WP2 TASK 2

# Optimal national and international infrastructures

## ABSTRACT

Task 2.2 had three main research questions: RQ1 (infrastructure): Identify the to be considered infrastructures and required datasets for power-to-X (PtX) product value chain optimisation. Analyse the required infrastructures to deliver the onsite PtX products to any other target site. Investigate the development of the infrastructure requirements over time. RQ2 (cost structures): Obtain the optimised cost structures of PtX products at any generic onshore site globally. Analyse the key structure elements of the global value chain for PtX products and the associated infrastructures. RQ3 (energy system integration): Identify the PtX product costs influenced in sector coupled energy systems versus de-coupled greenfield developments. The focus of RQ1 and RQ2 has been laid on e-hydrogen, e-ammonia, and e-methanol to capture pure hydrogen, carbon-free e-fuels and e-hydrocarbons for a broad variety of infrastructure analyses. RQ3 has been conducted on the case of Greenland (wind-based exporter) and Egypt (solar-based exporter), while respective research for Finland has not been allocated to this task. Main findings indicate that e-hydrogen shall be transported only for short distances of not more than a few hundreds of kilometres. e-Ammonia and e-methanol are best transported via ships beyond a few hundreds of kilometres. Excellent wind and solar resources emerge as the basis for e-fuels and e-chemicals exports, while in the short-term excellent wind sites are more attractive, then substituted by excellent solar sites. For production of e-methanol within Finland $CO_2$ pipelines are the lowest cost transport option and the power grids being the second, while power grids may be the more valuable infrastructure. Several new research questions have been identified for follow-up research. In total, eight scientific articles have been prepared as part of this task.

## MOTIVATION

PtX products represent a large fraction of final energy and non-energy use demand and require considerable infrastructure which partly has to be newly built. As the energy transition is ongoing and infrastructure projects require years to be realised an as early as possible investigation of the needs and challenges ahead is essential for proper planning and stakeholder discourse. Finland may be in the role of remaining an energy importer, with good chances to emerge at least a high degree of energy sovereignty with respective self-supply, and even PX export opportunities will arise. That requires the investigation of these fundamental archetypes.

## RESULTS

### Findings for infrastructure fundamentals for e-hydrogen, e-ammonia, e-methanol

Widely available and low-cost solar photovoltaics and wind power can enable production of renewable electricity-based **hydrogen** at many locations throughout the world. Hydrogen is expected to emerge as an important energy carrier constituting some of the final energy demand; however, its most important role will be as feedstock for further processing to e-fuels, e-chemicals, and e-steel. Apart from meeting their own hydrogen demand, countries may have opportunities to export hydrogen to countries with area limitations or higher production costs. It was assessed the feasibility of e-hydrogen imports to Germany and Finland from two case regions with a high availability of low-cost renewable electricity, Chile and Morocco, in comparison to domestic supply. Special attention was paid to the transport infrastructure, which has a crucial impact on the economic viability of imports via two routes, shipping and pipelines.

This study has found that despite lower e-hydrogen production costs in Morocco and Chile compared to Germany and Finland, additional transportation costs make imports of e-hydrogen economically unattractive (see Figure 1). In early 2020s, imported fuel costs are 39–79% and 34–100% higher than e-hydrogen produced in Germany and Finland, respectively. In 2050, imported e-hydrogen is projected to be 39–70% more expensive than locally produced e-hydrogen in Germany and 43–54% in the case of Finland. e-Hydrogen may become a fuel that is mostly produced domestically and may be feasible for imports only in specific locations. Local e-hydrogen production may also lower dependence on imports, enhance energy security, and add jobs.

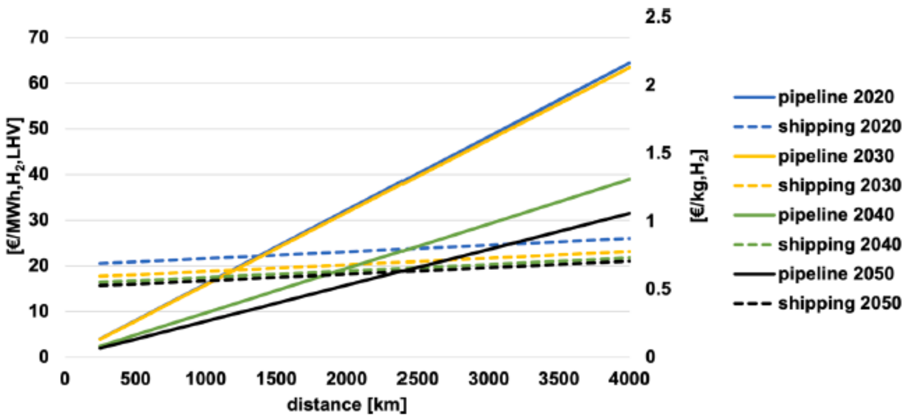
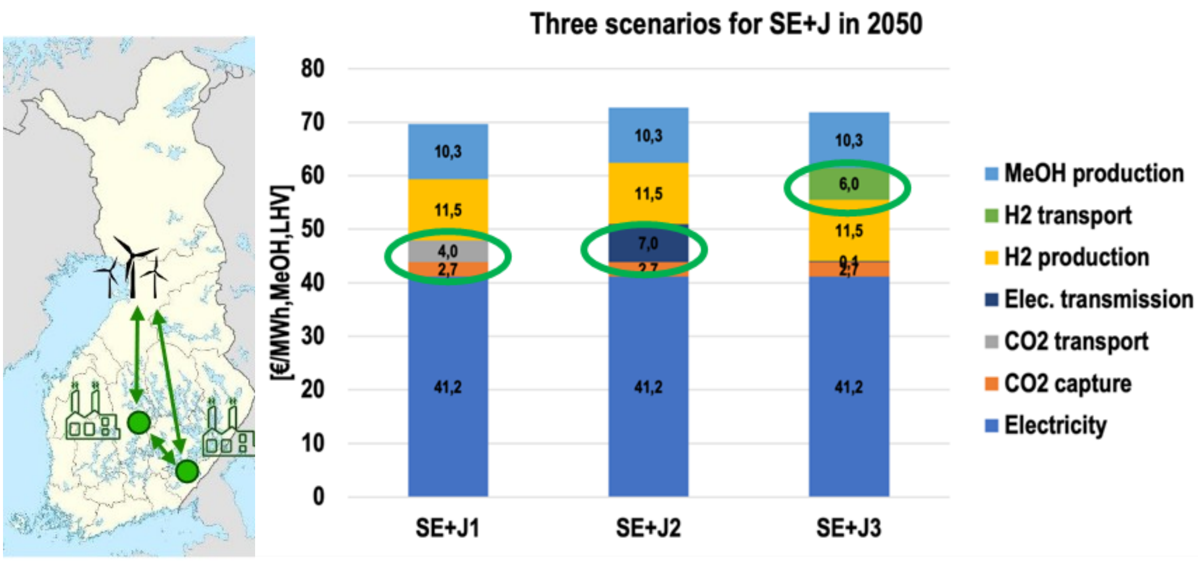



**Figure 1. Cost comparison of two hydrogen transportation options via pipeline and shipping in 2030, 2040, and 2050 for distances up to 4000 km.**

**Ammonia** is a key chemical for the agriculture and chemical industries, and a potential future marine fuel. Potential growth in ammonia demand further highlights the importance of ammonia production defossilisation to comply with climate goals. Widely available renewable resources and declining costs of solar photovoltaics and wind power enable the production of green e-ammonia at many locations and potential exports to countries with less optimal resources and other restrictions. It was compared the cost of imported e-ammonia to Germany, Finland, and Spain from regions with excellent renewable resources, Morocco and Chile, to the cost of local production, and to quantify potential economic savings due to trading. Transportation costs are calculated with techno-economic parameters reported in detail in the scientific publications (see e.g., Galimova et al., 2023a) to assess their impact on final import costs, and to allow comparison of shipping costs to pipeline transmission costs over various distances. Pipeline imports from Morocco were found to be significantly higher in cost compared to imports by sea from Chile and Morocco or local production. Imports from Chile were found to be economically feasible for Germany and Finland, with import costs 10–33% lower than domestic e-ammonia production in 2030–2050. Imports to Spain may be attractive in 2030s, but, after 2040, local solar resources enable local e-ammonia production costs at the same or lower cost as imported e-ammonia. Ammonia trading in the future may depend on access to the sea. Other factors such as creation of jobs, additional revenues, and energy security concerns may also impact e-ammonia trade.

**Methanol**, a key chemical industry feedstock, is expected to have an important role in high value chemicals production and as a clean maritime fuel. Renewable electricity-based methanol or e-methanol may be crucial for defossilisation of hard-to-abate sectors and to address climate change. It was examined the cost competitiveness of e-methanol production in solar-rich regions of Morocco and Chile compared to representative European countries of Germany, Finland, and Spain. Domestic European production costs were assessed against those from potentially exporting regions. Detailed analysis of pipeline and shipping costs was conducted to evaluate their impact on final import costs. Results indicate that Germany may benefit from imports from Morocco and Chile with 4–14% and 15–22% lower in cost in 2050, respectively. Finland can achieve cost reductions of up to 26% in 2030 and up to 37% in 2050 with imports. Spain, with its abundant solar resources, may not benefit from pipeline imports from Morocco, but can achieve 5–15% savings in 2030–2050 if e-methanol is imported by sea from Chile or Morocco. Shipping is found to be more advantageous for e-methanol trading than pipeline. Other factors such as energy security, tax revenues, and job creation should also be considered by potential importers.

Renewable electricity-based **methanol** is increasingly important for reducing the emissions of hard-to-abate sectors such as the chemical industry and long-range shipping. The main challenge with sustainable methanol, however, is the **supply of sustainable $CO_2$**. While point source $CO_2$ is cost-effective, it is not widely available. Availability of $CO_2$ raises the question of the optimal e-methanol production locations in case $CO_2$ point source and the best low-cost renewable electricity sites are located far apart. It was compared the relative transportation costs of electricity, hydrogen, and $CO_2$ to determine the **best methanol synthesis location** for the case of Finland, all based on new investments due to utilised existing capacities (see the Figure 2). The results show that transporting $CO_2$ to an electricity generation site for methanol synthesis is the lowest cost option for all years and scenarios. The cost difference across scenarios is initially limited, with methanol produced with electricity or hydrogen transported to a $CO_2$ source being 3-13% more expensive in 2030, but the difference rises to 5-15% in 2050, as the share of energy cost declines while the transportation infrastructure cost share gets more pronounced. Despite lower costs for $CO_2$ transportation, the slightly higher costs for power lines may be justified due to the higher flexibility and more diverse use cases. In addition to costs, other factors must be considered as well, such as safety, societal acceptance, long-term fuel demand, availability of input materials, and the risk of stranded assets. Moreover, municipalities that expedite regulatory approval could benefit from investments, additional revenues, and job creation.




A) B)

**Figure 2. A) Location of resources and transportation options B) Breakdown of projected e-methanol cost in 2050 in Finland. The transport cost share is displayed within a green circle. Abbreviations: SE – Southeast Finland, J – Jyväskylä; indicating different investigated cases.**

### Findings for energy system implications of e-fuels exports: Cases Greenland and Egypt

Climate change-driven temperature rise in the Arctic has been shown to increase faster than on global average, heavily affecting **Greenland**'s environment. Rich wind resources complementary with solar resources may enable a transition to a sustainable and selfsufficient energy system. Greenland's transition from a fossil fuels-based system to a 100% renewable energy system between 2019 and 2050 and its position as a potential e-fuels and e-chemicals production hub for Europe, Japan, and South Korea, has been investigated. Importing regions, such as Europe and East Asia, can benefit from some of the lowest-cost energy carriers in the world in 2030, and these energy carriers will continue to have a low-cost level in 2050. It was estimated that the production and export of e-fuels and e-chemicals would require up to 300,000 workers for construction and operations. Renewable energy enables a full defossilisation of Greenland's energy system, enhances energy security, and provides opportunities for additional export revenues.

Transitioning to renewable energy to mitigate climate change requires solutions for hard-to-abate energy sectors. It was investigated the techno-economic impacts of offering e-fuels and e-chemicals exports on an exporting country's energy system as it transitions to renewable energy by 2050. **Egypt** is used as a representative case study for sunbelt countries with adequate land area. Four scenarios with different system configurations have been investigated using the LUT Energy System Transition Model and compared to a reference domestic renewable energy system. The results show that Egypt can technically provide 10% of Europe's demand for e-fuels and e-chemicals starting from 2025 within land use constraints. The provision of e-fuels and e-chemicals exports enhances the domestic energy system performance by reducing the levelised costs of important feedstocks, carbon dioxide and hydrogen, as well as other domestic cost metrics and system losses. These findings are extendable and relevant to similar sunbelt countries. They are also relevant to European countries looking to fulfil their climate targets while diversify their energy imports sources.

## APPLICATIONS/IMPACT

The findings clearly indicate that infrastructure challenges have to be considered right in time. Hydrogen transportation via pipelines up to a few hundreds of kilometres is well doable, while longer distances lead to quite high costs and also hydrogen shipping lacks economic attractiveness. Ammonia and methanol transportation up to a few hundreds of kilometres is attractive with pipelines and thousands of kilometres via ships induces comparably low cost.

In conclusion, hydrogen shall be exported in form of its products. In case of differing locations for electricity and $CO_2$ for e-hydrocarbons a differentiated assessment is required as total costs are close, with $CO_2$ transportation the least cost whereas electricity transmission may be more flexible. Exports of e-fuels and e-chemicals most likely starts in regions of excellent wind resources and in 2030s sites with excellent solar resources may gain ground in exports. Domestic energy systems benefit in lower overall energy system costs from e-fuels and e-chemicals export due to scaling, flexibility, and good system integration options.

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