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Power-to-X in Norway

Project Report

University of California, Davis

Path to Net Zero Energy

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Project background

This work conducted a preliminary examination of Power-to-X (PtX) pathways in Norway. PtX refers to the process of turning renewable electricity into carbon-neutral fuels, such as hydrogen or ammonia. Our client - Dr. Iva Skov, representing Aalborg University in Denmark - has requested this research to set up pre-work for a future analysis of PtX pathways and possibilities in Norway. Specifically, our client requested that we acquire data for Norwegian PtX modeling software. While this was a key component of our research, we developed two additional analyses to further explore PtX implications in Norway. These sub-studies included a sectoral financial analysis of hydrogen pathways in Norway, and a geospatial analysis of current and planned PtX sites. Our findings will aid Dr. Skov in future PtX research endeavors and offer critical considerations for sector-wide PtX integration before widespread technological adoption.

PtX becomes a critical consideration when discussing Norway's decarbonization agenda. The country aims to cut emissions by at least 55 % compared to 1990's emissions by 2030. This is consistent with pursuing its commitments under the Paris Agreement and with the EU's Fit-for-55 policy (Government.no, 2022). The country also aims to become a low-carbon society by reducing its 2050 emissions 90-95% below the 1990 baseline. Norway's linkages to EU climate policy extend to its alignment with the bloc's climate legislation for 2021-2030 and the EU Emissions Trading Scheme (ETS). The ETS covers industrial plants, power plants, the petroleum industry, and commercial aviation (IEA, 2022). A carbon tax of approximately 766 NOK/tCO_2e acts as the market-based carbon reduction incentive for sectors not covered by the ETS, such as agriculture, buildings, and transport (Statistics Norway, 2020; IEA, 2022). The Norwegian government has also announced a separate target to cut emissions 40% below 2005 levels in these non-ETS sectors. In the face of increasingly stringent financial penalties and government targets on GHG emissions, key sectors of the Norwegian economy will turn to pre-existing and prospective decarbonization solutions such as PtX. This will be particularly relevant to sectors and processes that are difficult to decarbonize using commercially deployed solutions.

Literature review

PtX is a prospective technology that can create viable substitutes for fossil fuels in hard-to-abate sectors like energy-intensive industries, heavy-duty transport, and aviation (Ridjan et al., 2016; Eggers et al., 2023). The requirement of energy-dense fuels in these sectors makes it hard to decarbonize them directly with renewable power-driven electrification. Thus, it makes a case for carbon-neutral and energy-dense fuels as substitutes for fossil fuels (Skov & Schneider, 2022). All PtX fuel pathways involve hydrogen production through water electrolysis, followed by combining hydrogen with carbon or nitrogen to make methanol, methane, or ammonia (Skov et al., 2021). The conversion of renewable electricity into hydrogen is referred to as PtH, and its subsequent production into methanol, methane, or ammonia is referred to as PtM, PtG, and PtA, respectively.

Since its conception, PtX has always been characterized as a strategy to link electricity generation with other energy supply and end-use sectors to manage intermittent power generation from solar and wind. This strategy is called sector coupling (Sterner and Specht, 2021). There are efficiency losses in applying sector-coupling to convert renewable power to PtX fuels compared to direct electricity use. For example, Sterner and Specht (2021) provide representative round-trip efficiency figures for power-to-hydrogen and other PtX pathways like PtG. Generic efficiency estimates for PtA and PtM are also available for different production methods (Ammonia Energy Association, 2017; EASE, 2021). It is important to note that these efficiency figures can vary across different techniques for PtX fuel production, storage, transport and utilization methods. Nonetheless, the constraints on direct electrification of high temperature processes in sectors like industry, the requirement of energy-dense fuels in certain modes of transport, and the limits of existing long-term energy storage options for intermittent renewable power can make a potentially viable case for PtX (Sterner and Specht, 2021).

Because of its considerable flexibility under different use cases and substitutability for carbon-heavy fuels, PtX could be an option to assist Norway in meeting its national decarbonization goals. Norway aims to achieve up to 95% below 1990 levels of reductions in greenhouse gases by 2050 (Norwegian Ministry of Climate and Environment 2019). Existing research suggests that Norwegian hydrogen can be crucial in decarbonizing the country’s heavy-duty transportation and industry (Norby et al. 2019; Zhaurova et al. 2023). For example, Damman et al. (2020) used the TIMES-Norway model to explore hydrogen production pathways in Norway, finding that hydrogen demand in these sectors could increase drastically toward 2050 to comply with decarbonization policy goals. Such a push for this fuel could encourage a larger domestic market for Power-to-Hydrogen (PtH).

If PtX is to develop into a viable option for Norway’s decarbonization, it is imperative that studies explore the financial viability of the processes and the localized impacts of siting PtX projects. Hydrogen justice should be considered at six levels: procedural, distributive, restorative, relational, recognitional, and epistemological justice (Müller 2022). Being aware of the beneficiaries of the PtX transition and its negative externalities from a financial perspective will help decision-makers compensate for the impact of the transition on communities and engage in just decisions.

Methodology

Power-to-X Database

To model PtX pathways and possibilities in Norway, our first deliverable required us to collect the latest input data on Norway's energy system. We used the EnergyPLAN model structure from Lund et al. (2021) and a list of aggregated inputs from a 2016 Norwegian EnergyPLAN modeling study to guide our data collection process (Askeland et al., 2020). The frameworks outlined in both Lund et al.(2021) and Askeland et al. (2020) segmented the input data into the energy system's supply and demand side parameters. The appendix section of Askeland listed out each parameter on which the authors collected input data for the Norway Energy PLAN model. Consistent with these frameworks, our input data collection also looked for updated data on Norway's energy supply and demand flows. Most data inputs were sourced from the web-based query tool on the Statistisk Sentralbyrå (Statistics Norway) website, Norway's statistics bureau. After data had been downloaded from the website, the data was cleaned and processed in R and Excel. Processing mostly involved changing the dataset format from wide to long and turning it into panel data. Finally, all individual data inputs were combined into one large dataset, with each model input parameter on a separate sheet. Details on any data missing, altered or requiring further explanation were provided in separate data notes files submitted alongside the compiled dataset. The data notes file also matched our compiled data set with the input data collected by Askeland et al. (2020).

On the supply side, our input data search started with Norway's total primary energy production, supply, imports, and exports. This was followed by a data query on the power and heating sectors. The supply side datasets stated the total production, supply, imports, and exports values. These values were further broken down by energy generation sources, such as coal, natural gas, biomass, etc. Electricity supply numbers from the power sector were broken down by generation sources and linked to a dataset on the power plant's nameplate output capacity. The power generation capacity was also classified into hydro, thermoelectric, wind, and solar, highlighting the corresponding capacity for each resource. Other supply-related parameters we collected data on included district heat production profile, waste incineration for energy, and hydro resources classified into different types like pumped storage. Most of the collected data was stretched into a time series spanning 1990-2021 for every supply-side input.

On the demand side of Norway's energy system, we assembled a dataset on the breakdown of energy consumption for Norway's transportation sector by fuel source. The financial model segment of our project used more granular transportation sector demand data that focused on international and domestic transport for maritime and aviation modes. Collecting data on the industrial sector energy demand breakdown was more challenging because there was no clear and consistent definition and data agreement among values in the Statistics Norway website, Askeland et al. 2020 paper, and the EnergyPLAN model framework. Tables on the Statistics Norway website classified energy demand for manufacturing and other industrial-related sub-sectors. However, it was unclear which sub-sectors would make up the total demand for industry and whether or not the definition of what constitutes industrial would be consistent across sources.

To address the industrial consumption mix, we referenced the final energy consumption figure titled “Manufacturing and mining” in our compiled dataset as a proxy for industrial demand. This was because it was listed as the third major energy demand source after transport and households (Statistics Norway, 2021). Then, we outlined the “industrial” term to include energy demand from the following Statistics Norway categories: “In manufacture of industrial chemicals”, “In other production”, “Manufacturing, const. and non-fuel mining industries”, and “Oil refineries”. We have confidence in this definition of industrial energy demand because the data we obtained using this definition matched the industrial energy demand source data in the IEA Norway 2022 report (IEA, 2022).

We excluded residential because the Norwegian energy system literature and discussion with our client suggested that the energy demand in homes and buildings was almost completely decarbonized via electricity from Norway’s low-carbon power generation mix. Similar to our approach in organizing supply-side input data, we noted the relative contribution of each energy resource in meeting demand across each sector.

Financial Model

We built a financial model (see link in Appendix D) to understand whether the transition to hydrogen was financially viable for industries using fossil fuels in Norway. We define financial viability as the point at which the price of hydrogen is the same or cheaper than fossil fuels. The financial viability of hydrogen is important for a fast and just transition. If hydrogen is too expensive, companies and services using fossil fuels will not be willing or able to utilize hydrogen and other carbon-free derivatives. If hydrogen is too expensive, governments could have to provide financial support to private companies to help them decarbonize without risking bankruptcy.

The first consideration of our financial model development was to determine its scope and limitations. Due to private data restrictions, we decided to focus on modeling national PtX pathways. We easily found hydrogen fuel costs, but capital costs were difficult to include in the model at a national scale. We did not know the extent of fuel cell, storage tank, or transmission line capacities needed to transition to hydrogen nationally. Therefore, our final financial model shows whether the cost of hydrogen fuel or its levelized cost of energy (LCOE) is cheaper than the cost of fuels currently used in Norwegian heavy transportation and industrial heating sectors. LCOE includes the capital costs, fuel expenditures, and operation and maintenance costs of hydrogen production. This metric helps us understand long-term hydrogen profitability and whether hydrogen production investments can be recuperated through product sales.

To build our model, we first collected data on the usage (in GWh) of coal, oil, and natural gas in the following sectors (use cases): Industrial heating, international air transportation, domestic air transportation, international maritime transportation, inland maritime transportation, and heavy ground transportation (trucks).

We then acquired energy cost data, which had to be converted to the Norwegian national currency (Krone) per GWh. After making these conversions, we calculated the total cost of energy by source for each fossil fuel and use case:

$$Energy\ Usage\ \ *\ \ Cost\ of\ Energy\ in\ [2022\ or\ 2030]\ = Total\ cost\ of\ fossil\ fuel\ per\ use\ case$$

We then calculated the equivalent quantity of hydrogen that would be needed to replace fossil fuel using the conversion ratio from the US Department of Energy (2021):

$$1\ GWh\ =\ 30030.03003\ kg\ of\ hydrogen$$

We applied the following formula:

$$Total\ use\ of\ energy\ by\ fossil\ fuel\ and\ use\ case\ in\ GWh\ \ * \\ 30030.03003\ =\ Hydrogen\ replacement\ in\ kg$$

Next, we identified the cost of these fuel quantities based on 25 hydrogen prices found in Norway, the EU, and the US. These prices were based on 4 renewable energy sources and two different hydrogen production techniques. We then calculated the cost of hydrogen to replace each fossil fuel in each use case through the following equation:

$$Hydrogen\ replacement\ in\ kg\ \ *\ \ Cost\ of\ hydrogen\ =\ Cost\ of\ hydrogen\ per\ use\ case\ and\ fossil\ fuel$$

Finally, we calculated the difference between the cost of energy by sector with fossil fuels and the cost of energy using hydrogen produced in various conditions and places. We repeated this with current (2022) costs and 2030 projected costs.

$$Total\ cost\ of\ fossil\ fuel\ per\ use\ case\ -\ Cost\ of\ hydrogen\ per\ use\ case\ and\ fossil\ fuel\ =\ Cost\ Difference$$

If the cost difference is negative, hydrogen is more expensive than fossil fuels. If the cost difference is positive, hydrogen is cheaper than fossil fuels.

PtX Project Mapping

The final objective of this study was to map current and planned PtX projects in Norway. PtX projects, particularly Power-to-Hydrogen, pose local challenges related to space availability, visual impact, economic burden shifting, and resource consumption (Dillman and Heinonen 2022; Fastech 2023). Other studies have shown that these projects can spur positive local benefits as well, such as job creation and ground pollutant reduction (Ampah et al. 2023). Therefore, this effort aims to analyze the existing spatial impact of these projects on communities and offer informed guidance to those impacted by forthcoming projects. Our methods build on existing research by authors like Wulf et al. (2020), who model and analyze

Power-to-X demonstration projects across Europe. In this case, the authors only compiled data for three existing Norwegian PtX applications, leaving a significant gap for projects that have arisen since 2020 and guaranteed forthcoming projects.

We first created an Excel database to house PtX project data[1], provided as an attachment to this analysis. Our analysis generates a more holistic view of the spatial PtX impacts by exploring the PtX sites themselves and their documented sites of supporting processes like direct air capture facilities or methanation plants. We conducted a web-based query to find existing and planned PtX projects in Norway and documented their coordinate data. Additionally, we noted important project features, as noted by Wulf et al. (2020), related to project electrical capacity, fuel use, Hydrogen electrolyzer type, electricity source, and CO2 source. While some of this data was not pertinent for our mapping - such as electrolyzer type - we provide this data to support future analysis endeavors.

The PtX project data was synthesized and uploaded into ArcGIS Pro alongside other data such as Norwegian municipalities and CORINE land cover data (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). The CORINE data classifies 44 land-use types, including two for continuous and discontinuous urban fabric. The data defines urban fabric as “Areas mainly occupied by dwellings and buildings used by administrative/public utilities, including their connected areas (associated lands, approach road network, parking lots),” (Kosztra et al. 2019). The discretion between ‘continuous’ and ‘discontinuous’ refers to the percentage of impermeable surface coverage; specifically, continuous is where such surfaces cover more than 80% of the cell size, 25 hectares, while discontinuous refers to 30% to 80% coverage (Kosztra et al. 2019). While the major content of both continuous and discontinuous urban fabric is residential and commercial services, these groups also include transportation hubs and buildings less than 25 hectares in size. We focused on the urban fabric classification within this analysis to represent communities who may be impacted by the PtX facilities. In addition to urban fabric, we explored PtX project proximities to agricultural and ecological land uses. Appendix B shows the following classifications used within our analysis.

PtX projects were converted to a point shapefile and modeled in the UTM Euref89 coordinate system. We used the Proximity Analysis Near tool to measure the distance from each PtX site to urban, agricultural, and ecological land uses from the CORINE 2018 database. Distances were quantified for both current and forthcoming projects. To supplement this, we ran a Kernel Density analysis, which calculates the relative concentration of sites on a cell grid. Doing so allowed us to identify Norwegian municipalities that fall within the high-density zones, and are, therefore, most at risk for impact by PtX project sites.

In addition to analyzing the spatial impact of PtX in Norway, we put forth guided suggestions for the impacted municipalities and project developers to advance justice within forthcoming project

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[1] Our analysis only includes PtX production processes powered by renewable energy sources. All forms of hydrogen production aside from green hydrogen, including steam-methane reformation, are not included in this analysis.

endeavors. Dillman and Heinonen (2022) establish that PtX can foster localized challenges for distributional, procedural, cosmopolitan, and recognitional justice. Some such challenges include long-term taxpayer costs, undemocratic project decision-making, extensive land and water resource use, and exacerbated industrialization of impoverished communities for project siting (Dillman and Heinonen 2022). We offer the guided suggestions by these authors to the communities impacted by forthcoming projects to advance equitable and just-based development of PtX.

Steps taken to address equity in project process

Our financial model gives PtX project decision-makers knowledge to make equitable decisions for communities. The division of hydrogen costs by use cases and fossil fuels make it easy for decision-makers to understand which communities will be first impacted. The data will help them know which sectors will profit from the transition, and which jobs will be lost from the reduction of fossil fuel consumption.

Equity is prominently addressed in the mapping component of our research. In addition to analyzing the spatial impact of PtX in Norway, we put forth guided suggestions for the impacted municipalities and project developers to advance justice within forthcoming project endeavors. Dillman and Heinonen (2022) establish that PtX can foster localized challenges for distributional, procedural, cosmopolitan, and recognitional justice. Some such challenges include long-term taxpayer costs, undemocratic project decision-making, extensive land and water resource use, and exacerbated industrialization of impoverished communities for project siting (Dillman and Heinonen 2022). We offer the guided suggestions by these authors to the communities impacted by forthcoming projects to advance equitable and just-based development of PtX.

Results & Discussion

Updated input data collection

The findings from our compilation of updated data on Norway's energy system highlight the target sectors where carbon-neutral PtX fuels would be a good fit as a decarbonization strategy. More detailed plots and visuals supporting the analysis of energy supply and demand flows can be found in Appendix F.

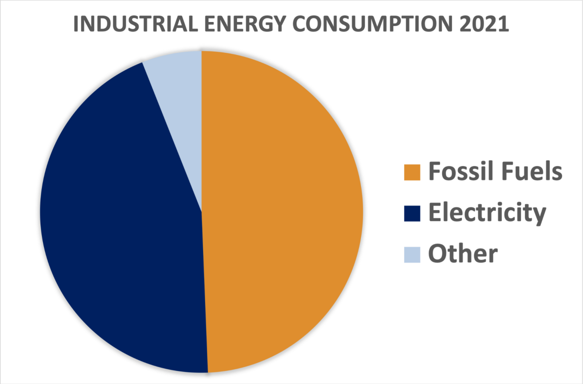

Figure 1: Industrial Energy Consumption Breakdown by source. About half of all energy consumed originates from direct fossil fuel combustion, while the remainder comes from electricity and other sources, respectively.

In the industrial sector, nearly half of the energy demand is met by electricity, while the other half comes from burning fossil fuels such as oil, natural gas, and coal (Figure 1 & Appendix F) . The industrial energy demand that has not been electrified most likely consists of high-temperature processes for which commercially viable electrification technologies are not widely available (Hydrogen Council, 2020; Deloitte, 2023). The goal of PtX fuels in the industrial sector is not to crowd out the opportunity for energy and heating demand electrification. The role of PtX is to tackle fossil fuel use for those industrial heating processes that cannot be decarbonized with electrification (Hydrogen Council, 2020; Deloitte, 2023). Similarly, in the transportation sector, we can see that energy demand is mostly supplied with crude oil and its derivative fuels (Figure 2 & Appendix F). Though Norway is headed towards direct electrification of its light-duty passenger vehicle fleet (IEA, 2022), PtX fuels can have an important role to play in decarbonizing modes of transport requiring more energy-dense fuels, such as heavy-duty truck transport, marine vessels, and aviation.

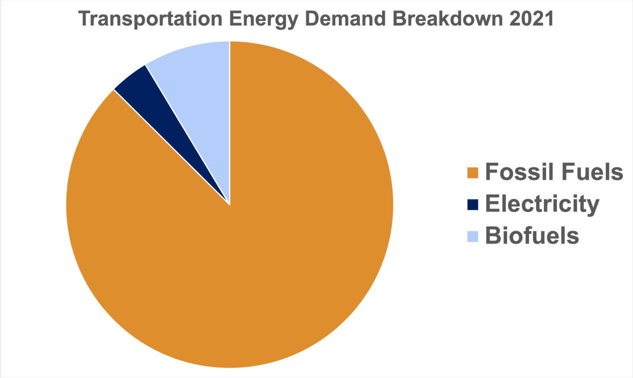

Figure 2: Transportation Energy Demand Breakdown by source. The chart shows that the majority of fuels used in the transport sector are fossil fuels, while a smaller portion comprises electricity and biofuels.

On the supply side, Norway's domestic energy production is dominated almost entirely by oil and gas (Appendix F). However, the export energy supply graphic (Appendix F) shows that nearly half of this is exported. Whatever oil and gas output that remains after accounting for exports is likely what is used to meet the fossil fuel demand predominantly in the country's industry and transportation sector. Though the overall domestic energy production is fossil fuel intensive, the power generation almost entirely consists of zero-carbon renewable electricity from hydroelectric and wind-generating units. The access to renewable electricity for the almost fully electrified residential sector energy demand also supports our reasoning to exclude buildings and homes as target sectors for PtX fuels in our analysis.

Financial Model

In total, we found 25 different hydrogen prices and modeled 364 scenarios.

In 2022, our results showed that Norwegian hydrogen is constantly more expensive than fossil fuels for industrial heating, air, and maritime transportation. Only an American LCOE of hydrogen at 25 Kroner/kg appears cheap enough to replace maritime fuel. However, since this cost is not from Norwegian production, it is less relevant to this study. We also found 10 scenarios in which Norwegian hydrogen could replace diesel used in heavy trucks. Some example costs where this holds true include general hydrogen production at €3.01/kg (Matalucci 2021), an electrolysis LCOE at €2.50 (Bloomberg, 2022), two onshore wind turbines-based electrolysis LCOE at €2.75 and €4.02/kg (FCHO Observatory), and one electrolysis sourcing electricity from the grid at €3.36/kg (FCHO Observatory).

In 2030, the most promising result comes from the Norwegian company NEL (Edwardes-Evans, 2021). The fuel cost from this company at €1.5/kg, could allow every use case to replace oil with hydrogen. Under this scenario, hydrogen would be cheaper for industrial heating, domestic air transport, international maritime transport, and inland maritime transport. For international air transportation alone, it would only cost about 376 million Krone to switch the entire industry to hydrogen. This amount is comparatively small when viewed at an industry-wide scale. For example, the revenue generated by Norwegian Air Shuttle alone in 2022 alone surpassed 18.8 billion Krone (Simply Wall St 2023). We anticipate that this may be a feasible shift in the case of direct fuel substitution.

Another potential frontier for hydrogen development in 2030 is the maritime industry. We found that it would only cost an additional 144 million Krone to replace natural gas in international maritime transportation, and 191 million Krone for inland maritime transportation. These costs are also relatively low compared to the market size of these industries, which is estimated at upward of 175 billion Krone (Norwegian Shipowners Association 2023). We expect that cost differences could be partially addressed by a slight increase in the cost of private maritime companies' services.

The results from our financial model suggest that replacing oil and natural gas by Norwegian hydrogen in 2030 seems possible. However, only one company, NEL, could produce cheap enough hydrogen to make this transition. One producer is definitely not enough to decarbonize all of Norway's carbon-heavy industries. The success of this transition can only happen if more hydrogen producers can reach such a low cost, innovators drop the cost of hydrogen, and the government provides subsidies to help private companies transition from oil to hydrogen.

PtX project mapping

In total, we classified 17 unique PtX or PtX-related projects in Norway (six current and 11 planned). Of these 17, three projects were located offshore, primarily for CO2 storage. The district with the greatest density of PtX projects was the Vestfold og Telemark province, with four projects. The closest municipalities impacted by these projects were Porsgrunn and Skien. The Rogaland province follows Vestfold og Telemark in PtX density with three projects. The Rogaland projects are situated near the municipalities of Sauda, Haugesund, and Karmøy. While existing PtX sites are dispersed around Norway, forecasted projects show growth on the northern and southern ends of the country. The results of the Kernel Density analysis confirmed these findings. For example, the analysis showed high current and future project clustering around the Porsgrunn/Skien area. Additionally, it found lower clustering densities around Haugesund and south of Bodø. Full maps of current and planned projects, as well as Kernel Density results, are provided in Appendix A.

All current projects (n=6) were located in urban land use zones. Similarly, all but two forthcoming projects are planned for urban land use zones. These projects, Longship/Northern Lights and North Ammonia, are planned for sites 3.2 kilometers and 590 meters away from the nearest urban land use zone, respectively. Due to the urban site favoritism, we can infer that these projects are or will be impacting surrounding communities.

In addition to urban land use impacts, we evaluated the PtX site proximity to agricultural and ecological landscapes. The proximity of each site to the nearest agricultural or ecological zoned area is provided in the attached PtX database. Agricultural site distance for current projects ranges from 404 meters to 5.1 kilometers, and for planned projects, from 90 meters to 11.3

kilometers. Due to such great distances from agricultural sites, likely, there will not be a direct impact on farmland. However, ranges for ecological landscape proximity showcase different results. The range for current projects spans 22 meters to 1.1 kilometers, and for current projects spans 0 meters to 7.5 kilometers. Two forthcoming projects have planned sites that overlap ecologically-zoned landscapes, meaning that there will likely be impacts on these ecosystems.

Sources of uncertainty

Data collection

Our data collection process contained a few inherent uncertainties. First, the data on Norway's energy system supply had to be supplemented and cross-validated with general data from the Our World In Data website, because the Norwegian source lacked a detailed power generation breakdown (Ritchie et al., 2022). We also turned to Our World In Data to provide a clearer foundation for non-hydroelectric renewable energy figures. Though solar-PV resources in Norway are relatively insignificant compared to wind and hydroelectric, we still required data on these resources to make a comprehensive input database. Other minor sources of uncertainty for supply-side data were related to dataset disagreement, particularly between data we found and the data parameters from Askeland et al. (2020). These are summarized in the excerpt from the data notes table in Appendix E.

Financial Model

One of the largest sources of uncertainty within the financial model is related to scaled costs. As these financial model results apply to national industry-wide levels, it is possible that hydrogen could be cheaper than fossil fuels at local or company levels. The reverse is also true: hydrogen may appear cheaper than fossil fuels at national and industry-wide levels, but in reality, is too expensive at a local or company level. These discrepancies have significant implications for the true financial viability of hydrogen; however, without a more comprehensive dataset, we are unable to discern reliable scaled hydrogen costs.

Comprehensive and reliable data produced clear uncertainties within the financial model. The reliability of data collected online is certainly questionable. Due to project logistical constraints, we were only able to acquire this online data within the research timeframe. Similarly, lackluster data in certain use cases meant we needed to exclude key analysis avenues. For example, we decided to abandon 2025 projected fossil fuel costs in our model as the projections are challenging to find. What data is available may be impacted by the volatility of current fossil fuel prices due to the Russia-Ukraine war, and therefore with high margins of error. We attempted to limit uncertainties by comparing data values between sources when possible and restricting the analysis to 2022 and 2030. We also had to exclude ammonia and methanol production from this analysis, due to similar data uncertainty concerns.

Another large source of uncertainty was the data associated with various transportation means. We could not find any data describing the energy usage of heavy truck transportation in Norway and had to calculate our values based on data collected from different sources. We assumed a certain quantity of energy based on these sources and calculations displayed on the model, but the margin of error is large with the total fossil fuel energy usage of trucks that we calculated. Similar issues arose with data differentiation between ferries and merchandise boats, and jets and commercial planes.

While the LCOE includes some capital costs, sole fuel costs do not include them. Therefore, even if hydrogen costs may look cheap for some projects, the capital costs should be added in some projects at the production level, and for most projects at utilization levels. For example, users may have to invest in fuel cells, storage tanks, or new aircrafts. We know that as many costs are not included, the results of the model are limited. However, calculating the cost of fuel could already be an interesting input for researchers.

Mapping

Our research relies on data that we collected from web-based queries. Therefore, the identified data and implications are limited to what we could find online. There is uncertainty surrounding the full extent of impacts from PtX siting in Norway that could be alleviated through in-person case studies and community communication. Future studies should check our findings within the counties of Nordland, Rogaland, and Vestfold og Telemark.

Discussion of equity implementation successes and challenges

The financial model reveals that the truck industry, followed by the maritime transportation industry, would primarily benefit from hydrogen use over oil. The air transportation industry and factory heating may also benefit similarly from such a replacement. These findings suggest that the PtX transition may be profitable for some industries and potentially offer better work benefits. However, because oil is the only fuel for which hydrogen can be an economical substitute, jobs in oil exploration and development may be highly affected. This is an important equity consideration for Norway, as the nation’s economy relies heavily on oil exports (Norwegian Petroleum 2023). It is possible that many Norwegians will lose their jobs in the oil industry because of the use of hydrogen instead of oil. Decision makers should make the professional reconversion of oil workers into hydrogen a priority. At the scale of the economy, as oil is an industry participating in Norway’s wealth, the Norwegian economy should plan to become a leader in hydrogen production. Future studies should address the risks to Norwegian oil jobs from the PtX transition.

One additional equity component of our research was to provide recommendations to three identified PtX hotspot communities. We focused our guided PtX recommendations on the regions of Vestfold og Telemark, Rogaland, and Nordland due to the proximity and cluster analyses. Within Vestfold og Telemark, our recommendations are tailored toward Porsgrunn and

Skien, a major cluster for PtX projects. For Rogaland, our recommendations are designed for Haugesund and Karmøy, a coastal community. Finally, we provide general recommendations for rural communities in Nordland, as the PtX projects are not sited near major municipalities. A full set of recommendations for each county is provided in Appendix C.

Our study was limited by available community-level data. We would have liked to analyze the impact of PtX sites on regions by census tract (or equivalent) to get a better grasp on impact extent to impoverished communities. This geospatial data was not easily accessible to us, and therefore leaves a gap to be filled by a forthcoming study. However, it is worth noting that Norway, in totality, does not face a significant amount of poverty. In 2022, the country reported that only 5.9% of its inhabitants faced at least one financial hardship (Statbank Norway 2023). A future study could examine if the 5.9% are directly or indirectly impacted by the growth of PtX.

Recommendations & Conclusions

Conclusions

This study evaluated the pathways and implications of PtX development in Norway. Acknowledging the country's forthcoming decarbonization agenda, it is clear that PtX may play a role as a carbon-neutral fuel substitute in the hard-to-abate industrial and transportation sectors. The financial viability of such a transition still remains unclear. For some scenarios, hydrogen formed through PtX may replace heavier transportation fuels. In other scenarios, the cost of oil and gas is too low for hydrogen to become a feasible alternative. However, as we show through this study, Norway is developing hydrogen through PtX projects regardless. By mapping out current and existing PtX sites, we recognize that the country may be tapping into external markets for PtX products in order to achieve financial viability. Siting these projects will surely induce local impacts; therefore, we highly recommend that regions consider equity in such developments.

Possibilities for Future Work

Future data-oriented research efforts towards PtX in Norway should take a more granular sub-sector level approach to find energy supply and demand flow data on energy-intensive sectors within the industry category. Transportation-related data collection could also focus on finding fleets of heavy-duty vehicles, marine vessels, and aircraft vessels that could switch to PtX fuels.

There are still many opportunities for future work to address equity in PtX research. For example, a future study could conduct ground-truthing within Norwegian communities to develop a first-hand community-centric perspective on how equity is built into the PtX planning process. While our research offers a foundation for examining PtX equity in Norway, we are limited by distance and language. We encourage our client to pursue a future study that provides a Norwegian perspective on equity successes and challenges in developing PtX projects.

Our financial model provides many opportunities for future research to expand upon our findings. We encourage a future study to integrate capital costs within our calculations, which would produce more robust results. In addition to capital costs, we also suggest that a further study exhaust additional avenues to find ammonia and methanol production data in Norway. This is a necessary gap to fill, as ammonia an methanol production make up a significant share of current and planned PtX projects in Norway. Finally, we suggest to our client that a sensitivity analysis be conducted to explore the relationships among cost flows within our data. There may be some variables that have a greater influence on the financial viability of hydrogen, therefore we suggest a future work divulge these relationships further.

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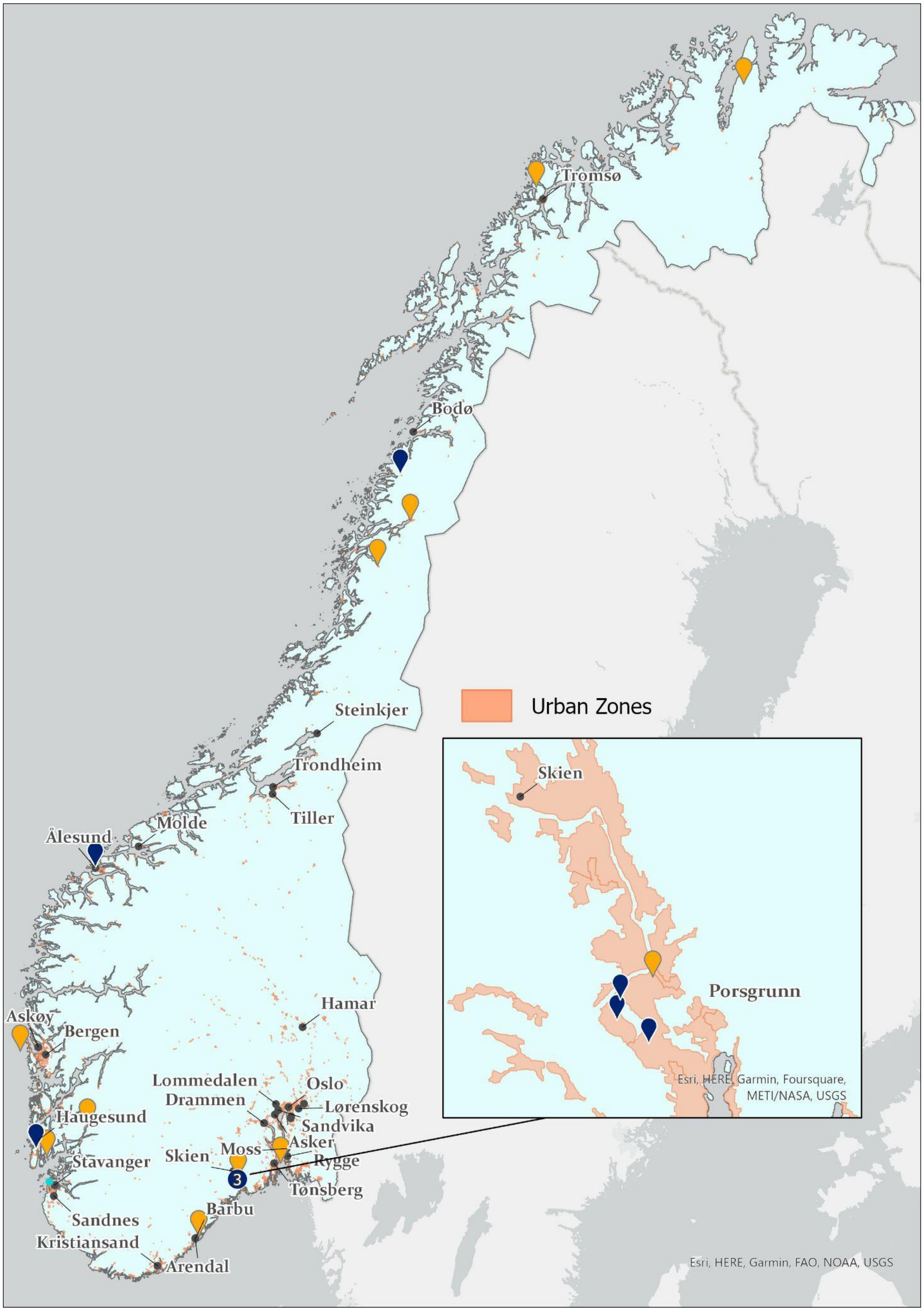
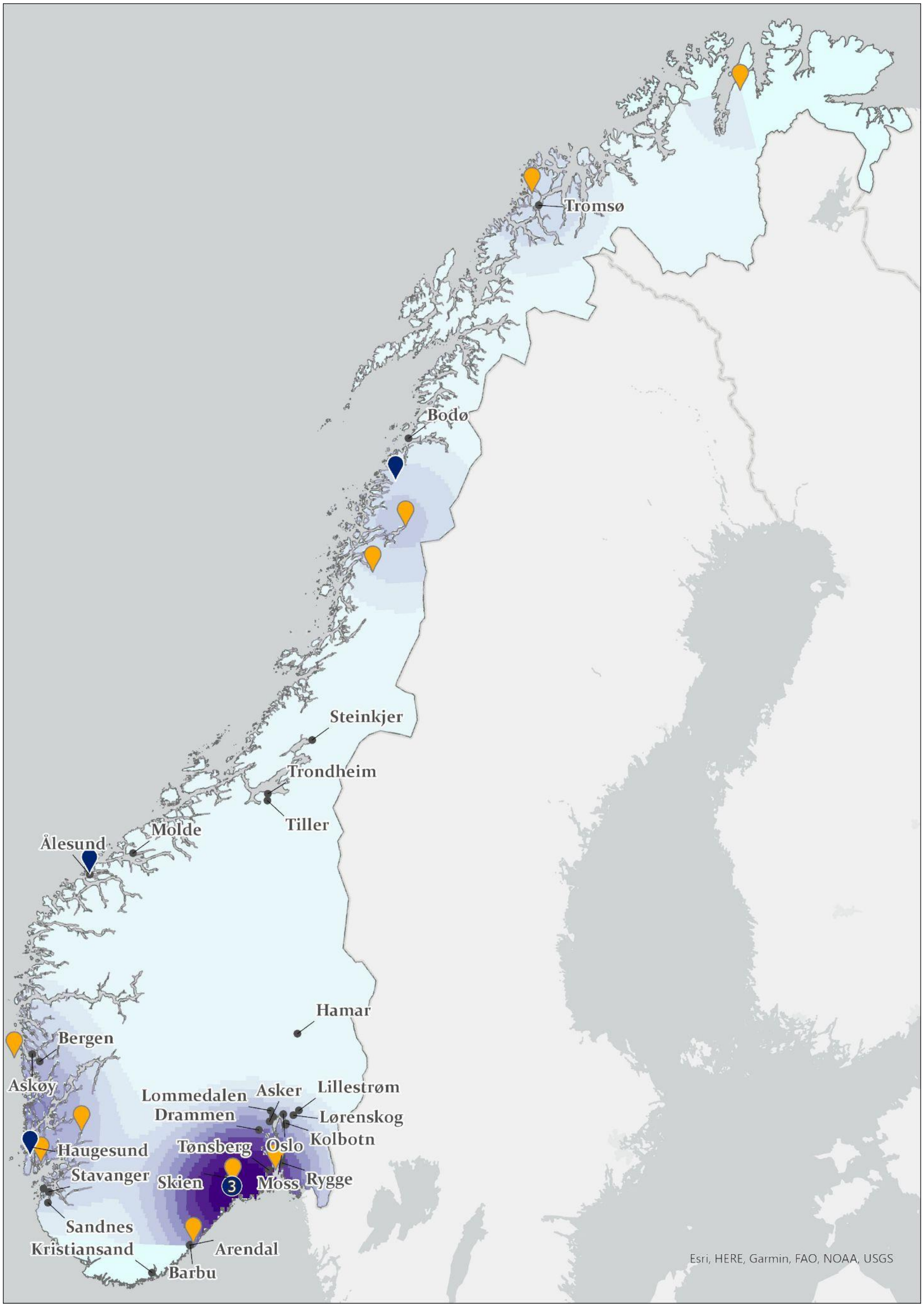
Appendix A: PtX project maps



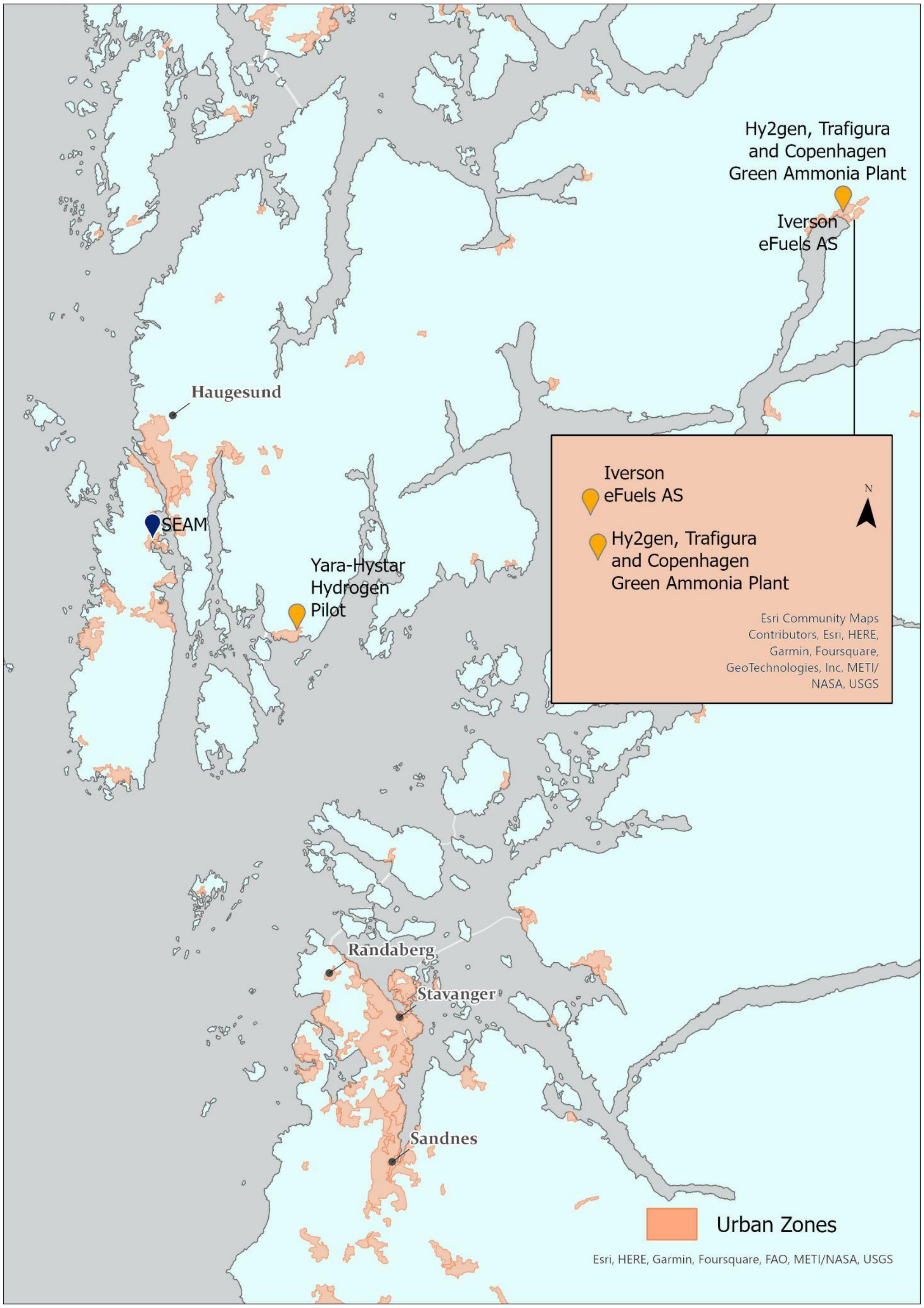
Map 1: Study areas with urban zones shown. Urban areas are classified within the CORINE land cover database. Dark blue points of interest are current PtX sites, and gold points of

interest are planned sites. An inset map shows a closer view of Vestfolg og Telemark county, focused on the Skien - Porsgrunn region.

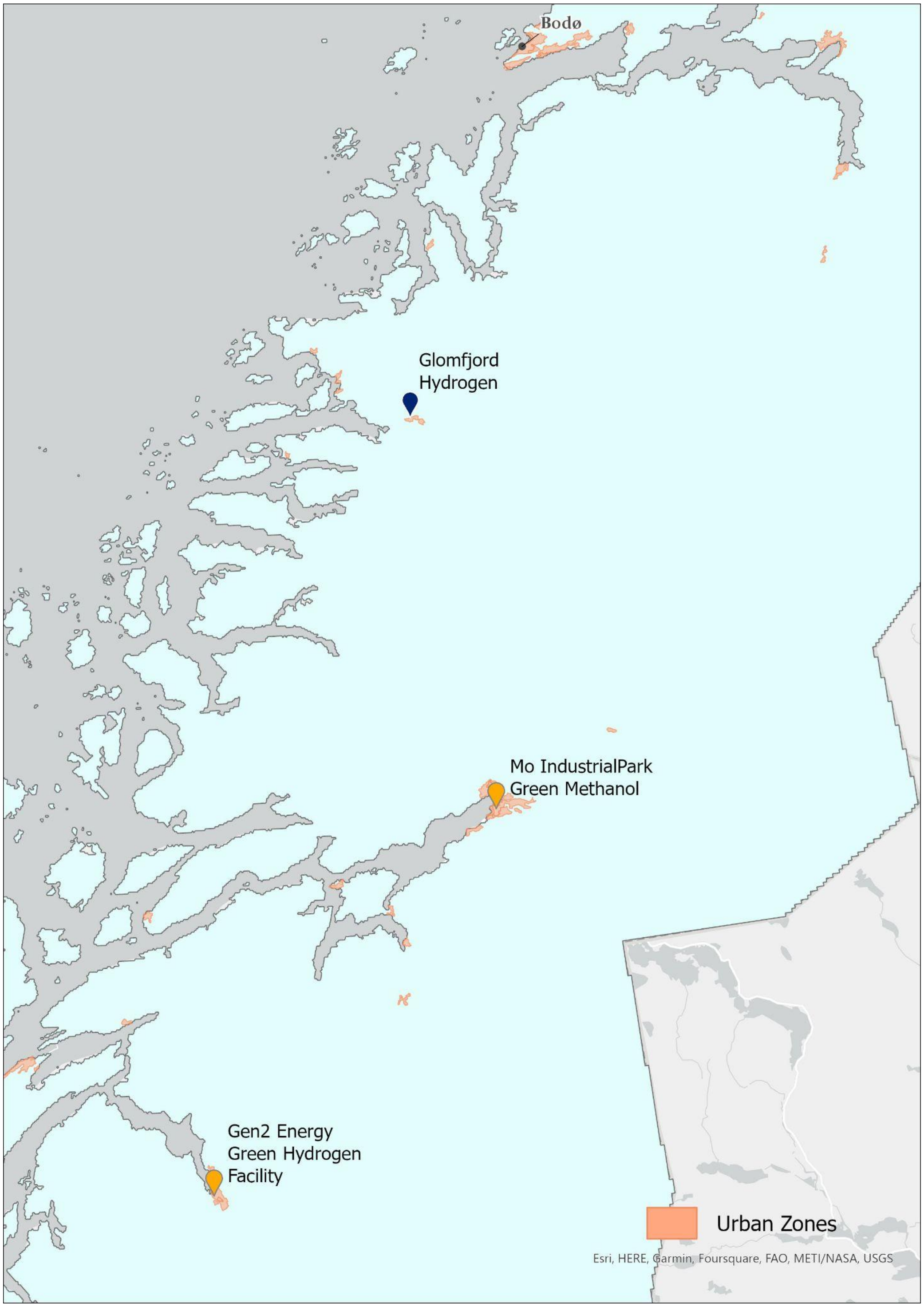


Map 2: Kernel density analysis of PtX sites within the study region. Purple zones indicate a greater clustering of PtX sites. Three major hotspots are identified: Vestfold og Telemark county, in the southeast; Rogaland county, along the southwest coast; and Nordland county, south of Bodø in the country's center.

Map 3: A closer view of the PtX hotspot in Vestfold og Telemark county. PtX sites are located on urban zones near Porsgrunn. All projects are currently in place; however, the Yara-Linde site is set for a planned retrofit to green ammonia production processes.



Map 4: A closer view of the PtX hotspot in Rogaland county. Four projects are shown: Three of them are planned PtX development sites, and one project is an existing site. All projects are sited near major waterway access for material transport and natural resource flows.



Map 5: A closer view of the PtX hotspot in Nordland county. Three projects are spread out throughout the county, located in the few urbanized areas of the region. The nearest major city is Bodø, located north of the PtX sites.

Appendix B: CORINE (2018) land cover classifications used

Land Use	CORINE Land Cover Code	Our classification
Continuous Urban Fabric	111	Urban
Discontinuous Urban Fabric	112	Urban
Industrial, Commercial, and Urban Spaces	121	Urban
Non-irrigated Arable Land	211	Agriculture
Irrigated Arable Land	212	Agriculture
Pastures, Meadows, and other Agriculture	231	Agriculture
Annual Permanent Crops	241	Agriculture
Land Principally Occupied by Agriculture	243	Agriculture
Agroforestry	244	Agriculture
Forests	311 - 313	Ecological
Natural Grasslands	321	Ecological
Moors or Heathland	322	Ecological
Transitional Woody Land Scrub	324	Ecological
Sparsely Vegetated Areas	333	Ecological
Wetlands and Bogs	411, 412	Ecological
Coastal Salt Marshes	421	Ecological
Intertidal Flats	423	Ecological

Appendix C: Equity Recommendations

Nordland

Nordland is a county in north-central Norway, known for its scenic beauty and raw material exports. The major city within this county, Bodø, is located at the north end of the county and houses most of the population (Nordland Fylkskommune, 2023). Nordland is known for being the second-largest hydropower producer in Norway. Our equity recommendations for Nordland are as follows:

1) Ensure communities have a clear, equitable say in the development of the planned projects Mo Industrial Green Park Methanol and Gen2 Energy Green Hydrogen Facility. This process will uphold procedural justice in the county's PtX endeavors. We recommend that developers meet with community leaders and local on-profits to limit negative externalities for surrounding populations. We also recommend clearly considering local pollution from planned facilities, if applicable. Pollution includes but is not limited to, unwanted impacts on air, water, local noise, local light levels, and traffic disturbances. These challenges should be clearly identified and discussed with communities for appropriate solutions.
2) Consideration of impact on local leisure activities. Both planned projects will be sited near water bodies, which play a critical role in Nordland's scenic tourism economy. Projects should work closely with professionals in fisheries, marine ecology, maritime transportation, and maritime tourism to evaluate possible impacts.
3) Forthcoming projects should recognize the distribution of costs and benefits along the hydrogen production value chain. Rather than importing labor, developers should seek to hire and retrain local laborers for positions within the hydrogen and ammonia generation projects. If these projects need to raise funds, they could raise money from participative debt or equity investments (crowdfunding) to allow inhabitants to benefit from the plant's positive cash flows directly. Even if the products from these operations are sold outside the Nordland market, local communities should also receive some benefits. The content of these benefits should be clearly communicated between developers and communities.

Vestfold og Telemark

Vestfold og Telemark is a county in southeastern Norway. It is home to the municipalities Skien and Porsgrunn, which house most of the county's population (Nikel 2019). Three PtX sites currently exist within the county: Herøya Jet Fuel, Hydrogen Pro, and the Nel Electrolyzer manufacturing facility. One project, the Yara-Linde Ammonia Plant, is set for a retrofit in late 2023. Our equity recommendations for Vestfold og Telemark are as follows:

1) Develop a clear, community-centric PtX strategy at the county scale (Høyland et al. 2023). Such a strategy would ensure the potential for clear, meaningful community input within the project planning process. In addition, it would allow the communities to establish and plan for long-term PtX development by pre-identifying project sites. By

proactively planning for forthcoming PtX sites, counties can limit clustered overdevelopment and reduce short-term project tensions. Similarly, communities could use a PtX plan to identify necessary infrastructure upgrades, such as increasing local electrical transmission capacity.

2) Developers should work with communities to establish a sense of local purpose associated with their project. To do so, project stakeholders should consider the intent of the PtX project, its local impact, and how to redistribute project benefits within the most impacted communities. For example, one project team might identify indirect financial means to support the surrounding community, due to its product leaving the domestic market. Vestfold og Telemark, being a relatively urbanized county, should clearly focus on how PtX endeavors can support sociopolitical goals in Skien and Porsgrunn.

Rogaland

Rogaland is a coastal county located in southwestern Norway. The region is dotted with island communities and split with deep fjords. Karmøy, an island off the county's northwestern coast, is the region's largest and most populated island. Stavanger, the county seat, is also known to be one of the country’s largest hubs for oil and gas exploration efforts (Gjerde 2023). Our equity recommendations for Rogaland are as follows:

1) Proactively address labor implications for a shift away from oil and gas. In order to equitably decarbonize an economy traditionally intertwined with oil and gas exploration, Rogaland must consider all facets of a carbon-neutral fuel shift. Developers and communities should clearly communicate about potential job shifts that may occur from fossil fuel displacement. Even if PtX products are sold internationally, this action may have indirect effects on Rogaland’s oil and gas markets. One way that developers and communities could address this is by establishing an intentional gas-to-PtX labor pathway, encouraging local job creation.
2) Quantify divestment from carbon-based industry and the benefits of the switch toward PtX fuels, especially in areas disproportionately impacted by emissions. Hydrogen produced from PtX processes is often seen as a viable, clean replacement for combusted fossil fuels, which are key inputs to some industrial activities (IEA 2022). One example of this is the county’s aluminum industry. Rogaland is home to one of the largest aluminum processing facilities in Europe, located in Karmøy. Aluminum smelting and refining rely on fossil fuels for high-temperature processes, resulting in harmful emissions for the local environment and human health. NOx, SOx, and Non-methane Volatile Organic Compound (NMVOC) emissions emitted during aluminum smelting could be abated if PtX hydrogen replaces fossil fuel combustion (EEA, 2016). Developers should work with communities to quantify the human health and environmental benefits of a switch to hydrogen in such instances. Part of this would require additional research to scope out and identify areas historically and disproportionately impacted by harmful emissions. We recommend that developers communicate closely with these areas to translate forth the negative and positive local impacts of PtX.

Appendix D: Financial Model

Access here:
https://docs.google.com/spreadsheets/d/18NPgO2WxFPtp70kWeyD-f5wJeVI1CnR36aFCwgUBnM0/edit#gid=795127725

Explanation and guide video to access here (please download it as it should only be available for 3 months):
https://ucdavis.zoom.us/rec/share/2dCPBMYGzbR5z1yL26BYNOZMAuHfae45IVEEuC4GM5kNprC_ITIDuj0dogrJGDQb.tffle-IwDEfF79Tu

Appendix E: Data Notes & Uncertainty

Askeland et al. 2016 Appendix Table Reference	Parameter	Sheet Tab	Notes
Table 2	Electricity Supply Mix	electricity_supply1, electricity_supply2	electricity_supply1, Electricity_supply2 both contain data on electricity generation mix but from two different sources. Electricity_supply1 contains generation data from Statistics Norway while electricity_supply2 contains data from Our World In Data. The Statistics Norway website did not have breakdown of thermal power plants and missed data on solar-PV generation.
Table 2	River Hydro	hydro_capacity_breakdown,electricity_supply1, electricity_supply2	Source cited used a different term than "river hydro (unregulated hydro)". Generation breakdown based on hydro type not

			available.
Table 2	Waste Incineration	waste_incineration_energy_recovery	Waste amounts energy recovery input data provided. Conversion and estimates to TWh were the author's assumptions and not data inputs hence not provided.
Table 2	Natural Gas CHP	electricity_supply2	No breakdown by CHP or conventional natural gas plant.
Table 2	Interconnections	NA	NA

Appendix F: Visuals & Plots for Compiled Input Data

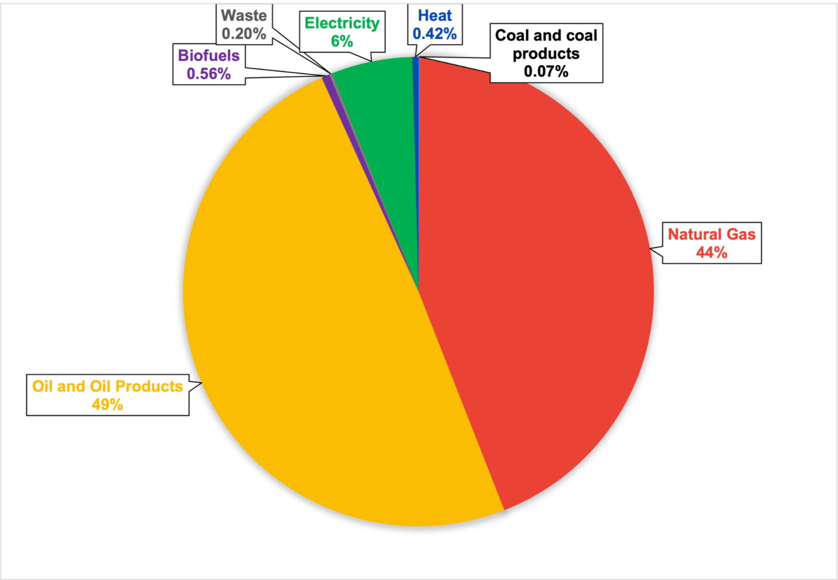


Figure F1: Norway’s Domestic Energy Production Breakdown 2021

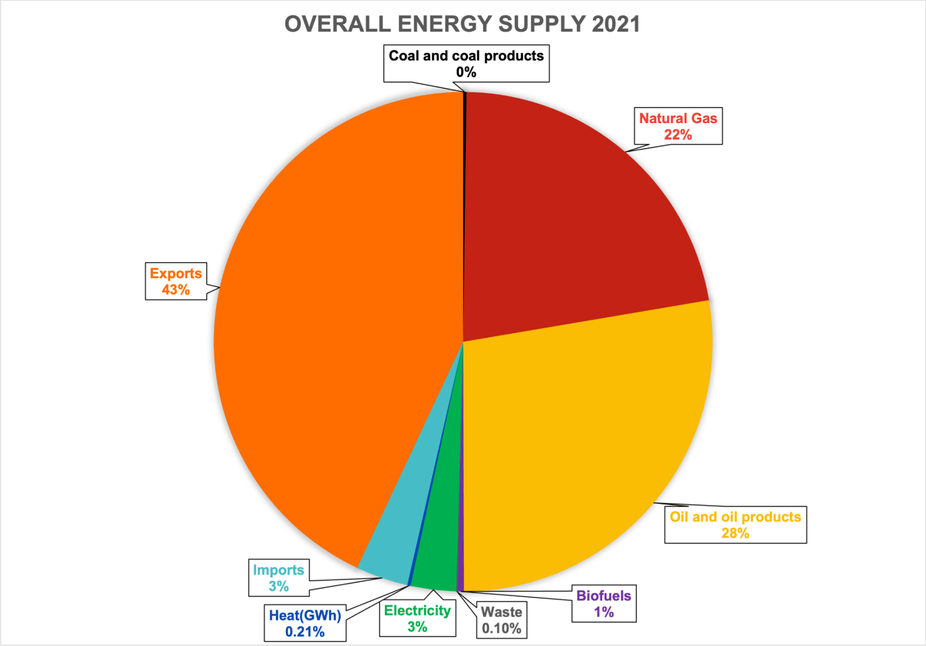


Figure F2: Norway's Energy Supply Mix Breakdown 2021 (inclusive of imports and exports)

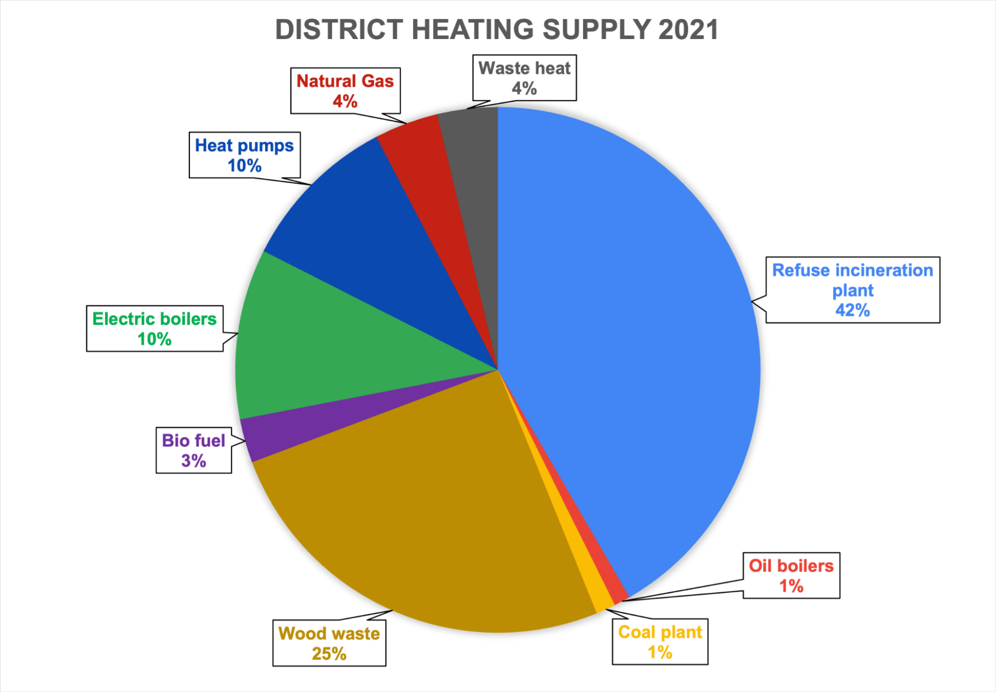


Figure F3: Norway's District Heating Production Mix 2021

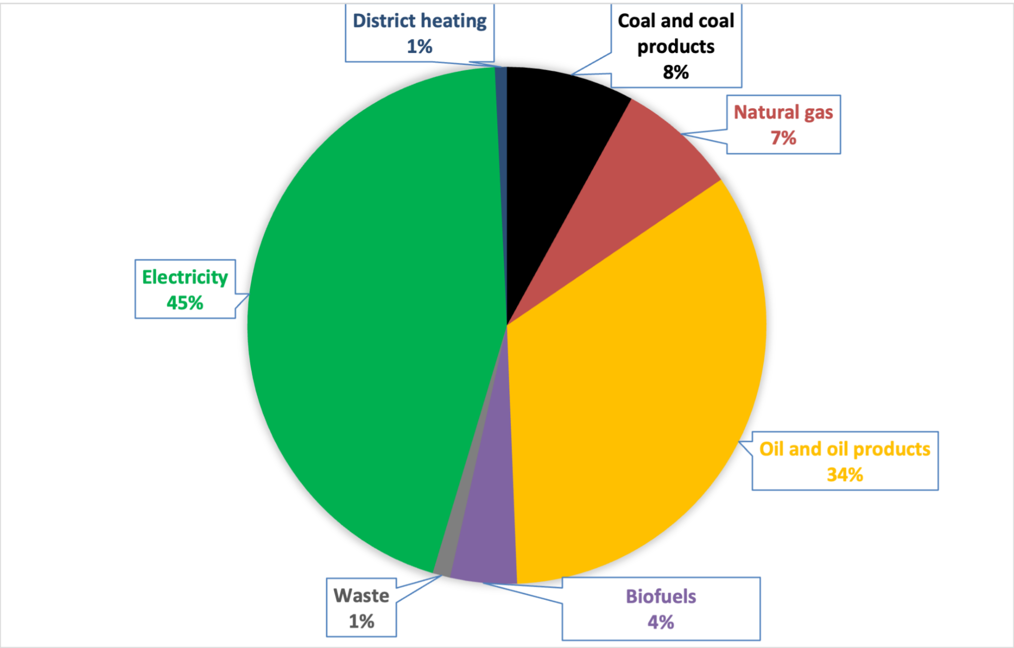


Figure F4: Norway's Industrial Energy Consumption Breakdown 2021

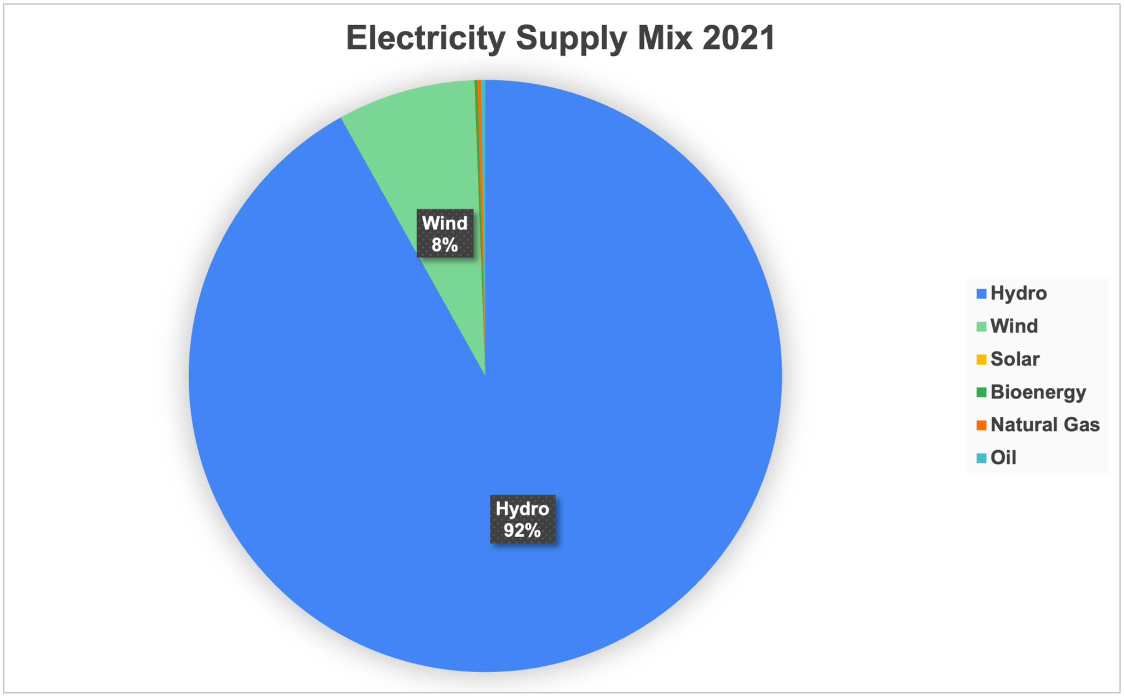


Figure F5: Norway's Electricity Supply Mix 2021

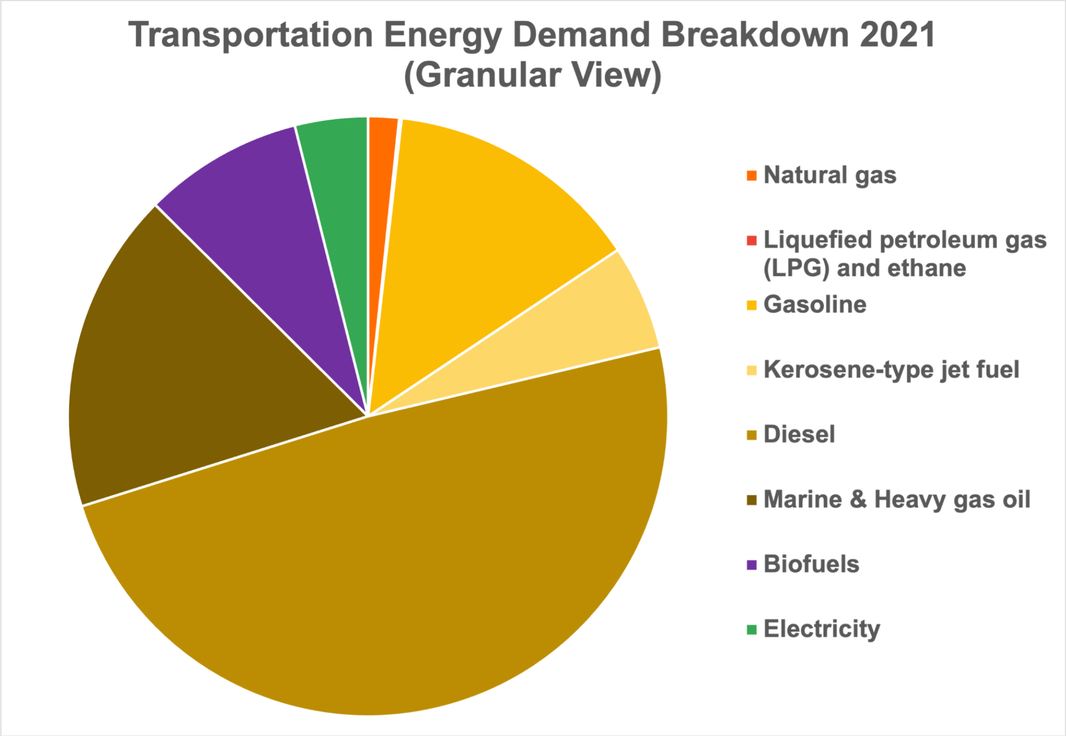


Figure F6: Transportation Energy Demand Breakdown by Source 2021: Granular View

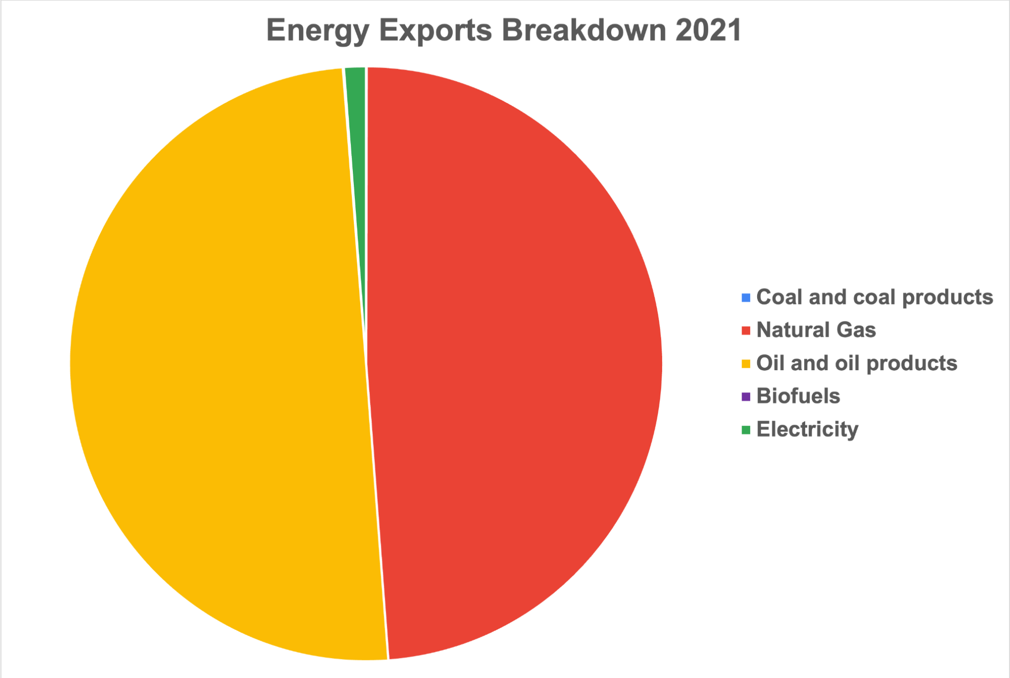


Figure F7: Energy Exports Breakdown by Source 2021