Green hydrogen production and export through sector coupling in Namibia - A study case for HYPAT project using open-source technologies

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HafenCity Universität Hamburg

Resource Efficiency in Architecture and Planning (REAP)

Master Thesis

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Abstract

Green hydrogen has a scope of becoming the fuel of the near future with increasing demand in recent years and is estimated to grow 2-folds by 2030. Green hydrogen production, however, needs renewable fuel of non-biological origin. To gain such fuels from renewable sources such as solar or wind, infrastructure expansion is necessary with high investment costs. Nevertheless, for a global hydrogen demand and supply economy, several world leading nations, including Germany, have drafted their national hydrogen strategy, to overcome future demands with potential import from other regions of the world.

Namibia, being one of those regions, is a point of interest for forthcoming investments and pilot projects. With the aim of developing a green hydrogen potential atlas (shortened HYPAT) in an ecological and sustainable way, several projects have been initiated by the German and Namibian governments. This research has explored the potential of Namibia as an exporter of green hydrogen to Germany using techno-economic analysis. Further risk assessment was done using sensitivity and comparative analysis to observe the effect of different indicators of the export potential. The open-source optimization model is used to optimize the energy system for fulfilling internal demand and to export extra potential as fuel to Germany in the form of green hydrogen. The linear optimization model simulates 30 administrative regions of Namibia for every third hour of a year to assess renewable energy generation potential in 2030. Furthermore, total systems costs and infrastructure expansion needed were modeled, analyzed, and discussed in the research work.

Significant renewable generation potentials for solar technologies were found in the regions of future investments, pilot project proposals as well as export locations. The cost benefits of hydrogen infrastructure expansion were explored for quantities ranging from 1-200 terawatt hours. The per unit cost of green hydrogen for lower export quantities was observed as similar to official reports and research literature from partner countries. The result further explored the extra investments needed for green hydrogen compared to gray and blue hydrogen in the energy mix.

Acknowledgment

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Contents

1 Introduction

> *Developing nations like Namibia have to find a balance between sustainable human development and rapid economic growth. Nevertheless, with active partnerships between high and low-income nations, such balances can be maintained.*
>
> —

Decarbonizing the energy sector of developing nations has bigger challenges as compared to developed nations. Limited energy transmission infrastructure, high renewable investment costs, and inferior industrial technologies are some of the major factors contributing to the challenge. While climate change is an anthropogenic phenomenon majorly arising due to the usage of fossil fuels for energy production, addressing the long-term benefits of their usage in energy transition cannot be neglected. The inter-dependency of major energy-intensive sectors such as industry, transport, and shipping is one aspect where the usage of alternative fuels such as hydrogen can ease the energy transition encumbrance, especially for developing nations.

The usage of diverse energy carriers within these sectors can increase the synergies in between and decrease the dependence on fossil fuels. Low-emission energy carriers such as hydrogen, synthetic hydrocarbons, and renewable electricity can lower further greenhouse gases. These gases such as - carbon dioxide and methane cause the environment to warm gradually and cause extreme weather conditions of severe droughts, fires, floods, and rising sea-level. Hence, the complex interaction of all parameters should be framed and optimized altogether for a sustainable energy transition.

Developing nations like Namibia have to find a balance between sustainable human development and rapid economic growth. Rapid energy consumption in industrial production leads to emissions of greenhouse gases (GHGs) which need to be limited as per the nationally determined contributions (NDCs) goals set to mitigate climate change and its effects. Nevertheless, with active partnerships between high and low-income nations, such balances can be maintained with active global collaboration and country-specific research and developments.

Namibia, a southern country in Africa with the least population density has ample renewable resources such as solar and wind to generate energy for its own consumption as well as to transport across the world. However, Namibia cannot fulfill its domestic energy demand and imports almost 61% of its electricity from neighboring countries such as South Africa, Zimbabwe, Angola, and Zambia. Limited energy infrastructure, lack of development strategy, and financial deficits are some of the major factors hindering its progress.

Hence, the master thesis work focuses on the energy system of Namibia, its current stance in terms of generation and transmission infrastructure, future expansion potential, and its role in the global hydrogen economy. The energy system is modeled for every 3rd hour of a year over the existing generation and transmission infrastructure in 30 regions of the country for 2030. Further enhancements are applied as sector-coupled components such as industry, transport, and residential to mobilize inter-sectoral energy transition using carriers such as electricity, gas, biomass, oil, etc. The energy system model is optimized for fulfilling the nation's energy demands as well as to export additional energy in the form of green hydrogen of 1, 5, 50, 100, and 200 Terawatt hours (TWh). System cost, generation capacity expansion, and pipeline infrastructure expansion are some of the indicators studied to explore the potential and possible synergies with existing partnerships and green hydrogen project proposals existing in Namibia.

1.1 Thesis Structure

The thesis work is divided into seven different sections. Each section delivers a part of the work, and its components are further divided into subsections for ease of understanding. Energy system modeling is a complex process of energy data analytics and optimization rules. Hence, these processes are covered in the chapters and the observations with conclusions at the end.

Chapter 2: Background

Here are the underlying concepts and how readers can understand the terms reused in the methodology. As Namibia is the focus of this research work, we outline the country's existing energy infrastructure, its climate goals for net-zero emissions, and existing partnerships for a hydrogen economy with countries in the world, especially Germany.

Chapter 3 : Literature review

This chapter summarizes the existing studies of similar research areas, accompanied by a literature review of past studies and related facts and figures. However, all of these studies have different objectives but share common traits with this research work. At the end of the chapter, the research gaps and possible synergies between the related work are summarised.

Chapter 4 and 5 : Objective and Design

This chapter 4 outlines the objective to assist current research on the green hydrogen economy. These are laid out in terms of two questions. The questions look upon future opportunities for Namibia as an exporter of green hydrogen to Germany. The methodology to achieve the research objectives are elaborated on in the chapter 5.

Chapter 6 : Result and Discussion

The evaluation of the model output for Namibia's energy system to support national energy demand and green hydrogen export is presented here. Formulated in three scenarios for 2030 - optimistic, realistic, and conservative, the cost benefits, energy infrastructure expansions, and possible risks are assessed and discussed.

Chapter 7 : Conclusion

Finally, the conclusions are presented along with the findings from the literature review and existing partnerships with Germany for a future hydrogen economy. With the aim of assisting policymakers to make investment decisions, possible value chain routes, and locations within the country with promising potential.

Chapter 8 : Supplementary information

Supplementary material on the study assumptions, model limitations, and simplifications are laid out in this chapter. The tabular data with extensive results are also stored here. In case of need for additional details, readers are referred to this section. This offers a holistic view to the reader of the extent of work done to complete this thesis.

Background

2

> *In NDCs report (2021), Namibia committed to align its existing policies and strategies with the Paris Agreement on the path to net-zero emissions by 2050*
>
> **— (Minister of Environment, Forestry and Tourism, 2021)**

2.1 Concepts

2.1.1 Energy Sector Coupling

Sector coupling (SC) or Sector Integration (SI) is an approach where the end-consumption sectors, like industry, mobility, and residential heating/cooling are complimented with added flexibility and improved modes of storage and distribution of renewable electricity. Schaber et al., state that “the concept of Sector Coupling (SC) or Sector Integration (SI) represents an approach to substitute fossil fuels with energy from renewable electricity sources in all end-consumption sectors, such as transport, industry, and residential heating/cooling". It, as a concept, supports establishing 100% renewable energy systems, adding flexibility and improved storage and distribution options to the use of renewable electricity (Schaber et al., 2013). (Ausfelder et al., 2017) describes sector-coupling as an integrated optimization of the whole energy system merging the power, mobility, and heat sectors. Further definition and a critical review can be found in the article from (Ramsebner et al., 2021).

2.1.2 Open-source technologies

Open-source technologies are widely available to the public to use, modify and redistribute („The Open Source Definition (Annotated)“, 2006). Due to its complete transparency, open-source technologies such as software and infrastructure tools are available for a variety of users from an application down to its source code. Furthermore, the global community of open-source users and developer maintain the quality and product features of such technologies. Open source has brought a revolution in the computing world and modern society. Well-known Software such as Linux – an operating system, Apache server for web hosting, and MySQL a database management system, are some of the foundations of modern computing technologies and they are all open source developed and updated by voluntary developers around the world.

The transparent methods of software development, via peer review, remove potential vulnerabilities and promote collaboration around the world to deliver high-quality technologies. The peer review aspect is held high in the scientific community, as it establishes a standard for research quality and possible scope of scientific engagement. Open-source technologies propose an attractive solution to scientists nowadays. Due to its global community of developers working voluntarily to achieve a common goal while avoiding the reinvention of the wheel and possibly upgraded resource availability at the other end. This research takes advantage of several open-source technologies to produce the results and provide a common platform for developers, researchers, and policy-makers to create solutions. These technologies range from openly available data sources to computational models.

2.1.3 Python-based power system analysis (PyPSA) framework

Python is an open-source computer language to develop easy-to-use scripts. It provides reusable packages developed by a wide community of programmers and data scientists. Due to its simplistic design, Python language has a wide community that collaborates to develop software used worldwide. Based on Python, power system analysis (PyPSA) is a framework containing a set of mathematical equations, computer algorithms, and design formats used for the design and optimization of a power network. Power systems framework, PyPSA is focused only on one energy carrier – electricity. Power system models are essential modern technology used for optimizing power infrastructure expansion and generator dispatch decisions.

Its major constituent is defined as below:

- Network – Container of the components buses, lines, links, storage, and stores.
- Bus: fundamental node of the network with attachments such as loads, generators, and transmission lines.
- Carrier: defines the energy carriers, AC, heat, oil, gas, and hydrogen.

- Global constraints: applied to know the optimized energy model such as share of renewable, generation capacity, and transmission capacity.

- Lines: transmission and distribution lines, connects two AC buses.

- Link: the controlled and bidirectional flow of different energy carriers between two buses, It can have multiple inputs and outputs. Used as an energy conversions technology such as electrolysis, steam methane reforming, and other carbon-capture technologies.

- Load: attached to a single bus/node and consumes PQ load (active and reactive power).

- Generators: attached to a single node and feeds in power. Converting energy from the carrier to the carrier type of the bus it is attached to.

- Storage units: Attached to a single bus and used for inter-temporal power shifting.

- Store: stores energy and inherits the energy carries from the bus it is attached to. Like buses and Links, storing is a fundamental component that can be used to build complex components like Generators, Storage units, CHPs, etc.,

Power system frameworks such as PyPSA optimize energy dispatch, storage, and transmission infrastructure. Such infrastructure components are a part of the energy network and drive the system cost and maintenance cost. For instance, each transmission asset has a capital cost whereas each generation and storage asset has capital and marginal cost.

A power system framework when combined with real-world data, is regarded as a model. Power system models are engines of current research work that drive meaningful results and conclusions from the model outputs. The research goals are to optimize the Namibian sector coupled model using an optimized power sector network as a basic building block. Such complex optimizations are run as simulations that reflect real-world scenarios and provide usable information as an output for research scientists and policy-makers.

2.1.4 Types of the hydrogen fuel

Based on the production methods, the hydrogen fuels are differentiated using a color code. These color codes define the production methods and the source of energy to produce them. Below is a terminology elaboration on the scope of the current research work (Federal Ministry for Economic Affairs and Energy, 2020; Fraunhofer ISE, 2023)

- Power-to-gas (PtG): The method of producing green hydrogen, using electrical energy for water electrolysis, in a gaseous form, is known as power-to-gas. The final product can be used as fuel or as a chemical for industrial processes.

- Green hydrogen: With an important condition of using renewable energy to power the electrolyzers independent of its underlying technology, the electrolysis of water produces green hydrogen. This is the cleanest form of hydrogen fuel available nowadays.

- Grey hydrogen: The steam reforming of natural gas produces grey hydrogen. It is the most emission-entrailing form of hydrogen fuel dominating industrial production and consumption today.

- Blue hydrogen: Hydrogen production is accompanied by carbon capture and storage technologies (CCS) to restrict carbon entering the atmosphere. Known as blue hydrogen, this fuel is considered as the low-emission form of hydrogen fuel.

2.2 The status quo of Namibia's energy sector

Under the Paris Agreement (2015), 194 parties have agreed to substantially reduce their greenhouse gas emissions limiting global temperature rise to under 2 degrees Celsius while pursuing further efforts to limit even to 1.5 degrees Celsius in this century. While supporting the sustainable development goals (SDGs), the parties agree to provide financial incentives to developing countries for climate adaptation, mitigation, and strengthening resilience. In the Nationally Determined Contributions (NDCs) report (2021), Namibia committed to aligning its existing policies and strategies with the Paris Agreement on the path to net-zero emissions by 2050 (Minister of Environment, Forestry and Tourism, 2021). These NDCs are mandatory to be reviewed every five years.

In the updated NDC, Namibia's GHG emissions are estimated as 24.167 MtCO2e in the business-as-usual scenario. In an unconditional target, Namibia committed to a 14 % reduction by 2030. However, it has a potential of almost 91% reduction by 2030 through various adaptation and mitigation measures constituting financial support of 5.33 billion USD. Major mitigation potential is found in sectors such as the Agriculture, Forest, and Other Land Use (AFOLU) sector (78.7%) followed by the energy sector with 11.6% of mitigation potential compared to (see table 2.1).

Tab. 2.1: Mitigation actions to achieve climate goals by 2050 are elaborated in Namibia's NDCs report (Minister of Environment, Forestry and Tourism, 2021). The energy subsector has a mitigation potential of 2.93 Mtons with specified interventions and the costs associated with it.

Energy subsectors	Mitigation actions to reduce greenhouse emissions	Capacity	units	Mt CO2e	Financial cost (Billion Euro)
Electricity	Additional solar/wind generation capacity to reduce imports.	288	MW	0.30229	0.653
Electricity	50% utilization of maximum hydro generation capacity	340	MW	0.22979	0.119
Heating	Fulfill heating demand with solar water heaters (SWH)	20,000	SWH	0.017	0.25
Transport	Hydrogen fuel for freight transport and fuel efficiency measures	20	%	2.244	0.232
Transport	Electric mobility	10000	Evs	0.007	0.05
Industry	Replace klinkers usage in cement production.	23	%	0.104	0.05
Industry	Hydrocarbons in refrigenration and air-conditioning	80	%	0.03068	0.176
			Total	2.93476	1.53

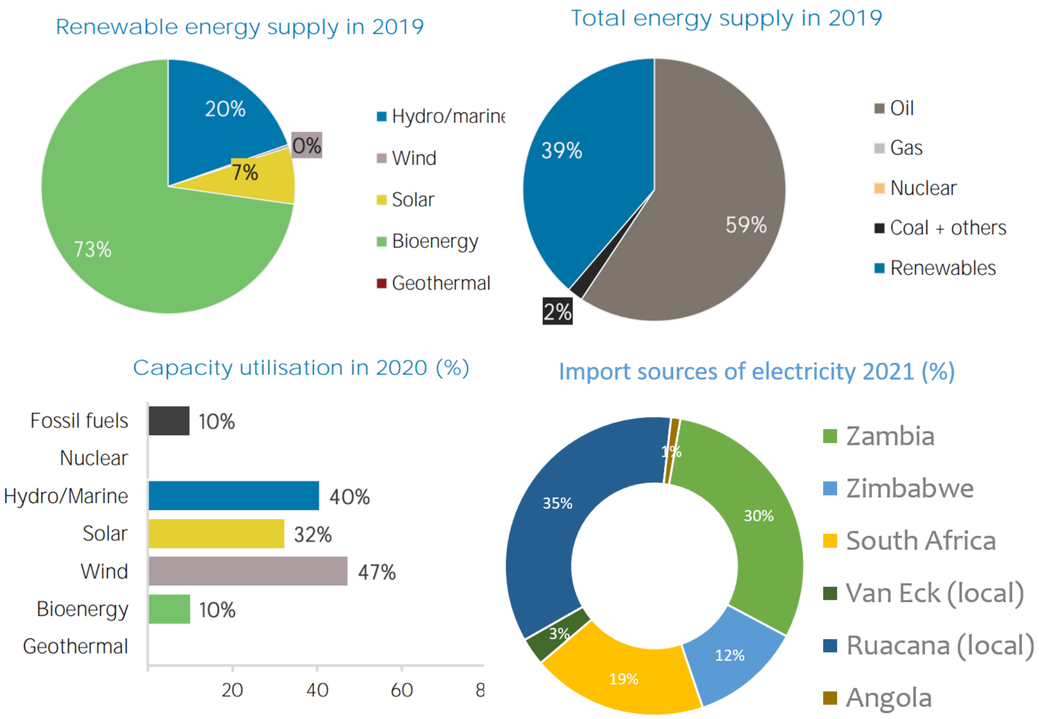


Fig. 2.1: Energy capacity, generation, and consumption in Namibia (2019-2021). The country has a major dependency on imported energy from neighboring countries. Although the local energy generated is predominantly from renewable sources. (Amesho et al., 2022; IRENA, 2021)

Namibia generates more than 90% of its electricity from renewable sources - which is not enough to fulfill the national demand for electrical energy (IRENA, 2021). Through recent policy reforms, Namibia aims to fulfill 75% of its total electricity demand and 100% of its peak demand from local electrical energy sources, its reliance on imported electricity is clearly visible in the fact that in July 2021, Namibia imported more than 60% of its total electrical energy demand out of which 55.2 % of electrical energy demand was from commercial processes (Amesho et al., 2022).

To decrease the import dependency and to de-carbonize the energy sector, several strategies - such as new renewable energy projects and the production of green hydrogen, have been proposed in institutional and regulatory frameworks of Namibia's energy sector. Under a joint communiqué of intent (JCoI) with Germany, energy system modeling proposed for Namibia, aligns with similar strategies internationally (BMBF, 2021a). The computation-intensive modeling based on data from Namibia's energy sector can create a cost-optimal solution for energy sectors and suggest strategies for policymakers to realize such goals of future hydrogen partnerships.

3

Literature review

> *While the existing studies have performed a techno-economic analysis of the transmission and distribution system of Namibia, the green hydrogen potential is not assessed.*

3.1 Global stance on hydrogen as a fuel

Global Hydrogen Review from IEA (2021) claimed that, in 2030, nearly 200 million tonnes (Mt) of hydrogen will be globally in demand to achieve climate neutrality in 2050 (International Energy Agency, 2021). To put in perspective, compared to the demand of 94 Mt in 2021, more than 93 Mt of which was produced from non-renewable sources. Hence, the production of green hydrogen to satisfy the current 2.5% of final global energy consumption in 2019 would need further research at a global scale. Every year rapidly rising industrial and power sector demand for hydrogen and ammonia – a widely used hydrogen-rich chemical for products ranging from the mining industry to fertilizers.

New strategies have emerged in the shape of 100 pilot projects globally to produce hydrogen and its derivatives such as ammonia and other PtX products used in the shipping industry. However, just four have reached a clear final investment decision (FID) or are under construction. Realizing these projects by 2030 would need production of 16-24 Mt/yr. of low-emission hydrogen comprised half-to-half from electrolysis and natural gas with carbon-captured technologies (International Energy Agency, 2021). Various researchers around the world are keeping a close look at the market trends and upcoming milestones (Acar & Dincer, 2019; Schlachtberger et al., 2017; Victoria et al., 2022). Wietschel et al., 2020 elaborated on the challenges and opportunities faced in Germany to import green hydrogen in a policy brief.

3.2 Hydrogen potential atlas (HYPAT)

Aligned with the objectives of the German national hydrogen strategy (BMBF, 2022; Federal Ministry for Economic Affairs and Energy, 2020), HYPAT's vision is to develop a cooperative future hydrogen economy. Moreover to develop a global hydrogen potential atlas and comprehensively identify the possible partner countries to Germany. This includes the significance of the production region for a secure, economic, and ecologically sustainable supply of green hydrogen.

Consequently, the Ministry of Education and Research, in Germany has announced a partnership with Namibia on importing green hydrogen as a part of the collaboration (BMBF, 2021a). HYPAT (Hydrogen potential atlas) is a result of such collaborative partnerships with research institutes (IDOS, 2021). The ongoing paper on HYPAT (Pieton et al., n.d.) describes a comprehensive study of different supply chain aspects to produce and export hydrogen from ten selected countries - Brazil, Canada, Chile, Kenya, Morocco, Namibia, New Zealand, Turkey, Ukraine, and UAE. HYPAT's working paper has also highlighted the globally existing techno-economic analysis conducted in recent years. The publication from (Breitschopf et al., n.d.) (working paper) describes the methodology behind the selection of the ten countries. Where it covers most of the selection criteria including global production and import locations, primary energy sources such as renewable and non-renewable sources, water stress, energy system optimization, and potential export value chain. Therefore, it is a holistic study done to support future hydrogen and PtX market development and energy sustainability.

HYPAT project has a part built upon open-source technologies, where a large community of researchers and scientists are working to develop better frameworks and computationally feasible energy system models. Which contains components ranging from primary energy sources for domestic supply, export potential of hydrogen and PtX products in an optimized energy system, to various transport routes. Looking at Namibia's Nationally Determined Contributions to net-zero climate goals by 2050 (Minister of Environment, Forestry and Tourism, 2021) such partnerships are significant to reduce carbon footprint in major industrial, transportation, and other energy-intensive sectors. In the paper, "Issues, Challenges, and Opportunities to Develop Green Hydrogen in Namibia", (Von Oertzen, 2021) expressed a multi-sectoral approach to enable a low-carbon economy and transform the socio-economic stature of Namibia. Complemented with the joint communique of intent between these countries (BMBF, 2021b), HYPAT project findings would be essential for policymakers to derive regulations, future pilot projects, and investment decisions.

3.3 PyPSA-Earth-Sec: Open source sector-coupled energy system model

An open-source optimization model - PyPSA-Earth-Sec is a spatially and temporally resolved energy system model, which stands out for its innovative approach to emission reduction and addressing energy storage concerns. It takes energy-intensive sectors such as industry, heating, and transport coupled together. To meet local energy needs and to export energy carriers, it uses existing or upgraded infrastructures, such as power generators, transmission systems, and gas pipelines existing in a region regarded as a node (see figure 3.1).

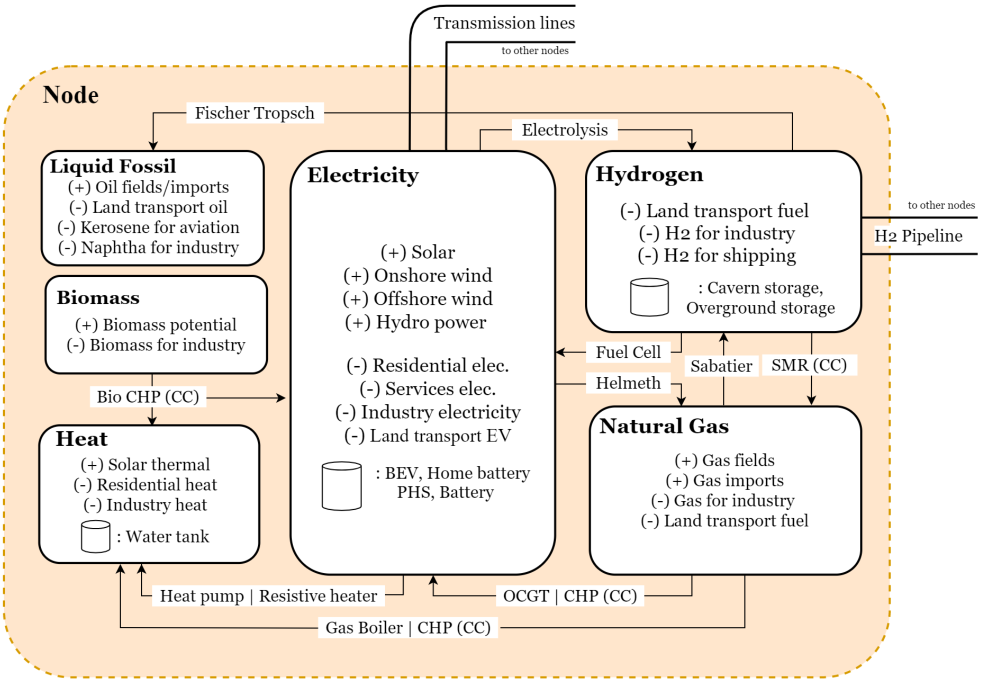


Fig. 3.1: A node depicted from the energy system model - PyPSA-Earth-Sec. The energy carriers are connected through power lines, pipeline lines, and various conversion technologies exhibiting an interconnected system of generators, storage, and transmission network. Source : (Abdel-Khalek et al., n.d.) (working paper)

It builds upon PyPSA-Earth - its parent model with electricity generation and transmission optimization capabilities covering the entire world. The demand sectors such as industry, heating, transport, biomass, and industrial feed-stock are included in the model. However, the greenhouse emissions from waste management, agriculture, forestry, and land use are not yet included, however, subjected to further development. Pypsa-Earth is a power sector model solely focused on electricity generation and dispatch optimization scenarios. Hence, Pypsa-earth is an integral part of the Pypsa-Earth-Sec model (Parzen et al., 2023).

Whereas the sector-coupled model includes not just electricity but other energy carriers such as gas, hydrocarbon-derived fuels, and synthetic products such as ammonia. These carriers provide efficient transfer of energy from one sector to another, for example, power-to-gas or Vehicle-to-grid systems. The sector-coupled model utilizes the power sector model as a base upon which other energy carriers are modeled. Given that, the scope of the research is the cost optimization of the energy system model and green hydrogen potential, Pypsa-Earth-Sec is utilized predominantly to produce the results. Moreover, the higher spatial-temporal resolution facilitates the strategic electrolyzer plant locations. These locations are a critical element for hydrogen production, logistics, and utilization in situ, and internationally.

The energy system model has been usually seen as a black box in which all the data, methodologies, and most importantly the assumptions are hidden behind a proprietary closed system. This leads to a lack of transparency and trust in the decision-making based on such models. (Pfenninger et al., 2018) discussed such experiences in "Opening the black box of energy modeling" through the illustration of challenges. It primarily covers critical aspects of open contribution and assurance of safe intellectual values. Furthermore, the article Pfenninger, 2017 elaborates on the perks of opening knowledge paths and collaboration between energy scientists and policymakers. The Pypsa-Eur-Sec model has been published and used for the sector-coupled model of European countries (Neumann et al., 2021). This precedes now rather a global initiative of (Parzen et al., 2022) to model the global power system. Overall, an in-depth global green hydrogen potential assessment requires elaborate scientific research. Also, an energy infrastructure with a viable green hydrogen economy needs a set of tools within an open environment for wide collaboration and transparency. The documentation with further information on the model is available at (Parzen et al., 2023). The open-source data and other model components can be found here („PyPSA meets Earth · GitHub", 2023).

3.4 Open Source Energy Modelling System (OSeMOSYS) in Namibia

(Allington, Cannone, Pappis, Walker, et al., 2021) used OSeMOSYS - an open cost optimization tool to perform the energy system optimization for Namibia for the period of 2015-2050. Using open source data, found in the repository (Allington et al., 2023), a techno-economic analysis was performed.

The energy system optimization is performed for three scenarios namely - the fossil future scenario, the least cost scenario, and the net zero by 2050 scenario. These scenarios explore the generation capacities expansion needed to fulfill the underlying constraints for each scenario. The scenarios assumptions and preliminary results are illustrated in the document (Allington, Cannone, Pappis, & Sridharan, 2021). The open data and resources are available in the repository (Allington et al., 2023) for energy analysts, and policy-makers to reproduce the relevant results.

3.5 Conclusion

Existing effort in energy system modeling in Namibia exhibits potential for future studies. While the existing studies have performed a techno-economic analysis of the transmission and distribution system of Namibia. The green hydrogen potential is not assessed in the related work summarized above. Hence, this research work is filling up the gap using open-source technologies and data. Nonetheless, the related work serves as a reference for future development of the global open-source energy system model - Pypsa-Earth-Sec and its findings on Namibia's energy system network.

4 Objective

> *The project named "SDG Namibia One" envisions an investment platform in Namibia to finance large hydrogen projects during development, construction, operation, and acquisitions attractive to investors*
>
> **— (Silo & Redactie, 2022)**

4.1 A push toward green hydrogen

Current climate pledges from governments require global production of up to 34 Mt/yr. low-emission hydrogen till 2030 (International Energy Agency, 2021). Whereas net-zero emissions by 2050 would need about three times more than the production rate of 100 Mt per year. Fewer than 1 Mt production of low-emission hydrogen in 2021, predominantly came from natural gas accompanied by carbon capture and storage technologies. This clearly displays the global stance of green hydrogen on current production technologies as it has not seen output as an energy carrier in the global market.

To produce low-carbon hydrogen such as green hydrogen, the widely used method is an electrolyzer powered with low-carbon electricity. Mostly produced from renewables such as solar photovoltaic, onshore, and offshore wind power. However, the current electrolysis technologies such as PEM (proton exchange membrane) have a higher cost. Renewable energy sources have an intermittent nature with variable energy output. Hence, the usage of renewable energy to produce hydrogen can be a less cost-effective and unreliable source of energy, if not optimized. International Energy Agency, 2021 also outlined that the energy demand uncertainty, a lack of favorable policy regulations, and insufficient infrastructure are some of the major challenges for the future hydrogen economy.

Germany has been at the forefront of hydrogen-related technologies and their industrial applications. The first hydrogen fuel cell-operated rail – also known as Hydrails started operating in March 2022. Similar ventures are being realized in other parts of the EU and around the world (Palmer, 2022). This shows an early indicator of hydrogen fuel demand in the transportation and logistics sector. These sectors are where diesel-operated engines are currently used in place of electrified mobility. Re-purposing existing diesel engines for hydrogen fuel as well as LNG terminals and pipelines can bring down the capital and marginal cost of hydrogen transportation and consumption. Nonetheless, there lies a huge uncertainty due to a lack of experience in realizing such projects (International Energy Agency, 2021).

4.2 Namibia - An export hub to Germany

One of the necessary goals of the HYPAT project („HyPat“, 2022) is to develop actions in terms of policy recommendations. Germany as well as the producing country – Namibia can benefit from the cost efficiency and security of a green hydrogen supply chain. This could have the potential of achieving nationally determined contributions from Namibia to the Paris Agreement.

With a joint communiqué of intent (JCoI) (Hillgenberg, 1999) establishing a German-Namibian hydrogen partnership, Namibia became the first official partner to receive an economic stimulus package - valued up to 40 million euros for cooperation in the field of green hydrogen(BMBF, 2021a). Under this partnership, Germany will support Namibia to produce green hydrogen with a cost per kilogram between €1.50 to €2.00 by establishing its hydrogen strategy as well as implementing it efficiently and sustainably. One aspect of this partnership is to jointly kick off a pilot project and enforce capabilities through training skilled professionals on site. This project will serve as a benchmark for future green hydrogen production initiatives and transportation strategies for exports to Germany (BMBF, 2021b; Rickel, 2021).

German Agency for international cooperation (GIZ) is supporting infrastructure development in Namibia and 14 other countries for a future hydrogen economy. The project named H2Uppp from GIZ has the objective of supporting small and medium enterprises (SMEs) to develop hydrogen projects and value-chain from generation to usage. The investments are valued at up to 41 Million Euros and commissioned by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The project activities in Namibia are carried out with the help of the German Chambers of Commerce Abroad (AHKs) (giz, 2022).

Another investment project valued up to 1.4 billion euros to develop a green hydrogen economy in Namibia. The Dutch Ministry of Finance and other private investors have developed a fund in cooperation with the Climate Fund Managers, the Environmental Investment Fund of Namibia (owned by the Namibian Government), and Invest International. The project named "SDG Namibia One" envisions an investment platform in Namibia to finance large hydrogen projects during development, construction, operation, and acquisitions attractive to investors (Silo & Redactie, 2022).

Several other projects to elevate the hydrogen economy are being developed or at the conceptual stage in Namibia for green hydrogen and ammonia production. With a project value of 5.66 million euros, the first green hydrogen fuel application demonstrated in the Walvis port environment with an electrolyzer capacity of 5MW and mobile refuel station of 945 Kg at 500 bar. This project aims to strengthen Germany and Namibia's cooperation in the green hydrogen economy (Rigava, 2022b). Along with another project in Walbis Bay valued at 25 million euros with a larger scale of 25-50 pilot plants of 5MW electrolyzers and 5MW photovoltaic solar systems (Rigava, 2022c). To decarbonize the railway fleet, one of the largest energy consumers in Namibia, a dual fuel comprised of diesel-hydrogen locomotives is proposed in the Walbis Bay to Kranzberg corridor. With a project value of 7.63 million euros, the project aims to develop Africa's first dual-fuel and a maximum of 50 locomotives (Rigava, 2022d). Another project lies in the same region at Daures Green Village to produce 350 kilotons per year of Ammonia in a total of four phases. The project is valued at 15.1 million euros for phase 1. The presence of mines in the area gives a commercial advantage to the production facilities (Rigava, 2022a). With the potential to produce 300 Ktons of Green hydrogen the Hyphen SCDI (Southern Corridor Development Initiative), project has the highest estimated investments valued at 9.4 billion USD. This project is the biggest green hydrogen economy-related development in Namibia with the potential to expand 5GW of renewable capacity and local industrious and workforce development (Rigava, 2022e).

4.3 Research Questions

The scope of this project and research objectives are defined in the form of two research questions. These questions define the boundaries for the research and expected outcomes.

Firstly, the energy system is analyzed for the green hydrogen export potential to Germany. Hydrogen partnerships between the German-Namibian governments are simulated through different quantity steps, investment risks, and de-carbonizing pathways. The following question summarizes the scope of this analysis. The research scope explores the techno-economic analysis of energy systems where total system costs (capital and marginal cost) are optimized towards a net zero hydrogen economy in Namibia. The intermediate year of 2030 was analyzed with a strong focus on the sustainable development of energy systems using three scenarios - optimistic, realistic, and conservative. Capturing the above-defined scope, the open optimization model hands over a constant hydrogen delivery time series and a normalized cost of hydrogen at the export locations.

Research question - 1: What are the future opportunities for Namibia in the green hydrogen economy as an exporter to Germany under the joint partnerships?

Secondly, the research scope explores the effect of rapid infrastructure expansion, strict policy implementation, and mixed hydrogen fuel on investment costs, renewable technology share, and normalized cost of producing a unit of hydrogen for export - using a comparative and sensitivity analysis.

Research question - 2: How can decision-makers assess the risks associated with green hydrogen export strategy and decarbonization of the Namibian energy sector?

The results serve as an indicator of opportunities and challenges to support the German-Namibian green hydrogen strategy for further steps in partnerships. Furthermore, the risk assessment with sensitivity and comparative analysis of the energy system model aids in a better understanding of the indicators of decision-making. This is vital to make informed investment decisions in complex energy infrastructures where energy-intensive sectors are coupled together.

5 Design

> *pypsa-earth-sec derives and delivers data from other models in the chain. These models are utilized to create Namibia's energy systems components such as energy demand, renewable energy generation potential, and hydrogen production.*
>
> —

5.1 PyPSA-Earth-Sec - linear optimization model

The techno-economic analysis is a method to assess the economic performance of an industrial product. The PyPSA-Earth-Sec, a techno-economic analysis model, is utilized to find the optimal cost of green hydrogen and PtX products at the import locations, in this case, Germany. The capital expenditure on the required power infrastructure expansion is minimized, along with the marginal costs for maintenance on an annual basis. This includes the generation and storage of renewable energy to produce hydrogen and transport it through pipelines, and shipping vessels.

The PyPSA-Earth-Sec model derives and delivers the data from other models in the model chain. These models are utilized to create Namibia's energy systems components. Comprises mainly of energy demand, renewable energy generation potential, and hydrogen production, each model has a specific function to perform in order to have a high spatial and temporal resolution. The different sectoral energy demands and renewable generation potential are considered in 30 regions of Namibia (see figure 5.1) with a minimum time-lapse of 3 hours.

5.1.1 Optimization approach

PyPSA-Earth-Sec allows for the twin optimization of investment and dispatches decisions to support the planning process for policy governance and technical infrastructure adjustments. In order to do so, the PyPSA framework is used to construct a sector-coupled model of Namibia's energy system. This combined model is known as PyPSA-Earth-Sec which aims to model not only Namibia but the energy system

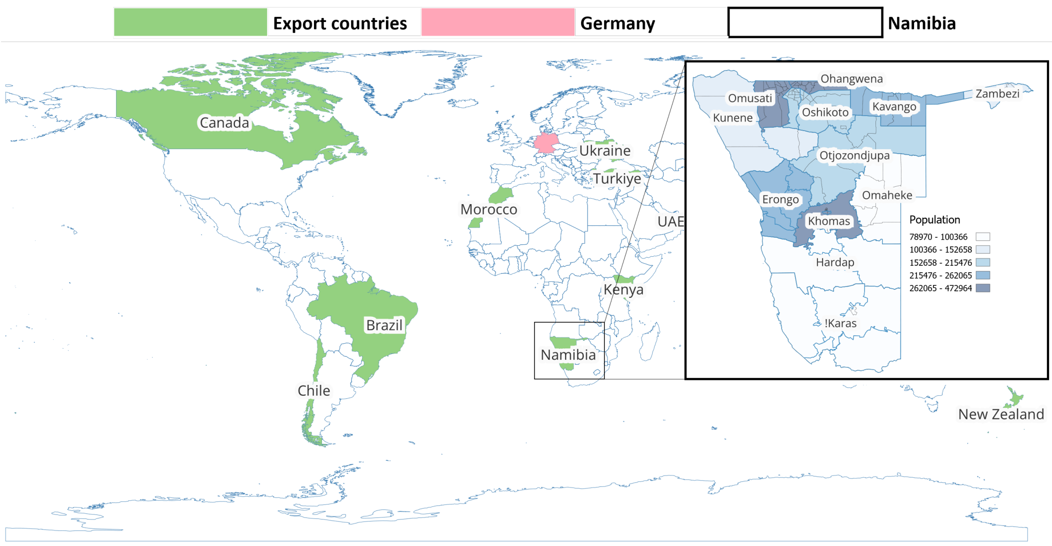


Fig. 5.1: In HYPAT 10 countries are selected for in-depth techno-economic analysis for green hydrogen potential, Namibia is one of them shown here with 30 regional boundaries from open GADM data in level-1 and level-2 merged into 30 regions. (source: (GADM, 2023; Pieton et al., n.d.))

of any country in the world. To extract optimal energy indicators from the model, commercial solvers are taken as a software tool to solve the linear optimization problem.

Furthermore, the energy demand is modeled using closed-source data from LEAP while supply and transmission use open-source data for industry, agriculture, navigation, aviation, and transport sector including electric vehicles. The energy carriers implemented in the model are power, heat, oil, natural gas, and hydrogen. For the transmission of such carriers, the existing energy infrastructure such as transmission power grid, natural gas network, future hydrogen network, utility-scale renewable power plants, and conventional generation assets on the supply side are modeled as well. Keeping the flexibility of the energy system in mind, several short and long-term opportunities named pumped-hydro, heat storage, P2G (power to gas), and power-to-liquid are also consolidated into the model.

According toNeumann et al., 2021, a mathematical representation of the energy system model such as PyPSA-Earth-Sec can be an equation written as follow:

$$\textbf{Min}\left[Yearly\ system\ costs\right] = \textbf{Min}\left[\sum_{n}(Annualised\ capital\ cost) + \sum_{n,t}(Marginal\ costs)\right] \tag{5.1}$$

The goal of the optimization equation stated above is to minimize the annual energy system costs. Including annualized system cost at each node n and marginal costs for each time-step t and node n.

The main constraints defined for the optimization approach should satisfy the local energy demand for each energy carrier at each region identified as a single node. Other constraints are to respect the local carbon emission targets for 2030 which are defined as a percentage of emissions in the base year of 2019. Land-use constraints such as protected areas or urban space are also excluded from building up new renewable energy systems. To realize energy transportation, the physical limitations of transmission grids and pipeline capacity are important constraints incorporated into the optimization equation.

A combination of data parameters and decision variable utilizes the objective function for minimizing capital and the marginal cost of the energy system. The data parameters are set up to reflect the real-world cost and capacity of the system while the decision variables are reserved for the computer algorithm to tweak and present a viable solution to the optimization problem.

$$\begin{aligned} \min \Big[\sum_{n,s} c_{n,s}\, \bar{g}_{n,s} + \sum_{n,s} c_{n,s}\, \bar{h}_{n,s} + \sum_{n,s} c_{n,s} \bar{k}_{n,s} + \sum_{n,s} c_l F_l \quad (Capital\ Cost) \\ + \sum_{n,s} W_t \Big[\sum_{n,s} o_{n,s,t}\ g_{n,s,t} + \sum_{n,s} o_{n,s,t}\ h_{n,s,t} + \sum_{n,s} o_{n,s,t}\ k_{n,s,t} \Big] \quad (MarginalCost) \Big] \end{aligned} \tag{5.2}$$

Each variable c and o are capital and operational cost respectively for a region called bus n having a generator/convertor/storage labeled s at a specific time stamp t. Furthermore, $\bar{g}$ is the nominal power of the generator with g being the dispatch of that generator on the line/pipeline with capacity F. The converted nominal power $\bar{k}$ yields converted energy k with a nominal capacity of storage $\bar{h}$ and energy flow of storage h for a snapshot duration of W_t.

5.2 Other models in HYPAT project model-chain

To achieve usable results from such a complex analysis, five model chains are combined together. These five models are LEAP, Enertile, PyPSA-Earth-Sec, Hytra, and H2ProSim. The model chain utilizes open-source data such as weather data, land use, water cost, power generation technologies, and transport infrastructure data. This serves as an input to perform an in-depth techno-economic assessment of the Namibian energy system, hydrogen, and Power-to-X export potential (Pieton et al., n.d.)

HYPAT takes advantage of active research in energy modeling (PyPSA-Earth) and close source technologies (Enertile, LEAP, Hytra, and H2PromSim). Even though,

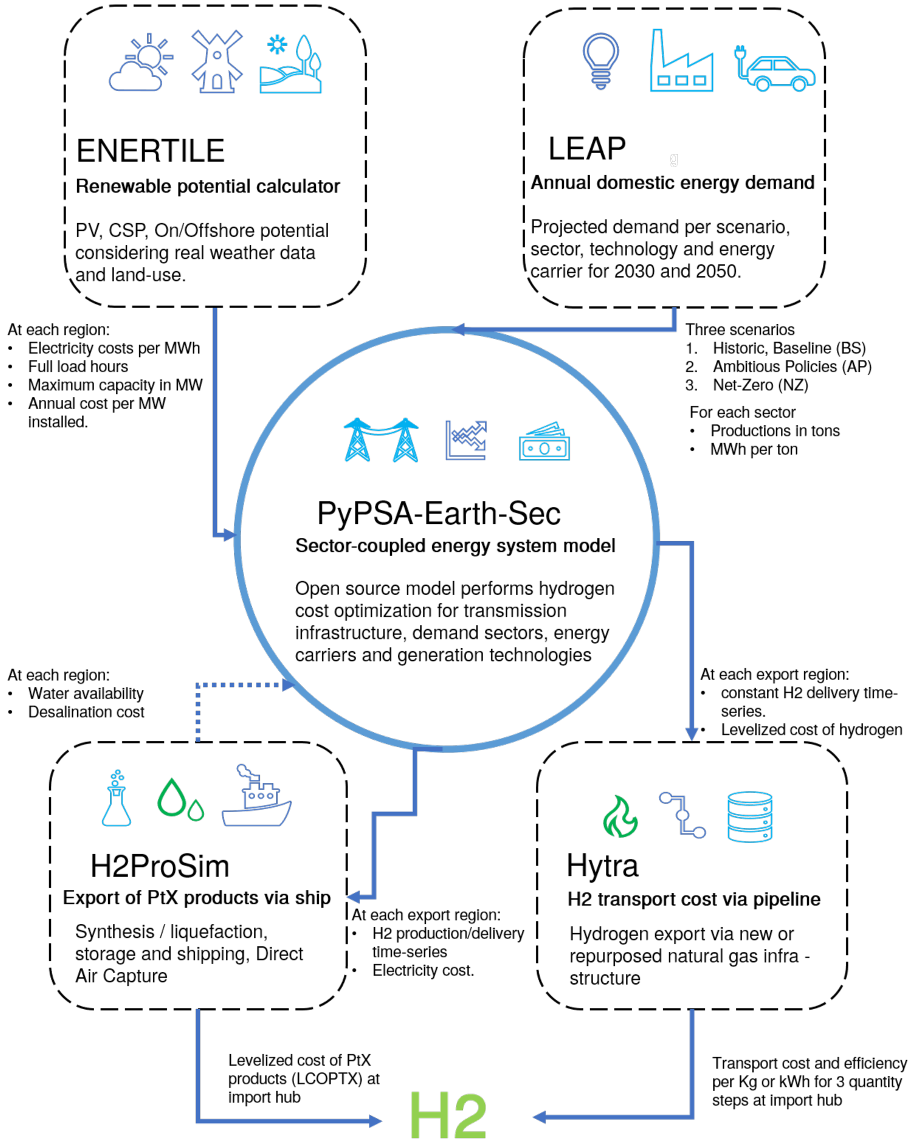


Fig. 5.2: Complete model chain for HYPAT with respective input/output and relationships. PyPSA-Earth-sec is the focus of this research, nevertheless, the other model chains provide input data and utilize output from it as shown in the figure.

the Pypsa-earth-sec is capable of producing such results with publicly available data and technologies. The input-output relationship is summarized in figure 5.2.

5.2.1 Enertile - Renewable potential calculator

Enertile - a model complemented with real weather and land-use data, provides an hourly time series of renewable energy potential. The maximum installable capacity of photovoltaic (PV), concentrated solar power (CSP), and offshore/onshore wind in 30 Namibian regions is a critical output from Enertile.

Overall, the entire model delivers annualized electricity cost per MWh, full-load hours, potential capacity in MW, and the annual cost per MW installed. The normalized hourly time-series data of each renewable technology are aggregated on a regional level. With these inputs, pypsa-earth-sec can optimize costs related to green hydrogen and its derivatives (PtX) production. These costs can be for future renewable capacity installation, infrastructure expansion, and electrolyzers.

Looking at the Global Administrative Areas (GADM) regions of Namibia, a few smaller regions are merged together. A total of 30 regional divisions are selected with proximity to the ocean and dense population distribution (see figure 5.1). The whole model chain takes 3-4 weeks to perform complete model runs excluding the initial data preparation duration. To efficiently use limited computation memory and data processing that can lead to long-model runs, computation constraints on regions and time-step are considered. Enertile uses ERA5 - a global weather data with 820000 stations worldwide for the year 2020 with a spatial resolution of 6.5 square kilometers (Hersbach et al., 2020). On the other hand, the land-use criteria use the GlobCover dataset from 2010 and exclude categories Ia, Ib, and II from the renewable utilization assessment (GlobCover, 2010).

5.2.2 LEAP - Annual domestic energy demand scenarios

Having a sound prediction of the annual demand for domestic energy is an essential input to optimizing the generation and dispatch of energy carriers. Focused solely on energy demand, the LEAP (Low Emissions Analysis Platform) is an engineering-based energy demand analysis tool developed at Fraunhofer IEG. LEAP is capable of tracking annual energy demand in all sectors of production, consumption, and resource extraction to produce national-level energy demand. This is achieved through a bottom-up approach where specific energy-intensive sectors such as steel, cement, and other industries' productions are estimated and projected in future scenarios, out of which the energy demand is forecasted individually.

Namibia-specific parameters such as population, Gross Domestic Product (GDP), energy intensity, and sector-specific fuel shares are the defining variables to calculate the final energy demand. Energy demand sectors such as Industry & Non-Energy, National Transport, Residential, Services, Agriculture, and International Bunkers are modeled separately in LEAP to achieve accurate estimates. As a modeling input to pypsa-earth-sec, scenario-based final energy demands for 2030 and 2050 are produced. It includes different sectors, sub-sectors, and carriers for three scenarios namely Baseline (BS), Ambitious policies (AP), and Net-Zero (NZ) in terms of climate goals.

5.2.3 Hytra - H2 transport cost via pipeline

Hytra is mainly used for analyzing the pipeline infrastructure to export compressed or gaseous hydrogen. With a 3-step approach, Hytra first selects a pipeline route and elongation. Secondly, it determines the size and other technical configurations, and Finally, the cost of transportation for the selected configuration. To have more cost-effective transport, Hytra also considers re-purposing existing natural gas and oil pipeline infrastructure for hydrogen transportation. The main outputs are the cost of hydrogen transport and energy efficiency per kWh or kilogram.

Due to cost constraints and efficiency bottlenecks, we consider pipeline transport up to 5000 km between import and export locations. With more than 11000 KMs of distance from Germany and no existing pipeline infrastructure in Namibia, transport via ship is considered the only mode of green hydrogen transportation.

5.2.4 H2ProSim - Export of PtX products via ship

H2ProSim models the export of five different PtX energy carriers at up to five export locations per country. These PtX products include ammonia, hydrogen, hydrocarbons, methanol, and Fischer-Tropsch synthesis products. The dynamic operation of synthesis and liquefaction plan, ship size, and ship fuel is configured in three different optimization scenarios. For the time horizon of 2030 and 2050. H2ProSim provides input to pypsa-earth-sec on water availability and desalination cost in each region. This is an essential parameter to calculate the operating cost of Electrolyser for hydrogen production.

The objective function minimizes the optimization equation for LCOPtX. It is dependent on variables such as the volume of hydrogen buffer and PtX storage, the capacity of synthesis/liquefaction, and the number of transport vessels required to import at a specific location.

5.3 Underlying optimization scenarios

The export costs are analyzed for Namibia in three different scenarios referred optimistic, realistic, and conservative scenario. These scenarios are primarily based on country-specific climate goals, their infrastructure needs, and the production cost of electricity, hydrogen, and PtX. Each scenario builds up for two separate time horizons of 2030 and 2050, nevertheless, the infrastructure investments done in 2030 are taken as a foundation for export quantities in 2050. This ensures that each quantity of export develops independently and is cumulatively added to the three scenarios scenario for the latest time horizon of 2050. However, for the thesis work, only the time horizon of 2030 is explored further. The analysis of time-horizon 2050 will be done in the scope of the HYPAT project.

The Financial risk of renewable technologies is assessed through interest rates classified as low, medium, and high as well as four quantity steps for export. In particular, the interest rates are taken for historic values for Namibia's risk premium indicating the risk in investing its businesses and equity risk premium between the years 2000-2020. Minimum values of both risk premiums yield - low-interest rate levels, whereas maximum and average are considered high and medium risk levels respectively.

For comparison of the export cost of PtX products across years, it is divided into four different export quantities. These quantities vary for 2030 based on the global demand for PtX, the levelized cost of electricity (LCOE) for renewables, and the demand fulfillment cap. For instance, in 2030, the quantities steps are defined as 1 TWh, 5 TWh, 50 TWh, 100 TWh, and 200 TWh annually.

Another relevant configuration type for the scenarios is the decarbonizing pathways which align with Namibia's climate goals for 2030. The three demand scenarios inherited from LEAP are Net-Zero (NZ), Ambitious policies (AP), and Baseline (BS) for the carbon-limit benchmark. The Net-Zero (NZ) scenario defines Namibia as being carbon neutral till 2030 with fast electrification of all sectors, the Usage of carbon-capture technologies, and limited usage of biomass - mostly in industry. Whereas, Ambitious Policies (AP) embrace slower decarbonization and restrictive infrastructure development.

5.3.1 The optimistic, realistic, and conservative scenario

The financial risk is stated as low in the optimistic scenario, bringing down export costs aligned with the decarbonizing economy with a Net-Zero climate goal by 2030. Energy infrastructure is established for electricity, hydrogen, and heat. The resulting LCOH and LCOPTX are used to calculate transport costs in a repurposed pipeline and for all available PtX technologies. Table 5.1 outlines the optimistic scenario for green hydrogen export.

Unlike the Net-Zero (NZ) pathway where higher electrification, lesser use of biomass, and higher use of liquid fuels are adopted for carbon neutrality, Ambitious Plans (AP) assume a rather slower decarbonization of the energy system. However, the energy carriers use the new pipelines for in-land transport, and small ships use fossil fuel for export via sea till 2030 (table 5.1)

The conservative scenario configures the financial risk at a high level compared to others, it also places the partial load operation flexibility to the minimum. New pipelines and smaller ships for the transport of green hydrogen and its derivatives are expected to drive up the capital as well as the marginal costs. This serves as the worst-case scenario and a factor in investment-related decisions. Table 5.1 summarizes the configuration in detail for all models.

Tab. 5.1: Optimistic, Realistic, and Conservative scenario configuration for three models in HYPAT for the years 2030 and 2050

		Optimistic	**Realistic**	**Conservative**
Model	**configuration type**	**2030**	**2030**	**2030**
LEAP	National decarbonizing pathways	Net Zero (NZ)	Ambitious Plans (AP)	Ambitious Plans (AP)
Enertile	Financial Risk	Low	Medium	High
		7.6 %	8.2 %	9.7 %
PyPSA	National energy infrastructure expansion	Moderate	None	None
	Export Quantities (TWh) Q2030 - 1, 5, 50, 100, 200	Q2030	Q2030	Q2030
	Carbon emission limit Megatons (10E6)	3.9 (decarbonize industry sector)	4.3 (mean value)	4.76 (emissions w.r.t 2019)

5.4 Sensitivity analysis parameters for risk assessment

In the linear optimization method, certain risk factors can be assessed using sensitivity analysis. Based on how sensitive is the energy system model to change in certain factors, a preliminary assessment of risk can be carried out, as is done in this research. These factors are helpful in determining the reliability of the assumptions carried out throughout the analysis.

1. **Slow de-carbonization with low-emission hydrogen in the system:** For a developing nation like Namibia with the lowest population density and minor energy-intensive sector, achieving net zero by 2050 could be easier relative to highly industrialized nations. However, by 2030 it will need higher investments in renewable technologies to cover its energy demands driving the costs higher. Therefore, low-emission hydrogen such as blue hydrogen can assist in filling gaps in a shorter period of time. Blue hydrogen - a type of hydrogen fuel extracted from natural gas with carbon-capture technologies, can assist to decarbonize the transport sector which is the highest-demand sector in Namibia.

2. **Limited hydrogen network expansion**: Namibia has no existing hydrogen pipeline infrastructure or a gas network. Using hydrogen as a fuel in different regions would need investments in developing such infrastructure, or refur-

bishing an existing gas network - which in the case of Namibia is not applicable. So, the initial cost of network expansion is considered a critical factor. Its effects are observed in the total system cost and the renewable energy utilized in the system.

3. **Effect of policy strictness on the energy systems** The strict policies favor the monthly production of green hydrogen using only renewable fuels (Commissioner for Energy, 2023). Whereas lenient policies have no such monthly constraints, the national emission goals are respected to produce such fuels. Cost factors such as capital and marginal cost are assessed to observe how policy implied affects the type of generation technologies installed with optimized capacity. Furthermore, the national demand and export quantities feasible under such policy cases are assessed for a favorable fuel mix.

5.5 Input data

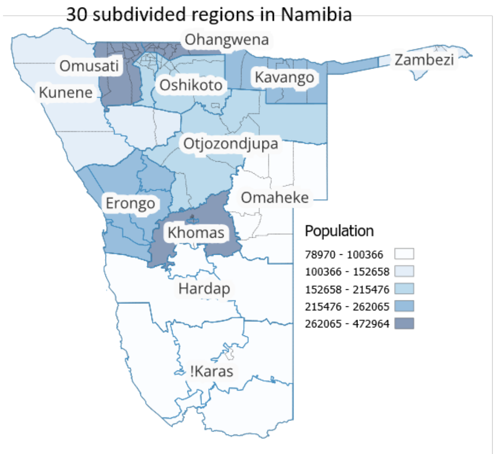
The following section outlines the data used for the energy system optimization to produce and export green hydrogen. The data sources contain open data as well as closed data produced within the Fraunhofer Institute. The sections below provide preliminary insights into the data and validations performed on the open data.

5.5.1 Enertile data: Renewable potential in Namibia

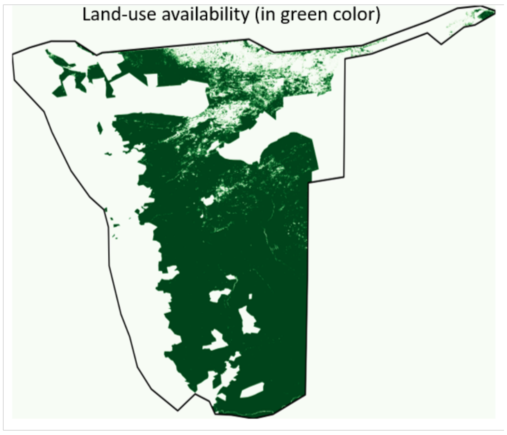
The renewable supply data is availed from Enertile for five different technologies - solar rooftop, solar photovoltaics, concentrated solar power, and offshore/onshore wind (Annex. 8.1). Using ERA5 weather data (Hersbach et al., 2020) and the land-use (GlobCover, 2010), an assessment of the renewable potential for Namibia is performed. The following figures display the renewable potential density over 30 regions of Namibia. It was found that the western and southern regions have a higher wind potential. The western part of the country has a higher solar potential, whereas the region around the capital Windhoek has a higher solar rooftop potential (Fig. 5.3).

5.5.2 LEAP data: Future energy demand in Namibia

Demand data is produced using a low-emission analysis platform (LEAP). The major energy-intensive industries are geographically located from publicly available data. Major production industries are steel, cement, and mining production. Whereas high energy demands are projected for the years 2030 and 2050 in road transport, residential, and agriculture sectors. The energy carrier hydrogen and electricity have

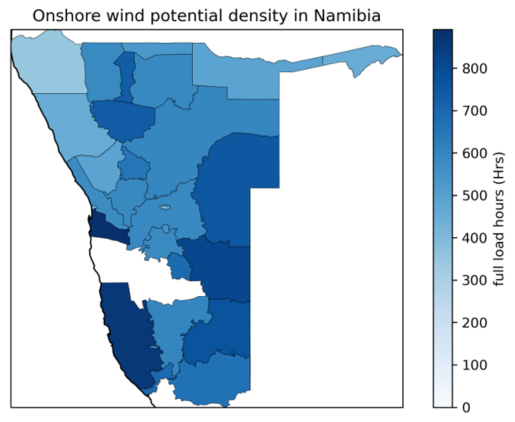


Spatial resolution of 30 regions
Each region is modeled every 3-hours for renewable capacity expansion and hydrogen export potential.

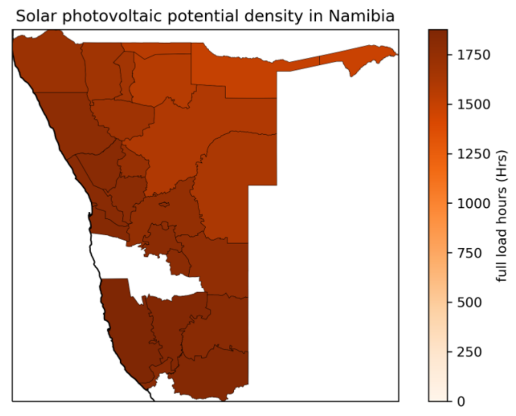


Excluded regions using global dataset
Global 100 m x 100 m raster indicates the type of land-use (forest, urban, industrial).

Fig. 5.3: A high spatial and temporal resolution of Namibia regions was modeled for every 3 hours of the year for renewable potential in 30 regions (left). The land use availability shown on the right depicts the available land for renewable generation in the country. (Own work, Data sources: (GlobCover, 2010; World Bank, 2017))



Onshore wind potential
Western and southern regions have higher wind potential



Solar photovoltaic potential
Western part of the country has higher solar potential

Fig. 5.4: Renewable potential distribution for wind energy in Namibia, excluding land use such as urban areas and protected areas produces the wind potential as shown in the figure (Left). Also, the renewable potential distribution for solar energy in Namibia, taking into account the land-use constraints and country risk profile, the potential is displayed for each region (Right). (Own work, Data sources: (Kleinschmitt et al., n.d.))

increasing demand. Whereas carbon-rich oil and natural gas demand is observed to be declining till 2050 (Annex. 8.1)

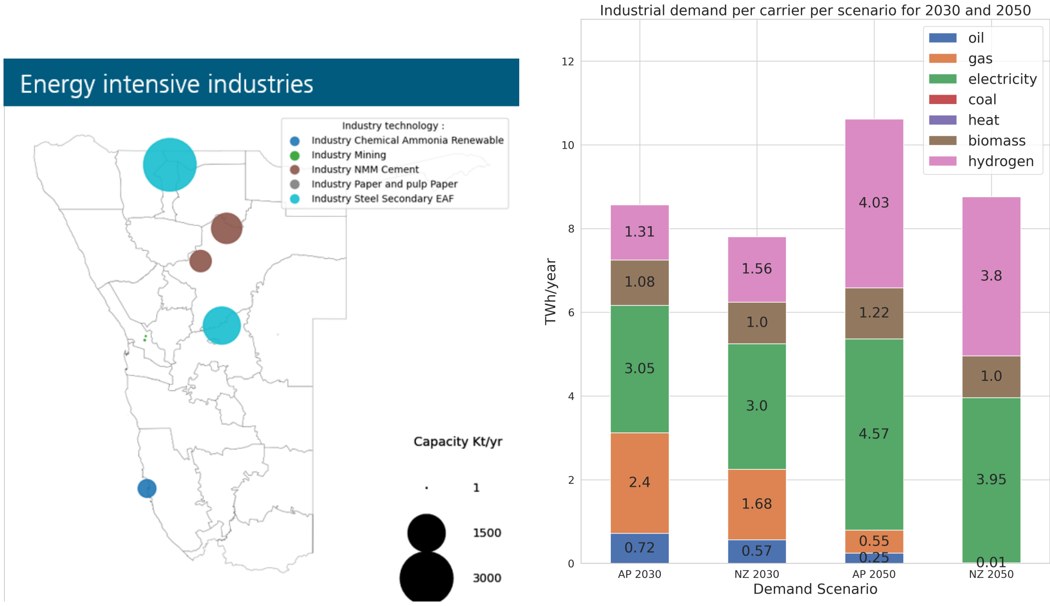


Fig. 5.5: Industrial production capacity and their regional location in Namibia. Cement and Steel are the energy-intensive industries in the country, a pilot project for renewable ammonia is also shown in the figure (Left). The energy demand scenarios for different energy carriers in 2030 and 2050. The demand for hydrogen and electricity demand depicts a positive growth in all scenarios while net-zero by 2050 shows no demand for oil and gas demand replaced with other carriers including biomass (Right). (Own work, Data source: LEAP)

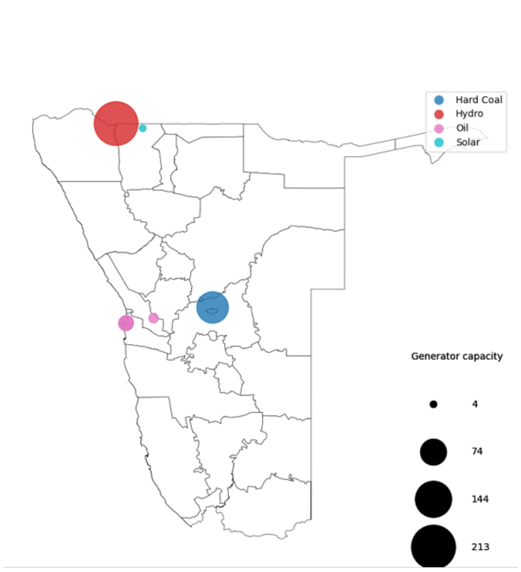
5.5.3 Open source data: energy infrastructure and ports

The optimization model is open-source and utilizes publicly available energy transmission and generation data. To validate, the model data is compared with other widely available data banks such as IRENA, IEA, and World Bank. The existing electricity generator's capacity of 486.5 MW comprises hydro, solar, oil, and gas power. The installed generation capacity is an essential input to the model performing further optimization of generation potential.

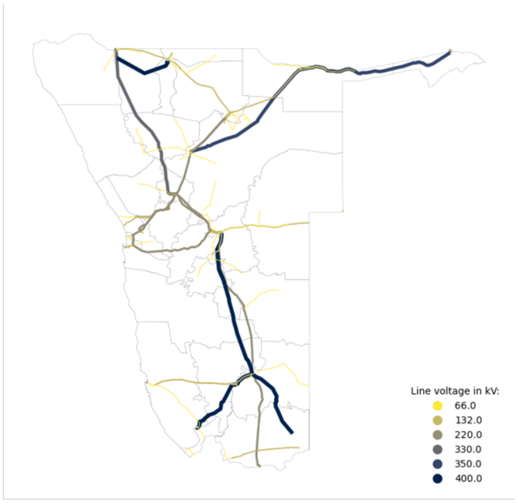
Tab. 5.2: Installed Generator capacity validation in Namibia

Generator	Capacity [MW] (pypsa-earth-sec) [2020]	Capacity [MW] USAID, 2022
Coal	110.63	122
Oil	58.0	41.0
Wind	2.1	7.0
Hydro	213.77	347
Solar	143	163

The power transmission network has a voltage range from 66 – 400 kV. There exists no pipeline infrastructure in the country. The power network lengths and topology validations are the two indicators of Namibia's grid infrastructure. The validated



Existing electricity generators
Total generation capacity of 486.5 MW



Electricity transmission network
Transmission network has voltage range from 66 – 400 kVs. No existing pipeline infrastruture.

Fig. 5.6: Power generators in Namibia with major sources from hydropower and hard coal. Small generation capacities exist for solar as well as oil-powered generators. Imports from other countries are utilized to cover the additional demand in the country (Left). Transmission network in Namibia for power dispatch throughout the country. The future infrastructure expansion of powerlines and pipelines is done along the existing network shown in the figure. Data source: PyPSA-Earth-Sec (Right). Data source: PyPSA-Earth-Sec

power network ensures that the transmission grid lines, especially medium and high voltage are present in the model. The open earth-osm model uses a machine-learning algorithm to detect power infrastructure such as power lines and substations („earth-osm“, 2023). Such complex computations can detect different voltage lines between substations and the number of circuits with high accuracy. As found in the validation performed, network topology contains a transmission network containing 47 substations (out of which 6 are planned) and voltage lines ranging from 66 kV to 400 kV (NamPower, 2021) (figure 5.7 and table 5.3). The total length of the power transmission lines is compared with sources such as the World Bank and NamPower. Each line length is computed in KMs and contains circuit information. The results from PyPSA-Earth are compared against other sources.

Tab. 5.3: Network length validation in Namibia

66kV	132kV	220kV	330kV	350kV	400kV	reference
3676.442	**2429.880**	**3614.401**	**556.226**	**2010.235 (2xcurcuits)**	**1232.067**	**pypsa-earth (clean)**
28053.842	2450.322	3514.743	556.171	1005.062	1103.130	World Bank, 2017
3575.000	2264.000	3207.000	522.000	953.000	1179.000	NamPower, 2021

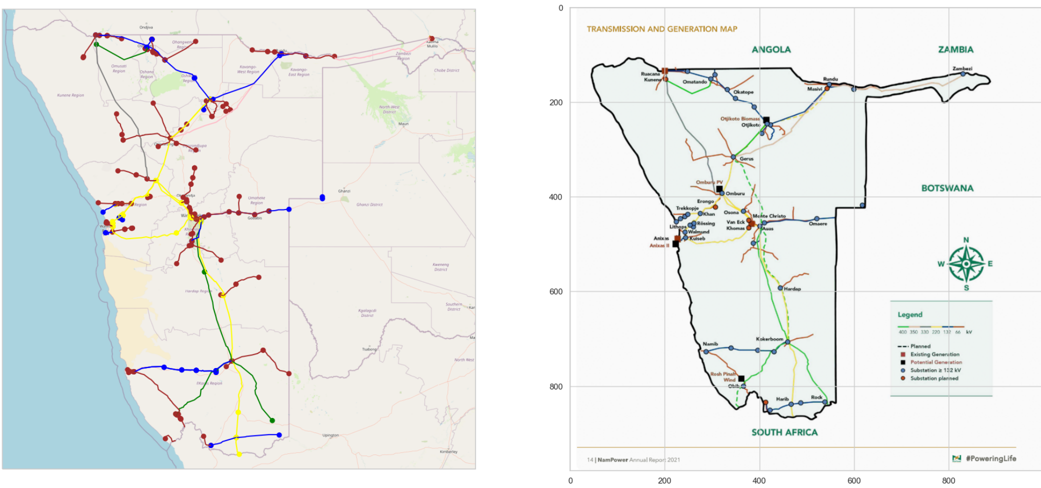
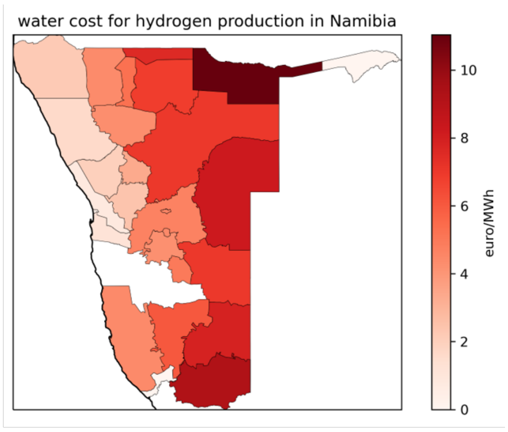


Fig. 5.7: The open data of transmission infrastructure is validated with a local data source - the power utility company of Namibia known as NamPower (right). PyPSA uses open street map data and image processing algorithms to find the powerline and substations attached to it (left). Data source: PyPSA-Earth, (NamPower, 2021)

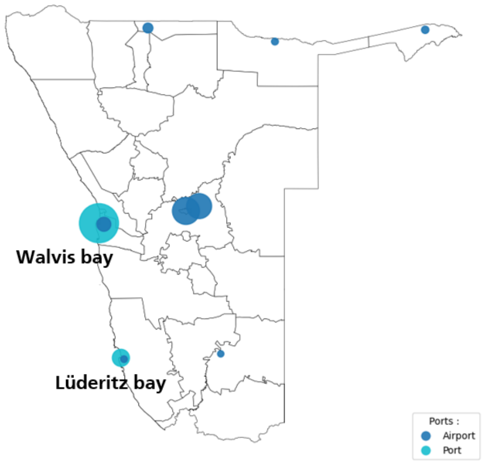
5.5.4 H2ProSim data: Water costs and export ports

Finally, the water cost to generate green hydrogen and export locations to transport to Germany are provided by H2Prosim. Summarized in figure 6.3, the water cost for hydrogen production is lower in the regions close to the ocean. The two major ports Lüderitz Bay and Walvis Bay are the designated locations for green hydrogen export from Namibia to Germany.

The following chapter 6 will evaluate the results found in the above-described data and scenarios. Further risk assessment using sensitivity analysis is performed to discuss the viability of real-world applications and better policy recommendations.



Water cost
The water cost for hydrogen production is lower in the regions close to the ocean.



Ports for potential export locations
Two major ports Lüderitz bay and Walvis bay are possible locations of green hydrogen export

Fig. 5.8: Shows the cost of water for green hydrogen production in Namibia. It serves as an annual marginal cost in operating the electrolyzer. Regions with lower costs are ideal locations to install such electrolyzers (Left). Shows the airports and ports located in Namibia. The size of circular patches defines the relative capacity of each port. The ports in the western part of the country are selected as export hubs for green hydrogen and PtX production. Data source: H2ProSim

Results and Discussion

6

> ❞ *Given that Namibia has more than 60 % of its electricity imported from neighboring countries, the system will need investments in generation capacities as well as infrastructure expansion to achieve self-sufficiency and climate goals.*
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6.1 Key Results

With the objective of finding the opportunities and risks associated with green hydrogen export from Namibia, the following evaluation is presented with key results, comparative and sensitivity analysis. The energy system is established for three scenarios containing infrastructure components such as generators, transmission lines, and hydrogen pipelines clustered into 30 regions and modeled for each region every 3 hours of the year giving it a high spatial and temporal resolution. Furthermore, the network is prepared for industry, transport, and heat demand coupled together to form a sector-coupled model. The optimization constraints are utilized to resolve the objective of minimizing the capital and marginal cost while exporting a green hydrogen quantity volume of 1 to 200 TWh. These constraints range from limited infrastructure expansion to carbon emission limits, and other parameters in the model are the country's interest rate. The following sections elaborate on the optimized network reflecting the required infrastructure developments, the costs of hydrogen, and renewable utilization to produce green hydrogen export quantities. Other supplementary results are available for reference in section 8.

6.1.1 Existing power network in Namibia - potential for future expansions

To optimize Namibia's energy sector, the existing network is utilized as a base for further expansions and infrastructure development. To satisfy the nation's internal demand and then export the excess energy in the form of green hydrogen gas, the renewable potential regions, power plants, and transmission lines are located with their generation capacities. This provides a platform for further expansions and a hydrogen transmission route to dispatch the produced hydrogen fuels using pipelines.

Comprised of 30 regions, the map below (see figure 6.1) displays the electricity generation buses and transmission infrastructure attached to it. The energy network

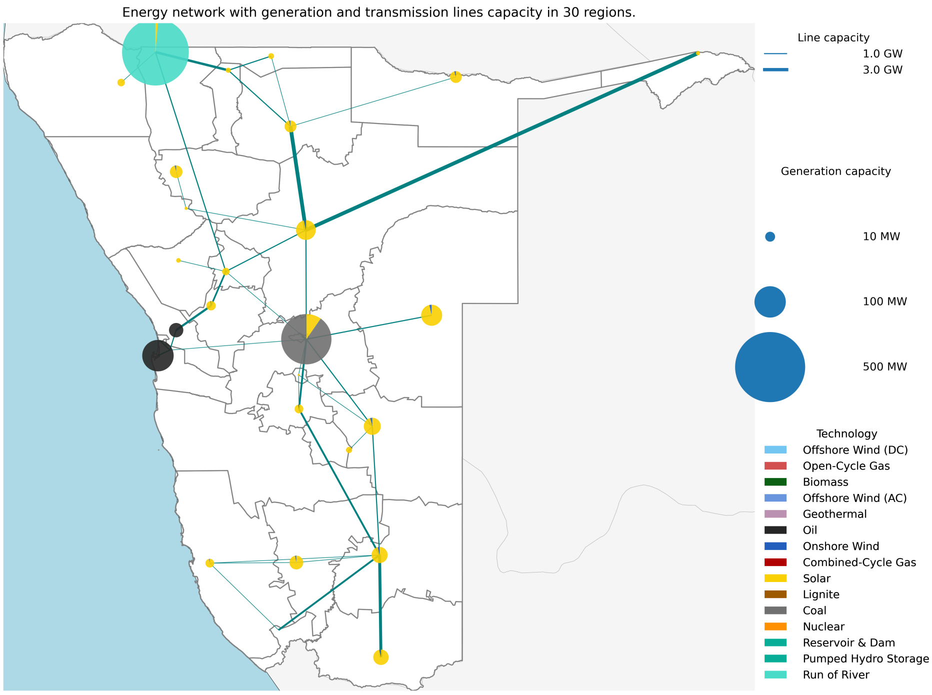

Fig. 6.1: The power sector of Namibia shown above contains generators and transmission lines simplified into 30 regions. Comprised larger capacities of fossil-based fuels and one hydro-power generator while dispersed solar generation capacities with a minimal share of onshore wind technologies. Own work. Data source: PyPSA-Earth-Sec

of Namibia has a high share of solar technologies spread over different regions, it accounts for more than 27% of the total generation share. Given the higher solar potential in the country, solar-related technologies, therefore, have a large part of investment potential. Currently, the highest share belongs to hydropower with more than 40% capacity share in the Omusati region situated in the northern part of the country. Followed by a 32% capacity share of conventional generators comprised of 10% oil-based and the rest of 22% based on hard coal. The least capacity belongs to the onshore wind with a share of less than 1% generation capacity (see table 6.1).

This depicts that the Namibian energy network is largely dependent on fossil-based fuels for one-third of its generation, however, the rest is renewable-based with a higher scope of solar and wind expansion in the near future. The constraint on the optimized cost restricts the expansion of power transmission networks due to the short time scale for the time horizon of 2030. Hydropower is restricted from expansion, as current climate change mitigation strategies and sustainable technologies to produce hydrogen. However, the model allows for hydrogen network expansion along the transmission lines for an optimistic scenario.

Tab. 6.1: Generation technology capacity and their share in Namibia. Data source: PyPSA-Earth-Sec

Technology	Solar	Hydro	Wind	Fossils
Capacity [MW]	144.6	213.77	4.73	168.64
Share %	27.2 %	40.2%	0.9%	31.7%

6.1.2 Generation capacities optimized for green hydrogen exports and national energy demand in 2030

Given that Namibia has more than 60% of its energy imported from neighboring countries, the system will need investments in generation capacities as well as transmission infrastructure expansion to achieve self-sufficiency. Referring to (figure 6.2 and table 6.2), the energy model expects 2.6 - 3.7 GW of solar generation capacity based on the three scenarios - optimistic, realistic, and conservative. The optimistic scenario with allowed hydrogen infrastructure expansion, lower both emission, as well as country risk, has the highest solar capacity expansion along with a minimal share of onshore wind. An additional capacity expansion of 3.7 GW in solar and 130 MW of onshore wind expansion is needed to satisfy the internal energy demand in the optimistic case. The other two scenarios, realistic and conservative, with no

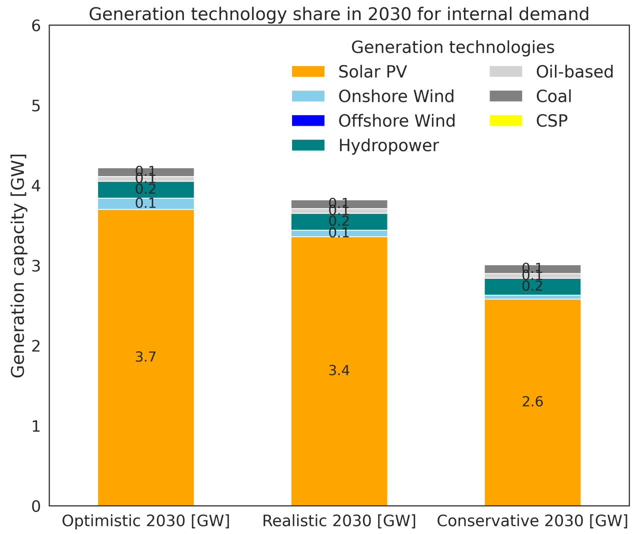

Fig. 6.2: The generation capacities needed for national energy demand in Namibia 2030. Own work. Data source: PyPSA-Earth-Sec

hydrogen network expansion, higher risk, and emission limit have a solar expansion of 2.6 GW albeit a higher expansion of gas-based open-cycle gas turbines (OCGT) of 300 MW. A minute expansion can be observed on the onshore wind in a realistic scenario. Hydropower has no expansion similar to oil and coal-based generators. The technologies used are majorly comprised of solar in all three scenarios. Gas production is significant in the realistic case due to its cheaper cost compared to other renewable technologies. Biogas on the other hand has emerged as a biofuel used for further capacity utilization in the network. The network has a minor share of biomass as well. With an available hydrogen network in the optimistic scenario, up

Tab. 6.2: Generation capacity expansion to satisfy internal demand and to fulfill the climate goals in three scenarios. Data source: PyPSA-Earth-Sec

		solar PV	onshore wind	Hydropower	oil	coal	OCGT
Optimistic 2030	Capacity [GW]	**3.70**	**0.14**	0.21	0.06	0.11	0.00
	Share [%]	64.97	2.42	3.75	1.02	1.94	0.05
	Expansion [GW]	3.56	0.13	0.00	0.00	0.00	0.00
Realistic 2030	Capacity [GW]	3.36	0.08	0.21	0.06	0.11	0.00
	Share [%]	71.25	1.69	4.53	1.23	2.34	0.02
	Expansion [GW]	3.22	0.08	0.00	0.00	0.00	0.00
Conservative 2030	Capacity [GW]	2.58	0.05	0.21	0.06	0.11	**0.33**
	Share [%]	74.94	1.36	6.22	1.69	3.22	9.61
	Expansion [GW]	2.43	0.04	0.00	0.00	0.00	0.33

to 42% of capacity is expanded in comparison to the conservative scenario. similarly, realistic has up to 30% more expansion in renewable technologies. With a higher emission limit in a conservative and realistic scenario (4.76 and 4.3 Mtons of CO2 eq.), gas technologies like OCGT are utilized whereas stricter emission limits need more renewable energy in the system as the case of an optimistic scenario. For national hydrogen demand in 2030 (see figure 6.3), the infrastructure needs in Namibia. The model electrolyzer capacity of less than 1 GW is installed near the western port and connected to other regions in the central and northern parts of the country using pipeline infrastructure of a capacity of less than 0.5 GW. These pipelines dispatch industrial hydrogen demand for steel and cement production.

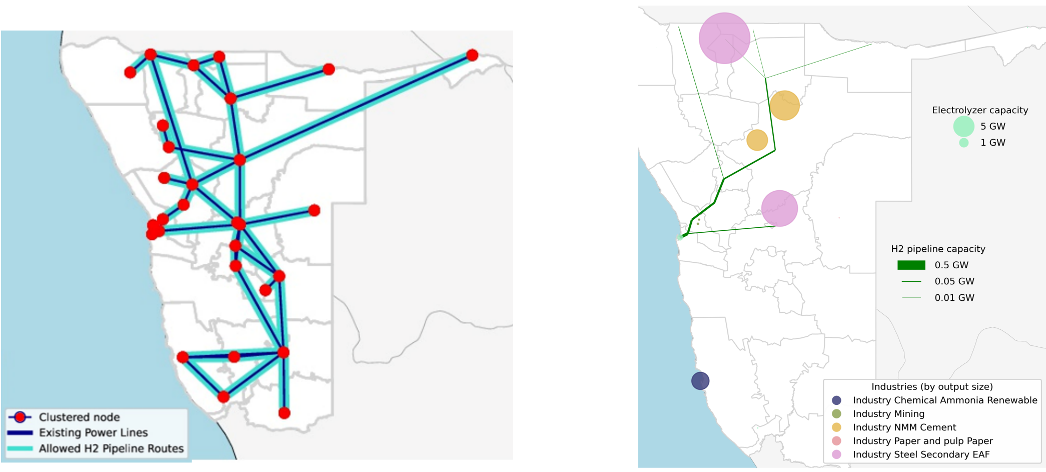

Fig. 6.3: (left) Allowed expansion routes topography in Namibia (right) Green hydrogen infrastructure in Namibia for 2030 for internal demand. The image above shows the hydrogen pipeline network along with electrolyzer capacity (optimistic scenario). These pipelines are connecting other electrolyzer locations and hydrogen demand industries such as steel, cement, etc. Own work. Data source: PyPSA-Earth-Sec

Solar photovoltaic, one of the major contributors to renewable generation with a share of up to 65% in Namibia, is also dominant in the production of green hydrogen using electrolyzers. With five different export quantities of 1, 5, 50, 100, and 200 TWh the additional solar capacity ranges from 1-175 GW. To use the additional capacity for producing green hydrogen, an electrolyzer capacity of 1-100 GW is needed. This capacity is in addition to the earlier determined capacities for internal demand. All three scenarios have similar capacities installed in export quantities with minimal difference (see figure 6.4).

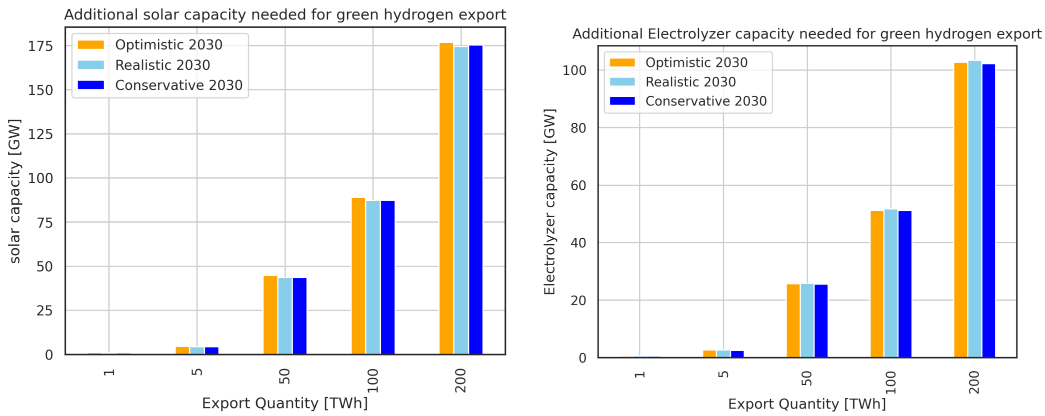

Fig. 6.4: Additional solar capacity (left) and electrolyzer capacity (right) are needed to support different export quantities of green hydrogen in Namibia in 2030. The scenario parameters have minimal effect on the expansion needed as shown in the images above. Own work. Data source: PyPSA-Earth-Sec

Tab. 6.3: Hydrogen infrastructure expansion (GW) in 2030 for national demand as well as export quantities of 1-200 TWh including national demand. Data source: PyPSA-Earth-Sec

Scenario	Hydrogen infrastructure component	National demand (ND)	ND + Export 1TWh	ND + Export 5 TWh	ND + Export 50 TWh	ND + Export 100 TWh	ND + Export 200 TWh
Optimistic	*H2 Electrolysis*	**0.73**	**1.30**	**3.37**	26.42	52.00	103.45
	H2 pipeline	0.80	0.92	1.9	20.47	31.96	36.40
Realistic	*H2 Electrolysis*	0.58	1.16	3.2	**26.47**	**52.28**	**103.98**
Conservative	*H2 Electrolysis*	0.56	1.12	3.08	26.17	51.72	102.83

Looking at the optimistic scenario (see figure 6.5), where the hydrogen network is expanded using pipelines, the electrolyzer capacities are plotted over the geographical locations in Namibia. The pipeline network is concentrated on the export locations in the western part extending outwards to other regions of the country. Walvis Bay is the largest port and export location with a higher electrolyzer capacity of up to 25 GW connected together with newly constructed pipelines to export 100 TWh of green hydrogen. For other quantities, both export locations (including Lüderitz Bay) have on-site electrolyzer locations with a capacity of up to 50 GW each. For each of the export quantities, the utilization of renewable technologies is analyzed as shown in figure 6.6. As solar technologies have higher utilization of up to 20%, it serves as the prime source of electricity for the operation of the electrolyzers. The electrolyzers used for the production of hydrogen have similar utilization (33%)

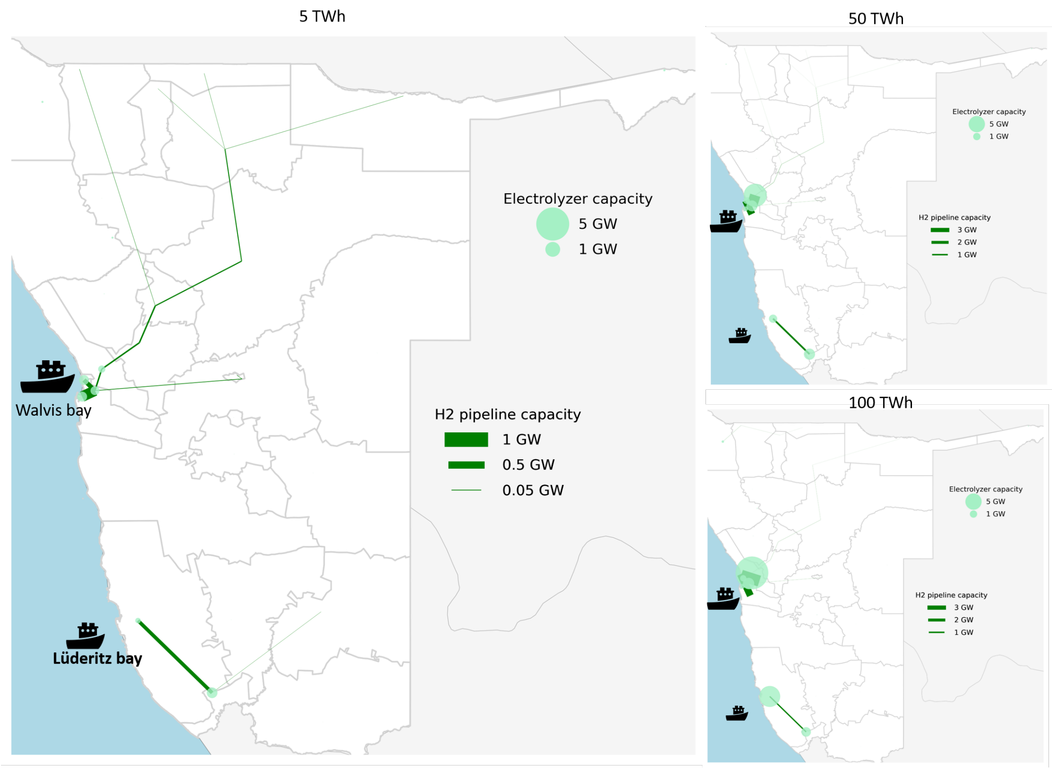

Fig. 6.5: Electrolyser and pipeline capacity for export quantity of 5 TWh (left) 50 and 100 TWh (right). Own work. Data source: PyPSA-Earth-Sec

compared to the ones at the export locations. The solar utilization at the export node is lower than that of the electrolyzer potential in terms of full load hours. To compensate for the electricity deficit, it utilizes electricity from other regions for green hydrogen production at higher export quantities. This shows an advantage of an integrated system over an island system with no grid connectivity for green hydrogen production.

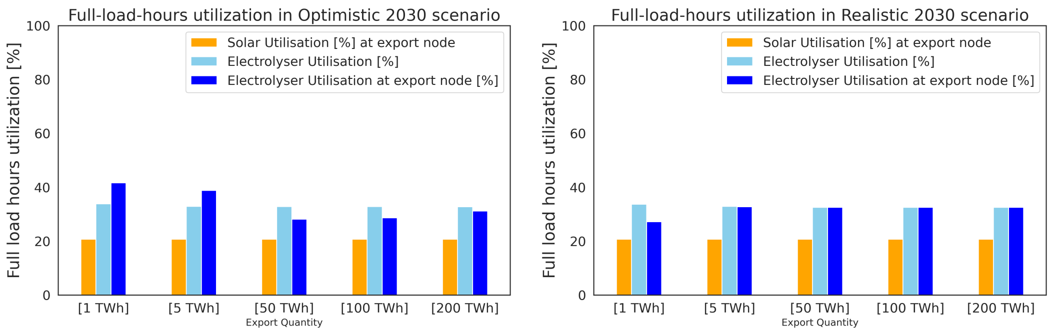

Fig. 6.6: Renewable Utilization for the hydrogen export in Namibia 2030. Displaying the characteristics of an integrated system by utilization of electricity to operate on full load hours despite limited availability at the export location. Own work. data source: PyPSA-Earth-Sec

6.1.3 System cost per technology for green hydrogen export including national demand in 2030

As observed earlier, the generation expansion of solar technologies dominates the energy system in 2030. Similar findings in figure 6.7, where this makes the capital cost share for solar 130 to 190 Million euros per year, comprising on average 68% of the total cost share. Followed by battery storage, for solar PV generation stability, with a capital cost of 40-60 million euros per year. It has 23% of the cost share compared to all other technologies. A small portion of the investment (7%) is allocated to onshore wind technologies making a capital cost of 20 million euros per year. Other technologies such as power-to-gas have a small share of 10 million euros comprised of 5% of the total cost.

Namibia has a large share of road transport oil demand in 2030 9 TWh (45% of total demand), which makes the marginal cost comprised mainly of oil stores. The 86% share of marginal cost (0.64-0.69 billion euros per year) for oil share. For industrial processes, the energy demand is satisfied with the usage of solid biomass holding 5% of the marginal cost of 40 million euros per annum. The rest of the costs include coal and gas with a yearly marginal cost of 30-50 million euros (2-4%) respectively.

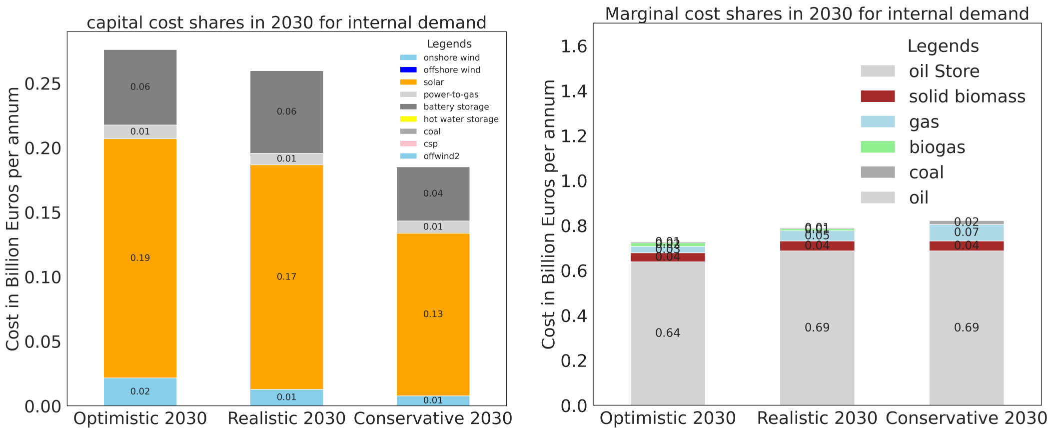

Fig. 6.7: The capital cost of energy network expansion for three scenarios (left) and Marginal cost components comprised of various energy carriers for the internal energy demand of Namibia (right). Own work. Data source: PyPSA-Earth-Sec

Keeping the hydrogen demand of 90 - 110 TWh in Germany for 2030 as a reference, the export quantity of 100 TWh from Namibia will have a total system cost range from 8.7 to 9.4 billion euros per year for three scenarios. The system cost comprises capital and marginal cost for expansions of energy generation and storage infrastructure. In a realistic scenario, these costs are 83% higher than the cost needed for satisfying the internal energy demand of Namibia at 1.11 billion euros per year. The cost constituents are investments needed in solar technologies primarily photovoltaic, hydrogen production, and storage technologies as well as energy carriers like oil into marginal costs. For 100 TWh export quantity, solar photovoltaics has 52.3% of the share in the investments followed by 37.6% investments in hydrogen production with electrolysis and storage technologies. The rest of the investments are done in the marginal costs for fuel such as biomass, oil, or gas. Comparison of three

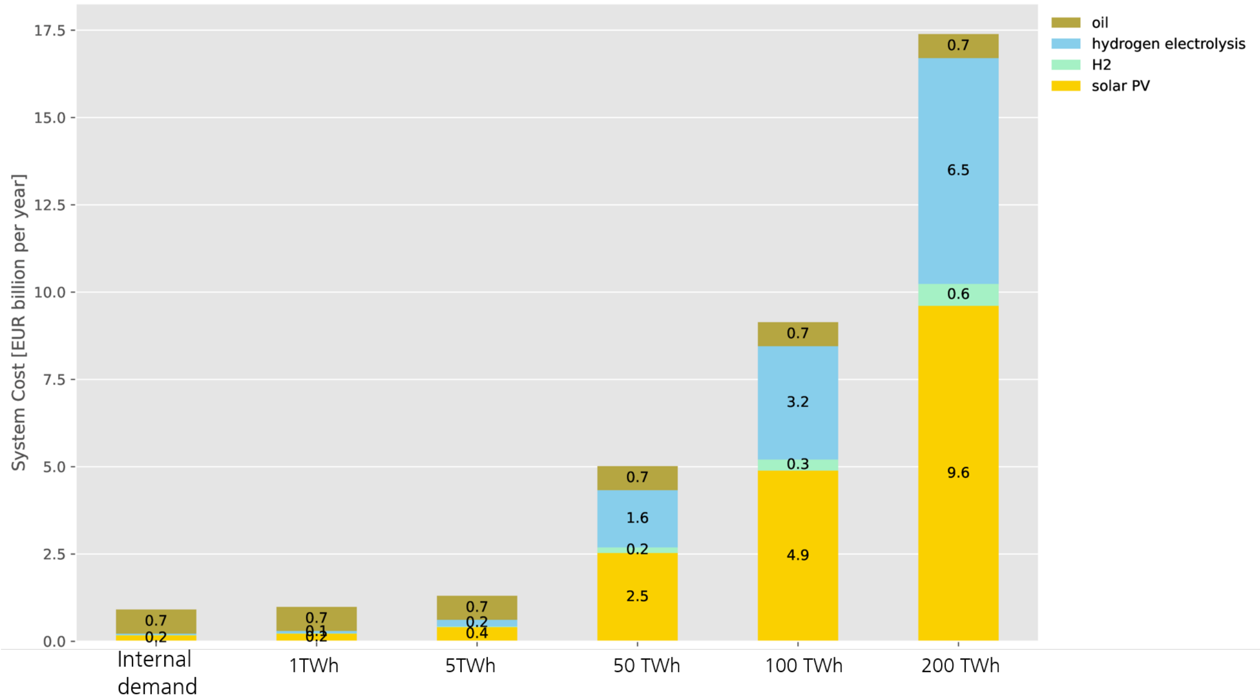

Fig. 6.8: System cost and technologies utilized in the energy system of Namibia in 2030. Own work. Data source: PyPSA-Earth-Sec

scenarios - optimistic, realistic, and conservative is described for the export quantity of 5 TWh and 200 TWh (see figure 6.8). The optimized system cost of the energy system in different locations ranges from fewer than 1 billion euros to 6 billion euros per year.

However, as shown in the figure 6.9 the major investments are located in the vicinity of the export location - the Walvis Bay and Lüderitz Bay port regions in the western part of the country. Due to the presence of hydrogen network pipelines in the optimistic scenario, the generation technologies such as solar and power-to-gas are located in the higher renewable potential rather than at the export location. This gives the system flexibility to invest in diverse regions and collect the final green hydrogen production using available network pipelines. In the conservative and realistic scenario, the investments are concentrated toward the southern part of the coastal region, mainly near Lüderitz port. Here the electrolyzers and generation capacities are placed together due to higher renewable potential and lack of a pipeline network to transport green hydrogen.

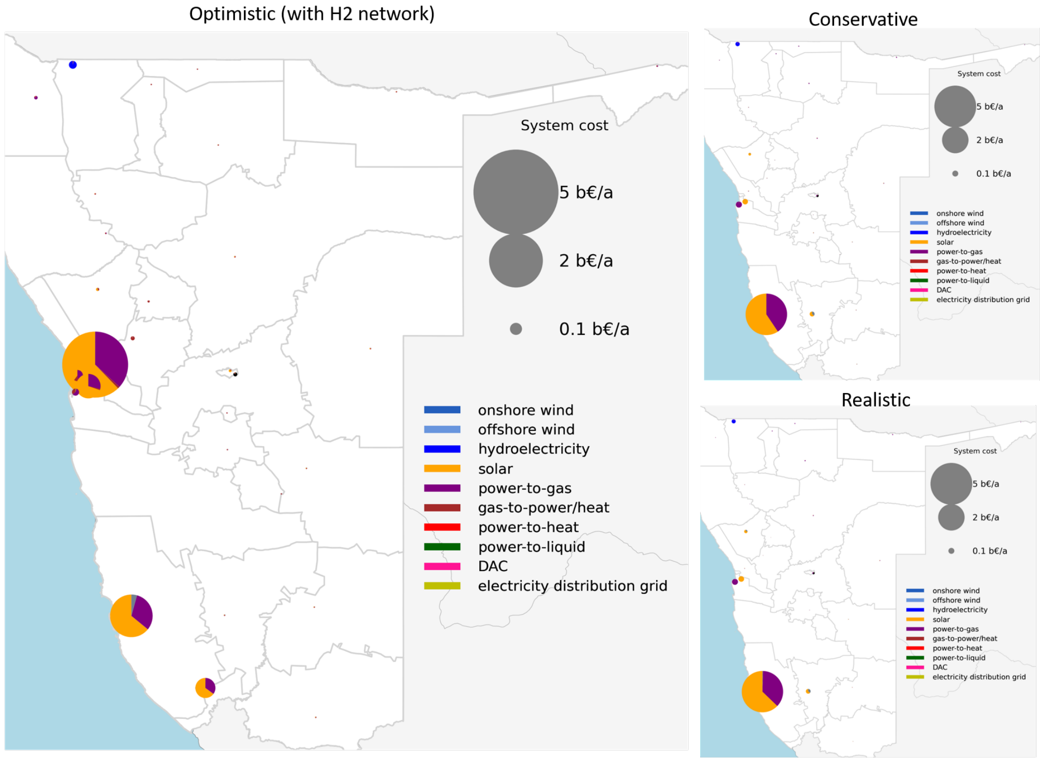

Fig. 6.9: System cost per year per technology in the energy system of Namibia to export 100 TWh worth of green hydrogen. Own work. Data source: PyPSA-Earth-Sec

6.1.4 Normalized cost of a unit of hydrogen at the export location

The normalized cost of hydrogen is the total system cost to produce one kilogram of green hydrogen. This excludes the cost of storage and compression at the export location and the transportation cost to the import hub. The normalized cost measured in euros per kilogram (€/kg) is comprised of capital cost and the marginal cost of the system. The system is made of renewable generation capacity expansion, hydrogen production as well as storage cost at the electrolyzer location along with hydrogen pipeline infrastructure to transport to the export locations. The normalized cost is extracted for quantities of 1, 5, 50, 100, and 200 TWh normalized to a kilogram of hydrogen assuming 33.33 KWh of usable energy can be extracted from 1 kg of hydrogen (H2data, n.d.).

Figure 6.14 displays the unit normalized cost of hydrogen for export quantities ranging from 1 to 200 TWh. The conservative scenario with a high investment risk premium, low emission, and no hydrogen infrastructure has the highest cost, while the lower cost of as small as 1.68 €/kg is found in the optimistic scenario for 1 TWh export. The realistic scenario has a cost premium of 1.94 €/kg for the same quantity. It can be observed that the cost curves show a lower cost for all export quantities in the optimistic scenario compared to others. It is due to the low-interest rate on investments, high emission allowance, and a hydrogen pipeline infrastructure.

Overall the cost ranges between 1.68 - 2.79 €/kg at the export locations of Lüderitz and Walvis Bay regions 6.4. The higher costs appear and level themselves when the model is pushed to export extremely large quantities. Smaller quantities of 5 - 50 TWh have a visible cost difference that can bring economic value to Namibia, if opted to export in similar conditions.

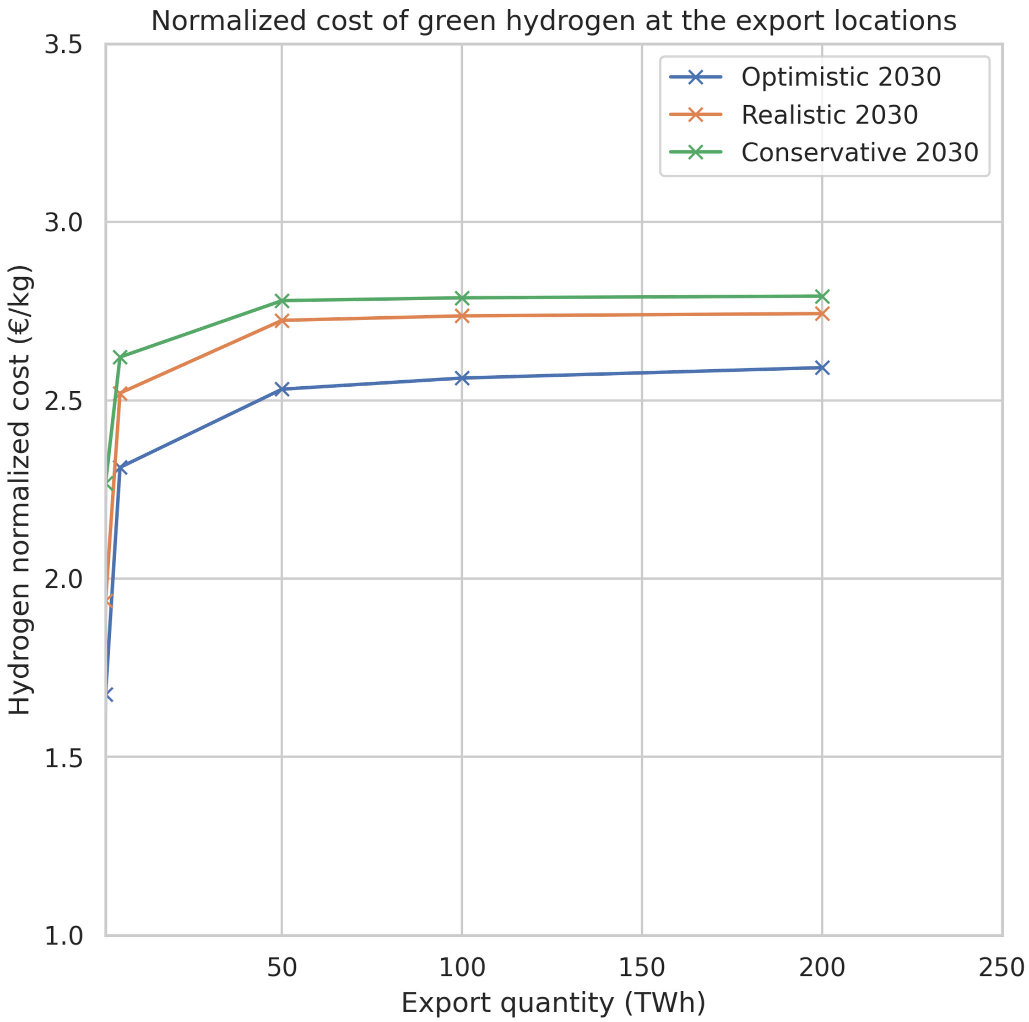

Fig. 6.10: The normalized hydrogen cost curve for export quantities of 1-200 TWh in Namibia for 2030. Own work. Data source: PyPSA-Earth-Sec

Tab. 6.4: Normalized cost of green hydrogen at the export locations (€/ kg). Data source: PyPSA-Earth-Sec

Scenario / Quantity	**1 TWh**	**5 TWh**	**50 TWh**	**100 TWh**	**200 TWh**
Optimistic 2030 [€/kg]	**1.68**	2.31	2.53	2.56	2.59
Realistic 2030 [€/kg]	1.94	2.52	2.72	2.74	2.74
Conservative 2030 [€/kg]	2.27	2.62	2.78	2.79	**2.79**

6.2 Risk Assessment in 2030: Sensitivity and Comparative Analysis:

The previous section provided a comprehensive analysis instrumenting three scenarios of the generation capacity expansion and investments needed for national demand as well as green hydrogen export. To explore the energy system in real-world conditions and assess the indicators such as system cost, normalized cost, and necessary infrastructure expansion. Hereafter, we look into the risk assessment of the green hydrogen economy in Namibia in a realistic scenario using sensitivity analysis of hydrogen network expansion. Along with, a comparative analysis to introduce blue and gray hydrogen in the system and how it affects the system cost and expansions needed. Furthermore, we look into whether producing hydrogen independent of origin sources (renewable or non-renewable) has a major impact on the energy system of Namibia.

6.2.1 Rapid expansion of the hydrogen network in Namibia

Namibia has no existing natural gas pipelines that take the re-purpose of existing pipelines for hydrogen transport out of the scope. Hence, in order to put investments in hydrogen network expansion, it is essential to analyze the effect of hydrogen pipeline infrastructure development on overall system cost and the normalized cost of hydrogen export in 2030. To do this, the energy system model optimizes the system cost for three different hydrogen pipeline capacity-length constraints of 750, 1500, and 2250 GWKm. The system costs are then compared for each export quantity as well as the normalized cost of hydrogen export. Expansion of the hydrogen pipeline increases the flexibility of the electrolyzer location. The electrolyzer capacities can be diversified into several locations where higher renewable generation potential and energy-intensive industries are located. Figure 6.11 schematically displays the electrolyzer locations with inherent capacity marked with a green circle, these capacities are connected together through pipelines of capacity ranging from a total of 750, 1500, and 2250 GWKm. Largen diversification of electrolyzer capacities are seen in higher capacity length whereas, on the lower end, capacities are clustered densely together in locations close to the export hub. Therefore, rapid expansion has clearly spread the technologies over the regions of Namibia inherently distributing the investment costs.

As displayed in the figure 6.12, the network length has no effect on the national demand (export quantity 0 TWh) in terms of the system cost. This essentially means that the nation's energy demand can be satisfied without any hydrogen pipeline infrastructure. The system takes care of the demand by installing electrolyzers near the demand sectors to avoid transportation via pipelines. Whereas for lower export quantities of 1-50 TWh, the network length of up to 750 GWKm decreases the cost by

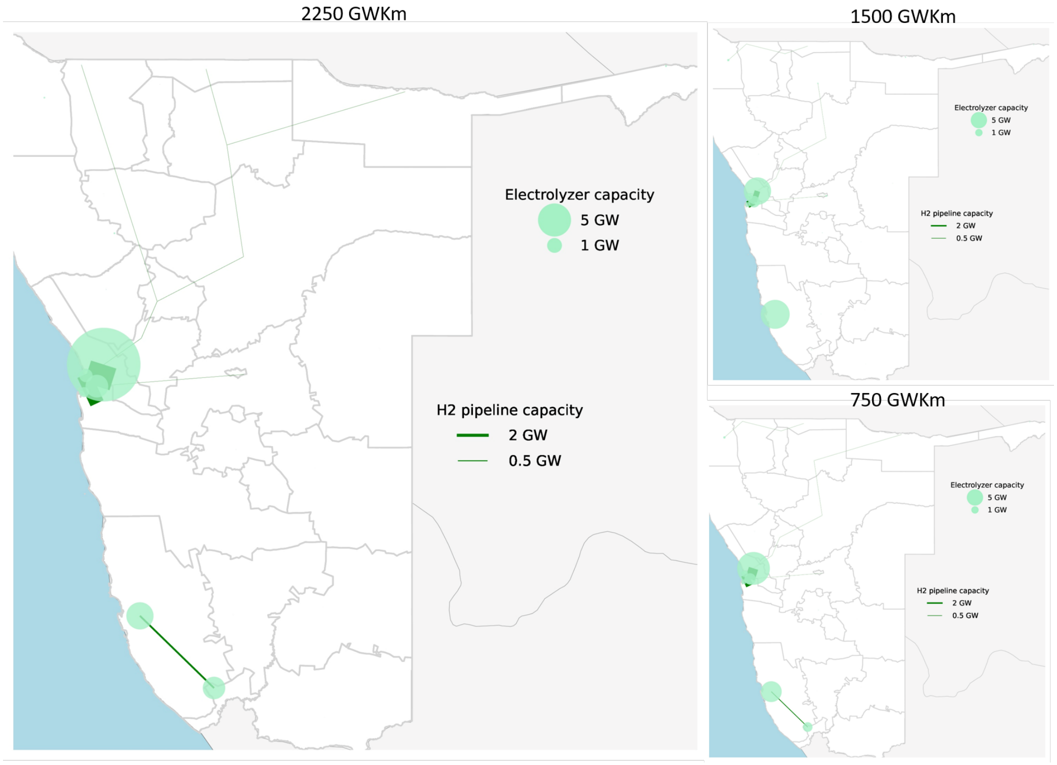

Fig. 6.11: The hydrogen infrastructure capacity includes electrolyzers and pipelines for a network length of 2250 GWKm (left), 1500 GWKm (right-top), and 750 GWKm (right-bottom). The infrastructure is scattered across the country and connected through pipelines for utilization at the source of demand and higher renewable generation potential. Own work. Data source: PyPSA-Earth-Sec

up to 1.8%. For higher export quantities of 100 and 200 TWh, the effect of network expansion is quite positive, which means that the system cost keeps decreasing with higher network limits. Although for smaller quantities the higher network lengths of 1500 and 2250 GWKm has minimal cost benefit. The overall cost benefit in 100 and 200 TWh for network expansion up to 2250 GWKm is 0.23 billion and 0.33 billion euros respectively. Despite having close to real results, the model sometimes displays inexplicable results. In the particular case of 5TWh export, the model displays abnormality in the results where the cost arises in the case of network length 2250 GWKm.

As a further elaboration, the normalized cost of green hydrogen export (euro/kg) in Namibia has a significant change due to the network expansion (see figure 6.13). Especially for the higher export quantities, the higher costs are clustered near the lower expansion (represented with the red color grid). The cost becomes lower as the network is expanded toward larger lengths of pipelines (green color grid). The lower export quantities, however, have the least response to the network expansion as also found earlier in the plots above. The normalized cost values range from 1.90 to 2.74 euro per kg, with the lowest value in the highest expansion limit of capacity

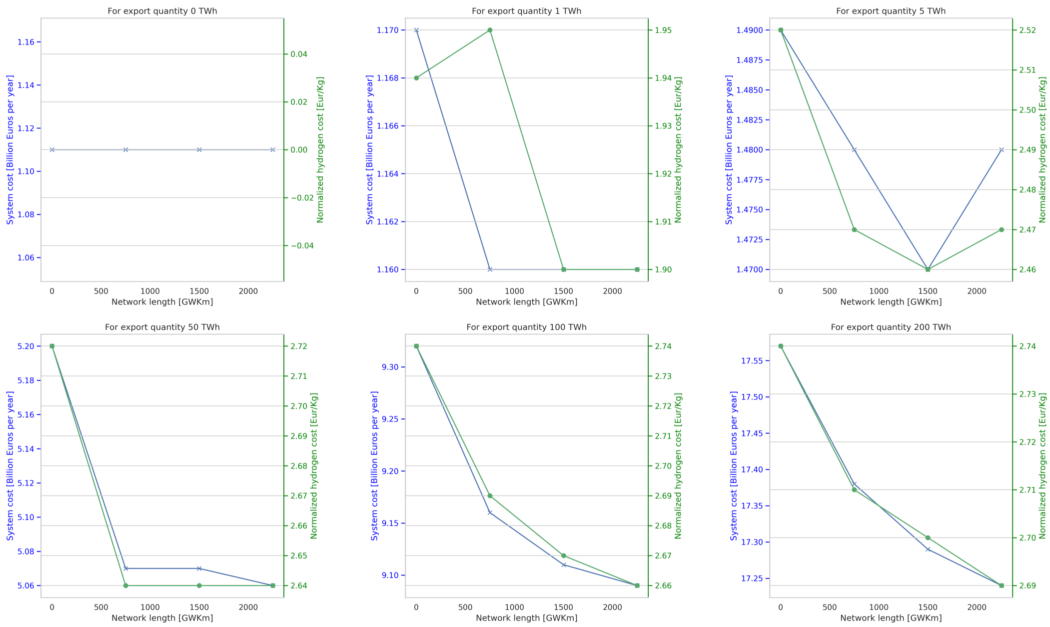

Fig. 6.12: The sensitivity analysis curves for export quantities display the system cost and normalized hydrogen cost for different hydrogen network expansion limits. Significant cost benefit is observed in higher export quantities. Own work. Data source: PyPSA-Earth-Sec

length. Moreover, the normalized cost keeps decreasing with increased length, while having a maximum cost premium per kilogram in the absence of any expansion. Maximum cost-benefit can be reaped in between the export quantity of 5-50 TWh with the expansion of 750 to 1500 GWKm.

Export Quantity [TWh]	Network Length constraint [GWKm]			
	0	750	1500	2250
1	1.94	1.95	1.9	1.9
5	2.52	2.47	2.46	2.47
50	2.72	2.64	2.64	2.64
100	2.74	2.69	2.67	2.66
200	2.74	2.71	2.7	2.69

Fig. 6.13: The colored grid table displays normalized green hydrogen cost (Euro/Kg)) for export quantities and hydrogen network expansion. The green and red signifies the lowest and highest costs respectively with intermediate values lying on the gradient. Own work. Data source: PyPSA-Earth-Sec

6.2.2 Strict green hydrogen policy vs national climate goal

The climate goals are essential criteria for the sustainable production of green hydrogen export. In terms of emission limits in 2030 of greenhouse gases Mt (Megatons CO2 eq.), the usage of fossil technologies is repressed. Realistically, the emission limit of 4.3 Mt for Namibia is the mean value of 2019 greenhouse emissions at 4.76 Mt and emissions of 3.9 Mt from the energy sector in 2030.

The strict policies where the system ensures the monthly production of hydrogen is based on renewable fuels of non-biological origin (RFNBO), the system cost, and the normalized cost is shown below (see table 6.5). For smaller export of 1 TWh, the system cost is 0.06% higher than the lenient policies where Namibia's own climate goals are respected till 2030. Also, the normalized cost of hydrogen export cost for 1 TWh hydrogen quantity is 1.5% higher in the case of a strict policy. However, for higher export quantities, the cost remains similar in both cases. This is due to the emission limit set, which forces the energy system to invest in fuels of non-biological origin, independent of the policy set (see figure 6.14).

Namibia has a high share of solar full-load-hours over a year with minimal seasonal variation. This ensures year-long renewable generations to power the electrolyzers for hydrogen production. The monthly matching of hydrogen policy thus has a minimal effect on total system cost unlike in countries with high seasonal variability of renewable resources.

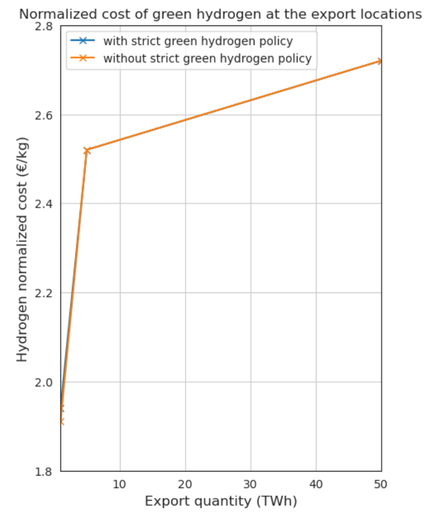

Fig. 6.14: The normalized hydrogen cost curve in strict hydrogen policy, and achieving climate goal of Namibia to export quantities of 1-50 TWh for 2030. The policy only affects the cost in a lower quantity of 1 TWh. data source: PyPSA-Earth-sec

Tab. 6.5: System cost of infrastructure expansion and normalized cost of unit hydrogen for export in five export quantities. data source: PyPSA-Earth-Sec

Scenario / Export Quantity TWh	1	5	50	100	200
With strict green hydrogen policy (total system cost [€{]}	1.171761e+09	1.491652e+09	5.200204e+09	9.324425e+09	1.757357e+10
With strict green hydrogen policy (hydrogen normalized cost [€/kg])	1.94	2.52	2.72	2.74	2.74
Without strict green hydrogen policy (total system cost[€])	1.171055e+09	1.492242e+09	5.201043e+09	9.324489e+09	1.757604e+10
Without strict green hydrogen policy (hydrogen normalized cost [€/kg])	1.91	2.52	2.72	2.74	2.74

6.2.3 Grey and blue hydrogen production in the energy system

As shown in table 6.6 and figure 6.15, the system utilizes a set emission limit for the usage of fossils in the system and invests in low-emission technologies for electricity generation. For hydrogen production using electrolysis or steam methane reforming (SMR) with carbon capture (CC) technologies. Depending on the production method the hydrogen fuel from electrolysis powered with renewable electricity is called green, the grey hydrogen is produced using a method of steam methane reforming, adding carbon capture termed the fuel blue. The system expansion cost is around 0.6% lower in the production of mixed fuel for all export quantities. However, major investments are allocated to solar generation and electrolysis technology. It can also be observed that in higher export quantities, system investments are higher in biogas - mostly composed of methane, which can be used to produce hydrogen using steam methane reforming, leading to increased investment in SMR technologies. Due to the investments in such technologies, the total system cost goes down compared to a system where only electrolysis is the preferred mode of hydrogen production.

Tab. 6.6: System cost of infrastructure expansion and normalized cost of unit hydrogen for export in five export quantities. data source: PyPSA-Earth-Sec

Export Quantity [TWh]	1	5	50	100	200
H2 with allowed SMR and SMR with CC (total system cost [€])	1.164232e+09	1.481080e+09	5.172592e+09	9.274294e+09	1.747671e+10
H2 with only Electrolysis (total system cost [€])	1.171761e+09	1.491652e+09	5.200204e+09	9.324425e+09	1.757357e+10

In the energy system with allowed investments in SMR technologies are allowed, the share of SMR is higher in the national energy supply of hydrogen with 27.7% and a minute share of 0.06% of SMR with carbon capture (CC) technologies. Namibia has no potential for carbon storage technologies in 2030. Hence, the captured carbon is utilized at the site for carbon feedstock technologies such as Fischer-Tropsch-Synthesis. This makes SMR CC an expensive technology for the system to implement. The SMR share decreases from 13.88% to 9.05% for export quantities of 1 to 200 TWh respectively. This depicts that the system favors electrolysis as the preferred 80% for hydrogen production with the least share of SMR and with carbon capture technologies (see figure 6.15 - right).

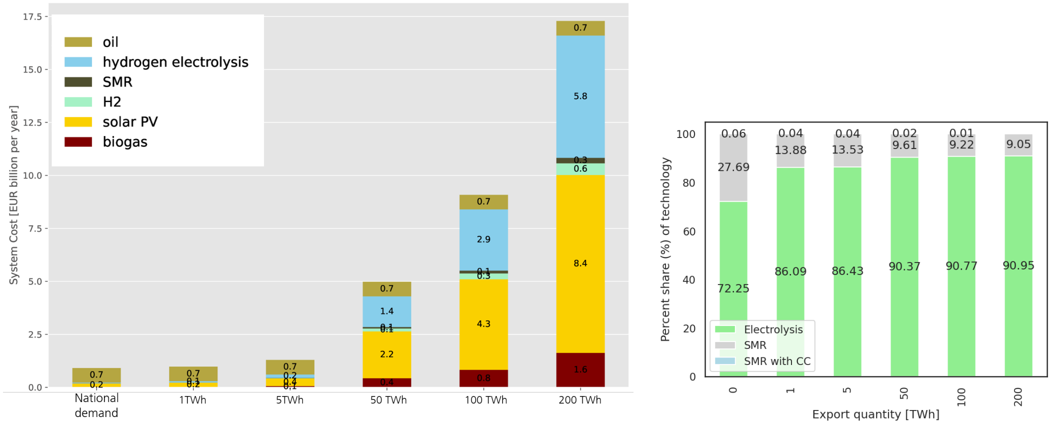

Fig. 6.15: Technology share in total system cost of expansions (left) and composition of hydrogen technology share in the case of allowed steam methane reforming (SMR) (right) for export quantities of 1-200 TWh in Namibia for a time horizon of 2030. Majorly composed of electrolysis the cost of green hydrogen is composed of investments in solar photovoltaics and electrolysis with a minute share of biogas and SMR. (Own work, Data source: PyPSA-Earth-Sec)

6.3 Discussion

- **Reduce electricity import with renewable expansion and industry decarbonization**: In 2021, Namibia imported 60% of its electricity from neighboring countries, out of which 55% is for commercial processes. With high renewable potential in the country, renewable generation capacities can be utilized to achieve the nation's demand with local sources. Expanding the renewable generation capacities up to 3.56 GW of solar technology accompanied optionally by gas generation can annihilate the dependence on imported energy. A slight expansion of onshore wind in the system is also favored as Namibia has better wind generation potential.

  Namibia has an ambitious climate goal, with a goal of decarbonizing up to 93% of its current GHG emission (the majority from Land use change and Forestry). Whereas, in the energy sector, the goal to decarbonize the energy sector has a limit set up to 4.3 Megatonnes per year. The current dependence on fossils generation with a share of 32% can be replaced in the long run with other energy carriers such as electricity from renewable sources or hydrogen generated from electrolysis for industrial processes in major industries of Namibia such as cement and steel. With an electrolyzer capacity of 0.73 GW, Namibia can fulfill its hydrogen demand in 2030. Complimented with a new pipeline infrastructure of a capacity of 0.80 GW, the industrial hydrogen demand in the northern part of the country can be transported using the network (see Fig. 6.3).

In terms of investments necessary to achieve self-sufficiency and the climate goals of Namibia by 2030, the major investment shares of 73% in solar technologies along with battery storage (21%) and power-to-gas technologies (6%). To fulfill the national demand for oil in the transport sector which contributes as the highest demand sector in the country investments up to 86% of the total marginal costs. The investment project such as 50 dual-fuel locomotives in Walvis Bay-Kranzbeg corridor (Rigava, 2022d) however provides an opportunity to reduce such the oil share in the costs. The investments are concentrated in the western part of the country in the vicinity of the export location namely Walvis Bay and Lüderitz Bay. The surrounding regions are interconnected with the existing power transmission infrastructure and newly constructed hydrogen pipelines to diversify the investments for an integrated system. However, for the sensitivity analysis, it was determined that the hydrogen network expansion has a minute impact on the system cost. This means that the national energy demand can be achieved without any investments in pipeline infrastructure.

- **Investment opportunities in resonance with project developments in Namibia**: The total investment of 2.2 billion euros from international partnerships, especially from European countries such as Germany and the Netherlands is established for Namibia. Institutions such as the German Agency for international cooperation (GIZ), the Federal Ministry of Education and Research (BMBF), and the Dutch Development Bank directed the research and investment platform to develop the hydrogen economy of Namibia (BMBF, 2021a; giz, 2022; Silo & Redactie, 2022). Existing hydrogen-related project activities are valued at 9.26 billion Euros to produce green hydrogen fuel and ammonia in the western part of the country (Rigava, 2022a, 2022b, 2022c, 2022d, 2022e). 4 out of these 5 projects are proposed to be situated close to the Walbis Bay region with a combined infrastructure of 10 MW electrolyzer capacity, 50 dual-fuel (hydrogen-diesel) locomotives, and 350 Ktons of green ammonia production plant. The other project named Hyphen SCDI, one of the largest projects in terms of area (4000 Km sq.) and investment values (8.7 billion euros), is situated close to the Lüderitz Bay region. These activities reflect the national stance as well as global interest in establishing a future hydrogen economy in Namibia.

The energy system model findings have infrastructure expansions and investments allocated in similar regions where the projects mentioned above are located. This further strengthens the analysis methodology and the conclusions inferred from the research work. Hence, this research work can provide early indicators of the optimal cost of renewable generation per technology (see figure 6.9 and table 6.4), required hydrogen infrastructure expansions (see figure 6.5 and table 6.3) and for energy resilience in Namibia (see figure 6.7 and table 6.2).

- **Integrated system to utilize the export potential**: The export potential of 1 TWh to 200 TWh is analyzed in the system for the expansions and extent of the investments. To export the equivalent of Germany's hydrogen demand in 2030 of 90 to 110 TWh (Federal Ministry for Economic Affairs and Energy, 2020) , an investment of 9.4 billion euros is needed in the energy system expansion. Which is 83% larger than what is needed to make Namibia import-free and achieve its climate goals. However, the investments are still composed majorly of solar photovoltaic expansion, hydrogen production, and storage. With the allowance of hydrogen pipeline infrastructure, the investments are scattered across western regions as well the electrolyzer's location and its capacities. The sensitivity analysis determined the advantage of the hydrogen network in larger hydrogen export quantities. Nonetheless, the optimized energy system takes advantage of the interconnected power-to-gas infrastructure to maximum output independent of renewable potential at the electrolyzer location.

  In JCOI (BMBF), The production of hydrogen in Namibia is estimated at 1.50 euro to 2.00 euros per kilogram. Whereas, in the energy system the normalized cost of hydrogen produced from renewable sources, also known as green hydrogen, was found to be 1.68 to 2.79 euros per kg. With a small difference of 10-30% in the hydrogen normalized price from the price stated via BMBF, the hydrogen economy of Namibia can be seen flourishing in the coming years with the required infrastructure expansions and favorable investment locations.

- **Rapid expansions of hydrogen infrastructure for export quantities**: Expansion of hydrogen pipeline infrastructure reap maximum benefits for the export quantities of 5-50 TWh as found in the sensitivity analysis earlier. In the absence of a hydrogen network, the system has maximum cost implications whereas higher expansion has minimal benefit. The ideal range of 750 to 1500 GWKm favors a normalized cost of 2.47 to 2.64 euros per kilogram. which has a long-term benefit in the system for further export capabilities towards mid-century. For internal energy demand, the expansion has no cost benefits, hence for the energy resilience of Namibia, all investments can be focused on generation capacity expansion alone.

- **With stricter hydrogen production policies from the EU**: The recent directives from the EU further restrict the production of hydrogen with renewable fuels of non-biological origin (Commissioner for Energy, 2023). The energy system was then optimized for strict and lenient climate policies to observe its effects on the cost. The strict hydrogen production policy has minimal effect on the cost due to Namibia's own stricter climate policy for 2030. The higher export quantities have a minimal difference in system cost and have similar per unit cost of hydrogen in both cases. For the export of 1 TWh, the cost-benefit of 0.06% on system cost and 1.5% on the per unit normalized cost, shows that Namibia is committed to the climate goals by decarbonizing its energy sector and laying a path for future renewable-based energy infrastructure.

- **Mixed hydrogen fuel for export**: Allowing grey and blue along with green hydrogen for export in the energy system gives a cost-benefit of an average of 0.5%. For the normalized cost of per unit hydrogen, the lowest export quantity has the highest cost-benefit of up to 10%. However, with the EU's stricter hydrogen production policies the usage of grey and blue hydrogen for export can be rendered as irrelevant. Nonetheless, to fulfill Namibia's internal energy demand, a cost-benefit of up to 1.3% can be taken with the usage of mixed hydrogen fuel. As of now, Namibia has no carbon storage potential in the country, hence the share of blue hydrogen is minimal where the captured carbon is needed to be stored after its release during the steam methane reforming. Despite this, the share of electrolysis-based hydrogen production is highest in all cases ranging from 72 - 90%. Therefore, investments in electrolyzer-based hydrogen production can be seen as a major opportunity for Namibia in the hydrogen economy.

6.3.1 Summary

The current research work focuses on the energy system of Namibia, its current stance, future expansion potential, and its role in the global hydrogen economy. The energy system is modeled on top of the existing generation and transmission infrastructure in the country for 2030. Further enhancements are applied in terms of a sector-coupled component of sectors such as industry, transport, and residential. The energy system model is optimized for fulfilling the nation's energy demands as well as to export additional energy in the form of green hydrogen of quantity steps of 1, 5, 50, 100, and 200 TWh. The summary of the results can be found in the following sections.

6.3.2 Energy system expansion to reduce imports

To achieve climate goals and reduce imports. Namibia's energy network needs a greater extent of energy generation and storage expansion. Higher investments in solar photovoltaic technologies are favored whereas battery storage systems have the major share. Hydrogen production technologies such as power-to-gas will be the preferred technology, however, the production of hydrogen from processes such as steam methane reforming has slight cost benefits. The hydrogen pipeline infrastructure expansion is not required for internal demand and can be fulfilled with the installation of electrolyzers at the demand regions. With nations' stricter climate goals, the energy system is inclined to invest in renewable fuels of non-biological origins, which means that no expansion is seen in oil or coal-based generation and a minute expansion of SMR with CC-based hydrogen production

6.3.3 Hydrogen export to Germany from Namibia

With no existing gas infrastructure in Namibia, the development of the hydrogen economy is quite a novice. With an 83% higher cost to support the export of 100 TWh, the system needs major investments in electrolyzer and hydrogen pipeline infrastructure. Solar photovoltaics and power-to-gas technologies connected with pipelines and transmission networks have the optimized potential to export large amounts of hydrogen. The normalized cost of a unit hydrogen produces is similar to the cost disclosed in JCOI from BMBF, however, the exact methodology and assumptions are unknown in that case. The pipeline infrastructure expansion is only beneficial in large quantity exports of 100-200TWh. This provides flexibility to locate electrolyzers at different locations in the network connected through pipelines. The integrated system such as the sector-coupled model of Namibia displays clear advantages over an island/segregated system by utilizing the renewable potential at other connected regions to operate electrolyzers at their full capacity. Hence, to maximize the efficiency of the system with lower investment costs, the integrated system of electrolyzers with power should be favored over standalone systems.

6.3.4 Open source technologies

Most of the findings of the optimized energy system in this research work are derived from an open-source energy system model called PyPSA-Earth-Sec. This model is being continuously improved by researchers and collaborators around the world for energy insights and investment decisions. With an aim of transparency, open collaboration, and reproducible results, PyPSA-Earth-Sec serves as a critical part of the model chain applied in the HYPAT project as well as the current research work.

6.3.5 Green hydrogen, and the need for global energy pattern change

Just 1% of green hydrogen was produced using renewable fuels of non-biological origin in 2021 globally. Hence, to achieve climate targets in 2030 and to produce green hydrogen, there is a need for change in the global energy pattern. Especially for energy-intensive sectors such as industry and transport, the primary sources of energy need a rapid transition to fossil-free alternatives. Green hydrogen is one of the fuels that has shown promise in a sector-coupled system to provide multiple energy carriers in the form of fuel for mobility, reducing agents for steel production, and electricity in all sectors. Namibia, as the study case, is modeled every 3 hours in an energy system with 30 regions to find the green hydrogen potential. Several indicators have shown the nation's potential for the future economy. Such an energy system has high investments in infrastructure expansions but provides sustainable solutions to energy demand and a pathway toward net-zero emission to fight climate change.

7 Conclusion

Namibia, a southern African country with the least population density after Mongolia in the world, has ample renewable resources to generate energy not just for its own consumption but also to transport it across the world. Unfortunately, as of today, Namibia still struggles to fulfill its own energy demand and imports almost two-thirds of its electricity from neighboring countries. Limited energy infrastructure, lack of development strategy, and financial deficits are some of the major factors hindering its progress. However, in recent years several global leading nations have shown interest in Namibia with financial investments and project proposals. These opportunities are critical for the sustainable development of the nation and its energy system to develop a hydrogen economy. Green hydrogen production and export are the centerpiece of these initiatives. With the optimization of the sector-coupled energy system of Namibia for 2030, this research work studies the interplay of such investment opportunities, the country's energy generation, and hydrogen export potential. Along with the existing projects, it proposes a hydrogen potential atlas for possible investment locations and necessary expansions then outlines challenges in achieving such goals at a nationwide scale. The results of this research work are obtained on a high spatial and temporal resolution of Namibia using open and closed source data to optimize the energy system using a high-performance cluster of computing technologies.

7.1 The Namibian energy network needs external support

According to a World Bank report (World Bank, 2017), Namibia belongs to an upper-middle income economic status with its infrastructure development ranked 72nd in the world, where Germany stands at 3rd. The electricity tariff of 0.15 EUR per kWh is the highest in southern Africa due to the import of 61% of its electricity from neighboring countries in 2021. Surprisingly, local generation is predominantly based on renewable energy with 90% of total generation. With low solar utilization of 32% in the country, the infrastructure gaps can be observed in the development of solar-related energy generation and other renewable technologies as well.

It is observed that to fulfill the internal energy demand of Namibia for 2030, solar generation capacities need an expansion of 3.5 GW compared to 144.6 MW installed as of 2021. This is a tremendous increase and has major cost implications to develop such infrastructure. The annualized cost of up to 190 million euros (68%) for solar generation infrastructure is needed along with 60 million euros (22%) to support the storage system. With other minimal costs of 7% to develop onshore wind technologies and a minimum of 3% of the total cost to develop power-to-gas producing green hydrogen for internal consumption. The major scope of expansion is found in the western regions of the country close to Walvis Bay and Lüderitz Bay region. The expansion of hydrogen infrastructure has no cost benefit to satisfy internal demand in 2030, whereas allowing blue and grey hydrogen decreases the cost by up to 1.3% making it an option for domestic consumption. Due to its resilience to seasonal variability, hydrogen production can be made year-long with minimal storage needs and higher electrolyzer full-load hours utilization.

These findings (as formulated in research question-1) serve as an indicator of potential investment locations and technologies necessary for national energy system development. The system cost, however variable, serve as an early estimation of investment shares needed for the expansion. Hence, to lay out a pathway for the future hydrogen economy, these findings can assist policy maker to derive informed investment decisions in Namibia.

7.2 A win-win partnership in the green hydrogen economy

To have an active role in the future hydrogen economy, the Namibian energy system needs to devise a foundation of import-free energy, de-carbonize its energy system, and develop infrastructure for export. With an 83% higher cost to support 100 TWh export in 2030 to Germany, the energy system will need 53% of that cost to expand solar photovoltaic technologies followed by 37% in hydrogen production and storage. The development of hydrogen pipeline infrastructure plays an important role to decrease the overall cost, especially in higher export quantities of 100 to 200 TWh. The normalized cost of per kilogram hydrogen at the export location is 10-30% higher than the estimation provided by the German Ministry of Education and Research.

Looking at the enormous costs of energy system development, the role of the existing project proposal and foreign investments becomes significant for Namibia. With huge renewable potential, lesser domestic energy demand, and scope for exporting the excess energy, Namibia can benefit from financial aid to develop its energy infrastructure from its nascent stage to a major hydrogen export player till mid-century. In response to the research question-2, the analysis finds the existing financial aid planned for Namibia adequate, if invested strategically in locations with high energy demand and high export potential such as the western and southern regions of the country.

7.3 Future Work

This research work is part of the HYPAT project work package exploring the green hydrogen export potential in Namibia and 9 other countries for 2030 and 2050. To deepen the research work done in 2030, smaller export quantities should be further studied to derive the optimal export quantity and subsequently understand the interactions of different parameters. Further work is needed to explore the potential in 2050 taking developments of 2030 as a foundation. The effects of the expansion of the electricity grid and hydrogen pipeline infrastructure in 2050 need to be analyzed further. As supplemental research, the energy system model of Namibia can be studied with neighboring countries. It could be interesting to see the interaction of cross-border energy system optimization for future partnerships and collaboration possible to develop a global hydrogen economy expanding beyond African borders.

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8 Supplementary information

8.1 Model parameters : Enertile, LEAP and PyPSA-Earth-Sec

Model parameters are defined for each model to carry out calculations. These parameters are based on previous research, or own assumption relying on literature. The tables below define the research carried out for each of the parameters and provide relevant information in a tabular form.

Table 8.3 contains parameters for the model - Enertile for the year 2030. Table 8.4 **??** contains the parameters for domestic energy supply data, containing different energy carriers, sub-sectors, and literature references. Finally, the table 8.5 outlines the parameters defined in PyPSA-Earth-Sec for energy infrastructure, domestic energy demand, and supply through primary and secondary fuels.

Tab. 8.1: LEAP aggregated data for energy demand distribution in TWh.

Demand scenario	Ambitious Plans (AP) 2030	Net Zero (NZ) 2030	Ambitious Plans (AP) 2050	Net Zero (NZ) 2050
total road	8.85	8.85	13.81	8.57
electricity residential	0.88	0.90	2.54	2.39
agriculture electricity	1.54	1.57	2.08	1.97
agriculture oil	2.81	2.24	1.66	0.45
residential heat biomass	1.39	1.22	1.56	0.92
residential biomass	1.21	1.09	1.15	0.81

Tab. 8.2: Energy carrier share in the final energy demand (TWh), for each scenario. Source LEAP

carrier	oil	gas	electricity	coal	heat	biomass	hydrogen
AP 2030	0.719298	2.400720	3.047154	0.0	0.0	1.084842	1.314679
NZ 2030	0.565197	1.683000	2.998559	0.0	0.0	0.997277	1.559072
AP 2050	0.245033	0.549429	4.569524	0.0	0.0	1.222382	4.032235
NZ 2050	0.013820	0.000000	3.945999	0.0	0.0	0.998076	3.800895

Tab. 8.3: Model parameters for Enertile

Sub category	Type	Parameter	Unit	2030	Ref.
CSP	Storage	Time	Hours	8	
CSP	Power plant	CAPEX	EUR/kWel	3326	own assumptions based onH2020 project MUSTEC (Schöniger 2020)
CSP	Power plant	OPEX fix	EUR/(kWel*a)	66	own assumptions based onH2020 project MUSTEC (Schöniger 2020)
CSP	Power plant	OPEX var	EUR/(kWhel)	0.00005	own assumptions based onH2020 project MUSTEC (Schöniger 2020)
CSP	Power plant	Lifetime	years	30	own assumptions based onH2020 project MUSTEC (Schöniger 2020)
PV	Gound mounted	CAPEX	EUR/kWel	662	own assumptions based on EEG-Erfahrungsbericht 2019
PV	Gound mounted	OPEX fix	EUR/(kWel*a)	8	own assumptions based on EEG-Erfahrungsbericht 2019
PV	Gound mounted	OPEX var	EUR/(kWhel)	0	own assumptions based on EEG-Erfahrungsbericht 2019
PV	Gound mounted	Lifetime	years	20	own assumptions
Wind	Offshore	CAPEX	EUR/kWel	3104 - 4248	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Offshore	OPEX fix	EUR/(kWel*a)	67	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Offshore	OPEX var	EUR/(kWhel)	0	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Offshore	Lifetime	years	20	own assumptions
Wind	Onshore	CAPEX	EUR/kWel	1006 - 1451	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Onshore	OPEX fix	EUR/(kWel*a)	20	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Onshore	OPEX var	EUR/(kWhel)	0	own assumptions based on EEG-Erfahrungsbericht 2019
Wind	Onshore	Lifetime	years	20	own assumptions

Tab. 8.4: Model parameters for LEAP

Sub category	Type	Unit	Description	2020	2030	Ref.
Industry Sector	Chemicals - Ammonia Production - Other Conventional	MWh/t	Energy intensity per tonne of Ammonia production	4,86 - 5,22	(-0,2%) - (-1,0%)	IEA 2021c
Industry Sector	Chemicals - Ammonia Production - Renewable	MWh/t	Energy intensity per tonne of Ammonia production	2,0 - 4,28	(-0,2%) - (-1,0%)	IEA 2018b, Material Economics 2019, Wang et al. 2021
Industry Sector	Chemicals - Ammonia Production - SMR	MWh/t	Energy intensity per tonne of Ammonia production	2,1 - 5,6	(-0,2%) - (-1,0%)	IEA 2018b, Material Economics 2019, Bazzanella et al. 2017, IEA 2021c
Industry Sector	Chemicals - HVC Production - LPG Route	MWh/t	Energy intensity per tonne of HVC production	4,22 - 7,63	(-0,1%) - (-0,1%)	IEA 2018b, Bazzanella et al. 2017, BDI 2021
Industry Sector	Chemicals - HVC Production - Methanol Route	MWh/t	Energy intensity per tonne of HVC production	1,4	(-0,1%) - (-0,3%)	Material Economics 2019, Neuwirth et Fleiter 2020
Industry Sector	Chemicals - HVC production - Naphtha Route	MWh/t	Energy intensity per tonne of HVC production	3,33 - 4,86	(-0,1%) - (-0,1%)	IEA 2018b, Bazzanella et al. 2017, BDI 2021
Industry Sector	Non Ferrous Metals - Aluminium Production - Primary Route	MWh/t	Energy intensity per tonne of Aluminium production	15,1 - 23,53	(-0,1%) - (-0,5%)	Neuwirth et al. 2022, Internal Fraunhofer ISI Source, International Aluminium Institute
Industry Sector	Non Ferrous Metals - Aluminium Production - Secondary Route	MWh/t	Energy intensity per tonne of Aluminium production	2,96	(-0,1%) - (-0,5%)	Internal Fraunhofer ISI Source
Industry Sector	Non Metallic Minerals - Cement Production - Clinker Production	MWh/t	Energy intensity per tonne of Clinker production	0,94 - 1,7	(-0,1%) - (-0,3%)	IEA 2018a, Internal Fraunhofer ISI Source
Industry Sector	Paper and Pulp - Paper Production	MWh/t	Energy intensity per tonne of Paper production	1,36 - 2,43	(-0,3%) - (-1,0%)	Neuwirth et al. 2022
Industry Sector	Paper and Pulp - Pulp Production - Primary Route	MWh/t	Energy intensity per tonne of Pulp production	2,86 - 4,15	(-0,3%) - (-1,0%)	Neuwirth et al. 2022
Industry Sector	Paper and Pulp - Pulp Production - Secondary Route	MWh/t	Energy intensity per tonne of Pulp production	0,14 - 0,41	(-0,3%) - (-1,0%)	Neuwirth et al. 2022
Industry Sector	Steel - Primary Route - Blast Furnace & Basic Oxygen Furnace	MWh/t	Energy intensity per tonne of Crude steel production	3,2 - 6,31	0%	Neuwirth et al. 2022, IEA 2020, Internal Fraunhofer ISI Source, Strefler et al. 2021, Prog
Industry Sector	Steel - Primary Route - Direct Reduced Iron & Electric Arc Furnace	MWh/t	Energy intensity per tonne of Crude steel production	1,33 - 6,06	(-0,5%) - (-2,0%)	Wang et al. 2021, IEA 2020a, IEA 2021a, Neuwirth et al. 2022, Material Economics 2019
Industry Sector	Steel - Secondary Route - Scrap & Electric Arc Furnace	MWh/t	Energy intensity per tonne of Crude steel production	0,29 - 1,44	(-0,5%) - (-2,0%)	Material Economics 2019, Wang et al. 2021, IEA 2020a
Residential Sector	Cooking	kWh/dwelling	Energy intensity per dwelling	349 - 1,817	(-0,63%) - (-1,75%)	EEA 2012, ODYSSEE MURE 2022, EC 2022
Residential Sector	Electrical Appliances	kWh/dwelling	Energy intensity per dwelling	331 - 3,024	3,0% - 1,50%	EEA 2012, ODYSSEE MURE 2022, EC 2022
Residential Sector	Space Cooling	kWh/dwelling	Energy intensity per dwelling	0 - 289	(-0,13%) - (-0,5%)	ODYSSEE MURE 2022
Residential Sector	Space Cooling	kWh/m2	Energy intensity per m2	0 - 66	(-0,13%) - (-0,5%)	Persson & Werner 2015
Residential Sector	Space Heating	kWh/dwelling	Energy intensity per dwelling	5,569 - 14,654	(-1,0%) - (-3,0%)	EEA 2012, ODYSSEE MURE 2022, EC 2022
Residential Sector	Space Heating	kWh/m2	Energy intensity per m2	87 - 231	(-1,0%) - (-3,0%)	ODYSSEE MURE 2022
Residential Sector	Space Heating	kWh/dwelling	Energy intensity per dwelling	1,489 - 3,256	(-0,25%) - (-1,0%)	EEA 2012, ODYSSEE MURE 2022, EC 2022
Transport sector	Freight - Internal Navigation - Ammonia Marine Engine	kWh/km	Energy intensity per vehicle km	60.4	(-0,40%) - (-1,0%)	Own assumption
Transport sector	Freight - Internal Navigation - Battery EV	kWh/km	Energy intensity per vehicle km	35	(-0,40%) - (-1,0%)	Own assumption
Transport sector	Freight - Internal Navigation - Conventional Marine Engine	kWh/km	Energy intensity per vehicle km	60.4	(-0,40%) - (-1,0%)	MKS 2018
Transport sector	Freight - Internal Navigation - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	46	(-0,40%) - (-1,0%)	MKS 2018

Tab. 8.4: Model parameters for LEAP

Sub category	Type	Unit	Description	2020	2030	Ref.
Transport sector	Freight - Internal Navigation - Methanol Marine Engine	kWh/km	Energy intensity per vehicle km	60.4	(-0,40%) - (-1,0%)	Own assumption
Transport sector	Freight - Rail - Diesel ICE	kWh/km	Energy intensity per vehicle km	145,8 - 178,6	(-0,08%) - (-0,30%)	IEA UIC 2015, DB 2021
Transport sector	Freight - Rail - Direct Electric	kWh/km	Energy intensity per vehicle km	55,50 - 100	(-0,08%) - (-0,30%)	IEA UIC 2015, DB 2021
Transport sector	Freight - Rail - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	100 - 150	(-0,08%) - (-0,30%)	Own assumption
Transport sector	Freight - Road - HDT - Battery EV	kWh/km	Energy intensity per vehicle km	0,89 - 1,75	(-0,25%) - (-1,0%)	Transport&Environment 2020, GFEI & ICCT 2019, Sachi 2021
Transport sector	Freight - Road - HDT - Diesel ICE	kWh/km	Energy intensity per vehicle km	1,25 - 3,11	(-0,75%) - (-2,0%)	GFEI & ICCT 2019, BDI 2021, MKS 2018
Transport sector	Freight - Road - HDT - Diesel Plug-in Hybrid	kWh/km	Energy intensity per vehicle km	1,3 - 2,2	(-0,75%) - (-2,0%)	Own assumption
Transport sector	Freight - Road - HDT - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	1,95 - 3,13	(-0,20%) - (-1,0%)	Transport&Environment 2020, DOE 2019, BDI 2021, Sachi 2021
Transport sector	Freight - Road - LDT - Battery EV	kWh/km	Energy intensity per vehicle km	0,17 - 0,88	(-0,25%) - (-1,0%)	Sachi 2021
Transport sector	Freight - Road - LDT - Diesel ICE	kWh/km	Energy intensity per vehicle km	1,1 - 2,1	(-0,75%) - (-2,0%)	webfleet 2021
Transport sector	Freight - Road - LDT - Diesel Plug-in Hybrid	kWh/km	Energy intensity per vehicle km	0,5 - 1,6	(-0,75%) - (-2,0%)	Own assumption
Transport sector	Freight - Road - LDT - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	0,67 - 1,67	(-0,20%) - (-1,0%)	Sachi 2021
Transport sector	Passenger - Internal Aviation - Battery EV	kWh/km	Energy intensity per vehicle km	41,00 - 71,60	(-0,40%) - (-1,0%)	Own assumption
Transport sector	Passenger - Internal Aviation - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	41,00 - 71,60	(-0,40%) - (-1,0%)	Own assumption
Transport sector	Passenger - Internal Aviation - Jet Turbine	kWh/km	Energy intensity per vehicle km	41,00 - 71,60	(-0,40%) - (-1,0%)	MKS 2018
Transport sector	Passenger - Rail - Diesel ICE	kWh/km	Energy intensity per vehicle km	19,85 - 25	(-0,08%) - (-0,30%)	DB 2021, IEA UIC 2015
Transport sector	Passenger - Rail - Direct Electric	kWh/km	Energy intensity per vehicle km	11,4 - 19,85	(-0,08%) - (-0,30%)	DB 2021, IEA UIC 2015
Transport sector	Passenger - Rail- Fuel Cell EV	kWh/km	Energy intensity per vehicle km	15,6 - 22,4	(-0,08%) - (-0,30%)	Own assumption
Transport sector	Passenger - Road - 2and3W - Battery EV	kWh/km	Energy intensity per vehicle km	0,05 - 0,07	(-0,25%) - (-1,0%)	GFEI & ICCT 2019
Transport sector	Passenger - Road - 2and3W - Gasoline ICE	kWh/km	Energy intensity per vehicle km	0,15 - 0,25	(-0,75%) - (-2,0%)	GFEI & ICCT 2019
Transport sector	Passenger - Road - Bus - Battery EV	kWh/km	Energy intensity per vehicle km	0,48 - 1,30	(-0,25%) - (-1,0%)	GFEI & ICCT 2019
Transport sector	Passenger - Road - Bus - Diesel ICE	kWh/km	Energy intensity per vehicle km	1,0 - 4,39	(-0,75%) - (-2,0%)	Vogel 2012, Landtag NRW 2020, GFEI & ICCT 2019, NREL 2016
Transport sector	Passenger - Road - Bus - Diesel Plug-in Hybrid	kWh/km	Energy intensity per vehicle km	0,9 - 2,7	(-0,75%) - (-2,0%)	Own assumption
Transport sector	Passenger - Road - Bus - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	2,67 - 4,0	(-0,20%) - (-1,0%)	Vogel 2012, Landtag NRW 2020, NREL 2016, WSW 2020
Transport sector	Passenger - Road - LDV - Battery EV	kWh/km	Energy intensity per vehicle km	0,13 - 0,24	(-0,25%) - (-1,0%)	GFEI & IEA 2021, FVV 2018, GFEI & ICCT 2019, ADAC 2022

Tab. 8.4: Model parameters for LEAP

Sub category	Type	Unit	Description	2020	2030	Ref.
Transport sector	Passenger - Road - LDV - Diesel ICE	kWh/km	Energy intensity per vehicle km	0,34 - 0,68	(-0,75%) - (-2,0%)	GFEI & IEA 2021, FVV 2018, BDI 2021
Transport sector	Passenger - Road - LDV - Fuel Cell EV	kWh/km	Energy intensity per vehicle km	0,22 - 0,40	(-0,20%) - (-1,0%)	FVV 2018, ADAC 2021, BDI 2021
Transport sector	Passenger - Road - LDV - Gasoline ICE	kWh/km	Energy intensity per vehicle km	0,37 - 0,77	(-0,75%) - (-2,0%)	GFEI & IEA 2021, FVV 2018, BDI 2021
Transport sector	Passenger - Road - LDV - Gasoline Plug-in Hybrid	kWh/km	Energy intensity per vehicle km	0,18 - 0,52	(-0,75%) - (-2,0%)	GFEI & IEA 2021, ADAC 2018, BDI 2021
Transport sector	Passenger - Road - LDV - LPG ICE	kWh/km	Energy intensity per vehicle km	0,35 - 0,83	(-0,75%) - (-2,0%)	ELGAS 2021, gazeo 2021, BMVI 2013, FVV 2018, BDI 2021

Tab. 8.5: Model parameters for PyPSA-Earth-Sec

Stage	Category	Sub category	Type	Parameter	Unit	2020	2030	Ref.
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant	CAPEX	EUR/kWel	3381.27	3210.28	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant	Lifetime	years	25	25	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant	OPEX fix	%/year	3.61	3.58	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant	Efficiency	per unit	0.3	0.3	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant	OPEX var	EUR/MWh	2.1	2.1	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant - Solid biomass	CO2 intensity	tCO2/MWh_th	0.37	0.37	Own Assumption
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Biomass	Power plant - Solid biomass	Price	EUR/MWh_th	12	12	Ruiz Castello et al. 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant - Coal	CO2 intensity	tCO2/MWh_th	0.34	0.34	Umwelt Bundesamt, 2021
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant	OPEX fix	%/year	1.6	1.6	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant	OPEX var	EUR/MWh_e	3.5	3.5	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant	Efficiency	per unit	0.33	0.33	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant - Coal	Price	EUR/MWh_th	8.15	8.15	BP 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant	CAPEX	EUR/kW_e	3845.51	3845.51	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Coal	Power plant	Lifetime	years	40	40	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant - Oil	CO2 intensity	tCO2/MWh_th	0.26	0.26	Own Assumption
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant	OPEX fix	%/year	2.57	2.46	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant	OPEX var	EUR/MWh	6	6	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	OPEX fix	%/year	4.95	4.95	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	SEC	MWh/tCO2	0.35	0.32	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	CAPEX	EUR/(tCO2/h)	7000000	6000000	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	Lifetime	years	20	20	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture - Compression	SEC	MWh/tCO2	0.15	0.15	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture - Compression	SHC	MWh/tCO2	-0.2	-0.2	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	SHC	MWh/tCO2	2.5	2	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Direct Air Capture	SHC	MWh/tCO2	1.25	1	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Pipeline	OPEX fix	%/year	0.9	0.9	Danish Energy Agency 2021a

Tab. 8.5: Model parameters for PyPSA-Earth-Sec

Stage	Category	Sub category	Type	Parameter	Unit	2020	2030	Ref.
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Pipeline	CAPEX	EUR/(tCO2/h)/km	2000	2000	Danish Energy Agency 2021a
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Pipeline	Lifetime	years	50	50	Danish Energy Agency 2021a
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Heat	Decentral Heating - Gas storage	OPEX fix	%	3.59	3.59	Danish Energy Agency 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Heat	Decentral Heating - Gas storage	CAPEX	EUR/kWh	0.03	0.03	Danish Energy Agency 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Heat	Decentral Heating - Gas storage	Lifetime	years	100	100	Own Assumption
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Heat	Decentral Heating - Gas storage charger	CAPEX	EUR/kW	14.34	14.34	Danish Energy Agency 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Heat	Decentral Heating - Gas storage charger	CAPEX	EUR/kW	4.78	4.78	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Storage tank	OPEX fix	%/year	1	1	Lauri et al. 2014
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Storage tank	CAPEX	EUR/t_CO2	2528.17	2528.17	Lauri et al. 2014
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	CO2	Storage tank	Lifetime	years	25	25	Lauri et al. 2014
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline	OPEX fix	%/year	4	3.17	Danish Energy Agency2021b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline	CAPEX	EUR/MW/km	226.47	226.47	EHB, 2021
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline	Lifetime	years	50	50	Danish Energy Agency 2021b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - NG Repurposed	OPEX fix	%/year	4	3.17	Danish Energy Agency 2021b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - NG Repurposed	CAPEX	EUR/MW/km	105.88	105.88	EHB, 2021
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - NG Repurposed	Lifetime	years	50	50	Danish Energy Agency 2021b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - NG Repurposed - Network repurposing level	Rate	% of 2020		(+0%) - (+30%)	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - Submarine	OPEX fix	%/year	3	3	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - Submarine	CAPEX	EUR/MW/km	329.37	329.37	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Pipeline - Submarine	Lifetime	years	30	30	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Tank incl. Compressor	OPEX fix	%/year	1.05	1.11	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Tank incl. Compressor	CAPEX	EUR/kWh	57	44.91	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Tank incl. Compressor	Lifetime	years	25	30	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Underground	OPEX fix	%/year	0	0	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Underground	OPEX var	EUR/MWh	(2.25)-(3.83)	(2.25)-(3.83)	Danish Energy Agency 2020

Tab. 8.5: Model parameters for PyPSA-Earth-Sec

Stage	Category	Sub category	Type	Parameter	Unit	2020	2030	Ref.
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant	Efficiency	per unit	0.35	0.35	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant - Oil	Price	EUR/MWhth	50	50	IEA 2022
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant	CAPEX	EUR/kW	343	343	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Crude oil	Power plant	Lifetime	years	25	25	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Underground	CAPEX	EUR/kWh	3	2	Danish Energy Agency 2020
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	H2	Storage - Underground	Lifetime	years	100	100	Danish Energy Agency 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	Classic dam	OPEX fix	%/year	1	1	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	Classic dam	Efficiency	per unit	0.9	0.9	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	Classic dam	CAPEX	EUR/kWel	2208.16	2208.16	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	Classic dam	Lifetime	years	80	80	IEA 2010
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	PHS	OPEX fix	%/year	1	1	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	PHS	Efficiency	per unit	0.75	0.75	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	PHS	CAPEX	EUR/kWel	2208.16	2208.16	Schröder et al. 2013
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	NG	Pipeline	OPEX fix	%/year	1.5	1,5	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	NG	Pipeline	CAPEX	EUR/MW/km	79	79	Own Assumption
2 - Transmisison and infrastructure	GAS INFRASTRUCTURE	NG	Pipeline	Lifetime	years	50	50	Own Assumption
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Storage	CAPEX	EUR/kWh	232	142	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Storage	Lifetime	years	20	25	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	OPEX fix	%/year	0.2	0.34	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	Efficiency	per unit	0.95	0.96	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	CAPEX	EUR/kW	377	228.06	Danish Energy Agency 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Gas	H2 - Electrolysis	OPEX fix	%/year	2	2	Danish Energy Agency 2022a
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Gas	H2 - Electrolysis	Efficiency	per unit	0.66	0.68	Danish Energy Agency 2022a
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Gas	H2 - Electrolysis	CAPEX	EUR/kW_e	650	450	Danish Energy Agency 2022a
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Gas	H2 - Electrolysis	Lifetime	years	25	30	Danish Energy Agency 2022a

Tab. 8.5: Model parameters for PyPSA-Earth-Sec

Stage	Category	Sub category	Type	Parameter	Unit	2020	2030	Ref.
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	Lifetime	years	10	10	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	CAPEX	EUR/kWh	323.53	202.9	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Battery	Home inverter	Lifetime	years	20	25	Danish Energy Agency 2020
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Fuel cell	Fuel cell	OPEX fix	%/year	5	5	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Fuel cell	Fuel cell	c_b	50oC/100oC	1.25	1.25	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	OHS	Lifetime	years	80	80	IEA 2010
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	ROR	OPEX fix	%/year	2	2	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Oil	Fischer-Tropsch synthesis	OPEX fix	%/year	3	3	Agora Energiewende 2018
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Oil	Fischer-Tropsch synthesis - CO2 capture	Rate	per unit	0.98	0.98	Ilkka Hannula 2015
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Oil	Fischer-Tropsch synthesis	Efficiency	per unit	0.8	0.8	Agora Energiewende 2018
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Oil	Fischer-Tropsch synthesis	CAPEX	EUR/MW_FT	757401	650711.26	Agora Energiewende 2018
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Secondary	Synthetic Oil	Fischer-Tropsch synthesis	Lifetime	years	20	20	Danish Energy Agency 2022a
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Fuel cell	Fuel cell	Efficiency	per unit	0.5	0.5	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Fuel cell	Fuel cell	CAPEX	EUR/kW_e	1300	1100	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Fuel cell	Fuel cell	Lifetime	years	10	10	Danish Energy Agency 2022b
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power lines	Grid - Infrastructure expansion level	Rate	% of 2020		(+0%) - (+20%)	Own Assumption
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVAC	OPEX fix	%/year	2	2	Hagspiel et al. 2014
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVAC	CAPEX	EUR/MW/km	432.97	432.97	Hagspiel et al. 2014
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	ROR	Efficiency	per unit	0.9	0.9	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	ROR	CAPEX	EUR/kWel	3312.24	3312.24	Schröder et al. 2013
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Hydro	ROR	Lifetime	years	80	80	IEA 2010
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT - NG	CO2 intensity	tCO2/MWh_th	0.2	0.2	Own Assumption
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVAC	Lifetime	years	40	40	Hagspiel et al. 2014
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVDC	OPEX fix	%/year	2	2	Hagspiel et al. 2014
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVDC	CAPEX	EUR/MW/km	432.97	432.97	Hagspiel et al. 2014

Tab. 8.5: Model parameters for PyPSA-Earth-Sec

Stage	Category	Sub category	Type	Parameter	Unit	2020	2030	Ref.
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Overhead - HVDC	Lifetime	years	40	40	Hagspiel et al. 2014
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Submarine - HVDC	OPEX fix	%/year	0.35	0.35	Purvins et al. 2018
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Submarine - HVDC	CAPEX	EUR/MW/km	471.16	471.16	Purvins et al. 2019
2 - Transmisison and infrastructure	POWER INFRASTRUCTURE	Power Lines	Submarine - HVDC	Lifetime	years	40	40	Purvins et al. 2020
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT - NG	Price	EUR/MWh_th	20.1	20.1	BP 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT	OPEX fix	%/year	1.78	1.78	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT	OPEX var	EUR/MWh	4.5	4.5	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT	Efficiency	per unit	0.4	0.41	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT	CAPEX	EUR/kW	453.96	435.24	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	NG	OCGT	Lifetime	years	25	25	Danish Energy Agency 2022b
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	OPEX fix	%/year	1.4	1.4	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	OPEX var	EUR/MWh_e	3.5	3.5	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	Efficiency	per unit	0.33	0.33	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	Price	EUR/MWh_th	2.6	2.6	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	CAPEX	EUR/kW_e	7940.45	7940.45	Lazard 2019
1 - Demand and Supply	DOMESTIC ENERGY SUPPLY - Primary	Nuclear	Power plant	Lifetime	years	40	40	Lazard 2019

8.2 Model results

The results of the optimized energy system of Namibia are laid out in this section in detail. Categorized via scenarios defined in the research work, each section delivers the system cost and hydrogen infrastructure required for the export of 1-200 TWh of green hydrogen except in one case where we look into the mix of blue/gray hydrogen as well.

8.2.1 System cost - mixed hydrogen in the system

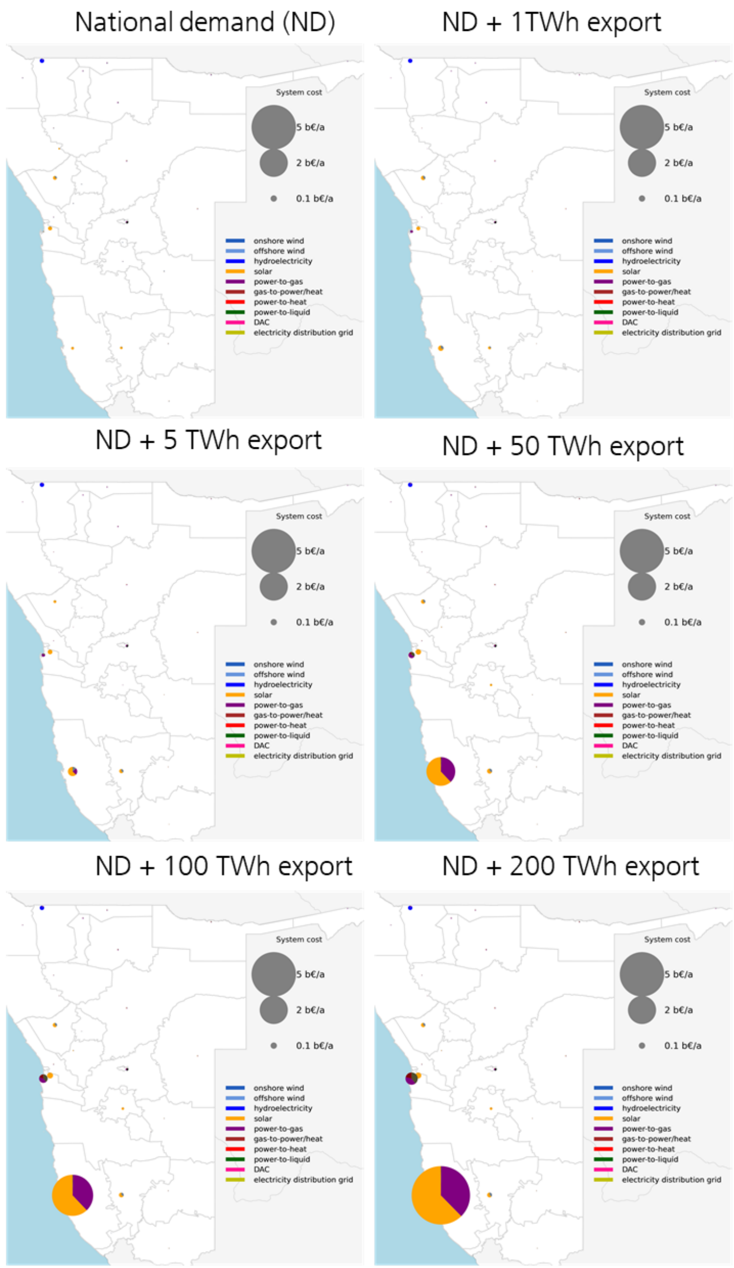

Fig. 8.1: System cost in case of blue and gray hydrogen in the energy mix.

8.2.2 Infrastructure - mixed hydrogen in the system

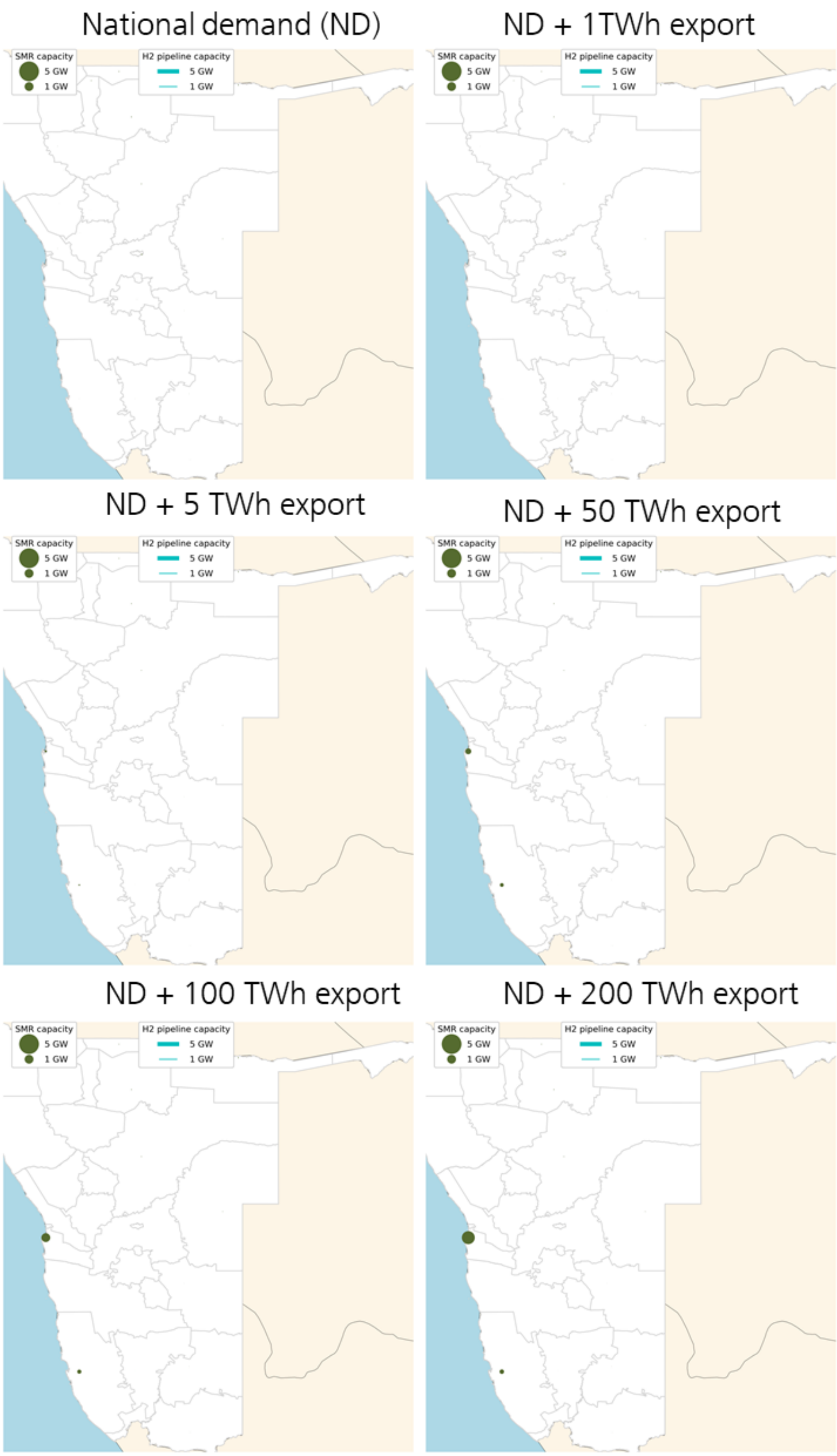

Fig. 8.2: Infrastructure in case of blue and gray hydrogen in the energy mix for various quantities

8.2.3 System cost - lenient hydrogen production policy

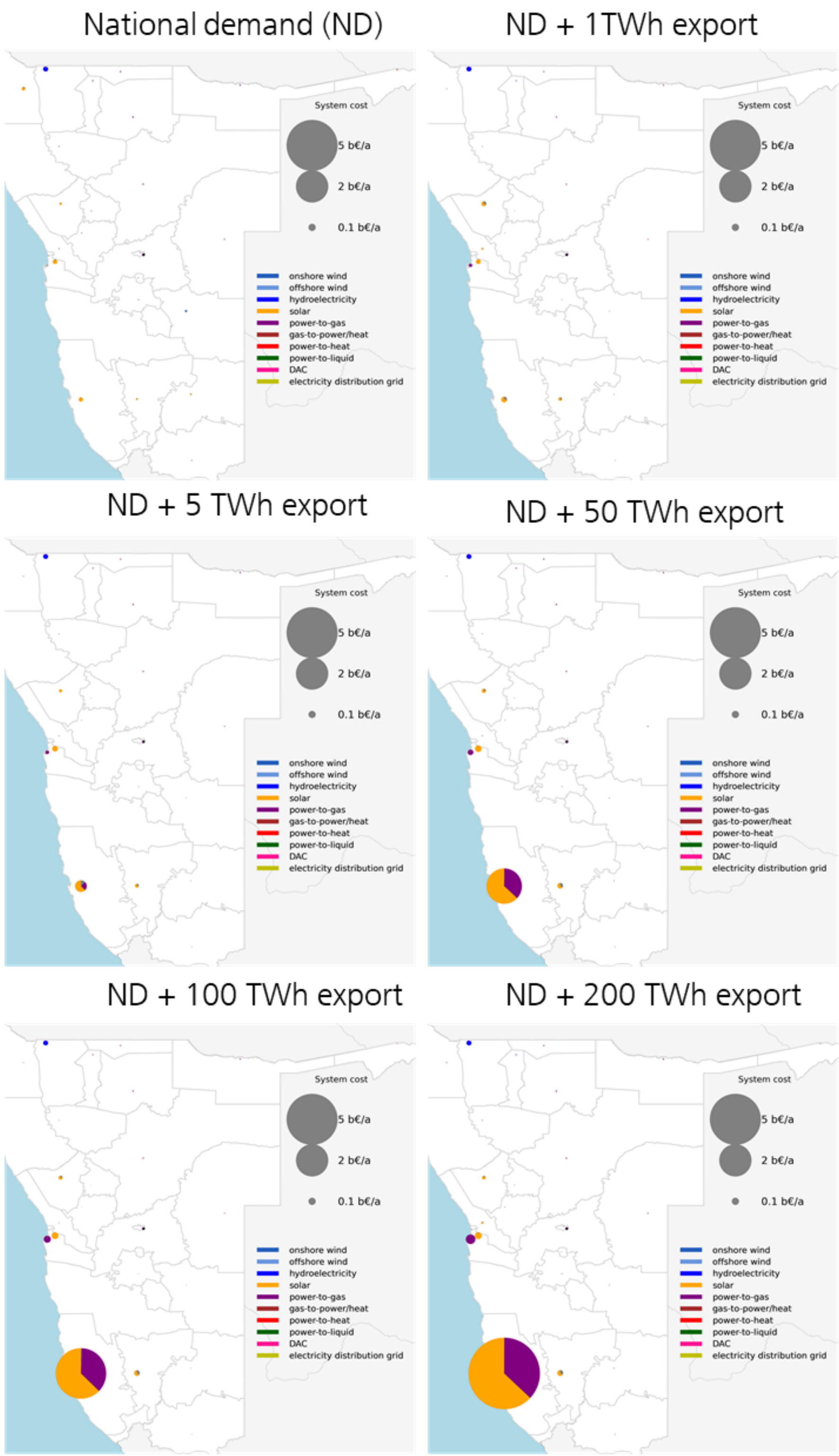

Fig. 8.3: System cost when a system has no obligations to produce hydrogen in terms of source of energy

8.2.4 Hydrogen infrastructure - lenient hydrogen production policy

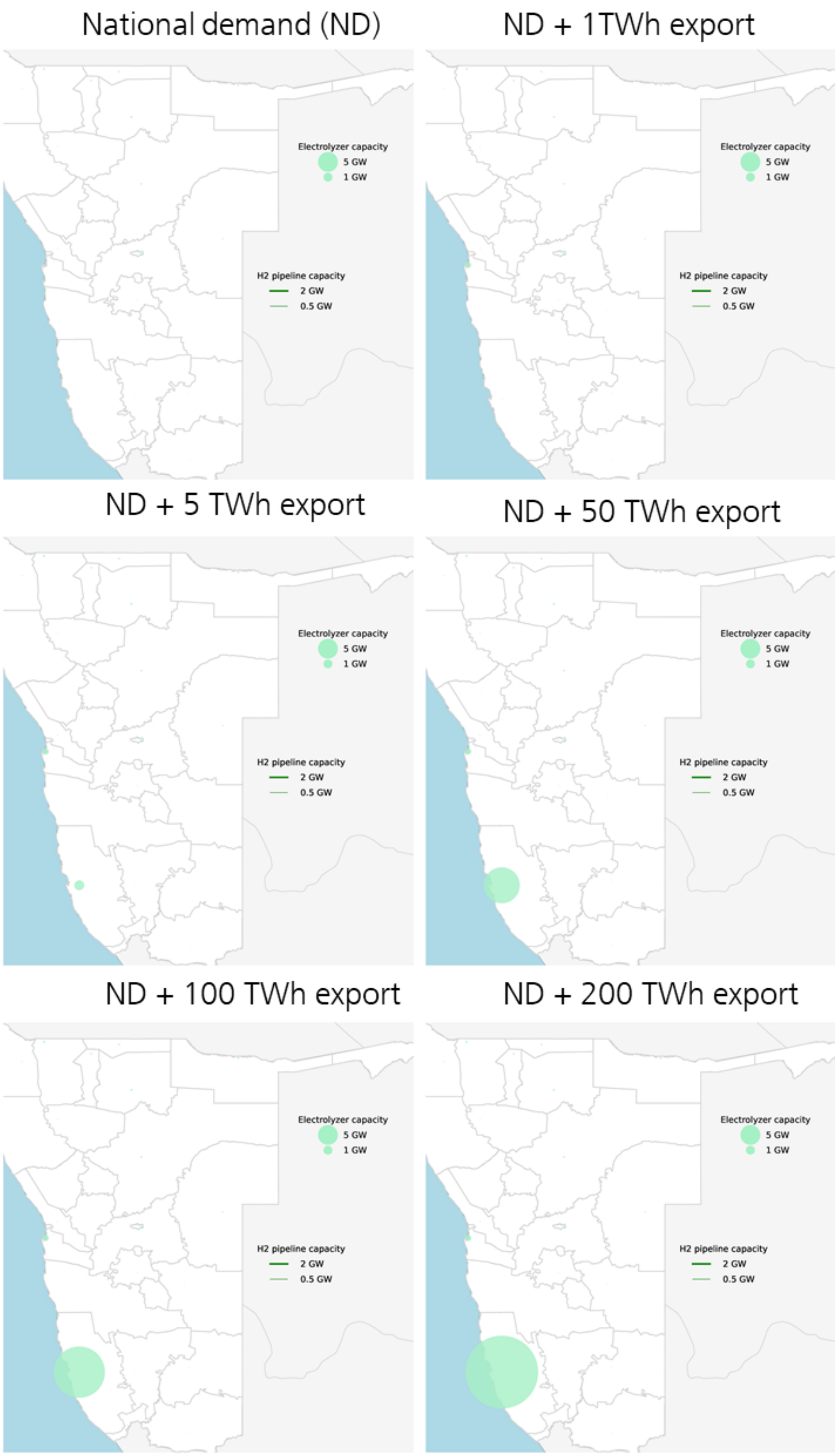

Fig. 8.4: Infrastructure when a system has no obligations to produce hydrogen in terms of source of energy

8.2.5 System cost - Allowed hydrogen pipeline infrastructure expansion

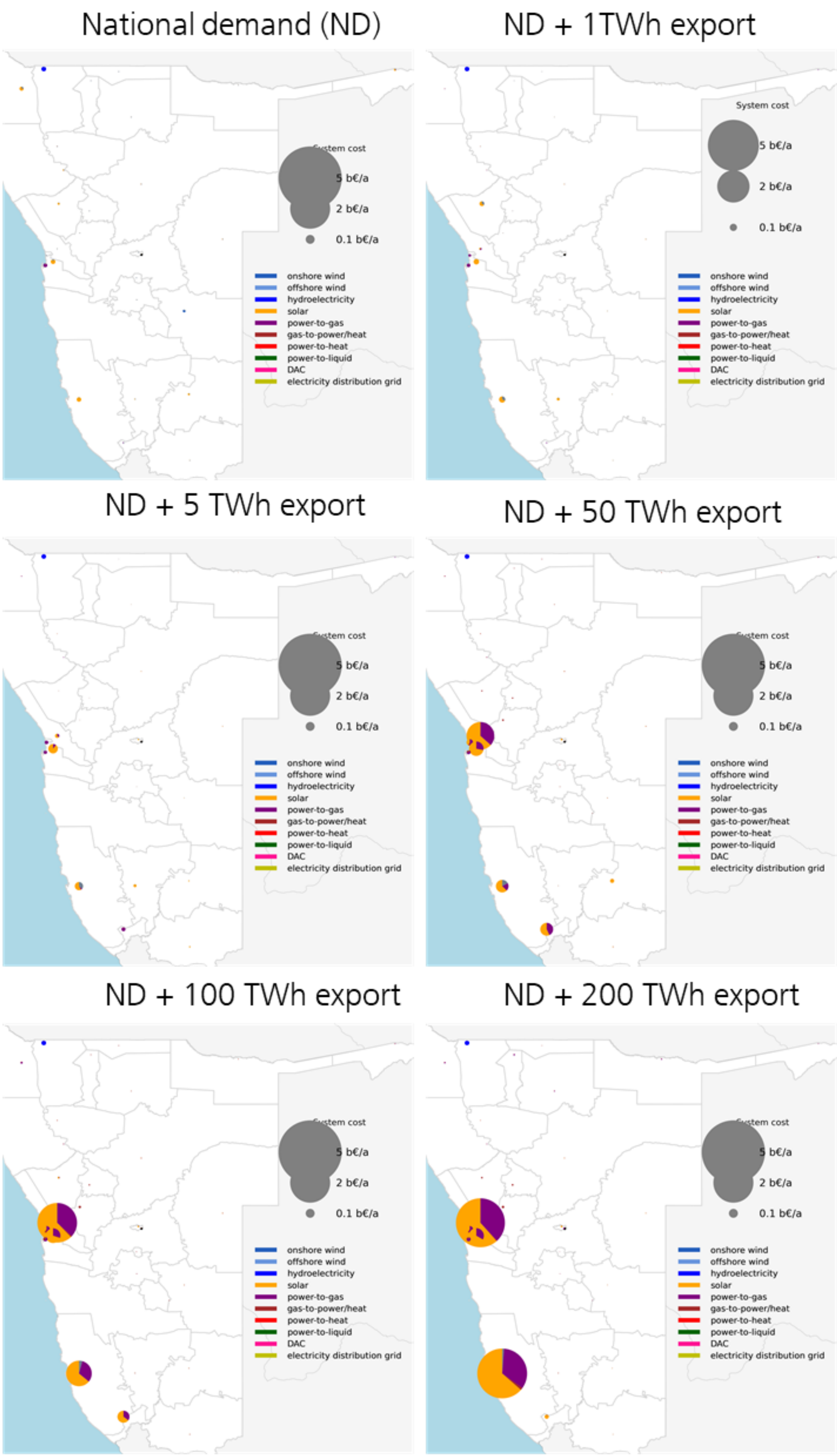

Fig. 8.5: System cost per technology and their location in the scenario with allowed hydrogen pipeline infrastructure expansion

8.2.6 Infrastructure - Allowed hydrogen pipeline infrastructure expansion

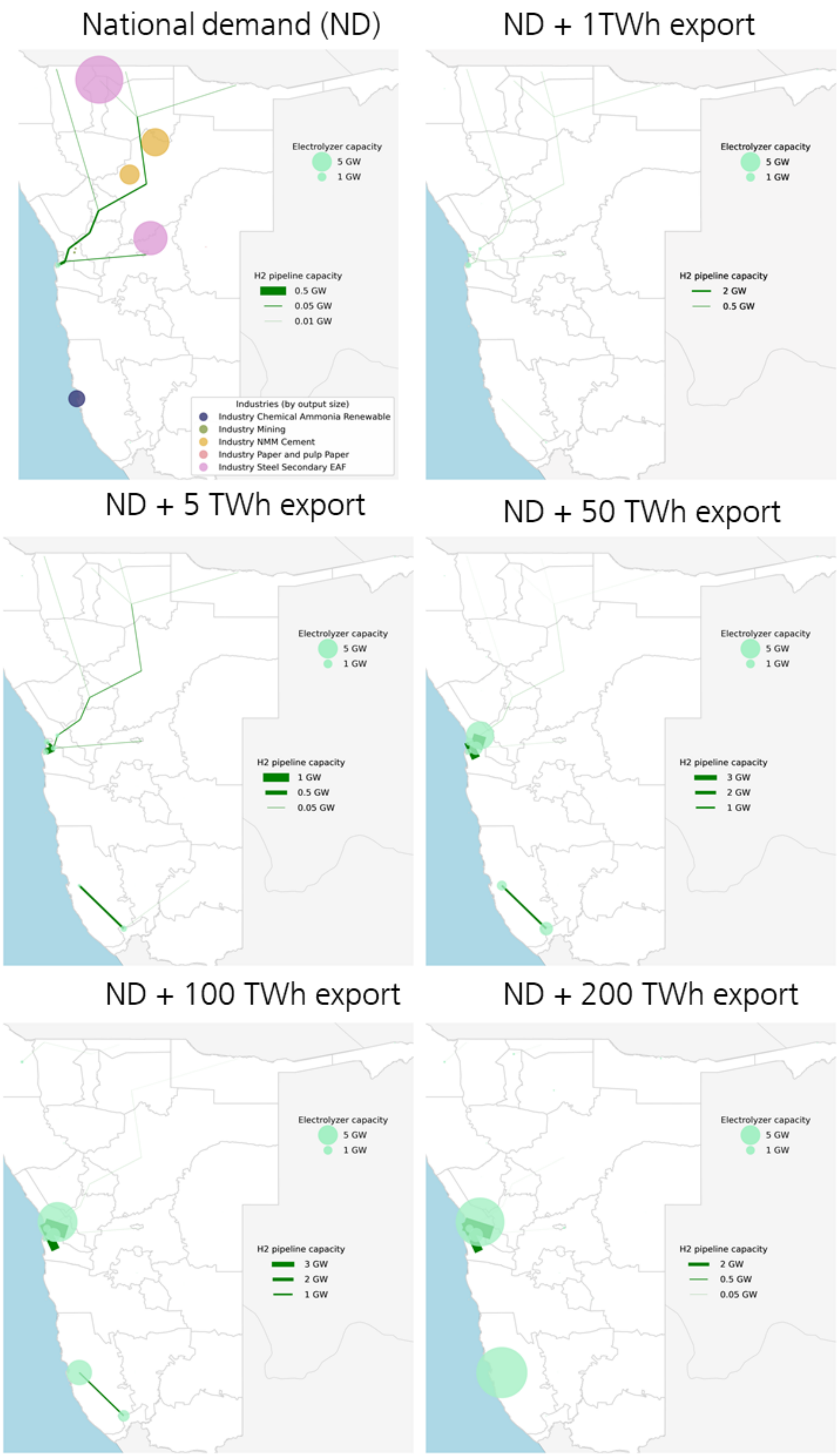

Fig. 8.6: Hydrogen pipelines capacity, electrolyzer capacity, and their location in the scenario with allowed hydrogen pipeline infrastructure expansion

8.2.7 System cost - Scenario with high GHG emission and country risk profile

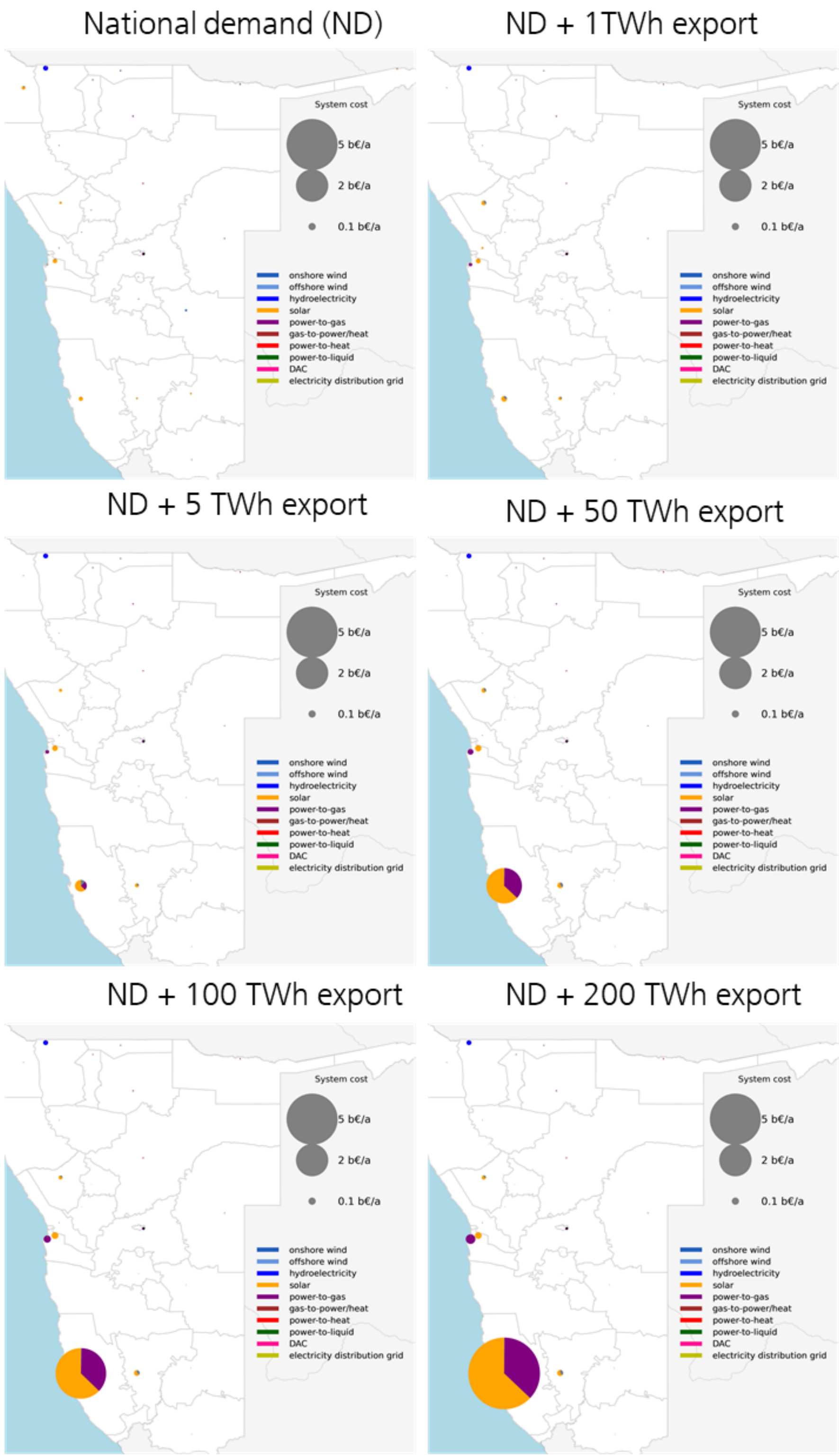

Fig. 8.7: System cost per technology in a scenario with high GHG emission and country risk profile

8.2.8 Infrastructure - Scenario with high GHG emission limit and country risk profile

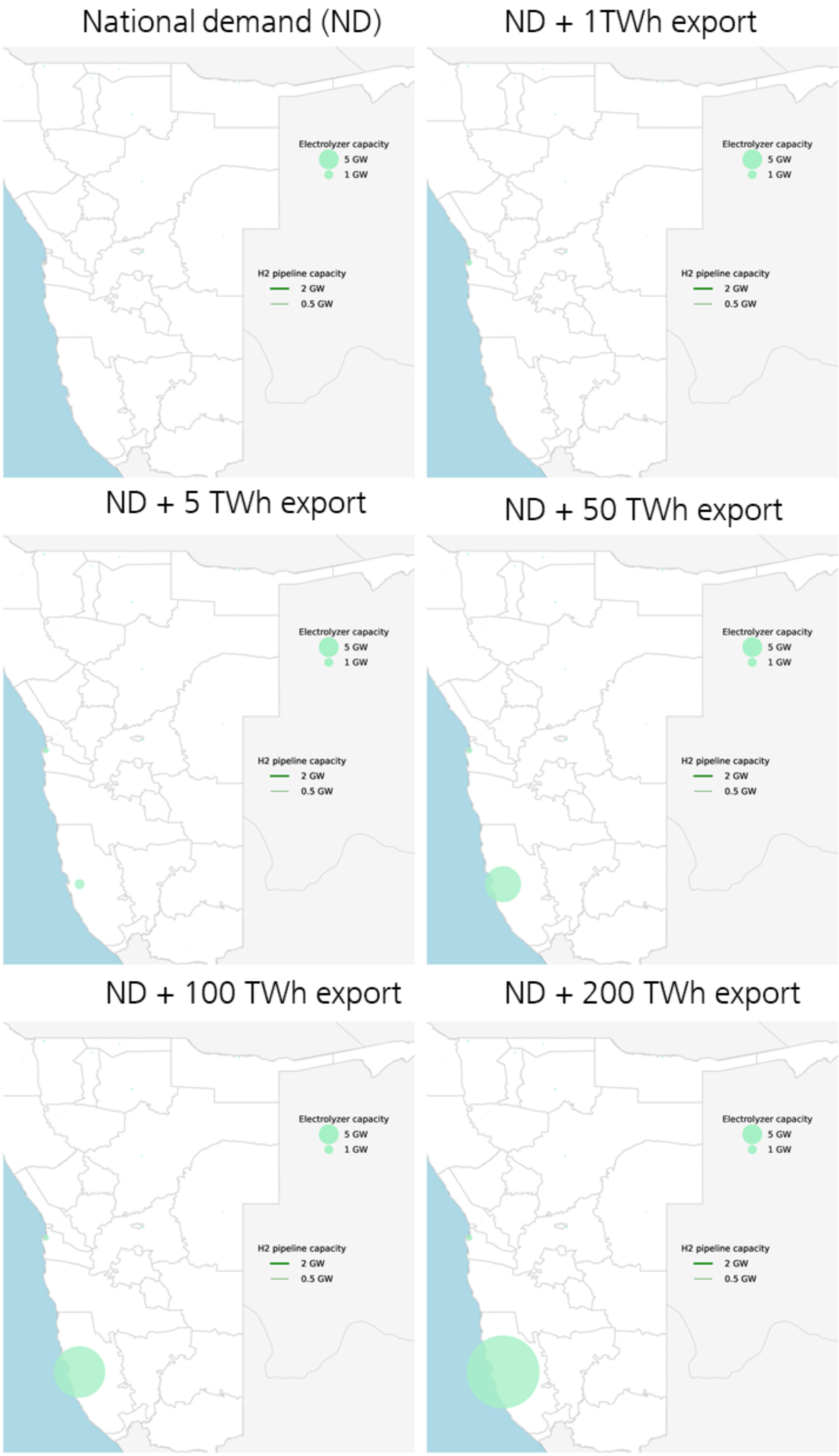

Fig. 8.8: Electrolyzer capacity and location - Scenario with high GHG emission limit and country risk profile

8.2.9 System cost - Scenario with highest GHG emission limit and country risk profile

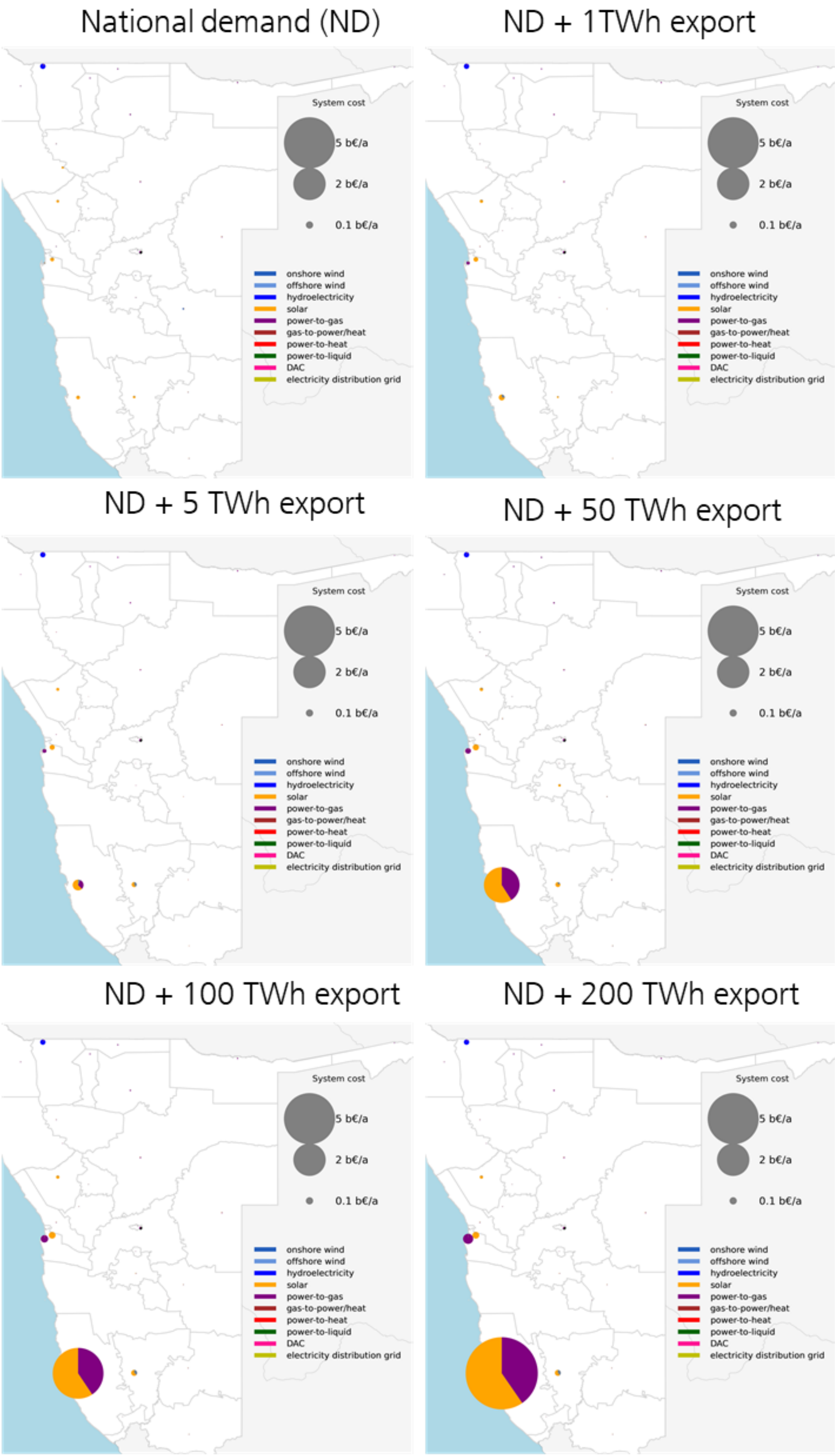

Fig. 8.9: System cost per technology in case of scenario with highest GHG emission limit and country risk profile (conservative)

8.2.10 Hydrogen infrastructure - for highest GHG emission limit and country risk profile

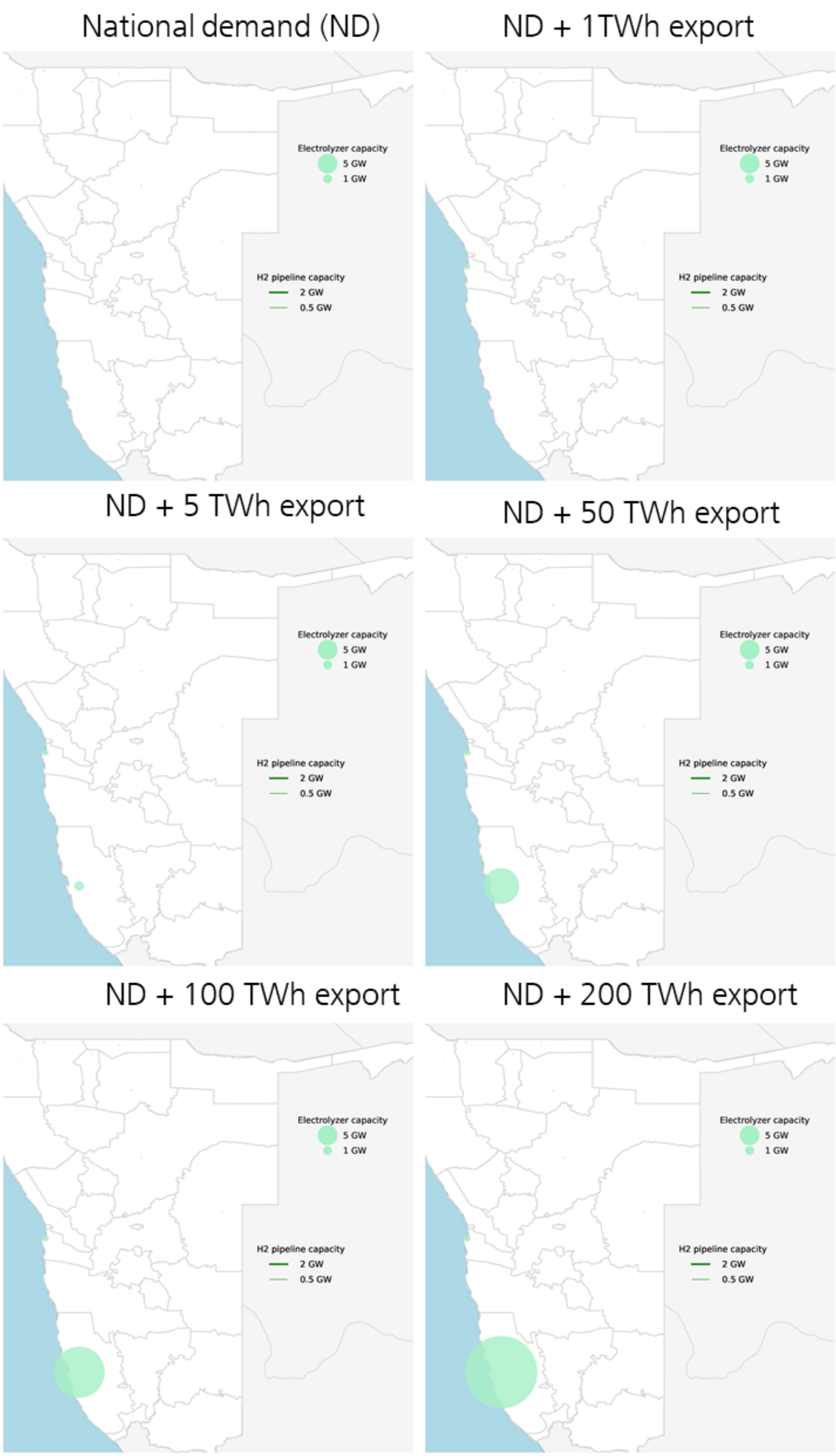

Fig. 8.10: Hydrogen infrastructure capacity - for the highest GHG emission limit and country risk profile (conservative)

8.2.11 Existing Hydrogen projects and their investment cost

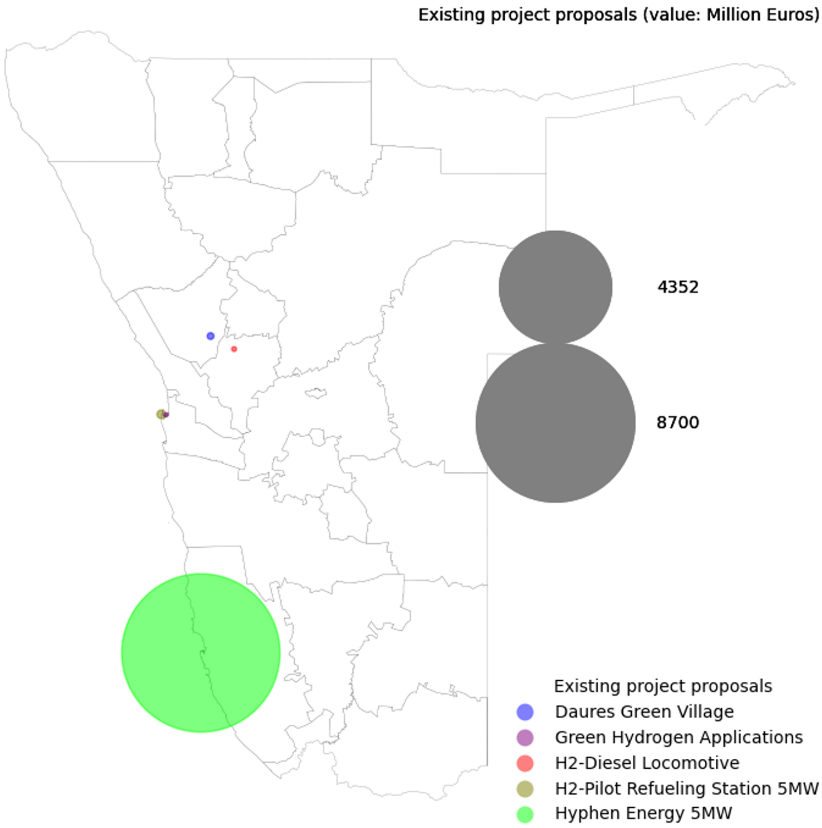

Fig. 8.11: Existing project proposal in Namibia to hydrogen push towards hydrogen economy

8.3 Additional tabular data

Additional tabular data extracted from model results and are present in the section below.

Tab. 8.6: Expanded generation capacities in Namibia for 2030 in three scenarios

Technology	solar	onwind	offwind	ror	oil	coal	csp
Optimistic 2030 Capacity [MW]	**4396.262550**	5.894398	0.163178	213.779148	58.014189	110.632435	0.222181
Optimistic 2030 Share[%]	72.450267	0.097139	0.002689	3.523074	0.956072	1.823219	0.003662
Realistic 2030 Capacity [MW]	2569.247858	81.597256	0.016239	213.779148	58.014189	110.632435	0.020182
Realistic 2030 Share[%]	75.027638	2.382818	0.000474	6.242817	1.694141	3.230708	0.000589
Conservative 2030 Capacity [MW]	3139.701874	**112.842644**	**0.090925**	213.779148	58.014189	110.632435	**0.154006**
Conservative 2030 Share[%]	58.969963	2.119413	0.001708	4.015206	1.089624	2.077901	0.002893

Tab. 8.7: Variation of system cost with an increased network length of hydrogen infrastructure

Network Length [GWKM] / Export Quantity [TWh]	**0**	**750**	**1500**	**2250**
0	1.11	1.11	1.11	1.11
1	1.17	1.16	1.16	1.16
5	1.49	1.48	1.47	1.48
50	5.20	5.07	5.07	5.06
100	9.32	9.16	9.11	9.09
200	17.57	17.38	17.29	17.24

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Colophon

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