THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Consequences of large-scale hydrogen use in the European transportation sector

– geospatial modeling of infrastructure, electricity costs, water risk, and land use

JOEL LÖFVING

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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Joel Löfving

Department of Mechanics and Maritime Sciences

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

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Joel Löfving
Division of Transport, Energy and Environment
Department of Mechanics and Maritime sciences
Chalmers University of Technology

Abstract

To decrease the greenhouse gas emissions from transportation and industry, the use of electrolytic hydrogen produced from renewable electricity and water has been suggested, to substitute fossil energy and feedstock. But electrolytic hydrogen hasn't been used directly in these sectors on a large scale before, and it hasn't been produced in large quantities in Europe either.

This thesis analyses potential consequences of future hydrogen use and production across Europe, in transportation including trucks, shipping, aviation, and industries including steel, ammonia, high value chemicals, and fuel production. Assessments are based on a geospatially specific model, SVENG (Simulating Vehicle Energy Needs Geospatially), built for this thesis. This model simulates specific geographical locations of hydrogen demand for transportation and industry, over a full year, which allows for modeling impacts with more consideration to local context. For transportation, the demand is modeled using detailed logistics data, which allows allocating demand with consideration to transportation flows. For trucks, demand is allocated along logistics route considering power demand due to differentiated influence from road speed and topography, which is shown to significantly impact the simulated location of hydrogen refueling stations.

The geospatial hydrogen demand data is used for four assessments: 1) evaluating implications of the EU Alternative Fuels Infrastructure Regulation (AFIR), and analyzing effects of different fuel mix scenarios on 2) electricity cost, 3) water risk, and 4) land use.

The hydrogen refueling stations required by AFIR are expected to provide more capacity than needed in some countries, which might result in excessive costs for unused infrastructure if hydrogen truck diffusion rates remain low. Electricity costs, in some regions, are heavily influenced by the energy transition pathway in transportation. Electrolytic hydrogen production may contribute to overextraction of water in some locations, even if the locations are not otherwise projected to have high water risk. Land use intensity of renewable electricity for producing hydrogen is low compared to biofuel production, but renewable electricity generation like solar and wind power faces other challenges like acceptance issues. Combining different fuels in the mix might offer an opportunity to manage land use issues.

Modeling results presented in this thesis have pointed towards different potential problems and benefits with some technical pathways, utilizing data and methods building on higher geospatial resolution than many previous studies, but still analyzing options from a continental perspective. The publication of new, geospatially detailed datasets will hopefully open new possibilities for further modeling of additional aspects.

Keywords: infrastructure, supply chain, EU policy, transport, energy, geography

List of publications

Paper I

Löfving, J., Brynolf, S., Grahn, M. **Geospatial distribution of hydrogen demand and refueling infrastructure for long-haul trucks in Europe**. Manuscript accepted for publication in *International Journal of Hydrogen Energy*.

Paper II

Löfving, J., Brynolf, S., Grahn, M., Öberg, S., Taljegård, M. **Consequences of large-scale hydrogen use in Europe**. Manuscript submitted for review.

Joel Löfving is the principal author of papers I and II, and contributed with the following to both papers: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Acknowledgment

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Contents

Abbreviations and acronyms

AFIR	Alternative Fuels Infrastructure Regulation
CAPEX	Capital expenditure
CO_2	Carbon dioxide
EU	European Union
FT	Fischer Tropsch
GHG	Greenhouse gas
GIS	Geographical information system
HRS	Hydrogen refueling station
HVC	High value chemicals
NaN	Not a Number
NUTS	Nomenclature of Territorial Units for Statistics
OPEX	Operational expenditure
pkm	passenger*km
RED	Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
SAF	Sustainable aviation fuel
SSP	Shared Socioeconomic Pathway
TEN-T	Trans-European Transport Network
tkm	tonnes*km

1. Introduction

To avoid catastrophic effects of climate change, emissions contributing to global warming need to decrease (IPCC, 2023). As a response, the EU has implemented a range of policies targeted at reducing emissions to net zero across the region by 2050 (European Council, 2024). Important to this so-called Green Deal is the mitigation of emissions from transportation, which currently represents about a quarter of EU greenhouse gas (GHG) emissions (European Commission, 2025b).

To achieve this, new solutions for powering vehicles are needed. A plethora of options have been suggested, many based on utilization of fossil free electricity. Batteries are enabling the direct electrification of an increasing share of light road transport, like passenger cars (Hardman et al., 2024). However, in spite of rapidly dropping battery prices (BloombergNEF, 2024), and the possibility that mobility providers may alter their operations to accommodate the characteristics of battery-electric vehicles (Plötz, 2022), it is not entirely clear that they will be as successful in facilitating the transition in heavier segments of the transportation sector. To manage the requirements on long-distance heavy-duty trucks, ships, and aircraft, alternatives are being explored.

Aside from batteries, electricity could be used indirectly in transportation through intermediate storage in hydrogen. Hydrogen can either be used for energy directly in a vehicle through electrochemical conversion or combustion, or it could be combined with other chemicals to form liquid fuels more similar to conventional fuels. These are commonly referred to as *electrofuels* (Brynolf et al., 2022). Other solutions are based on utilizing energy from biomass, for which the conversion into fuel in some cases requires some amount of hydrogen.

But which of all these solutions should we opt for? Transitioning to new energy carriers across societal functions is not simple. The growth of our current economic system has for the past century been enabled largely by cheap and readily available fossil energy (Unruh, 2000); to reach the EU's goals, we now need to substitute these technologies for renewables in just a few decades. Different end uses require different technical attributes, which makes technology choices more difficult, especially considering the interconnected and complex nature of our energy- and economic systems (Rittel & Webber, 1973). A solution that works well in a vehicle could be impractical in terms of energy supply. Therefore, a holistic understanding of the energy- and transportation system is needed to plan the development and deployment of the next generation of vehicles and supporting energy infrastructure.

The short time frame leaves less room for trial and error, which has spurred the use of modeling to attempt to quicker understand the pros and cons of different energy transition pathways (Pfenninger et al., 2014), not the least for studying production and distribution of hydrogen (Riera et al., 2023). Comprehensive models assessing hydrogen technology on a country- or continental level are presented in Blanco et al. (2018); Caglayan et al. (2021); Cantú et al. (2023); Kountouris et al. (2024); Lux and Pfluger (2020); Moreno-Benito et al. (2017); Neumann et al. (2023); Öberg et al. (2022); Samsatli et al. (2016); Seo et al. (2020) and Walter et al. (2023). The level of detail varies for different aspects throughout the articles, like time resolution and included technology options, but one thing they have in common is the geospatial dimension being aggregated to different extents. This is an understandable limitation, since the vast range of energy demand projections tend to aggregate demand on a regional- country- or even global level, and due to computational burdens of some methods when analyzing large and more fine-grained datasets.

However, local factors may greatly influence the cost and viability of a hydrogen supply chain due to significant investments needed in production and distribution (Küffner, 2022). The results from an energy systems model could, furthermore, differ depending on the geospatial level of aggregation, as shown by Ganter et al. (2024). This is especially due to the wide range of potential off-takers, their different characteristics and demand profiles, and the way these are clustered in different areas. Geospatially resolved data is thus needed to make projections that can be translated into actionable energy systems planning on the local level, and to perform analyses that acknowledge the complex dynamics between the macro- and local scale of the energy system; also in cases when assessments might be of a more aggregated nature. As shown in the works by Capros et al. (2014); Dekker et al. (2023a); Dekker et al. (2023b); Luderer et al. (2018) and Ruhnau et al. (2022), model structure, settings, and inputs have a significant impact on the result of the model, ultimately dictating what conclusions can be drawn from the results. Enabling geospatially detailed assessments is thus important to provide new perspectives for planning the future energy system.

Many aspects affect the respective viability of different pathways in such systems. Some of these aspects are not yet visible when studying early inventions since new problems arise with the scale-up and diffusion of novel energy technologies (Gallagher et al., 2012). These pathways and interactions with other systems are thoroughly uncertain, which is why this type of problems were referred to by Rittel and Webber (1973) as “wicked problems”. Their so-called “wickedness” can be expected to increase with a tighter integration of the transport- and energy systems (Yeh et al., 2024). Costs need to be kept at a maintainable level for the technology to be successful. There are also environmental limits; in trying to curb GHG emissions there is a risk of causing other problems, due to overuse of finite resources. Water is needed to produce electrolytic hydrogen, and the production of renewable electricity and biomass requires land. Before scaling up any energy system in transportation, we need to make sure that limits on these resources will not be transgressed.

Previous developments of transportation system technologies have focused on providing better services, like increasing comfort or speed (Grübler & Nakićenović, 1991). When attempting to promote technologies that should provide approximately the same service, but using renewable energy, we need policies that support their diffusion (Gallagher et al., 2012). This can be expressed as an act to change the "technological landscape" (Geels, 2002), for which new technologies typically need support to go from niche applications to the more mainstream landscape (Unruh, 2000). As part of the Green Deal, there are several policies aimed at guiding the transportation system in the desired direction, some of them targeting the increased use of hydrogen. These polices should be assessed in the light of any findings regarding different future pathways, to reflect on how they can better support a long-term viable system.

The aim of this thesis is to investigate consequences of future large-scale use of hydrogen in Europe, applying a wide geographical scope yet retaining a local perspective. This is done by:

- Presenting a trip-based model for simulating fuel demand from long-distance trucks, aviation, and shipping with high geospatial detail across all of Europe
- Evaluating the influence of including local factors like topography and road speed when modeling hydrogen demand distribution for long-haul trucks
- Assessing the suitability of the requirements in the Alternative Fuels Infrastructure Regulation (AFIR) for supporting hydrogen trucks
- Investigating the impact on electricity costs, water use, and land use, with a specific focus on hydrogen production, under different fossil-free fuel scenarios in transportation.

The thesis builds on two scientific papers. Paper I is concerned with developing and describing a model for simulating hydrogen demand from long-haul trucks across all of Europe in 2050, with high geospatial detail. The model is called SVENG (Simulating Vehicle Energy Use Geospatially), and it is used to simulate potential locations for hydrogen refueling stations (HRS) at truck rest stops along the highway. This data is provided to enable further studies on the energy system connected to hydrogen trucks in Europe. In paper II, this model is extended to simulate energy demand for the entire transportation sector (cars, buses, trucks, shipping, and aviation), considering individual flows where applicable, to create a bottom-up representation of hydrogen demand.

The data is used for different assessments. In paper I, the simulated hydrogen demand is compared to the hydrogen refueling infrastructure capacity required by the Alternative Fuels Infrastructure Regulation (AFIR) (European Union, 2023c). The impact on refueling infrastructure distribution from the model's capability to calculate truck power requirements using local characteristics on route is also evaluated. Paper II investigates impacts from the different fuel technology pathways on energy generation and cost, local water stress, and land use. This is done for five scenarios, representing separate pathways in the energy transition of transportation, which consider different levels of diffusion of battery electric vehicles, hydrogen, electrofuels, and biofuels in the different transportation segments. Ammonia, steel, plastics and refineries are modeled for industry, constituting a new dataset of heavy industries with a potential for future large-scale hydrogen demand.

To provide a frame for discussing the results from paper I and paper II, and their relevance to the ongoing energy transition, the thesis also includes a section with reflections on the philosophy of science in relation to modeling energy systems.

While technologies labelled low- or zero emission generally cause some GHG emissions during their life cycle, this thesis is not attempting to quantify the global warming potential of the different pathways. This thesis neither models any impacts from future potentially disruptive technologies, or the impacts of any demand-side measures.

2. Concepts

Many perspectives are relevant to understanding the implications of the energy transition in transportation. The technical potential of certain energy carriers, the current policy landscape on the EU level, and the methods and models used to project the future market and assess different alternatives are all part of the interdisciplinary knowledge needed in order to discuss the current state and the implications of selecting one pathway over the other.

2.1. Energy transition technology alternatives

As briefly described in the introduction, there are a number of solutions available for carrying energy without relying on fossil fuels.

Batteries can store electricity onboard a vehicle with very low losses, making it the most energy efficient alternative. However, batteries have traditionally been heavy (which increases the energy use somewhat) and large (which may decrease the cargo space). Additionally, they have a comparatively short range, and charging can take long time, although expected developments in battery and charging technology could improve this.

Hydrogen, on the other hand, could extend the range of vehicles. It is also lighter and faster to refuel than battery electric systems. However, the round-trip efficiency of a hydrogen-based system is lower, due to losses in both production and reconversion of hydrogen. This requires more electricity in total for the same work performed. Both battery-electric and hydrogen-based systems require new drivetrains, where the development of battery electric ones are currently progressing faster, which lowers the cost, meaning that a hydrogen vehicle is currently considerably more expensive. There are also very few locations where hydrogen is available for refueling vehicles, and deploying this system would require a large buildout of supporting infrastructure.

Electrofuels are synthetic energy carriers produced by combining electrolytic hydrogen with carbon dioxide or nitrogen. Depending on the type of energy carrier, they can be used with conventional drivetrains, with little or no vehicle adaptation, or they could be used in specific fuel cells. They can either be carbon-based, like methane, methanol, or synthetic diesel, or they could be carbon free, like ammonia. While being considerably less energy efficient in a well-to-wheel perspective, than batteries or pure hydrogen, and currently still expensive to produce, they are easy to transport and store and could utilize existing infrastructure.

Biofuels are liquid or gaseous fuels created through processing biomass. They are currently cheaper to produce than electrofuels and can be blended into, or replace, conventional fossil fuels in a similar way. Some biofuels are already on the market, either as a fuel on its own (as e.g. HVO100) or blended into conventional fuels.

2.2. Applicability of solutions to different transportation modes

The characteristics of different technologies make them more or less suitable for different applications.

So called "light" road transportation (cars, vans, etc.) is seeing a growing share of sales being battery electric (Hardman et al., 2024). Trucks have been slower to electrify, but sales shares are starting to increase in recent years (IEA, 2024). Hydrogen cars have existed on the market for a few decades, without sales taking off (Collins, 2024), but the longer range and shorter refueling times for trucks compared to battery electric setups (Zhang et al., 2025) have made hydrogen an interesting option for heavy long-haul applications. However, the rapid development in battery- and charging technology and potential for operational adaptations might mean that batteries can sufficiently cover the majority also of long-haul missions (Plötz, 2022). Conventional vehicles can be powered by fossil-free electro- or biofuels, which would extend their lifetime without relying on fossil energy.

It has been suggested that a significant portion of shipping could be operated on batteries (Kersey et al., 2022), but cost-competitiveness for different fuels in shipping varies between shipping segments (Kanchiralla et al., 2024). With different characteristics, hydrogen, or electro- and biofuels, could be preferrable in certain applications. Electro-methanol and Electro-ammonia, although less energy efficient, could transport larger volumes of cargo for longer distances, and methanol is currently the technology of the above with the largest order book in terms of total ship goods volume (DNV, 2024). Methanol and ammonia, additionally, are chemicals that are already handled in ports for other end uses, and adapting the supply chain for them might prove easier than electricity or hydrogen (Hoang et al., 2023). Hydrogen and electricity are more energy efficient, but might be more preferable for operations on shorter and more regular routes with predetermined access to energy (Hydle Rivedal et al., 2022).

For aircraft, there has been some tests with battery electric propulsion, where it is expected to mostly operate on shorter routes, due to the high weight of the batteries (Amadori et al., 2023). Hydrogen is projected to be able to run medium distances in the future (Svensson et al., 2024), while the long-haul flights (representing the vast majority of total energy in aviation) have higher power requirements and are easier served with jet engines, potentially using electro- or biofuels (Dahal et al., 2021). In this context, these fuels are often called sustainable aviation fuel (SAF), generally referring to drop-in fuels for aviation with a lower carbon footprint than fossil kerosene.

2.3. EU energy transition policies of interest to this thesis

Under the umbrella of the EU Green Deal (European Council, 2024) there are a number of policies aimed at facilitating the energy transition.

The Renewable Energy Directive (RED) (European Union, 2018) and its amendment (European Union, 2023d) stipulates that by 2030 at least 42.5% of the EU energy use should be from renewable sources. For transportation, there is a sub target for countries to choose to fulfill either 29% renewable energy or a 14.5% GHG intensity reduction by that year. Direct electricity, advanced biofuels and renewable fuels of non-biological origin (RFNBO) are counted with a higher energy content weighting towards the RED for certain applications. Annex IX of the RED contains a list of all biomass feedstocks considered not to be in competition with food and feed production, where part A is listing mostly agricultural and forestry residues for advanced biofuels and part B is listing used cooking oil and leftover animal fats. These are of special relevance, since they are considered to be sustainable feedstock streams and are thus favored in RED and other policies. Additionally, the RED requires 1.2% of the fuel supplied for ships in ports to be RFNBO in 2030.

The European Union Emissions Trading Scheme (EU ETS) (European Union, 2003) is a "cap-and-trade" mechanism, limiting the total emissions from included industries, but allowing enrolled entities to trade emission allowances with others. Aviation has been included for more than a decade (European Union, 2023a) but only covering flights within Europe. Shipping is included since 2024, and road will be included in 2027 (European Union, 2023b). For aviation and shipping, it is the emissions from the transportation activities themselves that is regulated, but for road it is the upstream fuel producers that will be subject to cap-and-trade for the expected emissions from the fuel they sell. For aviation, the use of SAF will for a certain period make the aircraft operator eligible for receipt of allowances covering part of the price differential between SAF and conventional jet fuel.

The AFIR (European Union, 2023c) stipulates requirements on access to fuel for different energy types in road transportation and shipping. For heavy-duty trucks, in relation to which AFIR is mainly discussed in this work, a certain number of charging points and HRSs are mandated at certain intervals along the Trans-

European Transport Network (TEN-T) (European Union, 2024a). For HRSs, this means one per 200km along the TEN-T core, and one in each urban node, according to the TEN-T definition. Each HRS needs to hold at least one pump, suitable for both light- and heavy-duty vehicles, with the capacity to store and dispense at least 1000 kg hydrogen per day.

The EU "heavy-duty vehicle CO_2 standard" (European Union, 2024b) requires that truck and bus manufacturers ensure that the fleet of vehicles sold in a year emits a certain percentage less CO_2 than the fleet sold in 2019. For trucks, this percentage increases in five-year increments until requiring a 90% reduction from 2040 onward. Buses sold by 2030 are already required to emit 90% less, with the limit reaching 100% by 2035. Cars and light-duty vehicles have their own standard (European Union, 2019), mandating decreasing emissions in five year increments until also reaching 100% by 2035.

FuelEU Maritime (European Union, 2023e) stipulates that the average GHG intensity (emissions per unit of energy used) of each ship with a gross tonnage above 5,000 needs to decrease by a certain percentage compared to a predetermined benchmark value (91.16 gCO_2-eq/MJ). The percentage increases every five years, until requiring an 80% reduction from 2050 onward. The use of RFNBO is rewarded with a "double reduction" of emissions during the first years of the policy. For ships on voyages between EU ports, 100% of the emissions are considered. For ships arriving from, or departing to, ports outside of the EU, half of the voyage emissions are considered.

ReFuelEU Aviation (European Union, 2023f) mandates a certain amount of SAF and renewable hydrogen make up at minimum a specified share of all fuel sold at European airports (except some with low annual throughput). This share is increased every five years, reaching 70% in 2050. Additionally, a certain share of the total sold SAF needs to be synthetically produced starting in 2030, reaching 35% in 2050, meaning that out of the total fuel sold 24.5% needs to be RFNBO. The remainder is allowed to be biogenic, although this share can only be produced from Annex IX feedstocks detailed in the RED (European Union, 2018) discussed above.

2.4. Energy systems modeling

Modeling allows abstraction, simulation, and "pseudo-experimentation" with a complex system (Helmer & Rescher, 1959) by reducing its complexity (Köhler et al., 2019), which is why it is often used to study one or more aspects of the energy system (Pfenninger et al., 2014). Objects of study at a society level of interest to include in energy systems modeling could be technology substitution, sector coupling, and energy system evolution; effects studied could be on e.g., costs, total emissions, or resilience. Choice of included technologies, and how these are represented, vary widely, as do the level of detail in certain dimensions, notably spatial and temporal (Ringkjøb et al., 2018). A large and growing range of frameworks are available, and they are applied to problems depending on a number of factors, like the aim of the research, the available data and hardware, and the preference and skills of the researcher (Silvast et al., 2020).

Linear (or integer/binary/nonlinear) optimization is often used to represent technologies and their investments and operation under a certain goal (like fulfilling some demand) and study their interactions in minimizing some outcome (typically cost). Studies for investigating a future European hydrogen supply chain are of special interest to this thesis. As an example, Neumann et al. (2023) optimized investments and operations of the whole electricity system, with a pronounced demand for hydrogen, and studied the effects on total system costs of allowing investments in a hydrogen pipeline and/or the electricity grid. Kountouris et al. (2024) compared the total system costs from optimizing the European energy system under different hydrogen supply strategies, like allowing imports and/or the production of blue hydrogen. Studies like these can improve our understanding of the implications of certain technological strategies.

The potential for high technical detail of optimization studies is one of their appeals, but at the same time it risks making problems exceedingly large, necessitating some simplifications and omissions to make them tractable (Pfenninger et al., 2014). Especially complex is the representation of the systems "surrounding" the technology, like the wider economic system, and even more so the interactions with human behavior and society. This is rarely represented in models (Krumm et al., 2022). Even when this representation is attempted, it is done rather rigidly, like the limits to renewables deployment in the Multinode model used for this study (briefly discussed in chapter 7) to account for public acceptance issues. And while the studies by Neumann et al. (2023) and Kountouris et al. (2024) mentioned above are very detailed, there are several aspects left out of the studies. One example – again with specific relevance to this thesis – is that neither of these two models consider different possible energy transition pathways in the transportation sector, which is itself a complex manifestation of political- and consumer choice in a sociotechnical system. This simplification is necessary both for the tractability of the problem, but also likely for the communication of their results. Nevertheless, it leaves more questions to answer, generally done through new modeling efforts, or uncertainty analyses, adding to the picture piece by piece.

Simulation is used for some problems, allowing system representations with more open and flexible mathematical formulations. As an example, Shoman et al. (2023) simulated the charging demand from battery electric trucks along European highways in 2030, and calculated the number and position of slow- and fast charging connections needed to meet it. Neuwirth et al. (2024) simulate the re-investments and upgrades in hard-to-abate industries across Europe under different scenarios on e.g. electricity- and hydrogen prices, to understand the potential rate of diffusion of certain technologies for decreasing their environmental impact. Both these studies represent possible system behavior in different ways, which allows answering questions from a standpoint of alternative perspectives. In this case, they contribute to the understanding of potential future geospatial distribution of demand for certain types of energy carriers. This can also be studied using optimization, as was done by e.g. Rose and Neumann (2020) and De Padova et al. (2024) investigating locations for, and demand at, hydrogen refueling stations. However, the computational burden from large datasets when using this approach means these studies face limitations on the geographical scope and number of different fuel options, not to mention technical detail. At the same time, economic optimization represents a rational behavior of consumers and industrial agents, providing an understandable logic to system organization which provides a different perspective to the simulations.

3. Energy systems modeling – a science?

As discussed in the introduction, the diffusion of novel energy technologies implies a change in the technology landscape (Geels, 2002). For societal planning, particularly in transportation (Grübler & Nakićenović, 1991), this poses a wicked problem (Rittel & Webber, 1973) exacerbated by lock-in of carbon technologies (Unruh, 2000). One central rationale for carrying out energy systems modeling activities is to assist in navigating these complexities (Pfenninger et al., 2014).

There are many different kinds of energy systems modeling. Problems could be concerned with the investments in, and operations of, a technical system in a strictly delimited engineering setting, or with understanding technology integration on a societal level, often in the interest of policymaking and governance. This thesis, and subsequently this chapter, is focused on the latter. Personally, I tend to think of this work as "research". For me, that word connotates an exploratory, iterative, and focused (albeit not always structured) search, for perspectives, considerations, understanding, or learnings about different aspects of the energy system.

However, when discussing, planning, and arguing over the whats and hows of research activities, one often revisits the discussion on whether a certain course of action could qualify as "scientific". Many values are obviously attached to that word, and researchers strive to uphold them in their practice. But what are those values? And how do they apply to society level energy systems modeling? Studying the future of chaotic sociotechnical systems under hypothetical scenarios, attempting to understand some out of an incomprehensibly large number of outcomes and effects, implies colossal uncertainty. This has prompted some, like Hoffman and Wood (1976) and Laitner et al. (2003), to refer to energy systems modeling as a form of *art* rather than science. Do classifications like this matter for what energy systems modeling results can be used for? Or their value to society? The purpose of this chapter is to reflect on the character, practices, and aims of energy systems modeling, and discuss those in relation to different definitions of science, to better understand their role and usefulness.

3.1. Classical notions of science

Most likely, Sir Karl Popper wouldn't think that energy systems modeling would pass for a form of science. One of the most influential philosophers of science, his criteria for science was that it should contribute to more accurate descriptions of the world, and accuracy should be ascertained through constant attempts at refuting one's own findings (Popper, 1953). Providing validations for a theory is not enough; only theories that could theoretically be tested and disproven would count as science. However, attempting refutation of an energy systems model or its results is likely impossible due to the complexity and changing nature of a sociotechnical system. Additionally, overcoming (or side-stepping) this complexity is the main rationale for using a model, as mentioned in the introductory paragraph of this chapter. This makes simplifications, estimations, and assumptions about a system necessary. If falsification was theoretically possible, it would defeat the purpose of the modeling effort, which was to save time and costs of actually constructing, deploying, and testing a system in practice. Furthermore, the emphasis of assessing technologies in a *future* system means most models would require validation by time-travel. Uncertainties thus seem to be an inherent attribute of forward-looking energy system models.

The notion of science as a strive for uncovering a set of fundamental laws describing the world is often referred to as "reductionism" (Ackoff, 1973), but has also been called "scientific monism" by e.g. Kellert et al. (2006). Prigogine (1988) described this as a quest to find a "knowledge of the world that God would have", and many classical schools of thought have emphasized some form of this goal. However, the complexity of problems associated with the development of society spurred criticism of the traditional reductionist view on science already more than a century ago. The German sociologist Friedrich Engels voiced his disapproval of this conception, and its transfer to other sciences like history and philosophy, writing:

> *"The analysis of Nature into its individual parts [...] were the fundamental conditions of the gigantic strides in our knowledge of Nature which have been made during these last four hundred years. But this method of investigation has also left us as a legacy the habit of observing natural objects and natural processes in their isolation, detached from the whole vast interconnection of things; and therefore not in their motion, but in their repose; not as essentially changing, but as fixed constants; not in their life, but in their death."*
>
> (Engels, 1877)

However, the reductionist objective of finding a definitive law is not shared with energy systems modeling. As discussed above, the purpose is rather to assist in navigating complex and ever-changing challenges, even though they can't necessarily be subjected to one unified set of rules. This difference in goals underlines the irrelevance of strict law-seeking in modeling. Does this mean that it is not to be considered scientific?

3.2. Modern notions of science

More recent works have provided new ways of thinking about science. Simon (1996) differentiates between practices concerned with understanding how the world *is* and how it *ought to be*. The latter, in his view, should be called "artificial sciences", as opposed to natural. Within this definition, any activity intended to improve a certain outcome should be defined as a "design". Niiniluoto (1993) states that, while initially all professions were based on some kind of "rule of thumb" practice, over time professions have been subject to "scientification", with increasing emphasis on formalizing rules for governing practices with the aim of improving them. He calls these improvement activities "design science", which are distinct from the practices themselves. Design- or artificial science doesn't have to be concerned with product development, it could as an example be improving agricultural yields by informing farming (practice) using agronomy (design science). Simon (1988) specifically uses linear optimization (a mathematical framework commonly used in energy systems modeling, as described briefly in section 2.4) as an example of artificial science. He says it allows exploring the preferable "inner environment" of different "possible worlds" meeting the criteria of an "outer environment", thus providing one formalized methodology for the pseudo-experimentation defined by Helmer and Rescher (1959).

Other attempts to recast definitions of science to allow dealing with complexity have gained popularity since the late 20th century; in contrast to scientific monism, Kellert et al. (2006) call one of these viewpoints "scientific pluralism". This view claims that a combination of many scientific efforts are required in order to represent different aspects of a problem; scientists will never arrive at one complete unified model for science, but must rely on understanding different (sometimes conflicting) perspectives. Aligica (2003) pointed out that classical physics provided a model that could simultaneously *explain* why nature behaved in a certain way and *predict* how it would behave given certain conditions; and that this requirement has subsequently been imposed on all other fields of science. He argues that research included in what he terms *future studies* should not be expected to comply with such criteria, but rather be seen as input to assist expert discourse. Ackoff (1973), discussing what he calls the *systems approach*, furthermore underlines the importance of not only relying on many different representations of a problem: this *multidisciplinary* practice might just as well be a sort of multi-reductionism, viewing different aspects of a problem in isolation without understanding how they connect or interact. Instead, an *interdisciplinary* approach is needed, where not only individual perspectives and inquiries are acknowledged, but also their relative dependencies to each other and the surrounding environment.

This plays into the *systems theory* model for scientific inquiry suggested by Capra (1988). He urges using “networks” as a metaphor for knowledge, rather than “building blocks”, and similarly moving from reliance on “structures” as a metaphor for the constituents of scientific world descriptions, towards one based on “processes” that are inherently interdependent, this should allow descriptions of reality to be dynamic and context dependent. Whereas old descriptions of science have been considered “objective”, this new paradigm should acknowledge the inevitability of personal or structural values being embedded in research. As such, they should be clearly “epistemic” – all science must explain how they define what can be known about the subject under study. History has shown that even the basic sciences’ descriptions of reality are not and cannot be complete, which also means that the scientific quest should be seen as one for “approximate descriptions” rather than an objective “truth”.

Artificial- and design science, as well as scientific pluralism, future studies, and interdisciplinary systems theory, all present frameworks with which energy systems modeling practices could be described and discussed from a scientific perspective. Many of the scientific perspectives discussed above are being carried and balanced by energy system modelers in their daily work (Silvast et al., 2020). However, the broader relevance of energy system modeling often pertains to policymaking (Pfenninger et al., 2014), and in the context of planning and public discourse, science has a particular standing: the label “scientific” is often used to assert judgments to be “objective” in public discourse on energy systems, especially drawing on the communicative power of quantitative results (Aykut, 2019). This is important for researchers and politicians alike in order to protect themselves from accusations of biased or bad decisions (van den Hove, 2007), often in support of what they (usually somewhat mistakenly (Azar & Sandén, 2011)) call “technology neutral” policies. This may result in a misuse of energy systems modeling results, bolstered by the scientific label, and is one of the reasons for e.g. Feyerabend (1993) being a vocal opponent of an elevated status of science altogether.

Thus, while there are multiple lenses through which energy systems modeling can be seen as scientific, there may be a disconnect between energy system research epistemology and the societal understanding and use of energy systems modeling results. The following section discusses some of the aspects that affect the context of modeling practice, and by extension the modeling results, in a way that may be useful to consider in scientific discourse.

3.3. Scientific context of energy systems modeling practice

In an ethnographic study of energy systems modelers in the UK carried out by Silvast et al. (2020), almost all participants stressed that their "models should not be used for predictive purposes […] because they cannot represent future uncertainty well enough". While large uncertainties are a common criticism of energy systems modeling (see e.g. Laitner et al. (2003) and Trutnevyte (2016)), this indicates that modelers are aware of the problems with predictability in future studies (Aligica, 2003), and have a focus on approximate descriptions in line with systems theory (Capra, 1988). Additionally, the modelers in the study by Silvast et al. (2020) state that policymaking is one of the most important purposes of their work. This is in line with Helmer and Rescher (1959) and Aligica (2003), who stress that one of the fundamental values of models is to allow experts and stakeholders to come together for decision-making in a structured and manageable option space (Brill, 1979), rather than provide definite truth.

By limiting and packaging the alternative outcomes to decide between, modelers contribute to the facilitation of decision-making, which apart from what options are chosen, also narrows the range of options emphasized in planning. Assuming a constructionist perspective, Longino (1990) proposes a view that researchers' scientific choices of things like problem formulations and methods are directly shaping the progress of society. Aykut (2019, emphasis in original) describes this aspect in energy systems modeling as influencing the "*discursive context* of policy-making by reducing the undetermined, 'open' future into an actionable set of 'plausible' development trajectories." It is thus important to be mindful of the way social, individual, and material aspects influence this task. But even if modelers carefully consider their own influence on the research results, communicating them to stakeholders introduce a multitude of further complexities. Ascough II et al. (2008) define two types of uncertainty in social interaction and communication: *decision-making* and *linguistic*. The former represents that when communicating with stakeholder groups, there is uncertainty in how (or whether) the results will be put to use, due to the values, knowledge, and goals of the people engaged in the discussion. The latter represents the difficulty in predicting future usage of results simply due to poor or mismatching communication, either through the use of vague or ambiguous wording, local jargon or abbreviations, or using explanatory structures that do not fit examples of a problem that relate well to the audience.

Being aware of and managing the influence of individual values, also in discussion with others, promotes epistemological clarity and thus plays into the systems theory model proposed by Capra (1988). It also necessitates reflecting on the way scientists' values and context of affect their work. Like Capra, Longino (1990) insists there cannot be objective science; the background, training, preconceptions, local situation, and experience will always influence the scientist in all aspects of their daily work. This has an effect on all aspects of the research endeavor, from issues of *which* questions are pursued, to *how* they are pursued, and *whose* perspectives are considered. This is also considered by Lakatos (1968), but with more emphasis on material and professional structures than social ones. In the case of energy systems modeling, this value-based influence is exerted through the selection of what groups in society to represent, which technologies to include, and in what manner these are represented, to name a few aspects (Laes, 2019). Different outputs can be generated when different models are used to study the same problem, as shown by Ruhnau et al. (2022). This suggests such structural aspects could have a potentially large influence of results.

Interdisciplinarity, a central part of the systems thinking model as defined by Ackoff (1973), serves to overcome some of the potential pitfalls of a skewed representation of values and backgrounds in a scientific group. By integrating perspectives across and between fields, knowledge can be built in the network structure proposed by Capra (1988), and researchers can build a more holistic understanding. However, there are many obstacles to truly interdisciplinary research, like insufficient skills in interdisciplinary work, and unfit funding schemes and publication processes (Schuitema & Sintov, 2017). One traditionally underrepresented field that has received more attention in recent years is social science. Sovacool et al. (2015) claims that the historic lack of social perspectives in energy science has stifled the field. They point to the strict focus on novel hardware as a factor limiting the usefulness of results. In their view, this may in part be attributed to the skewed representation of practitioners in the field. A majority are engineers or economists by training, leading to an emphasis on quantitative studies, which might neglect unquantifiable aspects to energy transition challenges. Also, the fact that most researchers are male and/or westerners from affluent institutions limit the level of heterogeneity in perspectives (Sovacool et al., 2015), one example of which can be seen in the geographical scope of studies on hydrogen systems (Zhang et al., 2025).

So, even though large-scale energy systems models focus on sociotechnical systems, the "socio" part is mostly rather crudely represented in energy systems models (Krumm et al., 2022), often as some kind of exogenous factor. Acceptance to deployments of renewable energy technologies is one area that has been readily identified as important to the future energy system, but still cannot be represented satisfactorily in models since it can't be sensibly understood in a generalized and quantitative way (Tsani et al., 2024). As per the example mentioned in section 2.4, this is represented by a percentage limitation on deployments on eligible land in the Multinode system used for this thesis. Sent (2006) claims that similar shortcomings in representing a heterogenous population are shared with economics, since the sum of economic welfare is calculated without consideration for the qualitative benefit to each individual. Agents are often aggregated into a single representational idiom, which can't mirror a diverse population. This inability to account for the many dimensions of variety in demographics and personal experiences and preferences, according to Sent (2006), creates overly mechanistic descriptions of society, which do not represent that the whole can be more than the sum of its parts, an important aspect of the systems approach (Ackoff, 1973). While optimization or simulations often rely on average agents following an economic rationale, ultimately the individuals making up society, with their different backgrounds and preferences, will collectively pick winners and losers in the energy transition (Gallagher et al., 2012). This means that subjective experience and local and momentary conditions can be more important than strict economic rationale in decision-making (Kahneman & Tversky, 1979; Simon, 1990). Energy systems researchers might never, due to what Edwards (2010) calls "data friction" and "computational friction", be able to completely represent these aspects in models. As discussed in the beginning of section 3.1, however, this is not the point of models. This rather serves to demonstrate some of the embedded complexities in interdisciplinary energy systems modeling, which require careful considerations of systems theory science.

This complexity, however, begs the question: Is there any point? Should researchers' time and energy be spent on trying to model problems that are obviously too massive to represent in a computer? Coyne (2005) claims that "wickedness" is the norm, not a modern deviation, and that attempts to define rationality over societal problems as generalized and rigid structures are mistaken – problems always need to be solved in their specific context. Any design (which, according to the definition by Simon (1996) described in section 3.2, could be e.g. a plan for an energy system) need to depart from locally specific context, assume that the solution is non-generalizable, and that it will never be perfect for everyone. An immeasurable number of values and viewpoints need to be balanced – in a research team or a group of decision-makers, yes, but even more so across multiple diverse cultures and societies. Priorities, wisdom, and the role of science, art, morality, and other concepts, vary between cultural systems, and their authority rests on the convictions of validity upheld by individuals in a group (Geertz, 1993). This needs to be considered and managed in any societal planning, which suggests that neither energy systems modeling nor any other field of science should be seen as a problem-solving panacea.

What does this mean for the status of science in public discourse? Feyerabend (1993) objected to a too narrow definition of “rationality”, based only on science. Even when trying to include many scientific perspectives, he writes that the result is a “patchwork” representation of reality, that can’t give the full picture of the world. This view could possibly be summarized as a version of multidisciplinarity as defined by Ackoff (1973) (briefly discussed in section 3.2), a sort of failed, multi-reductionist, attempt at interdisciplinarity. Feyerabend suggests that what is termed rationality should include not only science, but culture, art, and other values as well. Only then can rationality represent reality. This would be a more radical extension of interdisciplinarity and the systems approach, as defined by Ackoff. Considering the wicked and multidimensionally varying contexts in energy systems modeling, this extension might be valuable.

If we return to the suggestion that one of the most important applications of energy systems modeling is in policy- and decision-making (Silvast et al., 2020), then e.g. policymaking could be seen as a *practice* that modelers are attempting to improve. This would make energy systems modeling fit into the design and artificial science definitions by Simon (1996) and Niiniluoto (1993). While they more or less directly encapsulate many aspects covered by systems theory and its adjacent models, these frameworks are distinguished by a focus on the application and utilization of the results. Assuming a somewhat extreme perspective on design science, then if energy systems modeling activities aren’t aimed at assisting policymaking, then the modeling isn’t scientific. The importance of utilization again emphasizes the role of energy systems modeling as discourse facilitation, suggested by e.g. Aligica (2003), discussed in the beginning of this section. Utilization is, indeed, in itself important, but maybe *how* utilization happens is a deciding factor for whether modeling is scientific? Silvast et al. (2020) conclude that modelers themselves are aware of the epistemological considerations in models, but can scientific modeling results really be scientific if their utilization is not? For the whole research process to be scientific, also after results leave the desks of the modelers, maybe a critical aspect is to embed systems theory in communication. A greater emphasis on seeing results through to their application might allow broader interdisciplinary integration of perspectives, important to societal planning (Coyne, 2005).

Perhaps some of these considerations can distinguish scientific from non-scientific practice. Or, maybe it doesn’t matter if we call the practice research, science, or art. Ultimately, most good might be done by following the suggestion by Coyne (2005):

> “We have to be both scientist and poet.”

4. Modeling context and methods

The SVENG model, built for this thesis, is used to assess different aspects on the geospatial hydrogen energy system in Europe 2050. This has been done through simulation of hydrogen demand, policy assessment, energy systems optimization, and water- and land use assessment, for different scenarios and cases in the two included papers.

4.1. Scenarios and cases

In paper I, when modeling the distribution of hydrogen demand from a future European hydrogen truck fleet, we investigated six cases along two dimensions. For the *Base* case, on which the majority of the analyses are based, we assumed that 15% of all long-haul trucks were running on hydrogen, and that they were equipped with 75 kg hydrogen tanks. These parameters were varied independently for the other cases: three other cases also assumed 75 kg tanks, but 5%, 25%, and 35% diffusion rate of hydrogen trucks in the long-haul segment. Conversely, assuming a 15% diffusion rate, for two other cases the trucks were instead assumed to have 60 kg and 90 kg tanks.

In paper II, when modeling the future geospatially distributed hydrogen demand from both transportation and industry, the focus of the different scenarios is to represent five different pathways for the energy transition in the transportation sector. These are used to simulate a larger scope of hydrogen demand with high geospatial resolution across Europe. For each scenario, the share of a certain fuel used in a specific transportation mode is represented as a percentage of its total transportation work. See figure 1 for an overview of the assumed fuel diffusion in each transportation mode and scenario.

Road is represented by four different categories: cars, buses, regional freight, and long-haul freight. Shipping is divided into seven categories: liquid bulk, dry bulk, container, roro, other freight, cruises, and ferries. Aviation is segmented on flight distance: short (<300km), medium (300-2000km), and long (>2000km). The different energy types included are (battery) electricity, gaseous and liquid hydrogen, electro-ammonia, electro-hydrocarbons, and biofuels. Electro-hydrocarbons are represented as Fischer-Tropsch (FT) liquids in road, electromethanol in shipping, and through methanol-to-jet in aviation. Biofuels are considered produced as FT-liquids for road, biomethanol for shipping, and through ethanol-to-jet in aviation.

The *Fuel mix* scenario is designed to represent a mix of solutions in the future transportation energy system. The other four scenarios, *Elec prio*, *H2 prio, E-fuel prio*, and *Biofuel prio* each depict a future where one of these solutions are prioritized and used to a large extent. In each of the scenarios, the industries considered in the study are assumed to all convert their processes entirely to run on electrolytic hydrogen. These demand scenarios are narrative pathways (Aykut, 2019), designed to represent plausible trajectories, yet clearly represent extreme cases. Rather than attempting to deduce the "actual" future state, this manner of building a model serves to communicate the uncertainty of the future, and spanning up a "decision space" (Brill, 1979) that is clearly theoretical and exploratory. The scenarios are designed with consideration for the EU policies described in section 2.3.

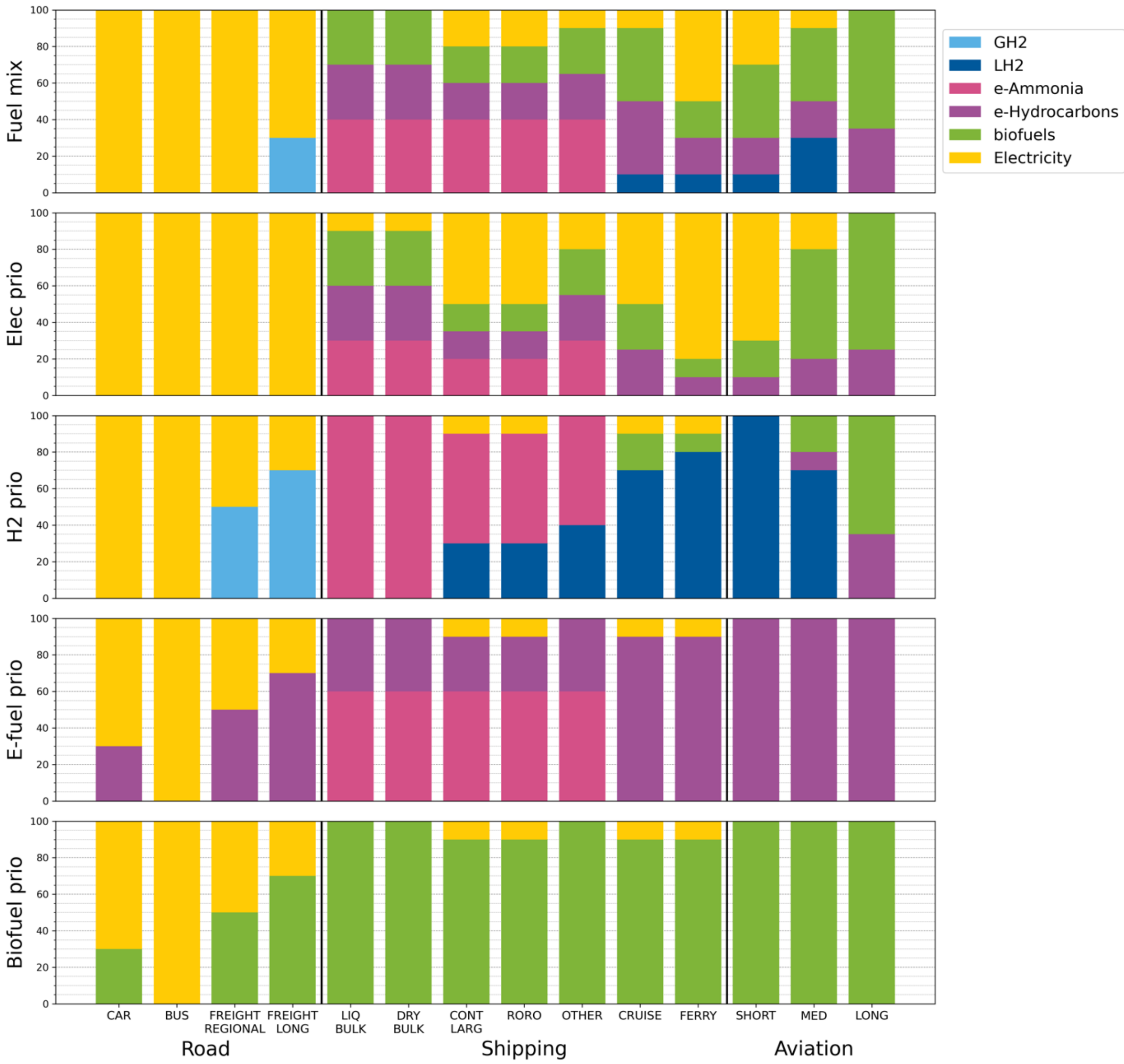

Figure 1: Share of total energy for each fuel type used in each transportation segment, for all scenarios in paper II.

4.2. Geospatial simulation of hydrogen demand

The simulated geospatial hydrogen demand distribution for long distance trucks, shipping, and aviation is based on data from the ETISplus database (Szimba et al., 2013). It contains data on flows of passengers and goods using different modes of transportation across all of Europe in 2010, which is used to calculate the location and amount of energy use for different fuels. The data has high geospatial resolution, generally on NUTS3-level (Nomenclature of Territorial Units for Statistics (Eurostat, 2021)) representing the most detailed level used for statistical purposes in the European Union. When calculating demand for shorter range transportation, considering liquid fuel for cars and buses, it was based on total EU transportation work from the JRC IDEES EU-dataset (Rózsai, 2024). For the energy use for cars and buses with electric propulsion, data from the Multinode model was used.

Linear regression models

To extrapolate the levels of transportation work in the dataset to 2050, linear regression was used to correlate annual transportation work for the period 2010-2019 from Eurostat (2023a, 2023b, 2023c, 2023d, 2023e) with GDP_{PPP} for freight modes and GDP_{PPP}/capita for passenger transportation from the World Bank (2023a, 2023b) for the same period. This was done on a country-by-country basis for each transportation mode, considering outgoing transport. Truck freight was computed separately between national and international volumes, and shipping was computed separately between the included ship types listed in section 4.1. The IIASA GDP projection for 2050 (IIASA, 2024) under the Shared Socioeconomic Pathway scenario 2 (SSP2) (Riahi et al., 2017) was then used with the individual linear regression models for each country and transportation mode to calculate its individual transportation work growth factor. The same procedure was used for the entire EU in bulk when extrapolating transportation work for cars and buses from (Rózsai, 2024).

Routing

To calculate and distribute energy demand, we considered simulated routes taken by the different transportation modes. For trucks, the route data simulated in Speth et al. (2022) (also used by e.g. Shoman et al. (2023)) was used. For shipping, we used the python plugin searoute.py (Halili, 2023) to calculate the sea distance between trading regions. For aviation, the distance between two airports was mostly included in the ETISplus dataset, but where missing this was calculated using the python plugin haversine.py (Rouberol, 2023).

Energy use calculations

The energy use distribution algorithm for trucks is described in detail in paper I. The route data was overlaid with topographical data from the European Space Agency (2023), and knowing the distance, speed, and inclination of each link on the route, the power and subsequently energy required to traverse each route segment could be computed. In paper I, it only applied to long-haul hydrogen trucks. In paper II, this algorithm was also used to calculate the energy demand from trucks with other drivetrains. Energy use for cars, buses and local truck freight was calculated using different average energy use factors applied to the total transportation work, described in Supplementary material of paper II.

For ships, the average energy use per transportation work in tonnes multiplied by km (tkm) for each of the different ship modes was calculated from the EU MRV (2019) reported energy use from ships in European waters. This factor was then used to calculate the energy use for a certain route based on the simulated distance and amount of goods flow. To represent different drivetrains, different factors were used to relate their energy efficiency relative to a conventional ship engine, which is detailed in paper II.

For aviation, energy use figures per passenger multiplied by km (pkm), for a simulated average aircraft in 2050, in three different distance segments, were shared by an industry expert. Similar to shipping, the energy use for each route was calculated based on flight distance and the number of annual flights. To account for differences in total system efficiency between future aircraft, an adjustment factor was applied to the different propulsion systems, also detailed in paper II.

Energy demand distribution and infrastructure aggregation

Demand for (battery) electricity and hydrogen for direct use is, for shipping and aviation, allocated for each journey back to the port/airport of departure. For hydrogen trucks, a search algorithm is used on each route to estimate where 70-90% of a hydrogen truck tank would be depleted and distribute the hydrogen demand along those nodes. On arrival, the tank of the truck is considered to be filled up in the nodes closest to the point of arrival. When all energy is distributed to the nodes, another algorithm is used to aggregate them into discrete HRSs, which are in turn distributed to current truck rest stops and existing refueling stations. The same algorithm for demand distribution is used for battery electric trucks, but not for aggregating discrete charging points.

All simulated demand for liquid fuels, i.e. biofuels, electro-hydrocarbons, and electro-ammonia are aggregated and distributed onto designated production facilities. The two former are distributed onto existing refineries, relative to their EU-ETS reported emissions as per Manz and Fleiter (2018). The same approach is used for distributing electro-ammonia, but onto existing ammonia plants relative to (and on top of) their current ammonia output (see paper II).

Amount and location of steel production comes from Global Energy Monitor (2024), ammonia from a number of databases and searches (listed with references in Supplementary material to paper II), and high value chemicals (HVC) from Neuwirth et al. (2024). Their hydrogen demand is calculated for producing current output with a hydrogen-based process. Current production volumes are assumed for all industries.

4.3. Assessing the AFIR

In paper I, we make a comparison of the simulated amount of HRS capacity that needs to be built in 2050 compared to the requirements set out in AFIR in 2030 (European Union, 2023c), for each case. Some countries' demand is projected to be lower, even far later, than the required supply in 2030. This is discussed in chapter 6. In this thesis, the analysis from paper I is complemented with one on the costs incurred for building underutilized infrastructure.

For calculating the added cost of building AFIR mandated HRSs beyond the simulated demand, we assume that each additional station is of the smallest allowed size, and has a utilization rate of 0. Annual CAPEX (capital expenditure) and OPEX (operational expenditure) figures, for different sizes of HRS with onsite production of hydrogen, have been calculated by Bracci et al. (2024). The study gives no CAPEX for stations serving 1 tonne of hydrogen per day, which is the smallest size qualifying for AFIR, and would correspond to the smallest (XS) size HRSs considered in paper I. We estimated this cost by fitting a second degree polynomial curve to the data on station CAPEX cost per tonne of hydrogen capacity, for other sizes provided in the report. This was done using the polyfit function from the NumPy (2024) package, and the resulting function was used to calculate the CAPEX for a station delivering 1 tonne of hydrogen per day. The resulting function is displayed in figure 2a), with CAPEX values from Bracci et al. (2024) in red and the calculated value in blue.

OPEX as defined by Bracci et al. (2024) is given for some values on average utilization rate for each station size. No value is given for a utilization rate of 0. We fitted a linear function correlating the utilization to the OPEX cost for a 2 tonnes per day size station, in the same manner as described above. The resulting function was then used to calculate the OPEX for a station delivering 0 tonnes of hydrogen per day. This is displayed in figure 2b). Using the 2 tonnes-station (corresponding to an S size HRS in paper I) may imply a slightly higher OPEX function than the actual costs for a 1 tonne-station, but OPEX has a marginal effect on the end result.

For each country with a simulated need for HRS capacity ($cap_{country}^{sim}$) that is lower than that mandated by AFIR ($cap_{country}^{afir}$), we calculate the cost for building excess capacity $C_{country}^{excesscap}$ as:

$$C_{country}^{excesscap} = \left(C^{capex}(1) + C^{opex\_2t}(0)\right) \cdot \left(cap_{country}^{afir} - cap_{country}^{sim}\right) \quad \textit{Eq. 1}$$

where C^{capex} and C^{opex_2t} represent the two cost functions defined above.

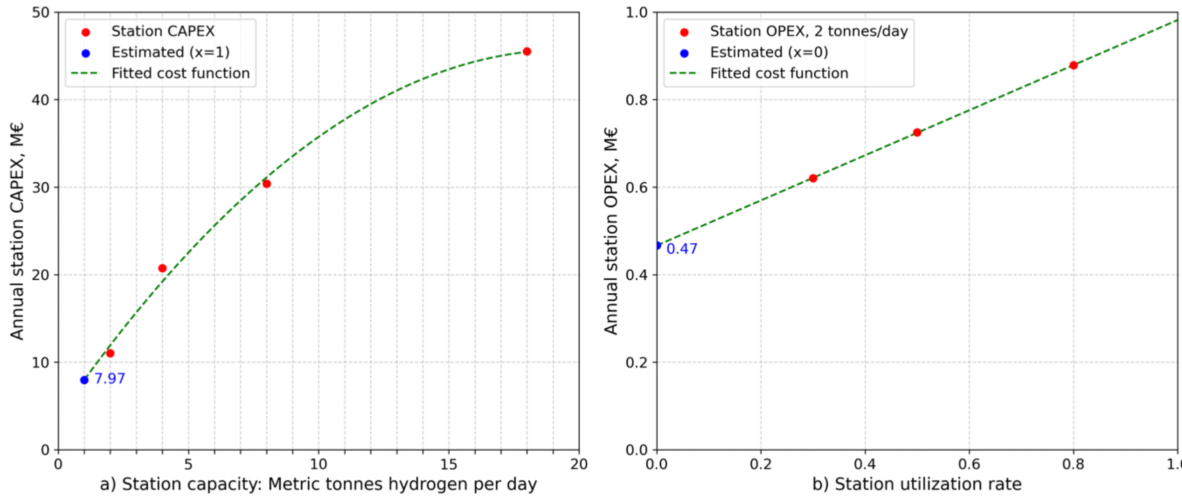

Figure 2: Curve fit estimations of CAPEX (a) relative to station capacity, and OPEX (b) relative to utilization rate. Blue dots indicate computed values for an HRS with 1 pump and a utilization rate of 0.

4.4. Energy systems optimization

For investigating the energy generation and electricity cost impact from hydrogen production under different energy futures in transportation (paper II), we used the Multinode model first presented by Göransson et al. (2017), then under the name eNODE. (Öberg et al., 2022) gives a more recent updated mathematical formulation of the model. Updated technology costs are given in paper II. It is a greenfield linear optimization model for investment and dispatch of energy technologies, representing the entire Europe as 56 regions, 51 of which are included in the electricity cost assessment. We run it for a whole year in 6-hour timesteps, for each of the five scenarios described in section 4.1. For simplification, the hydrogen demand in each region is aggregated and considered to be met as one. All hydrogen production is considered to be decentralized but grid connected, and as such no hydrogen distribution is included in the assessment.

4.5. Water- and land use assessment

Water use can be measured as either water *consumption* or water *withdrawal*. The former means water that is taken from a source and not returned, and the latter includes all water that was taken out, also containing the part that is eventually returned. Their impacts on available water resources are termed water *depletion* and water *stress*, respectively (Kuzma et al., 2023).

To investigate the impact on local water resources from water use in hydrogen production, an understanding of the water resource conditions in the local reservoir or sub-basin is needed. We used the Aqueduct 4.0 dataset from the World Resources Institute (2023), which contains projections for 2050 on water availability and "regular" outtake, and water stress and -depletion risk, at the sub-basin level across the world (Kuzma et al., 2023). After aggregating annual water use for hydrogen production on the sub-basin level, we added it to the modeled annual regular water use and compared the sum to the modeled available water and projected stress. This allows an assessment of potential contributions of hydrogen production to the overextraction of water.

For assessing land use for electrolytic hydrogen production, the main point of concern is the land required for electricity production if all electricity would be renewable. Total annual electricity demand was aggregated per country for the different scenarios, and a total land requirement was calculated for all of Europe using country specific solar- and wind land use factors calculated based on their potentials from the JRC ENSPRESO datasets (Nijs, 2019a, 2019b).

This is compared to the land use for cultivation of biomass for biofuels. The total area for biomass cultivation is calculated using the simulated land use intensity factor for the EU 2020 biofuel mix scenario with a 7% cap on conventional biofuels from the "Globiom report" (Valin et al., 2015). The yield of bio-jet is considered to be 60% of the conventional fuel energy content when producing it from ethanol.

As mentioned in section 2.3, there is a rather strong political favor for the so-called Annex IX-residues to be used in transportation in the future. Additionally, there are crop rotation practices that may provide biomass on arable land without competing with food and feed, as described e.g. by Englund et al. (2023). Thus, we calculate the land use that could be offset by the use of residues, for a high and a low case of residue availability for the transportation sector in 2050 given by Soler (2022). We also calculate the land area that could be offset by the annual output from miscanthus cultivation when combined in rotation with four years of other crops as described in Englund et al. (2023), using an ethanol yield factor estimated from Cerazy-Waliszewska et al. (2019). Residues and miscanthus are primarily assumed to offset jet fuel, which currently has the strictest regulations regarding feedstocks. Since jet fuel uses more feedstock per unit of final energy, this impacts the land use. If any residues or miscanthus remains after jet fuel demand has been met, then these are used towards road and shipping.

5. Simulating geospatial hydrogen demand

Two different hydrogen demand distribution datasets were created for this thesis, one in each of the included papers, appended on a format compatible with geographical information system (GIS) software. Figure 3 shows the simulated distribution and sizes of HRSs for supplying hydrogen to long-haul trucks across Europe in 2050 from paper I. This simulation was made for the *Base* case as described in section 4.1. The model prioritizes building smaller stations, which is an intrinsic characteristic of the HRS distribution algorithm. The density of hydrogen supply is highest in central Europe, in line with the higher volumes of transportation work there. These aspects are further discussed in paper I.

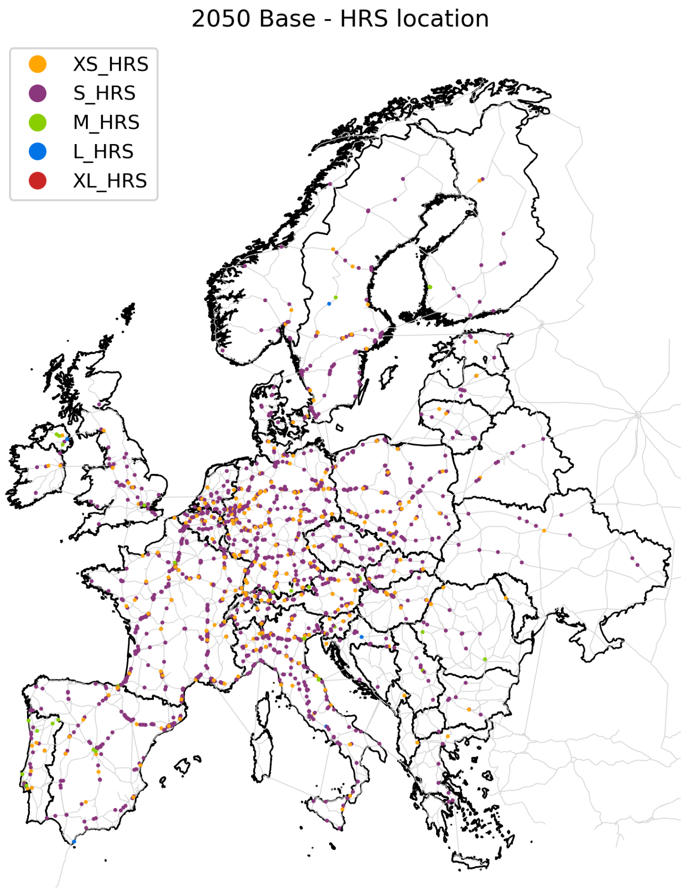

Figure 3: Location and sizing of HRSs for supplying hydrogen to long-haul trucks in Europe in 2050, assuming a 15% diffusion rate and 75 kg onboard hydrogen tanks.

One of the shortcomings of previous modeling efforts for hydrogen trucks discussed in paper I is the use of a factor for average energy use per km when modeling energy demand from trucks. In an attempt to overcome this, we added a capability for the algorithms presented in paper I to simulate locally specific power requirements for hydrogen trucks on route with higher detail. Hydrogen demand should thus vary between regions as a result of considering differences in speed and inclination, compared to using an average factor for energy use per km. To understand whether specific power requirements significantly impact the distribution of HRSs, the same model was run without this Dynamic Power algorithm, instead using an average energy use per km between all the dynamically modeled routes in the dataset. We call this version the Constant Power algorithm.

As shown in figure 4, there is a difference in results between these two model runs. Most notably, the number of hydrogen refueling pumps (as per the AFIR definition given in section 2.3) simulated for Germany is more than 200 fewer when using the Constant Power algorithm, a decrease by one third, while there are almost 300 more for Poland, a doubling of capacity. This points to the relevance of considering local vehicle power needs for specific routes, when planning for access to refueling infrastructure.

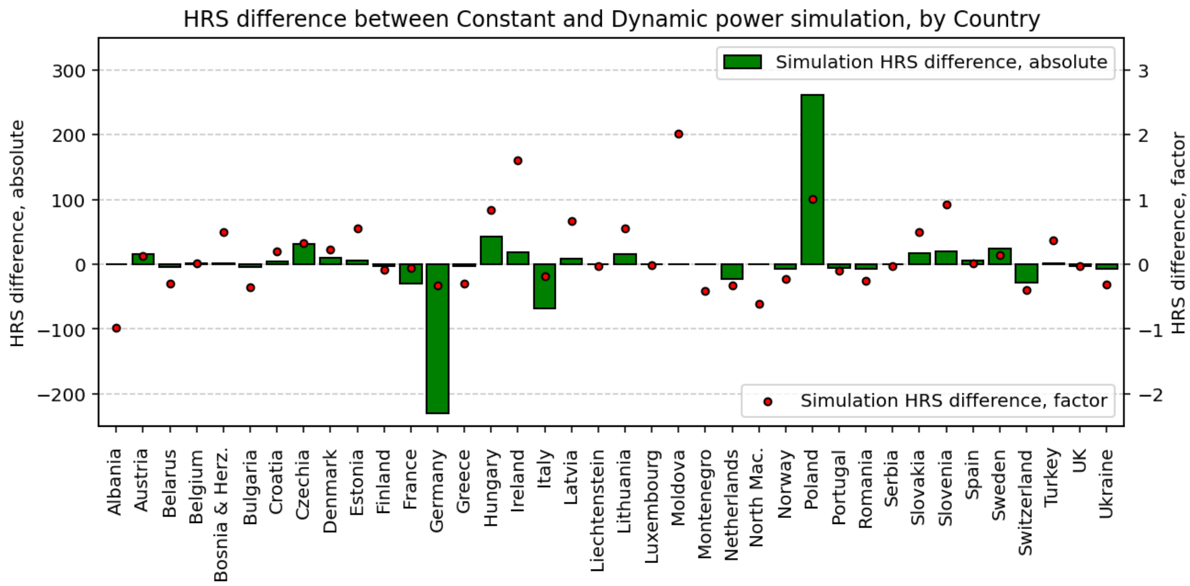

Figure 4: Absolute and relative (factor) difference in number of refueling pumps per country, between the results from running the fuel demand and distribution algorithm with the Constant and Dynamic Power settings respectively.

To complement the assessments on the refueling infrastructure for hydrogen supporting long-haul trucks, and be able to address other topics like the impact on the energy system and water- and land resources, a representation of the full potential scope of hydrogen off-takers is needed. In paper II, we added simulations of energy use for multiple kinds of fuel in other transportation segments, as well as hydrogen use in industry, under five different scenarios as described in chapter 4. Figure 5 shows the geospatial distribution of this demand in the *Fuel mix* scenario. These datasets are also intended to be distributed along with paper II, to enable even more analyses in this area.

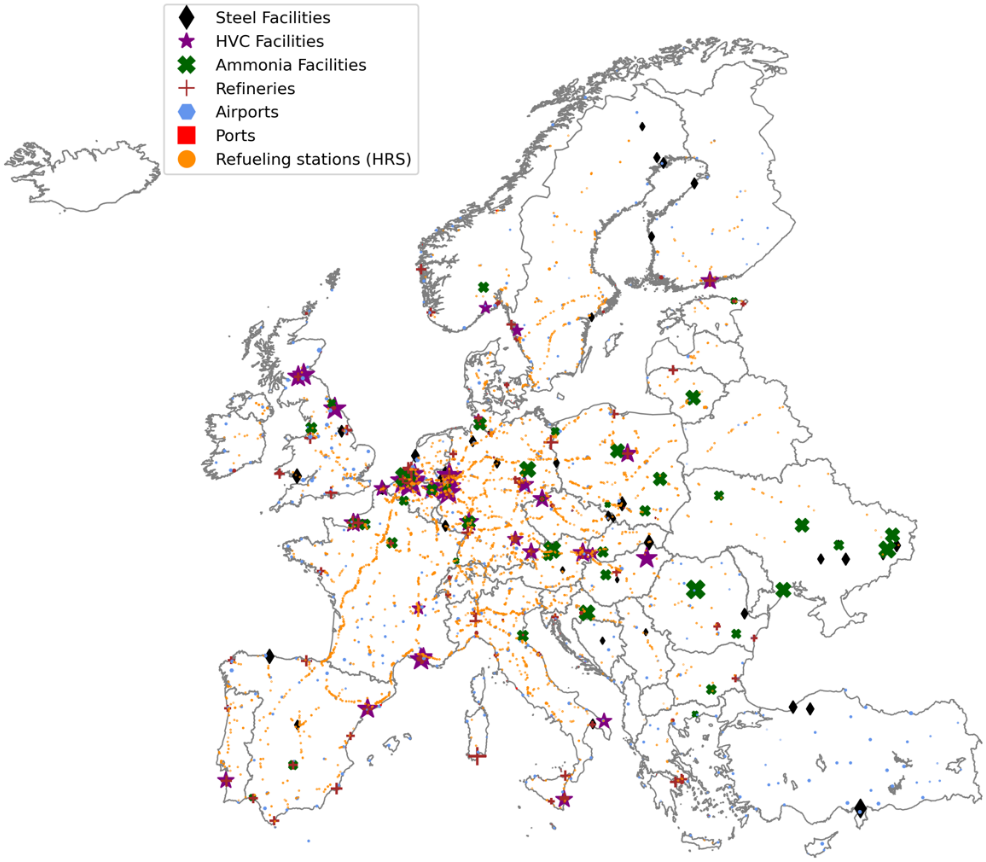

Figure 5: Location of hydrogen demand nodes across Europe in 2050. Types of hydrogen demand is indicated by shape and color, annual relative demand volume indicated by node size.

Many things will impact the actual future proliferation of hydrogen technologies, the volumes they will use, and their locations. There are multiple potential pathways for industry known today, and not all of them rely on hydrogen, as shown by e.g. Nyhus et al. (2024) for HVC and Speizer et al. (2023) for steel. A study by Neuwirth et al. (2024), from which geolocation data for HVC plants and some ammonia plants were gathered for this article, also discusses the potential reinvestment cycles of specific plants, studying the potential timeframe for transitions in specific locations. According to their results, only part of the plants in the different industry sectors will transition to hydrogen by 2050, which also needs to be considered. There are also considerable uncertainties in the specific locations. Assuming that current locations are used also for future, hydrogen-based industries, would make sense since there is already supporting infrastructure available. However, there is also a possibility that existing companies want to prolong the use of their current plants as they are, or retrofit them with less intrusive upgrades. Moreover, as shown in the energy use profile comparison in figure 4, the modeled demand for new infrastructure may change depending on which factors are considered.

The exact location of the nodes in the datasets is thus, arguably, not the most important information. The value lies in what new aspects can be modeled and tested, what new algorithms might be developed for analyzing future data, and ultimately what new perspectives are facilitated in decision-making. The specific locations, distances, the connecting road network, and differences in and character of off-taker demand are all characteristics of this datasets that may open new avenues of investigation. The availability of data is in itself a limiting factor of modeling research, and access to new datasets is necessary to spur innovation of modeling techniques (Wiese et al., 2018). Thus, while the datasets created for this thesis were intended to facilitate modeling of our own, we see making them publicly available to other modelers as an equally important goal.

6. Policy assessment: AFIR

The European Union (2023c) has agreed on AFIR, a regulation setting requirements for the access to alternative fuels and energy for transportation in each country. As outlined in section 2.3, countries are required to build one HRS with at least one pump for every 200km along the TEN-T core road network, and one in every urban node, by 2030. After modeling a potential distribution of HRSs in Europe for 2050, we wanted to understand how this demand-driven HRS network, proposed in paper I, related to the policy stipulated one.

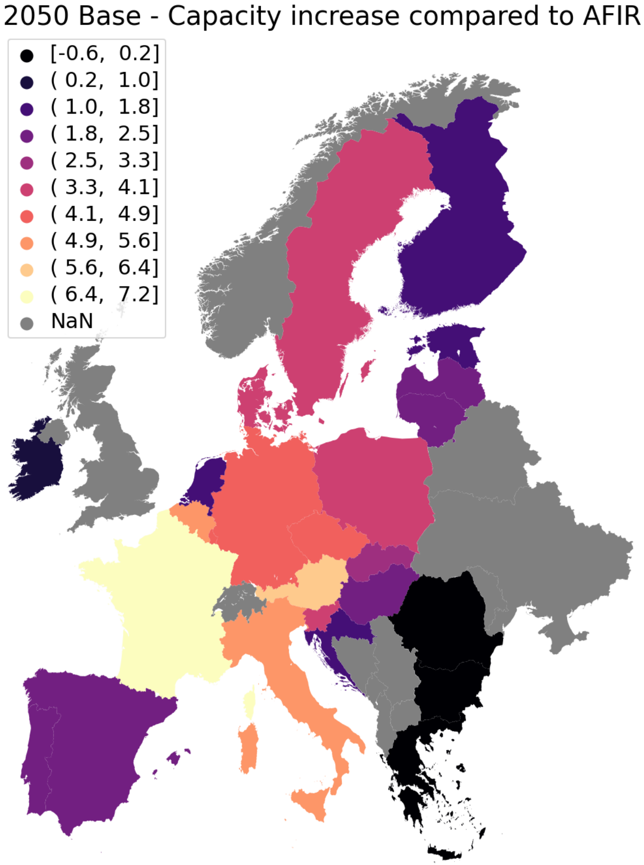

Figure 6: Added hydrogen supply capacity needed per country in the *Base* case in 2050, compared to the AFIR requirements in 2030. Grey countries with NaN (Not a Number) values are not members of the EU and thus not covered by the legislation.

The results for the *Base* case, shown as a map in figure 6, show that the relation between the required hydrogen capacity in 2030 and the modeled demand for 2050 varies a lot between the different countries. France would need to add more than 7 times the capacity required in 2030 if 15% of the long-haul trucks run on hydrogen in 2050. Similarly, for most of central Europe, several multiples of HRS capacity is required to meet demand in this case. This means that the AFIR capacity mandated in 2030 might be a good starting point for them, in serving a growing fleet of hydrogen trucks. However, for Bulgaria, Romania, and Greece the AFIR HRS requirements in 2030 would supply more hydrogen than is needed, even under the demand simulated for 2050 in this thesis, twenty years later. Investing in the mandated capacity in 2030 might thus imply a large cost for underutilized infrastructure in the years until the demand has caught up to the supply.

The same assessment, but for all cases investigated in paper I, is shown in figure 7. This allows comparison of added capacity required for different average tank sizes, and for different diffusion rates of hydrogen trucks as described in section 4.1. If only 5% of long-haul trucks run on hydrogen in 2050, then eight countries don't need as much capacity as was required by AFIR in 2030. Tank size variation only leads to marginal differences, since the same number of trucks refuel in slightly different locations.

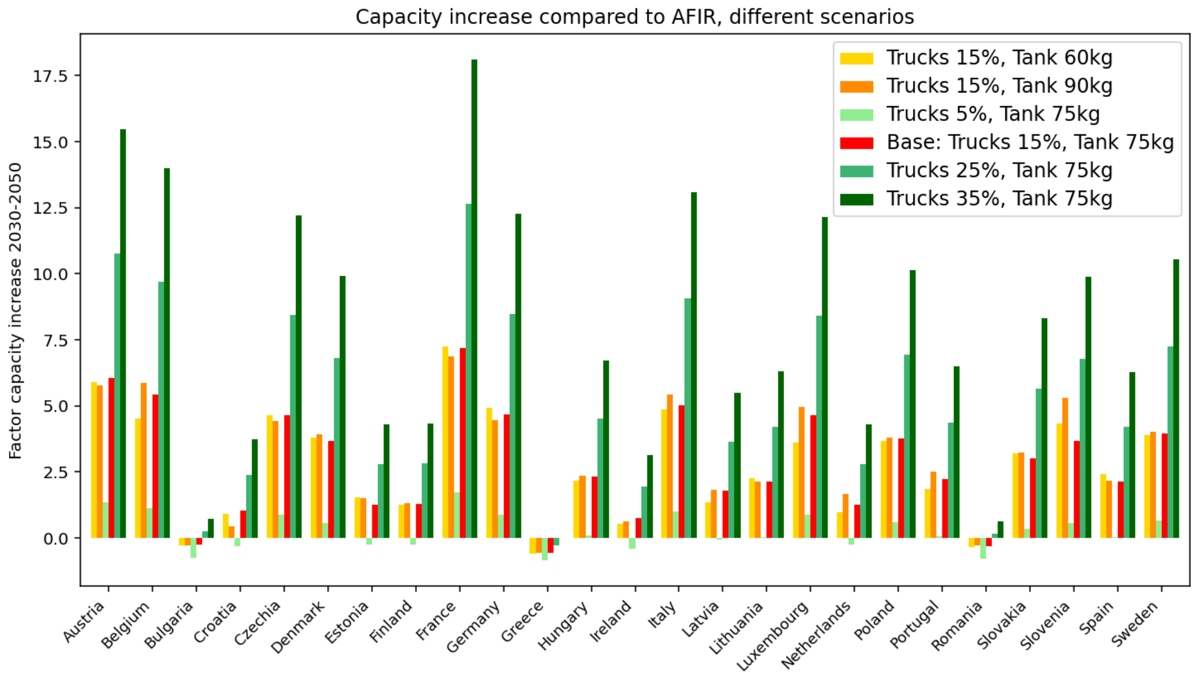

Figure 7: Added hydrogen supply capacity needed per country for all cases in 2050, compared to the AFIR requirements in 2030.

To understand the cost implications of complying with the AFIR in spite of low demand, an assessment of costs for building unutilized HRSs under different hydrogen truck diffusion cases was performed. This cost is calculated as the annual CAPEX and OPEX for HRSs making up the difference between those determined by simulated demand and those required by AFIR. These are assumed to have a capacity of 1 tonne of hydrogen per day, with no utilization, as described in section 4.3.

The result, as displayed in figure 8, implies a risk of incurring millions of euros in annual costs for unutilized infrastructure. If only 5% of long-haul trucks operate on hydrogen in 2050, almost 600 M€ in costs across 8 countries would be added annually to uphold an unutilized part of the refueling network, according to the simulation. The majority of this cost is in Romania, Bulgaria, and Greece, which also at 15% hydrogen truck diffusion together would incur added costs of more than 200 M€ annually. Assuming that truck diffusion is lower in 2030, and grows over time until 2050, accumulated costs in this period could become substantial.

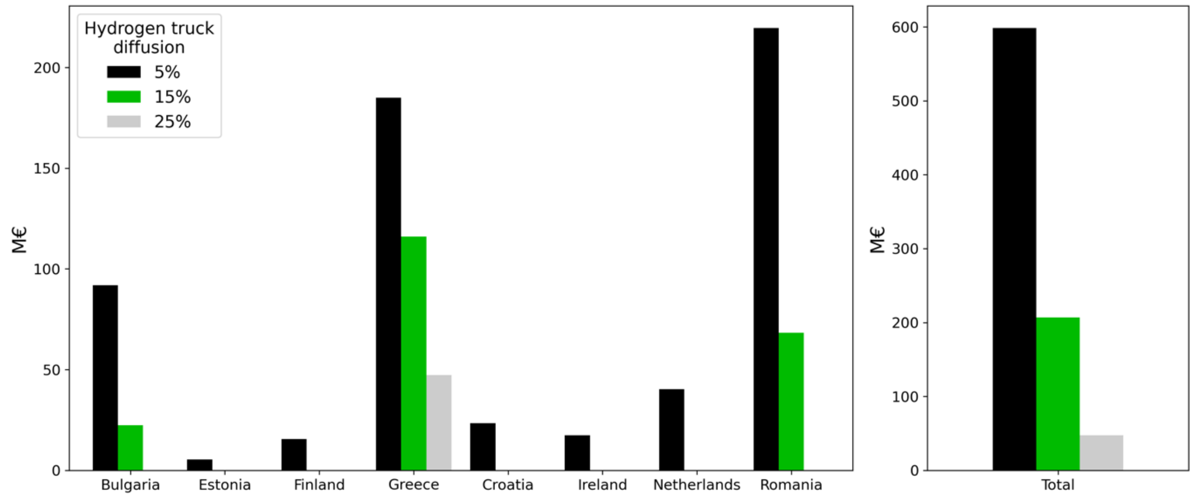

Figure 8: Added annual costs due to underutilization of HRSs built under AFIR, at different diffusion rates of hydrogen long-haul trucks in 2050.

This assessment, while being rather aggregated, gives some indication to the level of excessive costs that could potentially be imposed on countries with lower levels of transportation work. Greece would risk millions of euros in excess costs for underutilized infrastructure, unless more than 25% of their long-haul trucks run on hydrogen, whereas many countries can utilize their mandated supply with less than 5% of trucks running on hydrogen. The situation in countries with low levels of transportation work thus becomes paradoxical: they have lower levels of international transportation work, which results in a need for a higher share of novel technology in the fleet, to justify the mandated supply. This discrepancy needs to be considered by policymakers in the continued planning of the deployment of refueling infrastructure, the support of hydrogen truck diffusion, and the enforcement of AFIR. One of the guiding principles of financial sanctions due to noncompliance with EU regulations is that a penalty payment should be "higher than the benefit that the Member State gains from the infringement" (European Commission, 2025a), and such a penalty would indeed have to be very large to motivate the construction of unutilized HRS as simulated in this thesis, especially if hydrogen truck diffusion starts slow.

Using road distance and urban nodes as a determining principle for mandated infrastructure deployment is easy for legislators to understand, and there is value in solid and communicable legislation, which likely facilitated the process to pass the law in the first place. However, this analysis shows that this metric misses out on the *flows* of vehicles in the respective countries. Number of passing trucks and their novel technology uptake is what will ultimately determine demand for new infrastructure, and it is clear that the AFIR stipulated principles fail to capture some of the regional heterogeneities in this regard. This assessment is intended to inform any potential further development of the legislation, showing the influence of these aspects.

However, other aspects are left out of this assessment, like potential additional hydrogen demand from regional trucks. Furthermore, it also misses the potential mismatch of demand and supply location within a country, due to the 200 km rule potentially requiring HRSs in locations where they aren't utilized to the same extent. This could happen also in those countries where the total simulated hydrogen demand is higher than the total supply mandated by AFIR. There is also some nuance to the legislation, like the fact that it is possible to count urban node-HRS towards the 200km-HRS network, which could decrease the mandated number of stations, or that the 200km-rule also applies across borders, which could imply a need for more stations to connect individual country networks. Deploying a reliable and accessible refueling network is important to facilitate hydrogen truck uptake (Anderhofstadt & Spinler, 2019; Küffner, 2022) – a too *low* supply of hydrogen could imply other costs, like delayed logistics due to queues and necessary rerouting. With a larger demand, however, the market should be able to sustain a larger network beyond regulations. Until that happens, market barrier removal policies like the AFIR should be planned carefully to ensure they don't lead to unfounded prohibitive costs.

7. Electricity cost assessment

The average weighted hourly marginal electricity cost for 51 different regions around Europe (and the total European average) under the different scenarios used for paper II (see section 4.1), is shown in figure 9. These costs only represent the marginal value of electricity generation and transmission. Other costs like taxes, or local or regional electricity distribution are not included.

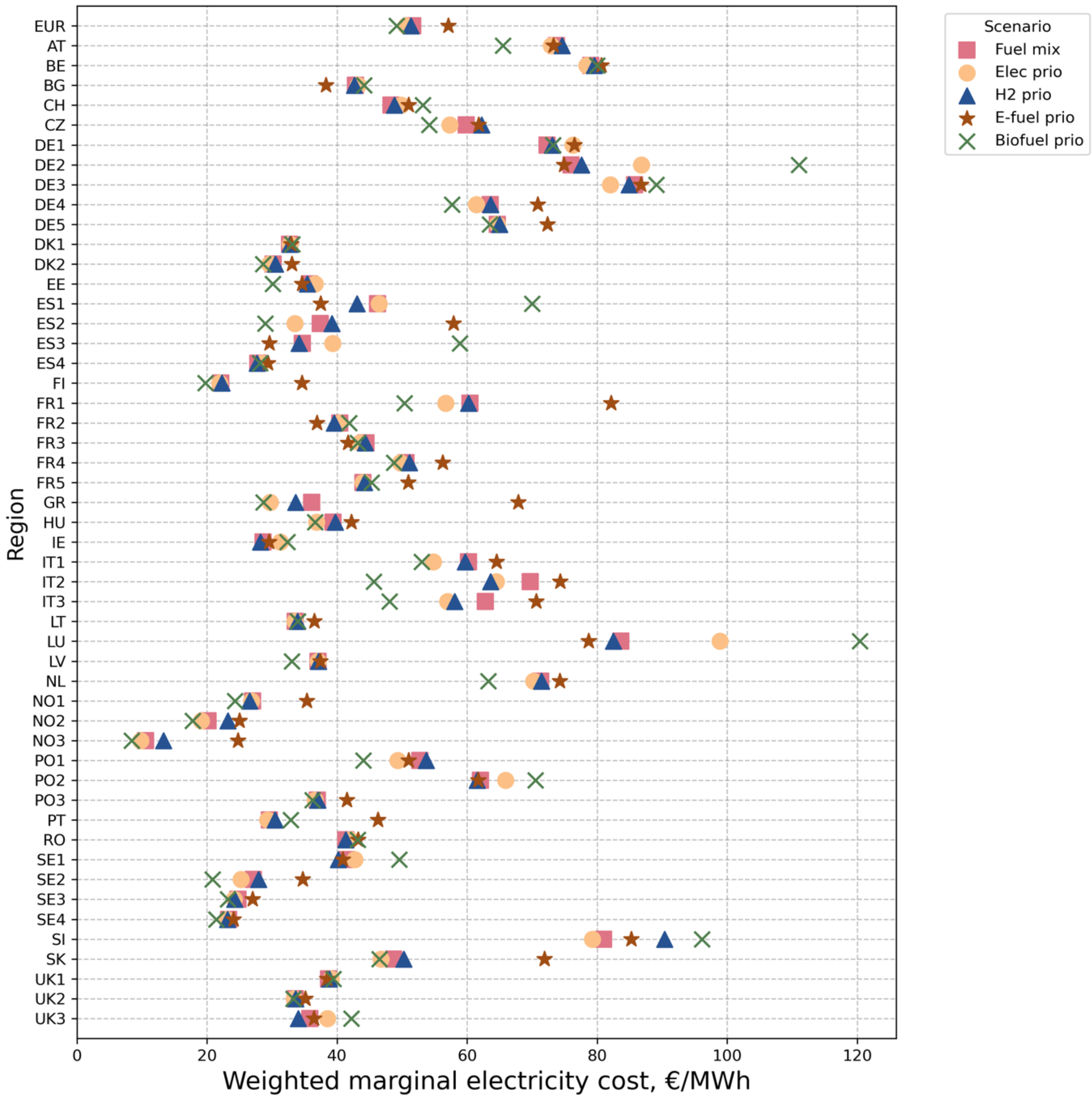

Figure 9: Average weighted electricity costs for the different regions included in Multinode, under the five different scenarios. Regions are defined in the appendix.

The only scenario where the European average electricity price stands out is the *E-fuel prio* scenario. Between the others, the average is very similar. However, the most important point indicated by these results is that regardless of the total average, electricity cost on the regional level can be impacted to a large extent by the energy transition pathway in transportation. When planning the promotion of one renewable energy technology over another, and the deployment of energy infrastructure to support them, this needs to be considered together with the many local practicalities that may vary between communities (de Oliveira Laurin et al., 2024).

The specific costs will be determined by many, very uncertain, factors. However, analyzing the modeled electricity cost dynamics between the scenarios can be of interest. The *E-fuel prio* scenario, as shown in figure 9, is distinctively more expensive, on average, for some regions (DE4, DE5, FI, FR1, GR, IT1-3, NO1, NO3, PT, SE2, SK). In the other scenarios, Greece, Italy, southern France (FR1), and northern Germany (DE4, DE5) cover demand on cheaper technologies like solar, but in the *E-fuel prio* scenario the model also builds nuclear power in these regions. A similar pattern is visible for Greece, Slovakia, and eastern Spain (ES2), but with coal power using CCS being built instead of nuclear. The model also prompts mid Sweden (SE2), southern Norway (NO1), and Finland to build a lot more solar parks, which are not very efficient in those regions, in the *E-fuel prio* scenario. Those regions, and Greece and Portugal, additionally build more wind power in this scenario. Northern Norway (NO3) sees higher electricity costs due to higher costs in neighboring regions.

While the total average marginal electricity costs are the lowest in *Biofuel prio*, this is the most expensive scenario for some regions (DE2, ES1, ES3, LU, PO2, SE1, SI), which can also be seen in figure 9. This is the only scenario in which nuclear isn't built in west Germany (DE2), and coal power with CCS is instead preferred by the model in achieving the lowest total system costs, which results in a high marginal cost per unit of electricity in this region. A similar strategy is modeled for Luxembourg. Higher levels of electricity use in south and central Spain (ES1, ES3) and eastern Poland (PO2) in the other scenarios comes with large investments in solar parks and battery storage. This drives the price for electricity generation down, but with the lower electricity usage in the *Biofuel prio* scenario, the model chooses not to invest in these technologies, resulting in high marginal electricity costs. Lower electricity demand prompts the model to build low-performing solar parks instead of high-performing offshore wind in southern Sweden (SE1). Slovenia, similar to NO3 in the *E-fuel prio* scenario, sees higher costs since they have less opportunity to buy cheap electricity from their neighbors in this scenario.

Driving the differences between scenarios is the fact that different amounts of hydrogen need to be produced around Europe. The total hydrogen demand, broken down per sector, are given in figure 10a. If all HVC would be made using a hydrogen-based pathway (considering the process deemed most mature by Nyhus et al. (2024)) then this is a major off-taker in all scenarios. Ammonia and steel are by comparison rather small. For transportation, direct usage of hydrogen is generally a small share, never significantly larger than the total hydrogen required for producing electrofuels for long-distance aviation. If allowing electrofuels in all flights, almost all shipping, and parts of the road sector, as in the *E-fuel prio* scenario, the total hydrogen production for transportation (considering conversion losses) alone more than doubles the current EU electricity usage at around 4000 TWh per year (IEA, 2023).

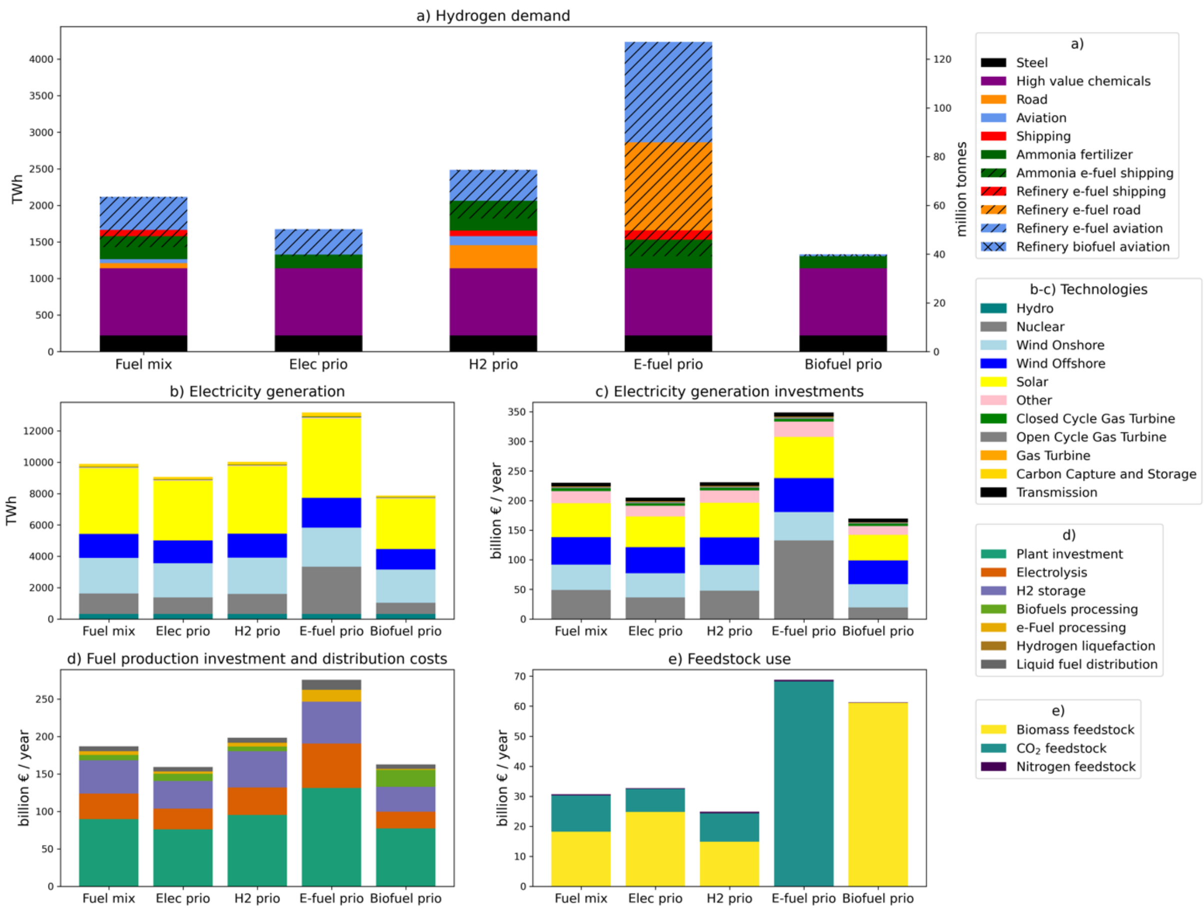

Figure 10: Energy system impacts under the different demand scenarios. a) Total hydrogen demand divided by sector. b) Total electricity generation divided by technology. c) Total electricity generation investments divided by technology. d) Total investments in fuel and hydrogen production, divided by technology. e) Total cost for feedstocks.

How electricity generation varies with increased hydrogen production is shown to figure 10b, showing that the *E-fuel prio* scenario requires more than triple the current electricity generation, significantly more than the other scenarios. This generation and the related investments shown in figure 10c are modeled in Multinode, as described in section 4.4. The other scenarios also require large amounts of electricity generation, and the major part in all scenarios is covered by solar and wind power. Note that electricity demand differs by thousands of terawatt-hours, and modeled costs differ by billions – still, as mentioned earlier, the variation in total average electricity cost between scenarios is not that large. Surely, a system with more electricity needs higher investment, but since the customer pays the marginal electricity cost, they may not be as affected as the investment costs would suggest.

In the *E-fuel prio* scenario, investments in solar and wind are closely followed by investments in nuclear power, as shown in figure 10c. The capacity of nuclear power is about 378 GW in the *E-fuel prio* scenario, around 140-160 GW in the *Fuel mix*, *Elec prio*, and *H2 prio* scenarios, and 94 GW in the *Biofuel prio* scenario, which is the closest to current levels. The difference is to a large extent due to limitations on land for onshore wind and solar power, which is cheaper and otherwise preferred by the model. The Multinode limit is set for these runs to 8% of eligible land in each region for onshore wind, and 5% of eligible land for solar, to emulate limits based on public acceptance for deployment of these power technologies. When increasing these limits to 10% and 8% respectively, nuclear power investments decrease by more than a third in the *E-fuel prio* scenario. Even if public acceptance issues are immensely more complex than a simple change of a parameter (Tsani et al., 2024), this comparison gives some indication to the potential of unlocking more space for generating renewables, which is investigated further in e.g. Price et al. (2022).

Figures 10d-e show other costs associated with production of fuel. Again, investment costs in the *E-fuel prio* scenario are high, but it is also interesting to study the costs for the *Biofuel prio* scenario. While the electricity generation investments in this scenario are the lowest, fuel production investments are higher than the *Elec prio* scenario, and the feedstock costs are among the highest. The total system cost is thus on par with the *Elec prio* scenario, and close to *Fuel mix* and *H2 prio*. This could mean that even if total system costs are similar, costs for fuel in a bio-rich system would be increasingly allocated towards fuel users, as opposed to shared across the energy system as would be the case with higher electrification.

The total energy system cost without a hydrogen grid for trading between regions published by Neumann et al. (2023) is 745 bn€/year, which is higher than all scenarios run in Multinode for this study. While we also publish cost values in figure 10, we would argue that the specific total system cost is not an interesting result – as future projections, there are large uncertainties embedded in the calculations, and the constitution of the considered energy system will likely be different from those given in both studies in many ways. Although the internal comparison between scenarios or cases are of main interest, we believe that showing the simulated costs has at least two benefits: it 1) makes results more relatable to a reader, since we are accustomed to thinking in terms of money, and it 2) makes results slightly more transparent, since system costs can be traced back to technology costs, giving a basis for discussing assumptions and scope of the model. E.g. presenting the results as normalized values could take the focus away from actual costs, which could be positive, but discussing the effects of certain technologies and their associated costs would be more difficult. Also, as done here, costs can be compared with another results from another article. However, presenting absolute cost values can also lead to that a reader would focus too much on the numbers, and if taken out of context they could be used in an unintended way beyond the control of the authors.

This is an example of considerations that modelers need to make in their communications of results, as discussed in chapter 3. It is often a very difficult task to understand how every potential reader may interpret, share, and utilize the results from a study, and how visualizations and wordings might affect the process. Nevertheless, choices like these need to be made deliberately to ascertain that all available measures have been taken to ensure that results are used in a sound way. One such action taken for this study was to split costs for electricity generation, fuel production, and feedstock into different subfigures, both for the sake of the discussion, but also to avoid too much emphasis on “the total cost”.

8. Water- and land use assessment

Production of electrolytic hydrogen requires water as feedstock. Previous studies investigating the impact of water use from hydrogen production on available water resources, e.g. the one by Tonelli et al. (2023), have claimed that it is unlikely to be an issue in Europe. But these studies compare national water demand to national water availability. Water depletion and -stress is a problem on the water basin level, which doesn't coincide with country borders. As such, we used the modeled hydrogen demand data to assess the potential impacts of hydrogen production at the sub-basin level, as described in section 4.5.

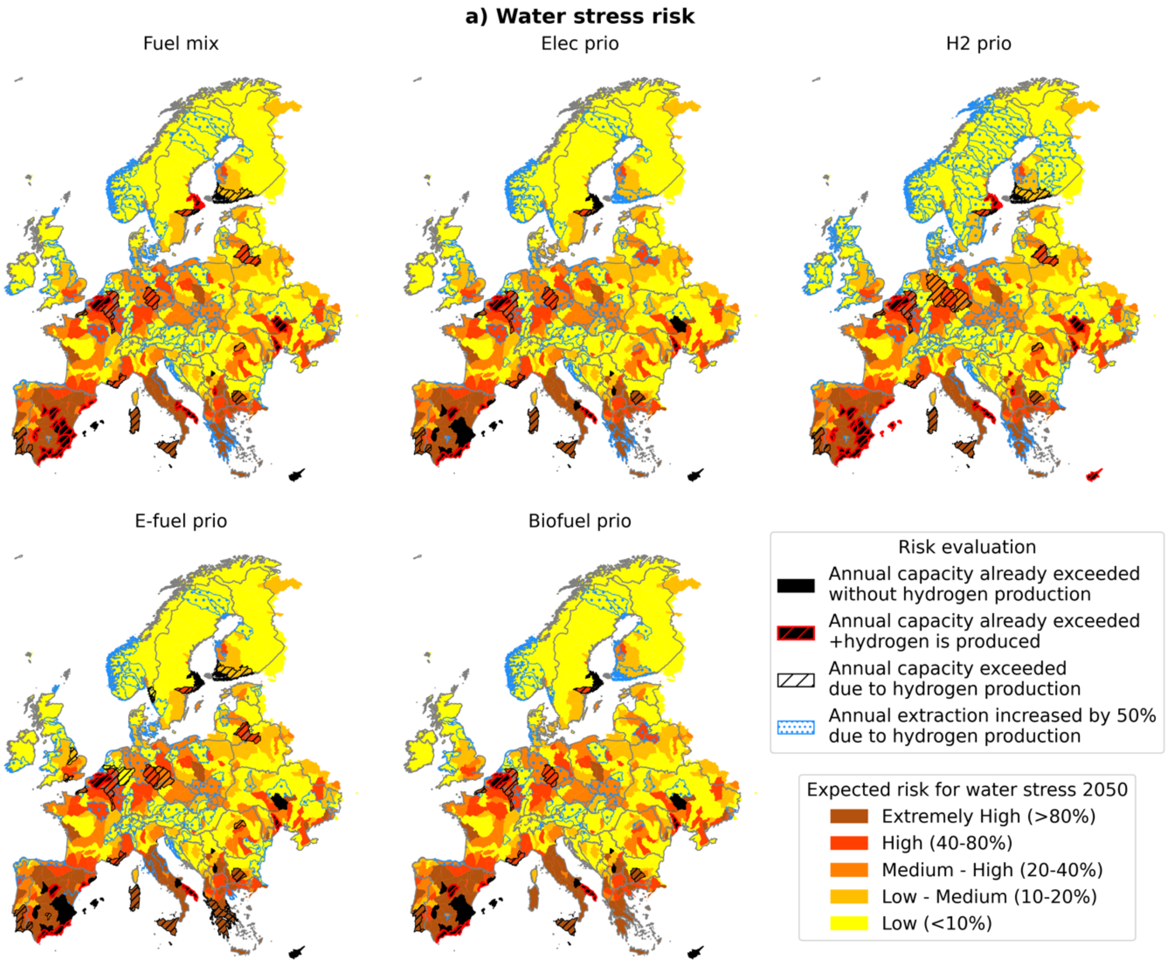

Figure 11: Colored areas indicate projected level of water stress risk for each sub-basin in 2050. The projected water availability is exceeded due to hydrogen production in dashed regions. Risk for water stress has increased more than 50% due to hydrogen production in regions covered with blue dots. Iceland has been left out of the figures for layout reasons, but they are not affected negatively by the system under investigation in any of the scenarios.

Figure 11 shows one map of Europe for each scenario in the study. Each map shows all sub-basins, with color indicating the level of water stress risk projected in the

Aqueduct database for 2050 (World Resources Institute, 2023). Regions where annual projected water withdrawal exceeds the annual projected sub-basin capacity, without additional stress, are colored black. Water stress is visualized in two ways: regions with dashed lines exceed their annual water capacity due to hydrogen production, and regions with blue dots increase their water stress risk by more than 50%. Especially for regions with large industrial clusters, there could be local overextraction. In the *E-fuel prio* scenario, this happens even in some sub-basins with low projected water stress risk like Bohuslän and Wales on the Swedish and British west coasts, respectively. The majority of blue regions, where water stress risk is increased, are low-risk regions. This makes sense since the relative impact of additional water extraction is larger in such a region. However, it does also happen in some scenarios for regions with higher risk levels. In the *H2 prio* scenario, direct hydrogen use in transportation is more widespread, and even if the annual capacity is exceeded in fewer areas than in e.g. the *E-fuel prio* scenario, the impact of increased water stress risk is more wide-spread. Even in low-risk areas, a substantial increase in water outtake could potentially be harmful to the local environment and should be properly assessed beforehand. Additional figures and assessments are included in paper II.

Even though water use from hydrogen is small compared to the total water use in a country or continent, which is shown also in other studies (Beswick et al., 2021; Newborough & Cooley, 2021), the results presented in paper II shows that considering local water availability is important when planning hydrogen production. Alternative streams of water should be utilized, like wastewater or desalinated seawater (Woods et al., 2022). Desalinated seawater processes are convenient since many larger off-takers in our dataset are located close to the sea, however they do imply a risk to the marine environment through their associated brine discharge, which should also be considered (Woods et al., 2022). Wastewater, on the other hand, poses an opportunity for synergistic effects according to Woods et al. (2022); the oxygen produced in electrolysis could be used in the water treatment facilities, which could lower costs. This could decrease the pressure from hydrogen production on other parts of the food-energy-water nexus (D'Odorico et al., 2018) and serve as an action to prevent future water crises (Grafton et al., 2025).

While this assessment serves to increase the spatial resolution of water use risk evaluation, it still lacks in temporal resolution. The coincidence of large-scale water use with other short term water pressures may exacerbate the risk, but this variability is not visible in this analysis. Additionally, the state and composition of the local ecosystem will make it more or less vulnerable to water stress, meaning that a simple measure of outtake over capacity might not provide the full picture of potential impacts from overextraction. This assessment should thus be seen as a first indicator that water use from hydrogen production is not to be considered unproblematic across the board in water-richer countries, but that each new-built facility should carefully consider the potential impacts from local water use.

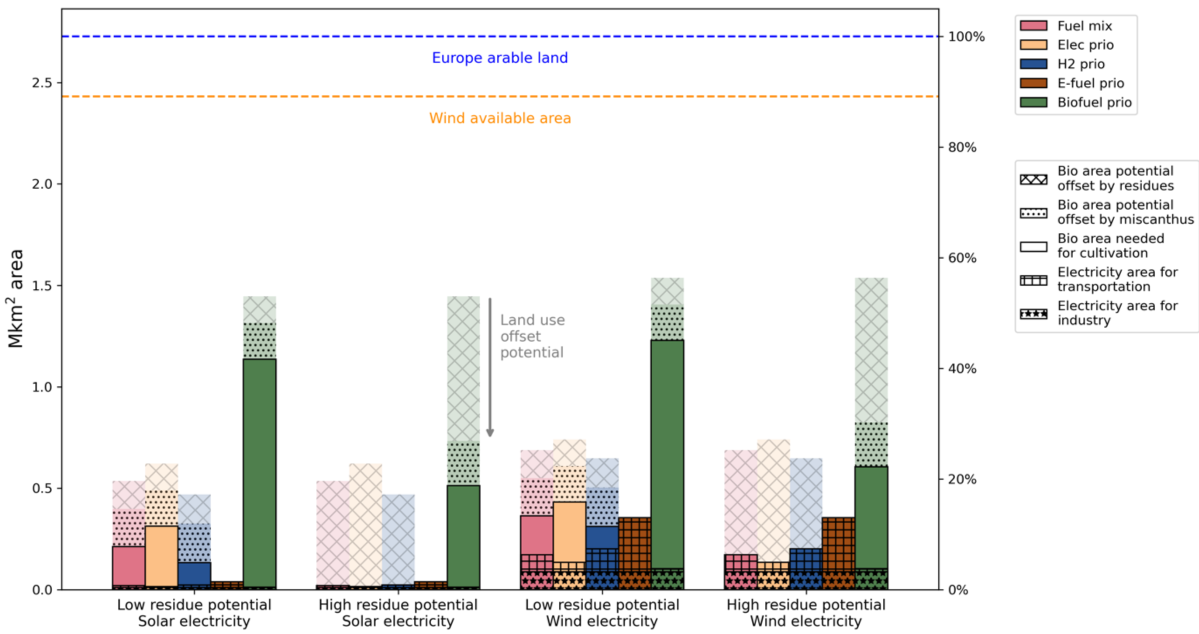

Figure 12: Land use for biomass production and variable renewable electricity generation in the five different scenarios. Shaded areas represent land use for biofuel feedstock cultivation that could be offset by alternative feedstock streams. The figure shows four cases with either high or low availability of Annex IX feedstock, and producing all electricity using only wind or solar.

Pressures in the food-energy-water nexus also pertain to those considering land use. Figure 12 shows different aspects of land use for the five modeled scenarios in paper II. The bars give the total land area required to produce electricity for transportation and industrial hydrogen production using only variable renewable electricity generation, and to cultivate biomass to supply the feedstock demand for biofuels. All electricity is considered to be produced by either solar (left two column groups) or wind (right two column groups), to test the extreme case of land use for variable renewable electricity generation. The shaded areas are the part of land use for biomass cultivation that could be offset by alternative streams, and this is shown for a high and a low potential scenario for Annex IX-feedstock (residue) availability. This in total makes four different cases. Even though EU legislation puts large emphasis on use of residual feedstock streams, Englund et al. (2023) claim that also cultivated crops could be utilized to produce biofuels while simultaneously promoting other positive values for the natural environment. They modeled the introduction of the grass *miscanthus* into the crop rotation on cultivated land around Europe, and saw several benefits including increased soil organic carbon, lower system GHG emissions, and less nutrient leakage and erosion. Additionally, they saw an *increased net output* of the total system, meaning slightly more food was produced while simultaneously providing miscanthus for biofuels production. The shaded, dotted part of each bar signifies the part that could be covered by the modeled miscanthus output under these practices from one of the cases studied in Englund et al. (2023). These activities are all compared to the total arable land in Europe (FAOSTAT, 2024), as well as the total available area for wind power which includes eligible land both onshore and offshore (Nijs, 2019b).

Relying entirely on electrofuels would, if produced only by wind power, require large land areas, though some of them might be offshore. Solar would require less land in total, but both of these technologies are limited by acceptance issues (Dutta et al., 2021; Price et al., 2022). Using biofuels in targeted high-value applications would mean they could be produced from feedstock with low land use intensity, while decreasing the need for electricity generation investments, as seen in the chapter 7. If the full range of agricultural and forestry residues envisaged are available and utilized, then these streams seem able to cover most of the demands from the transportation system, as seen in the *Fuel mix*, *Elec prio*, and *H2 prio* scenarios in figure 12. However, making residue feedstocks available in large quantities may be a complex process, since they require adjusting the farm or forestry operation, establishing new and stable biomass supply chains and logistics solutions, ensuring cost efficient transportation, and trust in the revenue potential, to name some aspects (Lautala et al., 2015). Annex IX feedstock availability is thus uncertain. Therefore, this solution might benefit from being complemented with biomass cultivated specifically for biofuels using smart management practices, especially in a scenario of low residue availability, and especially considering potential connected environmental benefits (Englund et al., 2023; Popp et al., 2014). If these streams are not properly utilized, then other biomass in more direct competition with food and feed will be needed, even under a scenario of restrictive use where biofuels are only allowed in aviation, like the *H2 prio* scenario.

We have here attempted to provide some perspectives on how variable renewable electricity generation and biofuels for transportation could complement each other in the nexus between food, water, and energy. But perspectives these need to be carefully weighed alongside other information and viewpoints on the local and continental level. Effects of different land use practices are multifaceted and difficult to quantify in their entirety (Bentsen et al., 2019). Especially on this continental scale, future assessments of such a system easily becomes aggregated, and may misrepresent important aspects of the bioeconomy. Interest groups on the local level value risks and benefits of land use change due to biofuels production differently, and Palmer (2014) claims that attempts to outline a strategy on the EU level has shaped and simplified the discourse in a manner that overlooks local perspectives. He suggests that calculating aggregated effects from land use renders the impacts “placeless”, resulting in a narrowing of discourse, focusing on a few aggregated metrics and missing out on the specific impacts at the ground level. This is an example of how the social- and communication dimension of the research and policymaking space, and their interfaces, affect the outcomes of complex societal planning by impacting what is studied, how it is studied, and how results are presented, interpreted, and used, as discussed in section 3. The results presented here should be utilized with this in mind.

While we have provided an assessment with some new perspectives, and with more details than given by e.g. Rennuit-Mortensen et al. (2023) presenting a comparison on a similar but global and further aggregated scale, there is still a risk that the impacts presented here limits the discourse space as discussed above. We show that wind and solar may not take up the same amounts of space for the same of amount energy delivered to the transportation sector, but as mentioned recurrently throughout this thesis, a major concern to that deployment is the public acceptance of new developments (Tsani et al., 2024). Clearly, more perspectives need to be acknowledged to navigate land use issues for energy production.

9. Conclusions

Limiting the release of GHG emissions from transportation and industry is of great global importance, and the EU has proposed several policies aiming at facilitating the transition away from fossil energy. But navigating the investments in, and deployments of, systems for supporting alternative energy carriers is inherently complex, and it is important that they are assessed from a systems perspective in order to understand a broad range of consequences. Modeling results from SVENG, presented in this thesis, have pointed towards different potential problems and benefits with some technical pathways, utilizing data and methods building on higher geospatial resolution than many previous studies, but still analyzing options from a continental perspective. The publication of new, geospatially detailed datasets will hopefully open new possibilities for modeling of additional aspects.

Providing refueling infrastructure is important to facilitate uptake of new vehicles, but the AFIR might result in large costs for unutilized infrastructure if adoption of hydrogen vehicles lag behind. This risk is especially large for some countries with low freight volumes. When modeling the geospatial distribution of need for refueling infrastructure for long-haul hydrogen trucks, considering the dynamic power requirements due to varying road profiles have a significant influence on the results.

Considering the energy transition in the transportation sector at large, all studied pathways lead to an increase in needed electricity production, with varying impacts on costs to consumer in different regions. The *E-fuel prio* and *Biofuel prio* scenarios come with different significant challenges, such as regionally varying electricity cost, water risk, and land use pressures, underlining the case for using electro- and biofuels only in especially hard-to-abate transportation segments. Where biofuels are used, there are alternative feedstock streams beside crop cultivation that could contribute to energy supply with lower land use pressure. Water use for hydrogen production needs special attention in local planning to avoid undue effects from overextraction.

Modeling is only one tool among many, capable of facilitating certain specific perspectives and contributing to navigating future energy transition challenges. Model results should not be communicated as objective truths, but should invite other complementary perspectives to shape an open policy- and societal planning discourse. Regardless if it's labeled science, research, art, or something else, energy systems modeling should be done in a deliberately open and transparent way, mindful of social influence over process, result, and interpretation.

10. Future outlook

The model built for this thesis, SVENG, presents some new potential avenues for investigation. Here follows a few examples of directions that could further facilitate the understanding of consequences of using hydrogen and other fuels in different energy transition pathways in the transportation sector.

The route energy distribution module for trucks, in SVENG, could be adapted to other alternative energy drivetrains, and the average drivetrain efficiency considering local power requirements could be studied and compared for those as well. This would also allow for testing the energy use differences under different cargo loads. Interesting updates to the model would include better representation of refueling behavior.

The cumulative costs over time for unutilized HRS mandated by AFIR could be studied under different hydrogen truck technology diffusion scenarios, to better understand the cost impact of delayed truck rollouts.

Geospatial data on hydrogen demand throughout Europe could be used for assessments specifically focusing on different supply chain alternatives, like truck deliveries and pipelines, under different scenarios. This would facilitate an understanding for which strategies are preferrable under what circumstances, and might provide more insights on the added cost considerations for last mile off-takers.

It would also be interesting to use the SVENG model as it is but adapted to another geographical region, especially if other studies have been performed there, to compare results in order to learn more about the models.

Beyond modeling, it would be interesting to better understand other more qualitative aspects surrounding the deployment of hydrogen and other new energy technologies for transportation. What drives policy development in these areas, and how is the scientific community involved in shaping it? What might be required to train workers with the right competence to support the transition? By broadening the scope, maybe the results can have a wider utility.

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Appendix

Figure A1, below, defines the regions considered in the Multinode energy systems optimization model.

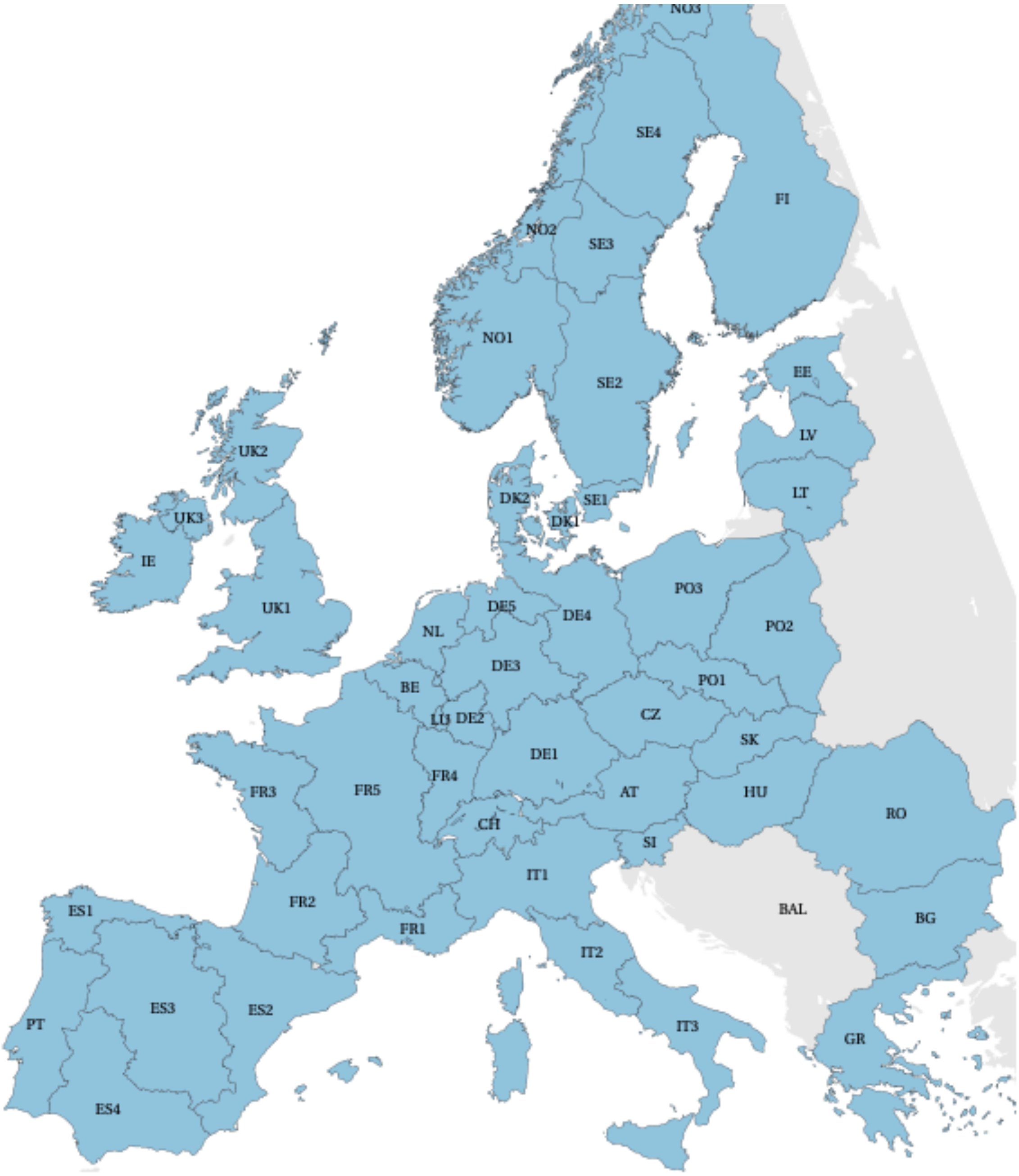

Figure A1: Regions considered in the Multinode energy systems optimization model. Image from Nyholm (2016).