WP6 TASK 6.1 and 6.2

Environmental and economic feasibility of PtX value chains

Report is combining T6.1 Possibilities and risks arising from climate issues and T6.2 Regulatory and financial risks threatening business

ABSTRACT

Tasks 6.1 and 6.2 had altogether three main research questions: (1) Does a product chain reduce greenhouse gas (GHG) emissions in a system level integrated to the existing infrastructure and how much studied product chain produces GHG emissions compared to its alternatives, (2) How cost effective it is to reduce GHG emissions by investing Power-to-X (PtX) solutions, and (3) How regulatory and financial risks threatens business? Most of the analyses were carried out in collaboration with HYGCEL WP1, WP3 and WP4.

The impact of electricity sources along with the different technological solutions, such as type of electrolyzers, H_2 delivery options and synthesis processes, and a possibility to reduce emissions compared to conventional fossil-based products were investigated using literature and life cycle assessment (LCA) as a method (question 1). Also cost efficiencies of value chains were evaluated by analysing H_2 delivery options (question 2). To reveal how the environmental and economic feasibilities of PtX value chains behaves in a system involving stricter criteria for renewable fuels of non-biological origin (RFNOB) (in practice H_2 production utilising temporal and regional renewable energy), a dynamic modelling with LCA and life cycle costing (LCC) was conducted from differently designed PtMethanol value chains (questions 1 and 3).

Results indicate that PtX value chains can provide extensive emission savings, which quantity is depending on end-product how the product is utilized (i.e., what it replaces). Green H2 results to least climate impacts as compared to blue H_2, turquoise H_2, and grey H_2. Carbon capture and utilization (CCU) applications cannot provide as extensive emission savings than green steel, e-ammonia* or green H_2. Green steel value chain was identified to provide the most emission savings. Notably, most of the investigated renewable based PtX solution can

provide up to 90% emission savings compared to their fossil-based reference products. When thinking emission savings from Finland's perspective, the quantity of consumable PtX products influence on overall emission savings. Finland can become an enabler for other regions climate targets, when exporting low-carbon products. In this case, Finland can gain "positive handprint" by providing low-carbon alternatives.

When evaluating H_2 transportation options, the H_2 pipeline transportation and on-site H2 production resulted to be the most feasible options compared to H_2 shipping or converting H_2 to e-methane and then back to H_2.

When evaluating the emission reduction costs and economic risks, H_2 production is the key factor determining the risks and costs in PtX value chain due to high CAPEX and OPEX costs. OPEX is mainly determined by electricity requirement to produce H_2. Because of these characteristics it seems to be difficult for a H_2 provider to achieve economic feasibility as an independent actor. To bring the H_2 production costs down, the price of electricity needs to be feasible, weighted average cost of capital should be low and or the provider needs investment subsidies. The predicted cost reductions of investments will also reduce the CAPEX related costs in the long or medium term. Due to high CAPEX costs, it can be reasonable to phase the investments to reduce economic risks. However, phasing the investments means that some of the emissions reductions are postponed compared to heavy one-time investment. For these results, see also results from HYGCEL WP1T3b.

* e-ammonia value chain can become CCU application, when refining ammonia to urea

MOTIVATION

Climate mitigation is one of the biggest reasons for the transition towards PtX economy. Green H_2 and its derivates have been shown to achieve greenhouse gas emission savings. However, to be truly sustainable the transition needs to be socially and economically feasible while being able to mitigate environmental and risks. For this it is important to identify which PtX value chains can achieve the highest emission savings and what are the "hotspots" for achieving economic feasibility. By knowing this it is possible to reach carbon neutrality while getting the most benefits out of this transition. Operational risks are discussed separately in HYGCEL WP6 task report 6.3.

RESULTS

Climate impacts of hydrogen production and delivery

An LCA study was made to compare climate impacts of different (differently produced) hydrogen. The investigated H_2 value chains were grey hydrogen, blue hydrogen, turquoise hydrogen (without carbon sequestration) and green hydrogen. The results (Figure 1) show that green hydrogen can achieve the lowest emissions per kg H_2 from the investigated value chains.

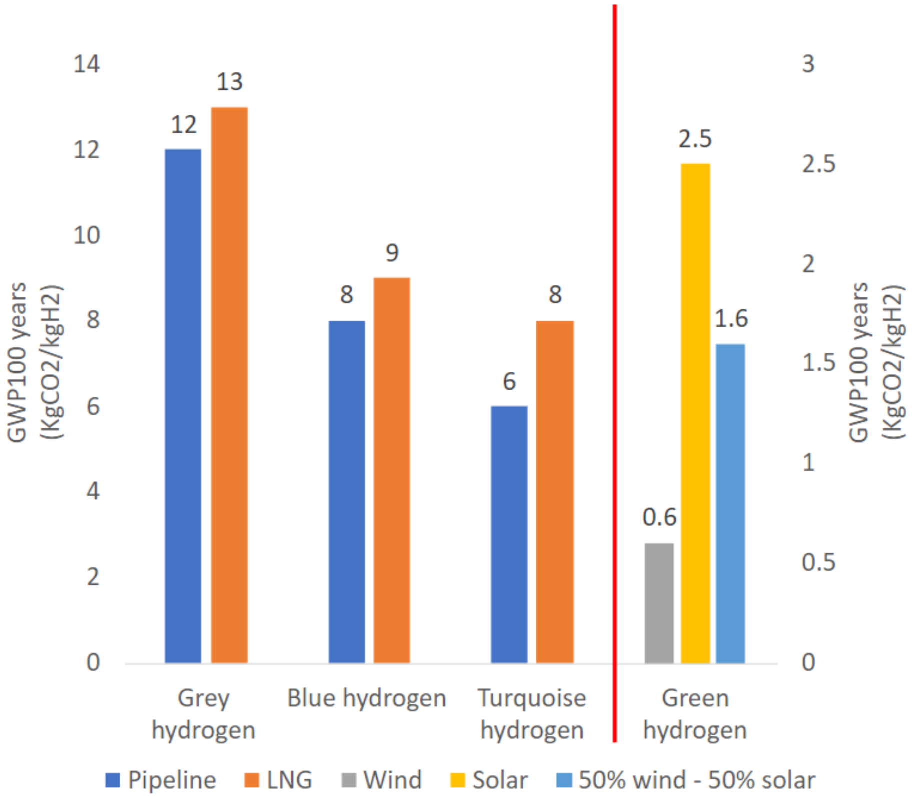

Figure 1. LCA results of examined hydrogen production technologies. Please note the different scales in left and in right.

Another LCA study was made to assess the climate impacts of green H_2 production by comparing different means to deliver hydrogen or its carriers. The investigated cases were **on-**

site H_2 production (case 1), **H_2 pipeline distribution** (case 2 and 4), **H_2 shipping** (case 5) and **H_2 conversion to e-methane and back to H_2** (case 3) (Figure 2). The study involved a possibility to utilize waste heat from electrolyzers for local district heating network.

It was shown that on-site H_2 production via electrolysis and H2 pipeline delivery resulted to least emissions. Shipping option caused the most emissions and conversion to e-methane and back to H_2 the second most. Interestingly, if the CO_2 from thermal decomposition of methane (TDM) process is sequestered cand acts as a sink, the method can result to carbon negative way to deliver H_2. For these results, see also HYGCEL WP3T1 report.

The utilization possibility of local district heating network was studied in different locations as different locations can have different district heat carbon intensity depending on its production method. Substituting district heating heat with waste heat from electrolyzers can sometimes result in substantial amounts of avoided emissions.

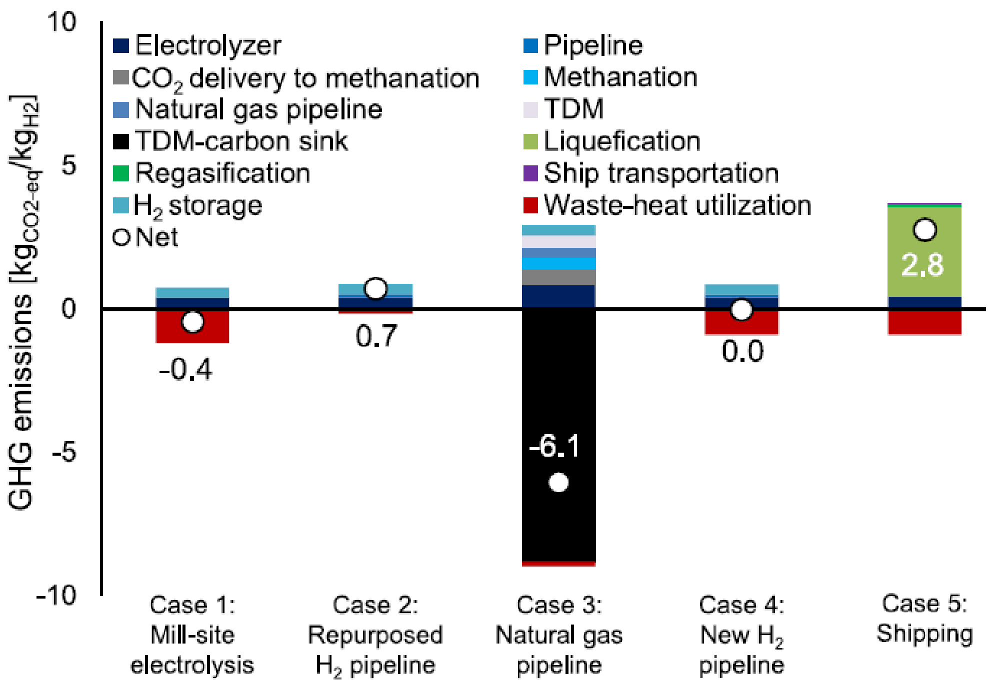

Figure 2. LCA results of H2 distribution methods.

Climate impacts of PtX value chains

The literature review was made on LCA studies to find out the climate impact of different PtX value chains. The study showed that when utilizing 1 kg renewable or nuclear based hydrogen, all the investigate PtX value chains can achieve up to 90% emission reduction as compared to their fossil-based reference products. The type of a reference product had a great impact on the magnitude of savings. (Table 1). PtSteel, PtAmmonia, PtHydrogen and PtFood can achieve the highest emission savings. From CCU pathways, PtMethanol and PtFuels seem to be the best performing value chains in terms of climate mitigation potentials. Power-to-Methane resulted to have the least emission saving potential. The literature review also revealed that typically e-fuels burns cleaner than fossil fuels, thus reducing outdoor air pollutants, such as NOx or particulate matter emissions, in addition to GHG emissions.

Table 1. Impact reduction potentials of different PtX pathways per 1 kg of H2 when using RE or nuclear to power H2 production

Ptx Value chain	H_2-required	Unit	Reference products	MIN, MAX [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]	MEAN [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]
PtHydrogen	1	kg_{H2}	H_2 From SMR; coal gasification	5.68–24.96	9.61; 22.96
PtSteel	0.051–0.059	kg_{H2}/kg_{Steel}	BF-BOF production route	21.4–38.96	31.97
Partial hydrogen injection	0.025	kg_{H2}/kg_{Steel}	BF-BOF production route	10.28–12.8	11.54
PtAmmonia	0.18–0.19	kg_{H2}/kg_{NH3}	Ammonia from natural gas	4.09–15.14	11.33
PtMethane	0.46–0.50	kg_{H2}/kg_{CH4}	Natural gas	1.28–6.8	3.91
Biogas upgrading	0.17–0.19	kg_{H2}/kg_{CH4}	Natural gas	9.52–15.35	12.43
PtSyngas	0.126	kg_{H2}/kg_{Syngas}	Syngas from natural gas or from coal	No reduction potential – 16.2	0.91; 8.11
PtMethanol	0.19–0.34	kg_{H2}/kg_{CH3OH}	Methanol from natural gas or coal	No reduction potential – 22.88	3.33; 8.92
PtFuel					
PtDiesel	0.30–0.64	kg_{H2}/kg_{Diesel}	Diesel	1.76–30.93	9.75
PtGasoline	0.48–0.64	$kg_{H2}/kg_{Gasoline}$	Gasoline	2.06–6.71	5.69
PtDME	0.23	kg_{H2}/kg_{DME}	Diesel (based on MJ)	5.03–8.49	6.37
PtJetfuel	0.20–0.64	$kg_{H2}/kg_{Kerosine}$	Kerosine	4.55–16,62	8.41
PtMethanol	0.22	kg_{H2}/kg_{CH3OH}	Diesel or Gasoline (based on MJ)	No reduction potential – 8.30	3.15
PtPlastics	0.50–0.58	$kg_{H2}/kg_{Plastics}$	Polypropylene from	No reduction	2.46

* Several different protein sources are present; thus, calculating the mean value is unreasonable. The reduction potential is highly dependent on what is substituted. Animal based protein sources can achieve the highest emission savings.

Reducing climate impacts versus timing the investments

The potential conflicts in investment timing from financial perspective and from climate perspective was studied using e-methanol production value chains as an example. The study was defined as follows; cumulative emission savings from 30-year timeline; different electricity prices and CO_2 sources; impact of H_2 leakage; avoided emissions due to waste heat utilization; value chains designed according to RFNOB criteria (temporal and regional renewable production). Dynamic modelling (Calliope) optimizing the PtMethanol infrastructure was applied.

The studied value chains:

- Case1: Point source of CO_2 using monoethanolamine technology (MEA) technology
    - A big one-time investment (750 MW electrolyzer)
    - Phased investments (first 150 MW electrolyzer is invested and after 10 years the capacity is increased to 750 MW)
- Case2: CO_2 from ambient air using direct air capture (DAC) technology
    - A big one-time investment (750 MW electrolyzer)
    - Phased investments (first 150 MW electrolyzer is invested and after 10 years the capacity is increased to 750 MW)

Optimisation results (Table 2) indicate that the cheaper the electricity price is the more e-methanol is produced resulting to higher cumulative emission reduction. However, the change is not significant. Similarly, the source of CO2 slightly affected the results: more e-methanol can be produced using direct air capture (DAC) instead of point-source utilisation (MEA) resulting in higher cumulative emission reduction.

The big one-time investment causes more cumulative emission savings compared to investing in phases: when comparing the lifetime emissions of produced e-methanol to natural gas derived fossil methanol production, the e-methanol causes 87% to 91% less GHG emissions. The DAC value chain can result in better cumulative emission reduction compared to MEA due to higher production quantities, but MEA value chain can achieve higher emission saving per produced kg of e-methanol, because less energy is required for capturing CO2 compared to DAC. H_2 leakage was found to cause approximately 0.5% to 0.7% from total emissions in e-methanol value chains, which is not a determining factor for environmental feasibility. Green H_2 production and compression were the most determining factors impacting to total GHG emissions. The avoided emissions through waste heat utilization can further decrease the system level emissions.

Table 2. Cumulative emission reductions during 30-year operation without waste heat utilization. Normal, low and lowlow means electricity prices for renewable energy generation. Case 1 investigates MEA application as a carbon capture technology and Case 2 utilizes DAC (results under review process).

	Case 1			Case 2
System boundary	Normal	Low	Lowlow	Low
Emission reduction (Cradle-to-Gate)				
One-time Investment [$Mt_{CO2\text{-}eq}$/30y]	-5,8	-6,2	-6,7	-6,5
Investing in phases [$Mt_{CO2\text{-}eq}$/30y]	-4,0	-4,2	-4,6	-4,2
Emission reduction (End use)				
One-time Investment [$Mt_{CO2\text{-}eq}$/30y]	-19,1	-20,2	-21,9	-23,3
Investing in phases [$Mt_{CO2\text{-}eq}$/30y]	-13,3	-14,0	-15,0	-15,3

A complementary study was made to investigate how much GHG emission savings can be achieved in Finland (domestic consumption) and outside of Finland (export), if Finlandutilizes 68.5 TWh of renewable electricity to H_2 production and utilizes it one at one time to produce different PtX products (article related to this is in a review process at the time of writing). The amount available electricity for H_2 production was based on a scenario provided by Transmission System Operators, TSOs, Fingrid and Gasgrid[1], as part of HYGCEL project.

The relative emission reductions per used kg of H_2 among different PtX value chains behaves similarly than the results in Table 1 (relative emissions per kg of product). However, the production and consumption quantities of different PtX products determines the total amount of emission reduction. For instance, fossil-based ammonia is consumed roughly 200kt in Finland in a year, but the total e-ammonia production potential far exceeds the domestic needs (Figure 3). This means that the most consumption-based emission reductions would realise outside of Finland. Interestingly, the current available biogenic CO_2 sources in Finland did not become a limiting factor for PtX value chains in this study. However, this changes if there is more available green H_2 to be used for CCU applications or some currently produced biogenic CO_2 sources will be disabled. Depending on whether the target is to achieve domestic carbon neutrality or to maximize global emission reduction potential, PtX value chains should be constructed differently.

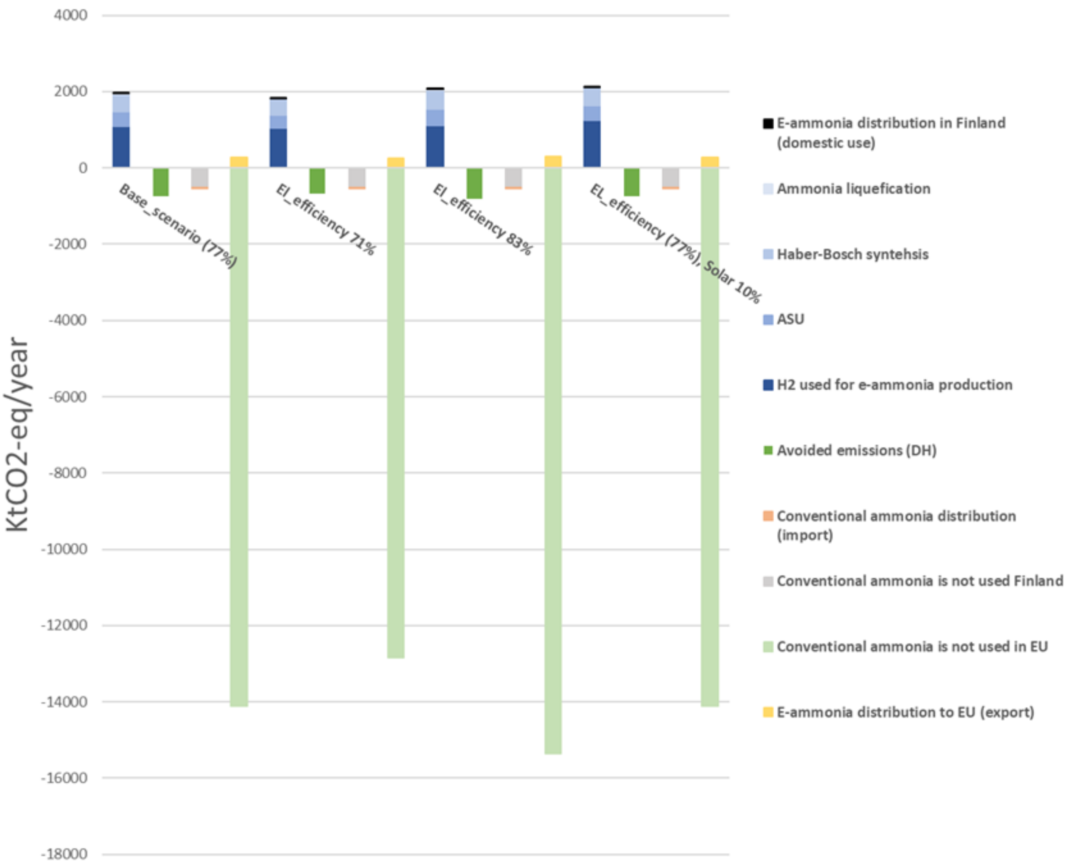

Figure 3. Comparison (LCA) of climate impacts of e-ammonia production and consumption substituting conventional ammonia within Finland (blue, dark green and grey bars) and outside Finland (light green and yellow bars)

Cost of GHG emissions savings and economic hotspots

The economic feasibility of PtX projects is important in achieving the climate goals. The most determining factor of economic feasibility in PtX value chains is H_2 production due to high CAPEX and OPEX costs. Those are expected to be lower in future. For example, electrolyzer CAPEXs are estimated to reduce even 60%, which then would significantly reduce the overall costs of a PtX value chain. However, the cost reduction is dependent on many factors and is uncertain. For instance, recently the electrolyzer prices have gone up instead of going down. Another factor having a major impact on economic feasibility is the cost of capital. One-time investments are capital intensive, and the economic risk is high. Overall, the high interest rates have slowed down the phase of energy transition. In addition to high CAPEX costs, green H_2 production is an energy intensive process. Thus, the electricity price has the most impact to the price of H_2 and to the price of final product.

The previously discussed e-methanol value chain study revealed that when compared to fossil-based methanol, the e-methanol value chain can become feasible without subsidies, when the price (of a fossil-based-) product is high, and electricity price is 27 €/MWh but requires money transfer along the value chain or some actors in the value chain need subsidies. One option is that one entity owns the H_2 and synthesis facilities, because the potential premium from the green product more clearly benefits the whole manufacturing chain. But then again, due to the capital intensity of these value chains, the economic risk for that entity would increase. For these results, see also HYGCEL W1T1.3b task results.

H_2 delivery methods affects to cost of delivered H_2. The cost analysis made for H_2 distribution methods revealed that conversion processes reduce economic feasibility. However, the cost of H_2 delivery is case dependent, thus no straightforward conclusion can be made from the analysis. For instance, the distance of H_2 delivery affects the order of preference. The TDM process provided additional benefits in the form of emission savings due to the possibility to use sequestered carbon as a carbon sink (Figure 2). However, the option was the least appealing method from an economic point of view. The shipping option was also found infeasible. Compared to on-site H_2 production or H_2 pipeline delivery, the price of H_2 increased 1.5 € to 5 € per kg H_2 for shipping and TDM option, respectively. However, it should be kept in mind that the investigation used fixed prices for electricity, which was 40 €/MWh. For more information, see HYGCEL WP3T1 task results.

With current fossil-based product costs, it will be a challenge for a PtX value chain to achieve economic feasibility. However, the gap between the cost of fossil-based products and PtX products is expected to narrow due to tightening regulations. For instance, the price of carbon permits is expected to be applied also in the transportation sector. However, the regulation development is dependent on politics, which is uncertain.

APPLICATIONS/IMPACT

The results indicate that properly designed PtX economy can not only help to achieve carbon neutrality targets in Finland and generate export products but also help other regions to achieve their targets. The environmental evaluations have shown that benefits from the transition are highly depended on how the H_2 is utilized in a value chain. For instance, e-methanol and green steel can achieve higher emission reductions than e-methane. The results also reveal that it will be a challenge for a H_2 provider to reach economic feasibility. Finland should focus on those PtX value chains achieving the highest emission reductions and produces the most economic added value. Based on the economic evaluation there is a need for public support, low-cost capital, cost reduction development and/or regulatory changes to start the transition, because with the current prices most of the PtX value chains cannot compete against fossil-based ones. PtX economy is in its starting phase, thus, there is still time to make smart decisions to obtain most of the benefits of it.

MAIN CONTACT

Jani Sillman, LUT, School of Energy Systems, jani.sillman@lut.fi

AUTHORS

WP6 authors: Jani Sillman, Husain Patel, Rami Alfasfos, Jouni Havukainen, Risto Soukka

Other authors: Satu Lipiäinen, Jaakko Hyypiä, Antti Ylä-Kujala, Nashmin Elyasi, Miro Lilja, Vesa Ruuskanen, Emma Laasonen, Lauri Leppäkoski, Hannu Karjunen, Ville Uusitalo, Esa Vakkilainen, Mari Tuomaala

REFERENCES

[1] Fingrid & Gasgrid. 2023. Energy transmission infrastructures as enablers of hydrogen economy and clean energy systems- Scenarios: Scenarios of the joint project between Fingrid and Gasgrid Finland. Web-document: https://www.fingrid.fi/globalassets/dokumentit/en/news/gasgrid-fingrid-hydrogen-economy-scenarios-5-2023.pdf [accessed 17.12.2024]