Delft University of Technology

Master Thesis

Pipelines and Politics: a hydrogen network between North Africa and Europe under economic and geopolitical constraints

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Preface

Over the past eight months, I have had the opportunity to fully immerse myself in this research project. Having previously explored network analysis in my bachelor thesis, I was eager to deepen my understanding of the field—this time in combination with policy-oriented challenges. The process of exploring that intersection has been both rewarding and intellectually stimulating. I am proud of the insights I have gained and the final result of this thesis.

I would like to extend my sincere thanks to my supervisors for their guidance, encouragement, and the many valuable discussions. First and foremost, I am grateful to Petra, with whom I met almost every week throughout this process. Her thoughtful feedback, caring approach, sharp (and sometimes firm) remarks, and engaging sparring sessions were a constant source of motivation and helped me grow both academically and personally. I also want to thank Aad for his valuable input and fresh perspective, which challenged me to think more broadly about the topic and to consider the wider implications of my work.

Lastly, I wish to thank my family, friends, and girlfriend for their unwavering support and for keeping me sane outside of my modeling efforts. Your encouragement and patience meant a great deal to me during this journey.

I hope you enjoy reading it!

Executive Summary

As Europe intensifies its decarbonization efforts, green hydrogen has emerged as a pivotal energy carrier in reducing emissions from hard-to-abate sectors, such as heavy industry and long-distance transport. While Europe has made considerable progress in expanding renewable electricity production, spatial and socio-political constraints limit its ability to meet future hydrogen demand domestically. To address this, the European Union (EU) aims to import a significant share of its hydrogen from regions with abundant renewable potential, particularly North Africa. This ambition, however, presents complex questions regarding infrastructure development, cross-border cooperation, and exposure to geopolitical instability.

This thesis addresses these issues by designing and analyzing a cross-continental hydrogen pipeline network connecting North Africa and Europe. The study is guided by the following central research question:

> *How can a cost-efficient and resilient hydrogen pipeline infrastructure be designed to connect North Africa and Europe, while accounting for geopolitical risks?*

The research begins with an assessment of hydrogen demand in European industrial clusters and the selection of suitable production sites in North Africa and southern Europe. The existing natural gas pipeline system serves as the basis for infrastructure planning, leveraging its spatial extent and potential for partial reuse.

To support this analysis, a multi-phase methodological framework was developed. First, a Steiner-based network reduction process was applied to eliminate redundant infrastructure elements from the gas network while preserving essential connectivity. Second, the reduced network was segmented into three clusters using the Girvan–Newman algorithm, enabling the application of optimization tools at a manageable computational scale. Third, the Optimal Network Layout Tool (ONLT) was used to design pipeline configurations that minimize infrastructure costs within each cluster. This required adapting the ONLT with an extended cost function that distinguishes between new construction, repurposing, and reinforcement. Finally, the optimized subnetworks were recombined and evaluated under a set of geopolitical and infrastructural disruption scenarios using the maximum flow algorithm. This approach enabled the assessment of the network's capacity and flexibility under different stress conditions.

The results indicate that under ideal cooperative conditions, full hydrogen demand can be met with relatively low capital investment. The baseline network, computed through cost-minimizing algorithms, makes strategic use of existing infrastructure while minimizing new construction. However, the analysis reveals that this approach lacks redundancy. In scenarios simulating geopolitical disruption, such as Algeria ceasing cooperation or sabotage of the Morocco–Spain connection, the network's ability to deliver hydrogen drops by as much as 12.5% without any change to its physical structure. This demonstrates a key vulnerability inherent in tree-like infrastructure systems optimized solely for cost.

Scenario-based testing also shows that partial repurposing of unused infrastructure can mitigate some of these losses. For instance, reactivating a pipeline between Morocco and Algeria in response to sabotage improves delivery from 87.5% to 92.7% of demand, though it requires more than €10 billion in additional capital investment. This finding illustrates that a modest increase in redundancy can significantly enhance network resilience. It also underscores the importance of planning such flexibility into the system from the outset, rather than as an ad hoc response.

The model developed in this thesis offers a replicable and scalable method for evaluating the economic and structural properties of large-scale hydrogen transport networks. However, several limitations remain. Future research should extend the cost function with country-specific parameters and dynamic pricing, integrate endogenous production modeling based on renewable resource availability, and explore alternative network topologies that balance cost and robustness. Developing dynamic and multi-stage planning models could further support long-term decision-making in the face of evolving technologies and market conditions.

This study contributes to the emerging discourse on green hydrogen infrastructure by demonstrating that an economically efficient and geopolitically robust pipeline network is achievable—if carefully planned. It shows that even within the limits of current data and tools, infrastructure strategies can be designed to support both decarbonization and energy security goals. By aligning technical modeling with geopolitical awareness, this research offers practical insights for policymakers, infrastructure planners, and energy strategists working toward a connected and resilient hydrogen economy between Europe and North Africa.

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1 Introduction

The accelerating impacts of climate change and growing geopolitical tensions are reshaping the global energy landscape. As the urgency to reduce carbon emissions intensifies, countries face the dual challenge of transforming their energy systems while safeguarding long-term energy security. This transition is not only technical—it is deeply political and strategic.

Amid this shift, hydrogen has emerged as a symbol of future energy ambitions. Green hydrogen holds the potential to decarbonize sectors where electrification is currently not viable, such as heavy industry and long-distance transport, also referred to as hard-to-abate sectors (Griffiths et al., 2021). It is increasingly viewed as a key pillar of the energy transition, capable of bridging regional imbalances in renewable resource availability and reducing dependence on fossil fuels.

At the same time, the global race to establish hydrogen supply chains is revealing new questions. Who will produce hydrogen, who will consume it, and how will it move across borders? What risks—economic, political, or infrastructural—could threaten its development? And how can countries cooperate in ways that are both equitable and resilient?

These questions form the backdrop to this thesis. They point to the growing urgency of rethinking how and where energy is produced, and how international cooperation can shape future energy systems. Nowhere is this more evident than in Europe, where decarbonization goals and geopolitical pressures increasingly intersect.

The European Union (EU) has positioned itself as a leader by setting ambitious decarbonization and energy diversification goals. As part of the European Green Deal, the EU has committed to ambitious climate goals, including net-zero greenhouse gas emissions by 2050 and a 55% reduction by 2030 compared to 1990 levels (European Commission, 2021a). While Europe is actively expanding its renewable energy capacity, it is expected to remain reliant on energy imports for the foreseeable future. This vulnerability was underscored by the energy crisis following Russia's invasion of Ukraine, which exposed the risks of overdependence on a single supplier. In reaction, the REPowerEU plan was launched to reduce reliance on Russian fossil fuels, accelerate renewable energy adoption, and diversify external energy sources (European Commission, 2022). Within this strategy, green hydrogen has emerged as a promising solution—not only for decarbonizing heavy industry, but also for strengthening Europe's energy resilience.

The EU's Hydrogen Strategy outlines a phased approach to scale hydrogen production and consumption, aiming to increase hydrogen's share in the energy mix to 13-14% by 2050 (European Commission, 2020). It also states an interim goal of producing up to 40 GW or 10 million tonnes of hydrogen by 2030 domestically, while also importing the same amount. To match these import goals, the EU seeks cross-border cooperation with the Southern Mediterranean region. North African countries could be just that strategic area, rich in solar and wind resources, to develop large-scale hydrogen production and establish robust energy interconnections (European Commission, 2021b; Confédération Générale des Entreprises du Maroc, 2021). There are, however, complicating factors. The Southern Mediterranean is rife with geopolitical challenges, such as ongoing conflicts in Libya, Syria, and Western Sahara, as well as external interference from global powers such as Russia and China (European Commission, 2021b; Schaer, 2024; Keizer & Bartling, 2024). These tensions pose risks to energy security and the stability of the region, complicating the creation of a hydrogen network.

The geopolitical and environmental stakes also present an opportunity for strategic partnerships between the EU and its Southern neighbors. A hydrogen-based energy network can enhance energy security, reduce fossil fuel dependence and foster regional stability by promoting economic growth and cooperation if done right(European Commission, 2021b; Arezki, 2023). This research focuses on designing a cost-effective hydrogen supply network from North Africa into the EU to supply Europe's hard-to-abate industrial clusters, while taking into account geopolitical risks that may arise and their influence on energy robustness. The research will lead to policy recommendations designed to guide both the EU and North African stakeholders toward a sustainable and mutually beneficial energy partnership.

The societal relevance of this study lies in its contribution to one of the defining challenges of our time: how to transition to a low-carbon energy system that is not only technically viable, but also geopolitically resilient and socially just. As climate change accelerates and global tensions disrupt energy flows, Europe's push to decarbonize—especially in light of the crisis triggered by Russia's invasion of Ukraine—raises a fundamental question: where will clean energy come from, and how can it be secured fairly?

North Africa, with its abundant solar and wind resources, offers a promising answer. Linking this renewable potential to European demand through hydrogen infrastructure could enhance Europe's energy security while fostering economic growth in North African countries. However, such cooperation also brings risks. Without careful planning, it could deepen existing inequalities or create new dependencies.

This research contributes to a broader conversation about how cross-border infrastructure can be designed to support not just energy trade, but also long-term political stability, inclusive development, and international partnership. By engaging with the intersection of technology, policy, and global cooperation, the study addresses a growing societal demand for more equitable and resilient energy systems.

The academic relevance of this study stems from the integration of technical, economic, and geopolitical considerations into a unified framework for evaluating international hydrogen infrastructure. While much of the current literature on hydrogen transport focuses either on engineering design or on geopolitical analysis, this thesis brings these together into a more integrated approach. It introduces a methodological innovation by adapting large-scale, spatially detailed network data to tools traditionally used in network analysis. This allows for a more nuanced simulation of pipeline configurations under geopolitical uncertainty. In doing so, the research contributes to the broader academic discourse on energy transition strategies by illustrating how hydrogen networks can be designed to balance economic feasibility, resilience to geopolitical risks, and system-level efficiency. These insights support the development of more informed and adaptable frameworks for cross-border energy cooperation.

1.1 Literature review

To develop a comprehensive overview of existing publications on the matter, a literature review was conducted on hydrogen networks within Europe and North Africa. After an initial screening, a total of 15 sources were selected as they directly addressed core themes of cross-regional infrastructure challenges, cost optimization, and technological advancements specific to hydrogen networks within the European and North African contexts. These selected works provided a balanced view of the current landscape, highlighting both practical applications and unresolved challenges in hydrogen infrastructure development. The table below lists these sources and assesses them on different aspects. After, the insights that follow from assessing the sources are discussed. These insights are translated into knowledge gaps in section 1.2.

The conducted literature review reveals several recurring themes. Some variation lies in the geographical scope of the reviewed studies. While many focus on hydrogen projects within Europe—particularly in the North Sea region (Martínez-Gordón et al., 2022; Glaum et al., 2024; Brosschot, 2022) and the Netherlands (Geutjes, 2021; Nijmeijer, 2023)—others concentrate on intercontinental dimensions. Research by Cavana & Leone (2021) and Timmerberg & Kaltschmitt (2019) emphasizes hydrogen trade routes between North Africa and Europe, broadening the discourse beyond domestic infrastructure to include international cooperation and long-distance transport.

A second key theme concerns the present and future integration of hydrogen as cross-sectoral energy carrier. Studies like Neumann et al. (2023), Huisman (2021), and Brosschot (2022) mention that hydrogen can serve as buffer or stabilizing element in the energy systems, managing the fluctuating supply of renewable energy. In addition, research by de Waal (2024) introduces liquid organic hydrogen carriers (LOHC) as a promising alternative for flexible hydrogen transport, underscoring the expanding range of technological options available.

Cost considerations are mentioned extensively throughout the literature. Authors such as Geutjes (2021) and Neumann et al. (2023) point out the cost advantages of repurposing existing natural gas pipelines for hydrogen. Siderius (2022) focuses on the finances of the hydrogen refueling infrastructure, while de Pater (2016) investigates the economics of integrating renewable energy within the European grid.

Despite the optimism surrounding hydrogen's role in the energy transition, several critical challenges remain. The integration of variable renewable energy sources remains an issue, as noted by Martínez-Gordón et al. (2022) and Glaum et al. (2024). Uncertainty surrounding future hydrogen demand and supply complicates infrastructure planning, as hydrogen production and consumption is still limited (Huisman, 2021). Regulatory differences and the challenge of adapting existing infrastructure also present significant obstacles, according to Nijmeijer (2023), Geutjes (2021), and Brosschot (2022). Finally, hydrogen purity and material compatibility issues, particularly in pipeline systems, further complicate the technological transition, as examined by de Waal (2024).

1.2 Knowledge gaps

While several studies have examined the feasibility of a hydrogen network connecting North Africa to Europe, knowledge gaps remain in the analysis of infrastructure requirements, geopolitical implications and economic feasibility. Existing research has mainly focused on blending hydrogen into natural gas pipelines, yet the infrastructure expansion and alteration necessary for dedicated hydrogen transport remains underexplored. Additionally, extensive cross-border and intercontinental hydrogen transport is insufficiently analyzed as most studies focus on smaller scale networks. A more detailed and comprehensive network study is required to address these gaps.

Another research gap lies in the absence of a study on a highly detailed international network. Studies such as Huisman (2021) acknowledge the potential for detailed hydrogen infrastructure, but do not provide a fully developed model that accounts for a highly detailed spatial distribution. Further analysis is needed to determine the optimal layout for a cross-border hydrogen network with a detailed network structure.

Beyond technical considerations, the potential geopolitical risks associated with hydrogen imports from North Africa are not taken into account. While Cavana & Leone (2021) and Huisman (2021) explore aspects of cross-border energy cooperation, they do not assess the geopolitical dependencies that could impact large-scale hydrogen trade. The political environment in exporting nations and global geopolitics has great influence on the security of long-term energy agreements. Recent energy crises in Europe have demonstrated the risks of over-reliance on external energy sources, underscoring the need for diversification strategies and geopolitical risk assessments. Mapping these geopolitical trends will provide a clearer understanding potential political instability and supply disruptions.

The economic feasibility of large-scale hydrogen transport also remains uncertain. While studies such as Brosschot (2022) and de Waal (2024) provide initial assessments of transport costs, there is limited research on the financial implications of pipeline construction, repurposing, and reinforcement. As noted by Siderius (2022) and Nijmeijer (2023), refining cost models is essential for ensuring an economically viable hydrogen network. Further research is needed to evaluate capital investment requirements, operational costs, and the impact of market fluctuations on network stability and efficiency.

1.3 Research question and sub-questions

To address the current knowledge gaps, this study aims to support decision-making on the development of a cost-efficient and resilient hydrogen infrastructure. It focuses on the influence of geopolitical scenarios in shaping hydrogen infrastructure and the trade-offs between cost and resilience in infrastructure design. In doing so, the study contributes methodologically by demonstrating how large, geographical infrastructure data can be made compatible with existing network optimization tools. By simulating disruptive scenarios and exploring network responses, the research provides insight into critical network segments, structural vulnerability of the network and design strategies that can mitigate the impact of these disruptive scenarios.
These considerations lead to the following research question:

> *How can a cost-efficient and resilient hydrogen pipeline infrastructure be designed to connect North Africa and Europe, while accounting for geopolitical risks?*

1.3.1 Subquestions

To address the main research question effectively, it is divided into several subquestions.

1. *Where are hard-to-abate industrial clusters situated in Europe and what are their energy needs?*
2. *What are adequate locations in Europe and North Africa for the possible production of green hydrogen?*
3. *How can economic feasibility of repurposing and expanding an existing pipeline network for hydrogen transport be calculated?*
4. *How can a detailed network analysis be conducted on an extensive, detailed dataset with the tools available, while keeping computational time to acceptable levels?*
5. *Which geopolitical tensions exist that are of possible influence on a pipeline infrastructure between North Africa and Europe, and how can they be mitigated?*
6. *How can the performance of the system configurations be measured?*
7. *What is the most cost-effective approach for developing a pipeline infrastructure between North Africa and Europe?*

1.4 Thesis outline

This thesis is structured in nine chapters, each addressing a specific part of the research and collectively contributing to answering the main research question. The outline below provides an overview of the structure and indicates where each of the subquestions is addressed.

Chapter 1 introduces the context, societal and academic relevance of the study, the identified knowledge gaps, and the central research question. It also introduces the subquestions that will help answer the research question. Chapter 2 outlines the current hydrogen policy ambitions and existing energy partnerships between Europe and North Africa. It highlights the role of hydrogen in European decarbonization and identifies where industrial clusters are located, answering subquestion 2 and partially 1.

Chapter 3 introduces the theoretical foundation of the study. It explains the rationale for using graph theory and network optimization to model pipeline infrastructure. This provides the conceptual basis for answering subquestion 4. Chapter 4 presents the modeling approach developed for this research. It introduces the combination of network reduction, clustering, and optimization, and describes how the network is prepared for scenario analysis. Subquestions 3 and 4 are addressed here, focusing on cost modeling and how large datasets can be simplified and made compatible with infrastructure modeling tools. Chapter 5 describes the data sources and the operationalization of model parameters, including hydrogen demand, production capacity, and the spatial pipeline network. Subquestion 1 is completely answered in this chapter. Chapter 6 introduces the experimental design of the study. It presents the performance metrics used to evaluate system outcomes and explains how different geopolitical and infrastructural scenarios are constructed. Subquestions 5 and 6 are addressed in this chapter.

Chapter 7 presents the outcomes of the scenario simulations. It includes a detailed discussion of system performance, robustness, and the trade-offs between cost and resilience. The final subquestion (subquestion 7) is answered in this chapter, as the most cost-effective configuration is determined. Chapter 8 interprets the results in light of the broader academic and policy debate. It reflects on the methodological limitations and suggests directions for future research. Chapter 9 answers the main research question, synthesizes the key findings, and formulates policy recommendations for designing a cost-efficient and geopolitically resilient hydrogen pipeline infrastructure between North Africa and Europe.

2 Background and system context

This chapter provides the necessary background information to contextualize the modeling efforts in later chapters. While the introduction has already outlined the broader motivations and objectives of the study, this section dives deeper into the structural and technical foundations of the hydrogen network. It first explores where future hydrogen demand is expected to emerge and explains why Europe will be structurally dependent on imports to meet that demand. The chapter then defines the geographical scope of the model, identifies both consumer and producer countries, and presents an overview of Europe's and North Africa's existing gas infrastructure and repurposing possibilities for hydrogen transport. Potential hydrogen production sites are selected based on technical and environmental criteria, and supply assumptions are introduced to support the modeling setup. Finally, a stakeholder analysis is conducted to identify the most relevant actors and the criteria they prioritize. This background helps ensure that the subsequent modeling framework is grounded in realistic system characteristics and stakeholder needs.

2.1 Hard-to-abate sectors and the promise of hydrogen

Understanding where hydrogen demand arises is critical to shaping any future infrastructure. Among the most significant sources of this demand are so-called hard-to-abate sectors. The following section outlines the characteristics of these sectors and explains how hydrogen can serve as a viable low-emission substitute.

Hard-to-abate sectors present major challenges in the transition to a low-carbon economy. These sectors include iron and steel, cement, basic chemicals, petrochemicals, and long-distance freight transport such as shipping and heavy-duty trucking. What unites these activities is their combination of high energy intensity, reliance on fossil fuels, and emissions that are often intrinsic to the production process itself. Collectively, they are responsible for approximately 30% of global annual CO_2 emissions (Nault, 2022). Within this share, the iron and steel sector alone emits around 3.7 Gt CO_2 per year (Ashley, 2025), while cement manufacturing contributes another 8% of the global total (Purton, 2024).

Reducing emissions in these sectors is particularly difficult for several reasons. First, many industrial processes operate at very high temperatures—typically over 1000°C—which are difficult to achieve with direct electrification using renewable energy sources. Second, some emissions are inherent to the chemical reactions involved, as in cement production, where CO_2 is released during the calcination of limestone. Third, the sectors are built around long-established infrastructures that use fossil fuels like coke, oil, or natural gas, and replacing these systems carries both technical and financial challenges (Gupta, 2022).

Hydrogen presents a promising pathway to overcome these barriers. Clean hydrogen—produced via electrolysis using renewable electricity or from fossil sources with carbon capture—can fulfill several roles within hard-to-abate industries (Nault, 2022). It can provide high-temperature process heat, act as a feedstock in chemical reactions, or serve as a reducing agent in metal production. For example, in the steel sector, hydrogen can replace coking coal in the direct reduction of iron ore. In this approach, water vapor is emitted instead of CO_2, significantly reducing the carbon footprint of steel production (IEA, 2023).

Hydrogen also enables cleaner operation in other sectors. In the cement industry, hydrogen is being tested as a co-firing fuel for kilns and as a full substitute for fossil-based combustion (Purton, 2024). In heavy-duty trucking, hydrogen can extend the driving range of freight vehicles beyond what is possible with batteries, making it suitable for long-haul routes where frequent charging is impractical (Stauffer, 2024). These advantages make hydrogen particularly attractive for industrial clusters where carbon-intensive operations are geographically concentrated, as centralized deployment of hydrogen supply infrastructure—such as pipelines or electrolysers—can serve multiple nearby facilities efficiently.

Although low-emission hydrogen currently accounts for less than 1% of global hydrogen use (IEA, 2023), its uptake is accelerating. The emergence of commercial-scale hydrogen-based steel plants, co-firing trials in cement, and policy-driven expansion of hydrogen infrastructure all indicate growing momentum. For hard-to-abate industrial clusters in Europe, access to clean hydrogen could enable decarbonization pathways that are otherwise infeasible, making them a logical target for early investment in hydrogen networks.

2.2 The necessity of hydrogen imports for Europe

Although hydrogen shows promise as a decarbonization vector, it cannot be fully supplied by domestic means in Europe. The next section outlines why the EU cannot rely on internal production alone and why international cooperation, particularly with North Africa, becomes essential.

A couple of factors play a key role in the necessity of hydrogen import for the European market. The primary limitation lies in the availability of renewable energy. Producing green hydrogen through electrolysis requires large and consistent supplies of electricity from renewable sources such as wind and solar. However, many European countries are already facing constraints in land use, public acceptance, and transmission infrastructure, which limits the rate at which renewable capacity can be expanded (Nault, 2022).

As mentioned in section 1, the European Commission's REPowerEU plan, launched in response to the 2022 energy crisis, acknowledges this shortfall explicitly. It sets a target of producing 10 million tonnes of renewable hydrogen annually within the EU by 2030—but also includes a parallel target of importing an additional 10 million tonnes from non-EU countries (European Commission, 2022). This import goal reflects the reality that land-intensive solar and wind developments may be more feasible in neighboring regions with better natural conditions, particularly North Africa.

Electrolysis itself is also energy-inefficient, with conversion losses ranging between 30–40% depending on the system (IEA, 2023). This further amplifies the strain on limited renewable electricity. Even the Netherlands, one of the front-runners in offshore wind development, will struggle to meet both electrification goals and hydrogen production targets simultaneously. As stated in national planning documents, most future offshore wind capacity is already earmarked for direct electricity demand, leaving little surplus for electrolysers (Netherlands Enterprise Agency, 2021).

Taken together, these constraints imply that imports will be a structural component of Europe's hydrogen economy, not a transitional measure. Developing reliable supply corridors with neighboring regions is therefore a strategic necessity, rather than a policy preference.

2.3 Participating countries and demand clusters

To model the system of supply and demand effectively, we must understand which countries play a role in either or both. Although the broad geographical scope of the research was already established in the introduction, a network between North Africa and Europe, further specification is needed. The following section defines that defined scope by identifying key hydrogen-consuming and -producing countries, followed by a breakdown of clustered industrial demand.

The general scope is defined to a certain set of countries. Participating countries are chosen based on the presence of an extensive existing pipeline infrastructure in the country and proximity to existing connections between Europe and North Africa. The selection includes both consuming and producing countries. Consuming countries that were selected by these criteria are the Netherlands, Germany, Belgium, Austria, Switzerland, France, Spain, Portugal, and Italy. Several industrial clusters within the hard-to-abate sectors, referred to as hard-to-abate due to their high energy and emissions intensity, can be identified in these countries. Hydrogen is expected to play a significant role in decarbonization of just these sectors (Technology Executive Committee, 2023). The industrial clusters focus on steel, petrochemicals and chemicals.

Producing countries in Africa include Morocco, Libya, Algeria, and Tunisia, which were chosen for the same existence of infrastructure and proximity to European consumer countries. For domestic production, the Netherlands, Spain and Germany are chosen, since there are existing plans for large scale hydrogen production at hand. A further insight to industrial site selection and production locations will be given further on in this chapter.

2.3.1 Hard-to-abate industrial sites in Europe

In Table 1 the hard-to-abate industry clusters for participating countries are listed. These clusters all are dominated by steel production, petrochemistry and chemistry. The clusters were identified by consulting sources of European organizations representing the mentioned hard-to-abate sectors (Cefic, 2024; Concawe, 2024; Eurofer, 2023). In some cases, an industrial cluster has multiple sectors, such as Linz in Austria. This will be taken into account in determining a clusters demand by adding the cluster as one entry to the model.

Table 1: Industrial clusters by sector and country

Steel	Petrochemicals	Chemicals
[AT] Donawitz	[AT] Schwechat	[AT] Linz
[AT] Linz	[BE] Antwerpen	[AT] Vienna
[BE] Ghent	[FR] Gonfreville	[BE] Brugge
[FR] Dunkerque	[FR] Donges	[BE] Antwerpen
[FR] Fos-sur-Mer	[FR] Feyzin	[BE] Ghent
[DE] Bremen	[FR] Lavera	[FR] Le Havre
[DE] Dillingen	[DE] Burghausen	[FR] Port Jerome
[DE] Duisburg	[DE] Ingolstadt	[FR] Lamotte
[DE] Eisenhüttenstadt	[DE] Karlsruhe	[FR] Bazancourt
[DE] Salzgitter	[DE] Leuna	[FR] Villers-St-Paul
[DE] Völklingen	[DE] Neuhoff	[FR] Metz
[IT] Taranto	[DE] Rheinland	[FR] Mulhouse
[NL] IJmuiden	[DE] Gelsenkirchen	[FR] Lyon
[ES] Avilés	[DE] Salzbergen	[FR] Commentry
[ES] Gijón	[DE] Schwedt	[FR] Balan
	[DE] Harburg	[FR] Les Roches Roussillon
	[DE] Brunsbüttel	[FR] Grenoble
	[DE] Wilhelmshaven	[FR] Pau

Table 1: Industrial clusters by sector and country (continued)

Steel	Petrochemicals	Chemicals
	[IT] Porto Maghera	[FR] Berre
	[IT] Trecate	[FR] Lavera
	[IT] Sannazzaro	[DE] North Rhine Westphalia
	[IT] Busalla	[DE] Rhineland
	[IT] Ravenna	[DE] Palatinate and Hesse
	[IT] Falconara	[IT] Milan
	[IT] Porto di Vasto	[IT] Bergamo
	[IT] Taranto	[IT] Brescia
	[IT] Milazzo	[IT] Venice (Porto Marghera)
	[IT] Priolo	[IT] Ferrara
	[IT] Gela	[IT] Ravenna
	[NL] Vlissingen	[IT] Novara
	[NL] Rotterdam	[IT] Brindisi
	[NL] Pernis	[IT] Priolo–Augusta–Melilli
	[ES] Cartagena	[IT] Porto Torres
	[ES] Castellon	[NL] Rotterdam
	[ES] Huelva (La Rabida)	[NL] Chemelot
	[ES] La Coruña	[NL] Delfzijl
	[ES] Petronor (Somorrostro)	[NL] Eemshaven
	[ES] Puertollano	[ES] Huelva
	[ES] San Roque	[ES] Tarragona
	[ES] Tarragona	[ES] Barcelona
	[CH] Cressier	[CH] Basel
	[PT] Sines	[CH] Wallis
		[CH] Geneva
		[CH] Zug
		[CH] Lucerne
		[PT] Porto
		[PT] Estarreja
		[PT] Lisbon
		[PT] Sines

This section gives a general overview of which industrial clusters could be taken into account for hydrogen usage. The specific demand of the clusters and which can be provided with hydrogen, will be specified in subsection 5.2.

2.4 The existing gas network as a foundation for hydrogen transport

With demand centers and key actors identified, it is also important to understand the existing energy infrastructure across the study region. This section provides an overview of the current natural gas pipeline network in Europe and North Africa, which serves as a physical baseline for examining possible future hydrogen transport routes.

Europe and North Africa are connected by a historically well-developed network of natural gas infrastructure. This system has long supported cross-border energy flows and continues to play a central role in regional energy supply. Many of the countries involved in this study—both producers and consumers—maintain extensive domestic and international gas pipeline systems.

In North Africa, three main pipelines connect the region to Southern Europe. The Maghreb–Europe Pipeline (GME) links Algeria to Spain via Morocco. The Medgaz Pipeline provides a direct undersea connection between Algeria and Spain. The TransMed Pipeline, one of the oldest in the region, runs from Algeria through Tunisia to Italy. These systems are among the most significant gas export corridors from Africa to Europe and have supported energy trade for decades (ENTSOG, 2024).

Within Europe, countries such as Germany, the Netherlands, France, Belgium, and Italy are key nodes in an integrated gas network coordinated by the European Network of Transmission System Operators for Gas (ENTSOG). This network spans tens of thousands of kilometers and features multiple interconnections between national systems. High pipeline densities and numerous entry and exit points characterize much of Western and Central Europe, facilitating regional energy trade and enhancing grid resilience (ENTSOG, 2024).

Recent technical assessments suggest that a large share of this infrastructure—particularly high-pressure steel pipelines—could be suitable for hydrogen transmission with moderate retrofitting (Télessy et al., 2024). However, this section focuses only on presenting the physical system. More detailed assessments of conversion potential are addressed in later stages of this research.

Figure 1 illustrates the pipeline infrastructure across the selected countries in this study, showing the broad spatial reach and interconnectivity of the existing system. This illustration is created based on data of the The SciGRID_gas dataset, and specifically the merged IGGIELGN subset. This dataset is explained in detail in subsection 5.1.

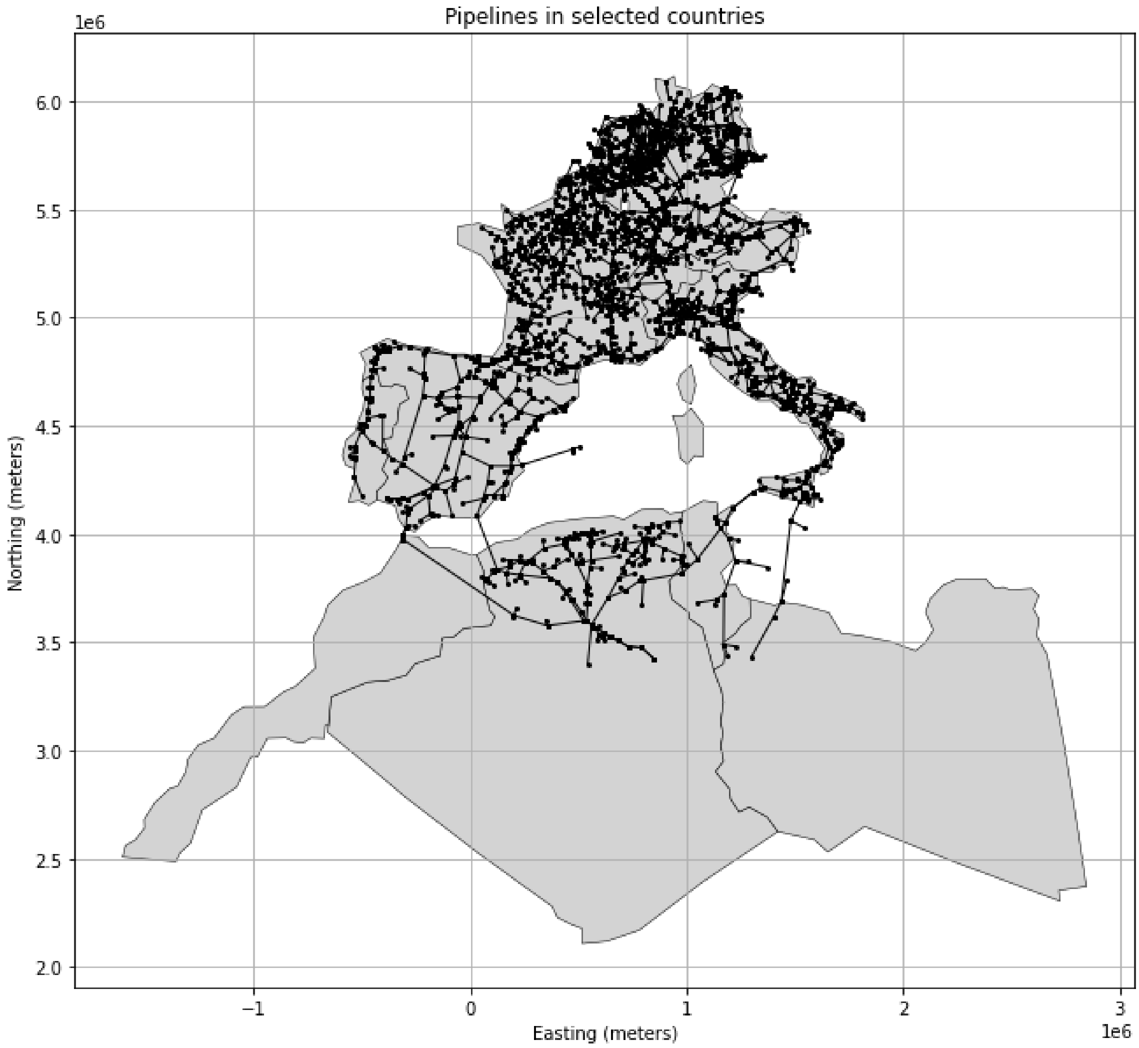

Figure 1: Existing gas pipeline infrastructure in selected European and North African countries (Diettrich et al., 2020)

The overview in this section highlights the physical infrastructure that may, in the future, be leveraged or adapted to support cross-border hydrogen flows. The scale and layout of the existing gas network provide an important reference point for assessing hydrogen transport potential in later stages of this research.

2.5 Production locations

With consumption and existing infrastructure addressed globally, the next focus is production. This section identifies optimal locations for hydrogen production in both Europe and North Africa, based on technical, geographic, and policy criteria. These include access to renewable energy sources, proximity to water and infrastructure, land suitability, and alignment with environmental and policy considerations. The objective is to select representative production sites that are both technically feasible and strategically located to support the envisioned hydrogen network. Based on these factors, a selection of production locations is proposed for both continents, distinguishing between current developments and future potential.

2.5.1 Factors for choosing hydrogen production location

Identifying the best spot to set up a hydrogen production site is subject to a lot of factors. A variety of geographic and infrastructural factors must be taken into account. The most pressing factors are specified below.

The first consideration is access to renewable energy sources. Setting up nearby a (potential) solar, wind, or hydroelectric energy facility is essential for enabling green hydrogen production through electrolysis (National Renewable Energy Laboratory, 2023). In addition to energy supply, water availability in great abundance is also necessary. Electrolysis requires substantial water input, so hydrogen production sites should be located near a reliable water source (de Haldevang, 2021). The presence of nearby infrastructure is another important factor. Access to existing transportation networks, including existing pipeline networks as well as power transmission lines, can significantly reduce logistical and construction costs (Boix, 2023).

Furthermore, land topography and elevation influence site suitability. Flat terrain is preferred for constructing large energy facilities, as it simplifies development and reduces capital costs. In some cases, moderate elevation can also improve solar panel efficiency due to lower temperatures, which improves the viability of solar-driven hydrogen production systems (Ali et al., 2022). Locating production sites near major demand centers offers additional advantages. Distance to industrial hubs reduces transportation needs and ensures a more direct supply chain (Ali et al., 2022). Lastly, environmental considerations must also be addressed. Hydrogen projects should avoid areas with ecological sensitivity and must comply with local and national environmental regulations, to avoid environmental interference and retain social acceptance(Boix, 2023).

Summing up, the optimal location for hydrogen production depends on a combination of geographic, environmental, infrastructural, and policy-related factors. Taking into account all these factors is essential to ensure that facilities are not only technically and economically feasible but also socially and environmentally sustainable. Selecting the optimal production location within each producing country is a complex task that warrants further investigation. While this lies beyond the scope of the present study, a couple of possible locations were identified and are further explained in the following sections.

2.5.2 Hydrogen production locations in North Africa

Taking into account the factors identified in section 2.5.1, a potential hydrogen production location for North African production countries is identified. Starting off with Benghazi, Libya, which presents favorable conditions due to its high solar energy potential and access to seawater. The area benefits from existing infrastructure and proximity to European markets, facilitating efficient hydrogen export (International Renewable Energy Agency, 2023). In Morocco, Chbika is well-suited for hydrogen production. The region offers direct access to seawater, has high solar energy potential and has been identified for large-scale hydrogen and ammonia production (Hernandez, 2024). For Algeria, Skikda in Algeria could be a good location due to its well-developed energy infrastructure, coastal location and integration with existing industrial operations. The area benefits from connectivity to European energy markets, supporting hydrogen transport via pipeline networks (Shaw, 2025). In Tunisia, Gabès is a strategic choice due to its coastal access, seawater availability, and potential for solar and wind energy development. Its existing industrial infrastructure further supports integration into hydrogen supply chains (Shaw, 2025). In Table 2 the locations with their coordinates are displayed.

Location	UTM zone 31 (Easting, Northing)
Libya, Benghazi	2120311.64, 3684051.80
Morocco, Guelmim-Oued Noun	-778787.59, 3277586.33
Algeria, Skikda	847687.28, 4087190.81
Tunisia, Gabès	1157204.22, 3771988.07

Table 2: Identified hydrogen production locations in North Africa and their UTM coordinates (Zone 31).

2.5.3 Hydrogen production locations in Europe

Several large-scale hydrogen production projects are being developed across Europe to support the energy transition and reduce dependence on fossil fuels. Multiple of these locations could be suitable as production sites for this study. The locations that were included are sites where green hydrogen is already produced or going to be produced in future years.

The North Sea, particularly north of the Wadden Islands in the Netherlands, is in demand for the development of large-scale offshore hydrogen production. The Netherlands plans to develop an electrolysis capacity of approximately 500 MW, with production expected to start around 2031 (Rijksoverheid, 2023). The Q13a-A platform near Scheveningen, also in the North Sea, is home to the PosHYdon project, the first offshore hydrogen pilot in the Netherlands, integrating wind power with seawater electrolysis. Hydrogen is transported to shore via existing natural gas pipelines, demonstrating the potential for offshore hydrogen production at scale and reusing natural gas pipelines for hydrogen transport (TNO, 2024).

In Germany, Hamburg has emerged as a key hydrogen hub, with the Hamburg Green Hydrogen Hub using renewable energy sources for large-scale production. Its strategic location, combined with robust transport and port infrastructure, makes it a central distribution point for hydrogen in Europe (Čučuk, 2024). Monzón in Spain has been identified for natural hydrogen extraction, with an investment of €900 million to produce 250,000 tons of hydrogen over the next two to three decades. The region benefits from geological formations enabling natural hydrogen extraction and proximity to Spain's renewable energy infrastructure (Helios Aragon, 2025).

Location	UTM zone 31 (Easting, Northing)
North Sea, Wadden Islands (NL)	650000, 6100000
Q13a-A Platform, NL	542000, 5780000
Hamburg, DE	569800, 5934000
Monzón, ES	730000, 4670000

Table 3: Identified hydrogen production locations in Europe with UTM coordinates (Zone 31).

2.5.4 Concluding remarks

This section answers the subquestion:

What are adequate locations in Europe and North Africa for the possible production of green hydrogen?

By evaluating a range of geographical, infrastructural, and environmental factors, this study identifies eight candidate production sites—four in Europe and four in North Africa—that are well-positioned to support large-scale green hydrogen generation. These sites were selected based on current or planned hydrogen activity, access to renewable resources, proximity to water sources, and availability of infrastructure such as pipelines and ports. Although selecting the optimal production location within each producing country is beyond the scope of this study, the sites included offer a representative basis for modeling an international hydrogen supply network.

2.6 Supply capacity

This study assumes that total hydrogen demand can be met by its production and is evenly distributed across eight selected production locations. While this simplification helps maintain the computational feasibility of the model, it does not reflect the real-world requirements for large-scale hydrogen deployment. In practice, these eight sites are unlikely to meet future demand alone. A far greater number of production facilities will be necessary to achieve the capacity levels projected for a full-scale hydrogen economy. This modeling limitation should be clearly taken into account when interpreting the results and formulating recommendations.

The ability to expand hydrogen production depends not only on the geographic suitability of production sites but also on the availability of financial and physical resources. Developing a large-scale electrolyzer plant involves substantial investment: a 1 GW facility is estimated to require between €730 and €830 million, along with approximately 10 hectares of land per plant (van 't Noordende & Ripson, 2022). These figures illustrate the spatial and financial scale associated with expanding hydrogen production capacity for just a 1 GW facility and thus will be significantly higher for the scale of this research.

Crucially, large volumes of renewable electricity are needed to power these electrolyzers. Green hydrogen production relies heavily on solar and wind energy and must be available at large scale. For context, the largest operational solar farm in the world at this moment in time spans 809 square kilometers and delivers an installed capacity of 5 GW (Cuthbertson, 2024), not nearly enough to power even one of the proposed green electrolyzers. The dutch government has set a target of 21 GW in offshore wind capacity by 2032–2033 to support the growing demand for clean energy (Noordzeeloket, n.d.). The majority will not be available for green electrolyzers, another insight in the scale of the operation to provide enough energy for the electrolyzers.

Although this study does not model the production costs of hydrogen in detail, it is important to recognize the broader investment context in which hydrogen infrastructure is developed. Establishing production sites and building the renewable energy systems needed to power them requires extensive capital. These investments are typically undertaken through collaboration between public and private actors, such as governments and energy companies (Raaijen, 2025). Because it is difficult to estimate the financial contributions of each party with precision and the feasibility to do so on the assigned spots, the capital expenditure associated with hydrogen production and renewable energy deployment is excluded from the final cost analysis and policy recommendations presented in this research.

2.7 Stakeholder analysis

The development of a hydrogen supply network between North Africa and the European Union involves a diverse array of stakeholders, each with distinct roles and interests. Understanding these actors is crucial for ensuring the project's success and feasibility.

The European Union (EU) plays a central role by setting policy frameworks and targets for hydrogen production and import, aiming to achieve climate neutrality by 2050 (European Court of Auditors, 2024). Participating EU member states, such as Germany, Italy, and Austria, are actively involved in developing infrastructure like the SoutH2 Corridor to facilitate hydrogen transport from North Africa to Europe (Francesca Landini & Wacket, 2024).

North African nations, including Morocco, Algeria, and Tunisia, are key hydrogen-exporting countries with significant renewable energy potential. These countries view hydrogen exports as opportunities for economic development and job creation (Hydrogen Council and McKinsey & Company, 2024). However, concerns have been raised about the socio-environmental impacts of such projects, including displacement of local populations and depletion of water resources (Gayle, 2025).

Energy companies are instrumental in hydrogen production and infrastructure development. For instance, TotalEnergies is exploring green hydrogen and ammonia production projects in Morocco, aiming to export to Europe (Hernandez, 2024). Network operators, such as Snam in Italy, are responsible for managing the hydrogen pipeline infrastructure, ensuring efficient and safe operations (Francesca Landini & Wacket, 2024).

Local communities residing near hydrogen production sites or pipeline routes are directly affected by these developments. Their interests include environmental protection, fair compensation, and access to job opportunities. The social impacts of hydrogen projects are multifaceted, encompassing aspects such as community engagement, employment generation, and public health considerations. While these projects offer opportunities for economic growth and job creation, they also present challenges, such as land use changes and safety concerns. Prioritizing community involvement, ensuring equitable access to employment opportunities, and implementing robust safety measures are vital for realizing the potential benefits of hydrogen technologies while mitigating potential risks (Almaraz et al., 2023).

International organizations, like the United Nations and the World Bank, support sustainable development projects and emphasize the importance of environmental sustainability and compliance with international standards. The World Bank approved a $150 million project to promote clean hydrogen development in Chile. This project is the first-ever of its kind approved by the World Bank and will support the country's goal to achieve carbon neutrality by 2050. It includes innovative financing mechanisms that encourage green hydrogen use, stimulate economic activities, create jobs, and enhance local capacity building (Silva, 2024).

Researchers and academics contribute by providing insights into energy systems, geopolitics, and sustainability, aiding in the advancement of scientific understanding and practical implementation of models. An integrative review of 610 peer-reviewed journal articles from the last 50 years provides quantitative and impartial insight into the hydrogen economy, highlighting the importance of research in shaping hydrogen policies and practices (Sharma et al., 2023).

Investors, both private and public, are crucial for financing hydrogen infrastructure projects, seeking returns on investment and alignment with global energy transitions. The World Bank report Green Hydrogen in Developing Countries emphasizes that nations with good renewable energy resources could produce green hydrogen locally, generating economic opportunities and increasing energy security by reducing exposure to oil price volatility and supply disruptions (De Sisternes & Jackson, 2020).

Together, these stakeholders shape the technical, economic, and political landscape in which the hydrogen network will operate. Their involvement influences key decisions around production, transport, and governance. To ensure that the model developed in this thesis reflects these realities, the following subsection derives a set of evaluation criteria based on the interests and responsibilities of the identified actors.

2.7.1 Criteria for evaluating model outcomes

From the stakeholder analysis, several criteria important to the identified actors are derived: economic feasibility, energy security, geopolitical stability, environmental sustainability, social equity, and scalability and flexibility. These criteria are essential for designing an optimal network that addresses the concerns of all stakeholders. However, this research focuses specifically on creating a robust, cost-effective, and geopolitically stable network. Therefore, criteria such as environmental sustainability, social equity, and scalability and flexibility are acknowledged but not addressed within the scope of this study.

Economic feasibility refers to the cost levels of infrastructure construction. Evaluating the specific investments needed to establish the network is vital for assessing its economic viability. Stakeholders concerned with this criterion include the European Union, participating member states, North African nations, energy companies, network operators, and investors.

Energy security and robustness assess the system's performance under various conditions and potential disruptions. This aspect is of interest to the European Union, participating member states, North African nations, and network operators, as it ensures a stable and reliable hydrogen supply.

Geopolitical stability considers the impact of cross-border dependencies, potential political risks, and the necessity of governance frameworks. Addressing these geopolitical uncertainties is crucial for clarity on the geopolitical situation. The European Union, participating member states, international organizations, and North African nations are particularly concerned with this criterion.

2.8 Concluding remarks

This chapter has outlined the background conditions and structural context for modeling a future hydrogen network between North Africa and Europe. It began by identifying the demand drivers within hard-to-abate sectors and discussed why European production alone will be insufficient to meet future hydrogen needs. A regional scope was then defined, highlighting the key consumer and producer countries included in this research. The chapter further provided an overview of the current natural gas pipeline infrastructure, potential production locations, and the assumed supply capacity that informs the modeling exercise. Finally, the stakeholder landscape was examined, and relevant evaluation criteria were derived from their interests.

Together, these elements form the basis for the analytical and methodological decisions made in the remainder of this thesis. The next chapter introduces the theoretical framework used to conceptualize hydrogen infrastructure development under uncertainty and outlines the modeling approach designed to assess network performance under different scenarios.

3 Theoretical framework

The design of infrastructure networks is an important aspect of energy system planning. Involving the optimization of connectivity, capacity allocation and cost-effectiveness for example are common factors. To address these challenges, Heijnen et al. (2020) identify graph theory, mixed-integer (non-)linear programming (MILP) and agent-based model, each offering distinct advantages and limitations.

Graph theory provides a mathematical framework for analyzing network structures, enabling looking into connectivity, shortest paths, and flow optimization of a network. Within energy system modeling, graph-based approaches have been widely used to optimize networks, also hydrogen infrastructure, by identifying the most efficient transport routes and assessing network robustness (Baufumé et al., 2013; Huisman, 2021). Dijkstra's shortest path algorithm and the Ford-Fulkerson maximum flow algorithm are among the frequently used algorithms in network studies (Dijkstra, 2022; Ford & Fulkerson, 1956). The properties of these and others algorithms are well fit for designing and reviewing infrastructure networks.

MILP methods offer a more structured approach, allowing for the formulation of optimization problems that incorporate spatial constraints, economic factors, and operational limitations. These models have also been extensively used in energy system design(Moreno-Benito et al., 2017; André et al., 2013; Murthy Konda et al., 2011). Although MILP offers mathematically extensive and accurate solutions, it is computationally heavy and highly specific problem formulations, making it less flexible for dynamic network conditions.

Agent-based models (ABMs) provide a bottom-up approach that simulates interactions among decentralized agents, allowing the study of emergent system behavior. This technique is particularly relevant for decentralized energy systems and adaptive network planning. Ant Colony Optimization (ACO), an agent-based heuristic inspired by the behavior of social insects, has been applied to find shortest paths between locations of interest and could be used for the problem at hand(Dorigo & Blum, 2005). However, ABMs generally require extensive computational power and are less frequently used in large-scale infrastructure planning compared to graph-based and MILP methods (Heijnen et al., 2014).

Among these methodologies, graph theory is best fit for large-scale hydrogen infrastructure modeling due to its balance between computational efficiency and analytical depth. Unlike MILP, which necessitates detailed parameterization for each optimization problem, graph theory allows for a more intuitive representation of network structures while maintaining adaptability. Similarly, compared to ABMs, graph-theoretical models provide greater transparency and computational feasibility, making them particularly suitable for large-scale infrastructure design (Heijnen et al., 2020).

4 Methodology

As discussed in section 3, this research applies graph theory to evaluate the structure and resilience of a cross-border hydrogen pipeline network. A specific implementation of this theory is made possible by the Optimal Network Layout Tool (ONLT) developed by Heijnen (2020), which is designed for the planning of cost-efficient infrastructure networks such as natural gas or hydrogen grids.

The spatial dataset introduced in subsection 2.4 proved too large to be processed directly by the ONLT. As a result, several preparatory steps were required to simplify and segment the raw dataset—which contains thousands of pipeline segments and nodes—into a form suitable for network optimization. As a result, a multi-step modeling process was developed to reduce network size while maintaining as much of its characteristics as possible. This process forms the backbone of the academic contribution of this thesis.

4.1 Modeling structure

The modeling framework developed for this research consists of four sequential phases, each designed to manage the complexity of a large-scale hydrogen pipeline network and prepare it for optimization and scenario testing.

The first phase focuses on network simplification. The raw dataset includes 2889 pipeline segments and 2295 connection points across the selected countries, which is too large to be processed directly by the ONLT. To address this, the network is simplified using a Steiner reduction technique. This method removes pipelines and nodes that do not contribute to meaningful network connectivity, while preserving essential topological characteristics (Winter, 1987). A more detailed explanation of this technique is provided in subsection 4.2.

Even after the Steiner reduction, the network remained too large for the ONLT. Therefore, a second reduction step was introduced using the Girvan–Newman clustering algorithm. This method divides the network into smaller regions. It allows the network to be processed in parts, without losing the ability to model each region's internal connections. This step ensures that each subnetwork falls within the computational boundaries of the ONLT, as further discussed and explained in subsection 4.3.

The second phase involves applying the ONLT to each of the identified clusters. Within each cluster, the tool calculates an optimal pipeline layout connecting hydrogen producers and industrial consumers at minimum cost. It considers both the reuse of existing pipelines and the construction of new ones, taking into account the economic trade-offs between different pipeline configurations. The ONLT outputs a locally optimized layout for each subnetwork, which reflects realistic constraints related to geography, distance, and cost. A detailed description of the ONLT is given in subsection 4.4.

In the third phase, the optimized subnetworks are combined into one integrated hydrogen network. Since the ONLT cannot directly model inter-cluster connections, this step is necessary to prepare a full network for simulation. The output of the ONLT is stitched together into a unified topology that includes all pipelines and nodes selected during optimization, providing a coherent basis for further analysis.

The final phase of the methodology assesses the robustness of this integrated network using the maximum flow algorithm. Rather than recalculating the entire network for every disruption scenario, the max-flow model evaluates how hydrogen can be rerouted through the existing infrastructure under geopolitical constraints. The algorithm is particularly suitable due to its speed and ability to simulate flow redistribution within fixed topologies, as explained in subsection 4.6.

Together, these four phases form a coherent modeling structure that enables both the design and stress-testing of a transcontinental hydrogen pipeline network. An overview of this workflow is presented in Figure 2, summarizing the steps and transitions between each phase and showing when the ONLT could successfully be used.

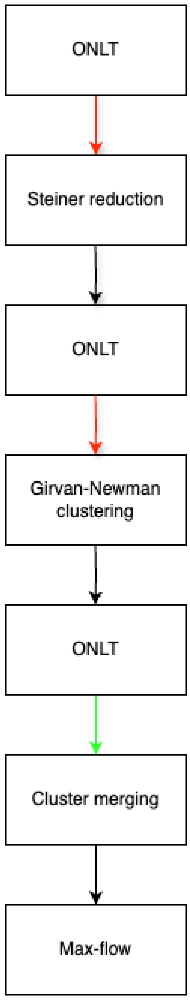

Figure 2: Modeling flowchart

4.2 Steiner reduction

As mentioned in this sections introduction, treating the chosen dataset with the ONLT is not possible within manageable time constraints. Simplifying the network without eliminating essential characteristics is therefore necessary. This can be done by applying Steiner's principles in large-scale network optimization (Winter, 1987). Using several reduction techniques inspired by heuristics discussed by Winter (1987), the network can be simplified while preserving its essential connectivity and minimizing overall cost. The primary reduction methods involve the removal or transformation of specific network elements to facilitate computational efficiency.

To illustrate how the Steiner reduction process simplifies the network, a step-by-step example is presented using a subsection of the pipeline system in the Netherlands and Belgium. Each reduction step is applied sequentially and explained alongside a corresponding figure, allowing the reader to follow the simplification logic as it is applied in practice.

The raw network is shown in Figure 3. The image reveals a dense and cluttered set of pipelines, many of which contribute little to the network's overall connectivity or optimization potential.

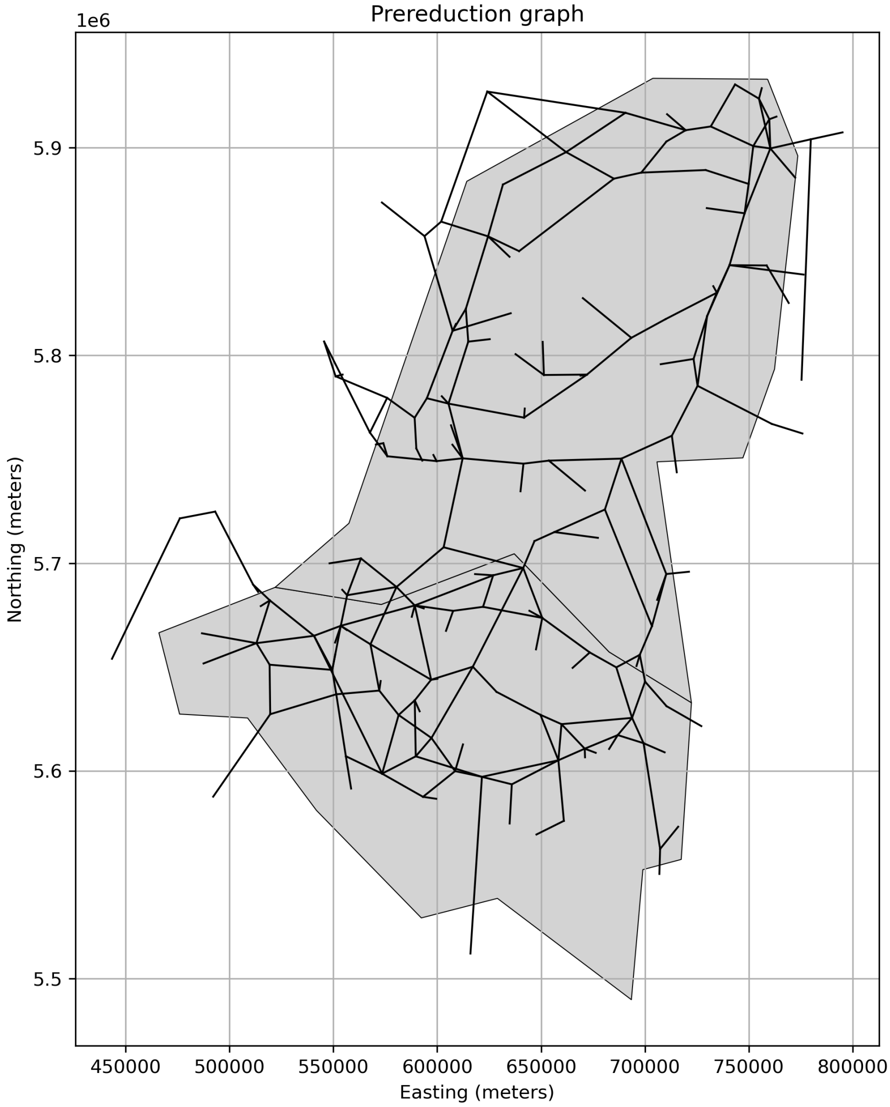

Figure 3: Graph before Steiner reduction

The first reduction step targets nodes with only a single connection—degree-1 nodes. These are removed along with their connecting pipelines, since they do not play a role in the broader network structure according to Steiner reduction principles Winter (1987). In Figure 4, the eliminated pipelines are shown in red. This step alone removes 70 pipelines from the network.

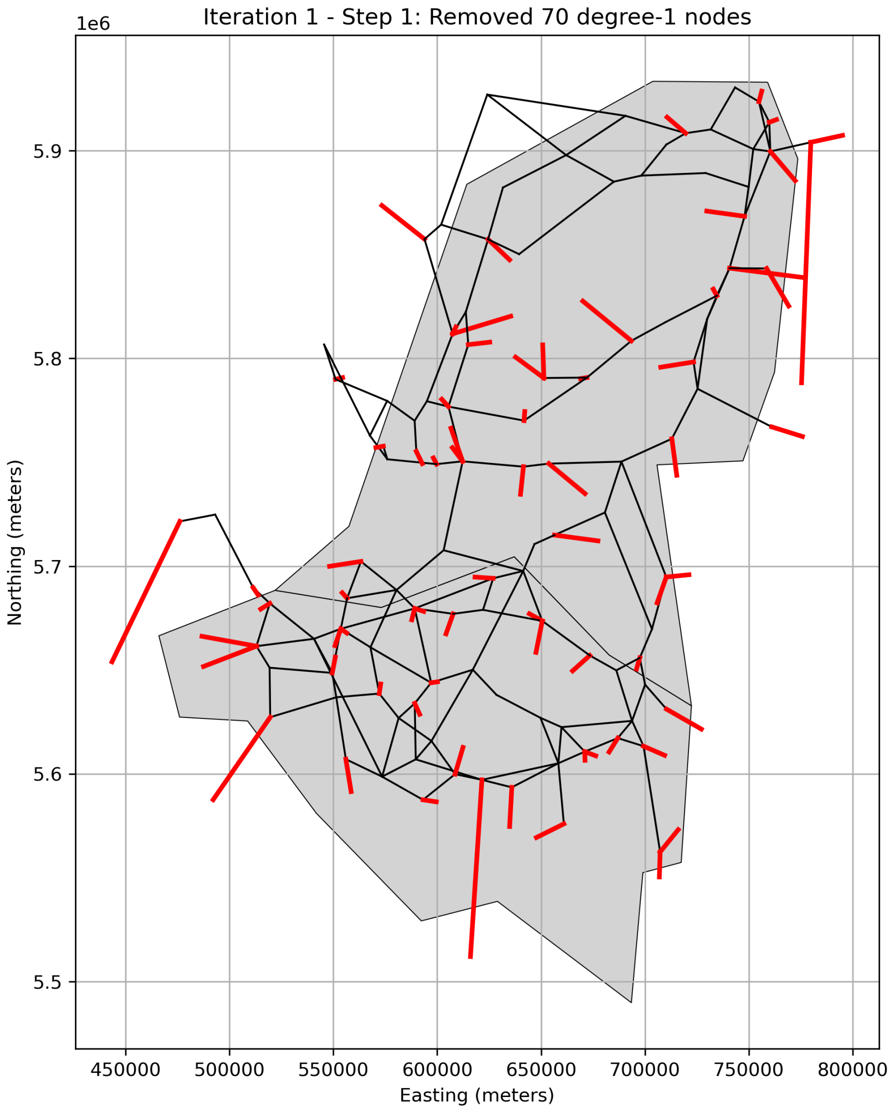

Figure 4: Steiner reduction - Removal of degree-1 nodes (red)

The second step focuses on nodes with exactly two neighbors. These are removed, and their adjacent edges are replaced by a direct connection between the two neighboring nodes. The new edge assumes the lower capacity of the originals to accurately mirror realistic flow. This step further simplifies the topology without altering critical flow paths, as shown in yellow in Figure 5.

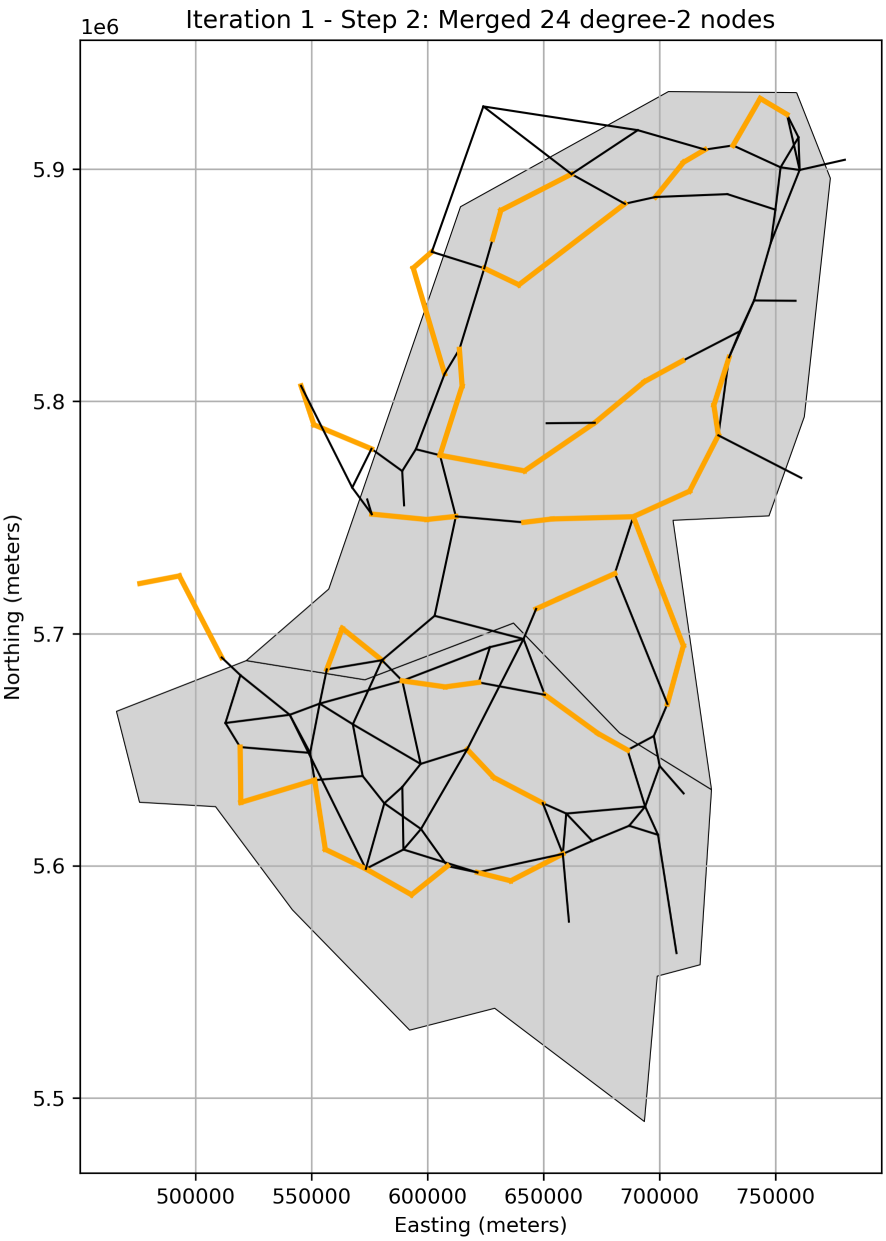

Figure 5: Steiner reduction - Replacing of edges connected to degree-2 nodes by direct edge (yellow)

A third simplification step involves the contraction of very short pipelines. These edges, often representing negligible spatial separation, are removed by merging their endpoint nodes into one. The contracted links are shown in blue in Figure 6, reducing the visual and computational complexity of the network.

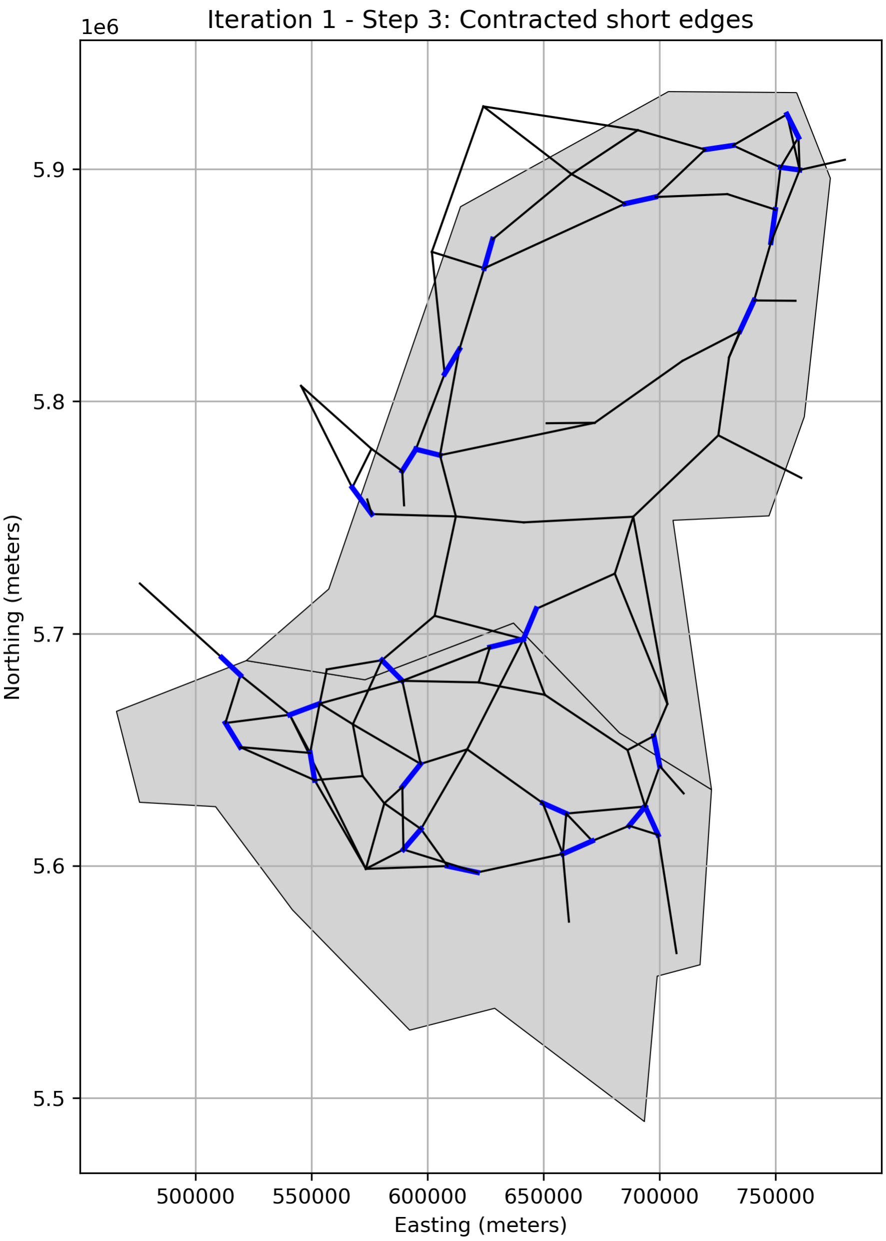

Figure 6: Steiner reduction - Contraction of short edges (blue)

After one full round of these reduction steps, the resulting network is shown in Figure 7. Compared to the initial configuration, it retains all meaningful structure while eliminating redundant or peripheral components. This streamlined version serves as a practical input for optimization tasks in later stages of the research.

Figure 7: Final graph after one round of Steiner reductions

4.3 Girvan Newman clustering

To prepare the network for optimization using the ONLT, the simplified network produced by the Steiner reduction still required further segmentation. The pipeline dataset remained too large and computationally complex for the ONLT to handle in one piece. As a solution, the network was divided into smaller, structurally coherent subregions using the Girvan–Newman clustering algorithm.

This algorithm is well-suited for identifying communities within a network—groups of nodes that are densely connected internally but only loosely connected to the rest of the network. It operates by iteratively removing the edge with the highest betweenness centrality, a measure of how often an edge lies on the shortest path between other nodes. These edges typically serve as bridges between communities, and their removal gradually fragments the network into distinct modules (Girvan & Newman, 2002; Wasserman & Faust, 1994).

The clustering process continues until a desired number of communities is formed. This segmentation allowed each subnetwork to be optimized independently in the ONLT. Additionally, the clustering process highlights which edges are most critical for maintaining overall connectivity, making them key points of interest for future robustness analysis.

To illustrate the application of the method, a reduced network from section 4.2 after of the Netherlands and Belgium was used as an example input for the algorithm. The clustering process begins by identifying and removing the edge with the highest betweenness centrality, and continues this process iteratively until the network is segmented into three distinct clusters. Each step is visualized below, allowing the reader to follow how the network's community structure gradually emerges.

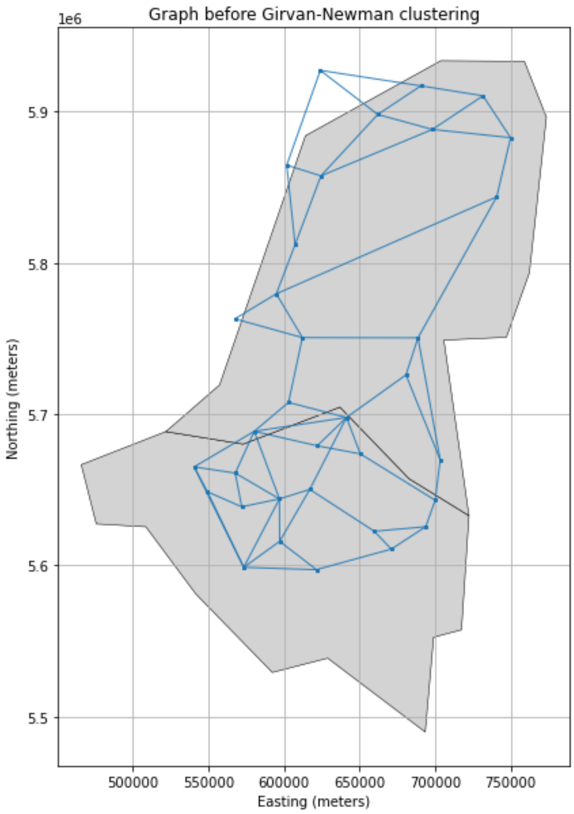

Figure 8: Graph before Girvan–Newman clustering

In the first step, the edge with the highest betweenness centrality is removed. This edge acts as a key connector between communities and its removal initiates the fragmentation of the network.

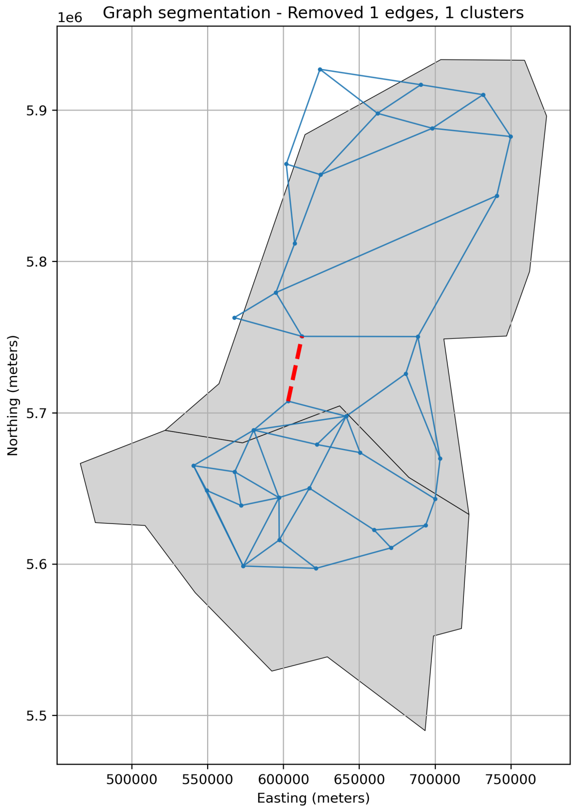

Figure 9: Girvan Newman clustering - After first edge removal (1 cluster)

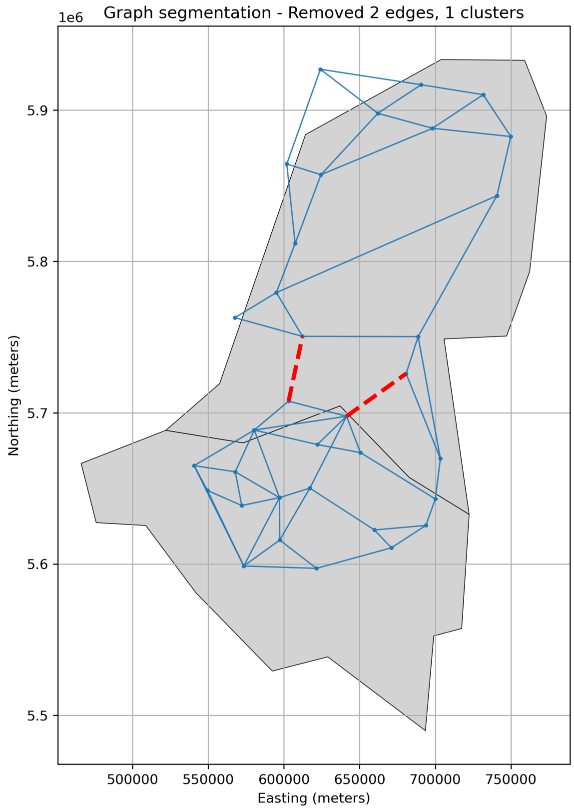

Figure 10: Girvan Newman clustering - After second edge removal (1 cluster)

With each additional removal, the internal structure becomes more apparent. As shown in Figure 11, the removal of three edges results in two disconnected subgraphs, marking the first major community split.

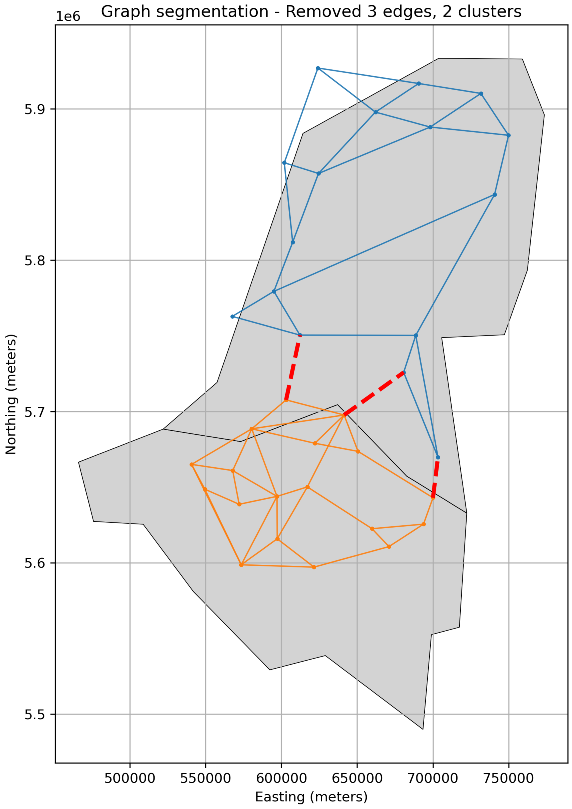

Figure 11: Girvan Newman clustering - After removal of 3 edges (2 clusters)

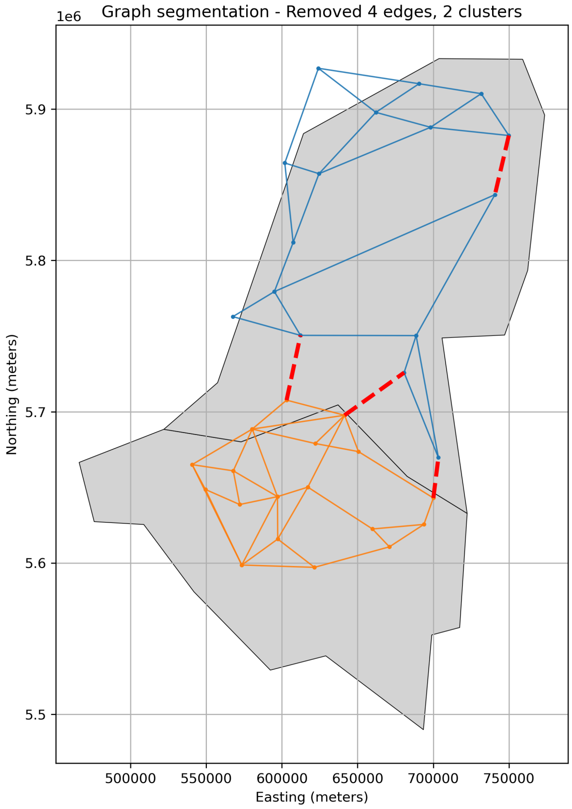

Figure 12: Girvan Newman clustering - After removal of 4 edges (2 clusters)

Following one more edge removal, the desired division into three clusters is achieved. Each cluster is visually distinct and structurally coherent, as seen in Figure 13.

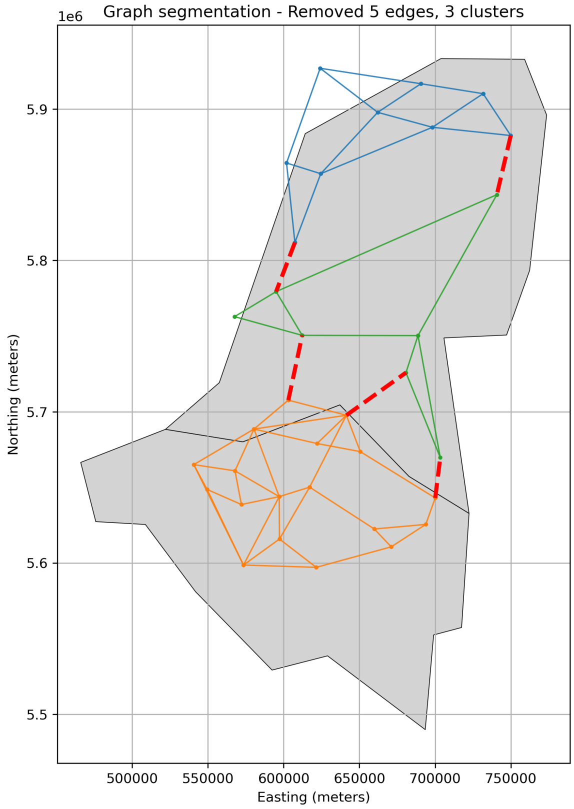

Figure 13: Girvan Newman clustering - After removal of 5 edges (3 clusters)

This process not only makes the network manageable for local optimization with the ONLT but also reveals the critical connections between regions. These identified inter-cluster edges are of strategic importance when evaluating the robustness of the hydrogen network under geopolitical or physical disruptions.

4.4 Optimal Network Layout Tool (ONLT)

The main method used in this research is the Optimal Network Layout Tool (ONLT), developed by Heijnen (2020). The ONLT supports the design of infrastructure networks such as a hydrogen pipeline system. In areas constrained by space, regulation, or uncertainty in supply and demand, infrastructure expansion becomes increasingly complex. The ONLT was developed to generate near-optimal network topologies under such conditions, allowing the user to plan systems that connect multiple actors across space and time while minimizing costs and respecting constraints.

The core of the ONLT is the generation of a network layout that connects supply and demand nodes via pipeline edges. These nodes and connections are derived from user-provided input, such as geographic coordinates, supply/demand volumes, optional routing constraints and existing connections. Existing connections from the present natural gas pipeline infrastructure are, as mentioned before, plentiful. This makes using the ONLT especially useful for this study.

4.4.1 Model outputs and their application

The ONLT provides multiple network solutions. Each represents a different way of connecting producers and consumers through a tree-like layout. The minimum spanning tree (MST) connects all terminal nodes with the lowest total edge length, without considering flow direction or capacity. The flow tree (FT), in contrast, incorporates flow direction and attempts to route supply to meet demand. Steiner trees, which allow the use of artificial split points (Steiner nodes), are excluded in this research to avoid complications in calculating costs and interpreting results. Only the MST and FT outputs are used.

4.4.2 Simplified example: ONLT in practice

To clarify the ONLT's internal workings, a simplified example is shown below using a sample dataset provided with the ONLT. The example proceeds through the MST and MCST steps to demonstrate the logic of network construction.

The first visualizations in Figure 14 show the supply and demand distribution across the network. They compare each terminal's input and output characteristics to establish a baseline.

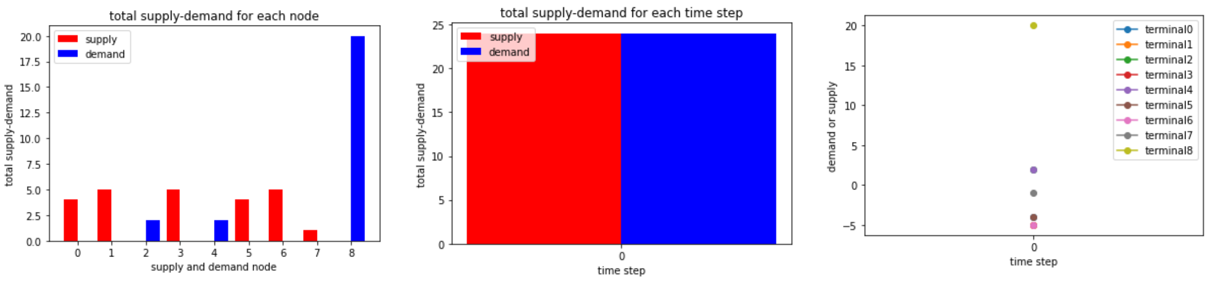

Figure 14: Supply and demand statistics of the simple input dataset (Heijnen, 2020)

In the next step, the model constructs the minimum spanning tree (MST), shown in Figure 15. This connects all nodes with the lowest total edge length but does not yet account for cost or capacity.

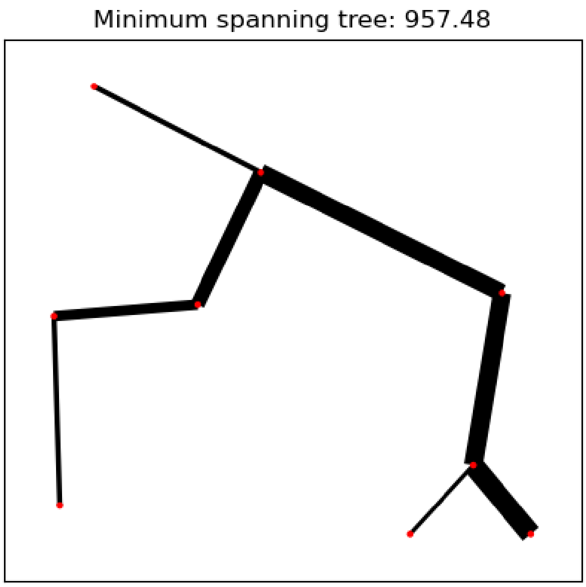

Figure 15: Minimum spanning tree of the simple input dataset

The MST is then refined into a minimum-cost spanning tree (MCST). The MST connects all nodes efficiently by length, but it does not consider the actual investment costs associated with different capacities, flow directions, or terrain characteristics. The MCST phase improves on this by rewiring the connections with respect to these costs.

This optimization is heuristic, meaning that early choices may restrict later ones, and global optimality is not guaranteed. Figure 16 presents a series of intermediate steps in this transformation process.

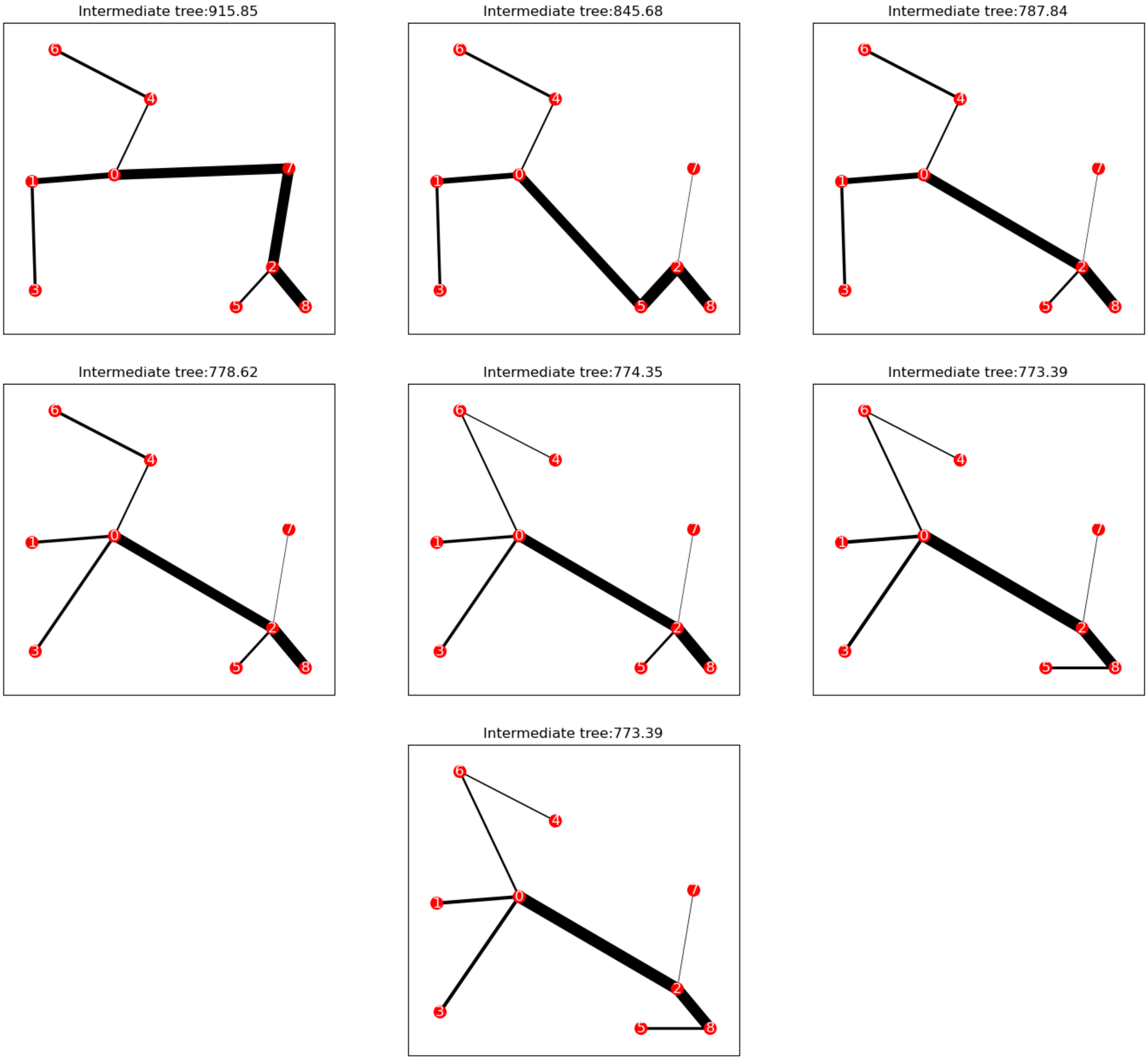

Figure 16: Intermediate steps to determining the minimum-cost spanning tree of simple input dataset

The final MCST is shown in Figure 17. This configuration reflects a cost-aware network that accounts for routing, flow, and the investment implications of each connection.

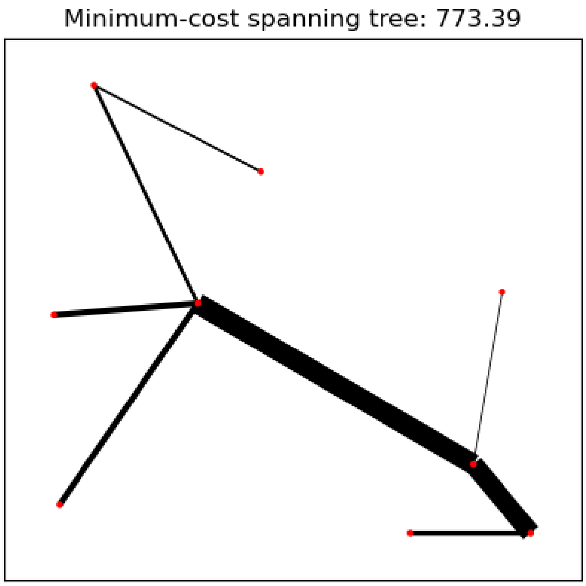

Figure 17: Final minimum-cost spanning tree of simple input dataset

4.4.3 Underlying assumptions and model adaptations

The ONLT is designed to generate efficient pipeline layouts under spatial, technical, and economic constraints. In its standard implementation, the model assumes that all newly created connections form a tree or forest structure. This constraint avoids loops and promotes cost-efficiency but limits network redundancy. All connections are considered bidirectional, and pipeline capacities are sized to meet the peak flow requirement on each edge. Optimization is carried out through a heuristic method, which means that early design decisions can constrain later ones, and global optimality is not guaranteed.

In this research, several adaptations were made to tailor the ONLT for hydrogen infrastructure planning. The most significant modification concerned the cost function. Unlike the original version, which considered only pipeline length, the updated function incorporates repurposing and reinforcement costs for existing infrastructure. These adaptations are described in detail in Section 4.5. The model now differentiates between the use of repurposable natural gas pipelines and the construction of new infrastructure. Repurposed pipelines are given a reduced cost weight, reflecting the lower capital investment required compared to new builds.

The physical landscape was simplified to make the model computationally tractable. Obstacles are represented as polygonal zones that impose a cost penalty rather than acting as absolute barriers. In this study, the Mediterranean Sea was modeled as such a zone. Pipelines crossing this obstacle incur higher costs but are not restricted outright. Other geographic features—such as mountains, rivers, or urban areas—were not included in the obstacle layer due to data availability and performance limitations. Similarly, routing constraints and storage nodes, which are supported by the ONLT, were omitted from the model because they did not provide additional value for the research questions posed.

Another important simplification was the omission of temporal dynamics. While the ONLT can be used to model infrastructure development over multiple time steps, this research applies it to a single moment in time. This allowed for a static but more detailed exploration of spatial layout and flow optimization.

Input to the ONLT included demand and supply terminal nodes, defined by geographic coordinates and respective hydrogen volumes. A terminal represents a node in the network that either produces (supply terminal) or consumes (demand terminal) hydrogen. These serve as the start and end points for pipeline connections and are the foundation of the network layout.

Lastly, only one types of output was used in this study: minimum-cost spanning tree (MCST). Minimum spanning trees are a step towards the more advanced MCST tree and are therefore not included. Steiner trees, which introduce artificial split points to potentially improve connectivity, were excluded to avoid complications in flow modeling and cost interpretation. This decision aligns with the goal of maintaining a clear and tractable structure for scenario comparison.

4.5 Pipeline cost function

Network cost is an important factor in the choice of network layout and is used within the model to optimize the layout for different scenarios. The cost function of the ONLT is a unitless cost function as the ONLT is not designed for providing a realistic cost overview, but rather for a generalized comparison of different network configurations. (Heijnen, 2020). The function uses a cost exponent β that scales costs with pipeline capacity, but does not explicitly model differences between hydrogen and natural gas pipelines or repurposing costs. To create a more realistic cost overview, the cost function must be revised.

4.5.1 New pipelines

A revised cost function is introduced to replace the embedded cost function of the ONLT. A study by Brown et al. (2022) focused on natural gas and hydrogen pipeline cost in the US and introduces the idea that pipeline cost is split into four parts: material, labor, right-of-way, and miscellaneous (surveying, engineering, direct labor supervision, project administration, other project overheads). These components follow a power function of pipeline diameter D in inches and length L in miles:

$$C_x = a_x \cdot D^{b_x} \cdot L^{c_x} \tag{1}$$

where C_x represents cost components for material, labor, right-of-way (ROW), and miscellaneous expenses. The coefficients a_x, b_x, c_x are derived from empirical regressions for different regions in the US (Brown et al., 2022).

Coefficients differ greatly for the different regions. None of the regions is representative for the situation this research explores. Brown et al. (2022), next to specific coefficients for the power function, also provides a more general approach for pipeline cost calculation, given in Equation 2.

$$C_x = a_x \cdot D \cdot L \tag{2}$$

a_x represents a constant, while pipeline diameter D is given in inches and length L in miles. The average values used for a_x that are taken as input values, are presented in Table 4. Note that due to the earlier mentioned massive differences per region in the research of Brown et al. (2022), huge variation can be seen for each cost component. For a complete accurate cost representation it is therefore needed to get accurate data to determine precise coefficients for each country, but is out of the scope of this research.
Summing these components gives the total cost function for new hydrogen pipelines. Since the original cost model used imperial units, all calculations are performed using diameter in inches and length in miles.

Table 4: National pipeline cost data (2018 USD per inch-mile) (Brown et al., 2022)

Statistic	Material	Labor	Miscellaneous	Right-of-way (ROW)
Average	24198	55313	26396	7119
Median	18880	29604	13633	2852
Standard deviation	23177	140451	50574	14331

$$C_{\text{new}} = C_{\text{material}} + C_{\text{labor}} + C_{\text{misc}} + C_{\text{ROW}} \tag{3}$$

4.5.2 Pipeline repurposing

A large part of network construction is reusing old gas pipelines as part of the network. Repurposing existing natural gas pipelines for hydrogen transport is more cost-effective, but requires modifications to the pipeline, for example to maintain material integrity or meet compression requirements. Because of the size of the network and the limited amount of knowledge and data of each specific pipeline, a generalized function for repurposing is introduced:

$$C_{\text{repurpose}} = f \cdot C_{\text{new}}, \quad 0.1 \leq f \leq 0.35 \tag{4}$$

where f is the repurposing factor. Large-diameter modern pipelines typically have a repurposing factor between 0.1 and 0.2, while older pipelines requiring extensive modification can have a factor of up to 0.35 (ENTSOG, GIE, Hydrogen Europe, 2021; Jens et al., 2021). The factor used for this research will be specified in subsection 5.5.

Some repurposed pipelines will not be used to their full capacity, as flow through them can be lower than their full capacity. It is, however, not possible to repurpose a pipeline partially. Because of that the full capacity of a pipeline is repurposed and the full costs are taken into account in the network creation.

4.5.3 Pipeline reinforcement

If the existing capacity of a pipeline is insufficient to transport the required hydrogen volume, additional reinforcement is required. The reinforcement cost follows the principle that extending the capacity of an existing pipeline is generally more cost-effective than constructing an entirely new one. This is modeled using a reinforcement cost factor cpc, which is also used in the standard ONLT cost function, which accounts for cost reductions associated with reinforcing an existing pipeline:

$$C_{\text{reinforce}} = cpc \cdot C_{\text{new}} \cdot \frac{Q_{\text{reinforce}}}{Q_{\text{total}}} \tag{5}$$

where:

- $C_{\text{reinforce}}$ is the total reinforcement cost for a given pipeline.
- cpc is the reinforcement cost factor, where $0 < cpc \leq 1$. If $cpc = 1$, reinforcement costs are identical to new pipeline costs, while $cpc < 1$ accounts for cost reductions. The factor used for this research will be specified in subsection 5.5.
- C_{new} represents the cost of constructing a new pipeline of the same diameter.

- $Q_{\text{reinforce}}$ is the additional capacity required beyond the current pipeline's capability.
- Q_{total} is the total required transport capacity.

The formula ensures that reinforcement costs scale proportionally to the missing capacity, while benefiting from economies of scale. If no reinforcement is required ($Q_{\text{reinforce}} = 0$), this term is omitted.

4.5.4 Cost comparison between onshore and offshore hydrogen pipelines

The cost of constructing a hydrogen pipeline over sea is substantially higher than building one over land. The offshore premium is driven by a combination of technical and logistical factors that significantly increase both capital and operational expenditure. One of the main cost drivers is the need for seabed preparation to stabilize the pipeline and protect it from hydrodynamic forces and mechanical damage (Sriskandarajah & Sreetharan, 1996). Offshore pipelines also demand corrosion-resistant coatings and higher-grade materials to withstand the saline environment and prevent hydrogen-induced cracking and embrittlement (IEA, 2023). The installation of offshore compressor and pumping stations introduces further cost premiums, driven by the engineering difficulty of operating such systems under marine conditions (Martínez-Gordón et al., 2022). Finally, monitoring and maintenance activities are more expensive offshore due to limited accessibility, rough sea states, and the need for advanced subsea inspection technologies (IEA, 2023).

Timmerberg & Kaltschmitt (2019) provide detailed cost estimates for transporting hydrogen via pipeline in their techno-economic assessment of hydrogen supply from North Africa to Central Europe. Their analysis quantifies both onshore and offshore transport costs under different pipeline configurations and cost assumptions.

According to their findings, onshore hydrogen transport costs range between €1.10 and €1.84 per MWh per 1000 km, depending on the pipe diameter and assumed capital expenditure. Offshore pipeline transport, by contrast, incurs higher costs, ranging from €1.59 to €3.11 per MWh per 1000 km. This implies that offshore transport is approximately 40–70% more expensive than onshore pipeline alternatives. A multiplier α based on these numbers is implemented into the cost function to capture the additional expense of offshore pipelines. The factor used for this research will be specified in subsection 5.5.

4.5.5 Total cost function

For networks that include a combination of new, repurposed, and reinforced pipelines—both onshore and offshore—the total cost function is formulated as:

$$C_{\text{total}} = \sum_i \left(\alpha_i \cdot \left[f_i \cdot C_{\text{repurpose},i} + (1 - f_i) \cdot C_{\text{new},i} + 1_{Q_{\text{reinforce},i} > 0} \cdot C_{\text{reinforce},i} \right] \right) \tag{6}$$

where:

- α_i is the offshore cost factor for segment i, applied only if the segment is located offshore. For offshore segments, $\alpha_i > 1$; for onshore segments, $\alpha_i = 1$.
- f_i represents the fraction of segment i that is repurposed.
- $C_{\text{repurpose},i}$ is the cost of repurposing the segment.
- $C_{\text{new},i}$ is the cost of constructing a new pipeline.

- $C_{\text{reinforce},i}$ is the reinforcement cost, included only when additional capacity is required.
- $1_{Q_{\text{reinforce},i}>0}$ is an indicator function ensuring that reinforcement costs are only applied when additional capacity is needed.

This function provides a unified framework for estimating the total network cost, ensuring that all relevant cost components—new construction, repurposing, reinforcement, and location-based cost multipliers—are correctly incorporated. It captures key cost variations across different pipeline strategies and geographical settings, while maintaining flexibility in optimizing network layouts. The new cost function therefore provides a more accurate estimation of hydrogen infrastructure costs by incorporating empirical cost models derived from natural gas and hydrogen pipeline data.

4.5.6 Concluding remarks

The renewed cost function is well suited to tackle the first research question:

How can economic feasibility of repurposing and expanding an existing pipeline network for hydrogen transport be calculated?

To answer this subquestion, the renewed cost function will be implemented in the model. Although the cost function does not give an exactly accurate number, it is much more specified than the existing cost function of the ONLT. Therefore, it provides a more realistic cost number that can be used for policy advice.

4.6 Maximum flow algorithm

Following the Steiner reduction and subsequent segmentation of the pipeline network using the Girvan–Newman clustering algorithm, an additional step is required to analyze system-wide hydrogen flow. The Optimal Network Layout Tool (ONLT) can generate optimal pipeline configurations for individual clusters, but is, as mentioned before, not suitable for evaluating the integrated network. To address this, the maximum flow algorithm is introduced as a complementary method.

After combining the different clusters, this algorithm can be used to evaluate how much hydrogen can be transported from producers to consumers across the entire network, taking into account the flow capacities of individual pipelines. It enables the assessment of overall network performance without rerunning the computationally intensive ONLT for every scenario, making it an effective tool for robustness analysis under geopolitical or structural disruptions.

The classical Ford–Fulkerson method provides the foundation for solving the maximum flow problem, iteratively identifying augmenting paths through which additional flow can be routed until no more improvements can be made (Ford & Fulkerson, 1956). For networks with integer capacities, this method is guaranteed to converge to an optimal solution. A well-known refinement, the Edmonds–Karp algorithm, enhances this process by using a breadth-first search to identify the shortest augmenting path in each iteration. In breadth-first search, the algorithm explores all nodes that are directly reachable from the source before moving on to nodes further away. This ensures that the path found in each iteration has the fewest possible steps, improving efficiency and avoiding unnecessarily long routes. The use of this strategy ensures a predictable runtime of $O(VE^2)$, where V and E are the number of nodes and edges, respectively (Edmonds & Karp, 1972). These properties make Edmonds–Karp particularly suitable for large infrastructure networks like the one considered in this study.

To illustrate the mechanics of this algorithm, a simplified example is presented. The system includes a single producer node (A) and a consumer node (I), connected by a network of intermediate pipelines. The structure of the network before any flow is routed is shown in Figure 18. Edge labels denote pipeline capacities in megawatts (MW).

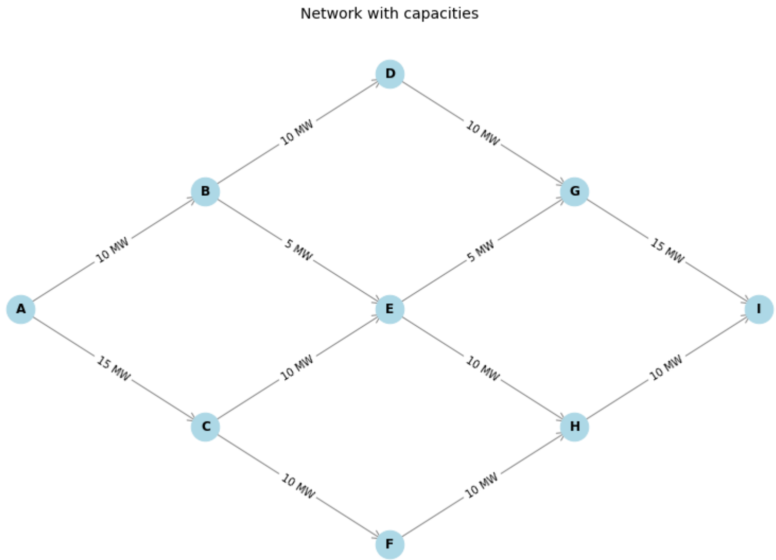

Figure 18: Simplified network before flow analysis. Edge labels represent pipeline capacities in MW.

After applying the maximum flow algorithm, the resulting distribution of flow is shown in Figure 19. Only edges that carry positive flow are highlighted, and the corresponding flow values are displayed in MW. This makes it easy to identify which parts of the network are actively contributing to the overall hydrogen transport.

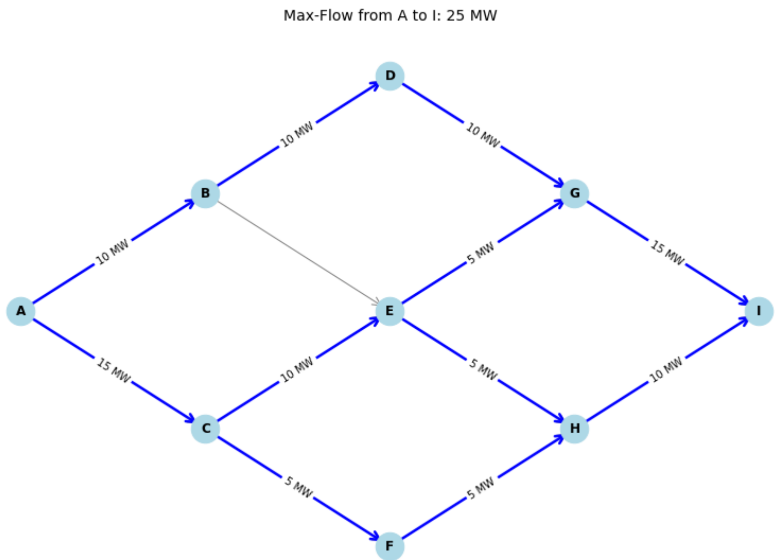

Figure 19: Flow distribution resulting from max-flow analysis. Edge labels represent actual flow in MW.

This example illustrates the usefulness of the maximum flow approach in evaluating the capacity and reliability of a hydrogen transport network. In this study, the method is applied to the fully integrated European–North African network to assess performance under normal operation and simulated disruptions. Its speed and consistency make it a valuable addition to the methodology developed in this research.

4.6.1 Usage for hydrogen network analysis

In the context of hydrogen pipeline systems, this flow-based approach can be used to evaluate whether network segments can meet expected demand, to identify bottlenecks, and to explore how disruptions or reinforcements impact overall network performance. Although simplified, this model provides insight into the ability of a given topology to support hydrogen transport under capacity constraints. Pipelines are treated as capacity-limited edges, and nodes represent production sites, storage locations, or consumption points.

While the max-flow approach does not account for dynamic effects such as pressure losses, time-varying demand, or bidirectional flows, its computational efficiency makes it well-suited for integration into modular network analysis workflows. In this study, it enables system-wide consistency checks after network segmentation, allowing for the evaluation of inter-cluster flow performance without sacrificing scalability or tractability.

4.7 Concluding remarks

The methodology developed in this chapter provides an answer to the following subquestion:

How can a detailed network analysis be conducted on an extensive, detailed dataset with the tools available, while keeping computational time to acceptable levels?

The proposed approach enables the analysis of a large-scale network by systematically reducing its complexity. This is achieved through a combination of network simplification via Steiner reduction and segmentation into manageable sections using Girvan–Newman clustering. These steps allow for the application of the Optimal Network Layout Tool (ONLT) on detailed pipeline data without exceeding computational limits.

Additionally, the incorporation of the maximum flow algorithm provides a complementary method for evaluating network performance, especially in the context of disrupted scenarios. It allows for efficient assessment of total flow capacity and identification of supply bottlenecks across the integrated network, thereby enriching the robustness evaluation of different configurations.

The methodological approach developed in this chapter relies on well-prepared and compatible input data. Chapter 5 outlines how the raw infrastructure and demand data were processed to meet these requirements. This includes key steps such as unit conversion, data clustering, and parameter calibration.

5 Data operationalisation

To apply the methodology described in Chapter 4, a wide range of data is required. This chapter outlines how the relevant datasets are selected, processed, and translated into model-ready inputs. It explains the practical steps taken to represent Europe's and North Africa's gas infrastructure and industrial demand in the model, including spatial clustering, estimation of missing values, and conversion of physical parameters. Assumptions and limitations related to data quality are also addressed, as these influence the interpretation of results in later chapters.

5.1 SciGRID_gas dataset

For an extensive indepth analysis of the existing gas network in Europe, a comprehensive dataset is needed. Identifying the most suitable dataset posed a significant challenge, as it needed to meet multiple criteria to ensure its applicability for modelling an extensive hydrogen network.

The first criterion was the inclusion of detailed geographical data on the location of existing pipelines. Although most of the available data sets contain this information, additional criteria had to be met to ensure compatibility with network modeling approaches. For example, the connectivity of the network, as datasets with missing pipeline segments leading to network fragmentation, were unsuitable for the modeling algorithm. A fully connected network is necessary to enable accurate simulations of gas or hydrogen flow across regions. Lastly, capacity data is required to facilitate flow analysis and provide insight into the transport capabilities of the infrastructure.

The SciGRID_gas dataset, specifically the merged IGGIELGN dataset, meets all these requirements. It integrates multiple data sources to improve modeling applications related to gas infrastructure and its potential repurposing for hydrogen transport (Diettrich et al., 2020). The dataset provides detailed spatial data, while also offering capacity values essential for conducting flow simulations. As a result, SciGRID_gas serves as a suitable foundation for analyzing and optimizing Europe's gas network for hydrogen transport.

5.1.1 Data sources and structure

The IGGIELGN dataset is compiled from multiple sources. Incorporating publicly available data, industry reports and infrastructure registries a extensive dataset is derived. These sources provide comprehensive information on Europe's and North Africa's gas infrastructure, enhancing the dataset's applicability for modeling gas and hydrogen networks. Table 5 summarizes the used data sources and more detail on the sources.

The dataset includes key gas transmission components such as pipelines, compressor stations, LNG terminals, storage facilities and interconnection points. Each of the components is stored in a separate dataset. Each component is associated with attributes like capacity, pressure, and geographical coordinates, facilitating comprehensive modeling of gas network infrastructure. For this research, the sub dataset for pipelines is used. Hydrogen storage and an extensive insight on the usage of compressors is out of the scope of this research, therefore the pipeline dataset is sufficient.

By integrating these diverse data sources, the IGGIELGN dataset provides the most complete dataset for analyzing gas transmission networks in Europe and North Africa and assessing their potential for hydrogen transport. However, variations in data quality and completeness across the dataset present limitations to this data. This will be further examined in section 5.1.3.

Table 5: Data sources for the IGGIELGN dataset

Data source	**Description**
InternetDaten (INET)	Extracted from publicly available sources and gas transmission operator reports.
Gas Infrastructure Europe (GIE)	Provides data on gas storage and LNG terminals
Gas Storage Europe (GSE)	Supplements storage facility data with additional operational insights.
International Gas Union (IGU)	Contributes information on peak injection and withdrawal rates for gas storages.
EntsoG-Map (EMAP)	Spatial data on European gas pipelines and associated infrastructure.
Long-term planning and short-term optimization (LKD)	Provides detailed infrastructure data, particularly for Germany.
National Grid (GB) and Norwegian Data (NO)	Regional datasets for Great Britain and Norway.

5.1.2 Pipeline attributes relevant to hydrogen adaptation

Several attributes within the dataset are critical for evaluating the feasibility of repurposing gas pipelines for hydrogen transport. These include pipeline capacity, given as the maximum volumetric flow per day in million cubic meters per day (Mm^3/d) and pipeline inner diameter in millimeters. Maximum allowable operating pressure and material composition are also a factor in repurposing pipelines. Different pressure values for the transport of hydrogen and gas and material properties are of particular importance in assessing the risk of hydrogen embrittlement. An in-depth assessment of these factors is outside of the scope of this research, but will be accounted for partially in assessing the cost of repurposing pipelines.

5.1.3 Dataset limitations

Due to limitations in data availability, the IGGIELGN dataset employs heuristic techniques to estimate missing values. These methods include statistical interference based on available pipeline characteristics, estimation of pressure and capacity through documented gas network trends and topological alignment of infrastructure components across different datasets. While these techniques improve dataset completeness, they introduce potential uncertainties.

A specific case of uncertainty is seen in the attribute max_cap_M_m3_per_d, which contains only 689 raw input values on 6263 entries in the dataset. The mean absolute error for this attribute is 24.4, whereas the mean value is 33.1, indicating significant uncertainty. All missing values were generated using the median of the raw input data, affecting the overall reliability of this parameter. Figure 20 gives a visualization of this specific case. Green bars are the raw input values, red bar is the histogram of the estimated values (Diettrich et al., 2020).

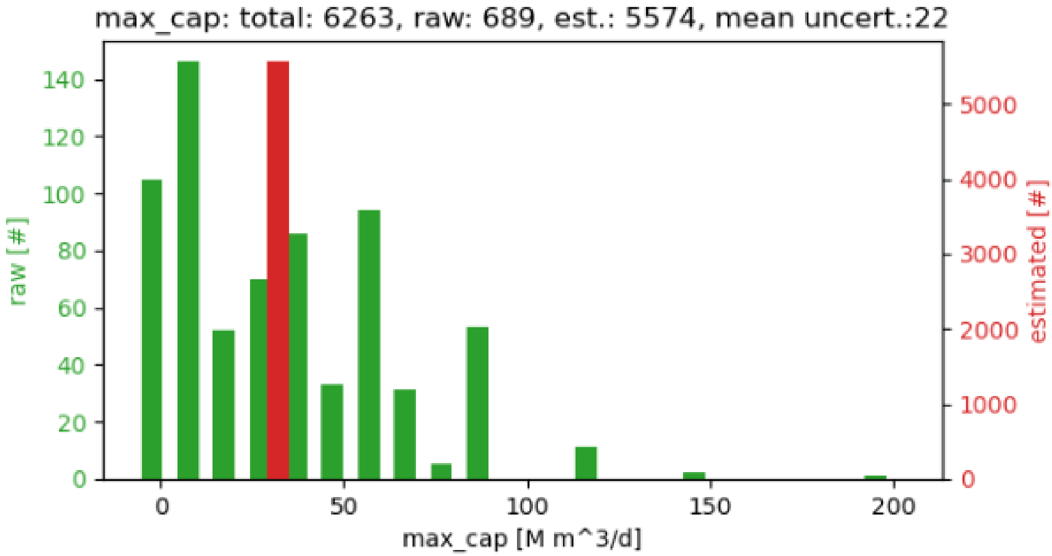

Figure 20: Sample plot of the raw and estimated values of the attribute max_cap_M_m3_per_d of the component PipeSegments.

Validation for critical values when relying heavily on the precise outcome of network simulations with this dataset is needed. For this research, the values in the dataset are used for implementation of the model without this extensive value validation. In the recommendations stemming from the outcomes of this research, the dataset limitations are addressed and taken into account.

5.2 Geographical distribution of consumers

subsection 2.3 outlined the spatial scope of this study and identified major hard-to-abate industrial clusters. However, direct energy consumption data for these clusters is not publicly available. To estimate industrial hydrogen demand, this section draws on consumer data from the SciGRID dataset.

In addition to pipeline infrastructure, SciGRID includes a subdataset containing information on gas consumers. The term "consumer" in this context refers to households, industrial facilities, power plants, and other end users (Diettrich et al., 2020). A total of 556 consumer elements are present in the INET dataset, of which 549 are connected to the network. Of these, 372 are located in the countries selected for this research. Each of these entries represents a raw input value. All information used for this component originates from the INET dataset, as summarised in Table 5, with the underlying data primarily sourced from Global Energy Observatory (n.d.).

Table 6: Relevant consumer elements in the IGGIELGN dataset (Diettrich et al., 2020)

Attribute	Description
capacity_E_MW	Value of installed electric power output in units of [MW].
capacity_TH_MW	Value of installed thermal power output in units of [MW].
source	Information on where the information of this element originated from.

Of the attributes available in the consumer dataset, `capacity_E_MW` is the most relevant for this study and is used as a proxy for hydrogen demand. This attribute reflects the installed electric power capacity of each consumer. While the dataset also includes `capacity_TH_MW` (thermal output), values for this attribute are only available for a small number of consumers. Since more than 90% of entries rely on estimated values for thermal capacity, it is excluded from the demand calculation in this research (Diettrich et al., 2020).

5.2.1 Processing and selection of consumer data

The ONLT is not fit for creating a model which provides all separate 372 consumers with hydrogen. A simplification is necessary, while maintaining regional representation and data completeness. To achieve this, consumers in a specified radius of an industrial clusters are merged and represented by this clusters.

To do so, consumer data is extracted from the SciGRID dataset. All consumer locations are transformed into a unified coordinate reference system, enabling accurate distance-based analysis. Consumers located within a specified radius are merged with and represented by an industrial cluster. This radius is set to 50 kilometers. If two clusters are within range of the consumer, the closest cluster in chosen to represent it. It is made sure that merging is applied separately per country to maintain national distinctions in energy demand. After clustering, the dataset is further narrowed down by selecting the 5 largest energy consumers in each country.

The raw dataset for participating countries and locations of industrial clusters are given in Figure 21. The figure shows that the demand information available is not as extensive for every country in the dataset.

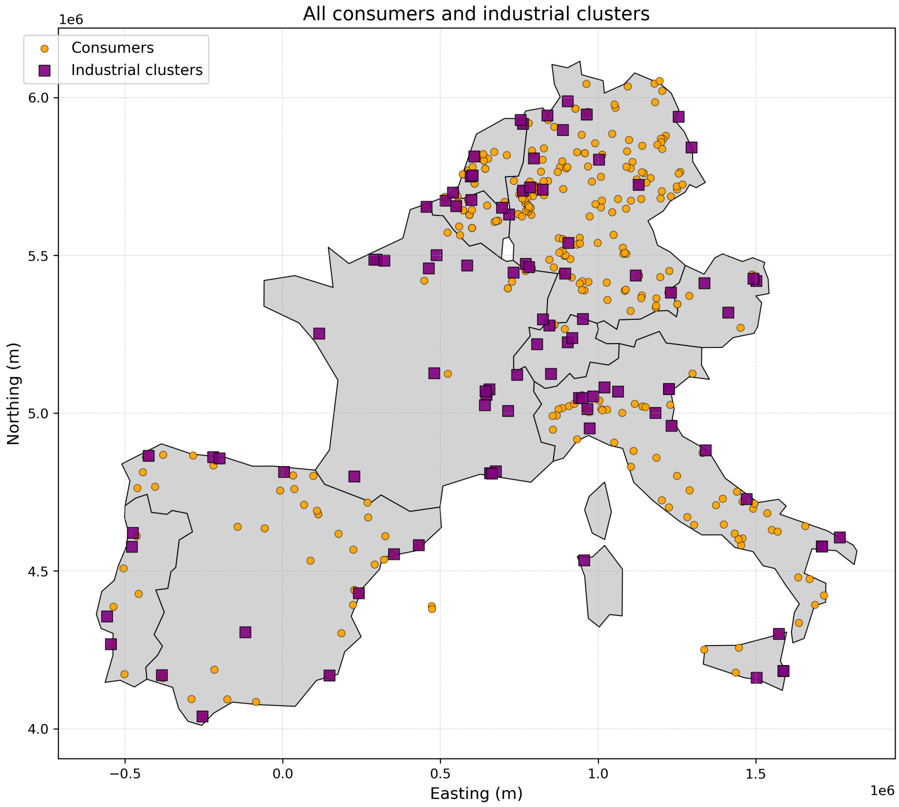

Figure 21: Consumers and industrial clusters

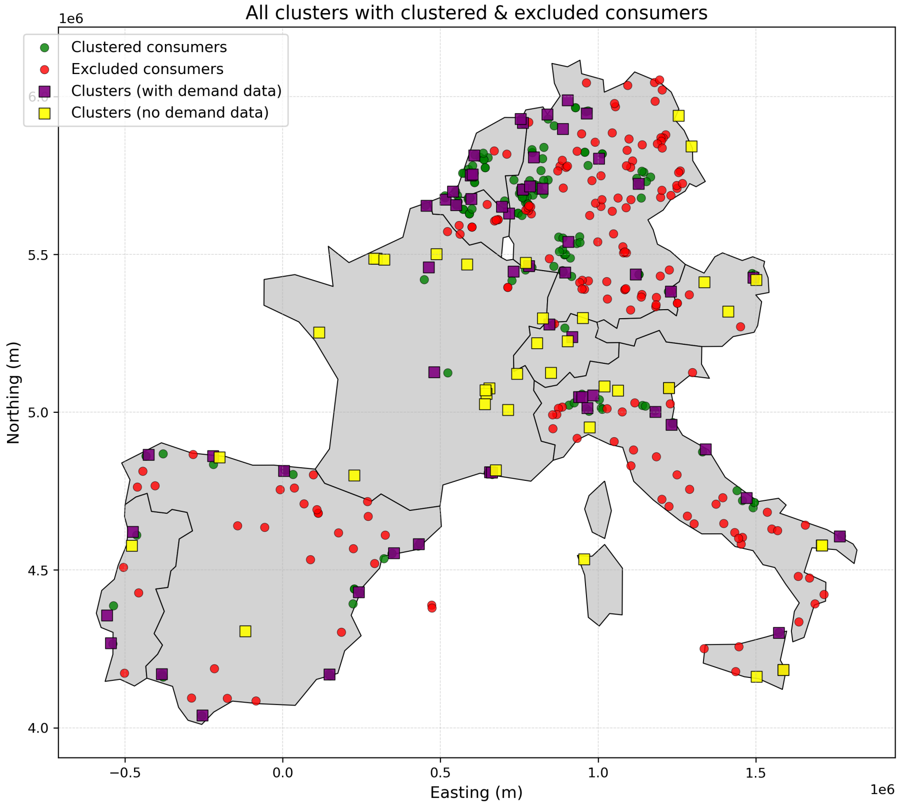

Figure 22: Consumer locations after clustering

Figure 22 shows which consumers are within range of an industrial cluster and can be represented by this cluster. It also shows which industrial clusters have no consumers in the neighborhood and because of that will have a demand of zero. Lastly, Figure 23 shows which 5 clusters are the largest for each country. For some countries, even some of the top 5 clusters are not allocated any demand, due to lacking demand data for those locations. These clusters are excluded from the model.

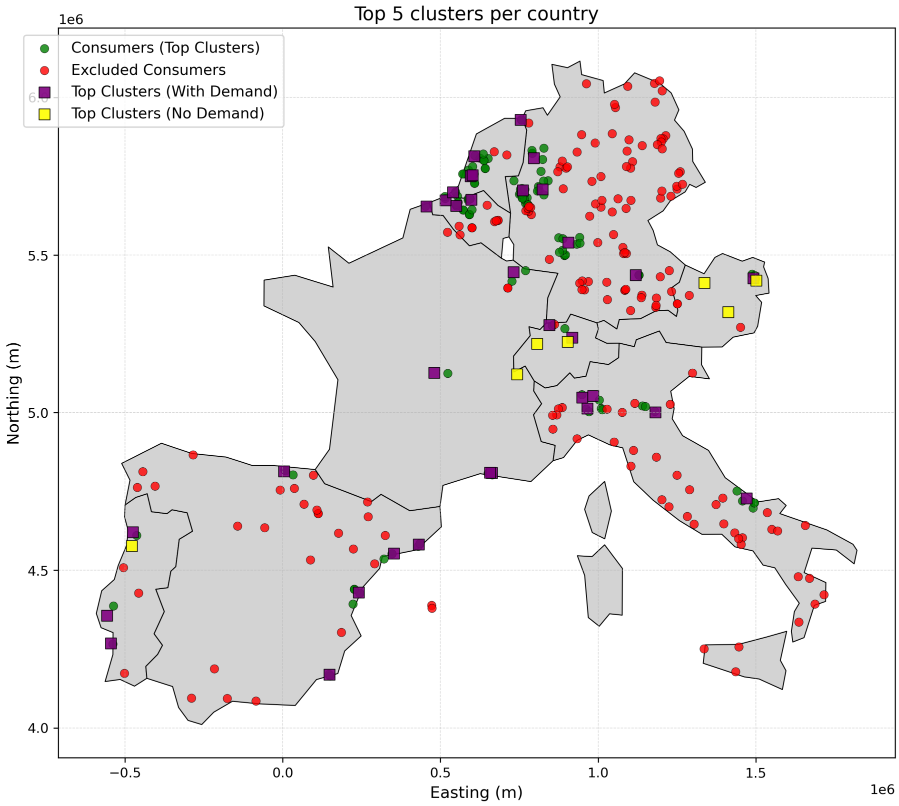

Figure 23: Top 5 clusters per country

In Table 7 an overview of the demand of consumers and delivery to industrial clusters is given. The total demand that is taken into account in the model of this research is 61.84 GW.

Table 7: Summary of hydrogen demand across consumer groups

Category	**Value (GW)**	**Share of total demand (%)**
Total demand (all consumers)	130.03	100
Delivered to identified industrial clusters	78.95	60.7
Demand of top 5 clusters per country	61.84	47.5

5.2.2 Limitations of merging method

From the figures in Section 5.2.1, it becomes clear that the availability of demand data varies significantly between countries. This limitation must be kept in mind when interpreting the model outcomes. Furthermore, as stated in the dataset description, the consumer data from the SciGRID dataset is not explicitly limited to industrial users. Consequently, the clustering method may capture demand from other sectors, leading to a possible overestimation of industrial energy needs at some locations.

While this dataset was not explicitly designed for industrial use, it provides a valuable approximation of regional energy needs by leveraging spatial proximity. By linking individual consumer entries to nearby industrial clusters, a geographically distributed demand profile is constructed that feeds into the hydrogen network model. However, for a more accurate and detailed assessment of hydrogen demand, especially at the facility level, country-specific and company-level industrial data would be required.

5.2.3 Concluding remarks

This section provides an operational answer to the subquestion:

Where are hard-to-abate industrial clusters situated in Europe and what are their energy needs?

Building on the identification of industrial clusters in subsubsection 2.3.1, this section translates those locations into a quantitative demand profile suitable for network modeling. Hard-to-abate industrial clusters are concentrated in countries with both high industrial energy demand and extensive gas infrastructure, including the Netherlands, Germany, Belgium, Austria, Switzerland, France, Spain, Portugal, and Italy. While direct consumption data for these clusters is not readily available, an estimate of their energy needs was obtained by spatially linking cluster locations to gas consumers in the SciGRID dataset.

Through clustering consumers within a 50 km radius and selecting the five largest clusters per country, the model incorporates a regionally differentiated yet computationally feasible demand profile totaling 61.84 GW. Although some uncertainty remains—due to the inclusion of non-industrial consumers and variations in data availability—the resulting dataset provides a functional basis for simulating large-scale hydrogen distribution scenarios. These limitations will be considered when interpreting results and formulating recommendations in later chapters.

5.3 Conversion of pipeline capacity to power ($\mathbf{Mm^3/d}$ to MW)

The SciGRID dataset gives hydrogen pipeline capacity in million cubic meters per day (Mm^3/d). However, industrial demand and generation capacity data is stated in megawatts (MW), a unit of power (MJ/s). A conversion from Mm^3/d to MW is needed for capacity and power level comparison, model creation and policy assessment, as explained in more detail in section 5.3.2. The following steps outline the conversion done from Mm^3/d of hydrogen flow to a continuous power output in MW.

5.3.1 Stepwise Conversion

First, the daily mass flow (in kg/day) is calculated, using the density of hydrogen, approximately $\rho \approx 0.0899\,\mathrm{kg/m^3}$ at standard conditions (The Engineering Toolbox, 2024b):

$$\text{Mass flow (kg/day)} = 0.0899 \cdot \text{max\_cap\_M\_m3\_per\_d} \cdot 10^6 \tag{7}$$

Here, max_cap_M_m3_per_d is the pipeline capacity in million cubic meters per day (Mm^3/d), and multiplying by 10^6 converts this value to cubic meters per day, after which it is multiplied by the hydrogen density to find the total mass in kg per day.

This is then multiplied by the mass flow by hydrogen's lower heating value (LHV), which is approximately 120 MJ/kg (The Engineering Toolbox, 2024a), to obtain the daily energy flow in megajoules (MJ/day):

$$\text{Energy flow (MJ/day)} = 0.0899 \cdot \text{max\_cap\_M\_m3\_per\_d} \cdot 10^6 \cdot 120 \tag{8}$$

Finally, to express energy as a continuous power (MW), the daily energy (in MJ/day) is divided by the number of seconds per day (86,400 s/day), noting that $1\,\mathrm{MJ/s} = 1\,\mathrm{MW}$:

$$\text{Power (MW)} = \frac{\text{Energy flow (MJ/day)}}{86{,}400\,\text{(s/day)}} \tag{9}$$

Combining everything into a single expression:

$$\text{Power (MW)} = \text{max\_cap\_M\_m3\_per\_d} \cdot 124.8611 \tag{10}$$

Hence, under the stated assumptions (0°C, 1 atm, LHV = 120 MJ/kg), $1\,\text{Mm}^3/\text{d} = 124.8611\,\text{MW}$ of hydrogen flow.

5.3.2 Application and significance

Expressing hydrogen pipeline capacity in MW rather than (Mm^3/d) enables direct comparison between pipeline volumetric capacity and industrial power levels. Industrial demand and generation capacity are often given in units of power, the conversion enables more a more well known and intuitive assessment of whether a pipeline segment can support specific consumer loads or supply quantities. Next to that, it is necessary for model creation, since flow through pipelines, consumer demand and producer supply must be in the same unit to run the model. Moreover, this approach helps infrastructure planning and policy assessment by providing a standardized metric, in line with common energy system indicators. Planners and policymakers can assess network constraints, prioritize upgrades, or compare scenarios using a consistent and widely recognized unit.

5.4 Relation between capacity and diameter

To estimate pipeline investment costs, the methodology introduced in Chapter 4 requires both the length and diameter of each pipeline segment. While length is directly available from the data, diameter must often be inferred from capacity. This section introduces the empirical model used to derive pipeline diameters based on estimated hydrogen flow.

5.4.1 Flow equations and the necessity of an empirical power-law approach

The relationship between pipeline capacity or flow rate and pipeline characteristics (like diameter) can be determined by physical laws. Two commonly used equations for describing fluid flow in pipes are the Hagen-Poiseuille equation for laminar flow and the Darcy-Weisbach equation for turbulent flow. However, these equations require knowledge of the pressure drop along the pipeline. Since pressure drop data is not available in this study, these theoretical models cannot be directly applied, necessitating the use of an empirical power-law approach.

In the absence of pressure drop data, an empirical approach is required to estimate pipeline capacity as a function of diameter. Empirical models derived from observed data provide a practical alternative by capturing underlying flow characteristics without requiring direct knowledge of pressure losses.

Several empirical models have been proposed for estimating pipeline capacity and optimal diameters Arumugam et al. (2021). One of the earliest formulations was presented by Bresse, which builds upon the relationship between diameter and volumetric flow rate under economic considerations. The Bresse equation, adapted from the work of Dupuit (1854), is given as:

$$D = k\sqrt{Q} \tag{11}$$

where D is the pipeline diameter, Q is the volumetric flow rate, and k is an empirical coefficient that depends on factors such as operating costs and energy efficiency. The study by Arumugam et al. (2021) found that the Bresse model performed well, even compared to more complex life-cycle cost analysis (LCCA) approaches, describing the relation between pipeline diameter and flow rate. To find the coefficient k, pipeline data from the IGGIELGN dataset can be used. This is explained in section 5.4.2.

5.4.2 Used data and model fitting using the Bresse equation

The IGGIELGN dataset contains pipeline diameter (`diameter_mm`) and maximum capacity (`max_cap_Mm3_per_d`), along with metadata describing the source of these values. As described earlier, a lot of missing values in the pipeline dataset exist and are substituted with the median value for the specific pipeline attribute. To ensure a fair fit, only pipelines where the `method` entry for both diameter and capacity was marked as "raw" or "log_raw" were included. 562 entries were find to be complete and valid. All missing values were removed. The original units were converted to SI units as follows:

$$D = D_{\text{mm}} \cdot 10^{-3} \quad (\text{m}) \tag{12}$$

$$Q = Q_{\text{Mm}^3/\text{d}} \cdot \frac{10^6}{86400} \quad (\text{m}^3/\text{s}) \tag{13}$$

The interquartile range (IQR) method was used to filter out outliers in pipeline diameter data. The IQR is defined as the difference between the 75th percentile (Q_3) and the 25th percentile (Q_1). All data points lying outside the range $[Q_1 - 1.5 \cdot \text{IQR},\ Q_3 + 1.5 \cdot \text{IQR}]$ were excluded to improve the robustness of the Bresse model fit. To determine the empirical coefficient k, regression analysis was performed on the filtered dataset, fitting the Bresse model to the observed values. This provided a value for k of:

$$k = 0.04118 \tag{14}$$

with R^2 score of 0.71306. While the Bresse model is not as accurate as traditional fluid dynamics models such as the Hagen-Poiseuille and Darcy-Weisbach equations, the Bresse model remains a practical and computationally efficient approach for estimating pipeline dimensions based on available capacity data.

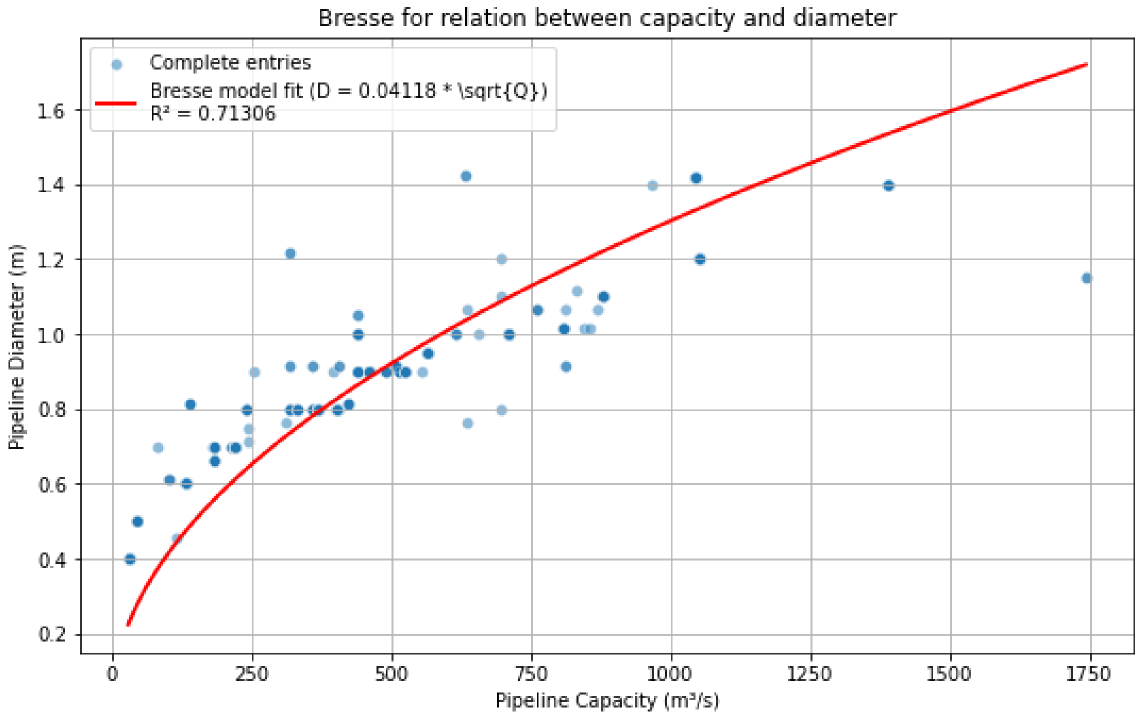

Figure 24: Bresse Model Fit

5.4.3 Usage of the fitted model

Capacity values are expressed in Megawatts to fit to the demand and supply of consumers and producers. To apply the Bresse equation for determining the size of new pipelines, these were converted to volumetric flow rate in cubic metres per second using the lower heating value (LHV) of hydrogen. Assuming an LHV of 120 MJ/kg and a density of 0.08988 kg/m³ (at standard conditions), the energy content of hydrogen is approximately 10.7856 MJ per m³. This gives the following conversion:

$$Q_{\mathrm{m^3/s}} = \frac{Q_{\mathrm{MW}}}{10.7856} \tag{15}$$

where Q_{MW} is the pipeline capacity in megawatts and $Q_{\mathrm{m^3/s}}$ is the equivalent volumetric flow rate.

5.5 Cost function implementation and parameter value setup

To apply the cost function introduced earlier, several practical steps are needed to translate pipeline characteristics from the dataset into cost estimates that can be used in the model. This section outlines how the cost function was implemented and how its parameters were calibrated based on literature.

All cost calculations are performed using pipeline diameter in inches and length in miles, to maintain consistency with the empirical coefficients derived by Brown et al. (2022). These unit conversions were applied systematically across the dataset prior to calculating pipeline costs.

Additionally, a repurposing factor f was introduced to account for the reduced capital expenditure associated with reusing existing natural gas pipelines for hydrogen. Based on values reported by ENTSOG, GIE, Hydrogen Europe (2021) and Jens et al. (2021), the repurposing cost factor used in this study is $f = 0.225$, the average of factors found in named studies. This reflects the substantial savings achievable when converting rather than constructing entirely new pipeline infrastructure.

For reinforced pipeline segments a correction factor cpc is applied to reflect partial cost savings. In this model, a value of $cpc = 0.9$ is used, under the assumption that while material and labor costs remain constant, right-of-way (ROW) and miscellaneous expenses are lower due to existing pipeline usage.

Finally, a multiplier α was implemented to capture the additional expense of offshore pipelines. According to Timmerberg & Kaltschmitt (2019), offshore transport is 40–70% more costly than comparable onshore segments. To reflect this, the average of Timmerberg's estimates is used, resulting in an offshore correction factor of $\alpha = 1.55$. This value is applied to all pipeline segments that cross the Mediterranean Sea, as identified in the spatial data.

Together, these parameter choices enable the cost function to be operationalized in a way that aligns with real-world infrastructure cost estimates, while maintaining compatibility with the structure of the dataset and the computational requirements of the model.

5.6 Concluding remarks

This chapter has laid the groundwork for the modeling activities presented in Chapter 4 by translating raw infrastructure and energy demand data into usable inputs. The SciGRID_gas dataset served as the core source for representing pipeline topology, capacity, and associated attributes, while industrial demand was approximated using spatial clustering of gas consumers around key industrial clusters. Conversions between volumetric flow and power were introduced to ensure unit consistency across supply, demand, and network flow, and an empirical diameter-capacity relationship was established to support cost estimation. Finally, the cost function parameter values were determined. Although several data limitations and assumptions were acknowledged, the processed dataset provides a technically coherent and geographically grounded basis for simulating a future hydrogen network between North Africa and Europe. section 6 will build directly on this foundation by detailing how these inputs are used to configure the model, define constraints, and evaluate network scenarios under different geopolitical and economic assumptions.

6 Experimental setup

6.1 Geopolitical risks of hydrogen transport

To explore the geopolitical risks associated with hydrogen transport from North Africa to Europe—particularly via repurposed natural gas pipelines—this section synthesizes insights from a range of academic and policy-oriented sources. The reviewed literature covers key themes including governance fragility, interregional energy relations, infrastructure vulnerability, and emerging power asymmetries between hydrogen-exporting and -importing regions.

A first set of risks relates to political tensions between countries involved in the hydrogen corridor. Green hydrogen diplomacy, particularly in contested areas such as the Western Sahara, has become a source of concern. Morocco's proposal to establish hydrogen production facilities in this disputed territory has the potential to intensify tensions with Algeria, which opposes Moroccan sovereignty over the region (Weko et al., 2023). As both countries are projected to play a key role in the modeled hydrogen network, unresolved territorial disputes may jeopardize cross-border cooperation (Sun, 2024).

Institutional fragility and governance asymmetries also present significant risks. According to Galan & Lindner (2024), long-term hydrogen trade between the Global South and the EU is vulnerable to elite corruption, regulatory capture, and limited rule of law. In countries like Morocco, where executive power is centralized and institutional checks are weak, there is a heightened risk that political rent-seeking could distort energy investments and erode trust in cross-border agreements.

Beyond governance issues, structural dependencies raise additional geopolitical concerns. Hydrogen, like oil and gas, may be subject to market concentration and strategic manipulation. Van de Graaf et al. (2020) argue that hydrogen exporters could use their position to influence foreign policy outcomes, creating new energy dependencies. This perspective is echoed by Frischmuth et al. (2023), who highlight the risk that European supply chains may become overly reliant on a narrow set of North African producers. Without a diversified set of suppliers, hydrogen imports could become a source of vulnerability rather than resilience.

Related to this, hydrogen infrastructure could replicate older path dependencies. As noted by Dejonghe et al. (2023), failing to diversify import corridors may reproduce the same geopolitical risks that have historically affected Europe's natural gas supply—namely, lock-in to politically unstable supplier regions. The importance of early planning to avoid such lock-ins is central to their analysis.

A recurring theme in the literature is the exclusion of local actors from early hydrogen partnerships. While international cooperation is essential, early-stage project structures tend to be dominated by large European firms and agencies. This dynamic, as outlined in Pepe et al. (2023), risks reinforcing existing power hierarchies, marginalizing local African institutions, and generating social or political backlash that could destabilize long-term energy relationships.

Security risks associated with cross-border infrastructure are also prominent in recent literature. The Nord Stream sabotage incident in 2022 serves as a stark reminder of the physical vulnerabilities of transnational pipelines (Virág & Tancsa, 2023). Energy infrastructure—whether undersea or overland—has become a potential target in geopolitical conflicts. Historical patterns of sabotage and terrorism in North Africa, particularly in Algeria and Libya, further highlight this risk. As discussed by Giroux (2009), energy infrastructure in these regions often suffers from weak perimeter security, making them susceptible to disruption.

In summary, the literature identifies a wide array of geopolitical risks facing future hydrogen transport between North Africa and Europe. These include regional disputes, institutional fragility, dependency on a limited number of suppliers, imbalanced governance structures, and risks of infrastructure sabotage. If these vulnerabilities are not actively acknowledged and mitigated, they could undermine the long-term stability and viability of a hydrogen network. As the next chapters shift toward network design and geopolitical scenario development, these risks will inform the assessment of system resilience under diverse political conditions. .

6.1.1 Conclusion

This section addresses the subquestion:

Which geopolitical tensions exist that are of possible influence on a pipeline infrastructure between North Africa and Europe, and how can they be mitigated

Hydrogen cooperation between North Africa and Europe is exposed to several geopolitical risks. These include regional tensions—particularly between Morocco and Algeria—institutional fragility, unequal governance structures, and the risk of replicating natural gas dependencies. Security concerns also arise from potential sabotage of cross-border infrastructure.

Mitigating these risks requires diplomatic efforts to manage regional disputes, stronger and more inclusive governance frameworks, diversification of supply routes, and improved infrastructure security. Addressing these challenges is crucial to ensure a resilient and sustainable hydrogen partnership.

6.2 Experimental design

Based on the geopolitical risks identified in section 6.1, a range of experiments can be set up to simulate the influence of geopolitical behavior on the network model. Model outcomes will be scored on different performance metrics, that will be further explained in section 6.3.

All scenario runs in this study are conducted using a consistent set of predefined parameters. These parameters define key physical and economic characteristics of the hydrogen network, such as the flow capacities of pipelines, cost assumptions for infrastructure development, and correction factors for repurposing or reinforcing existing assets. The complete parameter setup is presented in Table 8.

Table 8: Overview of fixed model parameters

Parameter	Value	Description
Repurposing factor (f)	0.225	Cost reduction factor for converting existing natural gas pipelines to hydrogen use. Based on values from ENTSOG, GIE, Hydrogen Europe (2021) and Jens et al. (2021).
Reinforcement correction factor (cpc)	0.9	Correction factor for pipelines placed in existing ROWs, accounting for reduced land and permitting costs.
Offshore pipeline multiplier (α)	1.55	Cost multiplier for offshore pipeline segments, reflecting installation and material complexity. Based on average cost increase from Timmerberg & Kaltschmitt (2019).
Capacity-to-diameter coefficient (k)	0.04118	Scaling constant used in the Bresse equation to estimate pipeline diameter from flow rate. Derived from empirical data fitting.
Hydrogen energy density	10.7856 MJ/m^3	Used to convert pipeline capacity to MW based on the lower heating value (LHV) of hydrogen and standard density.

The motivation and source for each value are further elaborated in Sections 5.4.2 and 5.5. With the fixed model parameters determined and stated, the conducted scenarios for this study are presented.

6.2.1 Scenario 0 – A peaceful cooperative world

This scenario represents the ideal case in which all participating countries, both in North Africa and Europe, fully cooperate. All designated production sites operate as intended, supplying hydrogen to the industrial clusters in line with their preferred demand. There are no geopolitical disputes or incidents of infrastructure sabotage. The network functions under optimal conditions, providing a baseline for evaluating disruptions in subsequent scenarios.

6.2.2 Scenario 1 – Regional dispute

As discussed in Section 6.1, regional tensions and political uncertainty in North Africa pose potential risks to international hydrogen cooperation. One particularly sensitive issue is the dispute over the Western Sahara. Should Morocco promote hydrogen development in this contested area and European developers engage with it, Algerian cooperation could be withdrawn. To simulate this risk, Scenario 1 models a breakdown in collaboration by stopping hydrogen production in Algeria. The scenario explores the consequences of this disruption on the network's ability to meet overall hydrogen demand.

6.2.3 Scenario 2 – Pipeline sabotage without preliminary insight

Section 6.1 also highlights the threat of targeted sabotage of critical energy infrastructure. In this scenario, the impact of such an event is assessed by simulating the destruction of the pipeline connecting Morocco and Spain. No anticipatory reinforcement is modeled, meaning no preventive adjustments are made to mitigate sabotage risk. However, the scenario does explore the extent to which flow can be rerouted through alternative existing paths that are not repurposed, assessing the effect of such adjustments on the network's ability to deliver hydrogen under disruption.

6.3 Performance metrics for evaluating model outcomes

To assess the viability and effectiveness of the proposed hydrogen network, a set of performance metrics is applied. They capture key dimensions relevant to both technical performance and broader socio-political considerations. These metrics are modeled on the criteria that followed from the stakeholder analysis (subsection 2.7).

Economic feasibility reflects the ability of the network to deliver hydrogen at competitive cost while ensuring fair economic returns. It captures both capital investment and operational expenditure, relevant to stakeholders such as the European Union, energy companies, and investors. Because of the updated cost function with a correct monetary unit connected to it, this criterium can be portrayed by cost.

Energy security and robustness assess the system's resilience to disruptions. This metric tracks the amount of flow through the network. A matching flow through the network equal to the demand of consumers is ideal, but will not be the case in all of the scenarios. The difference in that will portray the systems energy security and robustness.

Geopolitical stability is the last of criteria relevant for this research mentioned in **??**. It addresses the model's capacity to mitigate political risks through supply route diversification and robust cross-border governance mechanisms. It reflects the strategic stability of intercontinental hydrogen trade. This criterion, however, cannot be measured quantitatively; instead, it helped shaping the different geopolitical scenarios used in this study.

Other criteria that were identified during the stakeholder analysis (section 2.7), are environmental sustainability, social equity and scalability and flexibility. As stated before, these are excluded from this research and are therefore not taken into account as performance metrics.

Table 9: Performance metrics for hydrogen network evaluation

Metric	**Description**
Economic feasibility	Measures cost-effectiveness of infrastructure by reviewing cost function outcomes
Energy security and robustness	Indicates the system's ability to meet demand under disruptions

6.3.1 Conclusion

This section answers the subquestion:

How can the performance of the system configurations be measured?

The performance of the proposed hydrogen network configurations is measured using two key metrics: economic feasibility, energy security and robustness. These metrics capture both technical and strategic dimensions of system performance and are derived from the stakeholder analysis. Economic feasibility is assessed through the updated cost function, energy security is evaluated by comparing supply flow to demand. Together, these metrics provide a balanced framework for evaluating the effectiveness of different network scenarios.

7 Results

This chapter presents the results of the hydrogen infrastructure modeling process. It begins by detailing the preparatory steps required to reduce and segment the spatial pipeline dataset, ensuring it could be processed using the selected optimization and analysis tools. Following this, four geopolitical and infrastructural scenarios are analyzed to assess how the network performs under varying conditions of cooperation and disruption. These scenarios reveal trade-offs between cost-efficiency, structural redundancy, and supply robustness. Each scenario builds upon a common network structure derived from the baseline case and is evaluated using consistent performance metrics to ensure comparability.

7.1 Network reduction and segmentation

Before the hydrogen network could be optimized and analyzed using the ONLT and maximum flow methods, the original spatial dataset needed to be significantly simplified. The raw pipeline dataset contained 2889 pipelines and 2295 connection points across the selected countries, making it too large and complex for direct modeling. This section outlines the preparatory steps taken to reduce and segment the network into analytically manageable parts. The approach combines Steiner-based reduction with Girvan–Newman clustering, which together transform the raw network into a streamlined structure suitable for optimization and scenario analysis.

7.1.1 Steiner reduction process

The Steiner reduction method was applied to iteratively remove low-importance components from the network while preserving essential connectivity. Each iteration involved three key steps: (1) removal of non-terminal degree-1 nodes, (2) Replacing of edges connected to degree-2 nodes by direct edge, and (3) contraction of short edges between non-terminal nodes. These steps are grounded in classical Steiner tree principles, which aim to simplify networks without compromising their core structure (Winter, 1987). The Steiner reduction was explained by a simple example in subsection 4.2.

To maintain geographical realism and policy relevance, several modifications were made to the classical Steiner process. Cross-continental links—such as those connecting Africa to Europe—were excluded from simplification to preserve strategic integrity.

These steps were repeated across three iterations to maximize simplification without compromising network function. The resulting reduced network substantially decreases computational complexity while remaining structurally robust and geopolitically grounded.

The first iteration significantly reduced graph complexity. As shown in Figure 25, the original network was dense and redundant. The three sub-steps of the iteration removed 820 degree-1 nodes, merged 386 degree-2 nodes, and contracted several short edges.

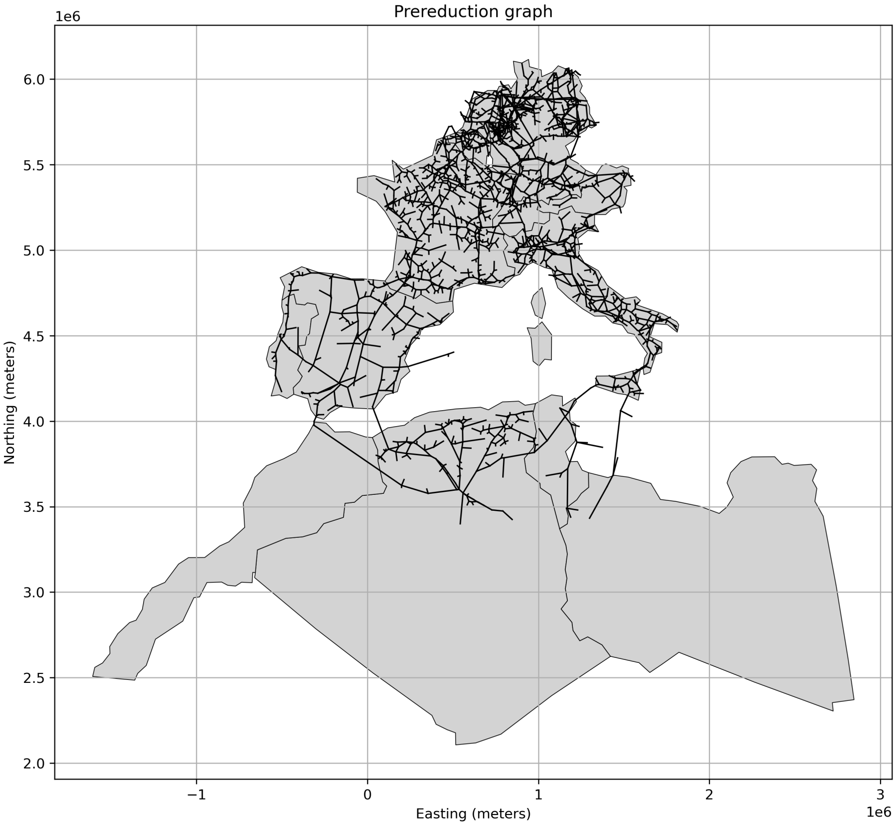

Figure 25: Steiner reduction – Initial full network before reduction

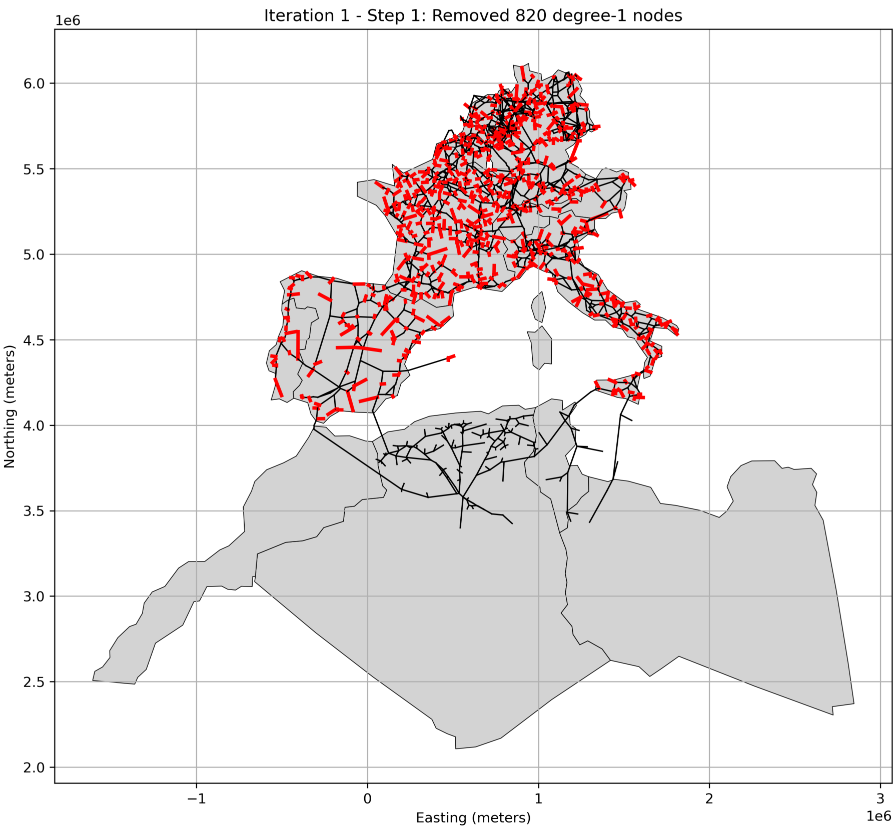

Figure 26: Steiner reduction – Iteration 1: after removal of 821 degree-1 nodes

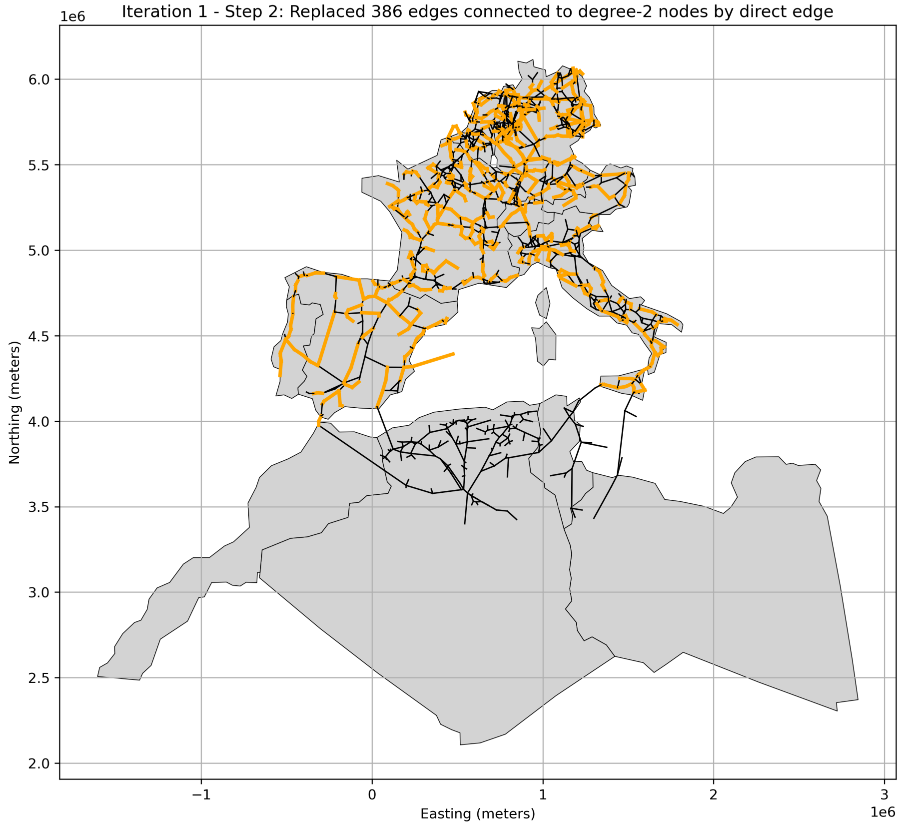

Figure 27: Steiner reduction – Iteration 1: after replacing 386 edges connected to degree-2 nodes by direct edge

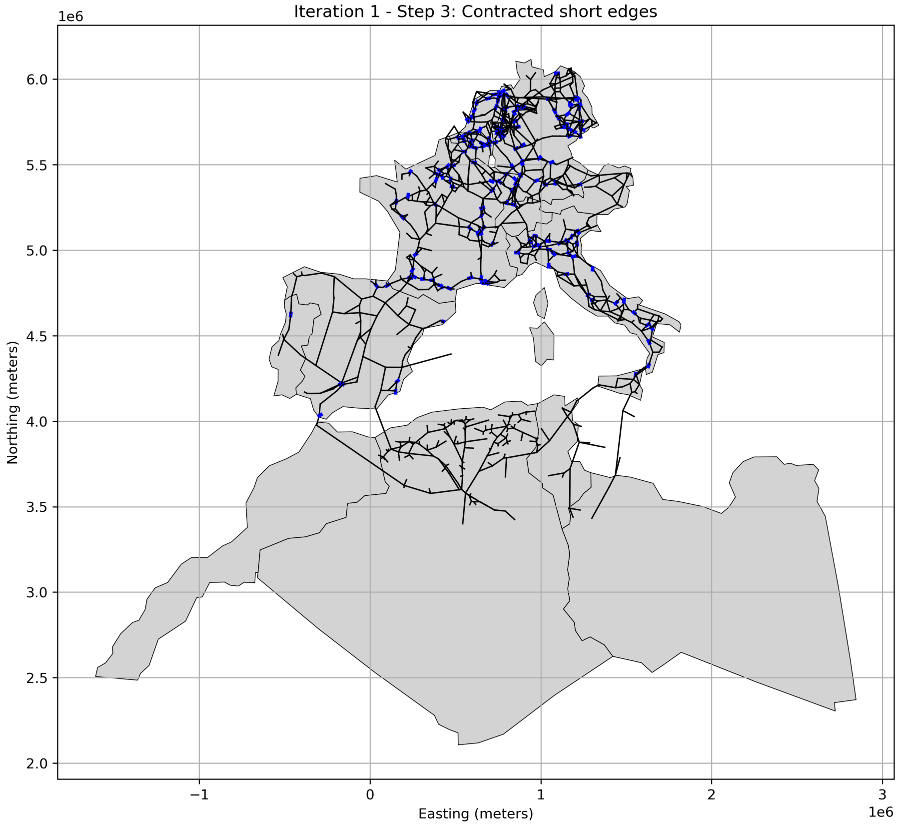

Figure 28: Steiner reduction – Iteration 1: after contraction of short edges

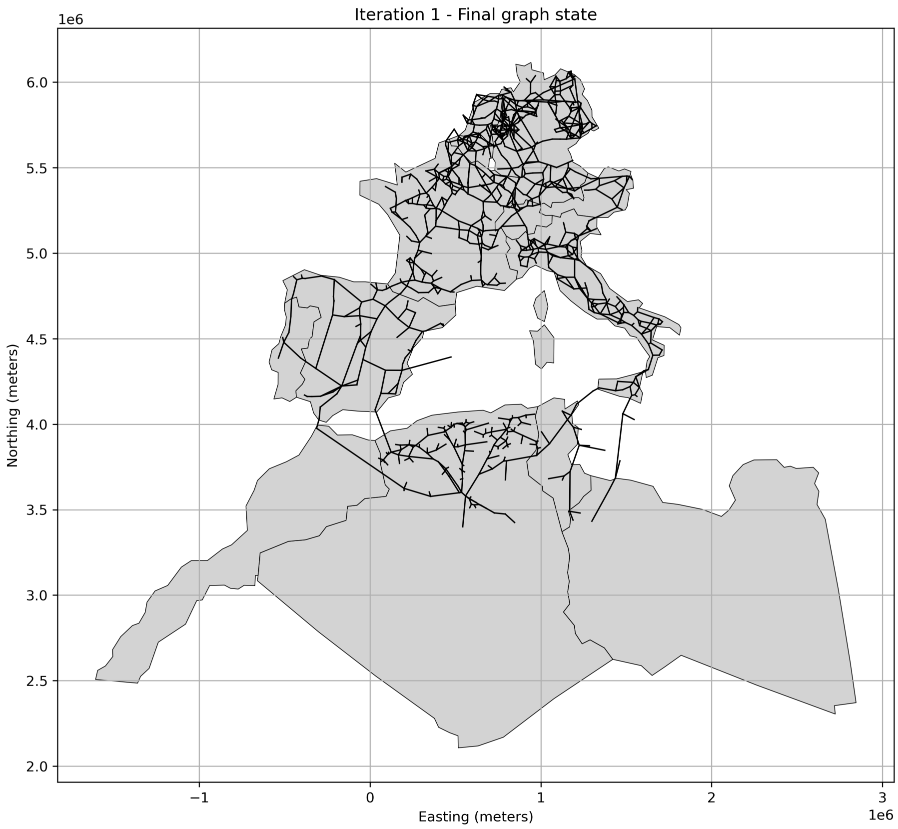

Figure 29: Steiner reduction – Iteration 1: final graph state

A second iteration was applied to further simplify the network. An additional 74 degree-1 nodes were removed, 162 degree-2 nodes were merged, and more short edges were contracted. The simplification from the first iteration allowed more nodes and connections to meet reduction criteria.

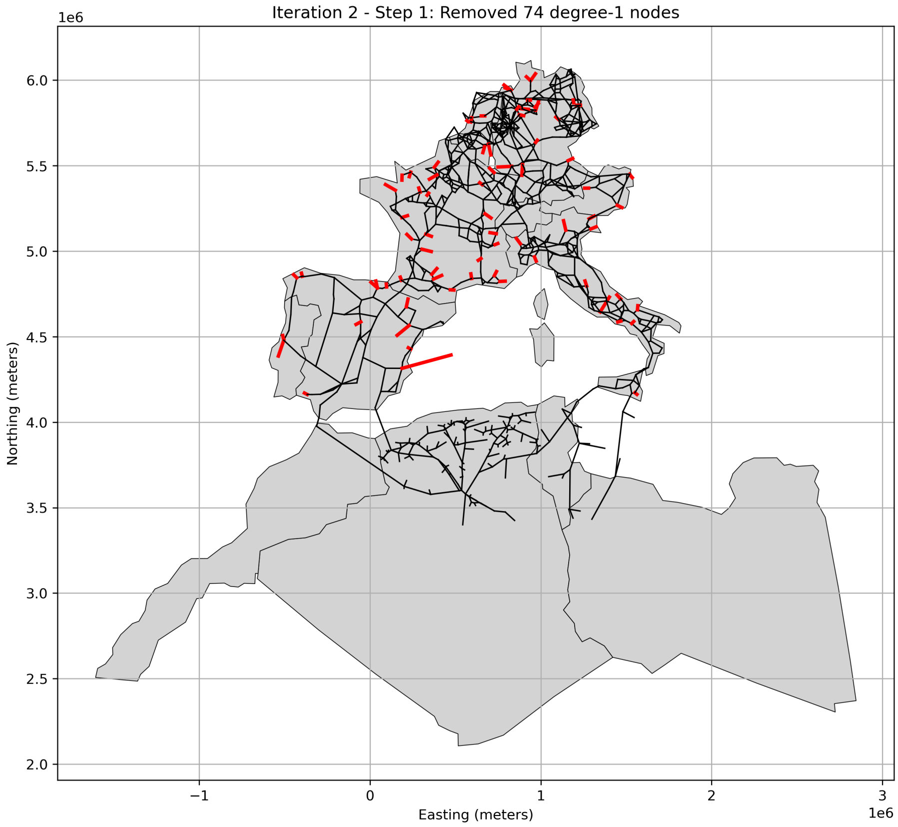

Figure 30: Steiner reduction – Iteration 2: after removal of 74 degree-1 nodes

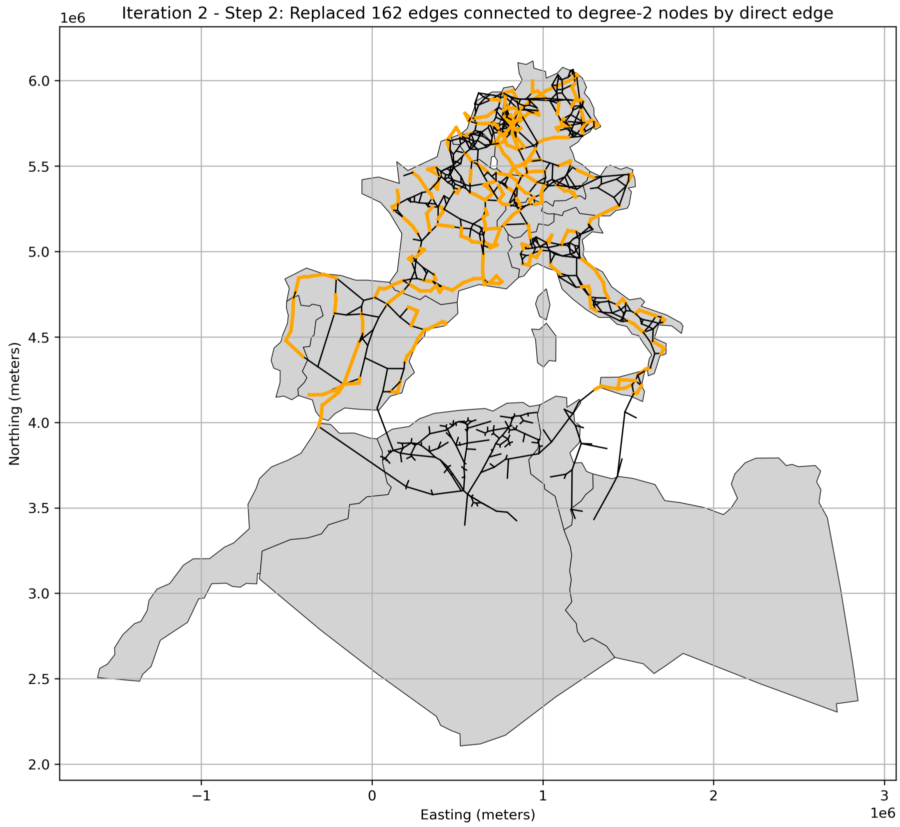

Figure 31: Steiner reduction – Iteration 2: after replacing 162 edges connected to degree-2 nodes by direct edge

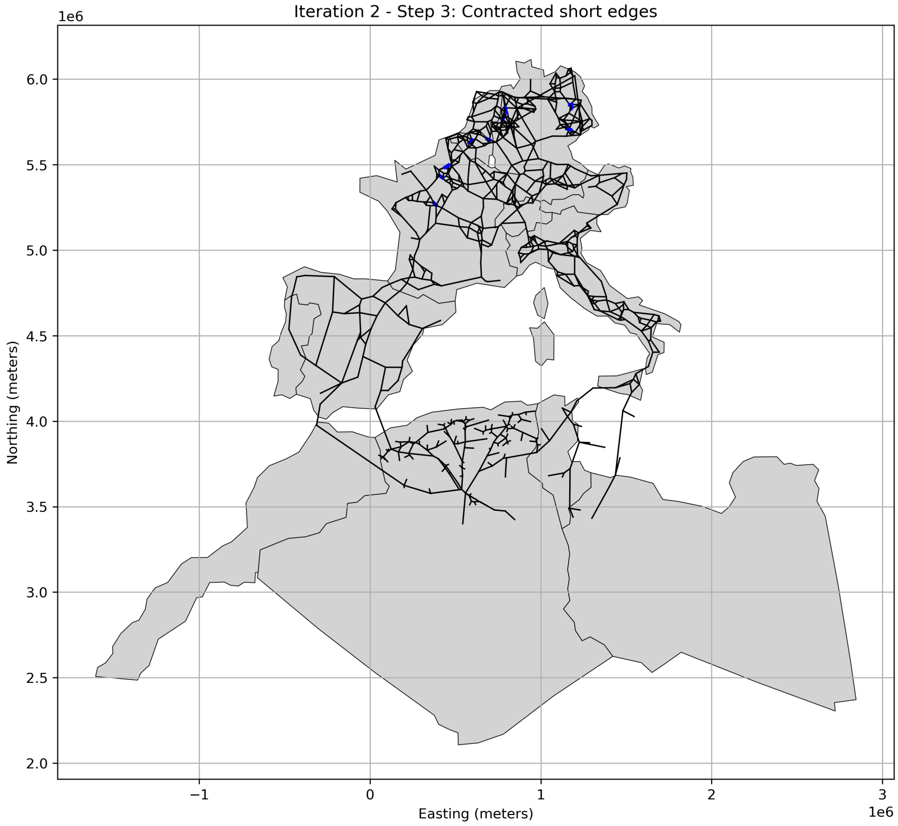

Figure 32: Steiner reduction – Iteration 2: after contraction of short edges

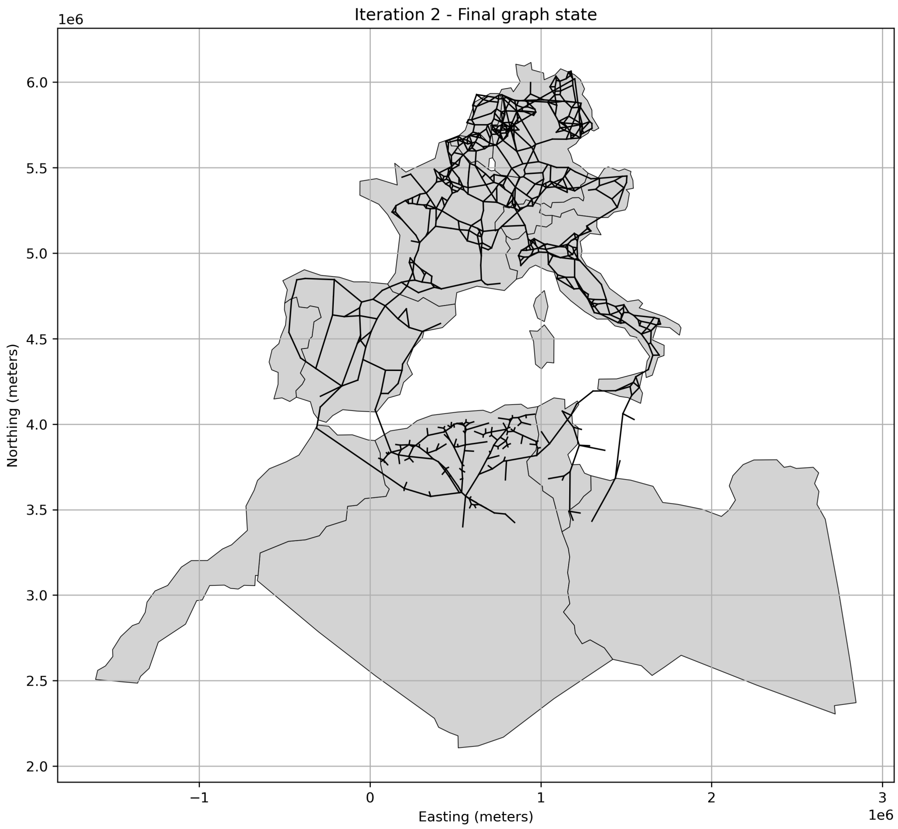

Figure 33: Steiner reduction – Iteration 2: final graph state

A third and final iteration was conducted to check for remaining simplification opportunities. Only a few components were changed: 7 degree-1 nodes removed and 48 degree-2 nodes merged. The absence of further change indicates stabilization of the network structure.

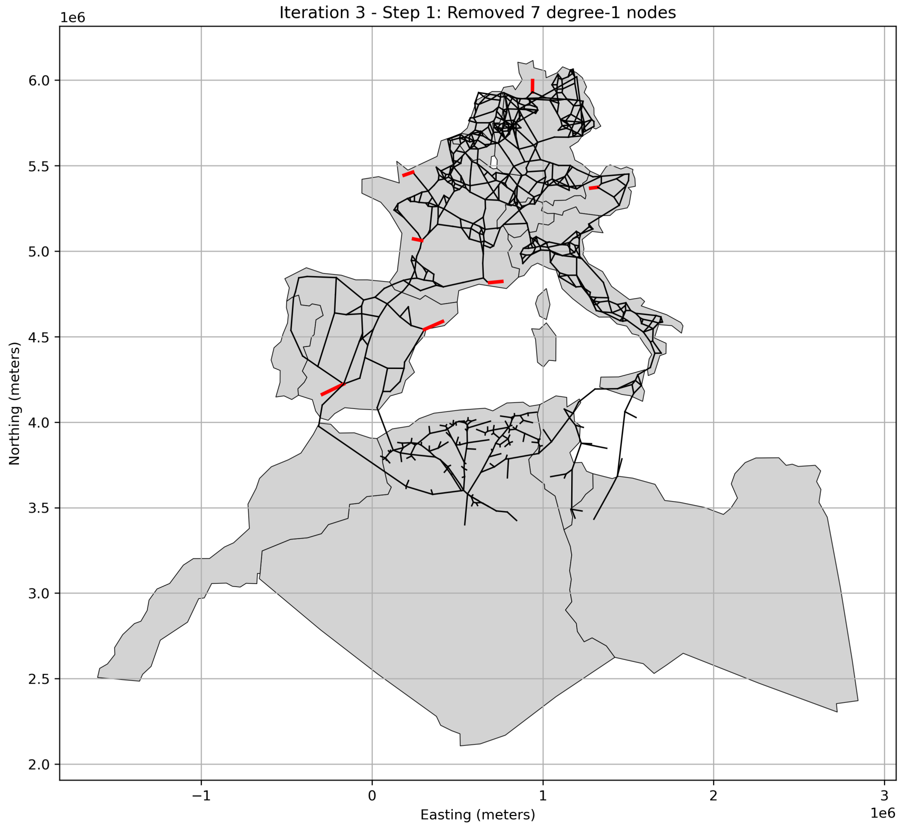

Figure 34: Steiner reduction – Iteration 3: after removal of 7 degree-1 nodes

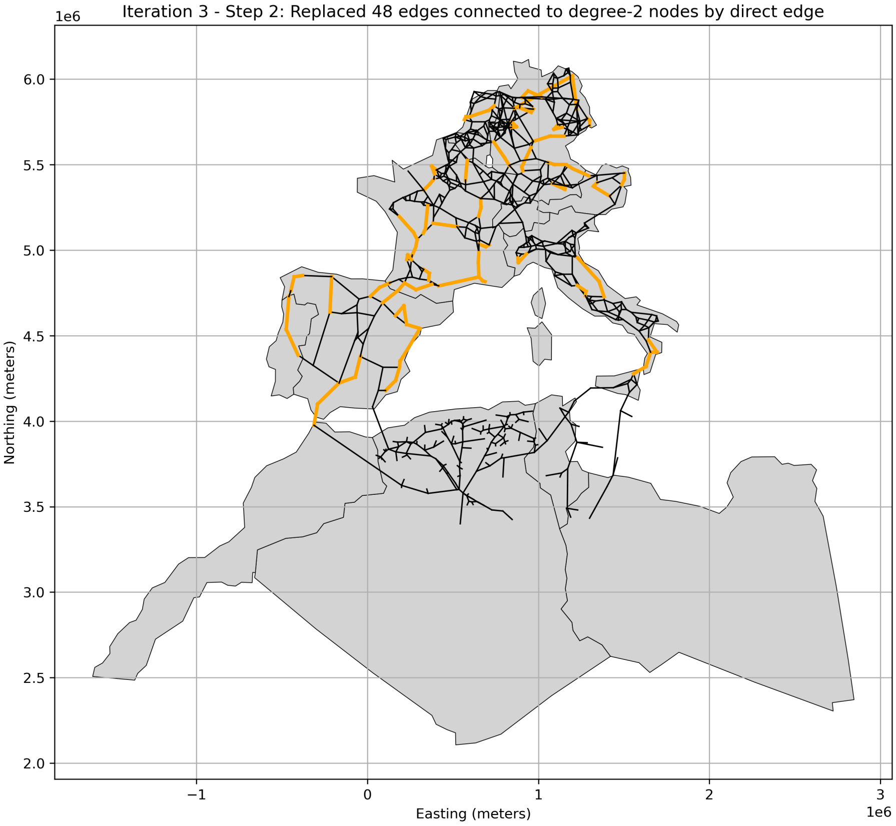

Figure 35: Steiner reduction – Iteration 3: after replacing 48 edges connected to degree-2 nodes by direct edge

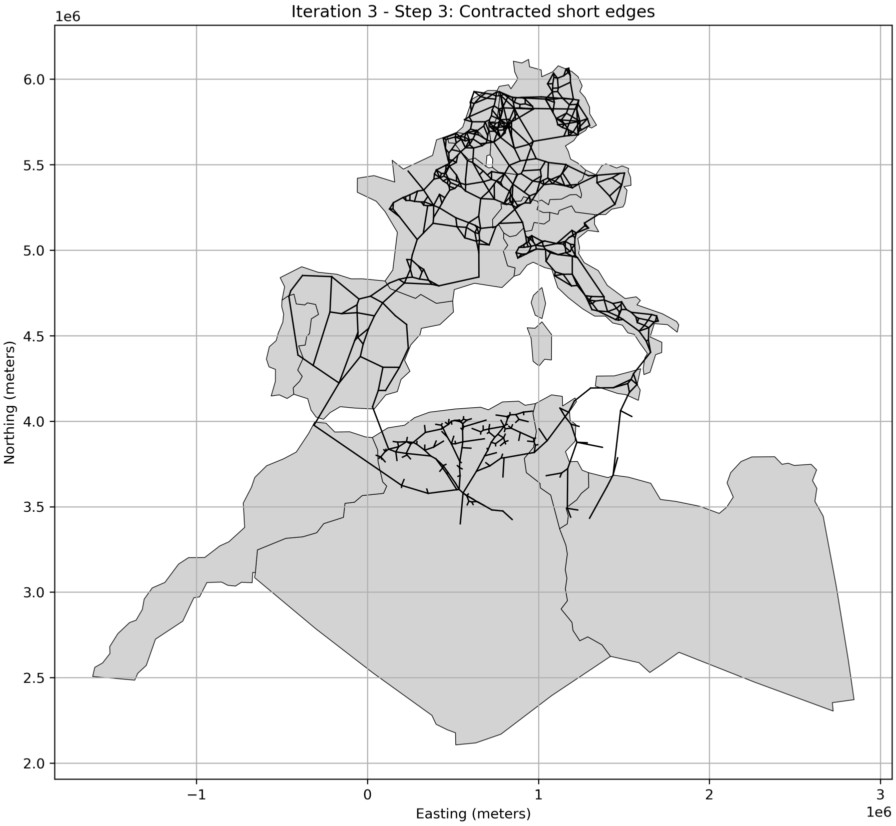

Figure 36: Steiner reduction – Iteration 3: contraction of 0 short edges

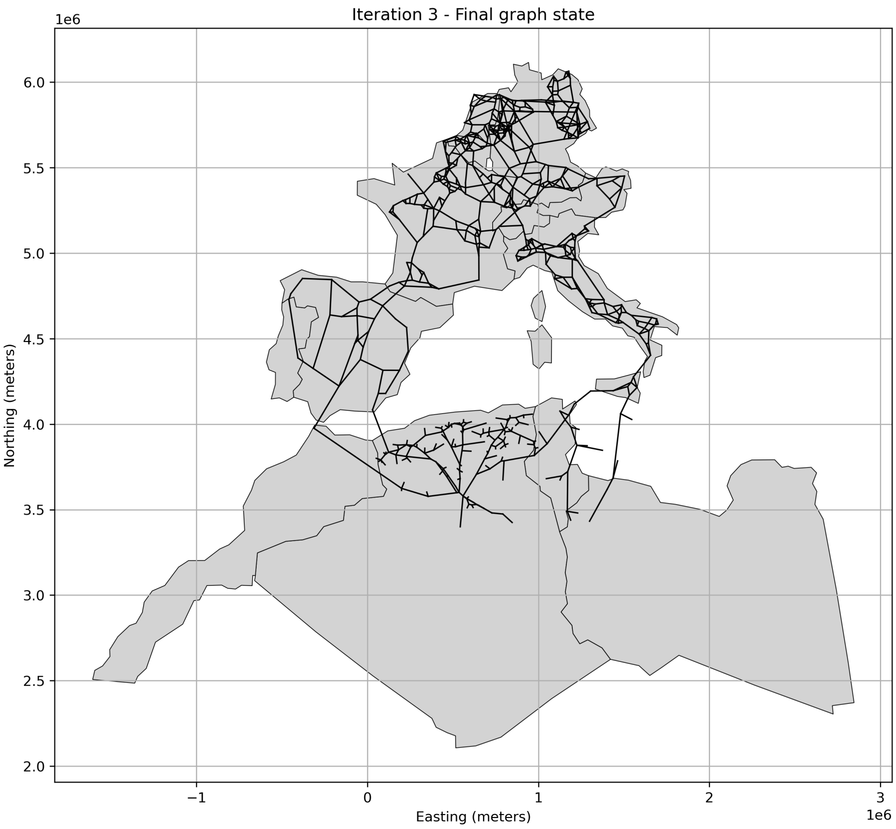

Figure 37: Steiner reduction – Iteration 3: final graph state

7.1.2 Girvan–Newman clustering

Once the full network was simplified, the Girvan–Newman algorithm was applied to divide it into operational clusters. In this research, three clusters were selected, as after testing this was found to be the perfect balance between geographical resolution and computational feasibility. This step allows the ONLT to compute layouts for each cluster independently, avoiding the computational limits of applying the tool to the entire network.

The figures below show the stepwise removal of edges based on betweenness centrality. As more high-betweenness links are removed, the network gradually separates into clusters. Final segmentation into three clusters is reached after six edge removals. A extensive explanation of this method is given in subsection 4.3.

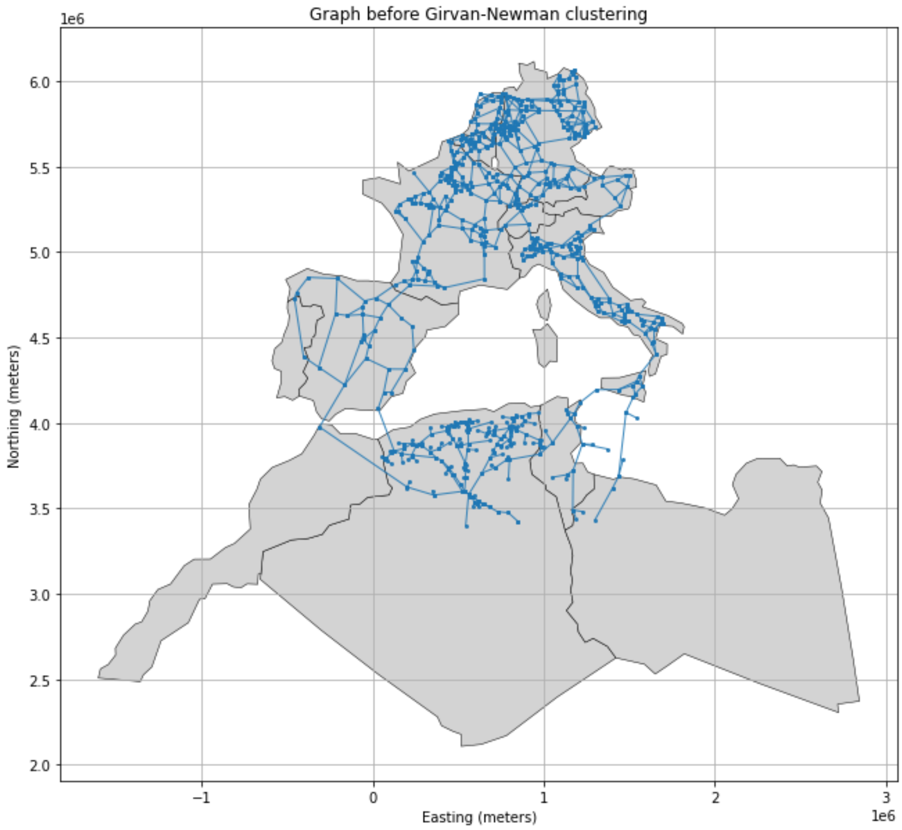

Figure 38: Initial graph before edge removals

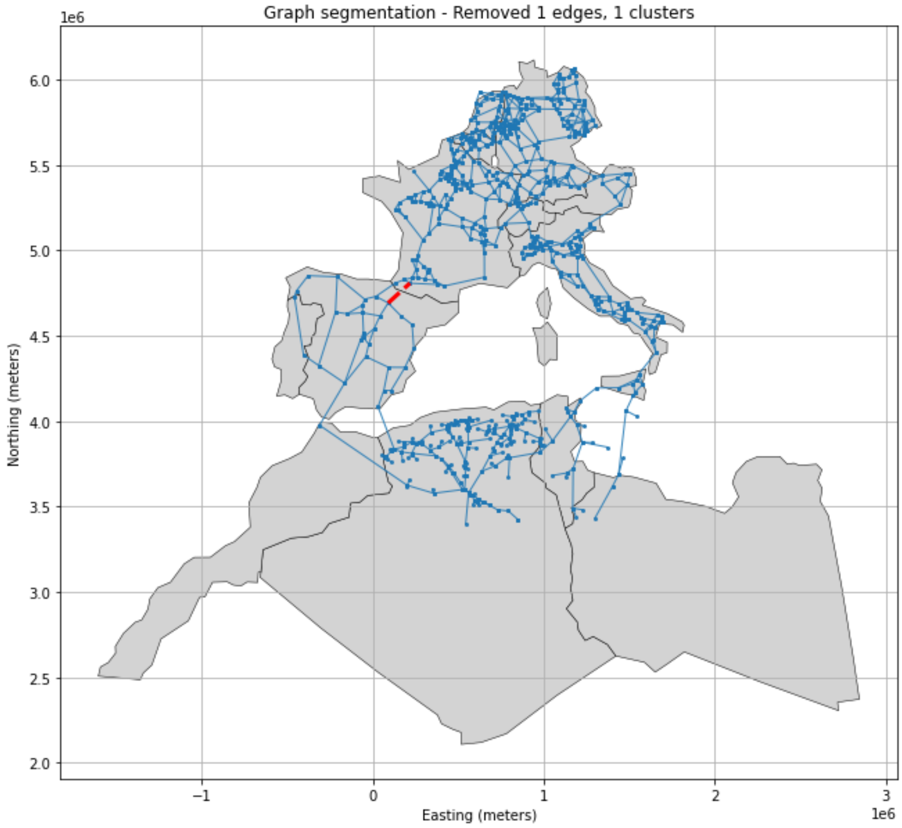

Figure 39: Girvan Newman clustering – After removal of 1 edge (1 cluster)

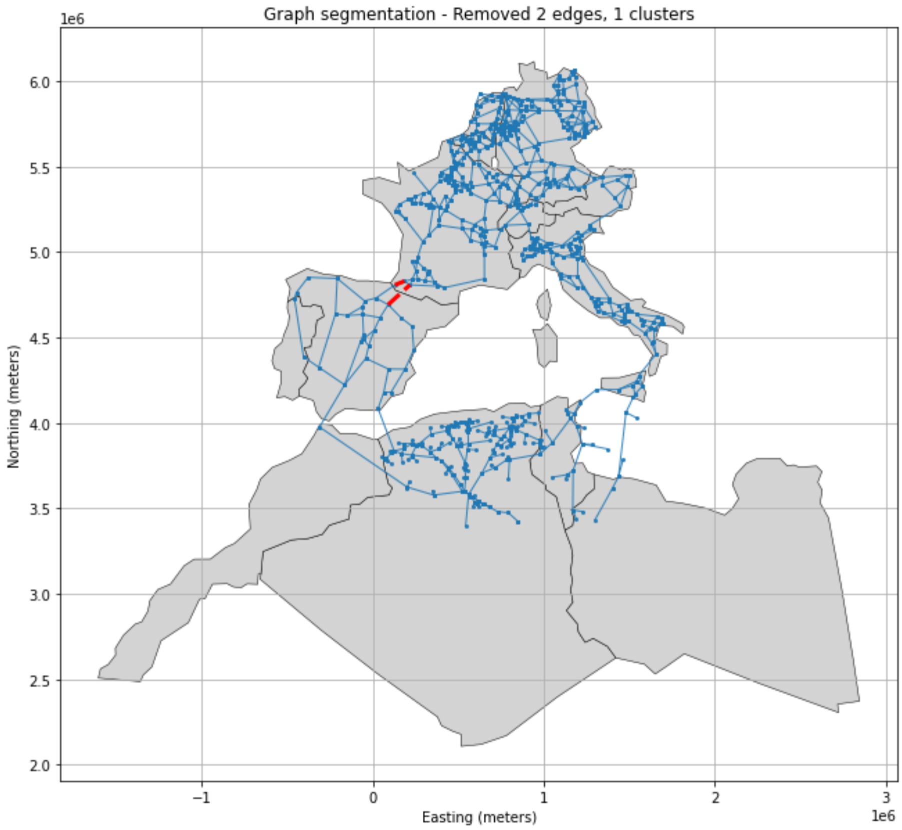

Figure 40: Girvan Newman clustering – After removal of 2 edges (1 cluster)

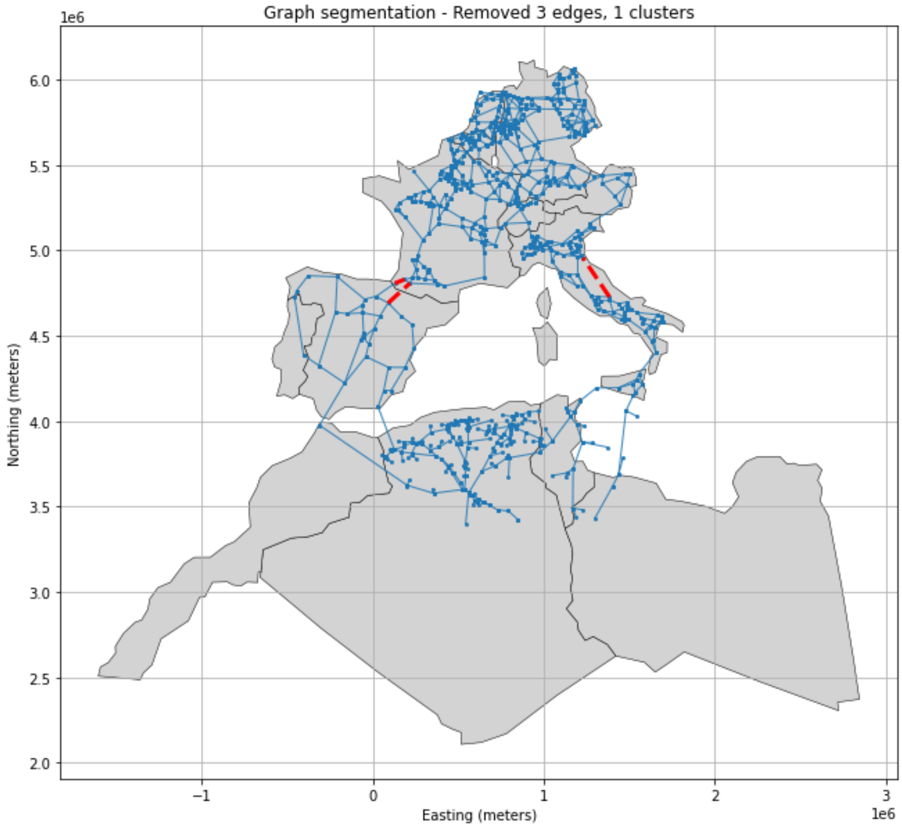

Figure 41: Girvan Newman clustering – After removal of 3 edges (2 clusters)

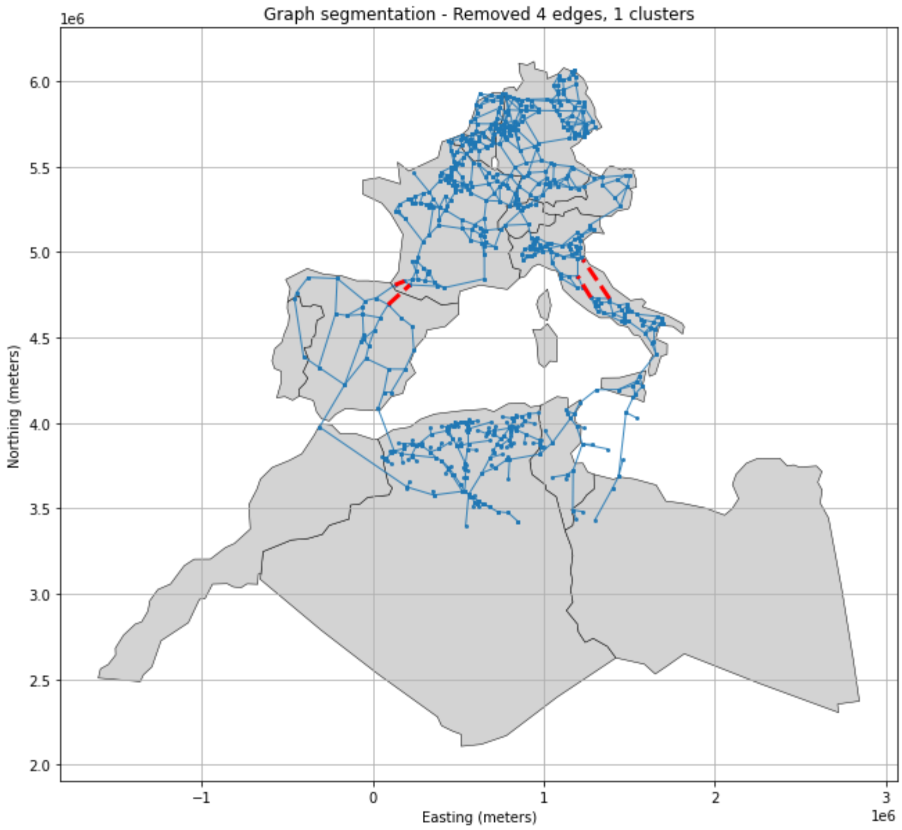

Figure 42: Girvan Newman clustering – After removal of 4 edges (2 clusters)

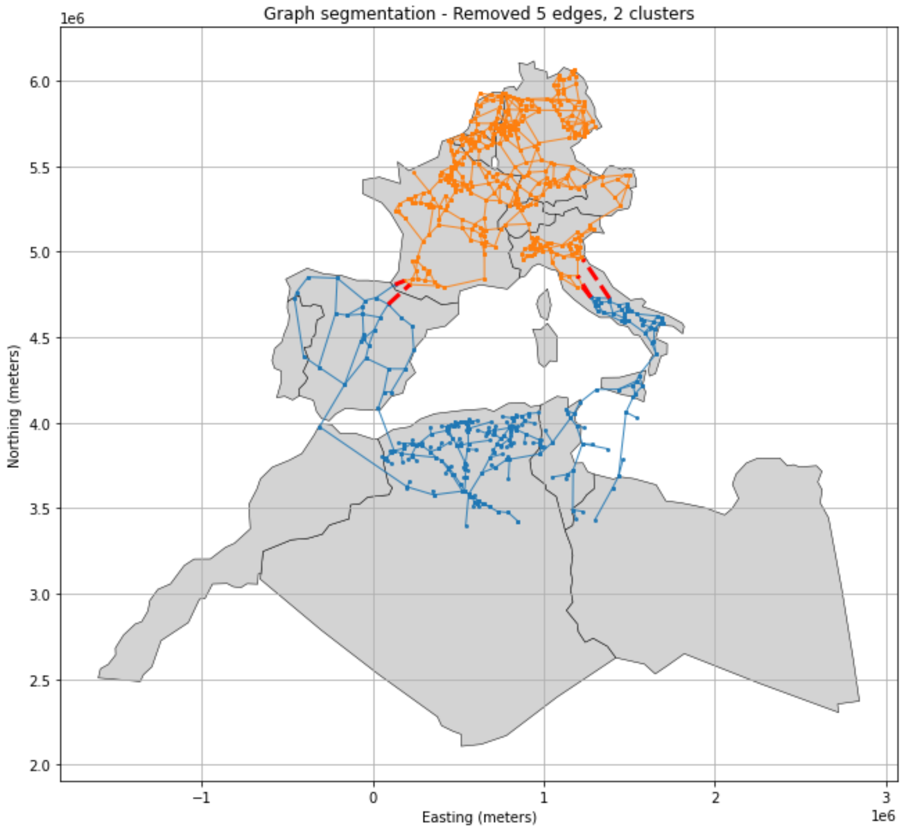

Figure 43: Girvan Newman clustering – After removal of 5 edges (2 clusters)

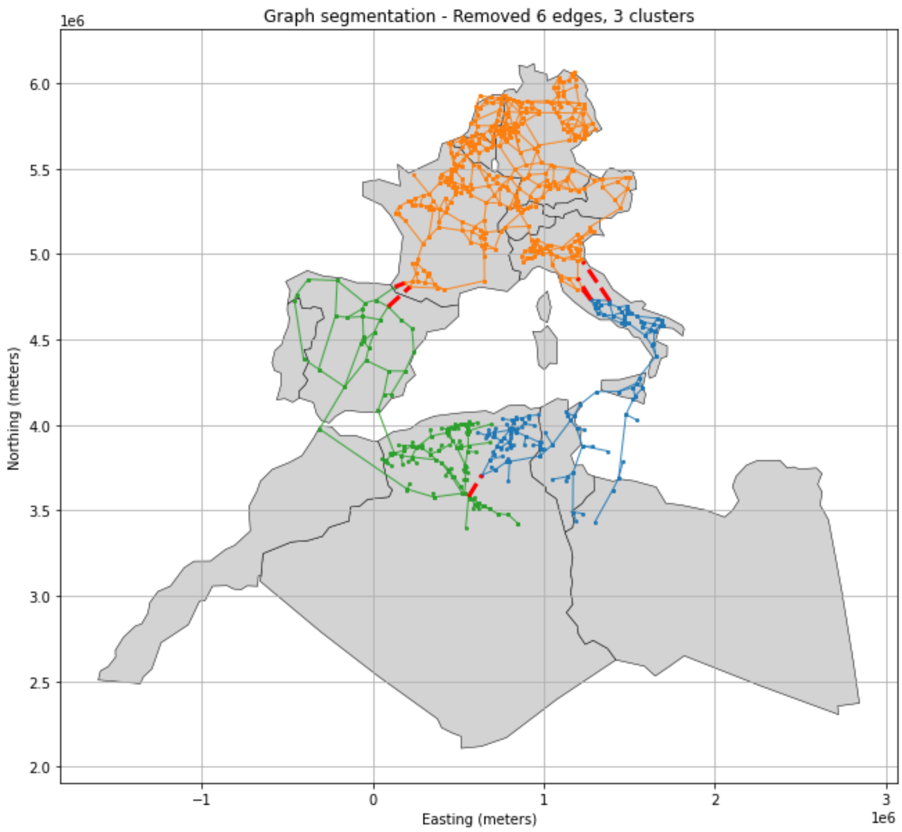

Figure 44: Girvan Newman clustering – Final removal to create 3 clusters

7.1.3 Concluding remarks

The network reduction and segmentation process successfully transformed the original spatial dataset into a computationally manageable structure without compromising essential geographical and infrastructural characteristics. The Steiner reduction method removed redundant nodes and edges in three successive iterations, while the Girvan–Newman clustering algorithm divided the network into three analytically tractable regions. These steps enabled the application of the Optimal Network Layout Tool (ONLT) within the computational limits of the modeling environment.

With each cluster independently optimized using the ONLT, the next step involves merging these localized solutions into a single integrated network. This integrated structure serves as the foundation for scenario testing using the maximum flow algorithm. By evaluating how the network performs under different geopolitical and infrastructural conditions, the model assesses both its efficiency and its resilience. The following section presents the outcomes of this scenario analysis.

7.2 Scenario results

With the network fully reduced, segmented, and locally optimized using the ONLT, the next phase involves recombining the three regional clusters into a single integrated hydrogen infrastructure. This unified network serves as the basis for testing how the system performs under varying geopolitical and infrastructural conditions. The following section presents the outcomes of four distinct scenarios. Each scenario simulates a different level of cooperation, stability, or disruption, allowing for evaluation of the network's capacity, efficiency, and resilience.

7.2.1 Scenario '0' - 'a peaceful cooperative world'

The first scenario that is presented, represents a 'peaceful cooperative world'. This scenario represents the ideal case in which all participating countries, both in North Africa and Europe, fully cooperate. A

Figure 45 presents the minimum-cost spanning tree (MCST) for Scenario 0, which integrates the three regional subnetworks optimized using the Optimal Network Layout Tool (ONLT). This structure represents the most cost-efficient configuration for delivering hydrogen from production to demand locations. Unlike standard ONLT applications that generate strictly tree-like layouts from scratch, the model in this study incorporates an existing gas infrastructure. As a result, the final network may contain alternative paths, for example if use of existing (repurposed) pipelines proves more cost-effective than constructing new pipeline segments. For example, the ONLT may opt for a longer but already existing route if extending a direct line entails higher costs. In this sense, the final layout deviates from ONLT's tree terminology and rather reflects a network. This can be seen for example in the connection area between France and Spain.

Newly constructed pipelines are shown in red. These pipelines are built to enable cheaper overall flow, optimizing for cost rather than just connectivity. Pipelines shown in yellow are reinforced existing pipelines. While already part of the original network, these did not have sufficient capacity to transport the required flow and were therefore upgraded. Pipelines shown in black are repurposed lines: they had adequate capacity and were already part of the network but needed to be adapted for hydrogen transport. As discussed in section 5.5, repurposing costs are estimated at 10% of the cost of constructing a new pipeline.

The network presents a couple interesting insights. The model chooses several offshore routes, notably from Libya to Italy and from Algeria to Spain. Despite higher costs associated with offshore infrastructure (see section 4.5.4), these routes reduce total network cost. The longer distances over sea, which could be seen as more vulnerable, are not considered problematic within the assumptions of this peaceful and cooperative scenario, but can be in other scenarios.

The table below summarizes the key performance metrics for this scenario. The total network cost amounts to €22.242 bn, with all consumer demand fully met. From an economic standpoint, such an investment is plausible given the European Union's strong commitment to renewable energy. The network achieves maximum energy security and robustness, as no capacity issues are observed. Geopolitical stability is assumed throughout, consistent with the cooperative nature of this scenario.

Table 10: Scenario 0: Cost comparison baseline

Metric	**Value**
Total cost (€)	€22.242 bn
Total demand (MW)	61,845
Total flow value (MW)	61,845
Supply / Flow value ratio	1.00

The MCST also presents the answer to the final subquestion:

What is the most cost-effective approach for developing a pipeline infrastructure between North Africa and Europe?

The outcome of the max-flow of scenario 0 is in fact the most cost-effective approach for developing a sufficient network between producing and consuming countries.

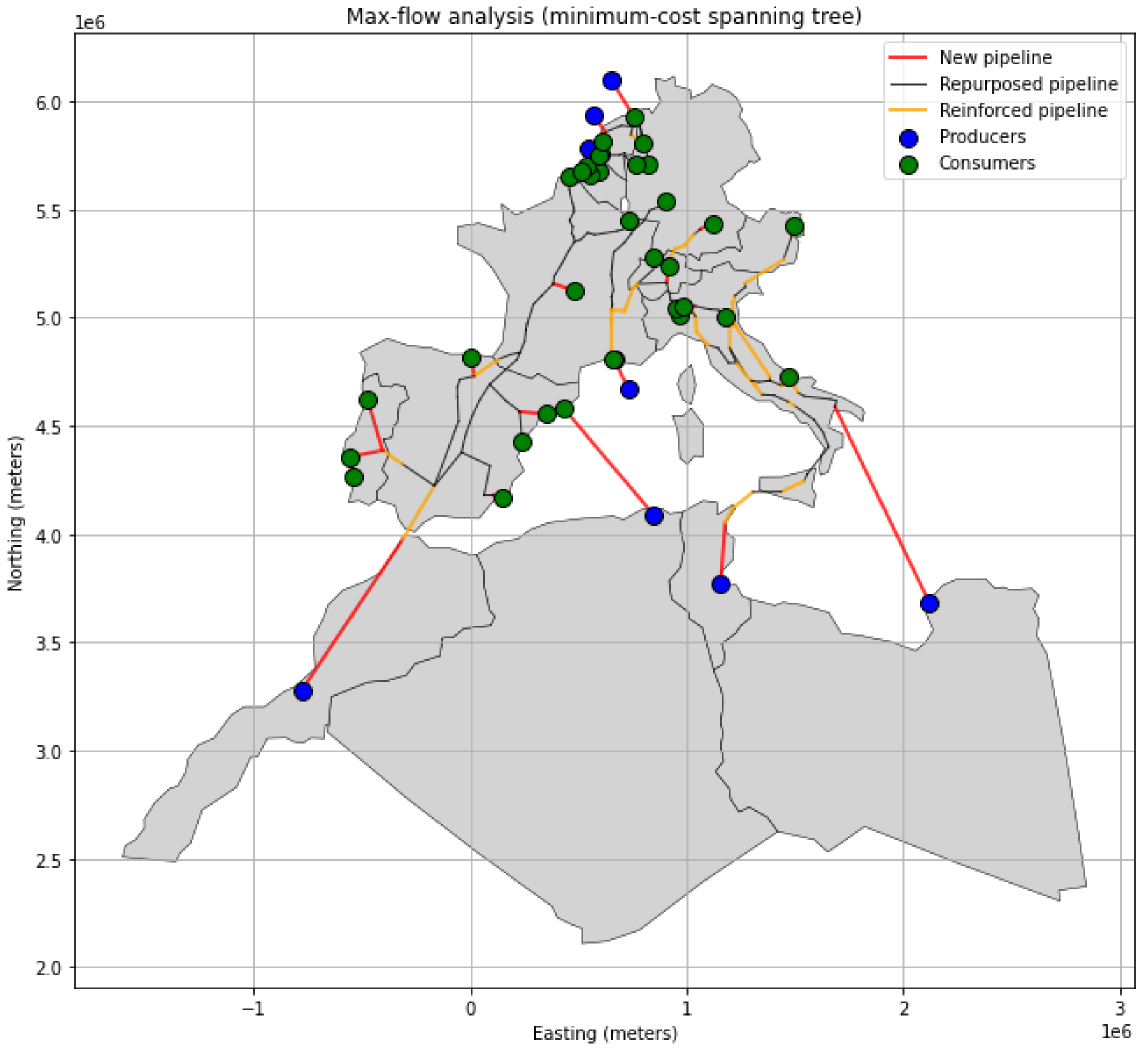

Figure 45: Minimum-cost spanning tree (MCST) scenario 0

To provide a comprehensive overview of the pipeline infrastructure considered in this study, Figure 46 visualizes both the full pipeline dataset and the subset of pipelines utilized in the optimized minimum-cost spanning tree (MCST). Many pipelines in the dataset show zero flow, indicating they were neither used nor repurposed in the final configuration of the max-flow network. Nevertheless, this visualization is useful for illustrating the contrast between the theoretical connectivity of the full network and the cost-efficient structure that results from the optimization process. To enhance the visibility of flow differences across the network, the color scale is capped at the 98th percentile of flow values. This means that the highest 2% of pipeline flow values are excluded from the color scale. This prevents a few extreme outliers from overshadowing the rest of the data, making more subtle differences easier to distinguish.

An important observation is the limited availability of alternative routes between North Africa and Europe. Aside from the direct connections constructed or expanded by the algorithm, few paths exist for routing additional flow. Because the ONLT optimizes pipeline capacity strictly based on demand, the model does only allows for redundant flow paths or buffer capacity through repurposed pipelines. This constraint limits the robustness of the cross-Mediterranean network and exposes it to potential supply disruptions. While this outcome is consistent with the cost-minimizing nature of the ONLT, it highlights a strategic vulnerability.

In contrast, the European portion of the network offers greater potential for redundancy. Many unused pipelines remain in place and could be repurposed to enhance regional flexibility and resilience. If network robustness were prioritized over cost alone, repurposing a broader set of assets could provide valuable backup routes.

Overall, the figure highlights how a large, geographically dispersed infrastructure can be reduced to a minimal functional network, but also reveals structural limitations. These characteristics could influence the energy security and robustness metrics introduced earlier under less stable geopolitical or operational conditions.

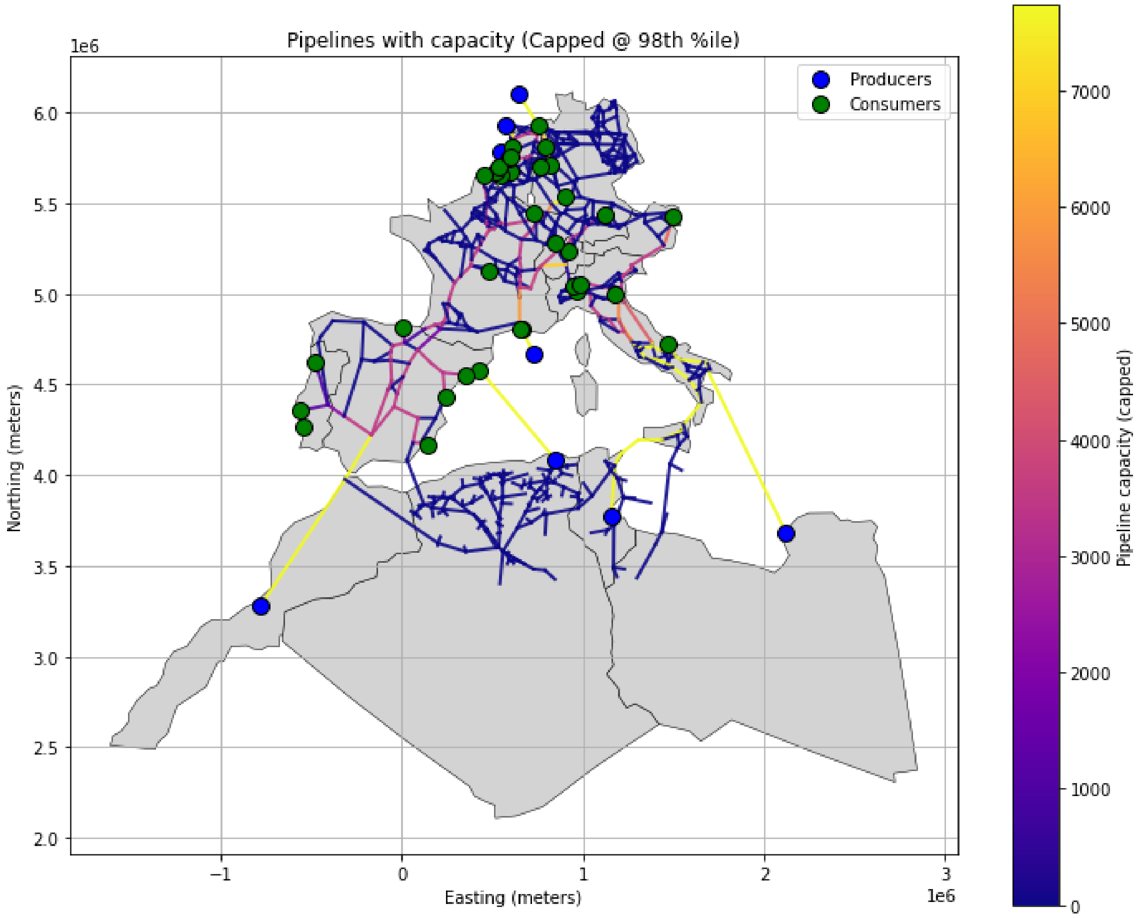

Figure 46: All pipelines in dataset with assigned capacities by max flow algorithm

As a final addition to Scenario 0, the flow through each pipeline is visualized to illustrate the distribution of hydrogen throughout the network. This is shown in Figure 47.

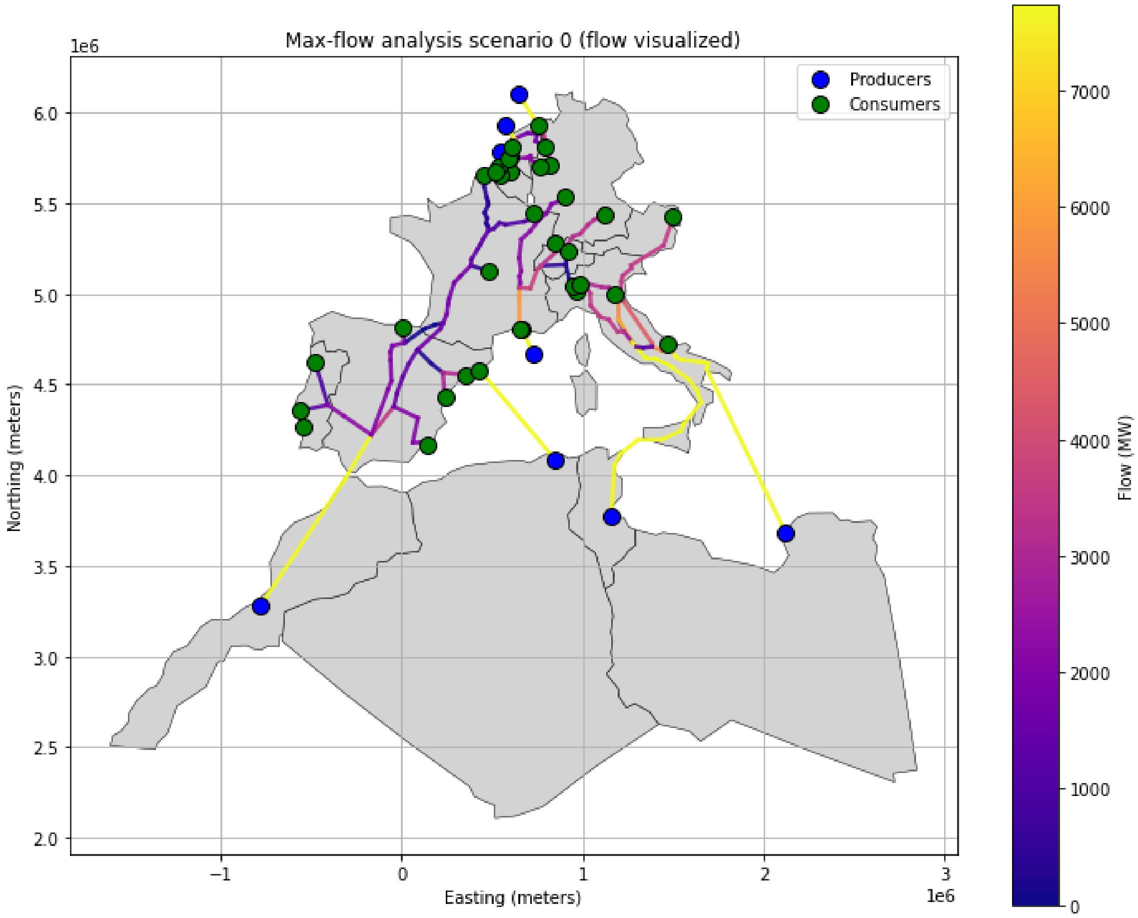

Figure 47: Flow through network scenario 0

7.2.2 Scenario 1 - Regional dispute

Scenario 1 explores the implications of a regional dispute, in which Algeria ceases cooperation and halts hydrogen exports due to escalating tensions with Morocco about the Western Sahara. The removal of Algeria as a producer has a significant impact on the network's ability to meet demand, as shown in Table 11. While the total network cost remains unchanged—since no additional pipelines are introduced—the cost of the unused Algeria–Spain connection is still included in the calculation, hence the same total cost for the network.

A comparison between the flow in scenario 0 (Figure 47) and scenario 1 (Figure 48) illustrates the network's sensitivity to the removal of a critical supplier. Not only does the Algeria–Italy flow disappear, but total delivered supply also drops substantially. These gaps reflect the lack of redundancy in the network and its sensitivity to the loss of a single production node.

Although the network structure remains the same, the supply/flow ratio drops from 1.0 to 0.875—indicating that only 87.5% of total demand is met in this scenario. This decrease demonstrates the network's limited ability to maintain energy security under geopolitical stress. However, it is important to note that the max-flow algorithm used in this model does not minimize delivery cost or distance, and multiple optimal flow solutions may exist. This means that which specific consumers are not served in the scenario is not uniquely determined by the model. It is therefore not possible to draw definitive conclusions about which specific consumers lose supply.

In real-world energy networks, particularly during crises or supply constraints, decisions about who receives supply first are influenced not only by technical factors but also by political and contractual considerations. For instance, a study on the resilience of natural gas networks highlights that during disruptions, such as geopolitical conflicts or natural disasters, the allocation of limited resources often requires strategies that consider fairness and political dynamics, not just technical efficiency (Carvalho et al., 2014).

Furthermore, research on supply chain management during crises emphasizes that operational complexities arise from factors like network configurations and provisioning systems. These complexities necessitate decisions that balance technical feasibility with political and contractual obligations (Durugbo & Al-Balushi, 2022). While these considerations are important, addressing them in detail falls outside the scope of this study.

Furthermore, the modeled dispute could have broader consequences for regional cooperation. Algeria's complete withdrawal from hydrogen trade not only impacts current infrastructure use but may also destabilize trust between North African countries and the EU. This could reduce willingness to engage in long-term hydrogen partnerships and complicate future investment in cross-border energy infrastructure.

Table 11: Scenario 1 performance metrics: MCST network under regional dispute

Metric	**Value**
Total cost (€)	€22.242 bn
Total demand (MW)	61,845
Total flow value (MW)	54,114
Supply / Flow value ratio	0.875

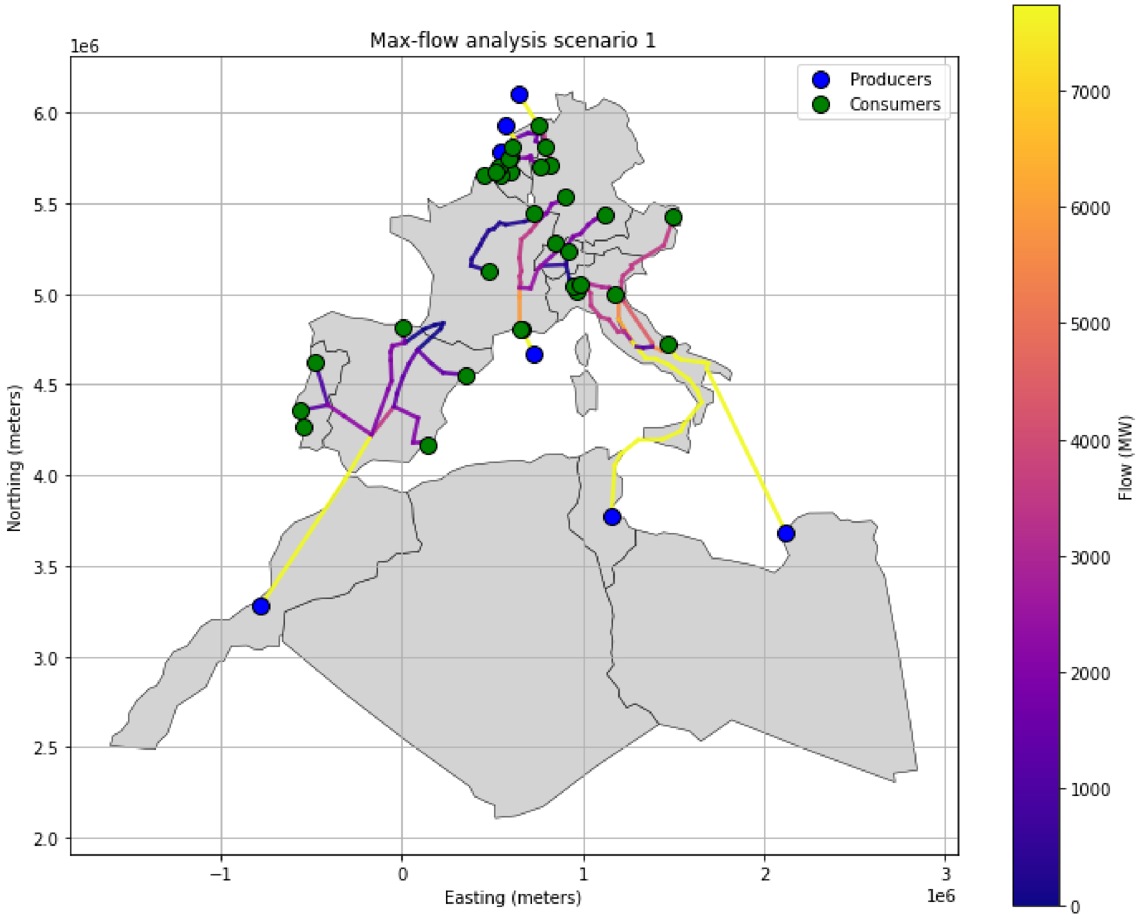

Figure 48: Flow through network scenario 1

7.2.3 Scenario 2 – Pipeline sabotage without repurposing

This scenario examines the consequences of a targeted infrastructure attack, in which the direct pipeline connection between Morocco and Spain is sabotaged. While hydrogen production levels remain unaffected, the network layout is compromised. The resulting distribution of flow is shown in Figure 49.

Due to the tree-like structure of the cost-optimized network, the loss of this single pipeline effectively isolates Moroccan production. Total flow drops to 87.5% of modeled demand—identical to the impact observed in Scenario 1, where production capacity was reduced. Although the flow visualization suggests that regions such as Portugal, eastern Spain, and parts of France and Belgium are particularly affected, such conclusions are only illustrative. Because the max-flow algorithm does not account for minimal cost, multiple equally optimal flow solutions exist. Real-world supply allocation under constraint would involve political and contractual decisions beyond the scope of this model, as already stated in subsubsection 7.2.2.

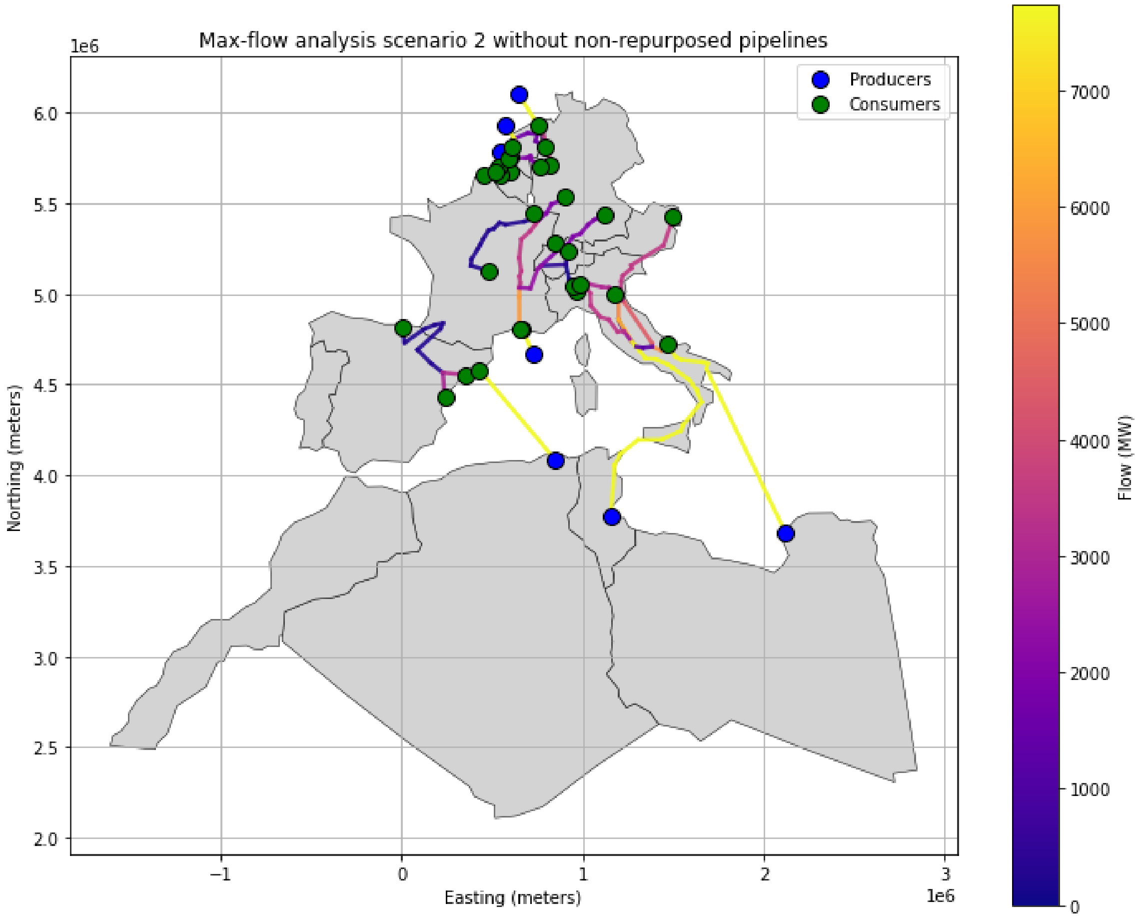

Figure 49: Scenario 2 – max-flow without repurposed pipelines

7.2.4 Scenario 3 – Pipeline sabotage with repurposing

In this alternative version of Scenario 2, the same pipeline sabotage occurs, but the model is permitted to leverage an otherwise unused existing connections. While excluded in the cost-optimized MCST due to its higher capital cost, this route provides an alternative pathway for Moroccan hydrogen to reach European demand via the Algeria–Spain corridor.

Repurposing this pipeline restores part of the lost supply. The updated flow pattern is presented in Figure 50. As shown in Table 12, the total supply-to-demand ratio improves from 0.875 to 0.927. However, this resilience comes at a financial cost. The repurposed pipeline was not part of the original MCST and would require an additional €10,672 bn in capital expenditure.

Table 12: Scenario 2 and 3 performance metrics comparison: With and without repurposed pipelines

Metric	**Without repurposing**	**With repurposing**
Total cost (€)	€22.242 bn	€32.914 bn
Total demand (MW)	61,845	61,845
Total flow value (MW)	54,114	57,288
Supply / Flow value ratio	0.875	0.927

It is important to note that the max-flow algorithm used in this scenario optimizes solely for the maximum quantity of hydrogen that can be transported through the network—it does not consider the cost of the routes used. As a result, the algorithm may activate pipelines that improve flow but are not economically efficient. The capital expenditure presented here therefore does not necessarily reflect the actual additional cost of achieving the improved supply ratio. A precise calculation of the cost-optimal way to restore flow would require a different modeling approach—one that jointly considers both cost and capacity. Such an analysis falls outside the scope of this study. This scenario highlights that while max-flow analysis is useful for assessing operational robustness, it cannot, on its own, generate cost-optimal infrastructure designs.

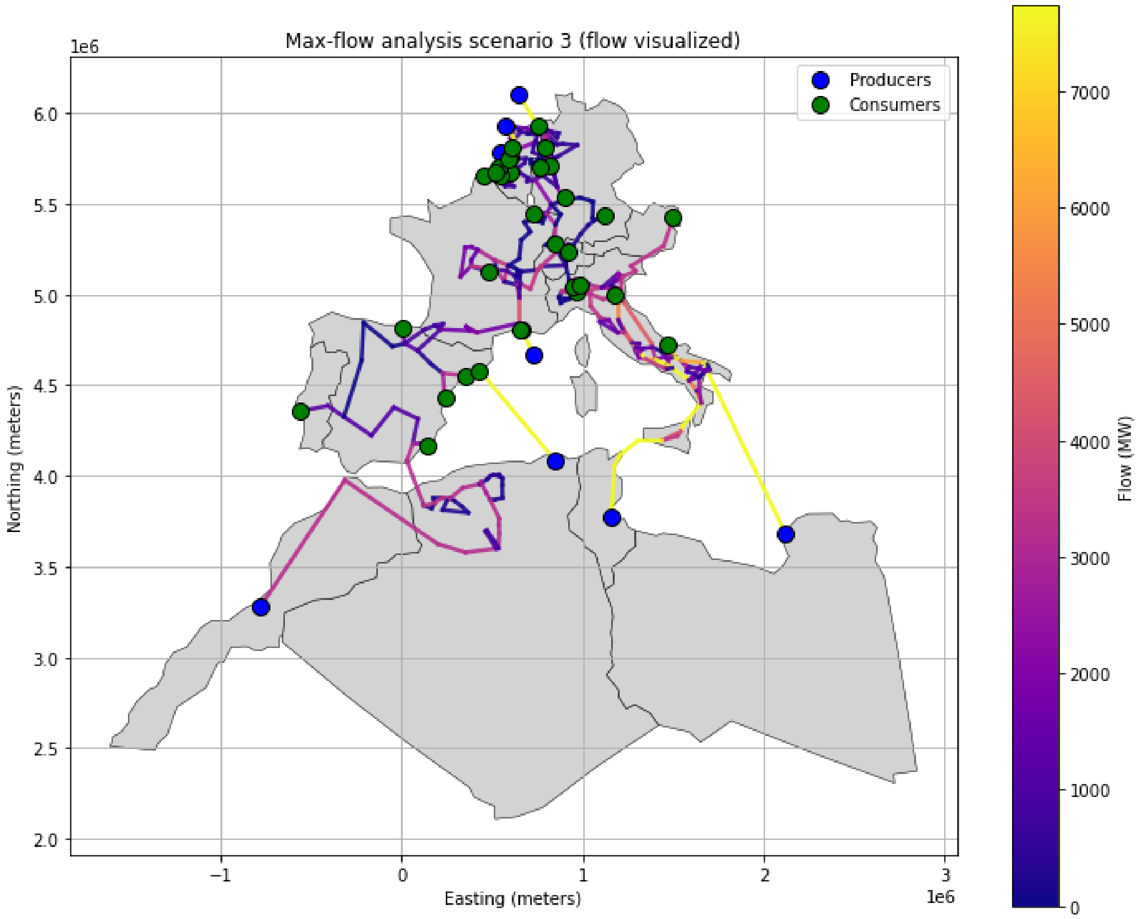

Figure 50: Scenario 3 – max-flow with repurposed pipelines

7.2.5 Concluding remarks

The four scenarios analyzed in this chapter provide insight into how the modeled hydrogen transport network between North Africa and Europe performs under different geopolitical and infrastructural conditions. Each case explores specific challenges related to supply reliability, network design, and structural flexibility.

Scenario 0 serves as a cooperative baseline, where all countries participate fully and infrastructure operates without disruption. In this setting, the minimum-cost spanning tree (MCST) results in a network that delivers the full hydrogen demand at the lowest modeled cost. However, the resulting layout shows limited redundancy, particularly across the Mediterranean, which could affect performance under less stable conditions.

In Scenario 1, a regional dispute results in Algeria halting hydrogen exports. Although the network layout remains unchanged, total supply drops to 87.5% of demand, indicating the network's dependence on key production hubs. This scenario highlights the influence of geopolitical conditions on supply performance.

Scenarios 2 and 3 simulate pipeline sabotage. In Scenario 2, the loss of the Morocco–Spain connection isolates Moroccan production, again reducing supply to 87.5% of modeled demand. Scenario 3 allows for the repurposing of an unused Morocco–Algeria connection, which raises the supply ratio to 92.7%, though this adaptation involves a substantial increase in capital expenditure. These scenarios show that existing but unused infrastructure can play a role in maintaining flow continuity when parts of the network are disrupted.

Together, the scenarios highlight trade-offs between cost efficiency and system robustness. They also show that the network's performance under stress depends on both its physical configuration and its flexibility to adapt to change. While the max-flow algorithm is effective in estimating capacity and identifying bottlenecks, it does not capture economic efficiency in its routing logic. As a result, flow improvements in scenarios with repurposed pipelines should be interpreted as technically feasible rather than cost-optimized.

These findings set the stage for the final chapter, which formulates policy recommendations for hydrogen infrastructure development based on the modeled outcomes.

8 Discussion

The scenario analysis presented in Chapter 7 provides a structured understanding of how the modeled hydrogen transport network between North Africa and Europe performs under varying geopolitical and infrastructural conditions. While each scenario shares the same underlying network layout—optimized in the idealized baseline (Scenario 0)—the imposed constraints simulate real-world risks, revealing how system performance shifts under disruption and what this implies for network design.

Scenario 0 (subsubsection 7.2.1) establishes the baseline. In this cooperative setting, all countries participate, no infrastructure is compromised, and the entire modeled hydrogen demand is met. The resulting network, optimized using a minimum-cost spanning tree (MCST), is highly cost-efficient. However, the tree-like structure that emerges from this cost minimization shows limited redundancy, particularly in cross-Mediterranean corridors. This leaves the network vulnerable to failure if a key link or supplier becomes unavailable.

Scenario 1 (subsubsection 7.2.2) introduces a regional dispute in which Algeria halts hydrogen exports. Although the network structure remains unchanged, the supply-to-demand ratio drops from 1.0 to 0.875. This drop illustrates the impact of relying heavily on a small number of major producers. Moreover, the network's static cost remains identical to that of the baseline scenario, as the connections to Algeria have already been made. This disconnect suggests that economic feasibility alone cannot capture the robustness of network performance under stress.

Scenario 2 (subsubsection 7.2.3) simulates infrastructure sabotage by removing the Morocco–Spain connection. Although Moroccan production remains available, the optimized network lacks the flexibility to reroute this supply. Again, the supply-to-demand ratio falls to 0.875. The similarity in outcome between Scenario 1 and Scenario 2 demonstrates that both supply and infrastructure disruptions can lead to equally severe performance degradation, despite different underlying causes.

Scenario 3 (subsubsection 7.2.4) introduces a form of adaptive response: the model is permitted to repurpose previously unused pipelines that were not in the MCST configuration. This alternative route restores part of the disrupted flow, increasing the supply-to-demand ratio to 0.927. However, the trade-off is financial—repurposing adds over €10 billion to the total network cost. Because the max-flow algorithm prioritizes volume rather than cost, the resulting route is not necessarily the most economically efficient. The scenario therefore is illustrative on how much improvement can be achieved when existing pipelines are repurposed with a cost indication rather than a complete correct number.

Across all scenarios, the selected performance metrics—economic feasibility and energy security and robustness—prove to be effective in highlighting the consequences of disruption. While the economic feasibility metric remains constant in scenarios where the physical network is unchanged, the delivered supply and system robustness vary considerably. This validates the inclusion of multiple metrics in assessing network quality. Moreover, it underscores the importance of going beyond simple cost assessments in future infrastructure planning.

Several broader patterns emerge. In Europe, the existing pipeline network provides flexibility through latent repurposing potential, even if these routes are not included in the initial MCST. In contrast, cross-Mediterranean links are more fragile, as the model builds only what is strictly necessary. This asymmetry in network redundancy reveals that different parts of the network require different design strategies. The MCST approach successfully minimizes capital expenditure under ideal conditions, but is less effective under stress. The inclusion of unused but available infrastructure—such as in

Scenario 3—demonstrates the value of strategic reserve capacity. However, a more nuanced approach would be needed to determine whether the added cost of such redundancy is justified under different risk assumptions.

While the max-flow algorithm is useful in evaluating capacity and identifying bottlenecks, it does not assess routing efficiency or cost. It cannot determine the most cost-effective way to maintain supply in disrupted scenarios. This means the algorithm should not be used on its own, but it can still play an important role as part of a broader modeling approach that also takes cost and route efficiency into account.

The findings from this chapter emphasize the need to think beyond technical optimization when designing hydrogen infrastructure. The network's performance under disruption is shaped as much by its layout and flexibility as by its original construction cost. The following chapter builds on these findings to formulate concrete policy recommendations for future infrastructure planning.

8.1 Limitations

As with all research, this study operates within a number of limitations that shape the level of detail and accuracy of its findings. While the central objective has been to provide insight into the development of a robust, cost-effective, and geopolitically stable hydrogen transport network between North Africa and Europe, several methodological and data-related simplifications were necessary to make the modeling governable.

Not all relevant actors or interests are represented in this research. Particularly, the interests of local communities, both in Europe and North Africa, are not explicitly accounted for. For any future implementation of the recommendations emerging from this study, meaningful engagement with these communities will be essential. Additionally, while the stakeholder analysis identified environmental sustainability, social equity, and network scalability as relevant considerations, these were ultimately excluded from the performance evaluation. The model instead focuses on three core pillars—cost, energy security, and geopolitical stability—chosen for their relevance and feasibility within the constraints of this study.

The simplification of the model's spatial and structural design follows directly from these constraints. The network is optimized using a tree-based structure, although not throughout the entire network, which is efficient in terms of cost but lacks redundancy. As shown in Scenarios 2, this structure offers no alternative routes in case of disruption, making the system vulnerable to single points of failure. Furthermore, the model does not account for physical obstacles such as seas, mountains, urban areas, or protected zones when determining pipeline routes. While it applies a cost premium for pipelines crossing seas—whether newly constructed, repurposed, or reinforced—it does not treat these areas as barriers to be avoided. This simplification means that some newly proposed pipelines may appear feasible in the model but may not be viable in practice. Integrating such spatial constraints would yield a more realistic network layout, but at the expense of greater model complexity and higher computational requirements.

Another core component of the model is the cost function, which—while improved over the simplified version embedded in the ONLT—still has its flaws. It relies on generalized data, as the cost coefficients were derived from U.S.-based studies averaged across regions. Consequently, the model does not reflect the cost diversity likely to exist across the participating European and African countries. Labor, materials, right-of-way, and miscellaneous costs can vary significantly between nations. This also holds for repurposing costs, which are treated in this study as a single constant, despite being influenced by pipeline-specific factors such as diameter, age, and compressor needs. Compressor station costs, pressure differences, and material composition are not modeled separately and are generalized into the repurposing factor f, even though they represent critical technical characteristics of real-world hydrogen transport. Including these details would increase the realism of the model but would require more detailed data and computing power.

The supply side of the model contains further simplifications. While production sites were selected based on current development plans or theoretical suitability—such as proximity to solar resources or seawater—the locations were not subject to detailed feasibility assessments. Moreover, production is assumed to be equally divided over the eight identified locations, regardless of current infrastructure or actual production potential. This assumption oversimplifies a complex reality, where infrastructure readiness, spatial constraints, and economic conditions vary greatly. It is also assumed that these sites can deliver the required volumes of hydrogen, even though most of them lack large-scale production infrastructure today. In reality, the total projected hydrogen demand is unlikely to be met by eight sites alone. A much larger number of production facilities will be required to scale capacity to future needs. This simplification, while necessary for keeping the model computationally manageable, must be taken into account.

On the demand side, limitations arise from the use of the SciGRID dataset, which includes gas consumer data but is not specifically tailored to industrial clusters. Industrial demand is estimated by clustering consumers within 50 kilometers of hard-to-abate industrial sites. This method introduces uncertainty: some clustered consumers may not be industrial users, while actual industrial clusters may be excluded due to lack of nearby data. In some countries, even among the five largest identified clusters, demand could not be allocated due to these data gaps. A more precise distribution of demand would require access to up-to-date, location-specific industrial hydrogen use data, preferably from national or company-level sources.

A final structural limitation lies in the way the pipeline dataset was simplified. To enable efficient computation, the network was reduced using clustering and contraction techniques. This made it possible to analyze a large infrastructure dataset, but at the cost of removing local network details—such as loop structures, minor interconnections, and regional specificity. Once simplified, these structural details cannot be recovered, meaning that local-level optimizations or fallback strategies are no longer testable within the model.

In addition, many model parameters are based on mean values due to limited data availability. This includes average cost coefficients, generalized repurposing factors, and approximated supply and demand figures. While these allow for a manageable and internally consistent model, they inevitably introduce uncertainty. The results should therefore be seen as indicative rather than predictive. Future research could address this by incorporating more detailed and country-specific technical, economic, and spatial information.

Despite these limitations, this research offers a useful and novel framework for evaluating cross-continental hydrogen infrastructure. It demonstrates how large, detailed networks can be simplified and analyzed under cost and political constraints, and provides insight into structural vulnerabilities and performance trade-offs. While the outcomes are not meant as precise forecasts, they contribute to a broader understanding of how hydrogen transport systems may function, where key risks lie, and which aspects require further investigation. Future extensions could expand the framework to include redundancy, environmental impact, and dynamic geopolitical conditions, forming a more complete basis for long-term infrastructure planning.

9 Conclusion

This study set out to answer the following research question:

> *How can a cost-efficient and resilient hydrogen pipeline infrastructure be designed to connect North Africa and Europe, while accounting for geopolitical risks?*

The findings of this research show that a transcontinental hydrogen pipeline network connecting North Africa and Europe is not only technically feasible but also economically viable—particularly under conditions of cooperation and infrastructure reuse. Using a combination of spatial network reduction, clustering, and optimization, this study demonstrated how such a system could be developed with the lowest possible capital expenditure while still delivering sufficient supply to Europe's hard-to-abate industrial clusters. Scenario 0 illustrated that when all countries participate and existing infrastructure is leveraged where possible, full demand can be met with minimal new investment.

However, the scenario analysis revealed that this cost-optimal design comes with structural vulnerabilities. Scenarios 1 and 2 showed that both political disruption (e.g., Algeria halting exports) and infrastructure sabotage (e.g., the Morocco–Spain pipeline) can result in significant performance losses—up to 12.5% of unmet demand—without any change to the physical structure or capital cost of the network. This illustrates the limitations of relying solely on cost-efficiency as the guiding design principle for cross-border hydrogen infrastructure.

Scenario 3 introduced an important insight: existing but unused infrastructure can improve system resilience if strategically repurposed. Although repurposing the Morocco–Algeria connection came at an added cost of over €10 billion, it restored nearly half the lost supply from the sabotage scenario. This demonstrates that moderate investments in redundancy can offer valuable insurance against disruption. Still, such a response must be planned in advance and supported by appropriate policy and funding frameworks.

The methodology developed for this study, combining Steiner-based reduction, Girvan–Newman clustering, the ONLT, and max-flow analysis, provided a practical and scalable approach to modeling large-scale hydrogen networks under geopolitical uncertainty. It enabled robust scenario evaluation without exceeding computational limits. That said, the max-flow analysis used here does not account for delivery cost or economic efficiency in route selection. While it offers valuable insights into network capacity and vulnerability, it cannot independently produce economically optimized responses to disruption.

In sum, this research shows that designing a hydrogen network between North Africa and Europe is not just a question of minimizing cost—it is also a matter of structural resilience. Modest levels of redundancy, such as repurposed secondary pipelines or distributed production, can significantly reduce vulnerability without requiring a full redesign. As the EU seeks to secure long-term hydrogen supply, investments that account for geopolitical risks and enable operational flexibility will be essential. This study contributes a modeling foundation for such planning and highlights the need for integrated approaches that combine technical, economic, and political dimensions.

9.1 Future research

This study provides a foundation for modeling a transcontinental hydrogen network, but several opportunities remain for future research to improve realism, expand scope, and increase policy relevance.

First, the cost function could be further refined. While this research introduced a more advanced cost representation than the original ONLT model, further improvements would require incorporating country-specific construction costs, labor rates, and material prices. In particular, repurposing costs should be differentiated by pipeline characteristics such as diameter, pressure class, and age, as well as compressor requirements. Integrating these details would yield a more accurate estimation of capital expenditures and allow for finer-grained policy recommendations.

Furthermore, the demand and supply modeling could be improved and be further investigated. On the demand side, access to detailed, location-specific hydrogen consumption forecasts for industrial cluster would enable more accurate allocation and sizing of infrastructure. On the supply side, a more dynamic production model that considers renewable electricity availability and cost could better reflect the real-world capabilities of each site. Moreover, incorporating local hydrogen demand within producing countries could highlight co-benefits and foster more equitable development strategies.

Third, the current methodology is limited by its assumption of a static tree-like network structure. While cost-effective, this topology lacks resilience under disruption. Future research could explore more resilient network topologies by allowing selective redundancy. For example, cost-constrained shortest path algorithms could be explored as a way to balance efficiency with redundancy, promoting the development of networks that maintain functionality under geopolitical or infrastructural disruptions.

Additionally, the model could be expanded by looking at the evaluation of hydrogen transport over time. The current model is static and assumes constant production and demand. In reality, hydrogen production and consumption will evolve over time, influenced by policy, technology, and market trends. A dynamic or multi-stage model would enable simulation of infrastructure build-out over time, better supporting long-term planning.

Finally, further exploration of geopolitical risks is warranted. This study incorporated simplified geopolitical assumptions to simulate disruptions, but future research could draw on scenario planning, political risk indices, or game-theoretical approaches to more rigorously model actor behavior, alliances, and conflict potential. Coupling these with infrastructure models could help assess not only resilience, but also strategic interdependence and leverage in hydrogen diplomacy.

Taken together, these future research directions would enhance the utility of hydrogen infrastructure models for both academic exploration and real-world decision-making. They would support more comprehensive assessments of cost, resilience, environmental impact, and political feasibility, critical ingredients for building a secure and sustainable hydrogen future.

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A AI statement

Throughout this research, ChatGPT (OpenAI, 2024) was used as a supportive tool during various stages of the research process. Its use was complementary in nature and did not replace the responsibility for any substantive or scientific decisions made. The model was applied for three main purposes: assisting in the identification of errors and simplifications during the modeling phase, exploring relevant literature and reflecting on conceptual questions, and restructuring and refining written text to improve clarity and coherence.

All outputs from ChatGPT were critically assessed and carefully verified before implementation. Its suggestions were never adopted without thorough review and were always adapted to fit the academic and analytical standards of this research. Full responsibility for the content remains with the author.

B Extensive results

B.1 ONLT

This section provides detailed visualizations of the ONLT (Optimal Network Layout Tool) outputs per cluster. Each cluster was derived from the Girvan–Newman clustering approach and individually optimized using the ONLT to generate efficient pipeline layouts.

B.1.1 Cluster 0

The following figures display the supply and demand distribution across Cluster 0, with individual demand levels per terminal node. Additionally, the minimum spanning tree (MST) and the minimum-cost spanning tree (MCST) layouts show how infrastructure was optimized to meet demand at minimum cost.

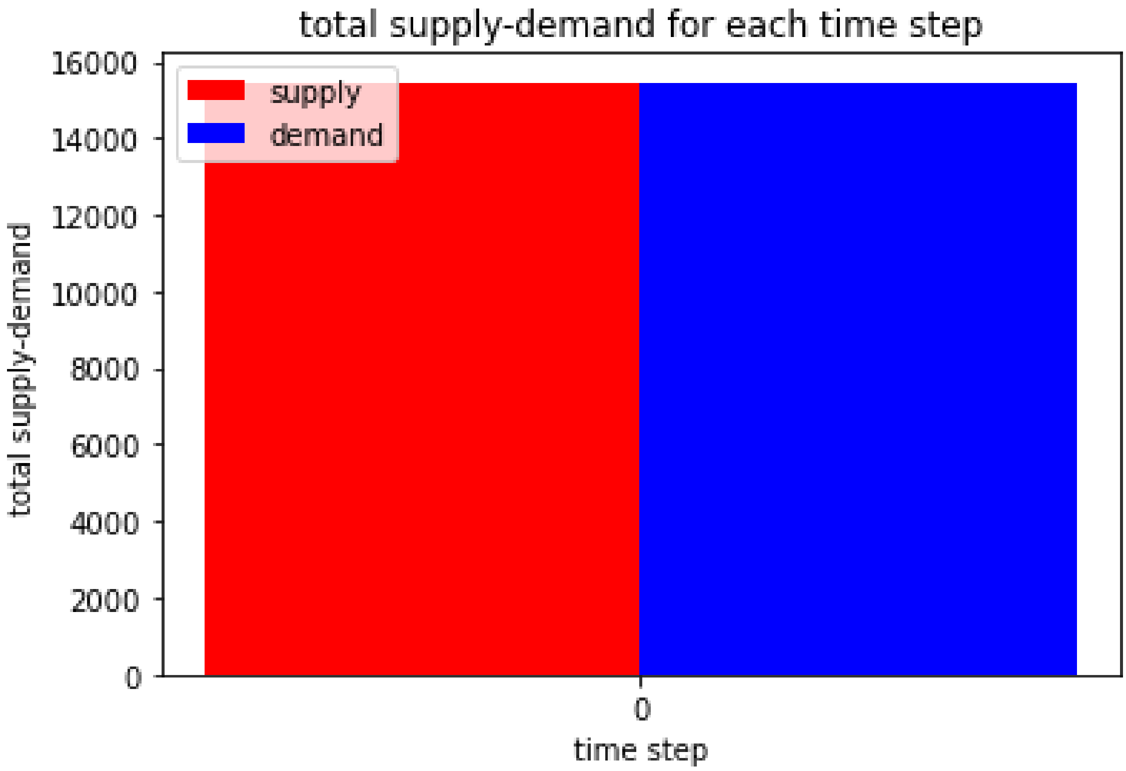

Figure 51: Supply-demand cluster 0

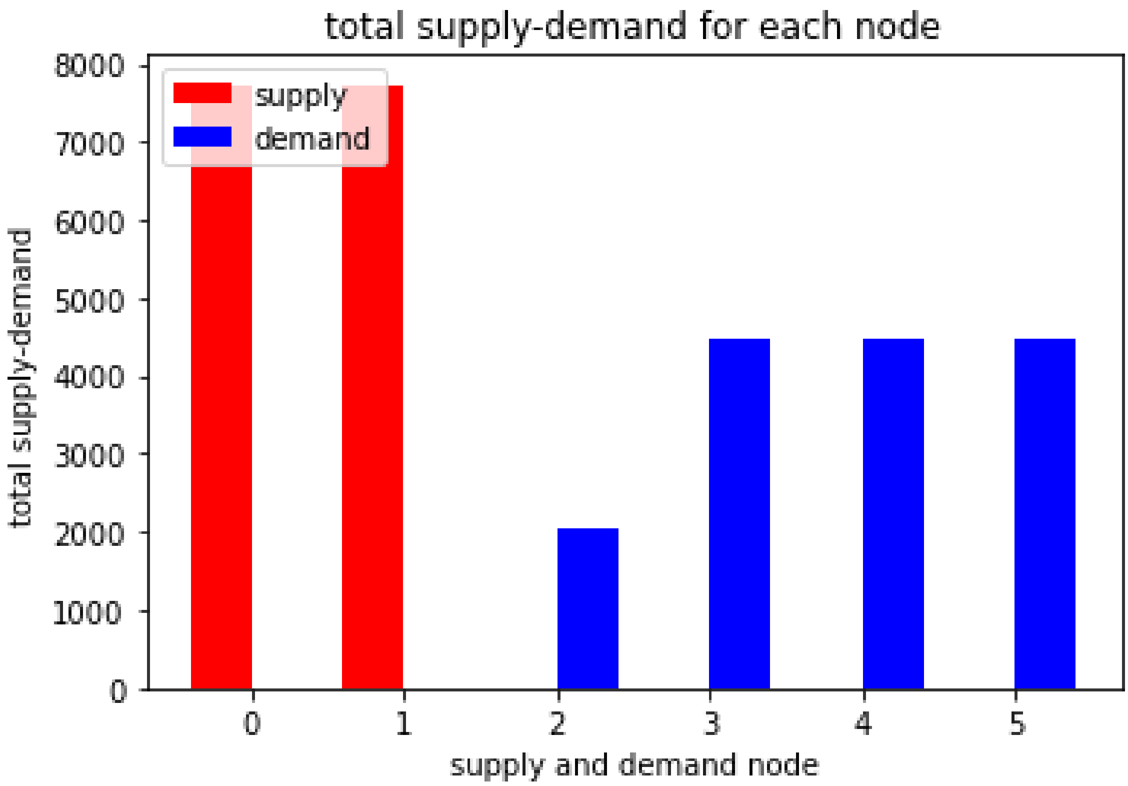

Figure 52: Demand per terminal node cluster 0

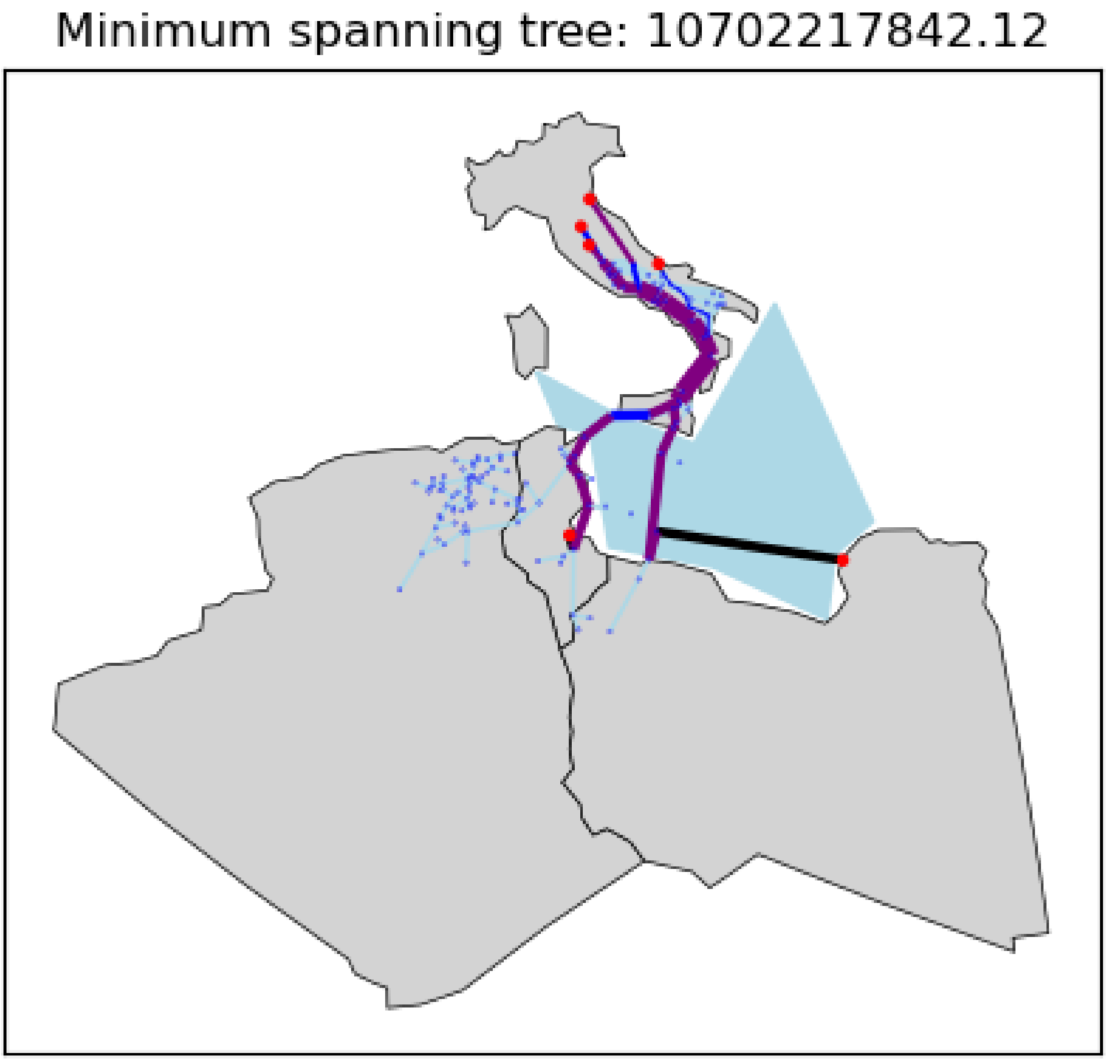

Figure 53: Minimum spanning tree (MST) cluster 0

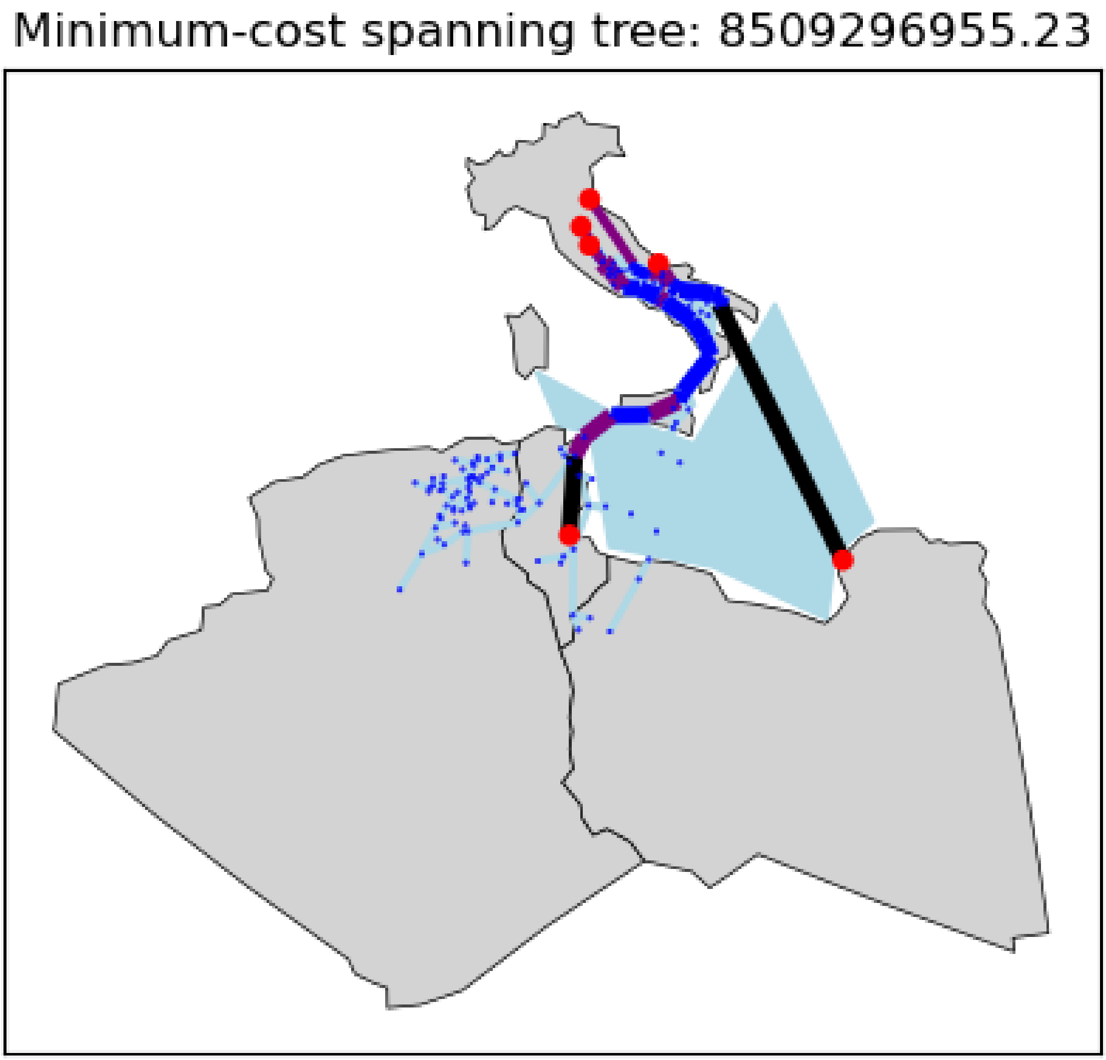

Figure 54: Minimum-cost spanning tree (MCST) cluster 0

B.1.2 Cluster 1

Being the largest cluster with the most terminals and obstacles, cluster 1 is computationally the most extensive. The plots show the supply and demand distribution and terminal node breakdown. The MST and MCST further illustrate how infrastructure was allocated for cost-effectiveness within this subnetwork.

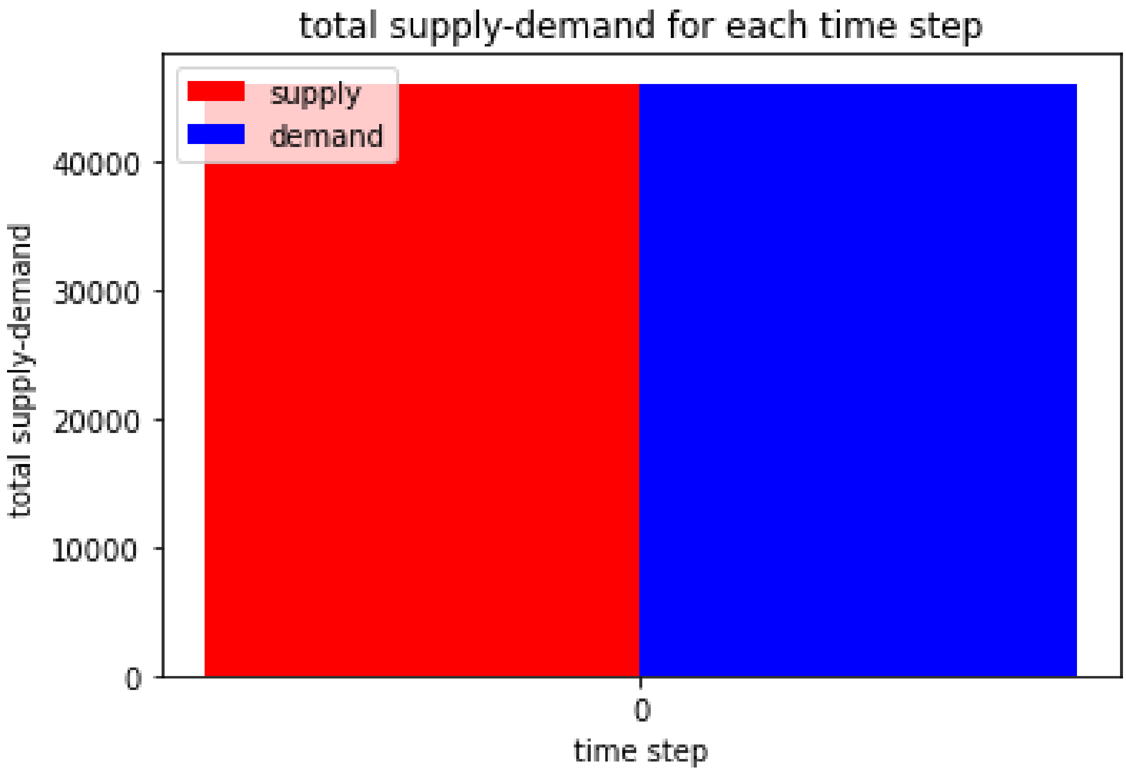

Figure 55: Supply-demand cluster 1

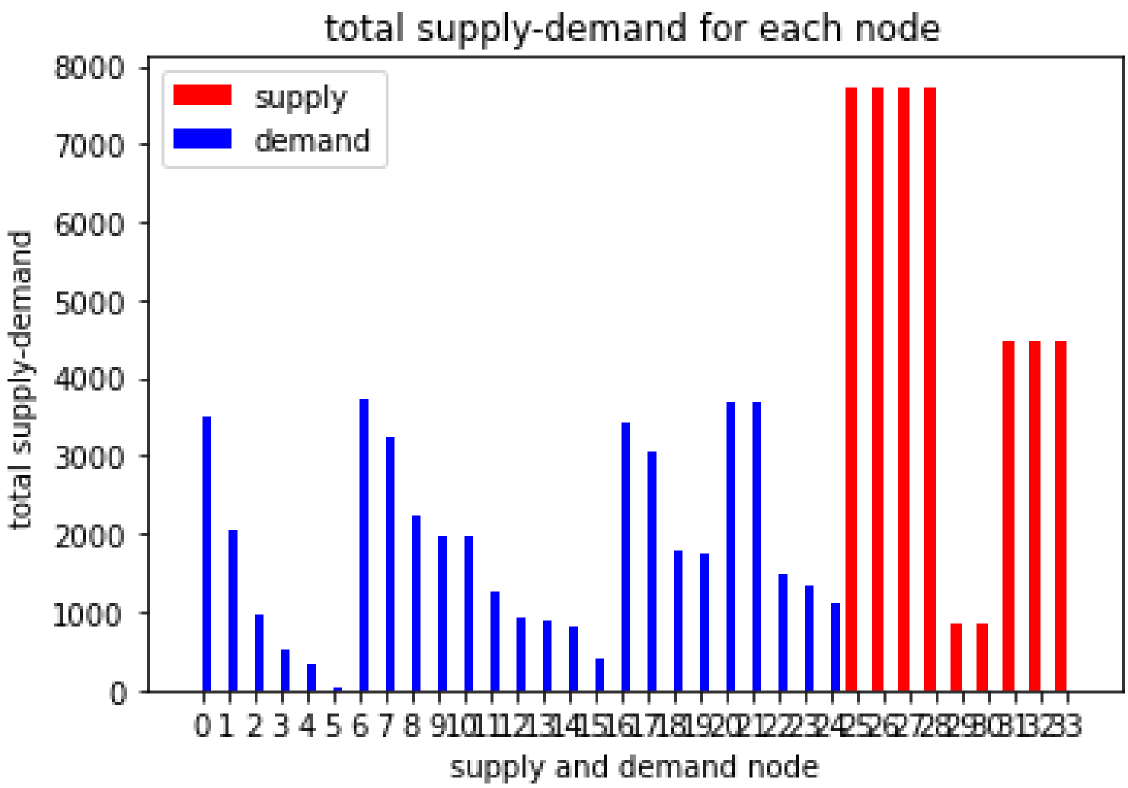

Figure 56: Demand per terminal node cluster 1

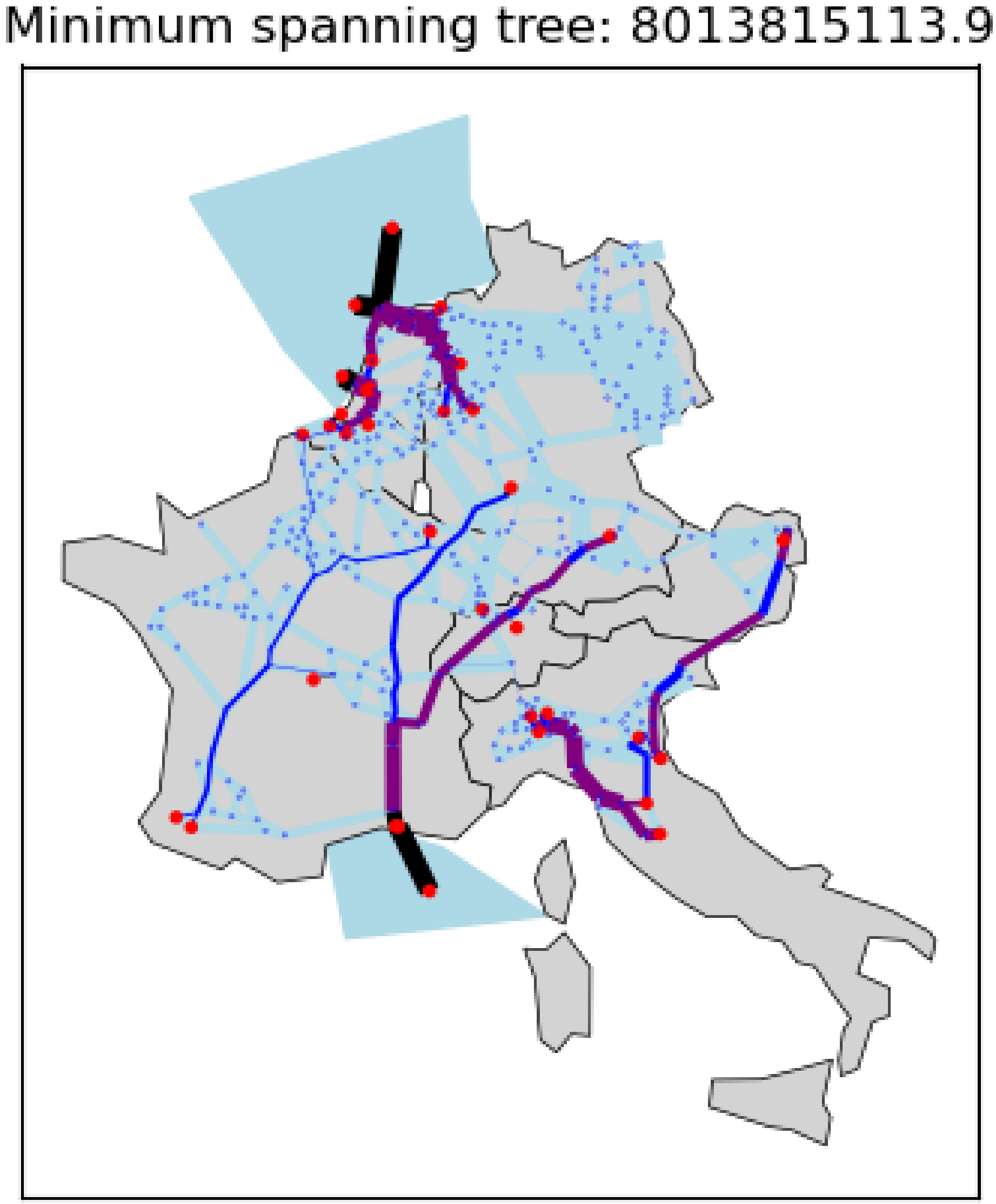

Figure 57: Minimum spanning tree (MST) cluster 1

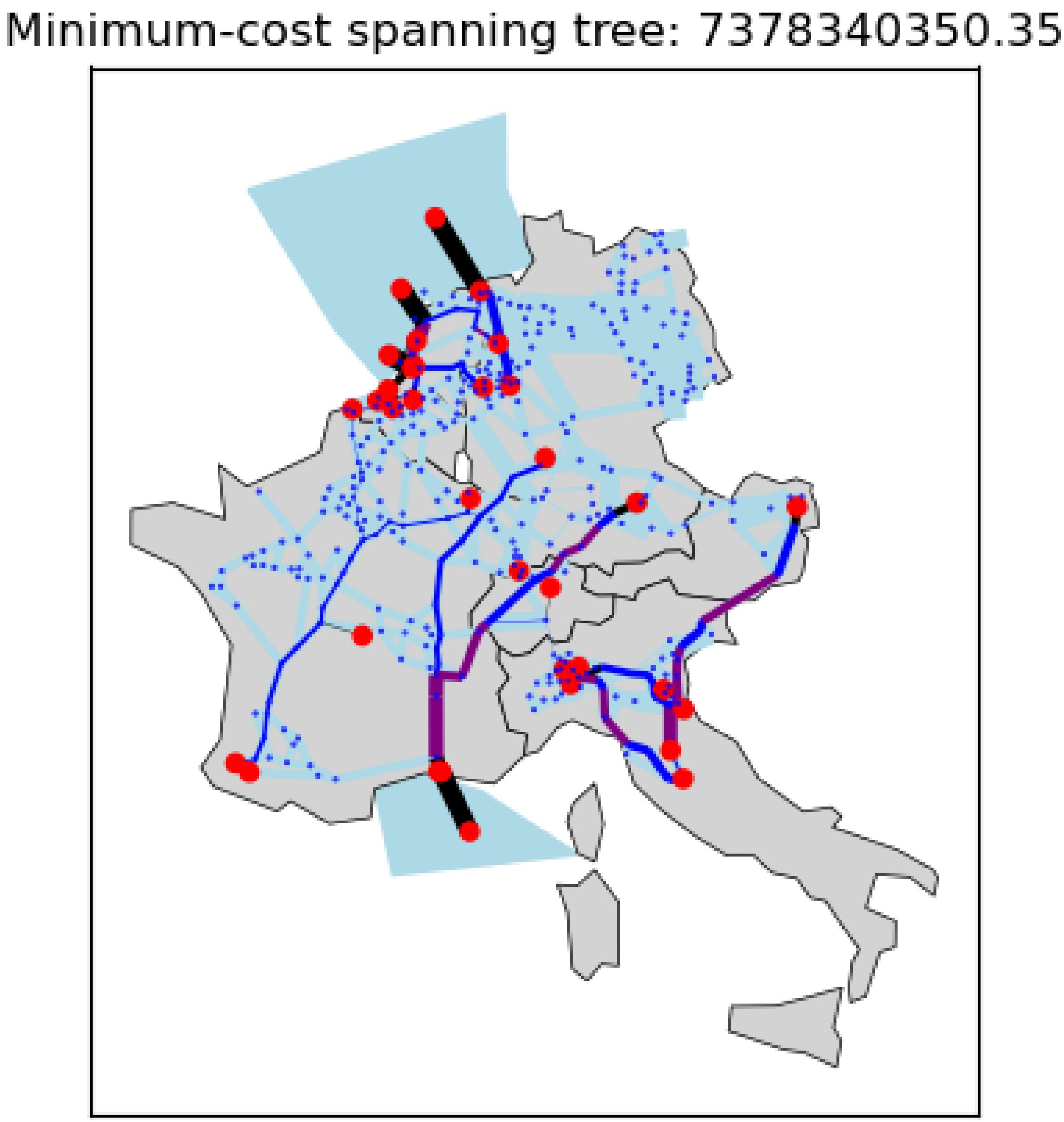

Figure 58: Minimum-cost spanning tree (MCST) cluster 1

B.1.3 Cluster 2

Cluster 2 completes the ONLT segmentation. The figures show how demand and supply are distributed, and how the spanning trees minimize cost while ensuring connectivity across the cluster.

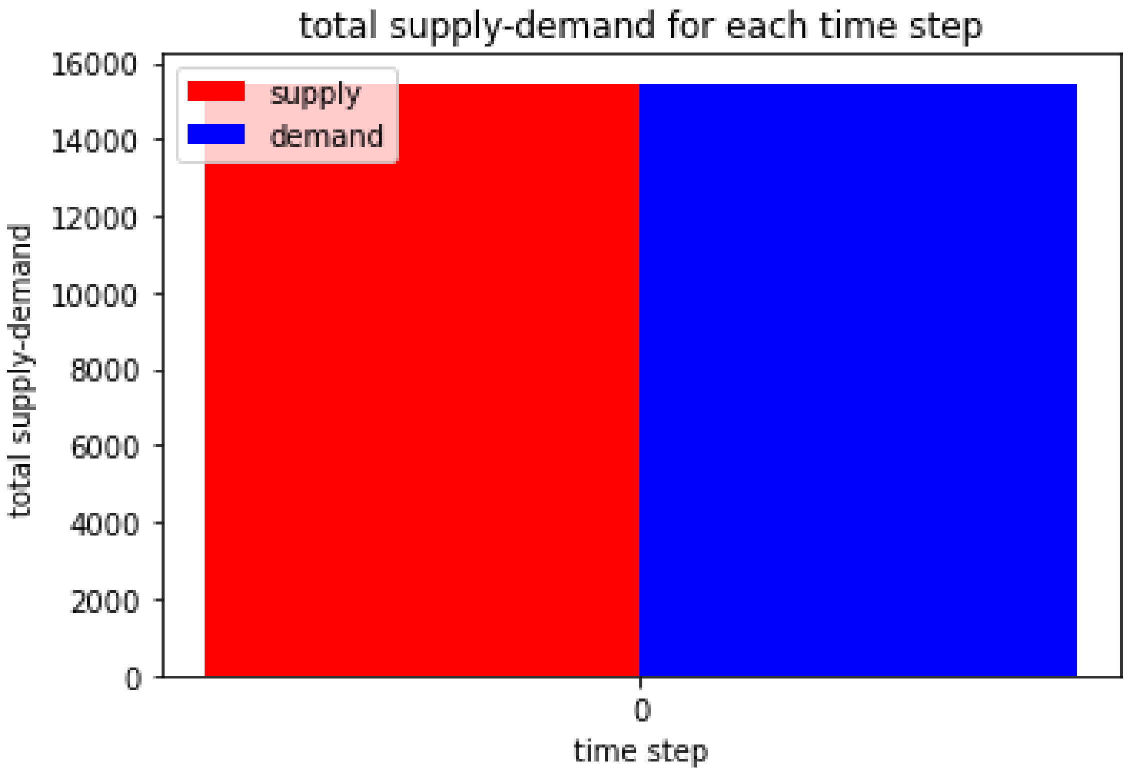

Figure 59: Supply-demand cluster 2

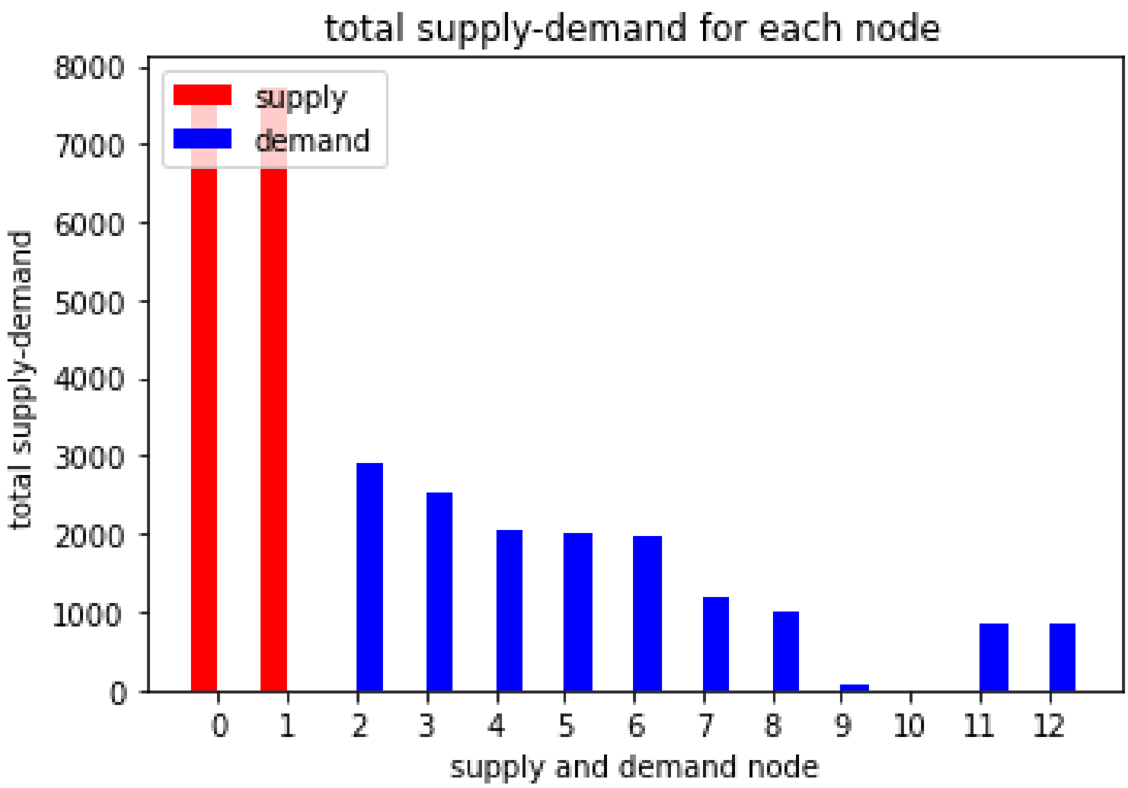

Figure 60: Demand per terminal node cluster 2

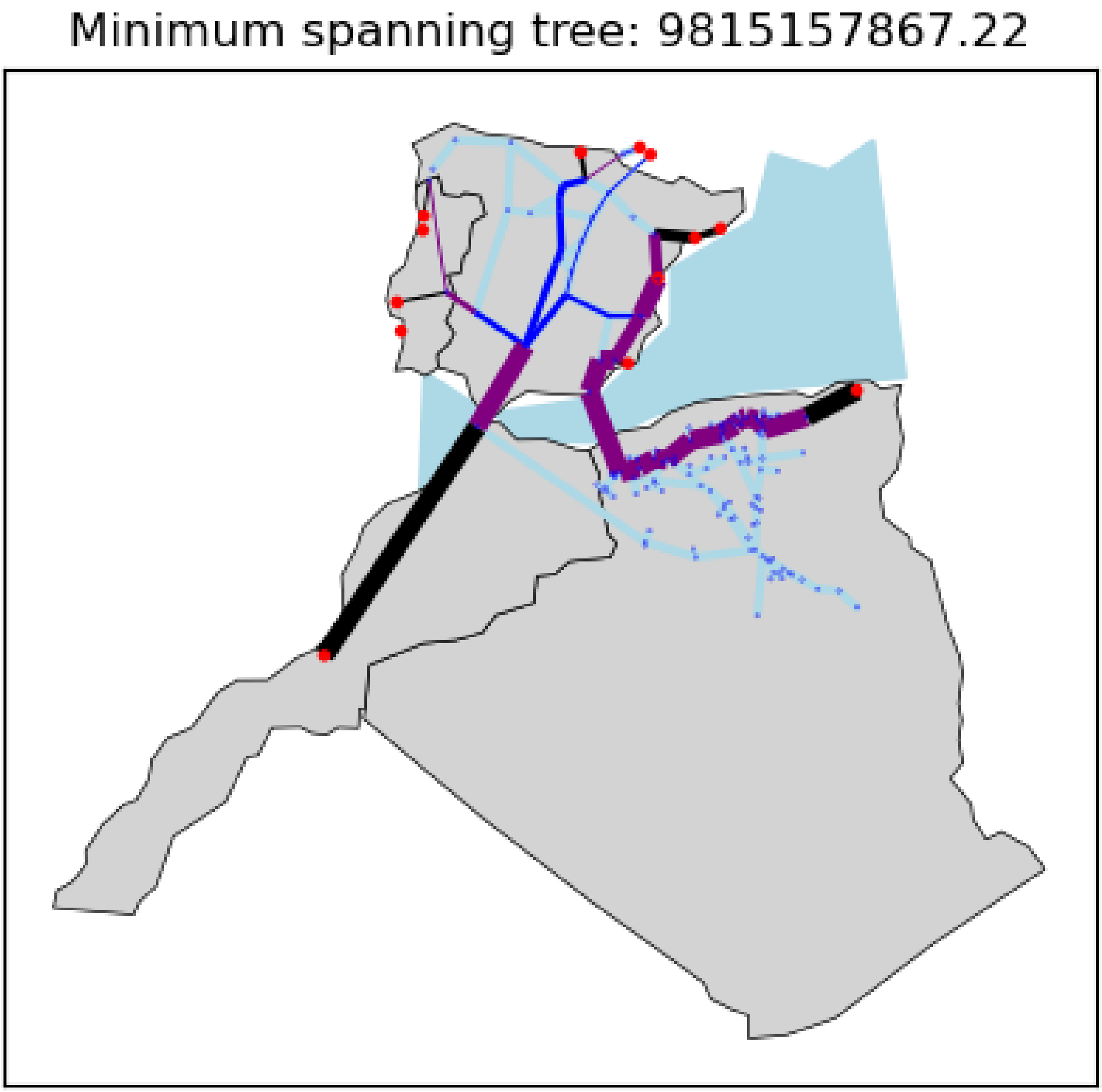

Figure 61: Minimum spanning tree (MST) cluster 2

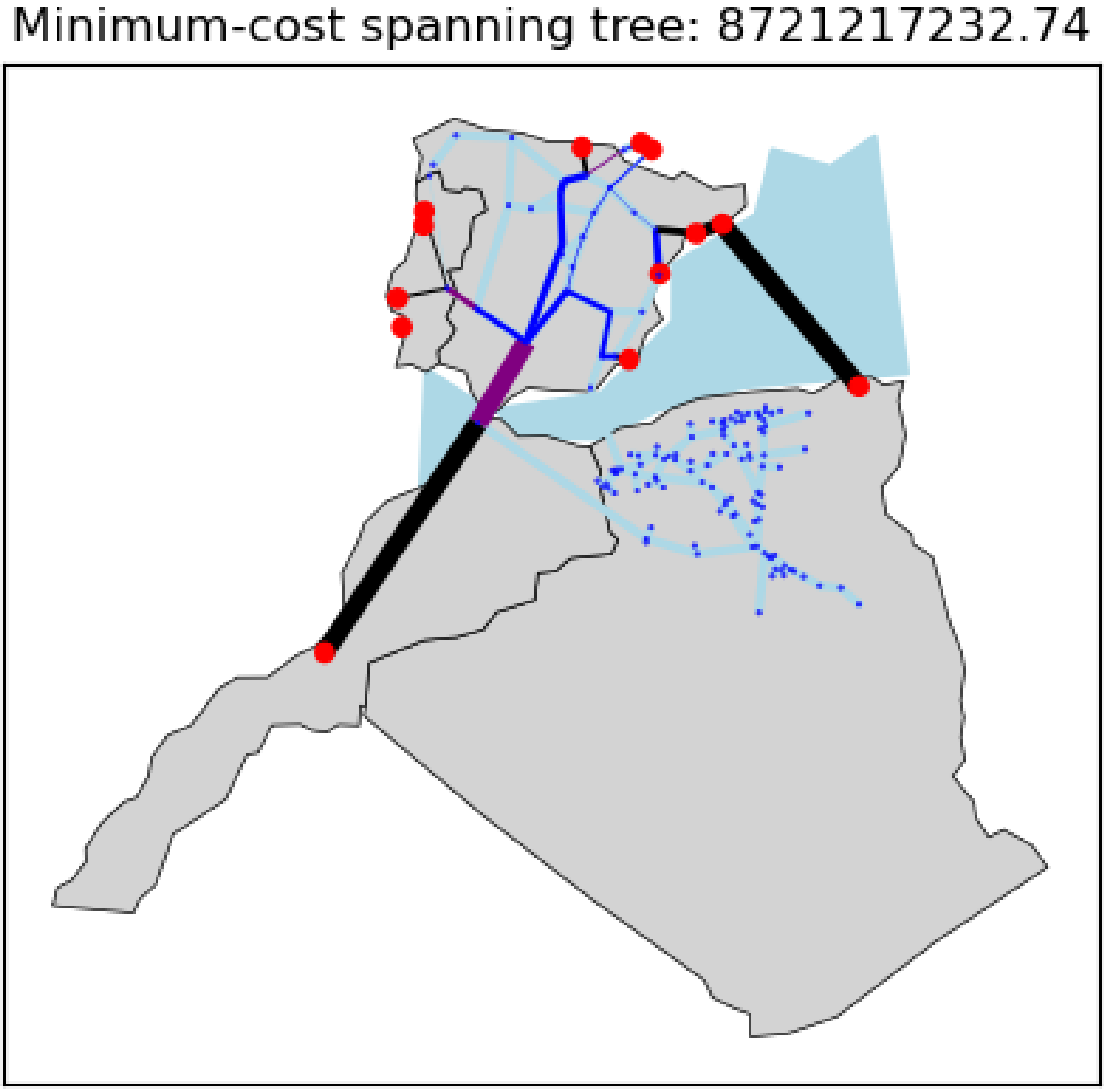

Figure 62: Minimum-cost spanning tree (MCST) cluster 2

C Model guide and overview

A variety of models and datasets were used to develop the hydrogen infrastructure model in this study. This appendix gives an overview of the corresponding scripts and how they support different steps of the research process, with references to the relevant chapters.

Data preparation FINAL.py takes the raw pipeline dataset from SciGRID and filters it to include only the countries relevant for this research. It visualizes the resulting network, checks whether it is connected, and if not, selects the largest connected component. Several data transformations are applied to prepare the network for use in the Steiner reduction process.

Steiner reduction FINAL.py performs the three rounds of network reduction using the Steiner-based methodology explained in chapter 4. It is also used to generate the illustrative figures for the explanation of the Steiner process shown in section 4.2.

Girvan-Newman clustering.py applies the Girvan–Newman clustering method discussed in section 4.3. It segments the network into three separate components, allowing for the modular application of the ONLT. The script also supports figure generation for explanation and visualization.

Preparation for ONLT converts the output of the reduced and clustered network into a format compatible with the ONLT. It creates a pipeline dataset that serves as the existing infrastructure input for the ONLT, in line with the workflow described in chapter 4.

ONLT - user_interface.py contains the main interface for the Optimal Network Layout Tool. It has been adjusted for this research, including new cost coefficients and the deactivation of steps 3 and 4, depending on the scenario. The ONLT is central to the modeling process, as presented in section 4.4.

ONLT - general_procedures.py contains the revised cost function developed for this research, as well as functionality for identifying pipelines that traverse obstacles. These cost adaptations are explained in section 4.5.4 and implemented to reflect repurposing and reinforcement costs.

Cluster combination.py is used after ONLT has processed the separate clusters. It recombines the three subnetworks into a single, integrated pipeline model, which is necessary for the global flow and scenario analysis discussed in chapter 6.

Maxflow FINAL.py applies the maximum flow algorithm to the recombined network. This script supports the scenario evaluation by visualizing the supply shortfalls and testing system robustness under different stress conditions, as described in chapter 7.

Bresse fitting method.py fits the relationship between hydrogen flow capacity and pipeline diameter using the Bresse equation. This relationship is used throughout the cost function and network calculations in chapter 5.

Consumer industrial cluster coupling.py links gas consumers from the SciGRID dataset to industrial clusters. This spatial coupling is used to estimate hydrogen demand distribution, as detailed in section 5.2.1, while also noting limitations in available demand data.