success. Addressing technological risks associated with the relatively early stage of commercial PtM deployment requires implementing thorough testing and validation of all key technologies at pilot and demonstration scales before committing to large-scale commercial plants(IRENA, 2020).Developing comprehensive contingency plans to address potential technical failures or significant deviations from expected performance is also crucial for mitigating the impact of unforeseen issues.

Mitigating financial and economic risks in PtM projects involves securing long-term offtake agreements with creditworthy buyers in sectors like shipping, aviation, or the chemical industry to provide revenue stability(Peak and Wind, 2022).Utilizing financial hedging instruments can help to protect against the volatility of energy prices and the costs of key feedstocks like renewable electricity and CO2(Ogunniran et al., 2025). Adopting a phased approach to the deployment of PtM plants, starting with smaller pilot or demonstration projects and gradually scaling up as technology matures and market demand grows, can help to reduce the initial upfront capital investment and allow for valuable learning and optimization along the way.

Conducting thorough environmental impact assessments early in the project lifecycle and proactively addressing any potential social concerns from local communities can help to ensure smoother permitting processes and greater public acceptance (Weinberg, 2021).Developing robust and well-defined permitting strategies, including early and consistent engagement with relevant authorities and stakeholders, is essential for minimizing delays and ensuring successful project approvals(Adegboyega et al., 2024)

Building a resilient supply chain for PtM projects involves diversifying the sources of critical feedstocks, such as renewable electricity and CO2, and working with multiple technology providers to reduce reliance on any single source(Ogunniran et al., 2025). Developing comprehensive logistical plans for the transportation and storage of hydrogen, CO2, and the final methanol product is also crucial for ensuring the reliable and efficient operation of PtM plants(Peak and Wind, 2022).

The best practices identified in the broader energy sector and the fundamental principles of project management are highly relevant to PtM projects. However, the complexity and novelty of PtM technology necessitate a tailored approach to these established strategies. Effective stakeholder engagement, careful technology selection, robust financial planning, and proactive navigation of the regulatory landscape are all critical for successful PtM development. Emerging strategies concentrate on technological innovation and system integration offer pathways to boost the efficiency and reduce the cost of PtM, enhancing its economic competitiveness. Lessons learned from the successes and setbacks of previous energy PtM, particularly those in the PtX and renewable energy sectors, are essential to minimizing risks and improving the chances of success in PtM endeavors.

Building a team of experts with a history in the industry brings invaluable, practical experience directly to the project. This pre-existing knowledge base fosters quicker strategic alignment and reduces the risks associated with unfamiliar territory. Their insights can anticipate challenges and drive innovation based on proven methodologies.

4 CRITERIA FOR SUPPLIER AND PARTNER SELECTION

The successful development and implementation of PtM projects, particularly from a project developer's perspective, are intrinsically linked to the careful selection of suppliers and strategic partners. As highlighted in the preceding chapters, the PtM value chain is complex, involving nascent technologies, significant capital investment, and multifaceted operational challenges(Cameli et al., 2024; Mbatha et al., 2024). Consequently, the choice of entities to provide critical components, technologies, and services, as well as those to collaborate with on a more strategic level, can significantly influence project viability, efficiency, and long-term sustainability. This chapter outlines key criteria that project developers, especially agile SMEs as focused on in this thesis, should consider when selecting suppliers and partners for PtM projects. These criteria are derived from best practices in complex industrial project management and tailored to the specific nuances of the PtM sector.

4.1 Technical expertise and technological maturity

Given the technological intensity of PtM projects, a primary criterion is the proven technical expertise and the maturity level of the technologies offered by potential suppliers and partners. This extends across the entire value chain, from renewable energy generation components to electrolysis, CO_2 capture, and methanol synthesis.

Electrolysis technology: For hydrogen production, suppliers of electrolyzers (Alkaline, PEM, SOEC) must demonstrate not only high efficiency and reliability but also experience with dynamic operation to accommodate intermittent renewable energy supplies(Akram & Kienberger, 2024).Developers should scrutinize performance data, operational track records, and the supplier's R&D pipeline for future improvements(Dieterich et al., 2020). The ability to provide robust Balance of Plant components is also critical(Badgett et al., 2024).

CO_2 Capture and Utilization: Suppliers of CCU technology must offer solutions that are effective, energy-efficient, and capable of delivering CO_2 at the required purity for methanol synthesis, minimizing catalyst poisoning risks(DJETTENE et al., 2022). In most case the suppliers have very deep experience with their chosen technology and R&D patents and good references of having previously provided the technolgies and or adequate data from their tests of how the technologies perform(Cameli et al., 2024). A critical factor in the suppliers for the PtM plant is the demonstrable scalability of their proposed solutions.

Methanol synthesis: Partners or technology licensors for methanol synthesis should possess proven expertise in reactor design, catalyst performance (especially for CO_2 hydrogenation), and process optimization(Mbatha et al., 2024). Evidence of successful operation, catalyst lifetime, and efficiency in converting green hydrogen and CO_2 to methanol under potentially variable load conditions is paramount(Berahim et al., 2023).

System integration capabilities and R&D: Beyond individual components, the ability of a partner or a consortium of suppliers to ensure seamless integration of these disparate technologies is crucial. Experience in managing complex interfaces and optimizing the overall PtM plant performance is a significant differentiator(Akram & Kienberger, 2024).

Project developers should seek suppliers and partners with a strong R&D focus, indicating a commitment to continuous improvement and adaptation to the evolving PtM landscape(IRENA, 2020).

4.2 Financial stability and economic viability

PtM projects are capital-intensive and often have long development and payback periods. Therefore, the financial health and stability of suppliers and partners are critical to mitigate project risks.

Supplier financial health: Developers should assess a supplier's financial standing through balance sheets, credit ratings, and market reputation to ensure they can fulfill contractual obligations, provide long-term support, and honor warranties(Suvvari & SAXENA, 2023).This is particularly important for critical, long-lead items like electrolyzers or specialized reactors.

Partner investment capacity: For strategic partners, especially in joint ventures or consortia, their ability and willingness to contribute capital, share financial risks, or facilitate access to project finance are key. Also, the project partners alignment with the project's long-term economic vision is essential.

Cost-effectiveness and value proposition: While upfront cost is a factor, the overall lifecycle cost (LCOM) and value proposition are more important(Madi et al., 2025). This includes operational efficiency, maintenance requirements, durability, and the potential for future upgrades. Suppliers offering competitive pricing without compromising quality or performance are preferred. Transparent pricing models and clear terms for after-sales service and spare parts are also important(Porter M.E, 1998).

4.3 Reliability, track record, and quality assurance

The nascent nature of some PtM technologies makes reliability and a proven track record particularly important.

Proven performance: Preference should be given to suppliers and partners with a documented history of delivering similar or related projects successfully. Case studies, client testimonials, and third-party verifications of performance claims are valuable(Arwadi et al., 2025). For newer technologies, evidence from pilot or demonstration projects is crucial.

Quality management systems: Robust quality assurance and quality control processes (e.g., ISO 9001 certification) indicate a commitment to delivering high-standard products and services. This reduces the risk of equipment failure and operational disruptions(Ogunniran et al., 2025).

Supply chain resilience: The ability of a supplier to manage their own supply chain effectively and ensure timely delivery of components, especially in a volatile global market, is critical to avoid project delays (Gobbo et al., 2018). Diversification of their own sourcing can be a positive indicator.

4.4 Strategic alignment and collaborative capability

For long-term projects like PtM, particularly when involving strategic partnerships rather than simple supplier-client relationships, alignment in vision and a strong collaborative spirit are indispensable.

Shared vision and goals: Partners should share the project developer's vision for sustainability, market development, and technological innovation. This ensures that strategic decisions are made cohesively(Falcone, 2023).

Collaborative approach: The ability to work constructively within a multi-stakeholder environment, share knowledge, and resolve challenges collaboratively is vital. This is especially true for SMEs who may rely more heavily on partner expertise(Ashraf et al., 2024).

Long-term commitment: PtM projects require a long-term perspective. Partners should demonstrate a commitment beyond the initial project phase, potentially including joint R&D, market development activities, or expansion plans(IRENA, 2020).

Cultural fit: While often overlooked, a good cultural fit between the project developer's team and the partner's organization can significantly enhance communication, trust, and overall project synergy(Adegboyega et al., 2024).

4.5 Risk management and mitigation capabilities

Given the inherent risks in novel energy projects, a partner or supplier's approach to risk management is a key selection criterion.

Proactive risk identification: Suppliers and partners should demonstrate a clear understanding of the potential technical, operational, and commercial risks associated with their offerings and the PtM project as a whole.

Mitigation strategies: Evidence of robust risk mitigation strategies, contingency plans, and performance guarantees can provide developers with greater confidence(Ogunniran et al., 2025). This includes addressing potential issues related to technology underperformance, supply chain disruptions, or fluctuating feedstock availability.

Contractual safeguards: Clear contractual terms regarding liabilities, warranties, performance guarantees, and dispute resolution mechanisms are essential to protect the project developer's interests(Suvvari & SAXENA, 2023).

4.6 Sustainability and local context considerations

As PtM is a cornerstone of the green transition, the sustainability credentials of suppliers and partners are increasingly important.

Environmental, Social, and Governance performance: Partners and suppliers with strong ESG policies and a demonstrable commitment to sustainable practices align better with the ethos of PtM projects(WORD ECONOMIC FORUM, 2023). This includes their own carbon footprint, ethical sourcing, and labor practices.

Local content and economic development: Particularly for projects like Koppö Energy in Finland, prioritizing suppliers and partners who can contribute to local economic development, utilize local supply chains, or provide local employment can be beneficial and align with national strategic goals. Energy storage methods utilizing methanol can be decentralized, but doing so requires inventing new process configurations. The reason is that such systems require less processing and operate with changing availability of hydrogen. This project’s main goal was to determine if new configurations for the PtMeOH process are economically feasible. It was suggested that for small-scale growth, the pressure should be controlled at 30 bar, to match an electrolyzer’s standard H2 delivery pressure. Small-scale systems cannot use a H2 compressor because it is costly and too complex. Since CO2 conversion is not possible in high temperature stages, several setups based on how the unconverted stream is processed were evaluated. In addition, the effects of coupling certain processes were examined. At high electricity prices, making methanol from renewable hydrogen was shown to be unprofitable in any setup because of how crucial the hydrogen cost was. Profit from recycling was only possible when electricity cost no more than 0.07 USD/kWh. Running PtMeOH together with biogas upgrading can permit cascade operation, with performance remaining strong from an economic point of view. For this reason, the small-scale PtMeOH process is possible only in situations where power rates are consistently low or if waste-handling facilities exist. Due to this research, we now know the key parameters essential for making the PtMeOH process economically valuable and pointing out when cleaner methanol production can be considered in the close future (Finnish Government Prime Minister’s Office, 2023). This also enhances social license to operate.

Regulatory compliance and familiarity: Suppliers and partners should have a thorough understanding of and compliance with relevant national and international regulations, standards, and certification schemes, especially those pertaining to renewable fuels and safety(PtX Hub, 2022).

In conclusion, the selection of suppliers and partners for PtM projects is a multi-criteria decision-making process that requires a holistic assessment. Project developers must balance technical requirements, economic considerations, risk factors, and strategic objectives. For SMEs, leveraging the strengths of carefully chosen partners can be a critical enabler for navigating the complexities of the PtM value chain and successfully bringing projects to fruition. A robust due diligence process, incorporating these criteria, will be fundamental to de-risking investments and maximizing the potential for success in this emerging industry.

5 SUMMARY AND CONCLUSIONS

This thesis investigated the key challenges and strategies in the development of PtM projects from the perspective of a project developer. The main findings indicate that the successful development of PtM projects requires navigating a complex landscape of technical, economic, regulatory, and market hurdles.

5.1 Addressing the research questions based on the study findings

Research question 1: What are the main challenges in implementing the PtM value chain from a project developer's perspective?

Findings indicate the primary challenges include high costs (CAPEX and OPEX), securing sustainable inputs (renewable electricity, CO2), policy and market uncertainties, and technical complexities related to system integration.

Research question 2: How do project developers tackle these challenges and catch the opportunity?

Effective strategies involve a combination of technical optimization, innovative financial models, long-term contracts, building strong value chain partnerships, and targeted policy support.

Research question 3: What are the criteria for choosing suppliers and partners for implementing the project?

Key criteria encompass technical expertise, reliability, financial stability, production capacity, long-term support, strategic alignment, and risk management capabilities.

Core challenges: The literature review and examination of challenges confirmed that high initial investment costs (especially for electrolyzers and CO2 capture units), the production cost of green methanol compared to fossil-based methanol, securing sustainable and affordable access to renewable electricity and CO2 sources, regulatory and policy uncertainties, and the development of stable markets for green methanol are among the most significant challenges. Furthermore, the technical maturity of certain components, the need for complex system integration, and managing the nascent value chains (green hydrogen and CO2) pose substantial technical and operational difficulties.

Importance of integrated strategies: Chapter 3 demonstrated that no single strategy alone can overcome these challenges. Instead, a combination of technical, financial, commercial, and policy solutions is required. Key strategies include process design optimization, selecting more mature and efficient technologies, innovative financing (e.g., blending public grants, venture capital, and project finance), securing long-term contracts for inputs (electricity, CO2) and outputs (methanol), developing new business models (such as selling carbon credits or grid services), and actively engaging with policymakers to establish supportive and stable frameworks.

Critical role of partner selection: The analysis presented in Chapter 4 underscored that careful supplier and partner selection is a fundamental strategy for risk mitigation and enhancing the probability of project success. Technical capabilities, financial stability, experience, strategic alignment, and the ability for long-term collaboration are crucial criteria in this selection. The ability to build a strong ecosystem of partners along the value chain (Franco, 2025)is essential for overcoming the complex and high-risk nature of PtM projects.

The Finnish context: Considering the context of Finland, the country possesses significant potential for PtM development due to its access to renewable energy resources (especially wind), a stable power grid, existing industrial infrastructure (which can be a source of CO2 or use methanol), and a strong commitment to decarbonization goals. However, challenges such as cost competitiveness compared to other regions, the need to develop hydrogen and CO2 infrastructure, and specific regulatory frameworks for PtX still exist. Successful strategies in Finland must leverage these advantages while proactively addressing these challenges.

5.2 Conclusions

PtM projects hold significant potential to contribute to the decarbonization of energy-intensive sectors like transportation especially maritime and the chemical industry, as well as aiding the integration of variable renewable energy sources. However, the development of these projects is associated with a considerable set of technical, economic, and market challenges that demand strategic and innovative approaches from developers.

This thesis has shown that overcoming these challenges requires a deep understanding of the entire value chain, from renewable electricity generation to the final consumption of methanol. Successful strategies must integrate technical aspects, financial considerations (capital raising and cost management), commercial elements, and regulatory dimensions (engaging with policymakers). Central to this is the establishment of strong partnerships and the careful selection of suppliers and partners based on technical, financial, and strategic criteria, playing a pivotal role in mitigating risks and ensuring long-term project success.

Despite the challenges, the outlook for PtM, particularly in regions like Finland with high renewable energy potential, is promising. Scaling up production, continuous technological advancements, and the creation of supportive policy frameworks can contribute to cost reductions and accelerate the deployment of this key technology in the move towards a sustainable future.

5.2.1 Recommendations for project developers

Based on the analysis, the following recommendations are offered to project developers, particularly SMEs, venturing into the PtM space:

Prioritize strategic partnerships: Actively seek and cultivate strong partnerships with technology providers, EPC contractors, offtakers, and financial institutions. Emphasize alignment in vision, technical competence, and risk-sharing capabilities.

Adopt a phased development approach: Start with thorough feasibility studies, followed by pilot or demonstration projects to validate technology and operational concepts before committing to full-scale commercial plants. This mitigates risk and allows for learning.

Focus on niche markets and offtake agreements: Identify early adopters and secure long-term offtake agreements, even if at an initial premium, to ensure revenue stability and project bankability. The maritime sector presents a significant near-term opportunity.

Embrace technological flexibility and innovation: Design plants for operational flexibility to accommodate variable renewable energy. Stay abreast of technological advancements in electrolysis, CCU, and synthesis to integrate cost-effective and efficient solutions.

Engage proactively with policymakers and regulators: Advocate for well-defined, reliable, and enabling regulatory structures and supportive policy, including carbon pricing, subsidies, and streamlined permitting processes. Contribute to the development of standards and certifications for e-methanol.

Conduct rigorous Techno-Economic assessments: Continuously refine economic models, considering sensitivities to electricity prices, CO_2 costs, and technological improvements. Optimize for Levelized Cost of Methanol (LCOM).

Leverage local strengths and synergies: In contexts like Finland, explore synergies with existing industrial infrastructure (for CO_2 or heat integration) and align with national climate and energy strategies to garner support.

5.2.2 Limitations and suggestions for future research

From the perspective of project developers, the PtM value chain and project execution encounter a number of obstacles that call for creative and smart solutions. Technical barriers to the scalability of production and capture technologies, economic uncertainty brought on by shifting markets and unclear regulations, logistical difficulties, and the sustainable supply of raw materials like CO2 and green hydrogen are some of these difficulties. Developers must carry out in-depth risk assessments, form strategic alliances with providers of scalable and proven technologies (who can offer reliable proof of performance at the necessary scale), and actively work with legislators to create supportive frameworks in order to get past these obstacles and take advantage of the opportunities in this developing field. Suppliers and partners are frequently selected based on a variety of factors, such as their extensive knowledge of pertinent technology, track record of success in related projects, capacity to deliver trustworthy performance data, and dedication to sustainability and innovation. Future research could concentrate on value chain and logistics modeling, quantitative and qualitative evaluation of the effects of various policies, target market dynamics and obstacles to the adoption of green methanol, and the creation of more thorough risk analysis frameworks associated with these projects in order to enhance our understanding of PtM project development.

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