HYPAT

H_2 Potential

Global Atlas of H_2 Potential

Sustainable locations in the world for the green hydrogen economy of tomorrow:
technical, economic and social analyses of the development of a sustainable global hydrogen atlas

HYPAT Working Paper 02/2023

Export Potentials of Green Hydrogen – Methodology for a Techno-Economic Assessment

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Disclaimer

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Executive Summary

This working paper describes the quantitative and model-based methodology used in HYPAT to assess hydrogen and Power-to-X (PtX) export potentials in the countries Morocco, Ukraine, Namibia, Turkey, United Arab Emirates, Kenya, Chile, Canada, Brazil, and New Zealand. The results of the techno-economic assessment are used as a basis for a global hydrogen and PtX atlas and as an indication of hydrogen and PtX price development.

A global evaluation based on different factors was carried out beforehand to choose ten potential hydrogen export countries for in-depth techno-economic assessment. The selection includes countries of different economic status, size, and from different world regions.

In HYPAT, a novel, country-specific and model-based methodology has been established in order to address the entire hydrogen supply chain for exports. The five models used are Enertile®, LEAP / MS Excel-based tools, PyPSA-Earth-Sec, Hytra, and H2ProSim. The main objectives of linking these models are to obtain the levelized cost of hydrogen (LCOH) or the PtX product (LCOPTX) incurred at the import location.

The core of HYPAT consists of an in-depth, country-specific, integrated energy system model combined with a detailed cross-regional hydrogen and PtX transport assessment. The methodology in HYPAT is distinguished by the fact that it is more comprehensive in comparison to other existing studies by combining many aspects of these studies in one modelling task: It incorporates a range of primary energy sources, integrates the domestic energy and export demand into the energy system optimization, and assesses numerous transport pathways for exporting H_2 and PtX.

Hydrogen and PtX export costs are analyzed for each selected country, for various export quantities, for 2030 and 2050, and for three different scenarios: *Optimistic*, *Realistic*, and *Conservative*. These scenarios are related to domestic energy transition ambitions, energy infrastructure evolution goals and the costs for electricity, hydrogen and PtX production.

Developing and running a complex model chain involves unforeseen interdependencies, increased model runtimes, high data requirements, and a range of interpretable results. Modeling a whole supply chain and its integration into the energy system results in a total runtime of 3-4 weeks per country (excl. country-specific initial data preparation and data input). Thus, a meaningful selection of scenarios, number of countries, years and quantity steps is essential in order to deliver results in a feasible time horizon. If country-specific data are not available, international and regional data are used in combination with our own country-specific assumptions based on the available data. The first complete model runs will show the resilience of the model chain. The results of the model chain as well as the results from the models themselves will be published in a format that is yet to be decided.

The subsequent steps involve applying the methodology to the ten selected countries and publishing country-specific results within the course of the year 2023. Further, a methodology will be developed for a global scale-up and the exchange between fellow researchers will be further intensified. As the first hydrogen imports to Germany of up to 100 TWh are expected as early as 2030, our goal is to rapidly support the establishment of sustainable hydrogen partnerships.

Zusammenfassung

Dieses Arbeitspapier beschreibt die Methodik in HYPAT, um Wasserstoff- und Power-to-X (PtX) Exportpotentiale in den Ländern Marokko, Ukraine, Namibia, Türkei, Vereinigte Arabische Emirate, Kenia, Chile, Kanada, Brasilien und Neuseeland quantitativ und modellbasiert zu bewerten. Die Ergebnisse der technisch-ökonomischen Bewertung werden als Grundlage für einen globalen Wasserstoff- und PtX-Atlas und eine Indikation der Wasserstoff- bzw. PtX-Preisentwicklung verwendet.

Zuvor wird eine globale Bewertung auf der Grundlage verschiedener Faktoren durchgeführt, um zehn potenzielle Wasserstoffexportländer für eine eingehende technisch-wirtschaftliche Bewertung auszuwählen. Die Auswahl umfasst Länder mit unterschiedlichem wirtschaftlichem Status, Größe und Regionalität.

In HYPAT wurde eine neuartige länderspezifische modellbasierte Methodik entwickelt, die aus fünf Modellen besteht, um die gesamte Wasserstoffversorgungskette für den Export vollständig zu erfassen. Die fünf verwendeten Modelle sind Enertile®, LEAP / MS Excel-basierte Tools, PyPSA-Earth-Sec, Hytra und H2ProSim. Die Hauptziele der Modellkette sind die Gestehungskosten des Wasserstoffs (LCOH) oder des PtX-Produkts (LCOPTX), die am Importstandort anfallen.

Ein detailliertes, länderspezifisches, integriertes Energiesystemmodell kombiniert mit einer überregionalen Wasserstoff- und PtX-Transportbewertung ist der Kern von HYPAT. Die Methodik in HYPAT zeichnet sich dadurch aus, dass sie im Vergleich zu anderen bestehenden Studien sehr umfassend ist, da sie viele Aspekte dieser Studien kombiniert: Sie bezieht eine Reihe von Primärenergiequellen ein, integriert die inländische Energie- und Exportnachfrage in die Optimierung des Energiesystems und bewertet zahlreiche Arten von Transportwegen für den Export von H_2 und PtX.

Die Wasserstoff- und PtX-Exportkosten werden für jedes ausgewählte Land, verschiedene Exportmengen, für 2030 und 2050 sowie für drei verschiedene Szenarien analysiert: Optimistisch, realistisch und konservativ. Die Szenarien stehen im Zusammenhang mit den nationalen Energiewendezielen, den Entwicklungszielen für die Energieinfrastruktur und den Kosten für die Strom-, Wasserstoff- und PtX-Produktion.

Die Entwicklung und Ausführung einer komplexen Modellkette bringt unvorhergesehene Abhängigkeiten, längere Modelllaufzeiten, hohe Datenanforderungen mit sich und generiert eine Vielzahl zu interpretierender Ergebnisse Die Modellierung einer gesamten Lieferkette und der Integration in das Energiesystem pro Land führt zu einer Gesamtlaufzeit von 3-4 Wochen (ohne die länderspezifische initiale Datenaufbereitung und Dateneingabe). Daher ist eine sinnvolle Auswahl der Szenarien, der Anzahl der Länder, der Jahre und der Mengenschritte wichtig, um Ergebnisse in einem realisierbaren Zeithorizont zu liefern. Wenn länderspezifische Daten nicht verfügbar sind, werden internationale und regionale Daten in Kombination mit eigenen länderspezifischen Annahmen auf der Grundlage der verfügbaren Daten verwendet. Erste vollständige Modellläufe werden die Belastbarkeit der Modellkette zeigen. Ergebnisse der Modellkette und der einzelnen Modelle werden in einem Format publiziert werden, das noch festzulegen ist.

In den nächsten Schritten wird die Methodik auf die zehn ausgewählten Länder angewandt und die länderspezifischen Ergebnisse innerhalb des Jahres 2023 veröffentlicht. Darüber hinaus wird eine Methodik für ein globales Scale-up entwickelt und der Austausch zwischen Forscherkollegen weiter intensiviert. Da bereits im Jahr 2030 erste Importe von bis zu 100 TWh nach Deutschland erwartet werden, ist es unser Ziel, schnell nachhaltige Wasserstoffpartnerschaften zu fördern.

Table of Content

Abbreviations

Abbreviation	Meaning
AP	Ambitious Plans Scenario
ASU	Air Separation Unit
BECCS	Bioenergy with Carbon Capture and Storage
BS	Baseline Scenario
CAPEX	Capital Expenditures
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DACCS	Direct Air Capture and Carbon Storage
ECMWF	European Centre for Medium-Range Weather Forecasts
FLH	Full-Load Hours
FT	Fischer-Tropsch
GADM	Global Administrative Areas
GDP	Gross Domestic Product
GH2	Gaseous Hydrogen
HYPAT	Hydrogen Potential Atlas
IEA	International Energy Agency
IEE	Fraunhofer Institute for Energy Economics and Energy System Technology
IRENA	International Renewable Energy Agency
IUCN	International Union for Conservation of Nature and Natural Resources
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen

LCOPTX	Levelized Cost of Power-to-X Products
LEAP	Low Emissions Analysis Platform
LH2	Liquefied Hydrogen
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MENA	Middle East and North Africa
MeOH	Methanol
NH3	Ammonia
NZ	Net-Zero Scenario
OPEX	Operational Expenditures
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
REDII	Renewable Energy Directive II (European Union)
WACC	Weighted Average Cost of Capital
WP	Working Package

1 Introduction

The HYPAT project creates a global hydrogen potential atlas to assess sustainable production locations based on technical, economic, political and social criteria. The project's findings will contribute to the development of a global hydrogen and PtX market.[1] Therefore, the aim of HYPAT is to identify important export and import countries for future hydrogen trade, as well as the potential trade quantities, production and transportation costs to derive a hydrogen market price.

This working paper deals with the establishment of a novel techno-economic model-based assessment of hydrogen and Power-to-X (PtX) supply potentials in potential future export countries as well as the transport to prospective import countries. There have been many recent hydrogen studies (incl. PtX) involving model-based techno-economic assessments of supply chains for different countries that include natural resources, as well as socio-economic and political aspects. Each of these studies is unique, as they have different technical and regional scopes. HYPAT aims to supplement the existing studies using a novel methodology to accelerate energy partnerships for hydrogen and PtX trade between countries in the near future.

As the first imports of up to 100 TWh to Germany are expected as soon as 2030 (BMWi 2020), multiple researchers from different institutions are currently working on questions related to hydrogen and PtX exports. Just as fossil energy carriers like natural gas or crude oil are regionally sourced and globally traded nowadays, a global trade is likely to emerge for sustainable energy carriers in the future, such as green hydrogen and PtX products. This section provides a basic understanding of the need to derive a methodology for hydrogen and PtX supply chain modeling in a future hydrogen trade. The basic characteristics that need to be considered are global hydrogen demand projections, the regional relevance in hydrogen and PtX production costs, as well as important requirements for sustainable supply chains:

- Hydrogen becomes indispensable as an energy carrier if greenhouse gas emissions are to be reduced by more than 80% compared to 1990 levels and is therefore regarded as an enabling technology for climate neutrality. It will probably be predominantly used for long-distance transportation (aviation, shipping), industry (steel, ammonia, High Value Chemicals), and in the power sector (power reconversion). Therefore, hydrogen demand is projected to have an average share of 4-11% (14-55 EJ or 4,000-15,000 TWh) in the predicted global final energy consumption in 2050; this includes the hydrogen used for chemicals, PtL, and electricity generation (Riemer et al. 2022).
- Renewable energy (RE) potentials are subject to significant regional variations and are of central importance for the generation costs of electricity, hydrogen and PtX products. In a global evaluation, (Kleinschmitt et al. 2022) show that Chile, Namibia, MENA, and Australia in particular are regions with the highest full-load hours (FLH) for PV and CSP. High wind FLH can be found in the United States, Canada, Northern Europe and in Patagonia (Chile and Argentina). Even though offshore wind has higher specific costs than onshore wind, offshore wind can play an important role in Europe and other regions, due to the limited acceptance of onshore wind plants and the resulting lower dependency on energy

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[1] Further information about HYPAT can be found at https://hypat.de/hypat/projekt.php.

imports. Regions suitable for renewable energy generation as a basis for hydrogen production are therefore of particular interest for consideration as future export countries (Kleinschmitt et al. 2022).

- Sustainable hydrogen and PtX supply chains must form the basis of sustainable future energy partnerships. Therefore, (Thomann et al. 2022) have defined sustainability criteria within HYPAT that need to be fulfilled for hydrogen and PtX supply chains, which are summarized as follows[2]:
    - Hydrogen is exclusively produced via electrolysis.
    - The only energy source allowed for hydrogen and PtX production are Renewable Energy (RE) plants, which have been additionally installed.
    - The entire energy system needs to be considered and hydrogen and PtX production embedded into it.
    - CO_2 is allowed from DAC or point sources.
    - Other environmental impact is kept to a minimum by excluding water-scarce or drought-prone countries, and by considering the use of salt water in case of regional water stress and the proximity of the production facility to protected areas.

Thus, hydrogen will be an important energy carrier to reach climate neutrality and its production costs will vary regionally. Therefore, a global trade in hydrogen is foreseen and the objective is to develop a methodology to assess international hydrogen and PtX supply chains techno-economically for different time horizons and export countries, where hydrogen and PtX production do not hinder the domestic energy transition. To project potential future hydrogen and PtX export costs, keep model runtimes to a minimum and foster hydrogen trade as soon as possible requires a detailed but globally scalable methodology involving meaningful scenarios, results and time steps. Additionally, the methodology developed and results obtained need to complement current research. Thus, it is crucial to take an inventory of the status quo in the numerous current H_2 and PtX export assessments as well as to highlight research gaps.

This working paper starts with a comparison of current techno-economic assessments of global hydrogen production in chapter 2. The methodology of the techno-economic assessment of hydrogen and PtX supply chains in HYPAT is presented in chapter 3. This includes a brief explanation of the methodological approach to country selection (chapter 3.1), the selection of export and import locations (chapter 3.2), as well as the model chain (chapter 3.3), and derived scenarios (chapter 3.4). In the following subchapters (3.5-3.9), the models used and their input and output data are described in more detail. This working paper is summarized in chapter 4, and further discussed in chapter 5, and an outlook is given. A technical annex is attached to this working paper with additional technical information on the models and the underlying assumptions. A list of parameters used in the models will be published separately as an MS Excel document.

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[2] See annex A.2 for further information.

2 State of the Art

Currently, several global studies are conducting techno-economic analyses to assess green hydrogen and PtX potentials (see the overview in Table 1).

Table 1: Techno-economic analysis of hydrogen and PtX export countries - Comparison of existing hydrogen and PtX potential studies.

Study	IRENA	PtX-Atlas	Heuser	Brändle	Lux	H2Atlas Africa	MENA Fuels	HYPAT
Regional scope								
Production locations	World	World[3]	World[4]	World[5]	MENA	Africa[6]	MENA	World [7]
Import locations	No imports	Germany	World	World	Germany	No imports	No imports	World[8]
Primary Energy								
Sources								
PV	x	x	x	x	x	x	x	x
Wind Onshore	x	x	x	x	x	x	x	x
Wind Offshore				x	x	x	x	x
CSP					x		x	x
Hydropower						x[9]		x
Biomass								x
Other								x[10]
RE plants - Restriction criteria								
Nature conservation areas	x	x	x		x			x
Urban areas		x	x				X	x
Land use factors	x		x		x		X	x
Cost of RE sources	x	x	x	x				
Water								
Sources								
Desalinated		x	x		x	x	x	x

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[3] 600 locations.

[4] 8 regions for wind, 15 for PV.

[5] 94 countries.

[6] West, South, and East Africa.

[7] 10 countries detailed. Results are scaled up to further roughly 70 countries. 90% of the global RE-potential will be covered.

[8] Demand regions.

[9] Hydropower will be added.

[10] Other primary energy sources considered include the current production and shift away from fossil energy carriers. Existing and planned nuclear power plants are also considered.

Study	IRENA	PtX-Atlas	Heuser	Brändle	Lux	H2Atlas Africa	MENA Fuels	HYPAT
Fresh		x				x		x
Water stress								
Considered	x	x				x		x
Energy system optimization								
National infrastructure								
Not considered	x	x	x	x		x [11]	x	
Distance to ports, pipelines and inland water sources		x	x					x
Power grid considered					x			x
Gas grid considered					x			x
Domestic energy demand								
Considered			x		x	x [12]	x	x
Grid connectivity								
No - Island plant systems	x	x	x	x	x [13]	x	x	
Yes - Integrated plant systems						x		x
Export								
Quantities - LCOH is calculated for								
Full RE potential	x		x[14]	x [14]			x	
Predefined quantity, extrapolated to full RE potential		x [15]				x [16]		

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[11] Not yet included.

[12] Considered when full potential is calculated.

[13] Not yet included.

[14] Full potential in different steps per country depending on FLH of RE plants.

[15] Plant configuration optimized for 1TWh/a, then extrapolated for available land.

[16] Costs calculated for 1% of full potential, then extrapolated to the entire nation's area.

Study	IRENA	PtX-Atlas	Heuser	Brändle	Lux	H2Atlas Africa	MENA Fuels	HYPAT
Multiple exogenously set quantity steps					x			x [17]
Transport pathways					[18]		[19]	
PL – GH2	x		x[20]	x	x			x
PL – GCH4		x			x			
Ship – LH2		x	x	x	x	x		x
Ship – LCH4					x			
Ship – LNH3								x
Ship – MeOH		x						x
Ship – FT		x						x
Ship – LOHC						x		x

IRENA recently published their global study on hydrogen potentials in 2050 (IRENA 2022b). In their study, they calculate the renewable energy potentials from wind and photovoltaic sources assuming different land restrictions for plant installations. The restrictions consider different land uses, excluding forests, nature-protected areas, buildings, and others (i.e., cropland natural). The electrolyzer size is optimized according to capacity factors for wind and solar plants at different locations. Taking an economic perspective, IRENA considers various weighted average costs of capital (WACC) per country and technology. The WACC are used to differentiate between an optimistic and pessimistic scenario. Moreover, IRENA includes a scenario with water restrictions.

In 2021, the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) published an interactive global atlas for hydrogen and PtX products (**PtX-Atlas**) (IEE 2022; Pfennig et al. 2022). The hydrogen and PtX potentials are calculated considering wind, PV, and a combination of both for more than 600 individual locations worldwide. Two electrolyzer technologies are used: The polymer electrolyte membrane, and the solid oxide electrolyzer cell. The production and shipping of six different PtX product types are calculated. For every location, the plant sizes for production and storage of RE, hydrogen and PtX products are optimized through linear cost optimization to generate a predefined amount of 1 TWh/yr. These results are then extrapolated to all the available land in the region via a plant density to calculate the full production potential. To determine the land available to install renewable energies, hydrogen and PtX infrastructure, several restricting factors are taken into account. These restrictions cover land, economic, infrastructure and water aspects, such as excluding nature conservation and residential areas, or economic aspects like excluding renewable potentials with a levelized cost of energy (LCOE) above 30 Euro/MWh for PV, and 40 Euro/MWh for wind. The distance to necessary infrastructure, such as ports and roads, is included for the production and export of hydrogen and PtX. Finally, water restrictions are added. Exclusively regions close to the coast

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[17] Optimization of energy system in terms of domestic energy demand and export quantities.

[18] Transport to Europe considering a distance factor.

[19] The production of FT products is considered, but no shipping costs.

[20] For inland transport only.

(desalinated water) and with low water stress (freshwater) are considered. For every PtX product, the export costs via ship to Germany are calculated using a specific factor in Euro/MWh, depending on the shipping distance and the PtX product. However, the study does not consider inland transport or export via pipeline, nor the integration of the PtX value chain into the local energy system. While production is optimized with a temporal resolution of one hour with respect to fluctuating electricity, shipping is calculated on an annual basis.

Heuser et al. 2020 study the potential future hydrogen markets evaluating both supply and demand at global level. Countries with particularly good PV and wind energy potentials are selected and multiple locations are analyzed with regard to their hydrogen production potential. The available land for renewable energies is selected by applying an algorithm that excludes nature conservation areas and built-up areas amongst other factors. In this approach, exclusively regions close to the coast are considered in order to use desalinated water. The production costs for the locations are aggregated according to the full-load hours (FLH) of the respective RE technology. This results in a merit order for hydrogen production, which is optimized to meet the global hydrogen demand according to IEA (International Energy Agency 2017). Hydrogen transport is modeled inland via pipeline and internationally by shipping liquefied hydrogen (LH2).

Brändle et al. 2020 evaluate the green hydrogen potential for 94 different countries. A literature review is performed to identify different capacity factors for both wind and photovoltaic. The capacity factors are aggregated to different clusters and a synthetic hourly time series is calculated for each cluster. Similar to other studies, the electrolyzer size is optimized considering different full-load hours for wind and photovoltaic plants. Subsequently, the hydrogen supply for different markets is evaluated by comparing the countries' potential and levelized cost of hydrogen (LCOH) with the potential of countries in the vicinity. The transport costs for hydrogen, either in liquefied form by ship or in gaseous form by pipeline, are added for imports from other countries. In addition to the global hydrogen studies, regional potentials are also evaluated, especially for Africa.

Lux et al. 2021 evaluate the RE potential in the MENA region using a system optimization model (Enertile®). This evaluation includes the local energy infrastructure and demand. Solar photovoltaics (PV), wind and concentrated solar power (CSP) are the renewable energies available for PtX production. The RE potentials are modeled with respect to their distance to the coast. For the production of hydrogen and PtX products in the Middle East and North Africa (MENA) region and their export to Europe, costs for water desalination are included and transport costs to Europe are considered via a distance factor.

In the **MENA-FUELS** project - by DLR (German Aerospace Center), Wuppertal Institut and izes - (Braun et al. 2022) analyze the costs and potentials for producing hydrogen and Fischer-Tropsch products in the Middle East and North Africa (MENA). They calculate the RE potential, hourly time series and LCOE for PV, CSP and wind electricity generation in a spatially resolved grid. Based on the hourly electricity generation, the production of Fischer-Tropsch products is simulated for every location and RE technology as isolated plant solutions. Different possibilities for electrolysis and Fischer-Tropsch plant locations (at either RE production sites or at harbors) including transportation costs are compared and the levelized cost calculated. Costs are included for water via seawater desalination and for CO_2 from point sources or direct air capture (DAC). The yearly hydrogen and Fischer-Tropsch production potential of all locations is aggregated per country and domestic energy demand subtracted to estimate the total export potential per country.

Forschungszentrum Jülich is analyzing the hydrogen production potentials of various regions in Africa in the ongoing project **H2Atlas Africa** (Forschungszentrum Jülich 2021). Initial results have been published in an interactive online atlas, but the full methodology has yet to be published. Currently, hydrogen production potentials and costs based on PV and wind energy are presented for the Economic Community of West African States. An extension of the H2Atlas Africa to Southern African countries is being planned. The factors considered for hydrogen production are the availability of land for RE plants and the different RE technologies. To assess the impact of groundwater availability, the hydrogen production potential is shown with and without groundwater use.

In **HYPAT**, 10 selected countries are analyzed techno-economically in-depth and the results are scaled up to a global hydrogen and PtX potential atlas. HYPAT differs in many respects from the other existing studies as it is more comprehensive regarding the following:

- A range of primary energy sources is considered for the domestic energy supply:
    - → Numerous primary energy sources are considered, such as PV, onshore and offshore wind, CSP, hydropower, and biomass.
    - → For the evolution of the energy system and a fossil phase-out, existing fossil and nuclear power plants are taken into account.
- Domestic and export demand are integrated into the energy system optimization:
    - → In order to build strong and sustainable energy partnerships, enabling the energy transition in the exporting countries is a priority. Thus, the domestic energy demand of the export country is considered, as RE can only be exported once domestic energy needs have been met.
    - → Production plants for electricity, hydrogen and PtX products for export are modeled as integrated processes within the national energy system instead of as segregated island solutions.
    - → Modeling the evolution of the energy infrastructure is based on the development of the domestic energy balance and predefined H2 and PtX export quantity steps.
- A range of transport pathways is assessed for H_2 and PtX exports:
    - → All the transportation technologies for H_2 and PtX are considered that are expected to be fully technologically ready by 2050 at the latest:
    - → New and repurposed hydrogen pipelines.
    - → Shipping for liquefied hydrogen, ammonia, methanol, Fischer-Tropsch products, and Liquid Organic Hydrogen Carriers (LOHC).
    - → Synthetic natural gas is not considered, as this might lead to lock-in-effects and slow down the realization of hydrogen infrastructures (Wietschel et al. 2022).

3 Methodological Approach

This chapter gives a detailed description of the HYPAT methodology for the techno-economic assessment of the hydrogen and PtX export potential of ten countries. The reasoning for the country selection is explained briefly in chapter 3.1. The methodology behind the choice of export and import locations is summarized in chapter 3.2. Chapter 3.3 describes the model chain to explain how the Enertile®, LEAP, PyPSA-Earth-Sec, Hytra and H2ProSim models interrelate. The main technical configurations of each model and the scenarios are found in chapter 3.4. Chapters 3.5 through 3.9 show how RE potentials (Enertile®), domestic energy demand projections (LEAP, MS Excel-based tools), national energy system optimization (PyPSA-Earth-Sec), exports via pipeline (Hytra) and by ship (H2ProSim) are modeled.

3.1 Country Selection

A global evaluation based on different factors was used to select ten countries for in-depth techno-economic assessment. These factors included renewable energy potentials and domestic projected energy demand for 2050, infrastructure quality, water stress, political stability, economic level and financial risks. Also considered were the existence of a national strategy for future hydrogen production and a current energy and hydrogen partnership with Germany. Moreover, existing studies of each potential export country were reviewed in order to identify possible knowledge gaps. The final selection encompasses countries with different economic status, size and from different world regions, as HYPAT uses the country-specific techno-economic results to scale up to a global hydrogen supply potential. The ten selected countries are listed in the figure and table below (see Figure 1 and Table 2). Further details of the selection and the parameters can be found in (Breitschopf et al. 2022).

Figure 1: **Selected export countries for in-depth techno-economic assessment in HYPAT.**

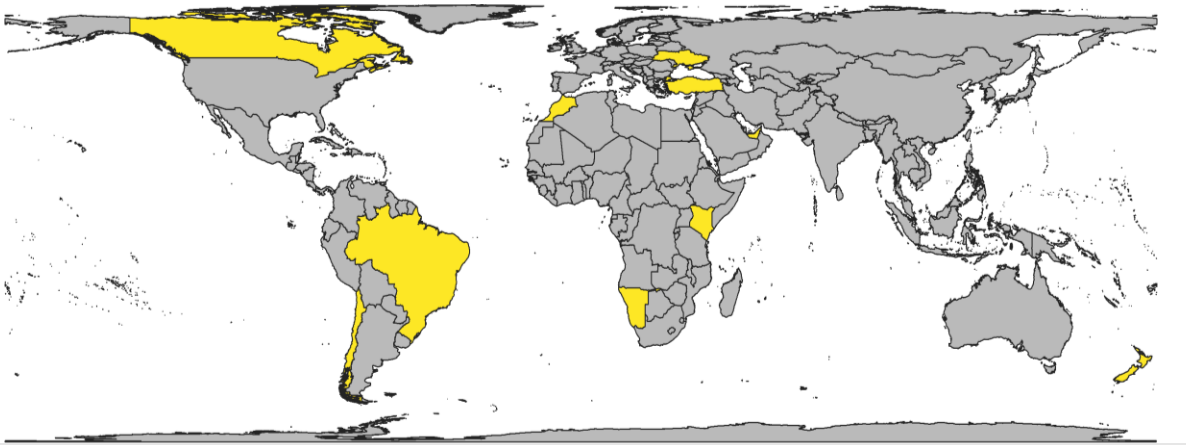

Table 2: Selected export countries for in-depth techno-economic assessment in HYPAT.

Country	Region	Economic status	Infrastructure[21]	H_2 strategy	Partnership with Germany (H_2, energy)
Morocco	North Africa	Lower middle income	2.43	Yes	Yes
Ukraine	Eastern Europe	Lower middle income	2.22	Draft	Yes
Namibia	South Africa	Upper middle income	NA	Yes	Yes
Turkey	Western Asia	Upper middle income	3.21	No	Yes
United Arab Emirates	Western Asia	High income	4.02	No	Yes
Kenya	East Africa	Lower middle income	2.55	No	No
Chile	South America	High income	3.21	Yes	Yes
Canada	North America	High income	3.75	Yes	Yes
Brazil	South America	Upper middle income	2.93	No	Yes
New Zealand	Oceania	High income	3.99	Yes	No

3.2 Export and Import Locations

3.2.1 Export and Import Locations for the Modeled Countries

For pipeline transport, the export and import location is chosen based on the routing of existing pipelines or the distance for new pipelines. For existing pipelines that need to be repurposed, the export location is the point where natural gas transmission pipelines exit the country. For new pipelines, an area closest to the import location is chosen that is suitable for pipeline exit (e.g., no large bodies of deep water). For import locations, the same criteria apply. If there are several points available for an export location, the one that results in the shortest transport route is chosen.

For transport by ship, export is possible from up to five different preselected harbor locations. The preselection of the possible harbor sites is based on the ports available and geographic conditions, like area availability and proximity to infrastructure. In addition to that, the selection process for export harbors ensures that the sites are evenly distributed along the coast. Existing ports with sufficient density and area are preferred over building new ports. If there are no

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[21] The infrastructure indicator is qualitative. It ranges from 0-5, where 5 is the highest: The higher the indicator, the better the infrastructure. The data are taken from the World Bank. As a reference, Germany had the highest score in 2018 with 4.37 (The World Bank 2018).

ports along a coastline, we assume that jetties can be built. Nevertheless, most existing ports need significant investments to be able to handle the expected volumes of PtX products and the ship sizes. As all selected countries have access to the sea, harbors of neighboring countries are not considered.

The ship transport is modeled either to the German harbor and first LNG terminal Wilhelmshaven or to international import hubs located in expected demand centers. The selection of export and import hubs is explained in the following chapter.

3.2.2 Export and Import Hubs

Depending on their renewable energy potentials, domestic primary energy demand and the resulting net RE surplus, countries can play a specific role in a future hydrogen trade market. They can be divided into three groups globally:

- Import hubs: These are countries (e.g. Germany, Japan) with RE deficits according to Enertile® and a demand literature study [22]. In these countries the future demand for hydrogen and PtX is projected to exceed their total RE domestic production potential. Import countries in close proximity to each other are further aggregated into import hubs.
- Export hubs: Potential export countries (e.g., the MENA region or Chile) are derived from the multi-criteria analysis conducted in HYPAT WP 2.1 (see Appendix 2.2 of Breitschopf et al., 2022). This analysis estimates RE surplus based on Enertile and includes a literature study of domestic energy demand, infrastructure and political stability, among other factors. Export countries in close proximity to each other are further aggregated into export hubs.
- Unclear trade status (Import and/or export hub): Some large economies have both a high demand for hydrogen and PtX products and large RE production potentials (e.g., China, USA or India). Depending on favorable market conditions, those countries could enter the hydrogen market as exporters or importers, or even both.

The resulting export and import hubs are shown in Figure 2. The circles around the centers of the import hubs have a radius of up to 5,000 km and indicate the average economic distance of the retrofitted and new pipelines, where the cost of transporting large quantities of hydrogen by pipeline is still lower than by ship. For the techno-economic assessment of the pipeline transport, a rerouting coefficient of 20% of the distance is taken into account. For PtX transport via ship, theoretically all transport routes between export and import hubs are conceivable - as can already be seen for the international LNG shipping routes today.

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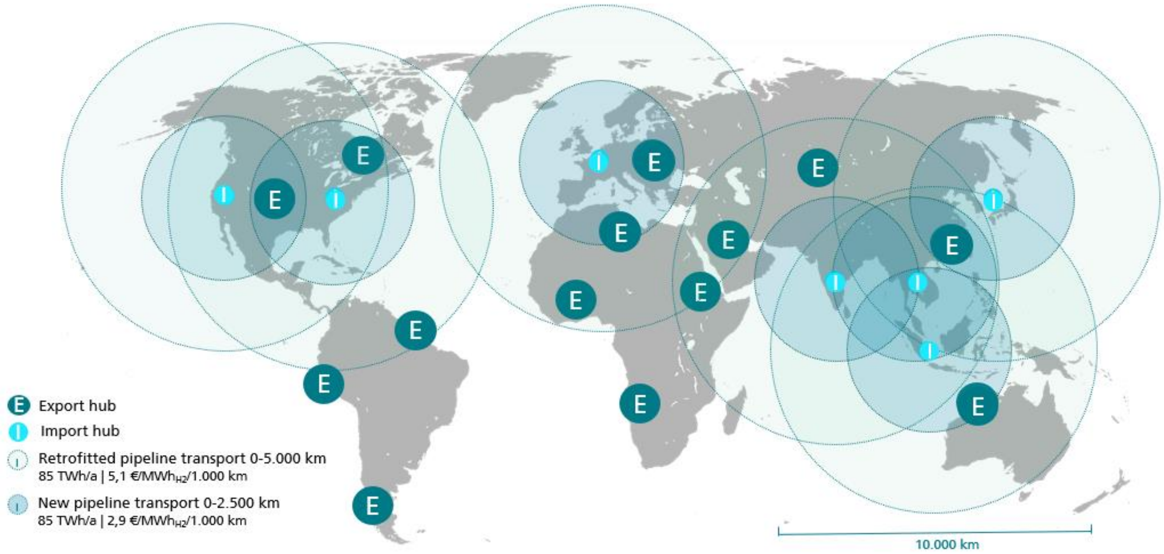
[22] Brändle et al (2021), (IEE 2022), Lux et al (2021), IRENA (2022), Hydrogen Council &McKinsey (2022); national hydrogen strategies

Figure 2: **Major global export and import hubs. A preliminary map; further developments will be provided in HYPAT Working Package 5.1.**



Export and import hubs are introduced in HYPAT to model the main international transport routes for green hydrogen and indicate major trade relations. Therefore, an export hub is understood as a location, where large quantities of hydrogen and PtX products can potentially be bundled to achieve economies of scale and to be exported via ship or pipeline to different import destinations. An import hub is understood as a demand center (e.g., Western Europe), where large quantities of hydrogen and PtX products are delivered and then distributed to their final destination.

For all the countries in close proximity to a certain hub, similar or even the same costs are expected for international transport. Therefore, the introduction of export and import hubs reduces the complexity in assessing hydrogen transport costs on a global scale and between multiple traders, and is a helpful abstraction for a global scale-up.

3.3 Model Chain

3.3.1 Overview

The model chain was developed to optimally connect the models in the project utilizing the unique strength of each model and to facilitate trouble-free data flow. The output of the model chain is the total cost of hydrogen and PtX products at the import locations for different scenarios, time horizons, and quantities (see chapter 3.4). These costs cover all steps of the supply chain: electricity generation and transmission, hydrogen production and storage, the synthesis processes and transportation via ship and pipeline. One main feature that is unique to the model chain and HYPAT is the integration of the supply chain into the respective national energy system while considering the domestic energy demand of the export countries. This allows the optimal utilization of the existing power generation and conversion assets, as well electricity and gas transmission infrastructures.

The model chain consists of five different models that are connected through several data linkers. Each model serves a unique purpose providing preliminary results to the other models as well as the final result at the end of the model chain. Each model is explained in more detail in the chapters 3.5-3.9. The chain can be described as a three-stage workflow: The first is supply and national demand, the second is transmission and infrastructure, and the third is synthesis and export.

Stage 1 Supply and demand models:

- The renewable potential calculator is part of the energy system model **Enertile**® (chapter 3.5) outputting the renewable potential for four different technologies (utility-scale photovoltaic, concentrated solar power, wind onshore and wind offshore). It considers land use and real weather data on a global basis. It has a high geographical and hourly resolution on a country/region base.
- **LEAP** is primarily an energy policy analysis software tool (chapter 3.6) used in our context to develop scenarios for the projected annual domestic energy demand per sector, technology and energy carrier. In addition to LEAP, sector-specific **MS Excel-based tools** were developed for cross calculations.

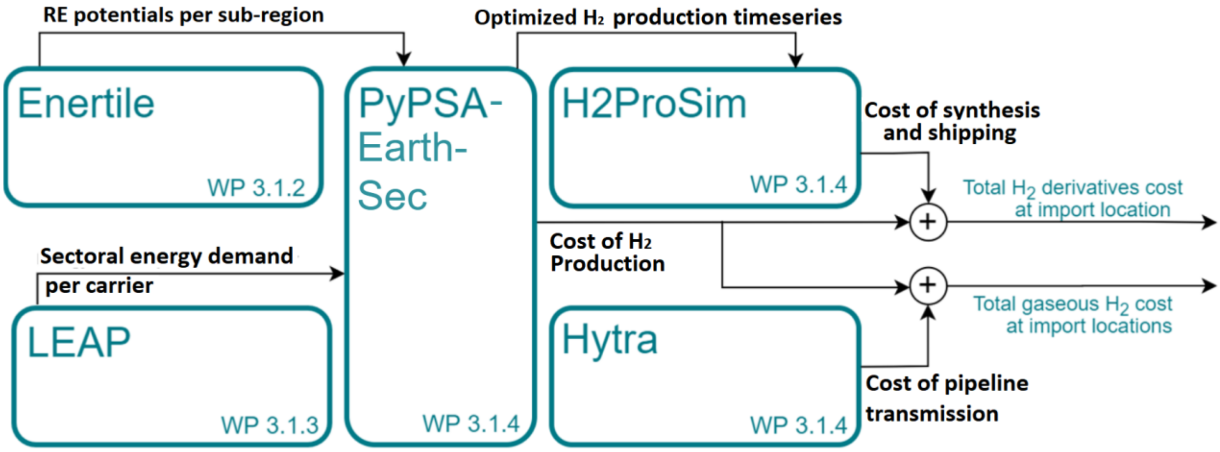
Stage 2 Transmission and infrastructure model:

- **PyPSA-Earth-Sec** (chapter 3.7) is an open-source sector-coupled energy system model with a total cost optimization problem at its core that incorporates different technologies, demand sectors, energy carriers and transmission level infrastructures.

Stage 3 Synthesis and export models:

- **Hytra** (chapter 3.8) is a techno-economic model for the calculation of hydrogen transport costs via pipeline and is used solely for the export of hydrogen. One of its focuses is the analysis of relevant existing natural gas infrastructures for potential repurposing.
- **H2ProSim** (chapter 3.9) is a techno-economic analysis and optimization tool for PtX value chains. It focuses on the export of PtX products including synthesis or liquefaction, storage and shipping.

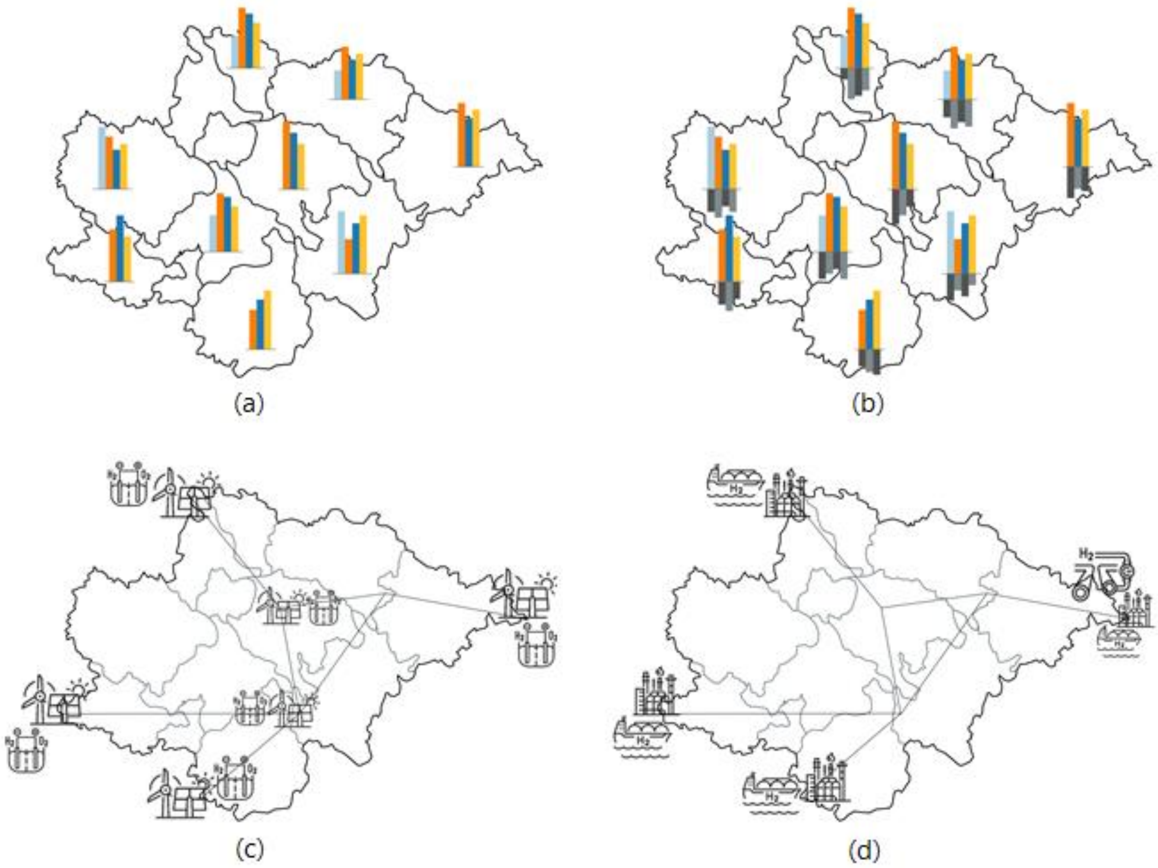
Figure 3 **Main data flow and connections in the model chain**



The main data flows in the model chain are summarized in Figure 3 and can be described as follows: The stage 1-models calculate the renewable energy supply potentials (**Enertile®**) and estimate the future sectoral domestic energy demand (**LEAP, MS Excel-based tools**). In stage 2, **PyPSA-Earth-Sec** uses these data and optimizes the national energy system and calculates the hydrogen generation cost and potential. The stage 3-models (**H2ProSim** and **Hytra**) calculate the cost of synthesis and export from the export countries to the corresponding import countries. The complete data flow between the models is explained in the chapters 3.5-3.9.

To illustrate the interaction between the models and a selection of the corresponding model outputs, the figures below show a simple representation of a fictional country. Figure 4a) displays the simplified output of the renewable energy potential at a regional level from Enertile®. Figure 4b) presents the regionalized sectoral energy demand for the different carriers generated by LEAP/MS Excel-based tools and post-processed by PyPSA-Earth-Sec. Figure 4c) shows an example distribution of the optimal capacities and locations for the electrolyzers and new renewable energy power plants. Finally, Figure 4d) illustrates the output from H2ProSim and Hytra for optimal synthesis plants and shipping fleets as well as an optimal export pipeline sizing.

Figure 4: **Different stage outputs of the model chain. (a) shows the renewable potentials of the different regions of the country (Enertile®). (b) shows the regionalized domestic energy demand for the different carriers (LEAP/MS Excel-based tools + PyPSA-Earth-Sec). (c) shows the optimized capacities and locations of the electrolyzers and the new renewable power plants. (d) shows the optimal capacities for synthesis plants as well as ships or pipelines at the export locations.**



(a) (b) (c) (d)

Each model is capable of functioning as a stand-alone complex. Consequently, each model provides a wide range of outputs; some are necessary for the model chain and some are important to complete the picture for the specific model results. The models have been modified with new features to enable a trouble-free functioning of the model chain. In the following sections, each model is explained in more detail, highlighting the input and output data flow and the relevant parameters.

3.3.2 Final Results

The main objective of the model chain is to calculate the levelized cost of hydrogen (LCOH) or PtX product (LCOPTX) delivered at the import location. These costs consist of the hydrogen production costs optimized in PyPSA-Earth-Sec, and the export costs calculated in Hytra for pipeline export, or in H2ProSim for shipping. To make different energy carriers with different gravimetric energy densities comparable, these costs are levelized via the delivered energy content. Alongside costs per MWh, costs per kilogram will be given as well.

Several intermediate results of the model chain are combined to determine the optimal LCOH and LCOPTX. As these intermediate results convey valuable insights regarding the potential of the assessed countries, a selection of them will be published together with the LCOH. The quantities of hydrogen and PtX products and the delivery at the import locations are available in an hourly temporal resolution from PyPSA-Earth-Sec, H2ProSim, and Hytra. The main RE results from Enertile® include the maximum capacity in MW_p, the full-load hours and the LCOE for different RE technologies, which are calculated based on a 6.5km x 6.5km grid worldwide and aggregated per region/country. An hourly time series is calculated for each renewable energy technology. The local sectoral energy demands in the selected export countries are available from LEAP in a yearly resolution.

The installed capacities of necessary plants and infrastructure in the cost optimum of the entire value chain will be derived from PyPSA-Earth-Sec and H2ProSim with a spatial resolution. These include RE plants, electrolyzers, inland transport infrastructure, storage, synthesis, liquefaction and the ships required for export. The optimal pipeline size and routing will be taken from Hytra.

All results will be calculated individually for every scenario, quantity and export option further explained in chapter 3.4 and published for each analyzed country.

3.4 Configurations and Scenarios

Overarching scenarios are derived from combining different model configurations. Each model is characterized by one or multiple configuration types:

- Export quantity steps (PyPSA-Earth-Sec, Hytra, H2ProSim) (see chapter 3.4.1)
- Interest rates (Enertile®, PyPSA-Earth-Sec, Hytra, H2ProSim) (see chapter 3.4.2
- Decarbonization pathways (LEAP/ MS Excel-based tools) (see chapter 3.4.3)
- National infrastructure expansion level (PyPSA-Earth-Sec) (see chapter 3.4.4)
- Pipeline export pathway (Hytra) (see chapter 3.4.5)
- Shipping export pathways, synthesis plant operation flexibility, ship size, and ship fuel type (H2ProSim) (see chapter 3.4.6).

The financial risk of investing in and running a plant is expressed in the interest rate, which is used to calculate the costs of renewable energy generation (Enertile®), national infrastructure expansion (PyPSA), and of hydrogen export by pipeline (Hytra) and ship (H2ProSim). Two different transportation pathways are considered for pipeline export: new and repurposed pipelines. Different national decarbonization pathways are considered for the energy demand projections (LEAP, MS Excel-based tools). The choice of decarbonization pathway also affects the ambitiousness of national infrastructure expansion (PyPSA-Earth-Sec) and the fuel type used for shipping (H2ProSim). Several transportation pathways exist for shipping alongside other configuration types.

Each model sets different technical configurations for the above-listed configuration types, which are bundled and classified as an *Optimistic*, *Realistic*, or *Conservative* scenario regarding domestic energy transition ambitions, infrastructure development goals, and costs for electricity, hydrogen and PtX production (see chapter 3.4.7). The resulting model-specific and country-related model chain runtimes are shown in chapter 0.

3.4.1 Quantity Steps

In order to make export costs comparable, the export quantities are set exogenously for all countries in the same manner and differentiated between 2030 and 2050, as summarized in Table 3. Varying producible export quantities are given as the input to consider economies of scale and the decrease in RE potential with increasing export amounts. Therefore, based on sufficient quantity steps, a cost-over-quantity curve is derived to show the potential and optimal costs for hydrogen and PtX production in each country.

For 2030, hydrogen and PtX export costs are calculated for each country for a total production of 1, 10, and 50 TWh per year. For 2050, the set export quantities increase to 10, 100, and 500 TWh per year.

A fourth quantity step is chosen based on a share of the RE potential to evaluate the total potential and a country's market power to produce PtX products. This quantity is limited based on the expected global hydrogen demand to prevent unrealistically large export quantities in countries with enormous RE potentials. The average hydrogen demand is projected to amount to 3,000 TWh in 2030, and 15,000 TWh in 2050 (Riemer et al 2022). We assume that a country can maximally either satisfy 33% of the global hydrogen demand (demand cap) in 2030 (or 20% of this in 2050), or export 5% of the domestic RE potential below 80EUR/MWh LCOE in 2030 (or 50% of the domestic RE potential below 60 EUR/MWh LCOE in 2050).

Table 3: Exogenously set export quantity steps for PyPSA, Hytra, and H2ProSim

Export quantities (PyPSA, Hytra, H2ProSim)	Year	
	2030	2050
RE - LCOE threshold[23]	80 EUR/MWh	60 EUR/MWh
Global demand	3,000 TWh	15,000 TWh
Demand cap	33%	20%
Country		
[Country name]		
	1TWh	10 TWh
	10 TWh	100 TWh
	50 TWh	500 TWh
	Min (5% of RE potential, or demand cap)	Min (50% of RE potential, or demand cap)

All country-specific export quantity steps are found in annex A.3.

3.4.2 Interest Rates

Three different interest rates, *Low*, *Medium*, and *High*, are calculated for each country and year (2030 and 2050) based on historical values for the equity risk premium and country-specific risk premium. The equity risk premium is the price of risk in equity markets. The country risk premium is country-specific and considers the additional risk of investing in a national business. The country risk premium is taken from the work of Damodaran 2021 and is calculated using the country default spread, which is estimated from Moody's local currency sovereign rating. Countries with an AAA rating, e.g., Canada, have a country risk premium of 0%. For more information, see (Wietschel et al. 2021).

Table 4 summarizes the assumptions made for each year and configuration. A table with the resulting country-specific interest rates can be found in Annex A.4.

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[23] The LCOE threshold limits the renewable energy potential at this value. The value changes from 2030 to 2050 to consider the future development of electricity generation from RE technologies. The limits of 60 EUR/MWh and 80 EUR/MWh consider all the different RE technologies. This LCOE threshold marks the maximal RE potential that is considered for the production of hydrogen and PtX products for export after meeting primary domestic energy demand.

Table 4: **Selection of interest rates. The interest rate is the result of the sum of the country-specific risk premium and the equity risk premium.**

Interest rate level	Risk premium	Year	
		2030	2050
Low			
	Country risk	Country risk minimum in 2000-2020	0% (all countries are considered AAA)
	Equity risk	Equity risk minimum in 2000-2020	Equity risk minimum in 2000-2020
Medium			
	Country risk	Country-specific value of 2020	Country-specific historical average in 2010-2020
	Equity risk	Equity risk value of 2020	Equity risk historical average in 2000-2020
High			
	Country risk	Country risk maximum in 2000-2020	Country risk maximum in 2000-2020
	Equity risk	Equity risk maximum in 2000-2020	Equity risk maximum in 2000-2020

3.4.3 Decarbonization Pathways

2019 is the base year for the domestic energy demand projections in HYPAT. Starting from then, future energy demand for 2030 and 2050 is estimated in three different scenarios: Baseline, Ambitious Plans, and Net-Zero Scenario. To reach **net-zero** (NZ), this study assumes that an export country becomes carbon-neutral by 2050. According to a comparison of the BIG5 energy system studies for Germany in the Kopernikus-project ARIADNE (ARIADNE 2022), carbon neutrality will be mainly achieved by

- a high degree of electrification,
- a low degree of biomass use, except for industry,
- in combination with Direct Air Capture and Carbon Storage (DACCS) and/or Bioenergy with Carbon Capture and Carbon Storage (BECCS),
- and hydrogen or PtL use, where no alternative technologies can be applied or due to poor regional infrastructure.

Based on the net-zero demand outcomes and fuel shares in 2050, the **Ambitious Plans** (AP) scenario assumes a slower decarbonization and infrastructure development. Moreover, the transition phase of AP uses more biomass in all sectors, and a relevant share of fossil energy carriers in 2050 for processes that currently rely on liquid energy carriers. The **Baseline** scenario

(BS) is mainly used for the purpose of comparison. In this scenario, no new technologies are introduced and efficiency measures are kept to a minimum. Since fostering the energy transition within the export country is an important HYPAT requirement for hydrogen and PtX exports, the BS is not considered further in the model chain.

3.4.4 National Energy System Expansion (PyPSA-Earth-Sec)

To optimize the national energy system, PyPSA-Earth-Sec optimizes the capacities of the electrolyzers, renewable energy power plants, newly built hydrogen pipelines and hydrogen storage options to meet domestic energy demand as well as the export quantities of hydrogen and PtX products. In the optimization, the model accounts for the limitations posed by the transmission infrastructure represented by the electrical grid and (repurposed) natural gas pipelines and relaxes them according to the envisioned expansion in the assessed scenario (AP, NZ). Different transmission infrastructure expansion levels are considered, which range from **none**, **moderate**, to **large**. For 2030, the scenarios are between **none** and **moderate** expansion. For 2050, the scenarios range between **moderate** and **large** infrastructure expansion. Additionally, the emission reduction targets vary for each scenario and year reaching at least **80%**[24] in 2050 compared to 1995 for **AP**, and **100%** decarbonized system in 2050 for **NZ**.

3.4.5 Export via Pipeline (Hytra)

Exporting hydrogen via pipeline can either take place in a **newly built** or in a repurposed pipeline. Using **repurposed** natural gas pipelines for hydrogen transport is considered optimistic, as pipelines are only available for repurposing if they are no longer used to transport natural gas. HYPAT stipulates that compression energy needs to be green. For **sustainable recompression** along the pipeline, the electricity can either stem from an electrical grid, from a dedicated RE island plant, or directly from the transported hydrogen. Since neither an existing electrical grid alongside the pipeline nor 100% RE electricity supply can be guaranteed, these options are not considered further. Instead, as is already the case with natural gas, hydrogen from the pipeline is used to power the compression. The model chooses whether to combine this with a RE island plant or not, depending on the renewable energy potentials in the area.

3.4.6 Export via Ship (H2ProSim)

Hydrogen can be exported by ship as either liquefied hydrogen (**LH2)**, ammonia (**NH3**), methanol (**MeOH**), liquid organic hydrogen carrier (**LOHC**), or as a Fischer-Tropsch synthesis product (**FT**) (e.g., eDiesel, eKerosene). The export of each PtX product is modeled individually. Other configurations for the synthesis and ship transport of PtX products include plant flexibility, ship size, and fueling type. Some degree of freedom is expected for the **operation flexibility** of synthesis plants, ranging between **low and high flexibility**. For more optimistic scenarios and in the longer term, synthesis plants are assumed to operate with high flexibility. For ships, it is assumed that only **small ships** will be available and used in the *realistic* and *conservative* scenario in 2030. **Large ships** will be available in the optimistic scenario and all calculations for

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[24] Hydrogen needs to be introduced into an energy system in order to reduce carbon emissions beyond 80% compared to 1995 (Riemer et al. 2022).

2050. Furthermore, ships are powered by **fossil fuels** until 2030. In 2050, the **sustainable** cargo is expected to be used as fuel for the ship.

3.4.7 Bundling Model Configurations to Scenarios

The complete run through the model chain is performed twice for three scenarios, once for the time horizon 2030 and once for 2050. These scenarios are named *Optimistic*, *Realistic*, and *Conservative* (see Table 5*)*.

Within each scenario, the 2050 time horizon builds on infrastructure investments from 2030. This is relevant for the models PyPSA-Earth-Sec, Hytra and H2ProSim. In these models, it is assumed that the infrastructure calculated for 2030 (in terms of renewable energy power plants, electrolyzers, synthesis plants and pipelines) remains installed in 2050, creating one pathway for each scenario and export quantity combination.

To give an example, for the *Optimistic* scenario and quantity step one (Q_1), this means that the infrastructure investment for quantity step one in 2030 ($Q_{1,\ 2030}$) forms the starting point for quantity step one in 2050 ($Q_{1,\ 2050}$) (with $Q_{1,\ 2050} \geq Q_{1,\ 2030}$). This approach allows the models to map a realistic and continuous build-up of hydrogen and PtX infrastructures as well as hydrogen and PtX exports between 2030 and 2050. Furthermore, the interest rates are low, so that the production and transportation costs for RE-electricity, hydrogen and PtL are at the lower end of the scale. The domestic energy demand of the export country follows a NZ path, and therefore, all carbon emissions are mitigated in 2050. Accordingly, the national infrastructure expands at a rapid pace to match the NZ criteria of the domestic energy system and hydrogen/PtL export infrastructure in 2050. Additionally, PtL plants can be operated at a high flexibility, and sufficient and well-sized ships powered by sustainable fuels are available in 2050 for exports. Natural gas pipelines can be repurposed to transport hydrogen.

Table 5: Model configurations and scenarios

Country			[Country name]					
Scenario			Optimistic		Realistic		Conservative	
Year			2030	2050	2030	2050	2030	2050
Configuration type (model)		Configuration						
Financial risk (Enertile®, PyPSA, Hytra, H2ProSim)								
		Low	x	x				
		Medium			x	x		
		High					x	x
National decarbonization pathways (LEAP)								
		Baseline						
		Ambitious Plans			x	x	x	x
		Net Zero	x	x				
National energy infrastructure expansion (PyPSA)								
		None			x		x	
		Moderate	x			x		x
		Large		x				
Export via pipeline (Hytra)								
	Construction							
		New pipelines	x		x		x	x
		Repurposed pipelines		x		x		
Export by ship (H2ProSim)								
	Energy carriers							
		LH2	x	x	x	x	x	x
		LOHC	x	x	x	x	x	x
		MeOH	x	x	x	x	x	x
		NH_3	x	x	x	x	x	x
		FT	x	x	x	x		x
	Flexibility for partial load operation							
		1 - low					x	
		2			x			
		3 - medium	x					
		4				x		x
		5 - high		x				
	Ship size							
		Small			x		x	
		Large	x	x		x		x
	Ship fuel							
		Fossil	x		x		x	
		PtL		x		x		x

3.4.8 Model Runtimes

Each model has a different calculation time per scenario, year and quantity:

- Enertile®: ~ 2 weeks (per interest rate)
- LEAP: ~ 1 minute (per decarbonization pathway)
- PyPSA: ~ 3 hours (per infrastructure expansion level, year and quantity step)
- Hytra: ~ 1 minute (per quantity step and interest rate)
- H2ProSim: ~ 1 hour (per PtX product, export location, year, quantity step, and interest rate)

This results in a total runtime of 3-4 weeks to model the entire supply chain for a country, for all scenarios, years and quantity steps, which does not involve the initial country-specific data preparation and data input. The model runtime highlights the importance of selecting scenarios in order to reduce complexity and deliver results in a feasible time horizon.

3.5 Renewable Energy Potentials (Enertile®)

3.5.1 Model Description

Within the HYPAT project, Enertile® renewable potential calculator 2.0 is used to calculate the potential of four different technologies: utility-scale photovoltaic, concentrated solar power, onshore and offshore wind. It uses global weather data, ERA5 for the year 2010 (ECMWF 2020). The model has high geographical resolution based on approximately 12 million 6.5 x 6.5 km^2 tiles worldwide. Land-use criteria are assigned to each of these tiles according to the GlobCover 2009 dataset (ESA 2010). A factor is allocated to each land use per technology, determining the land available to install renewable energy sources. Areas designated as protected area categories Ia, Ib and II according to the International Union for Conservation of Nature and Natural Resources (IUCN) were excluded when calculating the potential (IUCN). More details about this calculation can be found in (Franke et al. 2023) and on the long-term scenario website[25] (Sensfuß et al. 2022). Figure 5 depicts the calculation process within Enertile®.

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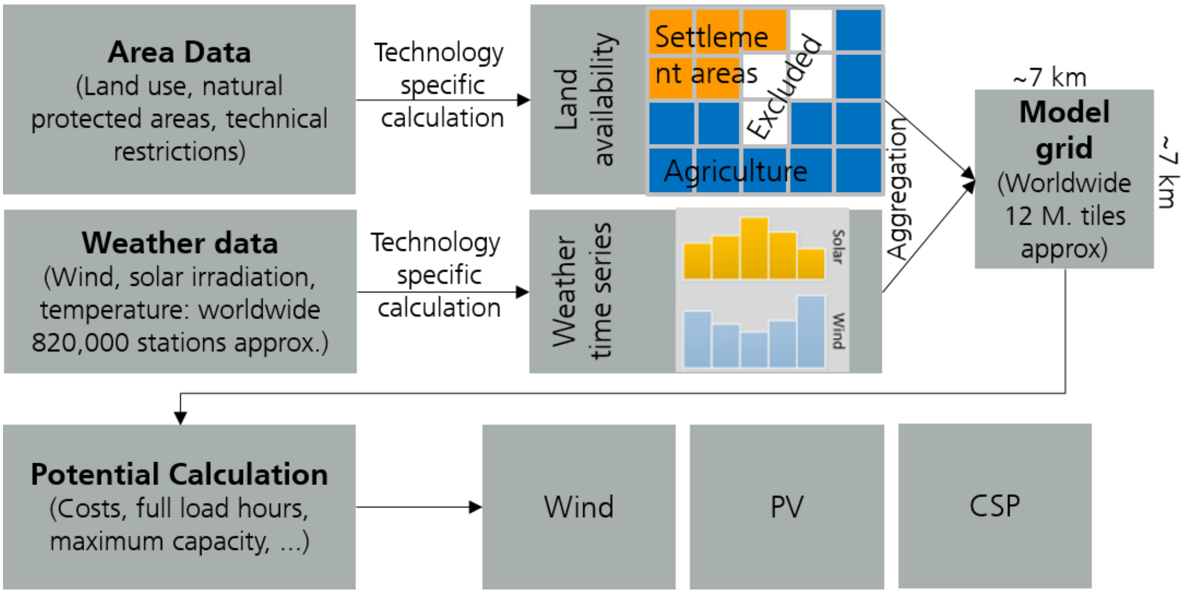
[25] https://www.langfristszenarien.de/

Figure 5: **Renewable potential calculation process in Enertile®.**



3.5.2 Input Data and Parameters

3.5.2.1 Weather Data (ECMWF 2020)

We use the global reanalysis ERA5 weather dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) to calculate the energy yield and the feed-in time series (ECMWF 2020). The dataset has an hourly resolution and a geographical resolution of 30 km. It covers the entire earth’s surface. It includes wind speed, temperature, direct irradiation and diffuse irradiation among others.

3.5.2.2 Land-Use Criteria

The RE potential is highly sensitive to changes in designated land-use. Hence, based on a literature review, land utilization factor values were assigned for use within HYPAT. Further details about the land utilization factors are found in Franke et al. 2023. The values allocated are shown in Table 6.

Table 6: Land utilization factors for the considered technologies

Land-use category	Utility-scale PV	CSP	Onshore wind	Offshore wind
Barren	20%	20%	50%	
Cropland natural [26]	2%	2%	20%	
Croplands	1%	1%	10%	
Forest	0%	0%	10%	
Grassland	10%	10%	40%	
Savannah	5%	5%	20%	
Shrub land	5%	5%	20%	
Water				30%

The highest land utilization factors are allocated to barren land. Barren land has no economically competitive use. CSP and utility-scale PV are assigned the same factors. We allocated higher factors to onshore wind than to solar technologies. The distance between wind turbines permits the land in-between to be used for other purposes and decreases their ecological impact. The mixed character of the category "croplands natural" permits a higher use factor than for croplands. Savannah and shrubland have the same factors. The factor for grassland is double the factor for savannah and shrubland, as the ecological impact is smaller. A 30% factor is assigned to offshore wind on water areas.

The area available for photovoltaics on open spaces is calculated using the following formula:

Equation 1

$$Available\ land = \sum_{Tile} \sum_{Land\ use.} TileSize * Fraction_{Land\ use.} * LandUseFactor$$

The example given below is for the calculation for a tile with 50% grassland and 50% barren:

$$Available\ land = 42.25\ km^2 * 0.5 * 0.1 + \ 42.25\ km^2 * 0.5 * 0.2 = 6.34\ km^2$$

Before starting the modeling, the tiles are allocated to the regions of the selected country. The regions are chosen according to different factors including the administrative division of the country, proximity to the ocean, and population distribution.

3.5.3 Output Data

The main output data of the Enertile® renewable potential calculator consists of three datasets:

- Annual values: Electricity costs per MWh, full-load hours, potential capacity in MW for the region, and annual costs per MW installed. The potentials are clustered in different

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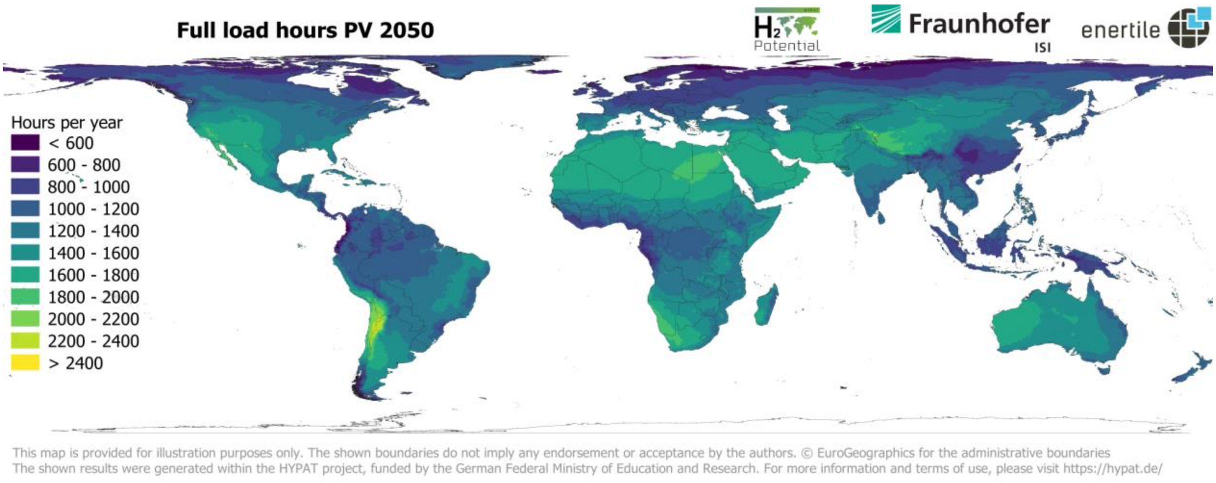
[26] Cropland natural is a mosaic that includes croplands together with grasslands/shrubland/savannah/forest.

steps starting at 0 (lowest electricity generation costs). These data are aggregated to a region/country level.

- Time series: Normalized hourly time series are calculated for each region, step and RE technology. The data are aggregated to a region/country level.
- Tile data: The full-load hours, the potential capacity in MW, and the specific electricity costs for each tile per technology. The tile data can be represented on a map as shown in Figure 6.

Figure 6: **Tile data shown in a map format. FLH for utility-scale PV in 2050 (Kleinschmitt et al. 2022).**



There are two different lots of calculations within the project HYPAT: worldwide potentials and the countries selected for in-depth analysis. The worldwide potential data (annual and hourly time series) were aggregated from an individual country basis. The details of this calculation are given in Kleinschmitt et al. 2022.

The selected export countries are divided into several regions. The regions are chosen according to different factors including the administrative division of the country, proximity to the ocean, and population distribution. The annual and hourly time series are aggregated here on a regional level. This provides higher granularity that is useful for the models within HYPAT.

3.6 Domestic Energy Demand Projections (LEAP, MS Excel-based tools)

3.6.1 Model Description

The Low Emissions Analysis Platform (LEAP) is a medium- to long-term scenario-based energy system modeling tool (Heaps 2022). LEAP can be used to track energy consumption, production and resource extraction in all sectors of an economy on an annual time-step. It covers the holistic energy balance of a region:

- Energy supply,
- Energy transformation,
- Energy demand. (Heaps 2022)

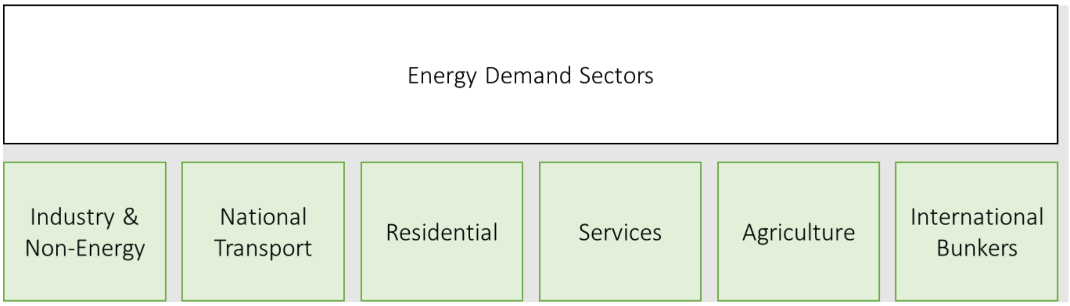
Since the national energy supply and transformation are modeled in more detail in Enertile® and PyPSA, in the HYPAT context, the LEAP framework focuses solely on energy demand. Simultaneously the energy demand evolution is cross-calculated using MS Excel-based tools, which have been developed in-house.

Different techniques exist to model energy demand evolution. According to TU Berlin, energy demand assessment is classified into five techniques: statistical, machine learning, metaheuristic, stochastic/fuzzy/grey, and engineering-based techniques (Verwiebe et al. 2021). The national energy demand assessment in HYPAT follows an engineering-based approach: Energy- and consumption-specific data are collected for relevant processes and end-uses, from which the national energy demand is calculated bottom-up. This allows the introduction of innovative processes within different scenarios, especially regarding future hydrogen usage.

The aim within HYPAT is to project the future energy (and hydrogen) demand of potential export countries. In the future, relevant quantities of hydrogen use are foreseen for specific end-uses and technologies (e.g., long-distance transport, steel production, etc.) (Riemer et al. 2022).

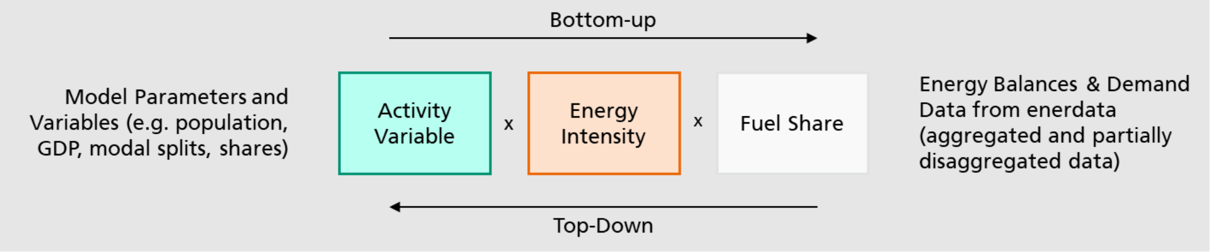
For the modeling, a methodology was applied that is detailed enough to depict all relevant energy-consuming processes and can be easily transferred to any country at the same time. To reach high estimation accuracy, each final energy demand sector shown in Figure 7 is modeled individually.

Figure 7: Overview of energy demand sectors



Inherent processes with high energy consumption or those subject to transformation are modeled with a higher level of detail. Country-specific parameters, such as population, gross domestic product (GDP), energy intensities and historical process- or sector-related fuel shares (here referred to as "shares") are adjusted to ensure the transferability to other countries. Missing parameters are approximated heuristically by breaking down the historical energy demand into the defined structure (see Figure 8).

Figure 8: Energy demand modeling: Using an engineering or process-based bottom-up vs. a heuristic top-down approach.



Depending on the sector, energy demand is modeled at different levels of detail. An overview for the individual subsectors can be found in annex A.5. In general, the projection of the future total final energy demand per year *y* and scenario *s* can be expressed as the sum of the final energy demand of the different sectors *s* in the respective year and scenario as shown in Equation 2. For each sector, this final energy demand can again be described in general terms as the sum of all subcategories S_i in the sector, and for each subcategory, the individual energy demand can be calculated using Equation 3 as the product of its activity level *AL* and its energy intensity *ei*. For the activity variable of each subcategory, we use shares to split the higher-level sectoral activity variable and assign it to the corresponding subcategory.

Equation 2

$$E_{tot,s,y} = \sum\nolimits_{S} E_{S,s,y}$$

Equation 3

$$E_{S,s,y} = \sum\nolimits_{S_i} AL_{S_i,s,y} \cdot ei_{S_i,s,y}$$

3.6.2 Input Data and Parameters

3.6.2.1 National Transport

The activity variable that determines the final energy demand of the **national transport sector** is the number of vehicle kilometers driven per vehicle type. To estimate this for each scenario and year, we account for several parameters, listed below:

- Population
- Mileage per person (e.g., average distance travelled in passenger-kilometers per person)

- Modal shares (e.g., share of road transport in passenger transport as a percentage of total passenger-kilometers)
- End-use shares (e.g., share of light duty vehicles in road passenger transport as a percentage of total road kilometers)
- Load factor (e.g., load factor of light duty vehicles in persons per vehicle)
- Technology shares (e.g., share of gasoline internal combustion engines in light duty vehicles as a percentage of total light duty vehicle kilometers).

The resulting vehicle kilometers are then multiplied by the estimated energy intensity of each vehicle type in a given year and scenario to obtain the final energy demand per vehicle type:

- Energy intensities (e.g., energy intensity of gasoline light duty vehicles in kWh/km).

Finally, we multiply the final energy demand of each vehicle type by the share of the different fuels for this vehicle type. Most vehicles use only one type of fuel, but there are multiple fuel options for some. Plug-in hybrid vehicles, for example, use both electricity and liquid fuels. For liquid fuels, there is also the option of substituting a certain share of fossil fuels with biofuels:

- Fuel shares (e.g., share of gasoline as a percentage of total energy demand for gasoline light duty vehicles).

An example calculation of the final energy consumption of gasoline light duty vehicles is shown in annex A.5.1.2.

The main parameters used for modeling the national transport sector are based on publicly available data from international organizations such as

- (UN 2019) for population developments in the medium variant,
- (IEA 2017) for general sectoral trends including mileage per person and modal shares, and
- (IEA et al. 2021) as well as (IEA et al. 2017) for specific fuel consumption.

However, many of the parameters are country- or region-specific and are therefore adjusted based on further literature research and own assumptions.

3.6.2.2 Industry: Energy & Non-Energy-Use

The energy demand $E_{I,s,y}$ in the industrial sector I for the Scenario s and year y is a sum of the energy demands of all industrial subsectors i (Equation 4).

Equation 4

$$E_{I,s,y} = \sum E_{I_i,s,y}$$

For the industrial sector, Enerdata aggregates energy demand data for the subsectors iron and steel, chemical, non-metallic minerals, non-ferrous metals, paper and pulp, and others (Enerdata 2022). The energy demand of each industrial subsector i can be divided into a technology-specific bottom-up calculated energy demand $E_{I_{i,T},s,y}$ using physical production as an activity variable, and a residual energy demand $E_{I_{i,unsp},s,y}$, here referred to as “unspecified energy demand” (Equation 5).

Equation 5

$$E_{I_i,s,y} = \sum E_{I_{i,T},s,y} + E_{I_{i,unsp},s,y}$$

In the bottom-up calculated energy demand, T refers to a specific production technology used in the subsector i. The following parameters are needed to model the energy consumption of relevant processes in the industrial sector bottom-up:

- Activity variables (e.g., physical production of steel in t/year)
- End-use shares (e.g., share of primary steel in % of total steel)
- Technology shares (e.g., share of blast furnace & basic oxygen furnace for primary steel making in % of primary steel)
- Energy intensities (e.g., energy demand of blast furnace & basic oxygen furnace per ton of steel in kWh/t)
- Fuel shares (e.g., share of coal in % of total energy demand for blast furnace & basic oxygen furnace)

The physical production volumes were taken from several sources, such as (Global Energy Monitor 2022) for steel, (U.S. Geological Survey 2022) for cement, and (FAOSTAT 2022) for pulp and paper production. In the chemical sector, few data are available for the production volumes of ammonia and HVC. For ammonia production, in-depth literature research is conducted for further information on country-specific production volumes.

The production volumes of HVC (AL_{HVC}) are obtained by dividing the feedstock volume $f_{HVC,i}$ by its specific feedstock consumption $SFC_{HVC,i}$ (Equation 6).

Equation 6

$$AL_{HVC} = \frac{f_{HVC,i}}{SFC_{HVC,i}}, \quad i = Naphtha, LPG$$

The annual consumption of naphtha and LPG are taken from Enerdata (Enerdata 2022) and the specific feedstock consumption of naphtha $\left(1.8\ \frac{t_{naphtha}}{t_{HVC}}\right)$ and LPG $\left(1.7\ \frac{t_{LPG}}{t_{HVC}}\right)$ are deduced from the IEA Petrochemicals report (IEA 2018b).

In the non-metallic minerals industrial sector, the energy consumption in cement production is calculated based on energy-intensive clinker production. The global average specific clinker consumption is taken from (IEA 2018a) for 2020 $\left(0.72\ \frac{t_{clinker}}{t_{cemen}}\right)$ and for 2030 on a climate-neutral path $\left(0.65\ \frac{t_{clinker}}{t_{cement}}\right)$ and linearly extrapolated up to 2050 within the NZ scenario.

All future technology shares and fuels shares are based on the BIG5 studies (ARIADNE 2022). In general, all production volumes are assumed to increase or decrease according to historical data. Energy demand for additional future exports of green hydrogen or green synthesis products is not considered in the national energy demand projections and modeled separately in the consecutive model chain. For the chemical sector, technology shares, fuels shares, and technology-specific energy intensities are taken from (IEA 2021), Fraunhofer ISI internal data, (Material Economics 2019) and (Wang et al. 2021).

For each process, a range of energy intensities is collected from the literature for different regions and years. Within this range, a plausible energy intensity is chosen to match the overall sectoral energy demand.

As an example, the calculation of the energy demand assessment for a specific energy carrier is shown in annex A.5.2.2. This calculates the coal demand for steel production in blast furnaces and then in basic oxygen furnaces.

3.6.2.3 Residential

For the **residential sector**, we consider different activity variables that determine the final energy demand, depending on the end use. While we use residential dwelling area for space heating and cooling, we use the number of dwellings for water heating, cooking, and electrical appliances. Each of these variables is then broken down into sub-variables for each end-use and technology, using end-use saturation and technology shares:

- Population
- Living space per person in m^2/person or persons per dwelling
- End-use saturation (e.g., saturation of space heating in residential buildings in percentage of m^2)
- Technology shares (e.g., share of heat pumps for space heating in residential buildings in percentage of m^2.

These specific activity variables are then multiplied by the energy intensity of each technology to estimate the final energy demand per end-use technology in a given year and scenario:

- Energy intensities (e.g., energy intensity of heat pumps for space heating in kWh/m^2).

Finally, we multiply the energy demand per end-use technology by the share of different fuels. This is particularly relevant for heat pumps that use electricity and geothermal or ambient heat as energy sources:

- Fuel shares (e.g., share of electricity in percentage of total energy demand for heat pumps for space heating).

An example calculation of the final energy consumption of electricity for heat pumps in space heating is shown in annex A.5.3.2.

The parameters for estimating the energy demand of the residential sector are particularly country-dependent. European values can only be transferred to a limited extent to other regions. However, these are still used for orientation, as significantly more data are available for European countries. Drawing on sources such as (ADEME et al. 2022; European Commission 2022a, 2022b), the specific parameters are heuristically adjusted based on our own additional country-specific assumptions. Furthermore, as is the case in the transport sector, population trends from (UN 2019) and general sectoral trends from (IEA 2017) are used for energy demand projections in the residential sector.

3.6.2.4 Other Sectors

For the **services and agriculture** sectors, we use the sectoral value added in millions of USD derived from (The World Bank 2022) as the activity variable and multiply it by sectoral energy intensity in toe per USD to estimate the future final energy demand. We then multiply the total sectoral final energy demand by the shares of different fuels to disaggregate it into different energy sources.

For **international bunkers**, we apply a similar methodology as for services and agriculture. However, since there is no sectoral value added, we instead use an activity factor as the driver of energy demand. We start with a demand factor 1 for the last historical year and change it according to the demand development for future international flights and marine transport depending on the scenario and year. By multiplying this factor by the assumed energy intensities and fuel shares, we estimate the specific future energy demands of international aviation and marine fuels per scenario and year.

3.6.3 Output Data

The modeling output includes scenario-based projections of final energy demand by sector, subsector, and energy carrier for the three scenarios BS, AP, and NZ in 2030 and 2050. For an overview of the energy carriers used, see annex A.5.5.1.

3.7 National Energy System Optimization (PyPSA-Earth-Sec)

3.7.1 Model Description

PyPSA-Earth-Sec (sector-coupled model of PyPSA-Earth) is a sector-coupled energy system model with high spatial and temporal resolution that allows the co-optimization of the investment and dispatch of multiple energy carriers serving different demand sectors. The model is based on the *PyPSA* framework (Brown et al. 2018) and builds on the PyPSA-Earth model (Parzen et al. 2022).

The demand sectors covered by the model are residential, land transport, industry, aviation, navigation, agriculture, and mining. The model also allows for the inclusion of extra country-specific sectors when necessary. In addition to electrical power, the model co-optimizes the dispatch and investment in the respective technologies of several energy carriers including hydrogen, natural gas, oil, heat, and biomass. The energy infrastructure in a country is considered by integrating the existing transmission power grid, the natural gas network, conventional generation assets, and utility-scale renewable capacities. Additionally, several short- and long-term flexibility options are considered in the form of storage and PtX technologies. These include battery electric vehicles, pumped hydro, heat storage, power-to-gas and power-to-liquid. The model accounts for carbon emission reduction by imposing a carbon cap that limits the permitted emissions by the energy system. The model will be explained in more detail in an upcoming paper (Abdel-Khalek et al. 2023 (in preparation)).

The configuration used for the assessment is a temporal resolution of 3-hour time steps to account for the intraday variability at a computationally feasible setting. The spatial resolution varies between countries and is based on the Global Administrative Areas (GADM) regions (Global Administrative Areas 2022).

The model's main objective is to satisfy the different energy demands for each carrier at each node at the lowest cost possible, including hydrogen for export. The main constraints include the emission cap, the physical limitations of the different components, the geographical limits on installing new capacities as well as the emissions target for each scenario. The linear optimization problem at the core of the model can be described as:

Equation 7

$$\min \sum_{n,s} c_{n,s}\,\overline{g}_{n,s} + \sum_{n,s} c_{n,s}\overline{h}_{n,s} + \sum_{n,s} c_{n,s}\overline{k}_{n,s} + \sum_{l} c_l F_l + \sum_{i} w_t \left[\sum_{n,s} o_{n,s,t}\, g_{n,s,t} + \sum_{n,s} o_{n,s,t}\, h_{n,s,t} + \sum_{n,s} o_{n,s,t}\, k_{n,s,t} \right]$$

Here, $\boldsymbol{n}$ is the clustered node label, $\boldsymbol{s}$ is the technology label, $\boldsymbol{t}$ is the snapshot label and $\boldsymbol{l}$ is the line/pipeline label. Additionally, $\boldsymbol{c}$ and $\boldsymbol{o}$ denote the capital and operation cost parameters, respectively. The decision variables are represented as follows: $\overline{\boldsymbol{g}}$ is the nominal power of a generator, and $\boldsymbol{g}$ is the dispatch at the specific time step. In the same manner, $\boldsymbol{k}$ and $\boldsymbol{h}$ represent the conversion and storage technologies, respectively, and $\boldsymbol{F}$ denotes the capacity of the lines/pipelines.

3.7.2 Input Data and Parameters

In addition to the input data provided by the other models in the chain, the model relies on additional open-source data to construct the energy system for the assessed country. These additional data include the existing generation units in the country provided by the PowerPlantMatching[27] package, which collects, cleans and combines different databases to provide power plant data as completely as possible (Gotzens et al. 2019). Additionally, the model relies on OpenStreetMaps (OpenStreetMap Wiki contributors 2017) with an additional step of data validation for electricity grid data and natural gas transmission networks. Finally, other important input parameters are collected manually, including: industrial cluster locations and capacities, cavern storage locations and capacities (see page 80), airports and ports locations, and traffic indicators.

3.7.2.1 Enertile® to PyPSA-Earth-Sec Connection

The renewable energy potential from Enertile® is added as an input to PyPSA-Earth-Sec to override the default profiles provided by open sources. The sub-divisions of each model are aligned so that each region for renewable energy potential in Enertile® corresponds to a clustered node in PyPSA-Earth-Sec, allowing direct data flow. The sub-divisions are based on GADM regions of each country with an extra step of post processing RE data in certain cases. The data inflow from Enertile® comprises the following:

- Renewable energy potential data as hourly time series for each of the technologies and sub-divisions.
- Maximum installable capacity for each technology at each sub-division in the country.
- The capital and operational costs for the different renewable energy technologies.

3.7.2.2 LEAP to PyPSA-Earth-Sec Connection

The sectoral demand data are fed into PyPSA-Earth-Sec from sector-specific MS Excel-based tools on a sub-sectoral national level. However, PyPSA-Earth-Sec requires regionalized data. Different disaggregation algorithms are derived to spatially allocate the demand for each carrier and sector in the country assessed. The algorithms are based on different parameters including population density, GDP distribution, locations of existing industrial clusters as well as the national and international transport infrastructure for aviation and navigation. The regionalization algorithms will be explained in further detail in an upcoming paper (Abdel-Khalek et al. 2023 (in preparation)). The data inflow from LEAP / MS Excel-based tool comprises the following:

- National energy demand data per subsector, process and energy carrier.

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[27] Part of the work is done in PyPSA-Earth.

3.7.3 Output Data

3.7.3.1 PyPSA-Earth-Sec to H2ProSim Connection

The connection between PyPSA-Earth-Sec and H2ProSim mainly comprises hydrogen-related data flow from the former to the latter, and water costs from the latter to the former. As a first step, large-scale ports in a country are identified as potential points for exporting hydrogen and PtX by ship. The corresponding synthesis processes required for exporting PtX products are carried out at the export locations. The clustered nodes within which the coordinates of these ports lie are identified as potential export nodes in PyPSA-Earth-Sec. The model optimization aims to satisfy the total hydrogen demand over the course of the year and delivers it to the specified export nodes in the cost-optimal shares between the ports and the cost-optimal delivery schedule. The data describe the quantities of hydrogen at the export locations, for which the following data flow from H2ProSim to PyPSA-Earth-Sec:

- Water availability and costs for usage of desalinated water per node are calculated within the scope of H2ProSim and sent to PyPSA-Earth-Sec to be included in the operating costs of the electrolyzers.

In addition, the following data flow from PyPSA-Earth-Sec to H2ProSim:

- H_2 production/delivery time series at export nodes as an output of PyPSA-Earth-Sec serving as an input to H2ProSim.
- Nodal electricity price at export nodes as an output of PyPSA-Earth-Sec to be used for electricity demand in conditioning hydrogen for export by ship, such as compression, synthesis/liquefaction, DAC, and air separation.
- Excess heat of electrolyzer operation in PyPSA-Earth-Sec.

3.7.3.2 PyPSA-Earth-Sec to Hytra Connection

Similar to the connection with H2ProSim, the connection between PyPSA-Earth-Sec and Hytra focuses on hydrogen data flow from the former to the latter. In addition, potential pipeline export terminals are identified in advance and the regions in which they lie are identified as potential pipeline export points for PyPSA-Earth-Sec. The hydrogen delivery time series is balanced within the optimization of PyPSA-Earth-Sec using the available flexibility and storage technologies integrated in the national energy system, resulting in a constant flow of hydrogen to the pipeline export locations.

The flow of hydrogen data from PyPSA-Earth-Sec to Hytra includes the following:

- A constant hydrogen delivery time series to the pipeline export locations.
- Levelized cost of hydrogen at the export locations to be used included in the variable cost of hydrogen delivery via pipelines

3.8 Pipeline Export Infrastructure (Hytra)

3.8.1 Model Description

Hytra is developed within HYPAT by the Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems (IEG). It focuses solely on the export of gaseous, compressed **hydrogen via pipeline** from an export hub to an import hub. Pipeline export differs from ship transport in several respects. Firstly, pipeline transport is (see A.7) continuous and not a batch-process. Secondly, not only the location and geography of the importing and exporting regions are important, but especially the routing between them. Obstacles such as mountain ranges and bodies of water can have a considerable influence on the routing, and can increase transport costs or even render pipeline transport impossible. In addition, pipeline transport is by its very nature less flexible than shipping regarding the choice of location. Finally, transport distance is a limiting factor for pipeline transport. This is once again different to ship transport, for which conversion and reconversion of the carrier substances have the highest influence on costs, while the distance traveled has only a smaller impact (IRENA 2022a). In contrast, the cost of pipeline transport increases with every kilometer of pipe and the energy efficiency depends on the number of recompressions that take place every 200-300 km along the route. For this reason, HYPAT only models pipeline transport for distances up to roughly 5,000 km between import and export hub (IRENA 2022b; Wang et al. 2020).

Because of these limiting factors, Hytra is only deployed for some of the countries selected for in-depth analysis (see 3.1). These are **Morocco, Ukraine, Turkey, United Arab Emirates** and, potentially, **Canada**. For Namibia, Kenya, Chile, Brazil and New Zealand, only transport by ship is considered as an export option.

Hytra takes **a three-step approach**. The first step selects the **route** of the pipeline and determines its length. The second step determines the **sizing** of the pipeline and its technical configuration. The third step is the **cost calculation** for the resulting pipeline configuration.

3.8.1.1 Newly Built Pipelines and Repurposed Pipelines

In a future in which the demand for natural gas and oil has decreased significantly, existing pipeline infrastructure could be repurposed to transport hydrogen. Repurposing pipelines is generally assumed to be cheaper than constructing new ones, although uncertainties remain high (Adam et al. 2020; IRENA 2022a, 2022b; Wang et al. 2021). Within HYPAT, the choice between repurposed and newly built pipelines depends on the **scenario**, see chapter 3.4 Configurations and Scenarios.

For some export routes in a repurposing scenario, pipelines only exist for parts of the route. In this case, gaps between existing pipelines are bridged with newly built pipelines, which results in a mix of repurposed and newly built pipelines along that route.

3.8.1.2 Pipeline Routing

The pipeline runs from an exit hub in the exporting country to the border of the importing country. If this route includes existing or planned (oil and natural gas) pipeline infrastructure**, the pipeline is always routed along it**. The reasons for this are a) it is presumed that land is available for further pipeline construction in parallel to existing ones, and the right of way is cheaper, and b) an existing pipeline avoids the aforementioned obstacles. It also makes it easier to compare the cost of repurposed and newly constructed pipelines, as they follow the same route and thus have the same length.

If there is no existing pipeline for the entire length of the route or parts of it, a routing exercise has to be performed using QGIS. We use a land-use and land-cover dataset to exclude areas such as densely populated ones or protected land. Based on the remaining areas, the shortest path between the export and import hub is then calculated, which equals the pipeline route.

3.8.1.3 Sizing of Newly Built Pipelines

The (inner) diameter of the pipeline is the main driver of capital expenditure (CAPEX) – the larger the diameter, the higher the CAPEX per km of pipe. Therefore, the diameter should be as small as possible, while still being big enough to allow the flow of the envisaged export quantity (Q_i). The flow, on the other hand, depends not only on the pipe diameter, but also on the pipeline (segment) length, the initial gas pressure and temperature, and the drop in pressure due to friction (Menon 2005). This relationship can be expressed using a flow equation. The flow equation chosen to size newly-built pipelines within Hytra is the **Weymouth equation**, as this is "used for high pressure, high flow rate, and large diameter gas gathering systems" (Menon 2005, p. 61) (see Equation 16). This equation is used to determine the cost-optimal combination of segment length, initial gas pressure, pressure drop and diameter for each considered quantity (Q_i).

The **segment** is the section of pipeline between two compressors. Gas enters the segment at high pressure directly after compression. As the gas moves through the pipeline, friction reduces the pressure and by the time the gas reaches the next compressor, it is at a lower pressure level. Compressors restore the high pressure. The number of compressor stations is thus determined by $n_c \geq \frac{L_P}{L_S}$, where n_c is the number of compressor stations along the route, L_P is the total pipeline length and L_s is the segment length. The energy efficiency of the transport (per kg_H2) and operational expenditures (OPEX) are determined by the number of compressor stations.

3.8.1.4 Sizing of Repurposed Pipelines

The pipeline diameter cannot be freely chosen for repurposed pipelines, as only existing pipelines can be repurposed. Furthermore, the diameters and number of parallel pipelines vary along the route, which makes the problem too complex for a simple flow equation. Thus, the **multiphysical network simulator** (MYNTS), developed by Fraunhofer SCAI[28], is used. The method is similar to (Ragwitz et al. 2022), p. 20ff . The natural gas network of the transit countries is plotted using publicly available information. The main parameters are the number, length and diameter of the pipelines and elevation of the network nodes. New compressor stations are built to transport hydrogen, as it is assumed that natural gas compressors cannot

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[28] https://www.scai.fraunhofer.de/de/geschaeftsfelder/network-evaluation-technologies/produkte/mynts.html

be repurposed. Then a hydrogen flow is simulated. Pipelines are added to the simulation manually with the objective to use as few additional pipeline-kilometers as possible for a respective quantity Q_i in order to keep transport costs as low as possible.

3.8.1.5 Recompression: Powering Compressor Stations

In the model chain, Hytra comes directly after PyPSA-Earth-Sec. According to the model definition, the initial compression at the start of the pipeline is still part of PyPSA-Earth-Sec, so that the gas enters the pipeline at high pressure (see annex A.7). The gas loses pressure during transport, which means it has to be recompressed at compressor stations every 200-300 km to re-elevate pressure levels. Within HYPAT, there is the constraint that not only the transported hydrogen but also the energy used during transport must come from renewable sources. To accomplish this, the model can choose between two options to power the compressors. The first option is to **use some of the transported hydrogen as fuel for the compressor**, as is customary with natural gas in natural gas pipelines today. The second option is to use **renewable island installations** in close proximity to the compressor station in conjunction with hydrogen from the pipeline for times when the renewable installation does not provide sufficient power. This combination avoids a costly battery installation. The renewable energy potential is provided by Enertile® for the area surrounding the compressor station. Within HYPAT, it cannot be assumed that electricity from the grid can be used, except as a fallback option.

3.8.1.6 Cost Calculation

The levelized cost of hydrogen delivered to the border of an importing country is calculated by combining all the cost items and dividing them by the lower heating value (LHV) of the total annual amount of delivered hydrogen. For the CAPEX items, the annuity method is used, where the CAPEX items $CAPEX_i$ are multiplied by their respective capital recovery factor (CRF = $\frac{r(1+r)^{t_i}}{(1+r)^{t_i}-1}$) (see Equation 8).

Equation 8

$$LCOH \quad = \frac{\sum_{i=1}^{n} CAPEX_i * \frac{r(1+r)^{t_i}}{(1+r)^{t_i}-1} + OPEX_i}{E\_H2}$$

With:
i = cost item/component
n = number of cost item
r = interest rate (WACC)
CAPEX = invest cost
OPEX = operation cost
t = operating life of component
E_H2 = Total energy delivered as hydrogen; LHV [kWh]

3.8.2 Input Data and Parameters

The pipeline dataset SciGRID gas is used as a base for European countries and transits (DLR 2020). Outside the scope of SciGRID gas, publicly available sources such as (openinframap.org

2022) are used. Using publicly available national network data, the (inner) diameter of the pipelines is adapted. The elevation of the nodes is set using the online tool “Earth elevation” (Dcode 2006), where the margin of error is around 1-2% (around ±10 m).

3.8.3 Output Data

The main outputs of Hytra are the transport costs and energy efficiency per kilogram or kWh of transported hydrogen. These are given for a specific transport task, which consists of a pair of import and export hubs and one of the four different quantity steps. The outputs are also scenario-specific. Another output is detailed information on each pipeline route for every transport task, especially for repurposed pipelines.

3.9 Shipping Export Infrastructure (H2ProSim)

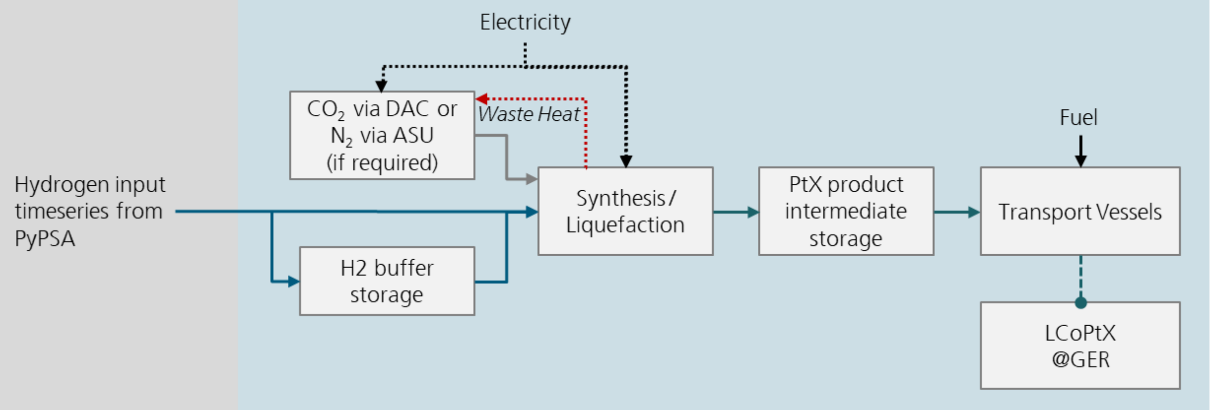
3.9.1 Model Description

PyPSA-Earth-Sec optimizes the distribution of the predefined export quantity of hydrogen over up to five export locations per country. The selection of the export locations is presented in chapter 3.2**Fehler! Verweisquelle konnte nicht gefunden werden.**. The preselection of the export locations is based on available ports and geographic conditions, such as area availability and proximity to infrastructure. In addition, the selection process for export harbors ensures that the sites are evenly distributed along the coast. The total amount of hydrogen for export is an input to PyPSA-Earth-Sec. Within the optimization of PyPSA-Earth-Sec, the amount of hydrogen for each export location is selected based on the cost optimum. The export from each location is subsequently optimized individually in H2ProSim. As explained in chapter 3.4.6, the export by ship is modeled in H2ProSim for five different PtX energy carriers. Further variations between the *Optimistic*, *Realistic*, and *Conservative* scenarios and between the years 2030 and 2050 are:

- the range in which dynamic operation of a synthesis or liquefaction plant is possible,
- the ship size and
- the ship fuel, as described in chapter 3.4.6.

Figure 9 illustrates the system layout for the production and transport of the selected PtX products. Hydrogen intended for export (results are delivered from PyPSA) is used as model input to H2ProSim in the form of a time series with hourly resolution.

Figure 9: System layout for export by ship modeled in H2ProSim



To align the dynamic hydrogen production from PyPSA-Earth-Sec with the limited flexibility of the synthesis and liquefaction processes, hydrogen can be stored in buffer storages. Storage options include underground caverns if available at the location, or artificial storage tanks with higher specific costs. The current load of the synthesis or liquefaction process is controlled by the actual storage pressure. A decrease in storage pressure also reduces the set value of the load for synthesis/liquefaction and vice versa. To the extent permitted by the dynamics of the synthesis plant, the model reduces the amount of hydrogen withdrawn from storage and prolongs the time until storage pressure reaches the minimum. Due to the process-inherent limitations (e.g., extremely low or high temperature and high pressures), synthesis/liquefaction processes can only be operated within a certain window. This is also part of the simulation models of synthesis/liquefaction plants. The mass balance between hydrogen input, storage and plant input is depicted in the following equation:

Equation 9: Hydrogen balance equation in H2ProSim

$$0 = \dot{m}_{H2_{PyPSA_{in}}} - \dot{m}_{H2_{Storage_{in}}} + \dot{m}_{H2_{Storage_{out}}} - \dot{m}_{H2_{Synth/Lique_{in}}}$$

For the production of ammonia, nitrogen is required, which is produced using an air separation unit (ASU). For methanol and Fischer-Tropsch synthesis products, carbon dioxide is required as a feedstock. The carbon dioxide is produced using DAC. Where available, CO_2 from concentrated point sources (e.g., cement industry) is also considered.

After synthesis/liquefaction, the produced PtX energy carrier is stored in an intermediate storage before its transport by ship. The shipping distance is determined based on real-world shipping routes. Transport to the German import location in Northern Germany is modeled with hourly resolution to represent realistic shipping behavior and determine the number of ships and the intermediate storage needed, factors that most analyses so far have neglected. The nonlinear behavior of H2ProSim enables integer optimization with whole numbers of transport vessels. Transport to the other import hubs in Central America and South and East Asia presented in chapter 3.2.2 is modeled in a simplified way by adjusting the transport costs to Wilhelmshaven to the different shipping distances.

Electric power consumption for all plants is determined and combined with the specific, spatially and temporally resolved power costs from PyPSA-Earth-Sec to calculate the electricity costs. The main power consumers are the compressors, synthesis/liquefaction processes and the production of educts (CO_2, N_2), if necessary. To ensure the availability of RE potential for these demands, their consumption is estimated and the total RE potential in PyPSA-Earth-Sec is reduced by this amount. Therefore, integrating the synthesis system in the overall energy system can be simulated, even though the value chain extends over both models.

The system is optimized by an integrated optimization algorithm in H2ProSim (non-linear optimization) towards the lowest PtX import costs by changing selected variables. Here, the optimization variables are:

- Volume of hydrogen buffer storage,
- Capacity of synthesis/liquefaction,
- Volume of PtX storage,
- Number of transport vessels.

The production capacity of DAC and ASU depend on the CO_2 or N_2 required for the synthesis processes and are therefore directly linked to the optimized capacity of the synthesis plant.

The objective of the optimization is to minimize the optimization variable, in this case the LCOPTX at the import harbor. It is calculated by combining the different cost items with the annuity method and dividing it by the total amount of PtX product delivered. To be able to compare the different PtX products with their varying energy density, the reference value is not the mass, but the energy content in MWh. The following equation is used to calculate the LCOPTX:

Equation 10: Calculation of levelized cost of the PtX products in H2ProSim

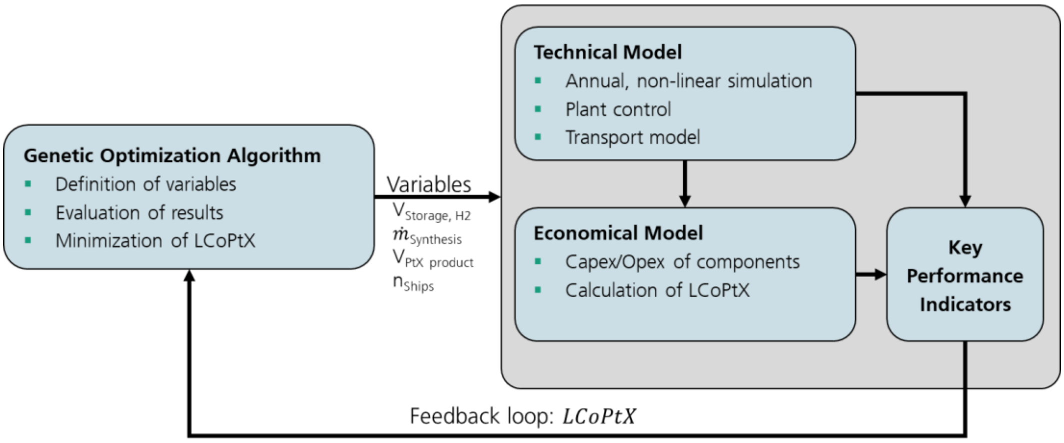
$$LCoPtX = \frac{\sum_{i=1}^{n} CAPEX_i * \frac{r(1+r)^t}{(1+r)^t - 1} + OPEX_i}{E_{PtX}}$$

With:
i = cost item/component
n = number of cost item
r = interest rate (WACC)
CAPEX = invest cost
OPEX = operation cost
t = operating life of component

E_{PtX} = Total energy delivered in PtX product

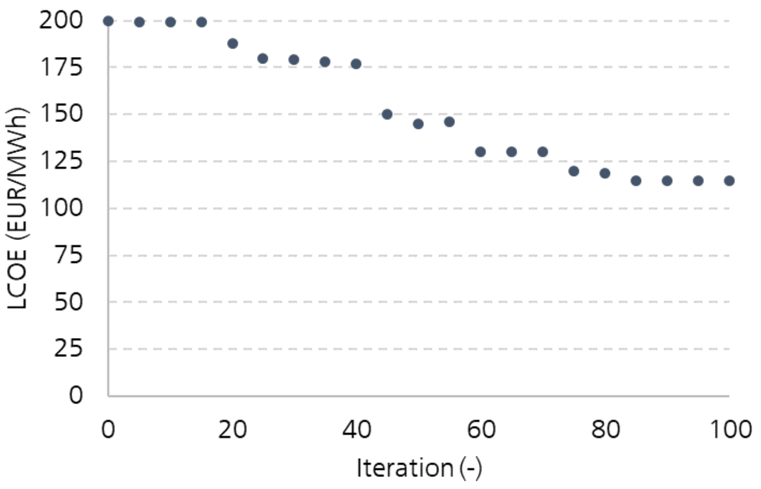
The optimization is based on several iterations of a genetic algorithm. After one iteration with several individual system simulations, the results are evaluated and results with low LCOPTX are favored for inheritance. The parameter set of the variables of the population in the next generation is based on mutation and crossover functions. Stochastic parameter variations are also used in each generation to avoid the optimization becoming stuck inside a local minimum. The optimization process is depicted in Figure 10.

Figure 10: Optimization functionality of H2ProSim



Due to the iterative process, the levelized cost of a PtX product decreases from generation to generation until no further operational improvement can be found. A typical evolution of the optimization process is depicted in Figure 11.

Figure 11: **Schematic illustration of LCOPTX reduction through iterative optimization in H2ProSim**



3.9.2 Input Data and Parameters

Three main groups of input data are needed to model the export in H2ProSim. As mentioned above, results from the energy system modeling in PyPSA-Earth-Sec are used in the form of spatially resolved time series for the production of hydrogen, the excess heat from electrolysis, and the electricity price.

Spatial data for the selected export locations make up the second group. The coordinates of the locations are used to determine shipping routes and distances, while data regarding the existence of underground storage caverns or CO_2 point sources are important to evaluate the costs for hydrogen storage, or carbon-based synthesis, respectively.

A large set of technical and economic parameters used to model plant behaviour and costs make up the third group of input data. These consist of internal data from Fraunhofer ISE as well as data from various literature sources. The full country-specific parameter set of the model chain will be published together with the modeling results.

3.9.3 Output Data

The modeling in H2ProSim yields various results. The main outcome and primary objective of the optimization process are the costs for storage, conditioning, and shipping of the PtX product, given as levelized costs in relation to the amount of energy. The LCOPTX can be given individually for all export locations and distributed along the value chain.

The economically optimum capacities and dimensions of the plants and ships required to export hydrogen and PtX products can be combined with the results from the energy system modeling to show the optimal infrastructure required to export a specific quantity of PtX products.

In addition to these values contributing to the final results of the model chain, there are various intermediate results available to evaluate the export process or the optimization in more detail. These include the losses and energy demands of the processing steps, or the yearly load curve or capacity factor of synthesis plants, storage, and ships. The demand for educts and the percentage to which CO_2 point sources have been exploited are of further interest. Other results can be obtained and used for specific situations

4 Summary

This chapter summarizes the HYPAT model chain methodology for the techno-economic assessment of ten potential export countries, outlines the reasoning behind the selection of these countries for modeling, and describes the model chain's related core value and range of results.

A global evaluation based on different factors was done beforehand to select ten potential hydrogen export countries for in-depth techno-economic assessment as a basis for global scale-up. The selection includes countries of different economic status, size and from different regions: Morocco, Ukraine, Namibia, Turkey, United Arab Emirates, Kenya, Chile, Canada, Brazil, and New Zealand. The selection criteria included the following:

- renewable energy potentials,
- domestic projected energy demand for 2050,
- indicators regarding infrastructure quality, water stress, political stability, economic level and financial risks,
- national hydrogen strategies and current energy and hydrogen partnerships with Germany,
- insufficient country-specific assessment or studies of H_2 and PtX export potentials.

The results from the techno-economic assessment of these ten selected countries are subsequently scaled up to create a global hydrogen atlas (incl. PtX), and also used as an indication of the global price development of hydrogen.

In HYPAT, a novel, country-specific, model-based methodology consisting of five models has been established to fully address the entire hydrogen supply chain for exports. Five models are interlinked in a model chain to give comprehensive insights into country-specific hydrogen exports. In a three-stage approach, the supply potential of each exporting country is modeled in-depth:

- In the first stage, RE potentials (utility-scale photovoltaic, concentrating solar plants, onshore and offshore wind) are calculated with the Enertile® model and domestic energy demand projections are considered simultaneously through sector-specific MS Excel-based tools and a systemic LEAP modeling.
- The second stage forms the center of the modeling chain, where RE potentials are used to meet domestic energy demand as well as export demand by modeling the national infrastructure evolution within PyPSA-Earth-Sec.
- The third stage models the export of hydrogen via pipeline in Hytra and the export by ship in H2ProSim. Hydrogen transport by ship is considered in different physical and chemical states: liquefied hydrogen (LH2), liquefied organic hydrogen carriers (LOHC), ammonia (NH3), methanol (MeOH) and Fischer-Tropsch synfuels (FT).

The main objective of the model chain is to calculate the levelized cost of hydrogen (LCOH) or PtX product (LCOPTX) delivered at the import location.

The core value of HYPAT is to provide an in-depth, country-specific, integrated energy system model combined with a detailed assessment of cross-regional hydrogen and PtX

transport. The methodology in HYPAT is distinguished by the fact that it is more comprehensive than existing studies owing to its combination of many aspects of those studies: It incorporates a range of primary energy sources, integrates the domestic energy and export demand into the energy system optimization, and assesses numerous types of transport pathways for H2 and PtX:

- **A range of primary energy sources are considered for the domestic energy supply,** such as PV, onshore and offshore wind, CSP, hydropower, biomass, and existing fossil and nuclear power plants.
- **Domestic and export demand are integrated into the energy system optimization:** To build strong and sustainable energy partnerships, enabling the energy transition in the exporting countries is a priority. As a result, RE is only exported after domestic energy needs have been met. Production plants for electricity, hydrogen and PtX products are modeled as integrated processes as part of a national energy system instead of segregated island solutions. The evolution of energy infrastructure is modeled in line with the domestic energy supply and demand and defined H2 and PtX export quantity steps.
- **A range of transport pathways are assessed for H_2 and PtX exports:** New and repurposed hydrogen pipelines, shipping as liquefied hydrogen, ammonia, methanol, Fischer-Tropsch products, and Liquid Organic Hydrogen Carriers (LOHC).

Hydrogen and PtX export costs are analyzed for each selected country, various export quantities, for 2030 and 2050, and in three different scenarios: *Optimistic*, *Realistic*, and *Conservative*. The scenarios represent differing energy transition ambitions, infrastructure development goals, and production costs electricity, hydrogen and PtX.

- Interest rates: The financial risk of investing in and running a plant is expressed using the interest rate applied to calculate the costs of renewable energy generation (Enertile®), national infrastructure expansion (PyPSA), and hydrogen export via pipeline (Hytra), and by ship (H2ProSim).
- Domestic decarbonization pathways: Different national decarbonization pathways are considered for domestic energy demand projections (LEAP, MS Excel-based tools).
- National infrastructure expansion: The choice of decarbonization pathway also affects the ambitiousness of national infrastructure expansion (PyPSA-Earth-Sec).
- Transportation pathways: New and repurposed pipelines are considered for export via pipelines. Several transportation pathways (LH_2, LOHC, NH_3, MeOH, FT) are considered for export by ship, in addition to other configuration types.

To illustrate a simplified example for 2050: In an optimistic scenario, the export costs for the selected export country are calculated with a low interest rate in a decarbonization pathway, which reaches climate neutrality by 2050 at the latest, and where the corresponding energy system infrastructure is established for electricity, hydrogen and heat. The resulting LCOH and LCOPTX are further used to calculate transport costs in a repurposed pipeline and all available PtX shipping technologies. The Infrastructure investments done in 2030 are maintained or even further extended in 2050.

5 Discussion and Outlook

This chapter discusses the challenges of the HYPAT model chain for the techno-economic assessment as well as further steps needed to foster international hydrogen trade.

Developing and running a complex model chain comes with unforeseen interdependencies, increased model runtimes, high data requirements, and a range of interpretable results.

- Firstly, developing and implementing a functioning model chain with different model frameworks, which were originally designed for other research purposes, poses unique challenges. First complete model runs will show the resilience of the model chain.
- Secondly, complex models and their integration into a model chain increase the overall model (chain) runtime. Modeling an entire supply chain for each country, for all scenarios, years and quantity steps results in a total runtime of 3-4 weeks, which does not include country-specific initial data preparation and data input. The model runtime shows that a meaningful selection of scenarios, number of countries, years and quantity steps is essential in order to reduce modeling complexity and deliver results in a feasible time horizon.
- Thirdly, the models themselves have high data requirements. Although country-specific data yield the highest estimation accuracy, such data are scarce or not available for some countries. In such cases, international and regional data are used in combination with our own country-specific assumptions based on the available data.
- Finally, the results of the model chain as well as the results from the models themselves will be published in a format that is yet to be decided. The results generated at the end of the model chain are based on modeling interactions and thus cover multiple supply chain aspects at a high level of detail. It is still to be evaluated which results will be selected and presented to help stakeholders understand what the next steps are to establish valuable hydrogen partnerships with export countries. Therefore, the format in which results are presented will play an important role.

The next step is to apply the methodology to the ten selected countries and to publish country-specific results within the course of the year 2023. Subsequently, a methodology will be developed for global scale-up and the exchange with researchers from similar studies/atlases will be further intensified. As the first hydrogen imports to Germany of up to 100 TWh are already expected in 2030 (BMWi 2020), our goal is to foster sustainable hydrogen partnerships rapidly. This needs to involve different kinds of target groups and communication strategies.

- The methodology described here will be applied to the selected countries Morocco, Ukraine, Namibia, Turkey, United Arab Emirates, Kenya, Chile, Canada, Brazil, and New Zealand to calculate future hydrogen and PtX export potentials. The results for each country will be published in individual papers in the next months.
- Further on, a methodology needs to be defined for how to use the country-specific modeling results of the ten selected countries to answer the overarching research questions of HYPAT, such as how a global hydrogen trade might evolve. This will require scaling up the

techno-economic results from ten countries to a global perspective and the ambitious methodology will have to encompass various aspects.

- Multiple researchers from different institutions are currently working on questions related to hydrogen and PtX exports. Thus, an exchange between HYPAT and other atlases and involved researchers was already initiated in 2021, which will be further intensified in the future.

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List of Figures

List of Tables

Es konnten keine Einträge für ein Abbildungsverzeichnis gefunden werden.

A.1 Modeling Parameters

A list of the parameters used is published as an MS Excel document and can be found under https://www.hypat.de/hypat/publikationen.php.

A.2 Sustainability Criteria for Hydrogen and PtX Supply Chains in HYPAT, based on (Thomann et al. 2022)

Supply Chain Aspect	Sustainability Criterion
2. Hydrogen production	
	• Electrolysis only, no other hydrogen production processes.
3. Energy sources	
	• Only additionally installed RE plants for hydrogen production, no bioenergy, no non-sustainable large-scale hydropower • Baseload capable RE plants (hydropower, geothermal) only if not needed for domestic energy transition. • Consideration of the entire energy system, embedding hydrogen production in the overall energy system. • In general, connection of electrolysis plants to the power grid. • Monitoring of RE generation and RE purchase when electrolysis plants are connected to the power grid. • If no connection to the power grid (isolated solution): mature control and (intermediate) storage concept necessary (fluctuations in RE and hydrogen generation).
4. Further processes for production of PtX	
	• Electricity for ancillary processes (synthesis, N_2, CO_2 extraction, building needs, seawater desalination) also from RE sources as indicated in 3. • CO_2 from DAC or point sources: according to the draft REDII, all C-sources are allowed as long as the C use does not initiate "additional operation" of the fossil source process (so-called "non-elastic" C-source).
5. Further environmental impacts	
	• Exclusion of countries if: 1) water scarcity according to Falkenmark indicator (available water < 1,700 m^3/(inhabitant*year)), 2) drought risk according to WRI (Drought Risk indicator > 60%), and 3) landlocked. • Regional consideration in modeling using WRI's "Baseline Water Stress" indicator: water demand for hydrogen production must be met by seawater desalination plants if BWS ≥ 40%. • At least 4 km distance from marine protected areas (Roberts et al. 2010).

	• No protected areas of the classification Ia, Ib or II according to IUCN are allowed for RE plants. • Basically: no negative environmental impacts, such as destruction of biotopes, species or damage to marine life.

A.3 Export Quantity Steps

Export quantities (PyPSA, Hytra, H2ProSim)[29]	**Year** 2030	2050
RE - LCOE threshold **Global demand** **Demand cap**	**80 EUR/MWh** **3,000 TWh** **33%**	**60 EUR/MWh** **15,000 TWh** **20%**
Country	TWh	TWh
Canada		
	1	10
	10	100
	50	500
	1,000	3,000
Brazil		
	1	10
	10	100
	50	500
	1,000	3,000
Namibia		
	1	10
	10	100
	50	500
	538	3,000
Chile		
	1	10
	10	100
	50	500
	491	3,000
Morocco		
	1	10
	10	100
	50	500
	428	3,000
Kenya		
	1	10
	10	100
	50	500
	361	3,000
United Arab Emirates		
	1	10
	10	100
	50	500

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[29] Values in brackets are not considered for modeling.

	146	1,295
Turkey		
	1	10
	10	100
	50	500
	199	989
Ukraine		
	1	10
	10	100
	50	500
	86	668
New Zealand		
	1	10
	10	100
	50	500
	(40)	(203)

A.4 Calculated Interest Rates for 2030 and 2050

	2030			2050		
Country	**Optimistic**	**Realistic**	**Conservative**	**Optimistic**	**Realistic**	**Conservative**
Morocco	6.90%	7.10%	11.10%	4.50%	8.60%	11.10%
UAE	5.00%	5.20%	8.10%	4.50%	5.90%	8.10%
Ukraine	9.80%	11.00%	21.90%	4.50%	15.90%	21.90%
Kenya	9.90%	10.00%	13.90%	4.50%	11.50%	13.90%
Chile	5.20%	5.40%	8.40%	4.50%	6.10%	8.40%
Namibia	7.60%	8.20%	9.70%	4.50%	8.40%	9.70%
Turkey	7.40%	10.00%	19.00%	4.50%	9.10%	19.00%
Canada	4.50%	4.70%	6.90%	4.50%	5.20%	6.90%
Brazil	7.10%	7.60%	17.50%	4.50%	8.60%	17.50%
New Zealand	4.50%	4.70%	6.90%	4.50%	5.20%	6.90%

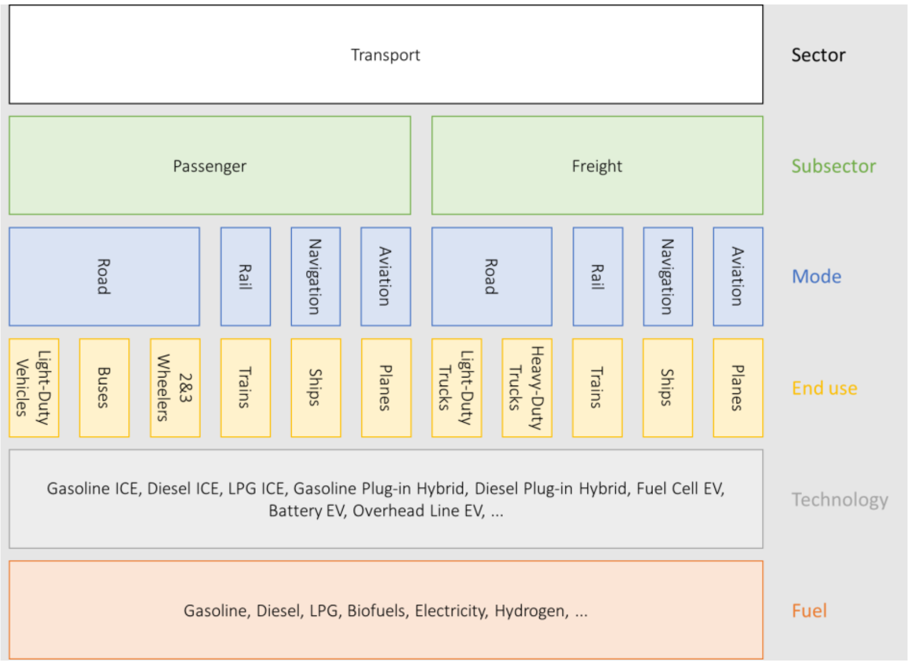
A.5 Domestic Energy Demand Projections (LEAP, MS Excel-based Tools)

A.5.1 National Transport

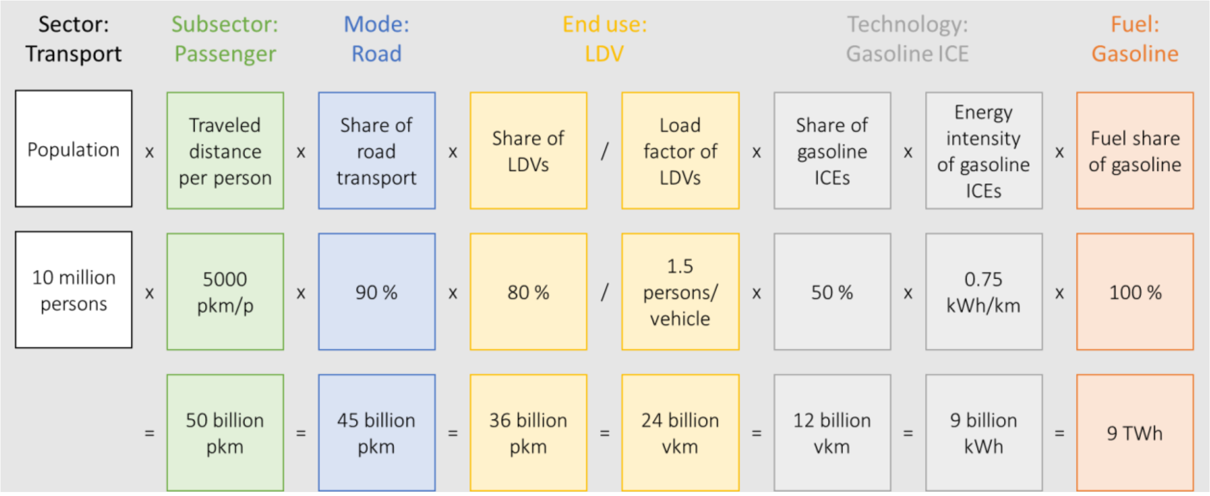
The national transport sector is divided into the two subsectors of passenger and freight transport. Each of these sectors is in turn split into four different modes of transport: Road, rail, navigation, and aviation. While there is only one end-use for each of the latter three modes, namely trains for rail, ships for navigation, and planes for aviation, there are different end-uses for road transport. For passenger road transport, we distinguish between light-duty vehicles (LDV), buses, and two- and three-wheelers (2&3W). The different end-uses can be powered by different technologies, such as internal combustion engines (ICE), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and battery electric vehicles (BEV). The majority of these technologies run on just one fuel. PHEV, on the other hand, use two fuels: electricity and either diesel or gasoline. There is also the option of substituting a certain share of oil-based fuels with biofuels in addition to synthetic fuels.

A.5.1.1 Model Structure

The final energy demands of the different energy sources in the national transport sector are projected using the breakdown described above and shown below using an engineering bottom-up approach.



A.5.1.2 Example Calculation: Gasoline Passenger Light Duty Vehicles



A.5.2 Industry

Industry comprises the energy-intensive subsectors iron and steel, chemical, non-metallic minerals, non-ferrous metals, paper and pulp, and other subsectors (food and tobacco, construction, mining, machinery, transport equipment, textiles and leather, wood, miscellaneous). Processes that are particularly energy-intensive and subject to transformation are analyzed in more detail by calculating the energy demand using an engineering bottom-up approach. These are steel, chemicals, non-metallic minerals, non-ferrous metals, and paper and pulp.

Steel is produced either from iron (primary route) or from steel scrap (secondary route). In the primary route, steel is produced using blast furnaces (BF) in combination with either an Open-Hearth Furnace (OHF) or the more commonly used Basic Oxygen Furnace (BOF). These fossil-based routes are run on energy carriers with high carbon contents and emissions. The Direct Reduction of Iron (DRI) is a new primary steelmaking technology, which allows the use of natural gas or even hydrogen as the energy carrier. In addition, hydrogen can be used to generate high-temperature process heat, so that hydrogen could be applied thermally in the primary route and even electrochemically in the DRI process. The secondary production route involves an Electric Arc Furnace (EAF), which is completely electric and less energy-intensive than primary steelmaking.

The production of **chemicals** considers both the energy and non-energy use of energy carriers. For the chemical use of energy carriers, see the section *Non-Energy Use*. The most relevant energy-intensive processes are ammonia and the production of high value chemicals (HVC), which are a precursor to, e.g., plastics (IEA 2018b). Other kinds of chemicals are aggregated under "unspecified chemicals".

Ammonia is produced by applying the Haber-Bosch Process, where hydrogen (H_2) and nitrogen (N_2) are synthesized to ammonia (NH_3). N_2 is extracted from the air, and H_2 is currently produced using the fossil-based processes steam methane reforming (SMR) or other conventional processes (e.g., coal gasification). In the future, hydrogen is assumed to be produced by water electrolysis. Nevertheless, this section for the production of ammonia only considers the energetic use. Most of the energy is used to separate N_2 from air and to synthesize N_2 with H_2.

The conventional production of HVC is highly dependent on resource availability. Regions rich in crude oil use cracking to turn crude oil into transportation fuels and naphtha, which is further cracked to produce HVC. Alternatively, Natural Gas Liquids (NGL) can be used as feedstock in refineries to produce liquefied petroleum gases (LPG) for HVC production. In the future, for climate-neutral HVC production, either synthetic naphtha or methanol can serve as a feedstock.

Non-Metallic Minerals (NMM) are split into cement production and the production of unspecified NMM (such as glass). Cement production is another energy-intensive process. Clinker is used to produce cement and is the main driver of energy consumption and process-related CO_2 emissions. Therefore, a lower clinker factor is envisaged for the future, even though clinker production is an important potential CO_2 point source. High-temperature process heat is required to produce NMM, for which hydrogen might play a significant role, depending on existing gas infrastructures.

Within the **Non-Ferrous (NF) Metals**, aluminum is the most energy-intensive production process. Production of other NF metals is aggregated under "unspecified NF metals". Similar to steel, there is a primary and a secondary production route for aluminum. In the primary production route, bauxite is used as a starting material and processed to aluminum oxide in the Bayer process, and then further electrolyzed to aluminum in the Hall-Heroult process. Alternatively, in the secondary route, scrap aluminum is recycled. Recycling is less energy-intensive and recycling shares should therefore be increased in the future. Both the Hall-Heroult process and recycling are based on electricity, and could thus rapidly achieve climate neutrality for aluminum production.

Paper and Pulp production: Pulp is the feedstock for paper production made from either primary sources, such as wood or other biomass, or from secondary sources, such as recycled paper. The production of paper requires high-temperature process heat, in which hydrogen might play a significant role, depending on existing gas infrastructures.

The analyzed subsectors are based on specific production technologies T, which have characteristic energy intensities used to determine the process-specific energy demand:

Equation 11

$$\sum E_{I_{i,T},s,y} = \sum AL_{I_{i,T},s,y} * \; ei_{I_{i,T},s,y}$$

$E_{I_{i,s},y}$ stands for an energy demand E within the industry sector I and the subsector i, calculated for the year y. Therefore, the production volume (or Activity Level) AL for this sector and technology T in year y is multiplied by its energy intensity ei in year $y1$. The production volume AL in year $y2$ is calculated by multiplying the production volume AL of year y1 by the Compound Annual Growth Rate of production ($CAGR^{AL}$) for technology T.

Equation 12

$$AL_{I_{i,T},S,y2} = AL_{I_{i,T},y1} * CAGR^{AL}_{I_i,S,y2-y1} * t_{I_{i,T},S,y2}$$

The $CAGR^{AL}$ is calculated based on historical production data to forecast production volumes for 2030 and 2050.

The energy intensity for technology T and year $y2$ is either taken directly from the literature or calculated by multiplying the energy intensity of year y1 by the Compound Annual Growth Rate of the energy intensity ($CAGR^{Eff}$):

Equation 13

$$e_{I_{i,high,T},y2} = e_{I_{i,high,T},y1} * CAGR^{Eff}_{I_{i,high},y2-y1}$$

The unspecified part of the energy demand in the analyzed industrial sectors is calculated similar to the specified part (Equation 14) using the same Compound Annual Growth Rate of the activity level ($CAGR^{AL}$) and energy efficiencies ($CAGR^{Eff}$).

Equation 14

$$E_{I_{i,unsp},s,y2}^{High} = E_{I_{i,unsp},y1} * CAGR_{I_i,y2-y1}^{AL} * CAGR_{I_i,y2-y1}^{Eff}$$

Other Sectors

The future energy demand in the other, and mainly less energy-intensive, sectors food and tobacco, construction, mining, machinery, transport equipment, textiles and leather, wood, and miscellaneous is calculated according to Equation 5. No technological aspects are considered for the less energy-intensive subsectors, thus $\sum E_{I_{i,T},s,y}$ is 0. Therefore, the energy demand in a less energy-intensive subsector is calculated based on historical energy demand, activities and efficiencies (Equation 15).

Equation 15

$$E_{I_{i,unsp},s,y2}^{Low} = E_{I_{i,unsp},y1} * CAGR_{I_i,D_n,y2-y1}^{AL} * CAGR_{I_i,y2-y1}^{Eff}$$

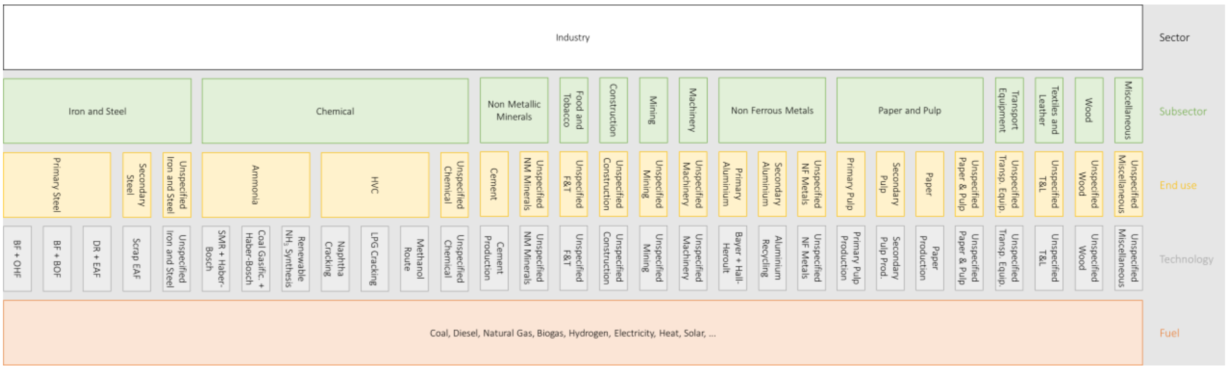
Here, $E_{I_{i,unsp},s,y2}^{Low}$ stands for energy demand E in a less energy-intensive sector i in scenario s and year $y2$. The energy demand of this sector in y1 is multiplied by its Compound Annual Growth Rate between year y1 and $y2$ for activity ($CAGR^{AL}$) and energy efficiency ($CAGR^{Eff}$). The CAGR in a less energy-intensive industrial sector is calculated as an average based on historical energy demand data for all countries of a development status D_n grouped according to the following:

- D_1 - Least developed country
- D_2 - Developing country
- D_3 - Advanced economy (new)
- D_4 - Advanced economy.

Non-Energy Use

Next to their energetic use, the use of energy carriers as feedstock is also considered in the chemical industry and other sectors. The non-energy use of energy carriers is considered for the production of ammonia, HVC, bitumen, lubricants and other products. For ammonia production, hydrogen made from natural gas, coal, oil or water can be used as feedstock. When producing HVC, we consider the raw material use of (synthetic) naphtha, LPG, and synthetic methanol. The consumption of bitumen, lubricants, and energy carriers (natural gas, oil, coal) for other unspecified chemical uses are taken directly from (Enerdata 2022). It is assumed that up to 100% of the energy content in natural gas and coal for unspecified chemical uses can be replaced by biomass by 2050.

A.5.2.1 Model Structure



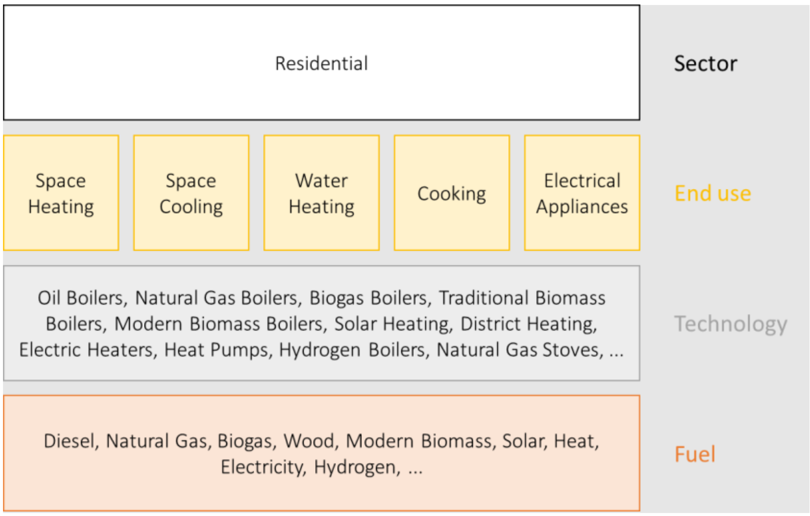
A.5.2.2 Example Calculation: Iron & Steel Sector

Sector: Industry	Subsector: Iron & Steel		End use: Primary Steel		Technology: BF + BOF				Fuel: Coal
No data	Steel Production	x	Share of primary steel	x	Share of BF + BOF	x	Energy intensity of BF + BOF	x	Fuel share of coal
No data	1 Mt	x	50 %	x	80 %	x	4.6 MWh/t	x	95 %
		=	500 kt	=	400 kt	=	1840 GWh	=	1748 GWh

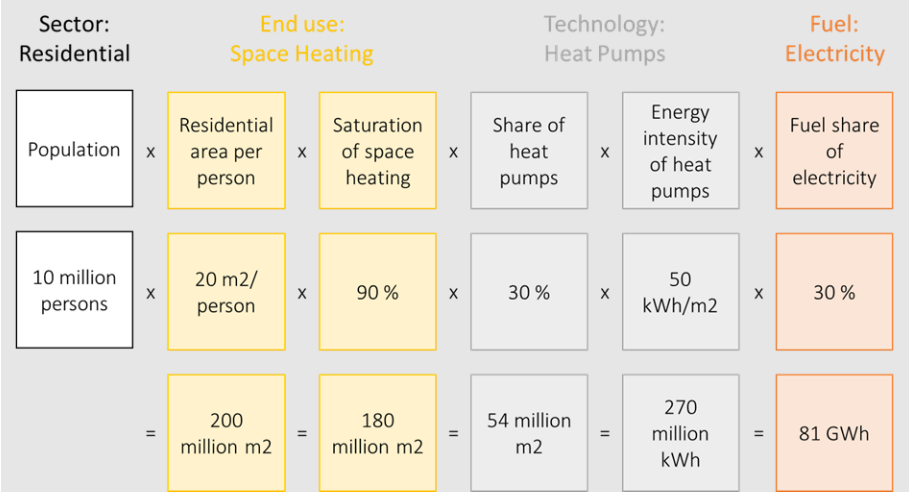
A.5.3 Residential

The residential sector is divided into five end-uses. Space heating and water heating can be covered by various technologies, such as boilers, direct use of solar or district heating, and heat pumps. Space cooling is covered by air conditioning, cooking by different types of stoves. Electrical appliances, including lighting, are summarized as one technology. Each technology is supplied with energy from different fuels. The final energy demand for these fuels is projected bottom-up, analogous to the industry and national transport sectors, based on the breakdown described here, which is shown below.

A.5.3.1 Model Structure



A.5.3.2 Example Calculation: Heat Pumps for Space Heating



Sector: Residential		End use: Space Heating				Technology: Heat Pumps				Fuel: Electricity
Population	x	Residential area per person	x	Saturation of space heating	x	Share of heat pumps	x	Energy intensity of heat pumps	x	Fuel share of electricity
10 million persons	x	20 m2/ person	x	90 %	x	30 %	x	50 kWh/m2	x	30 %
	=	200 million m2	=	180 million m2	=	54 million m2	=	270 million kWh	=	81 GWh

A.5.4 Other Sectors

For the other demand sectors, namely services, agriculture, and international bunkers, we apply a simpler method and directly extrapolate the sectoral final energy demand by multiplying an activity variable by an overall energy intensity for a given sector. To break it down by fuel, we then multiply the total final energy demand by its fuel shares.

A.5.5 Output Data

A.5.5.1 Energy Carriers and Groups

Energy carrier group	Energy carrier
Coal	Coal
Oil	Gasoline
	Diesel
	LPG
	(Jet) Kerosene
	Naphtha
	Bitumen
	Lubricants
Gas	Natural gas
Biomass	Modern biomass
	Wood
	Bioethanol
	Biodiesel
	Bio-jet kerosene
	Biogas
Renewable Heat	Solar
	Geothermal
District Heat	District Heat
Electricity	Electricity
Hydrogen	Hydrogen
Methanol	Methanol
Ammonia	Ammonia

A.5.5.2 Energy Demand Sectors and Main Subsectors

Sector	Main Subsector
Industry	Iron and Steel
	Chemical
	Non-Metallic Minerals
	Food and Tobacco
	Construction
	Mining
	Machinery
	Non-Ferrous Metals
	Paper and Pulp
	Transport Equipment
	Textiles and Leather
	Wood
	Miscellaneous
National Transport	Passenger Road
	Passenger Rail
	Passenger Air
	Freight Road
	Freight Rail
	Freight Water
Residential	Space Heating
	Space Cooling
	Water Heating
	Cooking
	Electrical Appliances
Services	-
Agriculture	-
Non-energy	Chemical Feedstock
	Others
International Bunkers	International Aviation
	International Navigation

A.6 National Energy System Optimization (PyPSA-Earth-Sec)

A.6.1 Estimation of Potential Cavern Storage

Cavern storage is generally cheaper than surface storage (in tanks or pipeline systems) and should thus be included in the model chain. Its availability, however, depends on the geology in a given region. An assessment of the local cavern storage potential of an exporting country is thus part of PyPSA-Earth-Sec. The types of storage considered include salt domes, aquifers, porous media and depleted gas fields. These storage types differ in their technological readiness for hydrogen storage. Furthermore, a thorough assessment of such geological potential for hydrogen storage is not available for every country. Hence, we also draw from other sources, namely studies on the CO_2-storage potential, natural gas storage data and studies on the prevalence of salt domes. Because the sources and storage sites vary in terms of technological readiness, accuracy and likelihood of successful hydrogen storage, they were allocated to different scenarios. This allocation is shown in the following table. It is used to assess country-specific underground storage potentials from the literature which could potentially be used for hydrogen in the future. The development status of an underground storage is assessed, together with the stored or potentially stored gas mentioned in the publication and the formation type. According to this classification, potential storage options are then assigned to a feasible time horizon for hydrogen storage and thus to a scenario. If no data or information are available for a region, storage can neither be excluded nor assumed with certainty – and the area remains "grey". In these cases, we decided not to assume any potential underground hydrogen storage in these regions.

Classification of underground storage potential and allocation to scenarios for the modeling within PyPSA-Earth Sec			**2030**			**2050**		
Development status	**Current or proposed stored gas**	**Formation type or historical use**	**optimistic**	**realistic**	**conservative**	**optimistic**	**realistic**	**conservative**
-	-	No information available; no investigations publicly available; no data						
Existing								
	Natural gas storage	Aquifers, porous media, depleted gas fields				x		
	Natural gas storage	Salt dome				x	x	x
	CO_2 storage sites	All types						
Planned or proposed								
	Hydrogen storage sites	Aquifers, porous media, depleted gas fields	x			x	x	x
	CO_2 storage sites	Aquifers, porous media, depleted gas fields				x	x	x
	All	Salt dome	x	x		x	x	x
Existing, planned or proposed								
	Oil reservoir	All types						
	All	Rock cavern						
	All	Salt structure except salt dome						
	Natural gas field	All types						

A.7 Pipeline Export Infrastructure (Hytra)

A.7.1 Pipeline Parameters

Equation 16: Weymouth

$$Q = 3.7435\ \times 10^{-3} E\left(\frac{T_b}{P_b}\right) + \left(\frac{P_1^2 - e^s P_2^2}{G T_f L_e Z}\right)^{0.5} D^{2.667}$$

Where:

Q = gas flow rate [standard m^3/day]

T_b = base temperature [K]; set to 288.15 K

P_b = base pressure [kPa]; 101.325 kPa

T_f = average gas flow temperature [K]; set to 293.15 K

P_1 = upstream pressure [kPa]

P_2 = downstream pressure [kPa]

L_e = equivalent length of pipe segment [km]

D = pipe inside diameter [in]

E = pipeline efficiency, decimal value between 0 and 1; set to 0.95

G = specific gas gravity (air = 1); set to 0.06966

Z = gas compressibility factor; set to 1.02

s = value to account for elevation difference; set to 0

A.7.2 Pipeline Operation Constraints

The intermittency of renewable energy sources and thus the intermittency of green hydrogen production via electrolysis raises the issue of whether pipelines can be operated with load changes that depend on the availability of renewable energy sources or whether they require a relatively static mass flow to keep pressure levels constant. The answer to this question has a significant influence on the overall system design. If dynamic operation is assumed, the system would not require storage after hydrogen production and compression. In this case, the hydrogen could be fed into the pipeline network directly after production, regardless of the quantity available. On the other hand, if a static mass flow is assumed, the system design would have to include storage after the electrolyzers, which would mean significant extra costs. The question of static vs. dynamic pressure operation has not been answered in practice as there are no high-volume hydrogen transmission pipelines currently operated on a scale comparable to the future envisaged hydrogen backbone or to pipelines such as Nordstream 1. We therefore explore different aspects in order to obtain a first plausible approach for modeling hydrogen pipelines within HYPAT. These aspects are:

- Conclusions drawn from the operation of natural gas pipelines
- Conclusions drawn from the operation of existing hydrogen pipelines transporting grey hydrogen
- Other studies on green hydrogen pipelines
- Insights from materials sciences.

Existing natural gas pipelines are operated with a more or less constant gas flow and thus constant pressure (Cihlar et al. 2021; Dieckhöner et al. 2013). This is due to the extraction of natural gas at constant rates to utilize the network capacities (Mischner et al. 2015). Apart from economic benefits, a broad consensus exists about the advantage of operating natural gas pipelines under static load (An et al. 2017; Krieg 2012; Laureys et al. 2022; Mohtadi-Bonab 2022; Zhao et al. 2016), as this reduces overall material degradation (An et al. 2017). If a pipeline is operated dynamically, significant effects on the fatigue properties of the pipeline material must be considered.

Existing hydrogen pipelines are also operated under static load at present (Laureys et al. 2022). In Germany, these hydrogen pipelines connect industrial clusters. The largest network with a total length of 240 km is located in the Rhine-Ruhr area and belongs to the industrial gas company AirLiquide (Ganz et al. 2019). The second network is located in the so-called Middle German Chemical Triangle and connects the chemical parks Leuna, Bitterfeld and Schopkau. This pipeline network with a total length of 150 km is operated by the industrial gas company Linde (Ganz et al. 2019). In addition to these hydrogen transport networks, a 30 km long hydrogen pipeline connects the sites Brunsbüttel and Hemmingstedt in the north of Germany and is owned by the refinery company Raffinerie Heide (Ganz et al. 2019). All of the abovementioned pipelines are small-scale and transport grey hydrogen between industrial clusters (Wang et al. 2020). Grey hydrogen is produced from fossil-based resources under steady-state conditions and is thus continuously available (Hermesmann et al. 2022). Therefore, existing hydrogen pipelines can be operated under static load. Only minor deviations of a few bars are accepted, which also do not occur abruptly, but over several hours to ensure that the pressure is kept within a certain range (Krieg 2012).

Many studies that focus on a pipeline infrastructure for hydrogen do not consider variability in hydrogen supply. Witkowski et al. 2017 analyze the infrastructure for hydrogen compression and pipeline transportation processes considering different mass flow rates with constant flow (Witkowski et al. 2017). The European Hydrogen Backbone Initiative develops a European hydrogen transmission network by combining reassigned natural gas pipelines into a future hydrogen network. Here, a steady hydrogen flow is assumed without considering the fluctuating green hydrogen production (Wang et al. 2020). (Cerniauskas et al. 2020) investigate the technical and economic potential of reassigning natural gas pipelines for hydrogen blending and pure hydrogen supply and assume a static pipeline load for all calculations. They also mention that the intermittency of renewable energy sources leads to an increase in load cycles, which accelerates fatigue crack propagation and thus increases material degradation. Hence, there is a need for more flexibility in the pipeline network. They conclude that more realistic transmission pipeline network scenarios are required for accurate results (Cerniauskas et al. 2020). To date, only a few studies exist that take the variability in hydrogen supply into account. Grube et al. (2018) examine the quantitative potential, costs and environmental effects of renewable hydrogen production, transmission and storage and assume constant hydrogen mass flow in the pipeline system. To maintain this constant hydrogen mass flow, a salt cavern near the hydrogen production site is used in their modeling to store surplus hydrogen if production exceeds pipeline capacity and to supply hydrogen in times of production shortages. The salt caverns are operated dynamically (Grube et al. 2018). In conclusion, many studies addressing the development of a hydrogen pipeline transport infrastructure assume a constant hydrogen flow rate without considering fluctuations in the load.

The effects of varying loads on pipeline material are currently under examination in material sciences. There is a lack of data regarding cyclic loading with hydrogen as a flow medium, so further investigation of this topic is needed (Laureys et al. 2022). However, there is some evidence that suggests that pipeline operation with hydrogen under a dynamic load will increase material degradation in comparison to a static one. Dynamic operation places stress on the pipe material and makes it more susceptible to hydrogen embrittlement (Krieg 2012). Especially surface defects, which favor hydrogen diffusion in the pipe material, pose high risks for crack initiation and propagation under dynamic operation, since plastic deformation can occur locally even though total deformation is in the elastic range (Brauer et al. 2018). Therefore, existing surface defects in pipelines represent a higher risk under dynamic operation compared to a static one (Krieg 2012). This can be especially important for reassigned and repurposed pipelines, which may have surface defects from their years of use.

In addition, dynamic operation of pipelines with hydrogen degrades the fatigue properties of steel. More specifically, operation with hydrogen accelerates the fatigue crack growth rate and diminishes the fatigue endurance, whereby the first is more pronounced than the latter (Laureys et al. 2022; Yan Hui Zhang 2010). Unfortunately, precise threshold values concerning the stress intensity factor at operating pressure in a hydrogen environment of different pipe materials, above which crack growth can be expected, are still missing (Krieg 2012).

The above-mentioned hydrogen degradation mechanisms are the result of various tests performed on pipeline materials of known composition. Information about the historical use, materials and composition of reassigned natural gas pipelines, which are assumed to make up a large part of the future hydrogen transportation network, is often missing or not available to the public. Furthermore, the pipeline state is likely to be inferior to newly constructed hydrogen pipelines than for newly constructed hydrogen pipelines. This can lead to an amplification of the hydrogen-induced material degradation, especially under dynamic operation.

Due to incomplete knowledge about the dynamic operation of hydrogen pipelines, it is unclear whether safe long-term operation can be guaranteed when assuming a dynamic hydrogen flow. Since the safe operation of pipelines with hydrogen under static loading has already been proven, static loading is the prerequisite within HYPAT for operating hydrogen pipelines. In order to maintain a constant hydrogen load, fluctuations in both supply and demand must be compensated. On the supply side, this can be done using hydrogen storages near the production site to bridge the times between over- and underproduction. Underground gas storages are already operated dynamically, switching between injection and withdrawal cycles (Cihlar et al. 2021). Above-ground storage tanks would face similar challenges regarding material degradation but, unlike pipelines, they could be replaced more easily (Krieg 2012).