

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

# **The Transition from Gas to 100% Hydrogen: Network Planning Methodologies and Challenges for the Energy System**

**André Oliveira Araújo Dias**

**U. PORTO**

**FEUP** FACULDADE DE ENGENHARIA  
UNIVERSIDADE DO PORTO

Master in Mechanical Engineering

Supervisor at FEUP: Prof. José Luís Alexandre

Supervisor at REN: Eng. Bruno Henrique Santos

July 22, 2024



# **The Transition from Gas to 100% Hydrogen: Network Planning Methodologies and Challenges for the Energy System**

**André Oliveira Araújo Dias**

Master in Mechanical Engineering

July 22, 2024



# Abstract

Green hydrogen is a priority on the agendas of nearly all developed nations seeking to decarbonize the increasingly complex energy system. H<sub>2</sub> provides a sustainable solution for hard-to-abate industries, either through direct use or as a feedstock, targeting the decarbonization of sectors currently outside mainstream electricity and gas networks. This dissertation intends to provide a useful methodology for planning hydrogen infrastructures, considering specific drivers, including geographic characteristics, production and consumption uncertainty, energy system integration, and financial viability. Furthermore, the research serves as a proof-of-concept for future adaptations, highlighting the importance of replacing the current analytical planning methods.

A thorough literature review was conducted to explain the rationale behind transitioning to hydrogen infrastructures and the processes for implementation. Current European projects are detailed, illustrating the developments in hydrogen networks that are expected to be commissioned. Moreover, this review summarized key network planning methodologies, drawing analogies from gas and electricity systems, and established the mathematical formulation that supported the subsequent work. The review also identified areas where the developed methodology could add value to the existing literature.

This method comprises three primary processes, each supported by a dedicated Python algorithm. The first phase involves mapping consumptions that could be replaced by green hydrogen across various regions using the Consumptions Mapping Algorithm. The second phase features a Decision Support System to define consumption scenarios, which are subsequently processed by the optimization algorithm. The final phase employs a broadly applicable Genetic Algorithm (GA), enabling project developers to determine optimal network parameters while addressing challenges in hydrogen infrastructure, such as market dependence, low initial consumption, environmental impact, and production site uncertainty.

Additionally, the methodology was applied to the CelZa project, a real-life case study involving Portugal and Spain's collaborative effort to establish a 100% hydrogen network connecting both countries and the rest of the EU. Focusing on the Portuguese segment, the study revealed a potential national H<sub>2</sub> consumption for CelZa ranging from 3.1 to 7.7 TWh by 2030, depending on the scenarios and assumptions. The average annual CO<sub>2</sub> emissions reduction was approximately one megatonne, representing 12.5% of the National Strategy for H<sub>2</sub> target for 2030. The GA results demonstrate a decreasing transportation cost as consumption increases, despite an increase in compression needs and, therefore, CAPEX. The maximum investment was 362 million euros, significantly lower than the current prediction of 414 M€, mainly because the developed method did not account for the initial investment needed to repurpose natural gas pipelines but reflected the cost through increased OPEX. The results indicate that the project's economic viability could be achieved with one-third of the predicted electrolysis capacity for Portugal in 2030 (5.5 GW), thus contributing to the decarbonization goals.

**Keywords:** hydrogen, decarbonization, network planning, optimization.



# Resumo

O hidrogénio verde é uma prioridade para a maioria dos países desenvolvidos que procuram descarbonizar um sistema energético cada vez mais complexo. O H<sub>2</sub> fornece uma solução sustentável para indústrias de difícil descarbonização, seja como fonte de energia ou como matéria-prima. Esta dissertação pretende fornecer uma metodologia útil para o planeamento de infraestruturas de hidrogénio, considerando factores específicos, incluindo características geográficas, incerteza de produção e consumo, integração do sistema energético e viabilidade financeira. Além disso, o trabalho desenvolvido serve como prova de conceito para futuras adaptações, destacando a importância de substituir os atuais métodos analíticos de planeamento.

Foi realizada uma análise detalhada da literatura para explicar a lógica subjacente à transição para as infraestruturas de hidrogénio e os processos de implementação. Os atuais projetos europeus são apresentados em pormenor, ilustrando os desenvolvimentos das redes de hidrogénio que se esperam vir a ser comissionadas. Além disso, esta análise resumiu as principais metodologias de planeamento de redes, estabelecendo analogias com os sistemas de gás e de eletricidade, e definiu a formulação matemática que apoiou o trabalho subsequente. A revisão também identificou áreas em que a metodologia desenvolvida poderia acrescentar valor à literatura existente.

Este método compreende três processos principais, cada um apoiado por um algoritmo em Python. A primeira fase consiste em mapear os consumos que podem ser substituídos por hidrogénio verde em várias regiões, utilizando o Algoritmo de Mapeamento de Consumos. A segunda fase inclui um modelo de apoio à decisão para definir cenários de consumo, que são subsequentemente processados pelo algoritmo de otimização. A fase final emprega um abrangente Algoritmo Genético (AG), que permite determinar os parâmetros ótimos da rede, abordando em simultâneo os desafios associados às infraestruturas de hidrogénio, tais como a dependência do mercado, o baixo consumo inicial, o impacto ambiental e a incerteza dos locais de produção.

A metodologia foi ainda aplicada ao projeto CelZa, um caso de estudo real que envolve a colaboração entre Portugal e Espanha para estabelecer uma rede de 100% hidrogénio a conectar os dois países e o resto da UE. Com o foco no segmento português, o estudo revelou um potencial consumo nacional de H<sub>2</sub> para o CelZa que varia entre 3.1 e 7.7 TWh até 2030, dependendo dos cenários e pressupostos. A redução média anual das emissões de CO<sub>2</sub> foi de aproximadamente uma megatonelada, representando 12.5% do objetivo da Estratégia Nacional para o H<sub>2</sub> para 2030. Os resultados do AG demonstram a diminuição do custo de transporte à medida que o consumo aumenta, apesar de um aumento da necessidade de compressão e, consequentemente, do CAPEX. O investimento máximo foi de 362 milhões de euros, sendo inferior à previsão atual de 414 M€, principalmente por não contabilizar o investimento necessário para converter os gasodutos de gás natural, refletindo ao invés o custo através do aumento do OPEX. Os resultados indicam que a viabilidade económica do projeto poderá ser alcançada com um terço da capacidade de eletrólise prevista para Portugal em 2030 (5,5 GW), contribuindo assim para as metas de descarbonização.

**Palavras-chave:** hidrogénio, descarbonização, planeamento de rede, otimização.



# Acknowledgements

As I finish a very important chapter of my life with this work, I have to say a few words dedicated to the people that helped me throughout this journey and took part in my professional and personal growth, making me the man I am today.

To REN for this amazing opportunity and FEUP for the academic background that will support my professional path.

To Bruno, for being more than a teacher or supervisor, without whom this work could not have been completed. For being a true friend and an example of humility, combined with amazing talent and dedication. I was fortunate to learn daily from a real role model who shaped my future as a professional and as a man.

To FEUP's supervisor Prof. José Luís Alexandre, for the support provided during this work.

To my friends, for allowing me to relax during busy periods and animating my life throughout this journey. A special note to the ones I made along the way, who certainly made it a lot easier and funnier.

To my parents, for teaching me to trust my abilities, providing me with every tool to use them, and fostering the ambition that allowed me to complete this journey. Everything I am, I owe to them.

To my brother and sister, for their friendship and support at every moment of my life, setting the highest standards for me with their amazing and unique talents.

To my grandparents for the unconditional love I received throughout my life.

Lastly, to Catarina, for being my biggest support and greatest listener. For providing me with peace in times of storm and setting a unique example of character by being the strongest person I know.

To all, I express my deepest gratitude.

I dedicate this work to the memory of my grandmother, who, I am certain, is the happiest person in the world right now.

André Dias



*“The best way to predict the future,  
is to create it.”*

Peter Drucker



# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Context and Motivation . . . . .	1
1.1.1	Green Hydrogen . . . . .	2
1.1.2	European Hydrogen Backbone . . . . .	4
1.1.3	CelZa Project . . . . .	4
1.2	REN . . . . .	6
1.3	Objectives . . . . .	6
1.4	Dissertation Structure . . . . .	7
<b>2</b>	<b>State of the Art</b>	<b>9</b>
2.1	Transition to Hydrogen Infrastructures . . . . .	9
2.1.1	Blending . . . . .	11
2.1.2	100% Hydrogen . . . . .	14
2.2	Gas Network Planning Optimization . . . . .	16
2.2.1	Network Planning Methods . . . . .	16
2.2.2	Main Drivers . . . . .	18
2.2.3	Mathematical Formulation . . . . .	19
2.2.4	Optimization Algorithms . . . . .	22
2.2.5	Hydrogen Supply Network Design Optimization . . . . .	23
2.3	Current European Developments . . . . .	24
2.3.1	Spain . . . . .	26
2.3.2	France . . . . .	27
2.3.3	Germany . . . . .	28
2.3.4	Portugal . . . . .	29
2.3.5	Projects with Commissioning Date in 2025 . . . . .	30
2.3.6	Financial Challenge . . . . .	32
<b>3</b>	<b>Methodology for the Implementation of Hydrogen Infrastructures</b>	<b>33</b>
3.1	Mapping of the National Regions Decarbonization Potential . . . . .	34
3.1.1	Objectives and Motivation . . . . .	34
3.1.2	Consumption Mapping Algorithm . . . . .	35
3.2	Planning and Optimization of 100% Hydrogen Networks . . . . .	35
3.2.1	Objectives and Motivation . . . . .	36
3.2.2	Optimization Process Description . . . . .	36
3.2.3	Decision Support System (DSS) . . . . .	37
3.2.4	Genetic Algorithm . . . . .	39

<b>4</b>	<b>Portuguese Case Study: CelZa</b>	<b>51</b>
4.1	The CelZa project . . . . .	51
4.1.1	Known Data . . . . .	51
4.1.2	Assumptions . . . . .	53
4.1.3	Scenarios . . . . .	60
4.2	Implications of Portuguese Interconnection Via Hydrogen Pipelines . . . . .	62
4.2.1	Methodology Application . . . . .	62
4.2.2	Results Analysis . . . . .	64
4.2.3	Results Discussion and Validation . . . . .	70
<b>5</b>	<b>Conclusions</b>	<b>73</b>
5.1	Main Conclusions of the Dissertation . . . . .	74
5.2	Hydrogen: Proposed Solutions and Emerging Opportunities . . . . .	75
5.2.1	Industrial Implementation of the Methodology . . . . .	75
5.2.2	Analytical vs AI . . . . .	76
5.2.3	Future Works . . . . .	76
<b>A</b>	<b>Overview of EU ´s Hydrogen Infrastructure Projects</b>	<b>79</b>
<b>B</b>	<b>EHB Projects Map</b>	<b>83</b>
<b>C</b>	<b>Germany ´s Hydrogen Infrastructure Projects</b>	<b>85</b>
<b>D</b>	<b>Search Space Calculations</b>	<b>87</b>
<b>E</b>	<b>Parents Selection Algorithm</b>	<b>89</b>
<b>F</b>	<b>Mapping of National Regions Decarbonization Potential</b>	<b>91</b>
<b>G</b>	<b>Portugal´s Population and Company Density</b>	<b>97</b>
<b>H</b>	<b>DSS Results for Consumption Inside Respective Areas of Influence</b>	<b>99</b>
<b>I</b>	<b>Results Output of the Genetic Algorithm</b>	<b>103</b>
<b>J</b>	<b>Optimal Network Parameters for the 54 Scenarios</b>	<b>105</b>
	<b>References</b>	<b>109</b>

# List of Figures

1.1	Colors of hydrogen (adapted from [3]). . . . .	2
1.2	P2P plant schematic using green hydrogen as energy storage [4]. . . . .	3
1.3	Hydrogen costs from electrolysis using grid electricity [5]. . . . .	3
1.4	Current map of the EHB projected infrastructure [6]. . . . .	5
1.5	Current H2med projected routes, with the overall data of the network [12]. . . . .	6
2.1	Energy content of gas blends in pipeline flow relative to the energy content of pure CH <sub>4</sub> and NG assuming an unchanged pressure drop and same pipeline dimensions [30]. . . . .	14
2.2	Hydrogen investment decision tree [2]. . . . .	18
2.3	Anticipated kilometers of commissioned hydrogen pipelines, per year [7]. . . . .	25
2.4	Natural gas consumption in 2022 by European countries (ktoe) [48]. . . . .	30
2.5	Schematic representation of the EHB’s main financial phases [7]. . . . .	32
3.1	Main drivers of the developed methodology. . . . .	34
3.2	Flowchart of the Consumption Mapping Algorithm (CMA). . . . .	36
3.3	Flowchart of the general optimization structure. . . . .	37
3.4	Flowchart of the DSS algorithm. . . . .	38
3.5	Area of influence generated for fictitious network. . . . .	39
3.6	General flowchart of the Genetic Algorithm. . . . .	41
3.7	Search space and example genotype for a simplified network with $z = 1$ and $n = 2$ . . . . .	45
4.1	CelZa’s projected route [12]. . . . .	52
4.2	Possibilities considered for the direction of the flow. . . . .	56
4.3	Critical locations of the production units. . . . .	57
4.4	Portuguese natural gas consumption by region in 2022. . . . .	65
4.5	Buffer generated for 10 km distance between the border and the pipe. . . . .	66
4.6	Decarbonization impact in ktoe per internal consumption scenario. . . . .	66
4.7	CO <sub>2</sub> emissions reduction per year, for the five scenarios of national hydrogen consumption through CelZa. . . . .	67
4.8	Initial usage tariff variation considering internal consumption and export quantities. . . . .	68
4.9	Initial usage tariff variation with total consumption. . . . .	69
4.10	CAPEX variation with required compression power. . . . .	69
B.1	Detailed map of the EHB infrastructure projects [7]. . . . .	84
E.1	Flowchart of the selection mechanism of individuals into a pool. . . . .	89
F.1	Portuguese natural gas consumption by region in 2022. . . . .	92

F.2	Portuguese natural gas consumption by region in 2022, excluding the domestic sector. . . . .	93
F.3	Portuguese natural gas, propane and butane consumption by region in 2022. . . . .	94
F.4	Portuguese natural gas, propane and butane consumption by region in 2022, excluding the domestic sector. . . . .	95
G.1	Population density in Portugal, 2021 [121]. Unit: [residents/km <sup>2</sup> ]. . . . .	97
G.2	Company density in Portugal, 2021 [121]. Unit: [companies/km <sup>2</sup> ]. . . . .	98
I.1	Example output of the GA. . . . .	104

# List of Tables

3.1	Consumption data obtained for the example used. Unit: [GWh]. . . . .	39
4.1	Existing network specifications of the pipes that will be converted to 100% hydrogen.	53
4.2	Hydrogen properties considered and respective references. . . . .	53
4.3	Fuels' HHVs considered and respective references. . . . .	54
4.4	Efficiencies and losses values considered (%). . . . .	55
4.5	Relevant pressure values considered in the operating specifications. . . . .	58
4.6	Exportation scenarios, considering variations of base capacities (5, 10 and 15 TWh).	61
4.7	Model matrix of scenarios for a specified area of influence A. . . . .	62
A.1	European partners' current consumptions and future perspectives regarding 100% hydrogen infrastructures. . . . .	80
A.2	European partners' 100% hydrogen infrastructure projects (corridors A, B and C).	81
A.3	European partners' 100% hydrogen infrastructure projects (corridors D, E and Germany). . . . .	82
C.1	Germany's projects overview. . . . .	85
H.1	Natural gas, Propane and Butane consumption in a 5-kilometer radius of CelZa. .	99
H.2	Natural gas, Propane and Butane consumption in a 10-kilometer radius of CelZa.	100
H.3	Natural gas, Propane and Butane consumption in a 20-kilometer radius of CelZa.	101
J.1	Results of the GA implementation for all scenarios (part 1). . . . .	106
J.2	Results of the GA implementation for all scenarios (part 2). . . . .	107



# Notation

## *Acronyms and Abbreviations*

AI	Artificial Intelligence
APA	Agência Portuguesa do Ambiente
API	Application Programming Interface
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CEI	Call for Expression of Interest
CEF	Connecting Europe Facility
CF	Capacity Factor
CMA	Consumption Mapping Algorithm
CO <sub>2</sub>	Carbon Dioxide
CoD	Commissioning date
DEVEX	Development Expenditure
DGEG	Direção Geral da Energia e Geologia
DN	<i>Diametre Nominel</i> (Nominal Diameter)
DSS	Decision Support System
EHB	European Hydrogen Backbone
EN-H2	Estratégia Nacional para o Hidrogénio
ENTH2	Eixo Nacional de Transporte de Hidrogénio
EU	European Union
EV	Electrical Vehicles
FID	Financial Investment Decision
GA	Genetic Algorithm
GHG	Greenhouse Gas
H <sub>2</sub>	Hydrogen
HHV	Higher Heating Value
IEA	(International Energy Agency
IRENA	International Renewable Energy Agency
IRES	Integrated Renewable Energy Systems
JSON	JavaScript Object Notation
LCOH	Levelized Cost of Hydrogen
LCOHT	Levelized Cost of Hydrogen Transport
LHV	Lower Heating Value
MoUs	Memorandums of Understanding
MSM	Mating Selection Mechanism
NPV	Net Present Value
NLP	Nonlinear Programming

OGM	Offspring Generation Mechanism
OSM	Offspring Selection Mechanism
OPEX	Operational Expenditure
P2P	Power-to-power
P2X	Power-to-X
PCI	Projects of Common Interest
REN	Redes Energéticas Nacionais
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
TSO	Transmission System Operator
UK	United Kingdom

### ***Nomenclature***

$A$	Control surface area
$B_{sys}$	Arbitrary extensive parameter within a system
$b$	Amount of B per unit mass
$c$	Speed of sound
$C_{max}$	Scalar that makes the merit function positive
$c_p$	Specific heat at constant pressure
$c_v$	Specific heat at constant volume
$CI$	Cash inflow
$CO$	Cash outflow
$CS$	Control surface
$CV$	Control volume
$D$	Diameter
$E_t$	Total energy carried by the network during operational life
$f$	Darcy friction factor
$g$	Gravitational acceleration
$HHV$	Higher Heating Value
$h_L$	head loss of pressure
$k_1$	Minimum pipeline pressure allowed
$k_2$	Maximum pipeline velocity allowed
$L$	Length of the pipe
$LHV$	Lower Heating Value
$M$	Molar mass
$Ma$	Mach number
$M_{sys}$	Mass of the system
$\dot{m}$	Mass flowrate
$N$	Years of life expectancy of the infrastructure
$n$	Number of time periods
$\hat{n}$	Unit normal vector to the control surface
$N_{pop}$	Population size
$P$	Power
$Q$	Volume flowrate
$\dot{Q}_{net,in}$	net rate of heat transfer into the system
$r$	Discount rate
$Re$	Reynolds number
$t$	Time

$\check{u}$	internal energy per unit mass
$V$	Velocity
$\mathbf{V}$	Velocity vector
$\mathcal{V}$	Volume
$\bar{V}$	Average value of the component of velocity normal to the section area
$\dot{W}_{\text{net,in}}$	net rate of work transfer into the system
$x$	Volume percentage
$y$	isentropic coefficient
$z$	height

***Greek Letters***

$\alpha$	kinetic energy coefficient
$\gamma$	Specific weight
$\Delta p$	Pressure variation
$\Delta p_c$	Pressure increase due to compressor work
$\Delta p_L$	Flow pressure drop
$\varepsilon$	Roughness of the material
$\mu$	Dynamic viscosity of the fluid
$\rho$	Fluid density



# Chapter 1

## Introduction

### 1.1 Context and Motivation

Global climate change constitutes a significant threat, leading to increasing catastrophic events. According to scientific consensus, carbon emissions are a primary contribution to this phenomenon, encouraging politicians to emphasize carbon-reduction initiatives. Hydrogen-based systems are emerging as attractive alternatives to traditional energy sources, with governments and investors worldwide encouraging the development of hydrogen supply networks to foster market creation [1].

While electrification is largely recognized as the key answer for decarbonizing the energy system, there is widespread agreement that hydrogen and renewable gases will also play vital roles in that process. Despite the steady phase-out of oil and coal in Europe's energy sector, natural gas remains significant. However, investments in natural gas infrastructure have become less appealing as a result of the European Union's (EU) commitment to transition to a fully decarbonized economy by 2050. Financial institutions are withdrawing the financing of key infrastructure, raising concerns about the viability of new natural gas projects [2].

The EU hydrogen plan seeks to reduce the cost of decarbonized gases by aggressively reducing electrolyser costs. Due to energy efficiency losses in green hydrogen production, "hard-to-abate sectors", such as the chemicals and steel industries, have emerged as priority areas for hydrogen adoption. Given the long-term fall in European natural gas demand, there is significant interest in using existing gas infrastructure to transport or store alternative gases, particularly hydrogen, in order to meet decarbonization goals. Aside from hard-to-abate sectors, gases are viewed as advantageous for balancing renewable energy sources (RES) and providing cost savings in transportation over electricity [2].

Ultimately, the gas industry may turn this predictable decline into an opportunity, retaining and future-proofing its well-established infrastructures. Hydrogen will play an active role either

by direct use or as a feedstock for ammonia, methanol or sustainable aviation fuel (SAF), aiming to decarbonize sectors that nowadays are not in the mainstream electricity or gas networks.

### 1.1.1 Green Hydrogen

Hydrogen can be produced from various primary energy sources, leading to different costs and emissions depending on the production process. To distinguish between these variations, hydrogen production systems are frequently labeled with colors such as grey, blue, turquoise, green, purple (or pink) and yellow (see [Figure 1.1](#)). Currently, the predominant form of hydrogen is grey hydrogen, produced via steam reforming of natural gas or coal gasification without carbon capture and storage (CCS). However, some sources differentiate hydrogen from coal gasification as brown or black hydrogen [3].

More than 40% of grey hydrogen is a byproduct of other chemical processes, which is unofficially known as white hydrogen (also used to classify natural occurring hydrogen). Grey hydrogen is widely used in industries such as petrochemicals and ammonia production, with approximately 6% of global natural gas and 2% of coal being utilized for grey hydrogen production annually [3].







	<b>Grey Hydrogen</b>	Hydrogen produced by fossil fuels, mostly natural gas and coal, causing CO <sub>2</sub> emissions in the process.
	<b>Blue Hydrogen</b>	Hydrogen produced by fossil fuels in combination with CCS, reducing the GHG emissions of the process.
	<b>Turquoise Hydrogen</b>	Hydrogen produced via pyrolysis of fossil fuels, where the by-product is solid carbon.
	<b>Green Hydrogen</b>	Hydrogen produced by electrolysis using electricity generated from RES.
	<b>Pink Hydrogen</b>	Hydrogen produced by electrolysis using electricity from nuclear power plants.
	<b>Yellow Hydrogen</b>	Hydrogen produced by electrolysis using grid electricity.

Figure 1.1: Colors of hydrogen (adapted from [3]).

Therefore, the transition from grey to green hydrogen is one of Europe's major priorities to accomplish its decarbonization goals.

In order to achieve carbon neutrality, the use of renewable energy must be maximized all year. Another appealing benefit of green hydrogen is that it addresses the intermittent nature of renewable resources, that require active demand response and multi-layer energy storage. Assessing supply security is crucial for renewable-based electricity generation, which needs dispatchable power to control demand changes. Green hydrogen, made from excess renewable electricity by

water electrolysis, addresses energy storage and seasonal variability. Using hydrogen in dispatchable power-to-power (P2P) plants provides reliability of supply while remaining carbon neutral [4]. Figure 1.2 shows a simple schematic of the operation of an H<sub>2</sub> P2P plant.

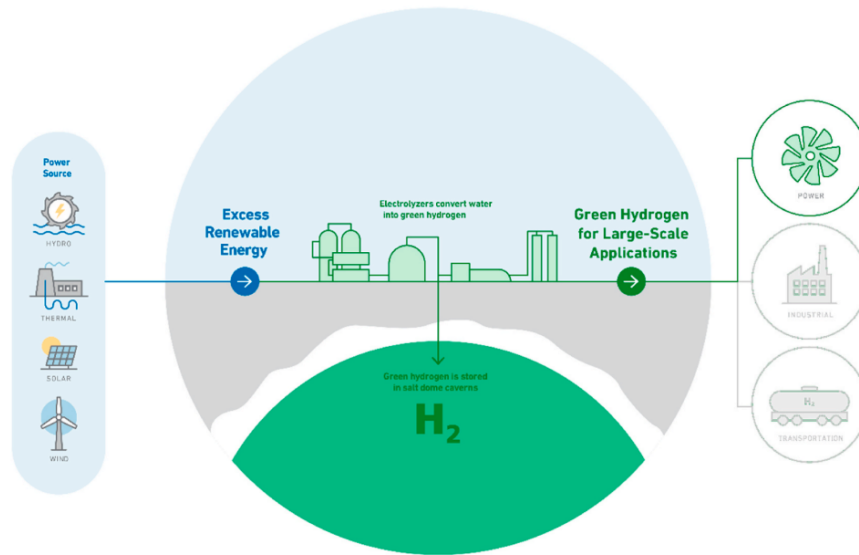


Figure 1.2: P2P plant schematic using green hydrogen as energy storage [4].

Green hydrogen production benefit from gains of scale as the electrolyzers' capacity factor is key to depreciate the investment costs in more produced energy throughout the lifetime of the asset. Therefore, networks are a key enabler to decrease the LCOH (Levelized Cost of Hydrogen), generating gains of scale by allowing market creation and synergies between producers and consumers. This scale effect is shown in Figure 1.3. Higher utilisation rates (full load hours) help to reduce the impact of capital expenditure (CAPEX), but for grid-connected electrolyzers this means higher electricity prices. Therefore, the lowest hydrogen costs are achieved in mid-load operation.

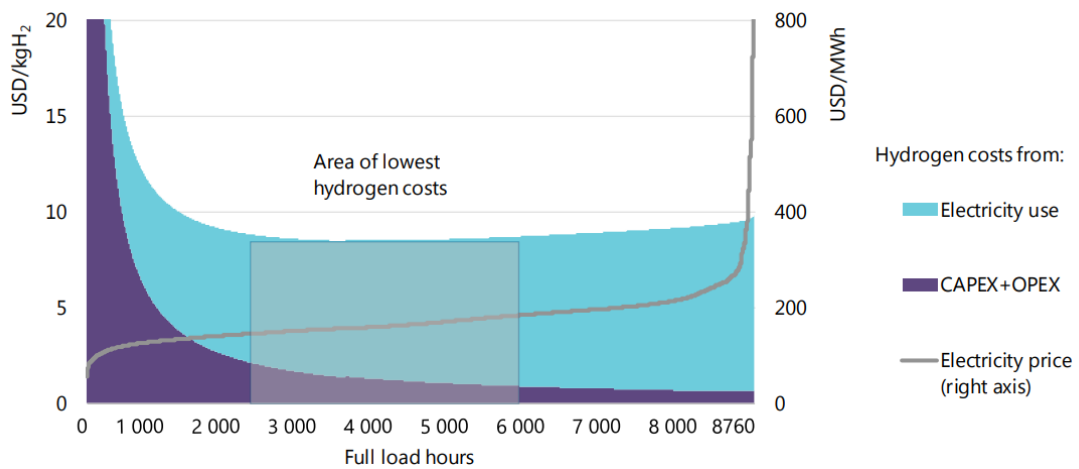


Figure 1.3: Hydrogen costs from electrolysis using grid electricity [5].

### 1.1.2 European Hydrogen Backbone

The European Hydrogen Backbone (EHB) initiative, comprising thirty-three energy infrastructure operators, aims to advance Europe's decarbonization efforts by establishing hydrogen infrastructures, to foster a competitive, pan-European renewable and low-carbon hydrogen market. It focuses on market competitiveness, supply and demand security, and cross-border collaboration to efficiently integrate renewable and low-carbon energy, connecting supply-rich regions with demand centers to reshape Europe's industrial economy and assure energy system resilience and independence. Achieving this ambition requires collaboration among EU Member States, adjacent nations, and a supporting regulatory framework. The suggested infrastructure pathway until 2040, based on national evaluations, is dependent on future supply and demand dynamics, requiring flexibility in route and time planning. Stakeholder interaction, including politicians and industry players, is critical to fulfilling this vision [6].

The creation of a European Hydrogen Backbone intends to have a critical role in developing a hydrogen market, which will use both repurposed gas infrastructure and new pipelines to efficiently connect supply and demand sites. Hydrogen pipeline infrastructure emerges as the most cost-effective option for long-distance hydrogen transport, outcompeting shipping for all reasonable distances within Europe and neighboring regions. The early establishment of a pan-European hydrogen network before 2030 can be vital for achieving Europe's energy transition goals, facilitating large-scale deployment of renewable energy and hydrogen production, leveraging cost advantages in production regions, and enabling imports. Progress on the EHB network is evident, with tangible advancements in corridor projects and 40 concrete projects representing 31,500 kilometers of hydrogen pipelines expected to be commissioned by 2030. Transmission System Operators (TSOs) are actively seeking contractual commitments to support investment decisions, with several already made. Leveraging their expertise in gas networks, TSOs are committed to making the EHB a tangible reality to accelerate Europe's energy transition [7] [8].

Figure 1.4 shows the schematic representation of the EHB projected pipelines in Europe's map.

### 1.1.3 CelZa Project

The H2Med project (Figure 1.5) is an ambitious endeavor that aims to establish a connection between Celorico da Beira in Portugal with Zamora in Spain (CelZa), as well as a maritime link between Barcelona and Marseille (BarMar), with a total investment of roughly 2.5 billion euros. CelZa is part of the H2Med and is projected to have a maximum annual capacity of 0.75 million tonnes of renewable hydrogen, spanning 248 kilometers and include a 24.6 MW compressor station near Zamora. Meanwhile, BarMar is expected to have a maximum annual capacity of two million tonnes, extending over 455 kilometers and featuring a 140 MW compressor station in Barcelona.

H2Med was first presented during the Euromed conference in Alicante on December 9, 2022, by the governments of Portugal, Spain, and France, with support from European Commission

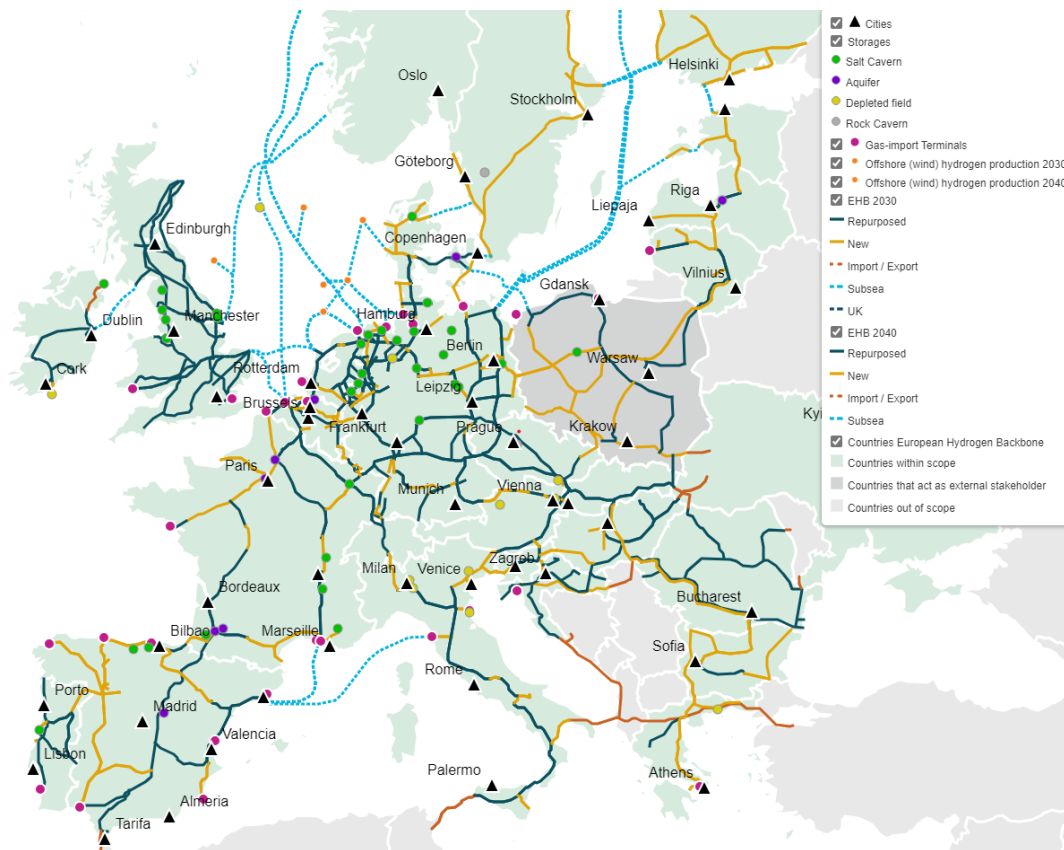


Figure 1.4: Current map of the EHB projected infrastructure [6].

President Ursula Von Der Leyen, as an important part of the REPowerEU program. In January 2023, Germany also announced its support. Following that, the Transmission System Operators (TSOs) of Portugal, Spain, France and Germany confirmed their support for the initiative during a Berlin event on October 18, along with the European Commission and German industry players. H2med was recently included on the Projects of Common Interest (PCI) list, increasing the likelihood of receiving financial assistance from the EU [9].

CelZa, a joint project between REN (Redes Energéticas Nacionais) and Enagás, is going to be the case study used in this dissertation and entails the construction of a 248 km pipeline to carry renewable hydrogen between Portugal and Spain, from Celorico da Beira to Zamora. The complete project includes the connection to the Portuguese Hydrogen Backbone project, officially known as ENTH2 (Eixo Nacional de Transporte de Hidrogénio), with the construction of one new hydrogen-only pipeline, from Figueira da Foz to Cantanhede. In addition, existing gas network parts between Cantanhede, Celorico da Beira, and Monforte will be converted to run entirely on pure hydrogen, as part of ENTH2. The project also involves coordination with gas Distribution System Operators along the pipeline route and evaluating supply options for users along the project's path. Each of the two TSOs involved, REN and Enagás, will fully own their section of the infrastructure: 162 km in Portugal, 86 km in Spain [10] [11].

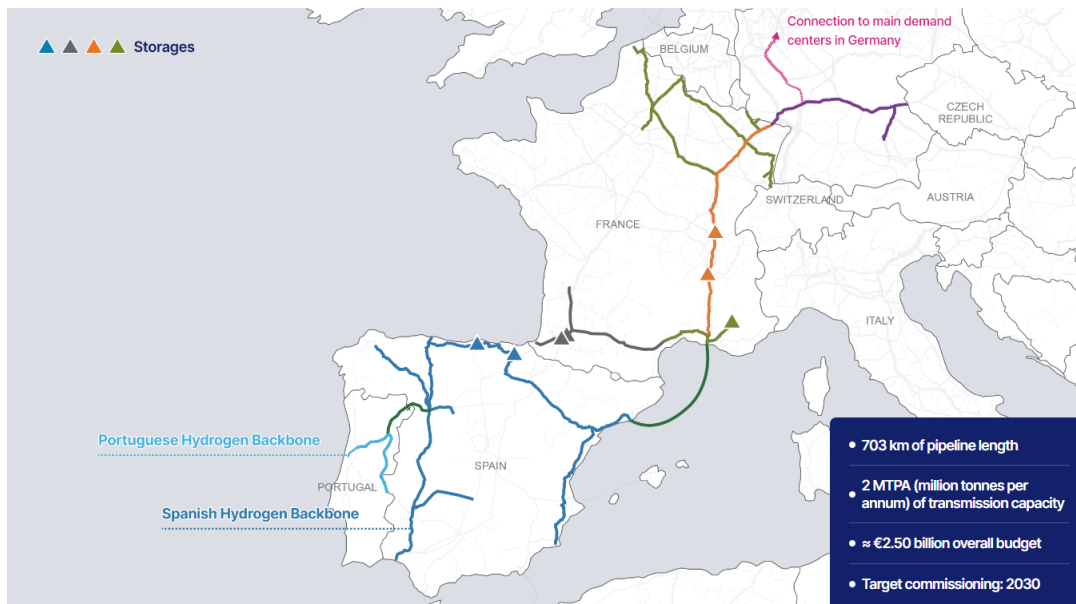


Figure 1.5: Current H2med projected routes, with the overall data of the network [12].

## 1.2 REN

The present work was done during an internship at Redes Energéticas Nacionais (REN), taking advantage of the extensive knowledge of the company regarding gas and electricity network planning. REN is the company responsible for the transmission of very high-voltage electricity and for the overall technical management of the National Electric System. REN also operates the National Gas Transport Network, which connects producers to consumption centers and the Spanish network, ensuring a balance between demand and supply of energy. The company also plays an active role in the national energetic transition, with the development of hydrogen projects, for example.

Integrating the Renewable Gases Planning department, it was possible to explore current projects of extreme relevance to Portugal and Europe in general, using one of them (CelZa) as a case study to apply the methodology developed throughout this dissertation.

## 1.3 Objectives

This dissertation does not intend to evaluate the efficiency or viability of hydrogen-based energy systems, since its main purpose is to provide useful support and a framework for the implementation of 100% hydrogen networks.

The developed methodology intends to address the complex and multi-disciplinary characteristics of hydrogen infrastructures that need to take into account the H<sub>2</sub> specific drivers. The demand-side approach adopted is motivated by the fact that hydrogen is market-driven, meaning its implementation is dependent on market existence. Furthermore, the work aims to establish a proof-of-concept for future adaptations, highlighting the importance of replacing the current analytical planning methods.

In addition, the application of the developed methodology using CelZa not only provides valuable insights for project development but also exemplifies the critical information that should guide government and TSOs steps towards the implementation of hydrogen networks. The value of this type of work lies in the fact that current literature related to the subject is not yet very deepened compared with other energy systems design challenges, since it is a relatively recent problem, fostered by the increased interest in green hydrogen.

## 1.4 Dissertation Structure

In the introduction performed ([chapter 1](#)), the context that motivated this work is presented, as well as some essential definitions for a better understanding of the document.

The following chapters start with a very detailed state of the art ([chapter 2](#)), exploring the challenges associated with the transition to hydrogen infrastructures while explaining the main reasons for this transition. Then, the current status of the European hydrogen projects and the existing literature regarding network planning methodologies are reviewed, while setting the mathematical formulation that supports this work.

In [chapter 3](#), the methodology developed for the implementation of hydrogen infrastructures is carefully explained, highlighting the reasons behind its architecture.

Moreover, [chapter 4](#) is dedicated to the implementation of the methodology in the CelZa case study, detailing the steps that should be followed in similar applications and analysing the results obtained.

Finally, [chapter 5](#) summarizes the main conclusions of the dissertation and provides the required guidelines for future industrial implementation of the methodology. Several suggestions for future works are provided.



## Chapter 2

# State of the Art

The creation of an integrated pan-European hydrogen network by 2030 is part of the European Union strategy to accomplish its energy transition goals, which include increased energy affordability, security and independence. Early infrastructure development may facilitate the possibility of large-scale deployment of renewable energy and hydrogen generation, resulting in cost-effective production and imports from third-party countries [7]. While hydrogen is widely regarded as a possible next-generation sustainable energy carrier, economic feasibility and safety issues remain key obstacles. Therefore, efficient design of the hydrogen supply chain network is critical for lowering investment costs and ensuring viability [13].

This chapter takes a deep literature review of the subject, in order to support the framework of this dissertation. The topics analysed include the transition to hydrogen infrastructures, gas network optimization-based planning and also an overview of the current European developments and perspectives.

### 2.1 Transition to Hydrogen Infrastructures

Following the conflict in Ukraine and the climate's global crisis, hydrogen has emerged as a focal point in the EU's accelerated decarbonization agenda, marketed as a versatile solution for deep decarbonization across hard-to-abate industries and an opportunity for the gas industry to strengthen its infrastructure networks, preparing for an eventual phase-out of natural gas [14] [4].

The EU is expected to witness an increase in the consumption of hydrogen as a strategic move to minimize carbon emissions and reliance on Russian gas. This increased effort towards energy security and decarbonization is planned mainly through the revamped "Fit for 55" plan, now known as "RePowerEU." Under this framework, the EU aims to achieve 1200 GW of renewable energy sources (RES) capacity by 2030, as well as large deployment targets for electrolysis capacity to produce renewable hydrogen. In the short to medium term, the EU's hydrogen strategy focuses on natural gas-based hydrogen production using steam methane reforming and carbon capture

and storage (CCS) technologies. On the other side, the long-term strategy focuses on non-fossil, renewable hydrogen [14]. Hydrogen is currently seen as critical to Europe's transition to a climate-neutral continent by mid-century, with demand expected to reach 2,300 TWh by 2050, accounting for 20-25% of total EU and UK energy consumption [8].

However, increased hydrogen demand does not necessarily mean that a hydrogen backbone is the best solution. Conversion of electricity to hydrogen through electrolysis can occur either close to the site of electricity generation or near the site of hydrogen demand. Instead of relying on a centralized hydrogen backbone, Europe could take a more decentralized strategy, leveraging a wider power network and taking advantage of the increased electrification predicted. This could be done strategically placing electrolyzers near hydrogen demand clusters. This decentralized system could potentially meet Europe's hydrogen demand without requiring long-distance hydrogen transportation. The basic assumption is that electricity transport infrastructure is less expensive than hydrogen transport equipment, and that a delivery system based on local electrolyzers can meet customer hydrogen demands while assuring a consistent energy supply.

The 2021 EHB report [8] looked further into the subject and concluded that both energy transportation strategies have benefits and drawbacks. However, the data indicates that pipelines, whether newly constructed or repurposed, are 2 to 4 times more cost-effective than power lines for high-volume energy transfer targeting hydrogen production, disregarding storage expenses.

A 2023 study [15] analyzed the potential role of a hydrogen network in the European energy system. The findings indicate that in net-zero emission scenarios, a European hydrogen network provides significant cost savings. The inclusion of such a network might cut system costs by up to 3.4%, especially if there is no need for power grid expansion. It also stated that the most significant savings are achieved by combining power grid expansion with the hydrogen network.

Despite these considerations, it is clear that the ongoing transition needs breakthroughs in hydrogen production, transport, and consumption technologies for a variety of purposes, including electricity generation and storage, transportation fuels and domestic consumption.

In 2020, a study by the University of Cologne [16], analyzing the long-term costs of low-carbon hydrogen through cost-minimizing linear optimization, found that shipping hydrogen proved to be more economically viable than pipeline transport for distances over 2000 km, assuming high prices for new hydrogen pipelines. However, with decreased construction and operation costs for dedicated hydrogen pipelines, this threshold is raised to 7000 km.

As retrofitting natural gas infrastructure represents a lower investment when compared to new pipeline development, this option has been widely considered. For example, the 2023 EHB report states the following: "TSO data shows that repurposed 20" pipelines represent 30% of the cost of new pipeline deployment. For all other sizes, repurposing costs are approximately 20% of the cost of new pipeline construction" [7]. This reuse of the natural gas pipelines may also present several other benefits, including availability and social acceptance, while allowing TSOs to avoid the economic losses that would result from the predictable natural gas decline [14].

Considering this, hydrogen transportation via pipelines is anticipated to become increasingly important, utilizing both existing natural gas infrastructure and new hydrogen pipelines. Next, the

analysis of blended hydrogen with natural gas and 100% H<sub>2</sub> infrastructure solutions are performed separately, considering the potential benefits, challenges and complementary characteristics.

### 2.1.1 Blending

Gas blending involves the mixing of different gases to alter the composition of a gas stream. In the context of hydrogen and natural gas blending, it entails combining hydrogen with natural gas within a gas network. However, hydrogen and natural gas possess distinct physical and chemical properties. While methane, the primary component of natural gas, is denser and has a higher volume, viscosity, and water solubility than hydrogen, the latter exhibits characteristics such as higher specific heat capacity, molecular diffusivity, auto-ignition temperature, and explosion and fire risks. Therefore, this mixture has to be done with caution, balancing the potential benefits with the possible downsides. Considering this, selecting an appropriate blending ratio becomes crucial to maintaining the safety and integrity profile of the pipeline [17].

Several ongoing initiatives are now examining the technological viability of blending hydrogen and natural gas. Most studies agree that to prevent pipeline damage without repurposing programs, the hydrogen concentration in the gas mix should not exceed 10-15%. Full repurposing to 100% H<sub>2</sub> is feasible with adequate inspection programs [2].

#### 2.1.1.1 Potential Benefits

Blending hydrogen with natural gas presents an opportunity to mitigate investment risk in hydrogen production and, under certain conditions, may even reduce production costs. Initially developed as a simple solution to decrease the carbon footprint of natural gas-dependent industries, blending requires no additional investment in repurposing existing infrastructures and may, therefore, take advantage of the extensive existing gas network. Moreover, it is viewed as a means to stimulate the growth of the hydrogen market, particularly in its early stages when supply levels are relatively low. Consequently, blending serves as an incentive for hydrogen producers to continue investing in the market without necessitating significant demand levels from specific offtakers. This approach allows demand to evolve around supply, rather than the other way around.

In addition, existing integrated energy systems face limitations due to the need for various energy storage facilities, such as electricity, cold and heat storage, whose capacities often struggle to meet actual demands. Furthermore, because of their small scale, these systems struggle to absorb enough renewable energy. Hydrogen, being ecologically friendly, provides a solution by converting renewable energy sources such as wind, solar, and hydropower into hydrogen. This hydrogen can subsequently be blended into the natural gas network, alleviating energy storage shortages while also increasing renewable energy consumption in typical integrated energy systems [18].

#### 2.1.1.2 European Developments

Several countries across UK and EU are investigating the possibility of injecting H<sub>2</sub> in their gas networks, although the main political focus is definitely the direct transition to 100% H<sub>2</sub>, as it

is analyzed in the following section. Despite that, there are even some blending projects already happening. For example, Austria currently allows concentrations of up to 10% hydrogen in the gas mixture [19] and UK published at the end of 2023 a strategic policy decision that supports the strategic and economic value of blending with maximum hydrogen concentration of 20% [20].

In the British case, blending is seen as a strategic technique to minimize volume risks for hydrogen producers and mitigate capacity uncertainties arising from infrastructure development delays, for example. Additionally, blending is set to help reducing the investment risk and production costs, especially in the absence of a major hydrogen transport infrastructure. Strategically may also help electrolytic hydrogen generation in places with limited electricity networks. However, its role is expected to diminish as the nation moves away from natural gas consumption in accordance with increasing decarbonization plans. As a result, blending is seen as a transitional strategy, with strategic value centred on risk reduction and cost optimization at the project and system levels [20].

The Irish TSO, Gas Networks Ireland, conducted a technical and safety feasibility study in 2022 [21] that had very positive results. The study is highly based in the results of the HyDeploy project, a pilot hydrogen blending project undertaken on two discrete networks in the UK (a University campus and a small town). Following the British government strategic policy decision, the project is still in progress, in order to support the future final decisions [22]. It demonstrated safe introduction of hydrogen blends on the distribution network, indicating that blends of up to 20% pose no material impact on the gas distribution network.

Similarly, Ireland's gas distribution network can handle hydrogen mixtures of up to 20%, and perhaps 100% with slight modifications. However, the study found that around 50% of Ireland's gas transmission pipelines require material testing to sustain current maximum operating pressures with greater hydrogen contents.

The German network operator Gascade has already confirmed the grid connection of HH2E green hydrogen production site in Lubmin, on the German Baltic coast, to the European Gas Pipeline Link, a 480-km-long natural gas pipeline system. HH2E is a German green-energy company and aims to initiate green hydrogen production by late 2025, with an initial focus on blending hydrogen to facilitate the transition away from natural gas and toward a more sustainable energy landscape. Upon availability, HH2E plans to utilize the "Flow - making hydrogen happen" pipeline, a significant onshore pipeline system stretching from the Baltic Sea coast to southern Germany, designated as part of the German hydrogen core network [23]. The blending of hydrogen in Germany is, similarly to UK, considered a possible intermediate step in the transition towards transporting pure hydrogen, although the clear main focus is in infrastructures capable of transporting 100% H<sub>2</sub>, as it is going to be analyzed further ahead.

Additionally, a 2023 Italian study [24] looked into blending hydrogen into the natural gas grid to reduce CO<sub>2</sub> emissions, with an emphasis on their national energy system. The results pointed that conversion of renewable energy surplus to hydrogen might reduce Italian emissions by 15%. Considering only the electricity generation sector, this reduction can reach up to 66% thanks to large Integrated Renewable Energy Systems (IRES) capability. While it may lower

fossil resource scarcity, there is concern about growing mineral scarcity as a result of renewables' material demands.

In April 2019, Italian TSO Snam introduced Europe's first 5% hydrogen-natural gas blend at Contursi Terme, Salerno. The project supplied two industrial firms for a month, generating global interest. Scaling this blend to Snam's network could add 3.5 billion cubic meters per year, reducing CO<sub>2</sub> emissions by 2.5 million tonnes—equivalent to Rome's car emissions [25]. Despite that, there are currently no hydrogen infrastructure projects in the country that consider blending.

Portugal's government currently envisions blending as one of the paths for climate neutrality. Therefore, REN has invested 5 million euros in their asset compliance program, for certification of gas transport, storage and distribution infrastructures to include hydrogen.

The TSO has certification for injections of up to 10% hydrogen mixed with natural gas in the National Gas Transmission Network and Carriço Underground Storage. It is also certificated up to 20% the Distribution Network operated by REN Portugal. By the end of 2024, the aim is to achieve certification for 100% transmission on these infrastructures [10].

Some European countries with smaller economies are also using or considering the use of blending, since it does not require a significant investment and is economically safer than a full transition to H<sub>2</sub>. Bulgartransgaz, the Bulgarian TSO, is currently working on the assessment and subsequent adaptation of the existing gas transmission infrastructure to work with up to 10% hydrogen [26]. Greece, Hungary and Romania are also among the "smaller" countries actively pursuing the development of this kind of project [27] [28] [29].

This is a time of great uncertainty since the majority of the European projects are still in the early phases of development. Considering this, operators from certain countries acknowledge the potential of utilizing blending as a strategy to facilitate the growth of the hydrogen market, despite not having specific projects in place. For that reason, these countries have not been included in the current analysis.

### 2.1.1.3 Risks and Challenges

Incorporating hydrogen into natural gas mixtures introduces important parameters that influence combustion characteristics and safety concerns. Variations in parameters such as the Wobbe index, flame speed, Higher Heating Value (HHV), and specific gravity make it difficult to ensure that blended gases are used within the gas quality thresholds [17].

The discrepancy in calorific value between hydrogen and natural gas influences energy flow throughout gas networks when using blended. Energy flow characteristics are dependent on network operation. For example, in cases where the pressure drop is constant and the flow is in steady state, the energy flow for natural gas (NG) and hydrogen mixtures fluctuates, as shown in Figure 2.1. The 100% number on the y-axis represents a pipeline that only uses natural gas, serving as a baseline for comparison.

Additionally, some very important details have to be taken into account. For example, hydrogen, like natural gas, has no odor, but strong odorants are added for leak detection. HyDeploy revealed that blends including up to 20% hydrogen had no effect on odor intensity at the dispersion

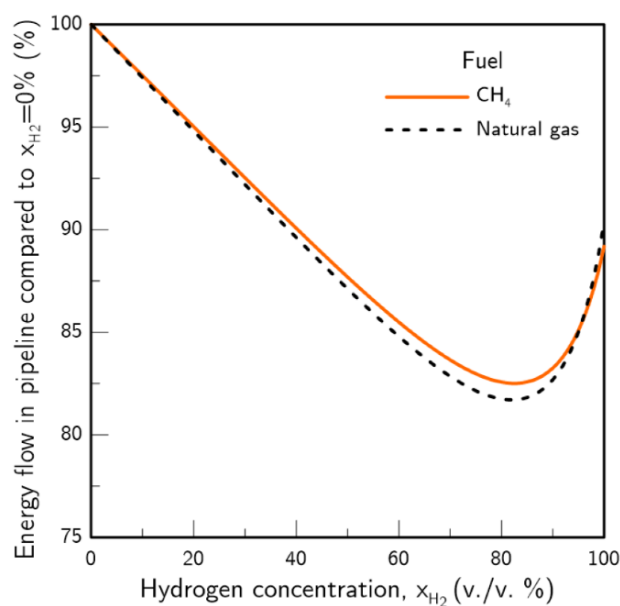


Figure 2.1: Energy content of gas blends in pipeline flow relative to the energy content of pure CH<sub>4</sub> and NG assuming an unchanged pressure drop and same pipeline dimensions [30].

level. However, it is of paramount importance to analyze the potential safety and economic impact of this change. Modifications to existing gas detection equipment are also required to accurately measure hydrogen/natural gas mixes. Furthermore, equipment used to measure carbon monoxide concentrations may require changes due to cross-sensitivity to hydrogen [21]. The hydrogen limit of compression stations initial design, as well as the increase in operating expenses and hydrogen embrittlement of pipeline steel, are all challenges to take into account, namely to develop adequate repurposing programs that require inspection frequency increase [24].

Furthermore, the lack of a reliable and cost-effective hydrogen transportation system creates a significant barrier to wider deployment. Off-site facilities, which carry hydrogen from intermediate production bases to fuelling stations by truck or pipeline, have substantial initial capital expenditures and low energy intensity to transport due to hydrogen's density and calorific value. On-site production facilities, on the other hand, provide localized production but sacrifice efficiency. Addressing these problems is critical to the effective integration of hydrogen blending into natural gas networks, which necessitates novel solutions to assure safety and efficiency while minimizing costs and logistical complexities [17].

### 2.1.2 100% Hydrogen

Considering the above information, it is safe to say that the majority of the H<sub>2</sub> infrastructure projects have as ultimate goal the establishment of 100% hydrogen networks.

Since the transition to 100% H<sub>2</sub> is the main subject of this dissertation and there is currently a major quantitative difference compared to blending projects, the European developments regarding this kind of projects are going to be presented ahead, in a separate subchapter (section 2.3).

### 2.1.2.1 Potential Benefits

The main benefits and drivers of the transition to infrastructures 100% hydrogen were already mentioned. Similarly to blending, the major objective is the decarbonization of the energy sector, complying with climate concerns and targets. However, with pipelines capable of transporting pure hydrogen, the scalability of the market is much greater comparing with only blending.

Energy storage is another major benefit of green hydrogen that was already mentioned and that would benefit from these infrastructures, since they would allow for the transportation to large storage facilities. Although the injection in the natural gas network also presents benefits in terms of avoiding renewable electricity curtailment, the transport of pure hydrogen can serve the industry-demanding clusters and could facilitate seasonal storage, acting as a buffer that could balance supply changes throughout the year.

This storage can be done in appropriate facilities, such as salt structures, which provide optimal underground storage for chemical energy with low cushion gas requirements. The overall storage potential for hydrogen in Europe is estimated to be 84,800 TWh [4].

Moreover, as the demand for hydrogen is mainly industrial, 100% H<sub>2</sub> pipelines, contrary to blending infrastructures, contribute to the decarbonization of industries that use hydrogen as primary feedstock, such as Ammonia production. Ammonia is a crucial chemical in the fertilizer industry, acting as both a fertilizer itself and as a foundational component for other fertilizer compounds. The fertilizer industry uses around 90% of global ammonia production. Its' synthesis, which uses the Haber-Bosch process, involves the reaction of nitrogen with hydrogen, with nitrogen taken from the air and hydrogen usually produced from fossil fuels by Steam Methane Reforming (SMR). Ammonia is already widely traded internationally and is attracting interest as a potential zero-carbon fuel, potentially expanding production and trade scales. Methanol and SAF are also examples of intensive consuming industries, that can use green hydrogen as a feedstock [8].

### 2.1.2.2 Risks and Challenges

The ambitious scale of the H<sub>2</sub> market proposals is primarily driven by global decarbonization initiatives. However, one of the most significant challenges lies in the current reliance on natural gas and coal for hydrogen production on an industrial scale worldwide. This reliance results in annual CO<sub>2</sub> emissions equivalent to those of Indonesia and the United Kingdom combined. Transitioning this existing scale towards a cleaner energy future necessitates two key measures: capturing CO<sub>2</sub> emissions from hydrogen production sourced from fossil fuels and increasing the supply of hydrogen derived from clean electricity sources [5].

The report [5] was prepared by the IEA (International Energy Agency) for the G20 in Japan, in 2019. This study also states that, in order to achieve this increase in green hydrogen, it is essential to stimulate commercial demand for clean hydrogen. To do so, it is crucial to address the remaining cost challenges associated with clean hydrogen technologies. While these are available,

their widespread adoption is hindered by cost considerations. Therefore, policies aimed at creating sustainable markets for green hydrogen are essential.

Such policies would provide a foundation for investments by suppliers, distributors, and users in clean hydrogen technologies. By scaling up supply chains, these investments can drive cost reductions.

## 2.2 Gas Network Planning Optimization

The present subchapter intends to review existing literature regarding gas network planning methods, in order to detail optimization-based hydrogen network design techniques and the main drivers that should be taken into account.

### 2.2.1 Network Planning Methods

Strategic planning is the systematic process of defining long-term goals and objectives, outlining courses of action, and allocating resources to attain these goals successfully [31]. In the case of an energy carrier network, for example gas, electricity or water, that strategic planning has to take into account several specific objectives and drivers. Considering the complexity of the problem, usually that planning process is ultimately improved through optimization algorithms.

Due to their analogous characteristics, such as capital-intensive operations and extended operational lifespans, electricity network planning provides useful insights that can be transferred to gas networks. According to [31], electricity distribution strategic planning takes into account current challenges such as economic regulation, infrastructure aging and fluctuating supply demands, as well as future changes and environmental consequences like climate change. Long-term planning seeks to discover the most economical solution for network structure and investment schedules, by examining numerous parameters and applying systematic approaches.

Since the 1950s, as electrification increased, models have evolved to address load flow and loss control, now including aging network effects and reliability considerations. Environmental issues, particularly climate change, present substantial hurdles, with annual weather variations affecting long-term forecasts. Adverse weather occurrences might reduce the cost-effectiveness of infrastructure projects [31].

Therefore, anticipating future demand, particularly with the rise of electric vehicles (EV) in the case of electricity distribution networks, is critical for strategic planning. Article [32] explores the effects of distributed generation and EV on power flow. These parameters must be analyzed in order to establish the reinforcement requirements for reliable and cost-effective network operation.

Keeping this parallelism in mind, some specific characteristics have to be considered when analyzing the strategic planning of gas pipelines. Pipeline networks consist mainly in supply and demand nodes, compressor stations and pipelines of varying dimensions and lengths. Compressor stations are critical in compensating for friction-induced pressure loss, representing a considerable operational expense in gas pipeline networks. Uncertainty, caused by factors such as supply,

demand, and equipment failure, poses a substantial challenge in the operation of these networks [33].

The existent literature of the subject is much more dedicated to the optimization problems that arise from gas network design, rather than the specific strategic process of network planning. However, some key aspects are commonly addressed:

- The main drivers of the planning have to be identified, similarly to the electricity networks;
- Gas network design is an optimization problem, subject to several constraints [34] [35] [36];
- As gas pipeline systems typically have extended operational lifespans, the strategic planning needs an integrated method that considers the long time horizon [36];
- When analyzing and comparing different approaches, it is critical to examine a variety of performance metrics, such as cost, operability, reliability, environmental impacts, safety, and social impacts [37].

Hydrogen transmission via pipeline is very similar to the natural gas case (considering the comparison detailed in [subsection 2.1.1](#)). However, some specific details have to be taken into account, regarding strategic planning.

The possible repurpose of gas pipelines is an important factor, harvesting the opportunity of already existing routing and assets, resulting in cost-effectiveness of the final infrastructure solution. Moreover, although H<sub>2</sub> has a significantly less negative impact in the atmosphere than CH<sub>4</sub>, safety concerns remain a crucial aspect. In general, new hydrogen-dedicated pipelines not only incur higher costs but also require more time for construction compared to natural gas pipelines repurposing [17].

The hydrogen investment decision tree developed by [2] is shown in [Figure 2.2](#) as an example of different considerations to have into account when planning hydrogen networks. It considers three different scenarios: blending, repurposing gas pipelines and construction of new dedicated hydrogen routes.

Additionally, the initial stage of the hydrogen market is a critical factor in network design since the supply-demand dynamics may be more complex in order to foster the ramp-up of H<sub>2</sub> consumption and production.

LNEG (Laboratório Nacional de Energia e Geologia) developed a powerful tool ([38]) in 2022 with the contribution of several companies, including REN, mapping the best areas for locating green H<sub>2</sub> production units in Portugal. The model considers three sublayers that account for terrain and land use, resources to power electrolysis and market conditions to commercialize H<sub>2</sub> [39].

In 2023, the European Commission also developed high-resolution atlas of energy demand across the EU, that aims to support the significant developments in European energy infrastructures, boosted by the radical transformation in the energy sector expected for the following years. It provides an unprecedented 1x1 kilometer resolution, showing how energy is consumed across Europe [40].

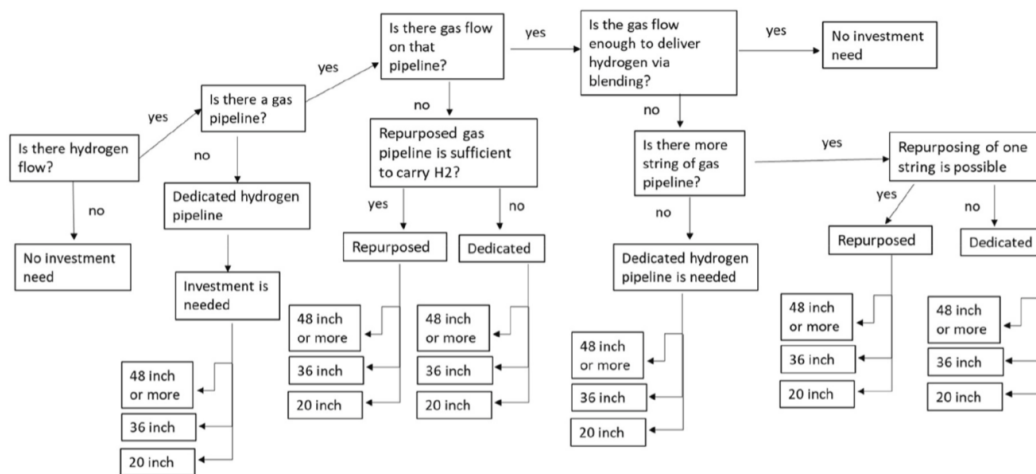


Figure 2.2: Hydrogen investment decision tree [2].

These two tools intend to be a considerably helpful support, by easing decision-making at various scales over the entirety of mainland Portugal and EU. With the rapid growth of the hydrogen economy, clear and accessible information is critical for supporting and empowering all stakeholders, both public and private, in this changing landscape.

## 2.2.2 Main Drivers

The similarities outlined between the gas and electricity industries suggest that their main drivers are nearly identical, with variations in specific technical details. Those general drivers naturally apply to H<sub>2</sub> network planning, albeit with some specific and unique considerations.

The design and development of natural gas transmission pipeline networks are multidisciplinary problems, requiring a wide range of engineering knowledge [36]. Portgás, a company owned by REN, is the responsible of the natural gas network of a big part of the north of Portugal. The company identifies six main drivers in their network strategic planning [41]:

- Network operation and asset management;
- Regulation;
- Commercial necessities;
- Consumption and capacity predictions;
- Regional development;
- Investment.

Similarly, the creation of a future hydrogen market faces numerous obstacles, particularly in establishing energy-efficient, ecologically friendly and cost-effective routes for delivering hydrogen to customers [37].

With multiple technical choices for manufacture, storage, distribution, and dispensing still in development, determining the most beneficial paths is challenging. When assessing these paths as feasible long-term options, performance metrics such as cost, operability, dependability, environmental impacts, safety, and social ramifications must all be taken into account [13].

Efficient design of the hydrogen supply chain network is critical for reducing unnecessary investment expenses. The key issues regarding the hydrogen supply chain include effective routing, diameter size and optimal repurposing of natural gas pipelines [42]. It is also of paramount importance to decide on the quantity and location of production plants and storage facilities, as well as optimizing production capacities, technologies and operating processes to reduce supply chain costs [13].

Since it is a recently used technology, predicting consumption and capacity for hydrogen presents greater challenges compared to natural gas. Consequently, supply-demand dynamics assume heightened significance, playing a critical role in the ramp-up of H<sub>2</sub>. Demand forecasts necessitate comprehensive analyses of potential consumers, while resource mapping is essential for identifying prospective centers of production. For that reason, many TSOs have already carried out a Call for Expression of Interest (CEI), where potential producers and consumers can manifest their intentions regarding the subject.

### 2.2.3 Mathematical Formulation

#### 2.2.3.1 Technical

From the technical point of view, pipeline dimensioning requires some mathematical correlations and physical assumptions. The following mathematical deductions are based on [43].

Equation 2.1 is the general form of the Reynolds transport theorem for a fixed, nondeforming control volume. This equation is widely used in fluid mechanics and other related fields.

$$\frac{DB_{sys}}{Dt} = \frac{\partial}{\partial t} \int_{cv} \rho b dV + \int_{cs} \rho b \mathbf{V} \cdot \hat{\mathbf{n}} dA \quad (2.1)$$

On the left side of the equation, we find the time rate of change of an arbitrary extensive parameter, denoted as  $B$ , within a system. This parameter could signify various quantities such as mass, momentum, energy, etc.

The first term on the right side of Equation 2.1 represents the change in  $B$  as the fluid moves through the control volume (CV). In this equation,  $b$  represents the amount of  $B$  per unit mass and  $\rho b dV$  represents the amount of  $B$  in a small volume ( $dV$ ), being  $\rho$  the fluid density. The time derivative of the integral of  $\rho b$  throughout the control volume determines the rate of change of  $B$  at a given instant. A positive time derivative suggests that  $B$  is accumulating within the control volume. The final term in the equation, which is an integral over the control surface (CS), represents the parameter  $B$ 's net flowrate across the entire control surface (the rate at which this  $B$  is carried across the control surface).  $\hat{\mathbf{n}}$  is the unit normal vector to the control surface,  $\mathbf{V}$  is the velocity vector and  $A$  is the control surface area.

The conservation of mass principle can be represented as

$$\frac{DM_{sys}}{Dt} = 0 \quad (2.2)$$

where  $B$  of Equation 2.1 is equal to mass and, therefore,  $b = 1$ . Considering steady state, where the first term of the right is equal to 0, the equation is reduced to

$$\int_{cs} \rho \mathbf{V} \cdot \hat{\mathbf{n}} dA = 0 \quad (2.3)$$

From this, it is possible to demonstrate that

$$\dot{m} = \rho A \bar{V} \quad (2.4)$$

where  $\dot{m}$  is the mass flowrate, constant across every section of the flow, and  $\bar{V}$  is the average value of the component of velocity normal to the section area  $A$ .

For incompressible flow, the volume flowrate,  $Q$ , is also constant throughout the flow and can be determined at any point by

$$Q = A \bar{V} \quad (2.5)$$

If we consider a circular pipeline, diameter  $D$  can then be determined by the following equation:

$$D = \sqrt{\frac{4Q}{\bar{V}\pi}} \quad (2.6)$$

The conversion of mass into the energy content carried by the fluid can be done considering the Higher Heating Value (HHV) or the Lower Heating Value (LHV). Choosing the first one, power ( $P$ ) is given by:

$$P = HHV \times \dot{m} \quad (2.7)$$

Another important parameter in pipeline dimensioning is the flow pressure drop. Generally, it is determined through Equation 2.8:

$$\Delta p_L = f \frac{\ell}{D} \frac{\rho V^2}{2} \quad (2.8)$$

In this equation,  $f$  is the friction factor (or Darcy friction factor). For laminar fully developed flow in a round pipe is given by

$$f = \frac{64}{Re} \quad (2.9)$$

where  $Re$  is the Reynolds number, calculated from the expression:

$$Re = \frac{\rho V D}{\mu} \quad (2.10)$$

In Equation 2.10,  $\mu$  is the dynamic viscosity of the fluid. Turbulent flows are also dependent of the relative roughness ( $\varepsilon/D$ ), where  $\varepsilon$  is the roughness of the material. In these cases,  $f$  can be estimated by the Haaland equation, for example:

$$\frac{1}{\sqrt{f}} = -1.8 \log \left( \left( \frac{\varepsilon/D}{3.7} \right)^{1.11} + \frac{6.9}{\text{Re}} \right) \quad (2.11)$$

The one-dimensional energy equation for steady-in-the-mean flow, valid for incompressible and compressible flows, is the following:

$$\dot{m} \left[ \check{u}_{\text{out}} - \check{u}_{\text{in}} + \left( \frac{p}{\rho} \right)_{\text{out}} - \left( \frac{p}{\rho} \right)_{\text{in}} + \frac{V_{\text{out}}^2 - V_{\text{in}}^2}{2} + g(z_{\text{out}} - z_{\text{in}}) \right] = \dot{Q}_{\text{net}_{\text{in}}} + \dot{W}_{\text{net}_{\text{in}}} \quad (2.12)$$

where  $\check{u}$  is the internal energy per unit mass,  $\dot{Q}_{\text{net}_{\text{in}}}$  is net rate of heat transfer into the system and  $\dot{W}_{\text{net}_{\text{in}}}$  is the net rate of work transfer into the system.

In pipe flow, the head form of the mechanical energy equation for steady incompressible flow between two points, without shaft work, simplifies to:

$$\frac{p_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2 + h_L \quad (2.13)$$

where  $h_L$  is the head loss between sections (1) and (2) and  $\gamma$  is equal to  $\rho g$ ,  $g$  being the gravitational acceleration. With the assumption of a constant diameter ( $D_1 = D_2$  so that  $V_1 = V_2$ ), horizontal ( $z_1 = z_2$ ) pipe with fully developed flow ( $\alpha_1 = \alpha_2$ ), this becomes  $\Delta p = p_1 - p_2 = \gamma h_L$ , which, combined with Equation 2.8 is equal to  $\Delta p_L$ . If there is work added by a compressor,  $p_2$  can be calculated using the  $\Delta p_c$  introduced by the compressor:

$$p_2 = p_1 + \Delta p_c - \Delta p_L \quad (2.14)$$

As a general rule for pipe flow, the flow can be considered turbulent if:

$$\text{Re} > 4000 \quad (2.15)$$

All these deductions are based on the assumption of incompressible flow. Most flows can be considered incompressible if the Mach number ( $Ma$ ) is less than 0.3 (Equation 2.16).  $Ma$  can be calculated by the ratio between local velocity  $V$  and the speed of sound  $c$  (Equation 2.17).

$$\text{Ma} < 0.3 \quad (2.16)$$

$$\text{Ma} = \frac{V}{c} \quad (2.17)$$

### 2.2.3.2 Economic

From the economic point of view, the dimensioning of hydrogen pipelines, like other networks, also includes some mathematical formulation. Every TSO base their business model in charging tariffs for the usage of its infrastructures. These tariffs can be calculated freely in liberalized markets or have to follow what is defined by a third entity in regulated markets. The last one is REN's case, where the entirety of its business is regulated by ERSE (Entidade Reguladora dos Serviços Energéticos) in Portugal.

However, even in regulated cases, the tariffs have to be calculated during the strategic network planning, in order to evaluate and optimize costs.

Since the objective of the tariff is to recover the investment pursued, it is calculated dividing the total costs (CAPEX and OPEX) during the entire life expectancy of the infrastructure ( $N$  years) by the total energy  $E_t$  (or hydrogen mass) carried by the network during that period (Equation 2.18).

$$\text{tariff} = \frac{\text{CAPEX} + (\text{OPEX}/\text{year} \times N)}{E_t} \quad (2.18)$$

Another important economic parameter is the Net Present Value (NPV). It is used as a method of investment profitability assessment and consists in the sum of the present values of incoming and outgoing cash flows over a given time period. A positive NPV represents a net profit, indicating project viability, whereas a negative NPV indicates a loss. When choosing between alternatives, the option with the highest NPV is preferred since it reflects immediate earning potential and adds value to the organization.

NPV can be calculated as follows:

$$NPV = \sum_{t=0}^n \frac{CI_t}{(1+r)^t} - CO_0 \quad (2.19)$$

In Equation 2.19  $n$  is the number of periods,  $r$  is the discount rate (the rate of return that could be earned from an investment in the financial markets with similar risk),  $CI_t$  is the cash inflow at moment  $t$  and  $CO_0$  is the cash outflow at moment 0 (initial investment) [44].  $r$  normally accounts both for the risk of investment and the time value of money or inflation.

## 2.2.4 Optimization Algorithms

As mentioned before, gas network design is generally treated as an optimization problem, subject to several constraints. In [45], the author defines optimization of mechanical systems as the methodical creation of an optimal design, chosen from all potential designs based on one or more predetermined objectives, while adhering to specified constraints.

Optimization methods can be divided into two main groups:

- **Classical optimization methods:** optimization methods for continuous and differentiable functions, that use differential calculus analytical techniques to find optimal solutions. There are two main strategies: line search methods, which look for the optimal point along a

straight line, and trust region methods. Newton, Quasi-Newton, Augmented Lagrangian and Conjugate Gradient Methods are examples of line search algorithms [45].

- **Metaheuristic algorithms:** computational intelligence paradigms utilized to solve complicated optimization problems, since accurate approaches are limited to small-scale cases. These algorithms are approximation approaches, that can obtain satisfactory solutions in tolerable timescales. The difference from heuristics is that the last ones are problem-dependent and efficient for specific tasks, but they may not be generalizable, whereas metaheuristics provide a generic framework applicable to a wide range of optimization issues.

Metaheuristics are generally metaphor-based, influenced by biological evolution or physical concepts, for example. They can be divided into three groups: evolutionary, swarm, and immune systems. Evolutionary Algorithms simulate biological evolution by employing selection, crossover, mutation, and reproduction operations. The most known example is the Genetic Algorithm, based in Darwin's theory of evolution, choosing the best individuals (possible solutions) for survival. Swarm Intelligence mimics the collective behavior of agents in communities by using decentralization principles seen in natural systems. Artificial Immune Systems are inspired by immunology and use clonal selection concepts to optimize. There are also non-metaphor based metaheuristics, such as Tabu Search [46].

Despite the most suitable method chosen, it is always necessary to define the **objective function**. It consists in the function whose value is going to be minimized or maximized by the optimal solution. A common example in network design is the total cost, which needs to be minimized.

Another common topic when analysing the optimization of this kind of energy systems is the fact that it should be treated as a nonlinear programming (NLP) problem. NLP is an area of applied mathematics that deals with problems where the functions involved are nonlinear, which in this case normally are, due to its complex and multi-disciplinary characteristics. This type of problem can be simplified as

$$\min_{x \in \mathbb{R}^n} f(x) \quad (2.20)$$

where  $x \in \mathbb{R}^n$  is the vector of design variables with  $n$  components and  $f: \mathbb{R}^n \rightarrow \mathbb{R}$  is the objective function.

### 2.2.5 Hydrogen Supply Network Design Optimization

Efficient design of the hydrogen supply chain network is critical for reducing unnecessary investment expenses. However, hydrogen network architecture poses several optimization challenges, due to the complex network configuration and multiple decision-making considerations involved [42]. There is extensive research in the literature regarding hydrogen pipeline design optimization. The majority of them intend to reduce the total cost of the infrastructure while being limited by several constraints.

A 2022 German study [42] developed an optimization-based method, using part of the German Hydrogen Core Network project (Wasserstoffnetz 2030, mentioned in the next subchapter) as a case study. The method builds on the current natural gas network to create the hydrogen network, allowing natural gas pipelines to be converted. It uses an optimization model nested within a local search to incorporate gas flow hydraulics, topology, and economic factors as building blocks. The approach constructs a neighbourhood of 190 different networks before identifying an ideal solution at a cost of 6233 million euros. This cost is consistent with the predicted 6000 million euros for the Wasserstoffnetz 2030, indicating the method's capacity to develop cost-effective hydrogen infrastructure within existing gas networks.

A Korean academic paper [13], published in 2019, explored the use of a genetic algorithm-based metaheuristic, in order to optimize a hydrogen supply chain network, with two transportation modes (pipeline and tanker truck) and replenishment cycles.

Additionally, in 2005, the Imperial College London partnered with BP in a joint study [37] to present a comprehensive optimization-based model for strategic long-term investment planning and future hydrogen supply chain architecture. Recognizing that there is no one-size-fits-all strategy to global hydrogen infrastructure investment, the purpose was to create a versatile model that can be used for a variety of situations, geographical regions, and case studies. Using Mixed Integer Linear Programming techniques, the model selects optimal investment plans and integrated supply chain topologies from a large number of choices. Taking into account a variety of performance criteria, including investment and environmental issues, the optimization process produces a set of optimal trade-off solutions that reflect competing infrastructure pathways.

Some other approaches included in their analysis a wider spectrum of the energy system. For example, [47] considers a network composed by: wind turbines, electrolyzers, fuel cells, compressors, pressurised vessels, underground H<sub>2</sub> storage, hydrogen pipelines, electricity overhead or underground transmission lines and fuelling stations. Given a big set of data, the objective was to minimize total network costs, determining several parameters, such as the optimal number, size and location of the components, whether to use electricity, hydrogen or both to transmit the energy, etc. The constraints involved the available land area and satisfying H<sub>2</sub> demand at all times.

## 2.3 Current European Developments

As mentioned in Chapter 1, Europe is currently developing a joint initiative to establish a hydrogen market and, ultimately, achieve the decarbonization goals, called European Hydrogen Backbone (EHB). Table A.1 of Appendix A summarizes each country's current consumptions and future perspectives regarding projects to develop infrastructures to transport pure hydrogen across Europe<sup>1</sup>.

Figure 2.3 illustrates the expected network length commissioned by date, regarding the EHB.

<sup>1</sup>The information presented in the table refers to the latest public information until March 2024. Empty sections represent either information that is not public or that is waiting for a decision by the stakeholders. Final energy consumption excluding the household sector and natural gas consumption are relative to Eurostat 2022 data [48]. All the information is also based on the EHB reports [7] and [6], while any specific references used are pointed out in the table.

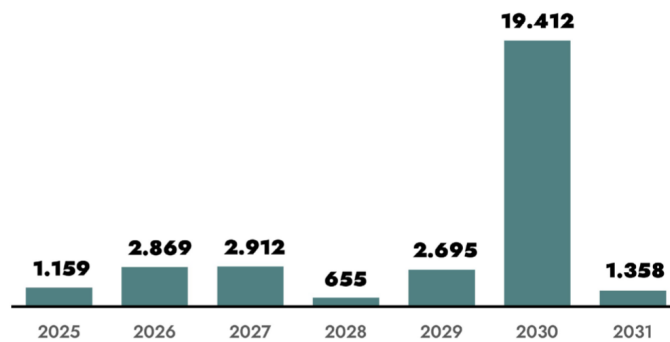


Figure 2.3: Anticipated kilometers of commissioned hydrogen pipelines, per year [7].

It is, however, important to notice that [Figure 2.3](#) reflects only hydrogen pipelines that belong to the EHB and also may differ from current data due to evolutions since the publication of [7]. The project's commissioning dates predicted for 2025, up to the present work's date, will be summarized further ([subsection 2.3.5](#)).

The EHB is mainly divided into five corridors, categorized from letters A to E, that connect all the participant countries. Germany belongs to all of them, so is usually a case considered apart from the rest. Each corridor already has several projects announced by the respective TSOs.

Corridor A enables the delivery of low-carbon hydrogen from North Africa and Southern Italy to Central Europe. The Southwest Europe and North Africa Corridor (B) proposes to deliver hydrogen to demand centres in Germany and beyond. The North Sea Corridor (C) accelerates hydrogen delivery to demand centres in western Germany by primarily leveraging offshore wind capacity. The Nordic and Baltic regions (corridor D) have an abundance of renewable energy resources, making them ideal for hydrogen projects and new Power-to-X (P2X, the process of turning hydrogen into something else) industries. Corridor E, also known as the East and South-eastern Corridor, intends to transport hydrogen from Greece or Ukraine to Bulgaria, Romania, Hungary, Slovakia, and Austria to Central Europe [7].

Considering this, the developments and expectations of the projects integrated in the EHB initiative are indicated in [Table A.2](#) and [Table A.3](#) of [Appendix A](#)<sup>2</sup>. All the information is based in [7] and other specific references, mentioned in the tables. The required conversions regarding the expected capacity of each project were calculated using [Equation 2.7](#). A major part of these projects were included in the European Union's list of Projects of Common Interest (PCI) in April 2024, becoming eligible for European funding and benefiting from easier permit-granting and regulatory support [49]. The detailed map with the main projects and the respective corridors is represented in [Appendix B](#).

Since this dissertation is mainly focused in the Portuguese national case, the rest of this sub-chapter takes a deeper analysis into the countries with higher proximity relative to Portugal (the

<sup>2</sup>The projects analyzed in the tables do not represent the totality of the EU projects regarding H<sub>2</sub> infrastructures. Projects not mentioned either were not comparatively relevant in terms of dimension, do not have sufficient information available at the moment, or were not included in the EHB report. Moreover, some of this projects belong to larger ones, that were omitted to avoid redundancies. CoD refers to the commissioning date.

participants in the H2med project), which are also among the ones with the biggest current natural gas network extension and also with the highest predicted investment in hydrogen infrastructure projects. Finally, the commissioning dates predicted to 2025 and the financial challenges are addressed.

### 2.3.1 Spain

Portugal's neighbour is for obvious reasons a very important strategic partner in a wide number of areas. Regarding hydrogen, Spain is also part of the H2med, the project mentioned in [chapter 1](#), with its Celorico da Beira-Zamora (CelZa) and Barcelona-Marseille (BarMar) connections [6].

As shown in [Table A.2](#), Spain intends to invest 1 billion euros in H2med. The BarMar project is an entirely newly built underwater pipeline, developed by Enagás and France TSOs GRTgaz and Teréga, with an estimated capacity of 215 GWh/day [50]. The CelZa project, as the key case study of this dissertation, will be analyzed in a different section.

These projects are envisioned by Spain TSO Enagás, authorized to operate as a provisional hydrogen transmission network operator under Royal Decree-Law 8/2023 [51].

They play an important part in establishing Spain as Europe's key renewable hydrogen hub, highlighting the importance of infrastructure in advancing decarbonization. Enagás intends to convert up to 70% of its gas pipeline network into hydrogen pipelines and formed Enagás Infraestructuras de Hidrógeno as a subsidiary to design, build and operate hydrogen transmission and storage infrastructure in accordance with national and European legislation, plans and roadmaps [51].

Aligned with this strategy, Enagás also proposes the development of two renewable hydrogen transmission axes in Spain, also known as the Spanish Hydrogen Backbone: the first axis includes the Cantabrian Coast, Ebro Valley, and Levante, while the second the Vía de la Plata Axis, which connects to the Puertollano Hydrogen Valley [51]. This backbone is estimated to require 4,9 billion euros of investment, according to [52]. Additionally, they intend to build underground hydrogen storage facilities in Cantabria and the Basque Country. The European Commission has recognized these projects, including the H2med connections, as European Projects of Common Interest (PCI) [49].

In 2023, Enagás carried out a Call for Expression of Interest (CEI) for the Spanish Hydrogen Backbone Network, with the results known in the beginning of 2024. More than 200 companies - producers and consumers, traders and other stakeholders - participated, demonstrating the huge interest across the industry [53].

From those companies, 45% enrolled as producers, 40% as consumers, and 15% as marketers, with 650 projects (65% production, 20% consumption, and 15% marketing). The results demonstrated that current supply and consumption predictions are consistent with the transport and storage infrastructure designs submitted to the PCI call. They also reveal emerging production and demand aggregation opportunities. According to the CEI scenario, Spain's need for green hydrogen would be around 1 Mt/year, exceeding the current annual usage of 600,000 tonnes of grey hydrogen, considering a scenario where renewable hydrogen production by 2030 is around 2.5 million tonnes per year, with an electrolysis capacity of 23.3 gigawatts [52].

### 2.3.2 France

French hydrogen development is focused in hydrogen basins, addressing high decarbonization necessities, resulting in a considerable demand for hydrogen and also green hydrogen production capacity, which is predicted to reach gigawatt levels to fulfill demand. GRTgaz and Teréga engaged market players in 2021, who stressed that, in addition to hydrogen supply competitiveness, supply diversification and security are critical decision-making criteria. Access to storage is particularly critical for balancing output and consumption, as it addresses not just short-term, daily, or hourly needs but also seasonal requirements [6].

France is also committed to the H2med project, with GRTgaz collaborating in the BarMar infrastructure. GRTgaz has six more projects regarding H<sub>2</sub> pipelines [54]:

- **HY-FEN** - Complementing the BarMar project, it will connect the Iberian Peninsula, France, and Germany via important hydrogen valleys along its route, particularly in the Rhône Valley. This hydrogen transportation infrastructure will stretch from southern France to the German border, integrating Germany in H2med. The project also includes several potential hydrogen storage locations. The HY-FEN infrastructure is expected to be around 1200 kilometers long and capable of producing 200 GWh per day.
- **HYnframed** - Grid project financed by the French state and supported by the South Region, that runs from Fos-sur-Mer to Manosque and serves industrial sectors, such as refining and petrochemicals. With a length of 150 kilometers, it will have a capacity of 25 GWh/day and intends to cut emissions by 4 Mt CO<sub>2</sub>eq/year. The first stage is expected to be commissioned in 2028.
- **MosaHYc** - collaborative project between France and Germany that spans 90 kilometers of hydrogen grid in conjunction with CREOS Deutschland. It entails repurposing around 70 kilometers of gas pipelines. The initial focus will be on industrial applications, with funding from the state under France 2030 program. The project is scheduled to begin operations in 2027, with a maximum capacity of 5.5 GWh/day.
- **RHYn** - hydrogen transportation initiative based in the Grand Est region, connecting France and Germany, with current investigations looking into a possible link to Switzerland. The project, which spans around 100 kilometers, entails converting 60 kilometers of gas pipelines for hydrogen delivery. It estimates a future capacity of 20 GWh per day.
- **WHHYN** - A cross-border pipeline between France and Belgium. The project, which is being carried out in collaboration with Belgian TSO Fluxys, aims to connect Valenciennes and Mons by 2028. Phase one covers 40 kilometers in France and 465 kilometers for the extension, with an interconnection capacity of 24 GWh/day and planned hydrogen consumption of 1.5 to 3 TWh. The third and last phase seeks to integrate WHHYN, mosaHYc, and HY-FEN, boosting capacity to 84 GWh/day by 2034. Financial support from Hauts-de-France and Valenciennes Métropole was given to the feasibility study stage.

- **DHUNE** - infrastructure project in Dunkirk, France, with plans to expand into Belgium, aimed at helping decarbonization in North-Western Europe. The first phase develops a hydrogen pipeline grid in Dunkirk, while the second expands it to Belgium. Phase one, funded by France 2030, is expected to be operational by 2027, with phase two to be completed by 2034. The project will be 50 kilometers long and have an interconnection capacity of 48 GWh/d at the Belgian border.

Teréga is also contributing to this vast range of projects. The HySoW project, involves a 600-kilometer pipeline infrastructure capable of transporting 16 TWh/year of decarbonized hydrogen across the entire South West region. It enables bidirectional transit between Marseille and Bordeaux. Additionally, hydrogen storage facilities in salt caverns in Nouvelle-Aquitaine are part of the project [55].

Teréga launched in 2023 a CEI with 34 H<sub>2</sub> projects being submitted - 10 of production, 17 of consumption and 7 a mix of both [56].

The French Strategic Committee of the Industry New Energy Systems (CSF NSE) released a techno-economic study in 2021, outlining the role of hydrogen infrastructure in enhancing France's industrial competitiveness and decarbonizing industry [57].

The study emphasizes a demand-driven approach for developing hydrogen transport and storage infrastructure, aiming to lower hydrogen costs for consumers. By optimizing investment costs across the entire value chain of hydrogen and electricity, including production, transport, and storage, the study suggests that connecting industrial clusters via hydrogen infrastructure could reduce the cost of renewable and low-carbon hydrogen by 10% by 2030 compared to scenarios without such infrastructure.

Furthermore, connection with European networks might reduce hydrogen costs by 32% by 2040, depending on surrounding nations' hydrogen initiatives and demand development. This infrastructure interconnection would also result in significant reductions in total investment costs, estimated at 9% by 2030 (300 million euros) and 19% by 2040 (3 billion euros).

### 2.3.3 Germany

As it may have been implied by the organization of [Table A.3](#), Germany plays a central and crucial role in the future Europe's H<sub>2</sub> market. The country is anticipated to import substantial quantities of hydrogen to fulfil its considerable national demand. The development of the network within Germany showcases key projects undertaken by various German TSOs, as part of the proposed Hydrogen Core Network. This network is designed to link domestic hydrogen production facilities with neighbouring countries for hydrogen imports into demand centres. The German TSOs work closely with FNB Gas and the Federal Ministry of Economics and Climate Action to coordinate the development of the network [7].

As of November 2023, the initially anticipated total length of the network of approximately 11,200 kilometers is expected to be optimized to 9,700 km, with the overarching objective being the connection of key supply and demand nodes to foster an open and competitive hydrogen

market. Total investment is predicted to be 19.8 billion €. Joint planning endeavors also aim to facilitate the establishment of comprehensive support mechanisms to minimize investment risks. The feed-in and feed-out capacities total approximately 100 GW and 87 GW, respectively, with about 60% of natural gas pipelines converted [58] [6].

In line with the network development plan for 2022-2032, German TSOs have recently released updated hydrogen network plans for an initial national hydrogen network by 2027 and 2032, based on market insights gathered in 2021. Feedback from the market and signed Memorandums of Understanding (MoUs) indicate significant interest in hydrogen transport capacity, underscoring the imperative to establish a national hydrogen network. The modeling of the hydrogen grid highlights the necessity to accommodate significant amounts of hydrogen, including imports from neighboring countries, emphasizing the pivotal role of cross-border collaboration in meeting Germany's hydrogen requirements [6].

The 19 specific projects where Germany is involved, mentioned in [Table A.1](#), are presented and summarized in [Table C.1](#) of [Appendix C](#).

Germany's Climate Protection Act calls for net-zero greenhouse gas (GHG) emissions across all economic sectors by 2045. According to an Oxford study published in 2024 [59], heating accounted for 59% of Germany's total energy consumption in 2021, with 21.6% coming from industry and 37.4% from residential and commercial sectors. Transportation was the second-largest industry, accounting for 27% of final energy use.

This paper investigated the scenarios for decarbonizing Germany's heating sector, one of them being the transition from methane to hydrogen. Natural gas and heating oil are currently the most used sources of heating in German buildings. In 2019, 9.5 million buildings were heated with natural gas and another 6 million with heating oil, accounting for over 80% of total buildings.

It reports that out of the 550 000 km of gas distribution pipelines, 95.9% are constructed from plastic or hydrogen-compatible steel, facilitating a transition to 100% hydrogen. Additionally, the majority of grid-linked facilities, such as meters and regulators, are compatible with hydrogen. The estimated investment required for adapting gas distribution grids is approximately €30 billion, excluding costs associated with customer switching.

This study concludes that the switch from methane to hydrogen will be necessary to fulfil the country's decarbonization objectives, reinforcing the future importance of hydrogen in Germany's energy system and contributing to the prediction of large consumption in the future.

### 2.3.4 Portugal

Hydrogen represents a crucial role in Portugal's decarbonization and economic strategy for the upcoming years. As mentioned before, the country belongs to the H2med project, with CelZa (case study of this dissertation) and the Portuguese Hydrogen Backbone, both projects led by the Portuguese TSO, REN, and recently included in the EU's PCI list [49].

Additionally, REN is working on infrastructure solutions to integrate multi-production and multi-consumption in the 100% renewable hydrogen value chain within local and/or regional ecosystems. The H2 Green Valley project consists of a series of complementary projects in the

green hydrogen value chain that aim to establish infrastructure for transportation and distribution. The goal is to open the first green hydrogen hub in Sines in the end of 2025 [10].

In June 2023, Portugal published the updated Energy and Climate National Plan [60], rising the expectations towards a green hydrogen market, in order to achieve climate neutrality in 2045 (five years before Europe's target) and also to contradict the country's tradition of being an energy importer, starting to export H<sub>2</sub> to European neighbours. In this plan it is emphasized the Portuguese unique conditions to produce renewable energy, predicting an electrolysis capacity of 5.5 GW in 2030.

In order to predict the future hydrogen consumption of Portugal, it is relevant to compare it's current natural gas consumption with other European countries (Figure 2.4), where the Portuguese demand as final energy in 2022 was approximately 1700 ktoe, achieving the fourteenth place in Europe [48].

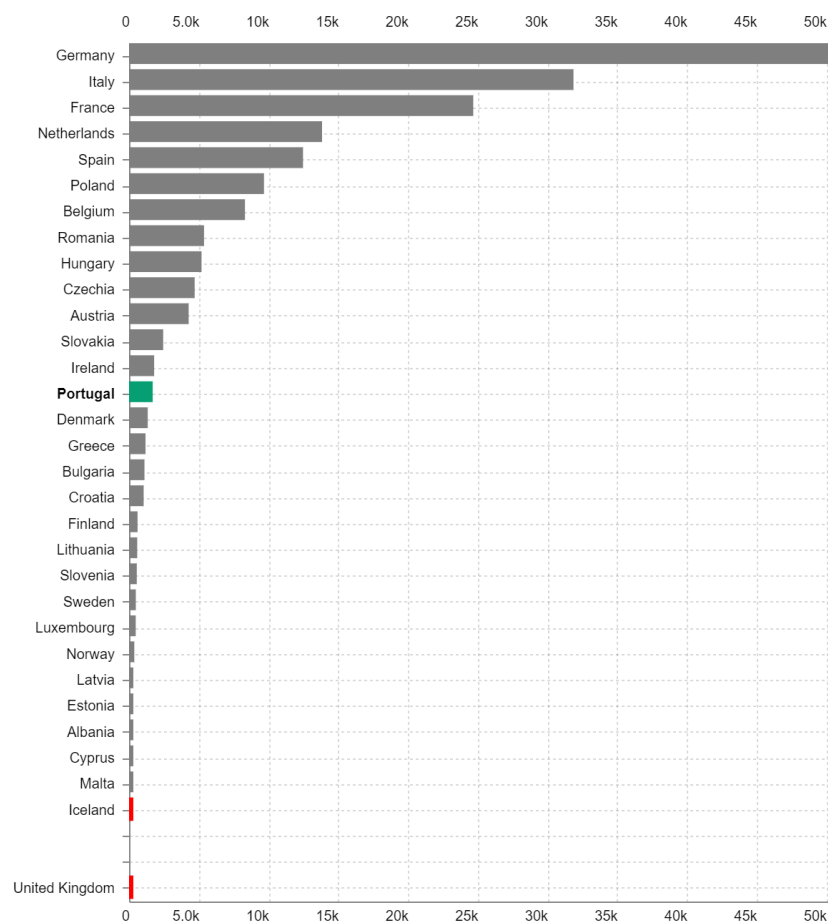


Figure 2.4: Natural gas consumption in 2022 by European countries (ktoe) [48].

### 2.3.5 Projects with Commissioning Date in 2025

There are currently seven European hydrogen pipeline projects that intend to have their CoD already in 2025:

- **Hydrogen Network Netherlands:** Gasunie is developing a national hydrogen network in the Netherlands, connecting five industrial clusters and facilitating both domestic and international hydrogen supply and demand. The network aims for initial implementation by 2025 in Rotterdam, with a focus on the northern region and connections to northern Germany. The first section of hydrogen infrastructure will be built over 30 km, ultimately spanning 1200 km, with approximately 85% of repurposed natural gas pipelines [61] [62].
- **Flow - Making Hydrogen Happen:** Intends to connect international hydrogen markets, with the conversion of the first pipeline sections in 2025, linking Lubmin to Stuttgart over 1100 km. Generation is expected to take place in Lubmin and the Baltic Sea with a 20 GW feed-in capacity, integrating various projects, such as Green Octopus Mitteldeutschland, HyPipe Bavaria and MosaHYc. By 2028, it is planned an expansion to Baden-Württemberg, one of the countries most industrialized areas, that will require 52 TWh of hydrogen by 2032, per a survey commissioned by the state's environmental government [63].
- **TH2ECO:** TH2ECO is structured into three phases to delineate the growth stages of the emerging hydrogen market. By 2025, the initial phase aims to inaugurate three electrolysis plants with a collective capacity of 25 MW in Thüringer Becken. Green hydrogen transport primarily relies on repurposing a 42-km natural gas pipeline. The pipeline connects GuD-Heizkraftwerk, the industrial park in Erfurter Kreuz, and Kirchheilingen's local natural gas grid, with unidirectional integration of natural gas rock reservoirs [64].
- **GET H2 Nukleus (H2ercules):** The GET H2 partners, which include bp, Evonik, Nowega, OGE, and RWE Generation, want to create the first publicly accessible hydrogen infrastructure. Their GET H2 Nukleus project will connect Lingen (with an electrolysis plant with a capacity of more than 100 MW at the RWE power plant) to industrial consumers in Gelsenkirchen, via a 130 km network. It aims to be the first H2 network in the regulated sector to offer nondiscriminatory access and transparent pricing. The existing gas pipelines of Nowega and OGE will be modified for 100% hydrogen transport, with Evonik additionally building a new partial pipeline between the Marl Chemical Park and the Ruhr Oel refinery bp Gelsenkirchen. It is part of the wider H2ercules project, which aims to build over 2000 km of pipelines by 2030 [65].
- **Energiepark Bad Lauchstädt:** Bad Lauchstädt Energy Park is a major power-to-gas project. Green hydrogen will be converted from a neighboring wind farm utilizing a large-scale electrolysis plant of up to 35 MW powered by renewable electricity. The green hydrogen, temporarily stored in a salt cavern specifically designed for this purpose, can be supplied into the hydrogen network of the chemical sector centered in central Germany, via a dedicated 25 km gas pipeline of ONTRAS, and used in the future for urban mobility solutions. It would be the first H2 cavern in continental Europe, as well as the world's first facility for storing green hydrogen. Trial operation will start in early 2025 and from the third quarter of

2025 the pipeline is scheduled to transport green hydrogen from the Bad Lauchstädt Energy Park for use in the TotalEnergies Refinery Central Germany [58].

- **HyPipe Bavaria – The Hydrogen Hub:** By 2030, there will be a hydrogen network that expects to run from Austria to the gates of Munich and further via Ingolstadt towards Baden-Württemberg. From 2025, the first pipeline section with a length of 14 kilometres will be commissioned in the Bavarian chemical triangle, followed by further regional project building blocks near Ingolstadt [66].
- **H2 Green Valley:** In Portugal, REN is working on infrastructure solutions to integrate multi-production and multi-consumption in the 100% renewable hydrogen value chain within local and/or regional ecosystems. The H2 Green Valley project, located in Sines, is led by REN Gas, which was awarded for funding from the Recovery and Resilience Plan. The consortium also comprises REN Gasodutos, Dianagás (Floene), Bosch Termotecnologia, Hylab, Instituto Superior Técnico and the International Iberian Nanotechnology Laboratory. The project consists of a series of complementary projects in the green hydrogen value chain that aim to establish infrastructure for transportation, storage, and distribution. The goal is to open the first green hydrogen hub in Sines by December 31, 2025 [10].

### 2.3.6 Financial Challenge

Upfront CAPEX (Capital Expenditure) and DEVEX (Development Expenditure) expenses are crucial, but merely a part of hydrogen network development. The EHB expects two distinct financial phases: the market ramp-up, which has limited demand and capacity bookings, and the mature market phase, represented in Figure 2.5.

During the ramp-up, difficulties regarding investment recovery may occur, preventing full revenue allowed by regulators under a largely similar application of natural gas infrastructure-based existing regulations. Operational revenue is critical for capital recovery, but low tariff revenue due to restricted bookings or uncertain user willingness to pay poses challenges. Furthermore, the ramp-up period may exceed the timeframe for operators to recover lost revenue under current laws. These financial dynamics highlight the complexities of transitioning to a hydrogen-powered economy [7].

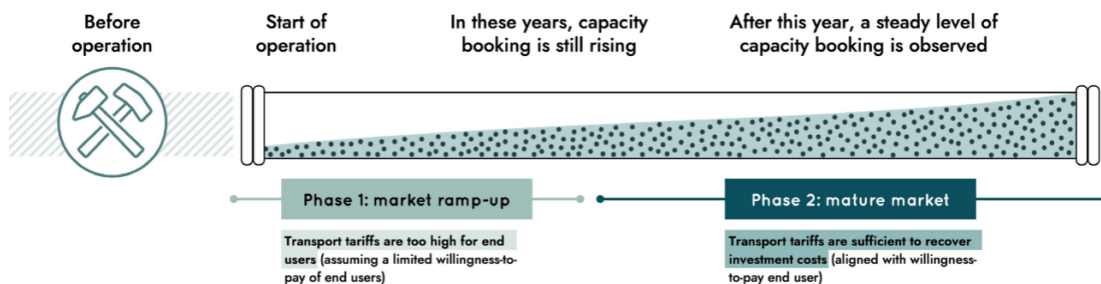


Figure 2.5: Schematic representation of the EHB's main financial phases [7].

## Chapter 3

# Methodology for the Implementation of Hydrogen Infrastructures

The present section of this dissertation explores the methodology developed to guide the future infrastructure transition from fossil fuels to renewable gases, in this case, to design and optimize 100% hydrogen networks. The methodology created and carefully explained throughout this chapter will be later applied to a real-life case study in [chapter 4](#).

There are many optimization methods applied to the design of gas pipeline networks, as referred in the literature review performed. The three main points where this development sets itself apart from the work already existing are the following:

- Considering the financial challenge outlined in [chapter 2](#), the methodology must account for the anticipated evolution of energy systems and markets. Failing to do so would result in planning and optimization processes that only address the initial ramp-up phase, thereby generating data that is inadequate for long-term strategic planning. On the other side, disregarding this initial challenging phase would result in an overly optimistic design.
- Given the great uncertainty surrounding the use of such hydrogen infrastructure, particularly in Europe, the optimization has to take into account the greatest number of possible market development outcomes. This uncertainty involves conducting sensitivity analysis for critical evaluation of the results, while other times it requires establishing certain assumptions and optimizing for the worst-case scenario (e.g., regarding production sites). A primary concern was to establish a foundation for future enhancements and adaptations of this methodology.
- Although the ultimate goal is to develop a mature methodology that can be generalized to different countries, the implementation of such requires consideration of specific aspects of the project location's economic and social development. These aspects, explored in this chapter, can serve as examples of the types of information that may be useful in different contexts.

The main factors that contribute to the developed methodology are listed in [Figure 3.1](#). As a market-driven commodity, H<sub>2</sub> is highly dependent on consumption existence, so this approach intends to quantify demand through diverse scenarios. CAPEX and OPEX (operational expenditure) involve several variables but ultimately will be the decisive factors for financial viability, while the project's implementation also depends on the environmental impact it can provide. In addition, scalability plays a critical role in this methodology due to the financial challenges that H<sub>2</sub> infrastructures will have to face in the early stages of market establishment.

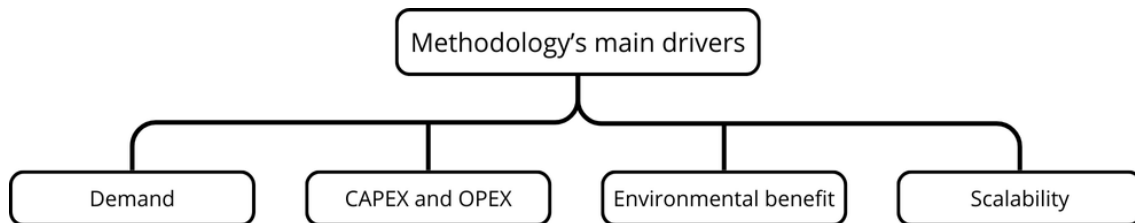


Figure 3.1: Main drivers of the developed methodology.

### 3.1 Mapping of the National Regions Decarbonization Potential

The initial phase of this methodology involves mapping the consumption of energy sources that could theoretically be replaced by green hydrogen across various national regions. Such a replacement would significantly contribute to the decarbonization of the energy system, aligning with the 2050 target for climate neutrality in Europe. The consumers' compatibility with 100% H<sub>2</sub> is out of the scope of the current thesis but is indeed another research topic to be addressed in future works, namely within the several market segments. The consumption data for this phase must be highly detailed and sourced from reliable government or reputable corporate entities.

#### 3.1.1 Objectives and Motivation

TSOs like REN play an intermediate role in the energy market, transporting the commodity (in this case, hydrogen) from the production sites to the consumption demand locations. Given the critical importance of demand in this kind of infrastructure planning, and adding to the recently renovated interest in hydrogen (with the green color immensely associated to it), the initial potential consumptions can be critical to the viability and survival of projects like the EHB. There will only be transport if there is production, and production will surely need at least interest from the market to indicate possible future consumption (in other words, buyers or offtakers).

This ramp-up phase already mentioned is one of the motivations for this kind of approach, with the system design starting with an analysis of the market. That is why several TSOs in other countries have developed the mentioned CEIs, to engage the market and explore the real possibilities for project implementation.

Although the consumption data already exists, there are three main reasons that encouraged these mappings:

- The data available is very raw. It is indeed very useful to search specific data, but it fails to give a sense of consumption by region. For such infrastructures, where location is critical, the quick and easy visualization of possible demand can be very useful. This spatial visualization also helps identify trends and opportunities.
- Another important aspect was to aggregate different kinds of energy sources (like propane and butane) and different energy sectors (to exclude domestic consumption, for example, due to technological uncertainty). Although the existing consumption data available already allows the consulting of a substantial amount of aggregated data, there is a need to identify the relevant energy sources and sectors that may accelerate the conversion of the gas industry through the implementation of renewable gases.
- Finally, this mapping had a decisive role in the subsequent optimization. In order to use the consumption data to design the network, this information had to go from a spreadsheet to a map, combining it with geographic data.

### 3.1.2 Consumption Mapping Algorithm

To evaluate the decarbonization potential of national regions and develop the corresponding maps, it is necessary to collect and integrate consumption data with geographic information.

As mentioned previously, this information should be sourced from reliable entities. Regional boundaries can typically be obtained from official government data, specifically GeoJSON files containing the country's geographic delimitations. GeoJSON is a file format for encoding geographical data structures using JavaScript Object Notation (JSON). Consumption data should be input via Excel files, with information disaggregated by region and sector.

Using these inputs, an algorithm was developed in Python. The detailed process for the Consumption Mapping Algorithm (CMA) is illustrated in the flowchart below (Figure 3.2). Geographic data is retrieved using an API (Application Programming Interface) provided by Google Maps to obtain coordinates based on location names.

## 3.2 Planning and Optimization of 100% Hydrogen Networks

The second phase of this approach consisted in the actual planning optimization process. The developed methodology is divided into two algorithms, both created using Python. The first one is a Decision Support System (DSS) that is later integrated into the second procedure, a Genetic Algorithm (GA). These algorithms comprise over 2,000 (two thousand) lines of code and will be carefully detailed in this subsection.

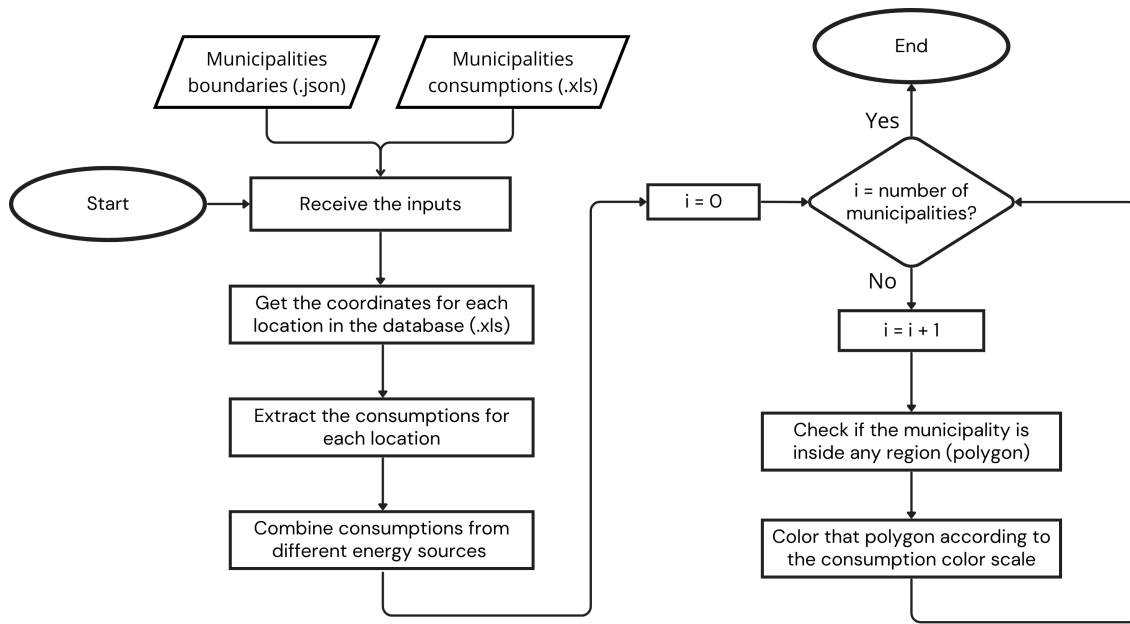


Figure 3.2: Flowchart of the Consumption Mapping Algorithm (CMA).

### 3.2.1 Objectives and Motivation

The main purpose of this procedure was already pointed out, as were its major differences from existing approaches. The division into two algorithms to execute the adaptation of planning methods that support the mentioned gas transition had the following crucial motivations:

- **DSS:** The mapping described in [section 3.1](#) has all the advantages identified. Despite that, it is missing an important feature in order to be integrated into the optimization: identifying the relevant consumptions for analysis. The purpose of this model is to allow the maximum generalization of this methodology by receiving different inputs and assumptions and providing the desired consumption scenario, based on the available data.
- **GA:** The selection of this specific algorithm for optimization had several reasons. First of all, it intends to be a proof of concept in the sense that we live in a world increasingly dominated by artificial intelligence (AI) and there is an urgency to go beyond the analytical methods, especially in complex and multi-disciplinary problems such as network planning. Due to its relevance, this reflection is going to be deepened in [chapter 5](#). Secondly, meta-heuristic optimization is ideal for this kind of problem, with immensely large search spaces and a considerable number of assumptions. Lastly, the versatility of this search algorithm ensures the viability of implementation in future adaptations.

### 3.2.2 Optimization Process Description

The complete optimization structure integrates both algorithms, utilizing the decision support system to supply the necessary consumption scenarios for optimizing the network through the genetic algorithm. This structure is summarized in the flowchart of [Figure 3.3](#).

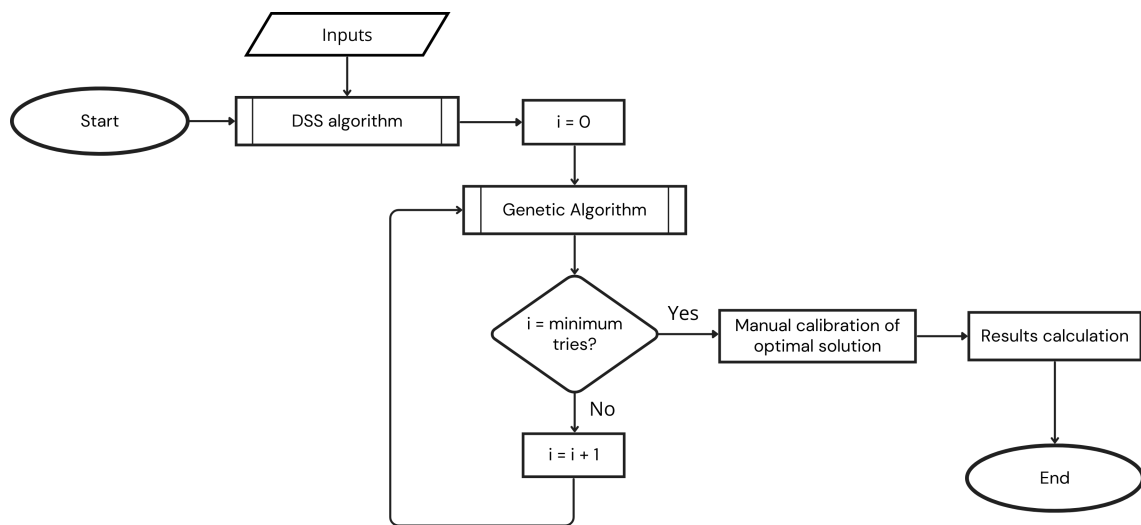


Figure 3.3: Flowchart of the general optimization structure.

As shown, the genetic algorithm is intended to be used a minimal number of times before proceeding to manual calibration and result calculation. This additional step reduces the probability of finding a sub-optimal solution, a common occurrence in meta-heuristic optimization. The following manual calibration allows the user to search near the found solution, identify the local optimum, and thereby increase the likelihood of finding the optimal solution.

This structure should be applied in the early stages of project planning, allowing for the prior definition of assumptions and scenarios to be analyzed. Following this approach for each scenario leads to identifying each case's optimal parameters for the network. Using that parameters it is possible to calculate several important project variables, such as CAPEX, decarbonization impact, expansion capacity, etc. The detailed planning methodology is described in the subsequent subsections, separately for the DSS and the GA.

### 3.2.3 Decision Support System (DSS)

The Decision Support System has a structure similar to the CMA, leveraging some of the work already completed. Specifically, the summarization of data, extraction of coordinates for each location, and the respective combination of consumptions from different sources are utilized in the initial part of this algorithm. However, instead of using regional boundaries as input, the DSS accepts KMZ files with the network's geographic drawings. The flowchart in Figure 3.4 represents the process followed by the algorithm.

The primary difference between the two algorithms lies in identifying the relevant consumptions for the projected network by generating an "area of influence" around it. This area is essentially a buffer designed to maintain a specific distance between the pipeline and the buffer boundaries. These boundaries indicate the maximum distance to consider when checking for consumptions, assuming the network can absorb consumption within that range.

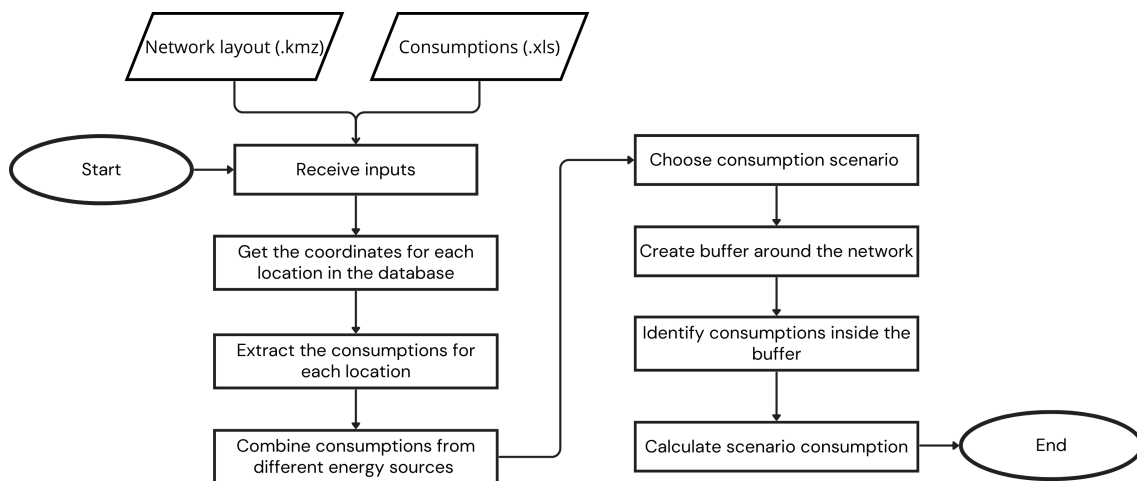


Figure 3.4: Flowchart of the DSS algorithm.

Ultimately, this algorithm processes the network layout and consumption files, prompts the user to select a scenario (e.g., export capacity, network area of influence, or variations of the base scenario), and calculates the consumption for that scenario. Moreover, the calculation identifies the consumption per pipeline section using geographical coordinate restrictions.

In order to systematize the methodology, an example is going to be analyzed step by step.

### 3.2.3.1 Example

For demonstration purposes only, a random network was created in a KMZ file format. This network connects two cities in Portugal (Porto and Chaves). Using the structure previously described, the network routing along with consumption files (in this case municipalities consumption data regarding natural gas, propane and butane) obtained from the Direção-Geral de Energia e Geologia (DGEG) data base [67], referring to the year of 2022, are provided as inputs.

Furthermore, a scenario is chosen with the following indications:

- No exportation (since there is no connection between Portugal and Spain);
- Area of influence of the network is considered to be 5 km;
- The hydrogen consumption corresponds to the conversion of all the consumption of natural gas, propane and butane in the regions inside the buffer.

With this information the algorithm provides the outputs shown in [Figure 3.5](#) and [Table 3.1](#). The first one represents the buffer created around the pipeline, while the second is the combination of the consumptions from different energy sources for the corresponding municipalities.

An important aspect to mention is the simplification used when identifying the consumptions within the buffer. The algorithm developed considers only the municipalities where the center of the city's coordinates fall inside the buffer. A more precise algorithm could allocate a percentage of the consumption proportional to the area of the region within the buffer. This simplification

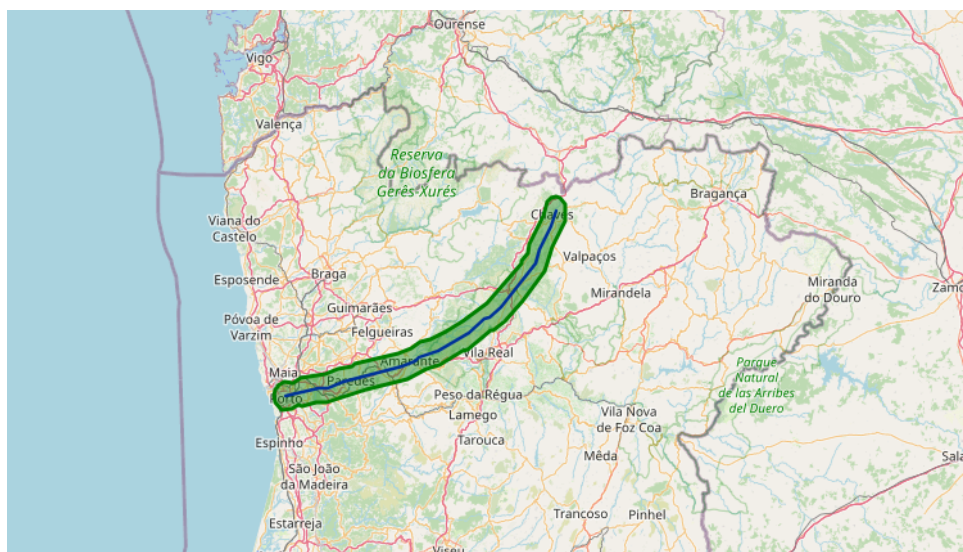


Figure 3.5: Area of influence generated for fictitious network.

Table 3.1: Consumption data obtained for the example used. Unit: [GWh].

Municipality	Total consumption	Domestic consumption	Total consumption w/o domestic
<b>Amarante</b>	52	28	24
<b>Chaves</b>	55	25	30
<b>Paredes</b>	57	29	28
<b>Penafiel</b>	69	23	46
<b>Porto</b>	714	190	524
<b>Valongo</b>	68	39	29
<b>Vila Nova de Gaia</b>	856	179	677
<b>Vila Pouca de Aguiar</b>	8	4	4
<b>Total</b>	1879	517	1362

is based on the premise that this methodology serves as a starting point for the project, thus an assumption. In practice, the inclusion of these industrial consumers in the grid connection will be analyzed on a case-by-case basis. That is the intention of the mentioned Calls for Expression of Interest (CEIs), done by several TSOs across Europe.

### 3.2.4 Genetic Algorithm

The Genetic Algorithm (GA), discussed in [chapter 2](#), is an evolutionary search algorithm inspired by Darwin's theory of natural selection, and is considered a type of artificial intelligence (AI). This algorithm operates on the principle that stronger elements have a higher probability of survival, while weaker ones are progressively eliminated [46].

In each generation, a population of individuals represents points in the search space and potential solutions. These individuals are encoded as character strings, similar to chromosomes, which is why the algorithm is termed "genetic." Each individual is assigned a score based on the fitness

of its solution to the problem, analogous to assessing an organism's effectiveness in competing for resources. The fittest individuals are more likely to reproduce, creating offspring that inherit traits from both parents. Conversely, less fit individuals are less likely to be selected for reproduction and eventually die out [45].

GAs draw a simplified analogy to biological systems, using terms such as chromosomes, genes, and mutation to describe their processes. In biology, organisms consist of cells containing chromosomes made up of DNA, which are divided into genes that encode specific proteins, each gene located at a specific position on the chromosome. Diploid organisms, like humans, have paired chromosomes, while haploid organisms have unpaired chromosomes. In diploid sexual reproduction, gene recombination forms haploid gametes, which combine to restore the diploid chromosome set in offspring [45].

GAs often mimic this haploid sexual reproduction, where offspring inherit a single version of each gene from their parents and are subject to mutations, introducing variations analogous to nucleotide sequence changes in biological DNA. In this case, a chromosome typically represents a candidate solution for the problem. Genes encode particular variables of the chromosome, while alleles are the possible elements of the alphabet that can constitute a gene. For instance, in binary encoding, a gene would be a sequence of zeros and ones, with an allele being one bit (0 or 1) [45].

GAs intelligently explore random searches by using historical data to guide the search towards higher performance areas. These algorithms generate high-quality solutions through multiple iterations. A major advantage of GAs is their independence from derivative information, making them broadly applicable, fast, and efficient. They can handle continuous functions and multi-objective problems, providing a list of good suggestions rather than a single solution, which is often beneficial in practical scenarios.

However, they are not suitable for all problems and do not guarantee optimal solutions. As a stochastic method, it risks converging to suboptimal regions, especially when the fitness landscape's amplitude decreases. Despite this, GAs can often tackle more complex optimization problems comparing with traditional math-based algorithms, so the method used should be adapted case by case.

The flowchart below (Figure 3.6) systematizes the general structure of the GA created, and the algorithm is further detailed.

### **3.2.4.1 Formulation of the problem**

The first step (as in any optimization process) is to define the problem. The main purpose of hydrogen networks is, as previously mentioned, to allow the transition from fossil fuels to renewable gases, aiming to help the environment and achieve climate neutrality. However, the design of the network has to take into account other factors, namely the financial viability of the project. For these two reasons, the optimization objectives identified were the following:

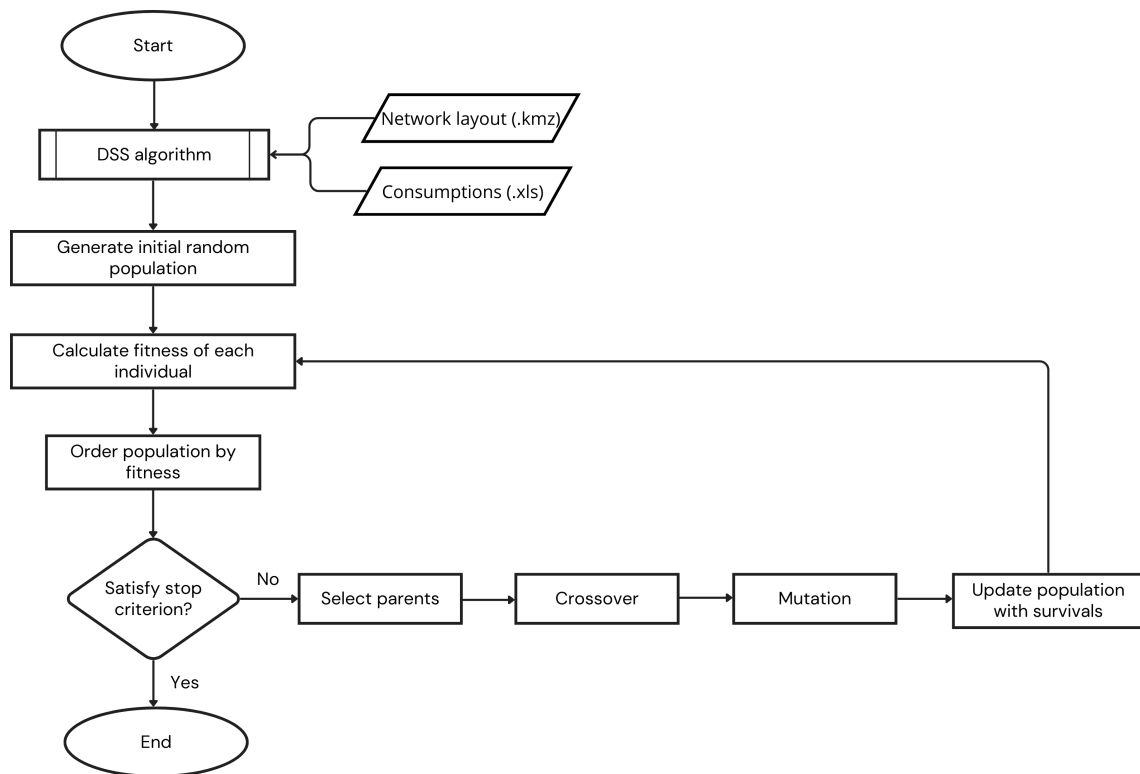


Figure 3.6: General flowchart of the Genetic Algorithm.

1. **Maximizing the expected decarbonization impact:** The existence of a hydrogen transport network allows for a direct conversion of major consumptions of other energy sources, namely natural gas and petroleum derivatives;
2. **Minimizing the investment required:** CAPEX is a critical factor that may affect the viability of any project. If it is too high, TSOs will not be encouraged to take action after the Financial Investment Decision (FID);
3. **Minimizing operation costs:** OPEX is another decisive factor for project implementation, for the same reasons mentioned for CAPEX;
4. **Minimizing transport costs:** Transport costs, charged through a network utilization tariff, will have a significant impact on the final commodity price. If it is too high, the conversion of fossil gases will not pay off for consumers, and demand will be insufficient to encourage production;
5. **Account for future increase in consumption:** According to what was deepened before, the hydrogen ramp-up phase is expected to present a challenge for TSOs, whose focus must be to minimize this impact by reducing the duration of this stage. That can only be achieved with increased consumption over time, as demand-supply dynamics adjust to form a mature H<sub>2</sub> market. To support that increase, the network has to be prepared for that expansion. Furthermore, the increase in clients will generate a higher return for operators.

A rather common purpose of pipeline optimization found in the literature (subsection 2.2.5) is to optimize the route's location. In this approach, that was not considered for two reasons: most hydrogen networks that are projected have a substantial portion of the grid expected to be the result of natural gas pipeline repurposing; there is a complex part of the problem that is related to legislation and that has a considerable variation between nations. Therefore, to assure methodology generalization and simplify the process, this feature was neglected, although it should be considered in future adaptations.

By analyzing the five identified optimization objectives, it is possible to observe both redundancies and conflicts. To maximize the decarbonization impact, future expansion must also be assured. Higher consumption translates to greater environmental benefits, making these two aspects intrinsically linked. Similarly, minimizing investment and operation costs will inherently lead to a lower tariff, as the first two objectives contribute directly to the third.

However, the reverse might not hold true. Minimizing the tariff could involve either reducing costs or increasing consumption, as illustrated in Equation 2.18. Increasing future potential consumption necessitates higher expansion capacity, which, in turn, raises costs.

On one hand, redundant scenarios simplify the formulation of the problem. On the other hand, conflicting objectives require finding an optimal trade-off solution that addresses all cases.

Considering this, the formulation of the problem is as follows:

Minimize the function

$$f(x) = t_1(x) + t_2(x) - h(x) \quad (3.1)$$

Subject to

$$g_1(x) \geq k_1 \wedge g_2(x) \leq k_2 \quad (3.2)$$

Being

$$t_1(x) = \frac{[\text{CAPEX}_1(x) + (\text{OPEX}_1(x)/\text{year} \times N/2)]/2}{E_{r1}} \quad (3.3)$$

$$t_2(x) = \frac{\text{CAPEX}_2(x) + (\text{OPEX}_2(x)/\text{year} \times N/2) + t_1(x) \times E_{r1}}{E_{r2}} \quad (3.4)$$

$$h(x) = \max_{i \in [1:n]} (A_i \times k_2) \quad (3.5)$$

$$g_1(x) = \min_{i \in [1:n]} s_i(x) \quad (3.6)$$

$$s_i(x) = \left[ \frac{(\dot{Q}_{\text{net,in}} + \dot{W}_{\text{net,in}})}{\dot{m}} - \left( \check{u}_{\text{out}} - \check{u}_{\text{in}} + \left( \frac{p}{\rho} \right)_{\text{in}} + \frac{V_{\text{out}}^2 - V_{\text{in}}^2}{2} - g(z_{\text{out}} - z_{\text{in}}) \right) \right]_i \rho_{\text{out},i} \quad (3.7)$$

$$g_2(x) = \max_{i \in [1:n]} \left( \frac{\dot{m}_i}{\rho_i A_i} \right) \quad (3.8)$$

where  $x$  is an array with all the relevant network parameters, being optimization variables or not ( $x$  constitution is deepened next), thus representing the phenotype.  $t_1(x)$  and  $t_2(x)$  are functions that provide the network utilization tariff in an initial moment and after half the life expectancy of the pipelines, respectively. Both equations (Equation 3.3 and Equation 3.4) are based on Equation 2.18, with the total cost of the first phase (as it includes the initial investment) divided between both tariffs. The function  $h(x)$  calculates the maximum consumption that the network can support. Generally, it would give  $\dot{m}_{max}/\rho$ , for every point in the network. If the flow is considered incompressible, this fraction becomes a constant and is equal to the maximum volumetric flowrate of the network, where  $n$  is the number of different sections of pipes (considering a different section each time the pipeline changes diameter or there is a connection point between two or more pipes).

Minimizing  $f(x)$  allows the optimization to find the **optimal trade-off point, where there are minimum tariffs with maximum network capacity**. As it is explained next, when calculating fitness, this function may require adjustments depending on the units utilized to adjust the weights of each function ( $t_1(x)$ ,  $t_2(x)$ , and  $h(x)$ ) in the evaluation. The subdivision of the tariff intends to reflect the evolution of the market and the dichotomy of capacity increase and tariff decrease in the future.

Regarding constraints (Equation 3.2),  $k_1$  and  $k_2$  are, respectively, the minimum pressure and maximum velocity allowed.  $g_1(x)$  gives the minimum exit pressure between all sections, with equation Equation 3.7 being a reformulation of Equation 2.12. This equation can be used to calculate the exit pressure in a general case, both for compressible and incompressible flows. In reality, most cases will use Equation 2.13 as the flows can be considered incompressible, that may even simplify to Equation 2.14 under the conditions specified.

The function  $g_2(x)$  calculates the maximum velocity of the network, both for compressible and incompressible flows, with the maximum value of  $\dot{m}/\rho$  in each section. In reality, for incompressible flows, that fraction is going to be the constant volumetric flowrate for each section. In addition, other constraints could be included in future adaptations, for example, maximum temperature or minimum network flexibility.

A very important final note regarding the objective function  $f(x)$  is that the tariffs it considers are **not the same tariffs that would be charged to consumers**. In a more objective sense, they should actually be defined as LCOHT, the Levelized Cost of Hydrogen Transport, since they are calculated in order to recover the investment and operation costs. Similarly, the subdivision of **the tariff does not reflect the variation of monetary charges to the customers and not even the variations of the LCOHT**, since the variation in consumption and costs are continuous. Nevertheless, it provides a check-up point in two different stages of the project, allowing for a future-oriented consideration integrated into the optimization.

### 3.2.4.2 Representation of the Population (Search Space)

In the context of GAs, utilizing the biological terminology explained, chromosomes represent candidate solutions to optimization problems, with genes encoding specific elements of these solutions. Typically, GAs use haploid individuals - each with a single chromosome - to simplify the mathematical representation of solutions. The genotype of an individual in a GA refers to the configuration of bits within its chromosome, while the phenotype denotes the real characteristics of the individual in the reality into which it is inserted [45].

As is usual in GAs, this algorithm does not operate directly on the actual solutions in the search space (phenotype). Instead, it works with the encoded representations, or genotypes, which facilitate the genetic operations required for the algorithm's progression. This separation between genotype and phenotype is fundamental, as it allows for more flexible and efficient manipulation of solutions. The process of encoding involves translating the design variables and the search space into a suitable code format that the GA can handle.

In this case, the population is a random generation of possible solutions. Each solution, or individual, corresponds to a set of network parameters. The parameters that can be selected as optimization variables in this approach consist in the different **new-pipeline diameters** and **compression stations** (location and capacity).

The genotype representation of the chromosome is the following:

$$[(D_1; D_2; \dots; D_z); (S_1; S_2; \dots; S_n); (C_1; C_2; \dots; C_n); (FS_1; FS_2; \dots; FS_n); (FC_1; FC_2; \dots; FC_n)]$$

where  $z$  is the number of new-pipeline diameters and  $n$  is the number of pipeline sections, as already mentioned.  $D$  is an integer that represents the value of the diameter,  $S$  stands for "section" and is a string that represents the pipeline section where the compression station is located and  $C$  is the respective capacity, or compression power, represented as integer. These parameters are represented in the genotype as lists and correspond to the initial network parameters.  $FS$  and  $FC$  represent the future compression stations that may be added until the second moment of evaluation, at half the life expectancy of the network.

This representation allows for the tariff division in two moments, as described in the formulation of the problem, taking into account the variation in compression power that may be required and the additional costs it can represent.

An important consideration is that the individuals do not take into consideration the exact compression stations. Instead, as a simplification method, it **is considered the compression power provided by pipeline section**. In practice, this power can be supplied by one or more compressors. Thus, this parameter aims to approximate the potential impact on total costs resulting from increased consumption, facilitating a more balanced evaluation of solutions. The precise sizing of compression solutions should be addressed in other stages of the project or, alternatively, incorporated into future adaptations of this methodology.

The major difference between the genotype and the array  $x$  previously mentioned is that some network parameters included in  $x$  are not considered optimization variables, such as repurposed

pipeline diameters, pipe lengths, infrastructure operational lifespan, injection pressures, etc., as those are fixed variables.

Figure 3.7 represents one possible search space, with  $z$  equal to 1 and  $n$  equal to 2, and an example of a possible solution (genotype) within that search space.

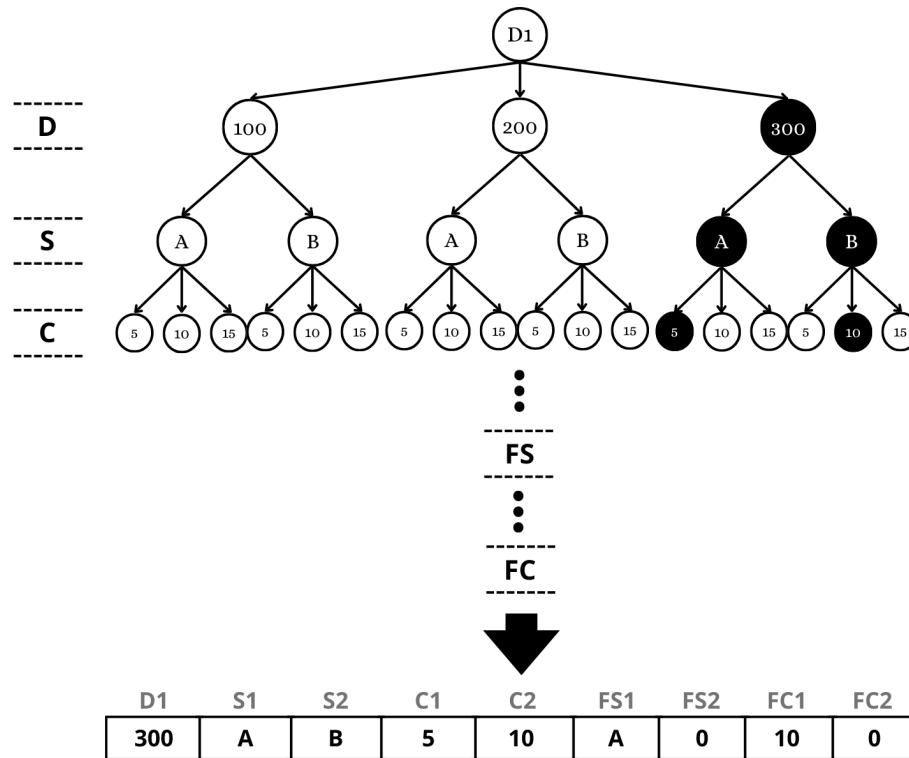


Figure 3.7: Search space and example genotype for a simplified network with  $z = 1$  and  $n = 2$ .

The chromosome of the individual is represented through its genotype, as shown in the figure, while genes can be identified as  $D_1, S_1, S_2$ , etc., with alleles being 300, A, B, etc.

In this simple case, it is possible to observe that the search space involves 2,883 different genotypes. However, excluding genotypes that represent the same real solution (phenotype), that number reduces to 768 unique individuals, which in terms of computational effort is not much.

However, another example can be analyzed to understand how easily the number of solutions can reach an enormous volume. If we had two new-pipeline diameters ( $z = 2$ ), ten options of diameter (10 standard values from 100 millimeters to 1 meter), three different sections, and 30 options for compression power, the search space would increase to an extraordinary number of  $3.2 \times 10^{12}$  different genotypes (calculations in Appendix D). To put this in perspective, 3 trillion seconds is approximately 100,000 years. **If we started checking solutions at a rate of one per second at the dawn of human civilization, we would still be checking today and for thousands of years to come.** This calculation reflects the complexity that such a planning methodology can involve and the necessity of using meta-heuristics. Appendix D shows the developed generic formulation that allows the calculation of the size of the search space for any optimization algorithm that uses this kind of solution representation.

In this methodology, a mixed-encoding representation is utilized, comprising both numerical and categorical (string) values. Such a representation is particularly useful in scenarios where the problem involves a combination of different data types. The numerical values represent continuous parameters that can be directly optimized (diameters and compression power), while the categorical values encode discrete options, in this case locations, allowing the GA to explore various configurations effectively. Each location option should be linked to one of the sections.

Using this mixed encoding strategy, the GA can efficiently explore and exploit the search space. The flexibility of mixed encoding allows for a comprehensive representation of real-world problems where different types of variables interact. By ensuring that each genotype maps to a valid phenotype, the algorithm can robustly evolve solutions that meet the desired performance criteria, making this approach suitable for these types of applications. However, binary encoding, which is the most common type of representation in genotype space, is also viable and (although less intuitive in the decoding process) could facilitate the genetic operations.

### 3.2.4.3 Merit Function

A critical part of this type of algorithm is the evaluation of individuals according to their performance, quantifying their relative value in the context of a population. The objective function,  $f(x)$ , defines the goal of the optimization process, measuring performance with respect to a particular set of gene values, independent of any other chromosome.

On the other hand, the merit (or fitness) function transforms the objective function into an allocation of reproductive opportunities, with respect to other members of the population. Its purpose is to assign a score to each individual.

In this case, the fitness function is characterized as follows:

$$Mer(x) = - [100 \times (t_1(x) + t_2(x)) - h(x) + \Gamma(x)] \quad (3.9)$$

Equation 3.9 shows the normalization process used in order to minimize the function, negating the objective function to make the individuals with lower values of  $f(x)$  the ones with higher scores, and vice versa.

The penalty function  $\Gamma(x) \geq 0$  is a constraint term related to the violation of the constraint of the problem  $g_1(x)$  and provides a penalty for all sections proportional to the differences between the minimum pressure in the network and the minimum pressure allowed  $k_1$ .  $g_2(x)$  is not included because the formulation of the algorithm does not allow for its violation, limiting the capacity using the maximum velocity  $k_2$ .

The function also uses an explicit remapping, multiplying  $(t_1(x) + t_2(x))$  with 100 to adjust the proportions of the function  $f(x)$ . The purpose of this modification is to increase the efficiency of the evaluation at the final stages of evolution, when the population is reaching convergence and the range of fitness values is reduced. The typical values of  $(t_1(x) + t_2(x))$  will be less than the unit (using €/kgH<sub>2</sub>), while the values of  $h(x)$ , if calculated in tonnes of hydrogen per year, are several times higher. That discrepancy can generate a tendency to prefer solutions with higher capacities

rather than lower tariffs, thereby missing the optimal point. The multiplication factor adjusts this difference, setting the typical values of both functions to the same order of magnitude.

To understand the effectiveness of this evaluation, three scenarios are going to be considered:

- **A network with minimal investment, designed to match initial low consumption needs without compression:** In this first case, the initial investment is very low due to the requirement for smaller diameters and the absence of compression. Consequently, the initial tariff for hydrogen transport,  $t_1(x)$ , will be low. However, the capacity for increased consumption will be severely limited, even with substantial compression power (that would also increase the costs and, inherently,  $t_2(x)$ ), due to the small pipeline size. Therefore, this solution would score low and is considered suboptimal.
- **A network with substantial expansion capacity:** This scenario would also yield a relatively low score in the fitness function, as the significant capacity would necessitate considerable investment. Given the low initial consumption, the initial tariff would be excessively high. This evaluation capability helps reject projects that are not viable during the ramp-up stage, while steering the optimization towards solutions with more realistic expectations for future consumption.
- **A network with moderate expansion capacity, requiring relatively smaller investment compared to the previous case:** This scenario represents the optimal trade-off. Both tariffs would not be excessively high due to the reasonable investment. The low initial consumption would be balanced by the absence of the need for compressors, while future compressor requirements would be offset by increased consumption.

#### 3.2.4.4 Genetic Selection

Darwin's theory of evolution states that the best should survive and reproduce to generate offspring. As a consequence, it is required to use selection methods to identify the individuals for reproduction or survival, usually called the *Mating Selection Mechanism* (MSM).

In this case, a hybrid solution of common selection methods was developed to create a balance between exploration and exploitation, a common concern across the different genetic operations of the algorithm. It is of paramount importance to assure the optimal trade-off between diversification and intensification, assuring the best solution is found without premature convergence.

This selection method uses both proportional and sort-based selection to choose individuals from the population, inserting them into a pool where parents will be chosen randomly (the detailed algorithm that selects individuals into a pool is shown in [Appendix E](#)). An important optimization parameter will be the probability of selection being performed by each method. Proportional selection is done via roulette wheel selection, while sort-based selection is done via tournament. Both methods are described below, along with their respective pros and cons.

- **Roulette wheel selection:** This method can be illustrated by an actual roulette wheel, where each individual has a circular sector whose size is proportional to their fitness. Chromosomes with higher merit values will be selected more often because they occupy more space. In this case, since the merit function can have negative values, it is transformed so that all values are positive, and the probability of selection for each individual can be calculated using:

$$P(x) = \frac{C_{max} + Mer(x)}{\sum_{j=0}^{N_{pop}} [C_{max} + Mer(x_j)]} \quad (3.10)$$

where  $N_{pop}$  is the population size and  $C_{max}$  is a scalar chosen appropriately to make the value of the merit positive. This proportional selection alone can make a good individual reproduce many times, destroying the diversity of the population rapidly over the generations and causing premature convergence.

- **Tournament selection:** In this approach, pairs of individuals are randomly selected from the population and those with greatest fitness are copied to the mating set. This model may be more similar to what happens in nature, giving rise to competition between individuals. Depending on the size of the tournament, this method can slow the convergence process while increasing the efficient exploration of the search space.

### 3.2.4.5 Crossover

After using MSM, two more mechanisms are required: the *Offspring Generation Mechanism* (OGM) and *Offspring Selection Mechanism* (OSM). These are used in the crossover operator, which consists in the recombination of genetic material from both parents to form a child, and are detailed below.

There are two crucial characteristics regarding the crossover operator: heredity, since it must ensure the presence of genetic material from both parents in the offspring, and validity, because the operator must produce valid solutions.

- **OGM:** The generation mechanism involves choosing random parts of both parents. This random selection is done in blocks to ensure the validity of offspring since the algorithm uses mixed encoding to generate the genotypes, as mentioned. For example, location lists can only be recombined with other location lists from either phase (*S* or *FS*). The same happens for the rest of the lists present in the genotype, that were mentioned before.
- **OSM:** In this methodology, all the offspring generated are included in the future generation, replacing the worst individuals. This approach is based on nature's dynamics, where offspring, independently of their abilities, are inserted into the population and have to compete with the best individuals for survival.

#### 3.2.4.6 Mutation

Genetic mutation is the process responsible for random changes in the genetic code of biological creatures. Similarly, the mutation operator inserts some randomness into the search to allow an efficient exploration of the search space. As mentioned in [45], *locality* is the most important feature in this type of operator, ensuring that small perturbations in the genotype also result in small changes in the phenotype.

First of all, to allow this diversity, the mutation operator developed is not only applied to offspring, as it can operate directly in the population, with a certain probability to be defined as an optimization parameter. Making the analogy with nature, there is also evidence that this process occurs in biological creatures, whose genetic code can be altered during their life course, according to their experiences and social interactions. This is a deepened subject in GAs' variation called the Memetic Algorithm (not explored in the context of this work).

Another feature of the mutation operator that is based on this principle is a random local search that was developed to improve the intensification of the algorithm in searching for fit individuals around a neighbourhood of solutions. Nevertheless, this local search should have a low probability of occurring since it significantly damages the efficient exploration capacity of the search.

Apart from these details, the general mutation operator used utilizes a number of different techniques to deal with mixed encoding. In synthesis, it randomly selects one of the following options:

- Generate a new random value for one new-pipeline diameter;
- Change the number of sections that use compressors and adjust the locations and capacities accordingly;
- Randomly change locations;
- Replace compression power with a new randomly generated value.

#### 3.2.4.7 Stopping Criteria and Results Tuning

This methodology suggests employing a common stopping criteria in GAs, which involves halting the process once a specified number of generations have passed without any improvement in the fittest individual. This threshold is another adjustable algorithm parameter that should, like the other parameters, be fine-tuned to optimize the method's performance.

Often, this adjustment involves a degree of trial and error due to the difficulty in precisely determining the optimal parameters for the algorithm's performance.

Finally, it is strongly advised to conduct a manual local search after the algorithm has converged. This involves adjusting and fine-tuning the results to identify the best neighborhood solution, as the differences might be minimal and challenging for the algorithm to consistently detect. This manual search process is also incorporated into the algorithm.



## Chapter 4

# Portuguese Case Study: CelZa

The methodology detailed in [chapter 3](#) aims to serve as a valuable tool for hydrogen network planning and design. This chapter will focus on applying the developed optimization methods to a real Portuguese project for 100% hydrogen transport and interconnection with Spain. This approach will not only demonstrate the practical application of this methodology but also provide critical information and analysis for the project deployment. The conclusions drawn may be significant for the project developer, REN, and are intended to support social and political informed decisions, to shape the country's action plan in the coming years, contributing to the extensive literature on the future evolution of the energy system.

### 4.1 The CelZa project

CelZa was already introduced in [chapter 1](#) and will, as mentioned, serve as the case study for the application of the developed methodology. This project follows the agreement announced on October 20, 2022, in Brussels by French President Emmanuel Macron, Spanish Prime Minister Pedro Sánchez, and Portuguese Prime Minister António Costa. The leaders of these three countries agreed to establish a European corridor for green hydrogen transport, which includes a new interconnection between Portugal and Spain, linking Celorico da Beira in Portugal to Zamora in Spain, as well as a maritime pipeline connecting Barcelona in Spain to Marseille in France. In this work, the CelZa project will be considered in its complete form, including the national H<sub>2</sub> network project, commonly known as the Portuguese Hydrogen Backbone and officially called ENTH<sub>2</sub> (Eixo Nacional de Transporte de Hidrogénio).

#### 4.1.1 Known Data

This Portuguese project serves as the ideal case study for this dissertation for several reasons, but particularly because it is, at the time of this work, in the exact development phase to which this

methodology applies (the pre-feasibility stage). Therefore, there are a lot of variables and uncertainty associated with it. However, a considerable amount of information is already known, which is going to be analysed separately for CelZa and ENTH2. The complete project totals an expected investment of 414 M€ (four hundred and fourteen million euros) and predicts a maximum capacity of 750 ktH<sub>2</sub>/year (thousand tonnes of hydrogen per year), with the expected commission date being January 1, 2030.

On April 8, 2024, the European Commission officially published the new list of Projects of Common Interest (PCI), including both CelZa and ENTH2. This makes the two projects eligible for European funding, particularly under the EU program *Connecting Europe Facility* (CEF) [49].

#### 4.1.1.1 Iberian Interconnection (CelZa)

CelZa is expected to have an extension of 248 km, with the majority of it being located in Portugal (162 km), and the predicted investment, with no funding, is 204 M€ [11]. The complete route is shown in Figure 4.1, although the exact location has not yet been fully defined by REN or approved by Portuguese regulators.

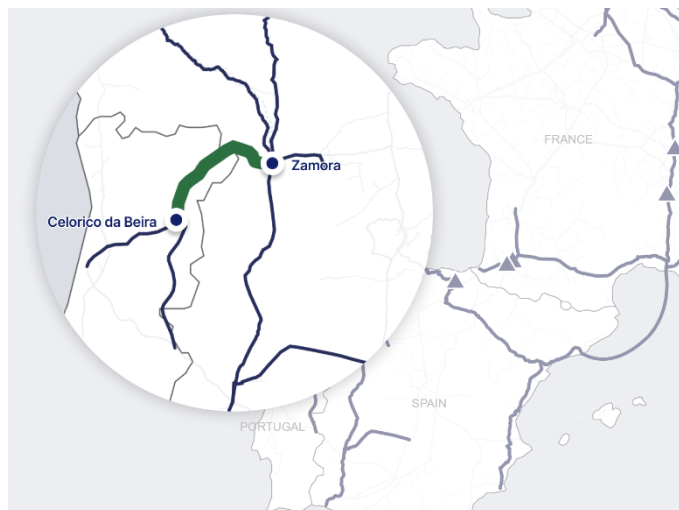


Figure 4.1: CelZa's projected route [12].

The diameter of the new pipeline is not completely defined, but it is expected to be 28" (twenty-eight inches), or 700 millimeters, in the Portuguese part, with a compression station of 24.6 MW (megawatts) located in Spain.

#### 4.1.1.2 Portuguese Backbone (ENTH2)

The ENTH2 is composed of a new fifty-kilometer line between Figueira da Foz and Cantanhede, as well as the repurposing of the existing natural gas pipelines Cantanhede - Mangualde, Mangualde - Celorico da Beira and Celorico da Beira - Monforte. Currently, there isn't any study for the new pipeline from Figueira da Foz, but the expected investment, considering the additional cost of

repurpose, is 210 million euros. The diameters and lengths of the existing pipes are summarized in [Table 4.1](#).

Table 4.1: Existing network specifications of the pipes that will be converted to 100% hydrogen.

Connection	Length	Diameter
Units	[km]	[mm]
<b>Cantanhede - Mangualde</b>	67.35	500
<b>Mangualde - Celorico da Beira</b>	47.25	700
<b>Celorico da Beira - Monforte</b>	183.55	300

## 4.1.2 Assumptions

The architecture of this optimization framework allows for several future adaptations. As the project evolves and the number of degrees of freedom decreases, the reliance on assumptions is reduced, thereby enabling more informed decision-making.

As a primary case study used to apply the developed methodology, several assumptions were made with the single purpose of simplifying the problem. However, some of these assumptions arose from the significant uncertainty inherent in this type of project, as this planning method is situated early in the value chain during the embryonic stage—the pre-feasibility engineering studies. If this process concludes that the project may be viable, it should be followed by a detailed project analysis. The specific assumptions are detailed below.

### 4.1.2.1 Properties

To achieve an accurate model of the problem, several parameters have to be quantified, particularly the fuel and pipe material properties.

Starting with hydrogen, it was considered to have an operating temperature of 25°C and an average pressure of 75 bar in order to determine the required properties for future calculations. These properties are resumed in [Table 4.2](#).

Table 4.2: Hydrogen properties considered and respective references.

Property	Symbol	Unit	Value	Reference
<b>Dinamic viscosity</b>	$\mu$	Pa · s	$9.054 \times 10^{-6}$	[68]
<b>Density</b>	$\rho$	kg / m <sup>3</sup>	5.81	[69]
<b>High heating value</b>	HHV	kWh/kg	39.4	[68]
<b>Specific heat at constant pressure</b>	$c_p$	kJ/kgK	14.49	[70]
<b>Specific heat at constant volume</b>	$c_v$	kJ/kgK	10.24	[70]
<b>Molar mass</b>	M	kg/mol	$2.016 \times 10^{-3}$	[68]

To determine the roughness ( $\epsilon$ ) of the material used in the pipe, it was considered the value for commercial steel, presented in [43], which corresponds to 0.045 millimeters. As for the universal gas law constant, it is considered 8.314 J/molK.

Regarding the HHV of other fuels (natural gas, propane and butane) relevant for this analysis, they are summarized in [Table 4.3](#).

Table 4.3: Fuels' HHVs considered and respective references.

Fuel	Natural gas	Propane	Butane
Unit	kWh/Nm <sup>3</sup>	kWh/kg	kWh/kg
HHV	11.67	13.84	13.72
Ref.	[71]	[72]	[73]

#### 4.1.2.2 Infrastructure

An important simplification of the problem was to fix an assigned diameter to the new pipeline connecting Figueira da Foz to Cantanhede. For this reason, the only optimised diameter will be the actual part of CelZa, the connection between Celorico da Beira and Vale de Frades.

This decision was made in order to ease the understanding of the methodology, considering also that this part of the Portuguese Hydrogen Backbone does not have any undergoing study at the time of this work. In the future, it will surely be useful to integrate this diameter as a variable of the optimization. The diameter considered was the same of the pipeline it is going to be connected to, and that already exists between Cantanhede and Mangualde, which is 500 mm.

Another simplification was to assume the first two lines in [Table 4.1](#) as one single pipeline with 500 mm between Cantanhede and Celorico da Beira. This assumption had the only purpose of reducing the number of restrictions in the optimization, making the process more understandable as a first approach. However, this simplification will not introduce a significant error since it will mainly overestimate the pressure loss in this section.

The operational lifespan of the infrastructure considered in this analysis was 40 years, even for the repurposed pipelines.

#### 4.1.2.3 Compression

As it was detailed in [chapter 3](#), the inclusion of compression as a variable in the optimization process aims to achieve a more realistic solution that accurately reflects the impact of consumption on the project's CAPEX and OPEX. However, this incorporation does not substitute for a comprehensive dimensioning of the compression stations within the network. Detailed dimensioning should be undertaken during the initial project development and continuously throughout the network's lifespan, in accordance with consumption patterns. This approach only ensures that the network's capacity consistently meets the required constraints at any given time, determining the power required for compression in each section to satisfy the initial assumptions, rather than specifying the dimensions of the compressors.

Consequently, it is necessary to calculate the pressure increase provided by the compressors as a function of power, as will be further elaborated. The calculations are performed in accordance with [\[74\]](#), using the equations presented below:

$$\text{Work} \left( \frac{J}{kg} \right) = \frac{\frac{y}{y-1} \cdot \frac{R \cdot T_1}{M} \cdot \left[ \left( \frac{P_2}{P_1} \right)^{\frac{y-1}{y}} - 1 \right]}{\text{isentropic efficiency}\% / 100} \quad (4.1)$$

$$\text{Power (kW)} = \frac{Q \cdot \left( \frac{\rho}{3600 \cdot 1000} \right) \cdot \text{Work} \cdot \left( 1 + \frac{\text{leaks}\%}{100} \right)}{\left( \frac{\text{mechanical efficiency}\%}{100} \right) \cdot \left( \frac{\text{electrical efficiency}\%}{100} \right)} \quad (4.2)$$

where  $y$  is the isentropic coefficient, equal to  $c_p/c_v$ . [74] is a website from an engineering company with the same name, that developed a software for hydrogen projects support. These functions are the ones utilized for the dimensioning of the H<sub>2</sub> compressors, based on several scientific sources. In fact, [75] shows the same formulas for the calculation of work and power, relative to reciprocating compressors.

Using both equations it is possible to solve for  $p_2$ , the output pressure, knowing or estimating the other variables. The values considered for efficiencies and losses are stated in Table 4.4.

Table 4.4: Efficiencies and losses values considered (%).

Efficiencies	%
Isentropic	65
Mechanical	79
Electrical	95
Losses	%
Leaks	3

In this approach, an operational lifespan of 20 years for the compressors is considered. Additionally, it is assumed that the compressors operate in redundancy, meaning two identical compressors function at 50% capacity each to ensure continuous operation in the event of a malfunction.

#### 4.1.2.4 Production Sites

The location of the production sites is still a huge uncertainty and a critical part of the project. The most realistic prediction available is the mentioned H<sub>2</sub> atlas [38], that maps the best areas for locating green hydrogen production units in Portugal.

Therefore, in this planning, there was no early consideration of any specific sites for supply. This introduces a variable of uncertainty, especially when calculating the pressure drop along the pipe, due to the lack of knowledge regarding injection points. Considering this, the present analysis considers the extreme cases that would result in critical conditions for operating velocity and pressure loss.

Being an exportation network, the flow can only follow one of three situations, shown in Figure 4.2.

Considering this information, it is important to combine the two extreme cases: maximum operating velocity and maximum pressure loss.

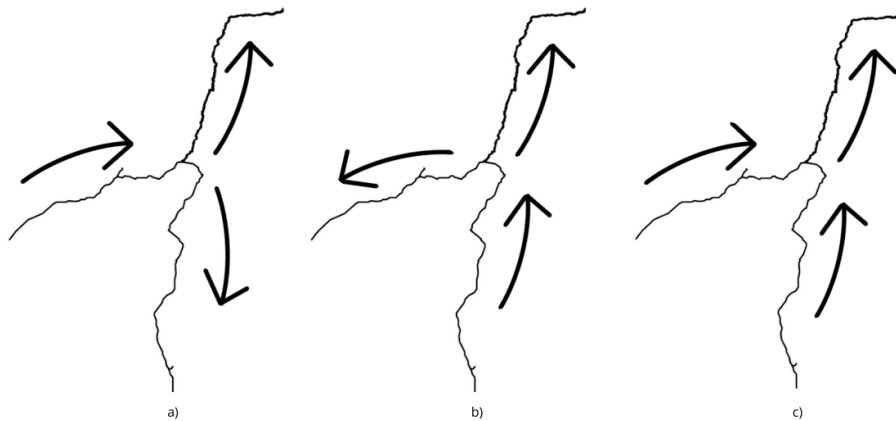


Figure 4.2: Possibilities considered for the direction of the flow.

Velocity is determined by the geometry of the pipeline (diameter) and the flow rate required, according to [Equation 2.5](#), which can be used since [Equation 2.16](#) is verified. As a consequence, critical velocity will be obtained when all the consumption is matched by production injected in one of the two existing pipeline sections (one of them with the added new pipeline from Figueira da Foz to Cantanhede). Regarding the new pipeline from Celorico da Beira to Vale de Frades, the location of the production sites does not affect the velocity, since, by the flow direction demonstrated in [Figure 4.2](#), the amount of hydrogen circulating is independent from this placement.

In addition, pressure loss is influenced not only by the flow rate and geometry but also by the length of the pipe. The critical pressure drop will occur if the production is centralized in one pipe (similar to velocity), while the injection point is situated at the furthest distance, requiring the hydrogen to traverse the entire length of the pipeline. The critical location for production considered will therefore be one of the following, represented in [Figure 4.3](#).

Another important consideration pertains to the production sites. If all production were concentrated in Monforte, the network's capacity would be inherently limited to just over 250 ktH<sub>2</sub>/year (thousand tonnes of hydrogen per year) due to the smaller diameter of the Celorico da Beira - Monforte section (300 mm). Consequently, this scenario was disregarded (case *b* in [Figure 4.2](#)). It is assumed that if consumption approaches 250 ktH<sub>2</sub>/year, production will need to be distributed across other sections to accommodate any intended expansion.

#### 4.1.2.5 Pressure

Hydraulic modelling may be the most challenging part of the physical concerns of this kind of network due to the extensive number of variables that can affect the nature and development of the flow. These variables are almost entirely associated with a certain degree of uncertainty, due to the variability of the operating conditions and the unpredictability associated with the early stage of project development. For these reasons, several assumptions were made regarding pressure when calculating the pressure loss and operating conditions.



Figure 4.3: Critical locations of the production units.

At the time this work was developed, there was no indication that the hydrogen network would have different specifications compared to the national natural gas network. Therefore, it is assumed that the pipelines are designed for a maximum pressure of 100 bar but operate at 84 bar. The minimum allowable pressure considered was 60 bar (higher than for natural gas). It is important to recall the points mentioned in [chapter 2](#) about hydrogen. It is commonly known for being the lightest element in the periodic table and, therefore, the lightest gas in the universe. So, even though it has an extremely high specific energy (available energy per unit mass), the volumetric energy density is particularly low. Per volume, the energy content of hydrogen is even a lot lower than most other fuels and energy carriers, like natural gas. As a consequence, to provide the same amount of energy at the same pressure, the flow rate will have to increase substantially compared to natural gas.

Additionally, the characterization of injection points is crucial for flow modeling. As mentioned, the injection points considered will be the critical ones. However, the pressure at which hydrogen is injected into the grid also plays a central role in these calculations. The assumption made was that the injection pressure is equal to the maximum operating pressure of 84 bar. Given that electrolyzers can vary significantly regarding the output pressure of hydrogen, it is assumed that it is the producer's responsibility to ensure the required pressure.

Regarding the pressure loss calculation, as the Mach number is always less than 0.3, according to the condition presented in [Equation 2.16](#) the flow can be considered incompressible. Checking [Equation 2.15](#), we can see that the values of Reynolds will be a lot higher than 4000 for the

parameters shown in [Table 4.2](#) and for the velocity range inside the pipeline <sup>1</sup>. Therefore, the flow should be considered turbulent. For these two reasons, the pressure loss calculation is done using [Equation 2.11](#).

Finally, the variation of pressure between two points will be done using [Equation 2.14](#) for every constant diameter section of the network, considering that the pipes are horizontal, which means the difference in elevation between the two points is negligible. The pressure loss when changing diameters is also considered negligible, as occurs for every local loss throughout the network. There is no consideration of deterioration of the pipe with time. [Table 4.5](#) summarizes the values considered regarding pressure, with the maximum velocity admitted inside the pipeline being 20 m/s.

Table 4.5: Relevant pressure values considered in the operating specifications.

Variable	Value (bar)	Description
$P_{inj}$	84	Injection pressure
$P_{min}$	60	Minimum pressure allowed
$P_{op}$	84	Operating pressure
$P_{des}$	100	Design nominal pressure

#### 4.1.2.6 Costs

The optimization process will be significantly influenced by economic viability, which serves as a crucial driver for the initiation of innovative projects. Assessing economic viability requires the calculation of both capital and operational expenditures as functions of the optimization variables. Specifically, it is essential to quantify these costs for both pipelines and compressors. All calculations are grounded in the existing literature and are defined as indicated below, reminding that these are first-approach assumptions and can be revised for future adaptations. The division of the tariff in two moments considers that, at half the life expectancy of the infrastructure (twenty years), 85% of the network's capacity is used.

- **Pipeline:** The infrastructure itself naturally constitutes the primary component of investment costs. It is important to recognize that all equations found in the literature are approximations and, as such, may either underestimate or overestimate CAPEX and, consequently, OPEX, since the latter is typically calculated as a percentage of capital expenditure. [Equation 4.3](#) and [Equation 4.4](#) are derived from [76] and [77], respectively, and refer to newly built pipelines.

$$CAPEX_{newpipe}[\text{€}/km] = 3,400,000D^2 + 598,600D + 329,000 \quad (4.3)$$

$$OPEX_{newpipe}[\text{€}/year] = 2.5\% \times (CAPEX_{newpipe} \times L) \quad (4.4)$$

<sup>1</sup>For the maximum velocity of 20 meters per second,  $Ma$  is approximately 0.06. Regarding Reynolds, for an average velocity of 15 meters per second (m/s) and a pipe diameter of 700 mm,  $Re$  is equal to  $4.8 \times 10^6$ .

Equation 4.3, where  $D$  refers to the pipe diameter in millimeters, was obtained in [76] for distribution networks, with the primary difference from transmission networks being the exclusion of recompression station costs. This calculation considers an upper pipeline cost assumption to reflect the higher material costs for hydrogen networks, which may require enhanced materials and increased wall thickness. However, since this study was conducted in 2010, this increase may already be offset by inflation, potentially leading to a slight underestimation of costs. Despite this, the validity of the results will be analyzed in the subsequent sections. In Equation 4.4,  $L$  refers to the length of the pipe in kilometres.

For the cost of repurposing, the assumption made is based on [78], assuming that there is no investment ( $CAPEX = 0$ ), with an aggravated calculation of OPEX to reflect higher maintenance costs and potential additional initial investments. This calculation is performed using Equation 4.5 and the quality of this assumption will be further analyzed.

$$OPEX_{rep.pipe}[\text{€}/\text{year}] = 5\% \times (CAPEX_{newpipe} \times L) \quad (4.5)$$

- **Compressor:** Hydrogen compressors significantly influence both initial investment and operational costs. Operational costs can be subdivided into maintenance and energy consumption, with the latter being highly dependent on the energy sources utilized and their respective prices. Moreover, CAPEX is influenced by various factors, including engineering, civil works, transportation, labor costs, and the type of technology employed. Consequently, the following estimation is intended to be a preliminary approximation, aimed at providing a general indication of the impact of compression power on the network costs.

$$CAPEX_{comp} = 3.6 \times (75,700 \cdot \text{Power}^{0.38}) \quad (4.6)$$

$$OPEX_{comp} = 4\% \times CAPEX_{comp} \quad (4.7)$$

Equation 4.6 is adapted from [74], which bases its formulation in [79] and [80]. OPEX is calculated as a percentage of CAPEX (Equation 4.7), based on [78].

Moreover, operation costs regarding the use of compressors have another important factor relative to energy consumption. The latter is intrinsically linked to the compressor's utilization factor, which ultimately depends on the consumption patterns. This aspect can have a severe impact on the total project cost, but its prediction can be quite complex, thus being neglected in the present analysis. Therefore, as OPEX is merely calculated as a percentage of CAPEX, the costs can be underestimated.

### 4.1.3 Scenarios

In order to reflect the uncertainty associated with hydrogen market development and provide useful data for project implementation, there is a need to define a wide range of scenarios for consumption.

#### 4.1.3.1 Mappings

For the purpose of consumption mapping, four scenarios of decarbonization via replacement with green hydrogen were considered:

- Total natural gas consumption;
- Natural gas consumption without the domestic sector contribution;
- Total natural gas, butane and propane consumption;
- Natural gas, propane and butane consumption without the domestic sector contribution.

Two base scenarios are considered: one where natural gas is the only energy source selected for replacement, and another where propane and butane are included. Although hydrogen can theoretically replace all these fuels, its practical implementation depends on several factors, mainly the financial competitiveness of hydrogen prices. If these consumptions (propane and butane) persist in the current energy system, it is because the natural gas network could not provide the commodity at sufficiently low prices or availability to encourage replacement. A compelling future analysis will be to determine whether hydrogen will face the same challenges or emerge as the ultimate solution to replace all fossil fuels in gas industry. However, this discussion is highly complex and beyond the scope of the current planning stage, thus all scenarios are considered.

Given that the initial focus of decarbonization via hydrogen replacement is anticipated to be on the industrial sector due to its substantial consumption levels, variations of both scenarios that exclude domestic consumption are considered. If industrial consumption can justify the construction of a transportation network, future distribution networks will account for this demand in their expected subsequent adaptations to distribute 100% H<sub>2</sub>.

The selection of these scenarios for analysis neglects the fact that not all non-domestic consumption is industrial. In fact, according to [67], approximately 16% of the natural gas consumption in Portugal was from services in 2022. Even though those scenarios could be mapped in future works, the chosen options provide useful insights into the decarbonization potential through hydrogen implementation and a basis for pre-feasibility analysis in the early stages of project development.

#### 4.1.3.2 Network Planning

As previously mentioned, this methodology requires the input of initial consumption scenarios to proceed with the optimization. The chosen scenarios, detailed below, were selected to provide

a wide spectrum of possibilities. The main purpose was to inform future conclusions by identifying the most realistic and optimal scenarios to be considered. In total there were 54 scenarios considered, combining different predictions for internal consumption (national consumption that could be transported via CelZa), several possibilities for export capacity and three different areas of influence (buffer size).

The five scenarios considered for initial internal consumption were the following:

- **C<sub>1</sub> - Base scenario:** Conversion of the totality of the natural gas, propane and butane consumption, without the domestic sector contribution;
- **C<sub>2</sub> - Conservative variation of base scenario:** 50% of the consumption predicted in the base scenario;
- **C<sub>3</sub> - Base scenario with flexibility of the electric system:** Base scenario plus electrolysis capacity required to fulfill electricity demand in times of insufficient renewable production (prediction of 336 GWh for 2030, based on [4]);
- **C<sub>4</sub> - Conservative variation of base scenario plus flexibility:** 75% of the consumption predicted in C<sub>3</sub>.
- **C<sub>5</sub> - Second variation of base scenario plus flexibility:** 50% of the consumption predicted in C<sub>3</sub>.

Regarding exportation, it was considered three base initial amounts per year: 5, 10 and 15 TWh. The scenarios for external consumption taken into account follow the matrix present in [Table 4.6](#).

Table 4.6: Exportation scenarios, considering variations of base capacities (5, 10 and 15 TWh).

E1	E2	E3
100%	75%	50%

Taking this information into consideration, the final scenarios are different combinations of what was previously defined:

- $S_1: C_1 + E_1$ ;
- $S_2: C_2 + E_3$ ;
- $S_3: C_3 + E_1$ ;
- $S_4: C_4 + E_2$ ;
- $S_5: C_5 + E_1$ ;
- $S_6: C_5 + E_3$ .

Considering that the DSS algorithm requires the definition of an area of influence ([subsection 3.2.3](#)), three distances to the network will be considered: 5, 10 and 20 km. Therefore, the total scenarios can be aggregated in three different matrices, one for each area size, totalling the 54 scenarios mentioned. One model matrix is shown as example in [Table 4.7](#).

Table 4.7: Model matrix of scenarios for a specified area of influence A.

Base exportation	$S_1$	$S_2$	$S_3$	$S_4$	$S_5$	$S_6$
5 [TWh]	I - A	IV - A	VII - A	X - A	XIII - A	XVI - A
10 [TWh]	II - A	V - A	VIII - A	XI - A	XIV - A	XVII - A
15 [TWh]	III - A	VI - A	IX - A	XII - A	XV - A	XVIII - A

The maximum exportation capacity considered for the initial operation of the network was 15 TWh, which can be converted to approximately 380 ktH<sub>2</sub>/year, a little over half the capacity predicted for CelZa.

## 4.2 Implications of Portuguese Interconnection Via Hydrogen Pipelines

### 4.2.1 Methodology Application

The process described in [Figure 3.3](#) was used to apply the developed methodology. The subsequent sections specify this application for each algorithm.

#### 4.2.1.1 Consumption Mapping Algorithm

Following the methodology developed in [chapter 3](#), the first step was to assess the decarbonization potential of the national regions using the scenarios chosen. The consumption data was obtained from the Direção-Geral de Energia e Geologia (DGE) database [\[67\]](#), referring to the year 2022. Additionally, the geographic data was retrieved using an API provided by Google Maps to obtain coordinates based on location names. For the regional boundaries (municipalities), the geographic information was derived from the GeoJSON file of the CAOP2023 (Carta Administrativa Oficial de Portugal 2023) [\[81\]](#). The combination of the different energy sources consumptions was done using the HHV values, shown in [Table 4.3](#).

Taking this into consideration, the CMA was used for each scenario, following the process shown in [Figure 3.2](#), and the results were obtained (to be analyzed ahead).

#### 4.2.1.2 Decision Support System

The next step in the planning methodology was to use the DSS algorithm in order to determine the consumption values of the different scenarios described in the previous subchapter.

To do so, the same consumption data used before was given as an input, together with the KMZ file with the CelZa pipeline geographic layout. Regarding the KMZ file, the layout was designed using the existing files of the national gas transportation network and one of the projected

layouts for the new CelZa pipeline. For the new pipe connecting Figueira da Foz to Cantanhede, a simplified route was designed since there is currently no available study for that section.

After that, using the same process as in the CMA for the consumption combination, the 54 scenarios previously explained were chosen and provided to the algorithm, which calculated each consumption value.

#### 4.2.1.3 Genetic Algorithm

In this part of the methodology, network optimization was performed for each initial consumption scenario using the genetic algorithm described throughout [subsection 3.2.4](#) and the assumptions detailed in [subsection 4.1.2](#). The first step was to define the representation of the individuals in the population through each individual's chromosome. The genotype considered, in accordance with the assumptions made and using the same terminology as before, was the following:

$$[(D_1); (S_1; S_2; S_3); (C_1; C_2; C_3); (FS_1; FS_2; FS_3); (FC_1; FC_2; FC_3)]$$

This generic genotype represents the genes of each individual, with the alleles (possible values for the genes) taking the following values:

- *D*: The only diameter considered as an optimization variable was, as already explained, the one corresponding to the new pipeline between Celorico da Beira and Vale de Frades,  $D_1$ . The possible values considered were the sixteen standard nominal diameters for pipelines used in the industry, from 100 millimeters (4 inches) to 1.4 meters (56 inches). The inclusion of such extreme values allows for better diversification of the population and increases competition amongst individuals.
- *S*: The sections considered for the hydraulic modelling of the network and, therefore, for the locations of the compressors were the connection between Figueira da Foz and Celorico da Beira (check assumptions in [subsection 4.1.2](#)), represented by letter *A*, the pipeline from Monforte to Celorico da Beira, represented by letter *B*, and the new CelZa pipe (*C*).
- *C*: The values for the compression power are assumed to range between 1 and 30 MW, using such extreme values for the same reason mentioned for diameters.
- *FS*: The future sections considered for compressor locations are the same as the initial ones.
- *FC*: The future capacity ranges for the compressors are also the same as the previous ones.

Using [Equation D.2](#) in [Appendix D](#), it is possible to calculate the number of different chromosomes present in the search space, totaling an impressive number of  $14.2 \times 10^9$  possible solutions.

The hydraulic modelling, assuming the simplifications justified in [subsection 4.1.2](#), calculates the final pressure of each pipe. It takes into account the critical pressure loss along the pipeline and the compression power (if any) of the specific individual. For every section, it is verified that there is a compressor. If so, there are two possibilities: if the pressure reaches the minimum

operating pressure allowed, the compressor is "placed" at that location, and the inlet pressure into the compressor is considered to be 60 bar (minimum pressure); if it never reaches the minimum, the compressor is placed at the end of the section, where the pressure has the most significant loss.

Then, using [Equation 2.14](#), the algorithm calculates the pressure at the end of the pipe. In each situation, it is considered the extreme case for the flow, detailed in [subsection 4.1.2](#). For example, in section *C*, the new CelZa pipeline, the critical pressure drop will correspond to the situation where all production is done in Figueira da Foz. If so, the injection pressure into the pipeline will be the final pressure obtained in pipe A (or B, if it is inferior, since it is the critical case that should be considered).

In this modelling, the calculation of the initial flowrate in each pipe takes advantage of the DSS feature of separating the consumption per pipeline section. For example, the critical scenario for pipe *C* is to accommodate all the consumption around that section with the added total export volume. It would not make sense to also take into account consumption from other sections.

The merit is then assessed using the fitness function ([Equation 3.9](#)). The penalty function  $\Gamma(x)$  is calculated by adding the differences between the final pressure and the minimum one allowed, each time the restriction  $g_1(x)$  is violated.  $t_1(x)$  and  $t_2(x)$  are obtained in €/kgH<sub>2</sub>, while  $h(x)$  is calculated in tH<sub>2</sub>/year (tonnes of hydrogen per year).

With this information, the optimization process was completed for each scenario using the genetic operators previously described.

## 4.2.2 Results Analysis

### 4.2.2.1 Consumption Mapping Algorithm

Any replacement considered in the CMA scenarios would, of course, result in major contributions to the decarbonization of the Portuguese energy system, with the mentioned 2045 target for climate neutrality. The map shown below in [Figure 4.4](#) is the result obtained relative to the first scenario mentioned, i.e., for total natural gas consumption. This scenario, along with the other three, is represented in [Appendix F](#) for better visualization.

The results obtained clearly demonstrate the discrepancy across the country regarding gas consumption, with a high correlation between population density and energy consumption. However, there are some municipalities in the interior of the country with considerable consumption, as shown in [Figure 4.4](#), because of the relevant industrial sector in those regions. Therefore, it is also worth mentioning the correlation between energy consumption and company density. Additionally, in [Appendix G](#), it is shown the population and company density in Portugal, where it is visible the high discrepancy that was also found in the energy consumption mappings.

The concentration of energy consumption is so pronounced that only 9 out of 278 continental municipalities accounted for more than 50% of the total natural gas consumption in 2022. Consequently, it is evident that the CelZa network will primarily be situated in regions with low consumption, adding another obstacle to the project.

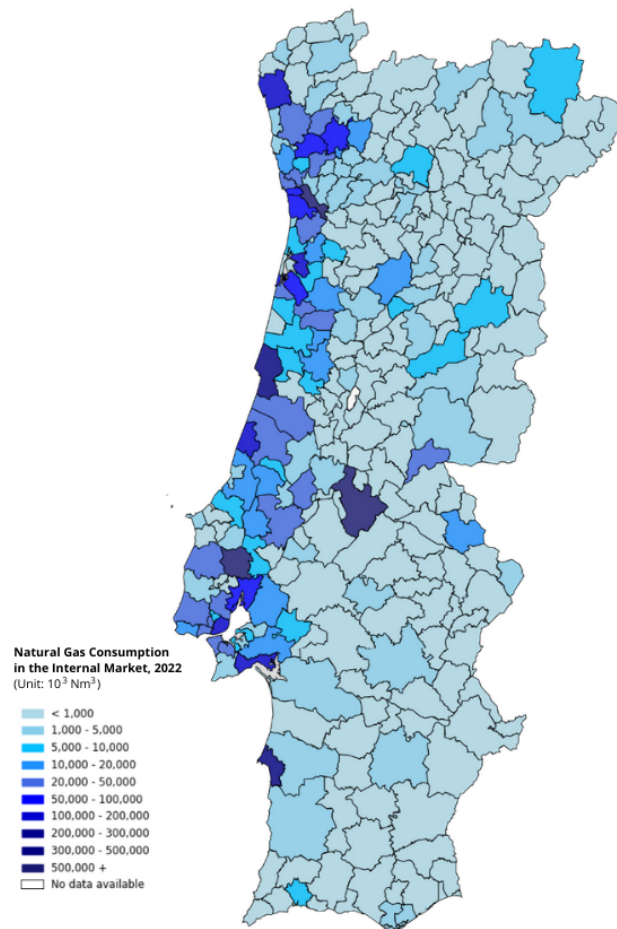


Figure 4.4: Portuguese natural gas consumption by region in 2022.

#### 4.2.2.2 Decision Support System

The developed DSS algorithm was applied to each of the 54 scenarios at the beginning of the optimization process, confirming the previous statement of low consumption around the network.

In [Appendix H](#) the results obtained for each area of influence considered (5, 10 and 20 km maximum distance to the pipeline) are resumed in three different tables. It is possible to verify that the total non-domestic internal consumption may range from 6.3 to 7.4 TWh, meaning that if all the natural gas, propane and butane consumptions were converted into hydrogen, there would be a hydrogen need of transportation for internal consumption of 187 ktH<sub>2</sub>/year in the most optimistic scenario, which is 25 % of the expected capacity of CelZa. Considering that the total non-domestic consumption is not entirely industrial and that connecting all consumers within a 20-kilometer radius may be impossible, this consumption may be overestimated. Despite that, it is still a very significant value, taking into account the unfavourable location of the network that was verified earlier. This information was crossed with exportation and national consumption scenarios, to get the 54 results.

[Figure 4.5](#) shows the buffer created around CelZa for the ten-kilometer radius case.

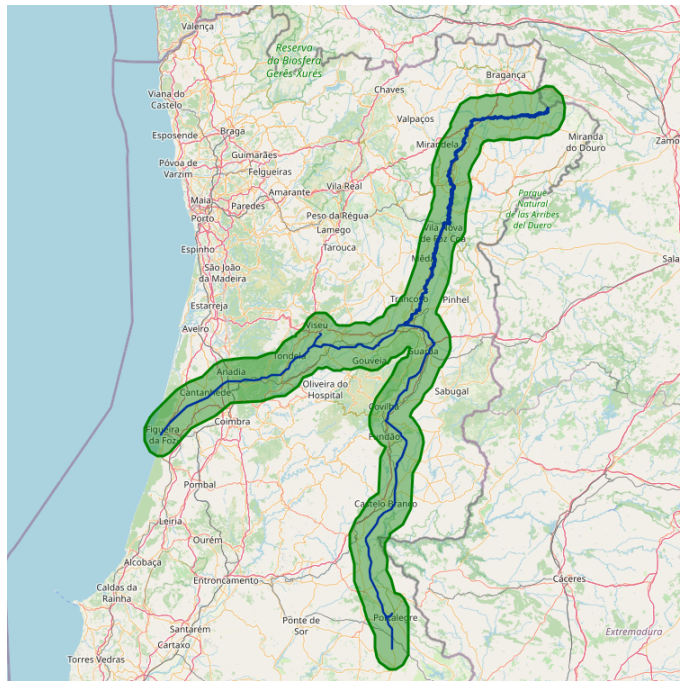


Figure 4.5: Buffer generated for 10 km distance between the border and the pipe.

Moreover, the algorithm results show the immediate decarbonization impact in Portugal for every internal consumption scenario considered. The average environmental benefit calculated was 424 ktoe (kilotonnes of oil equivalent), indicated in Figure 4.6.

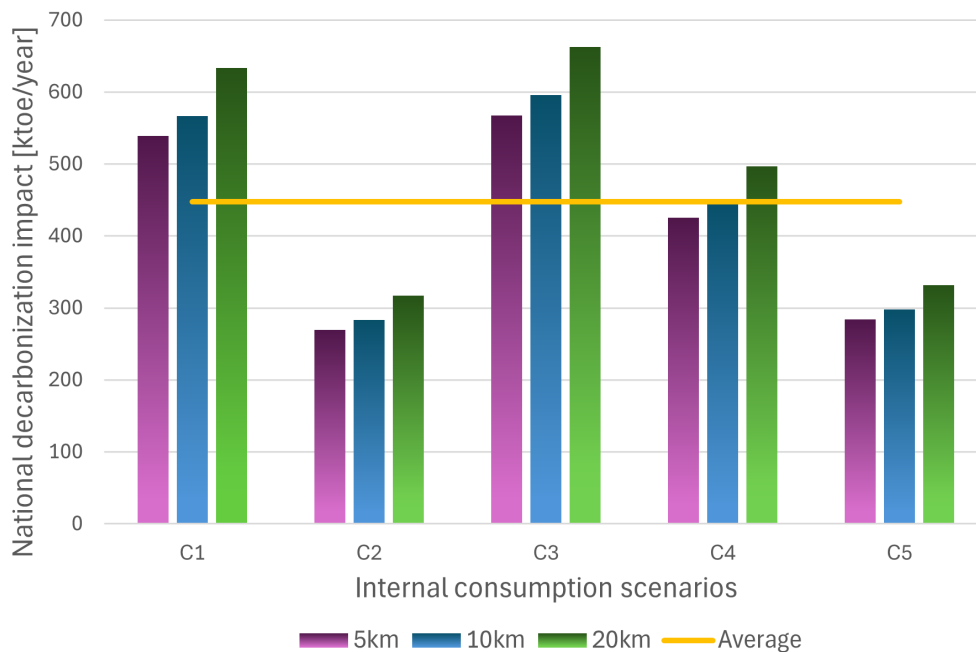


Figure 4.6: Decarbonization impact in ktoe per internal consumption scenario.

Taking advantage of the desegregated data by energy source, also provided by the DSS algorithm, it is possible to calculate the reduction in CO<sub>2</sub> emissions that would result from each scenario of initial internal consumption of hydrogen (forecasted to 2030, but based on 2022 data). For that purpose, it was considered the CO<sub>2eq</sub> (carbon dioxide equivalent) emission factor for each gas, stated in [71] and [82], since they are used as primary energy.

To account for the CO<sub>2</sub> reduction enabled by the flexibility of the electric system, it was assumed that when renewable production cannot meet the required electricity demand, the shortfall would be supplied by a thermoelectric power plant operating on a combined cycle using natural gas. According to the latest report from the Agência Portuguesa do Ambiente (APA) on the emission factor of electricity in Portugal for 2023 [83], the emission factor of such power plant is estimated at 0.384 tCO<sub>2eq</sub>/MWh, based on an efficiency of 53.4% in electricity production<sup>2</sup>.

In Figure 4.7, it is shown the CO<sub>2</sub> emissions reduction per year, for all scenarios of initial internal consumption, ranging from 639 to 1576 ktCO<sub>2</sub>.

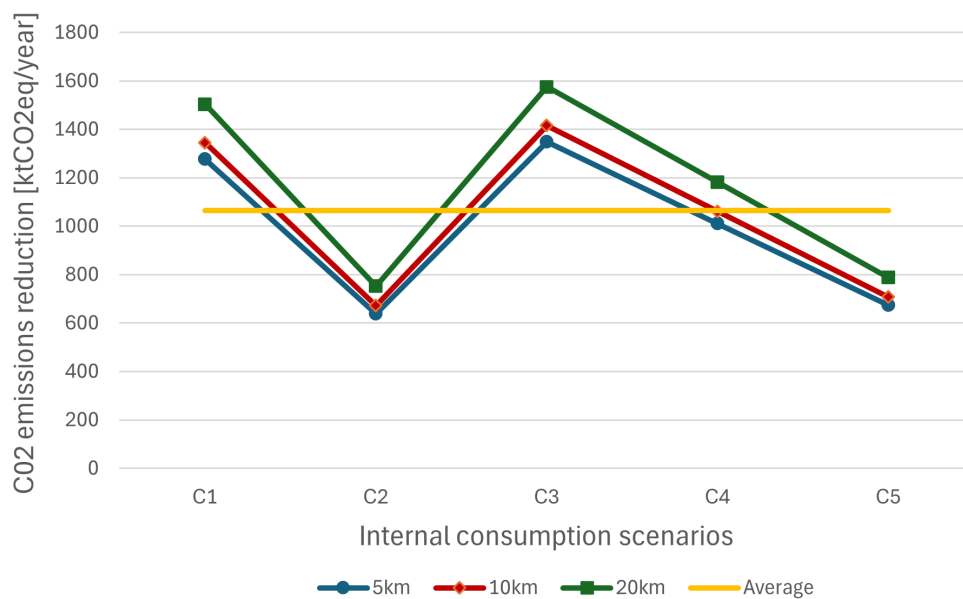


Figure 4.7: CO<sub>2</sub> emissions reduction per year, for the five scenarios of national hydrogen consumption through CelZa.

The average scenario of approximately 1 Mt (one megatonne) of CO<sub>2</sub> reduction represents 12.5% of the best-scenario target of the Portuguese National Strategy for H<sub>2</sub> (EN-H2) for 2030 (8 Mt of CO<sub>2</sub>, per [11]).

<sup>2</sup>The hydrogen demand for the flexibility of the electric system, calculated in [4], is based on the assumption of electricity generation via an H<sub>2</sub> power plant using stationary fuel cells, with an efficiency of 55% in 2030. Therefore, the electricity that would need to be produced by the thermoelectric power plant in C3 is 185 GWh.

### 4.2.2.3 Genetic Algorithm

The GA implementation provides an output with the main information about the optimal solution found. In [Appendix I](#), a random example of the algorithm's output is shown.

After completing the optimization process for the 54 scenarios proposed, the optimal (or near-optimal) parameters were obtained for each case. The totality of the results is shown in [Appendix J](#).

Regarding the initial tariff, an interesting analysis can be performed using the graph shown in [Figure 4.8](#), where it is possible to identify the scenarios of internal consumption and exportation that would result in an acceptable value for the tariff. The maximum transportation cost was considered to be 0.15 €/kgH<sub>2</sub> (euros per kilogram of hydrogen), to represent at most 10% of the total commodity cost (LCOH). This value assumes that hydrogen can be produced at 1.5 €/kgH<sub>2</sub>, which is a rather optimistic prediction, considering that, according to [8], only near 2050 can the majority of green hydrogen supply to Europe be produced below that value. However, this optimistic view selects a more conservative criteria, which is required due to the possible underestimation of operational costs that was mentioned and the neglect of inflation. Moreover, the real tariff charged to consumers may be higher to create revenue, even with support mechanisms installed.

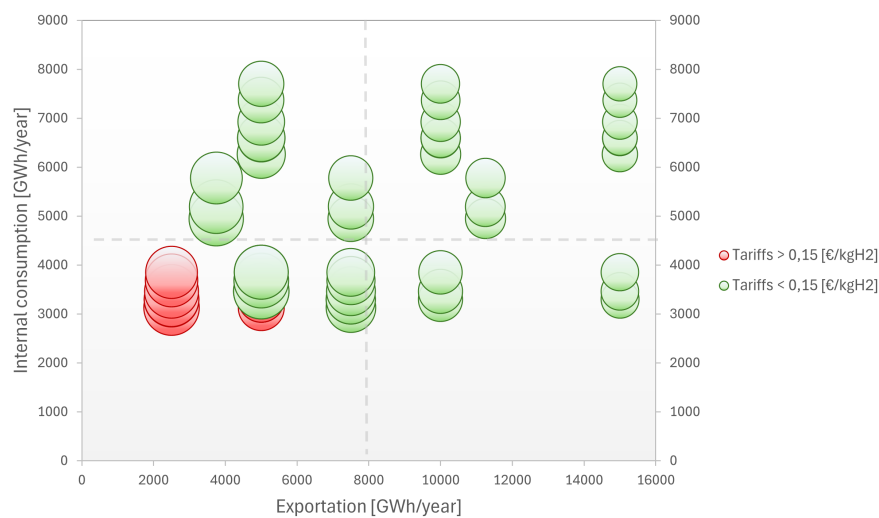


Figure 4.8: Initial usage tariff variation considering internal consumption and export quantities.

Analyzing the provided data, it is possible to observe through each circle's area that if initial national consumption is limited (less than 4 TWh/year), there is a substantial dependency on Spain's consumption to ensure project's viability.

In addition, it is possible to observe the variation of the tariff  $t_1$  with initial consumption in [Figure 4.9](#). This graphic shows the expected decreasing tendency of transportation costs, by plotting the 54 scenarios considered. It is visible that, as we approach the maximum network capacity, the tariff (or LCOHT) tends to near 0.05 €/kgH<sub>2</sub>. This type of plot allows the identification of the required total consumption for project's financial viability, which in this case is approximately 200 kilotonnes of H<sub>2</sub> per year.

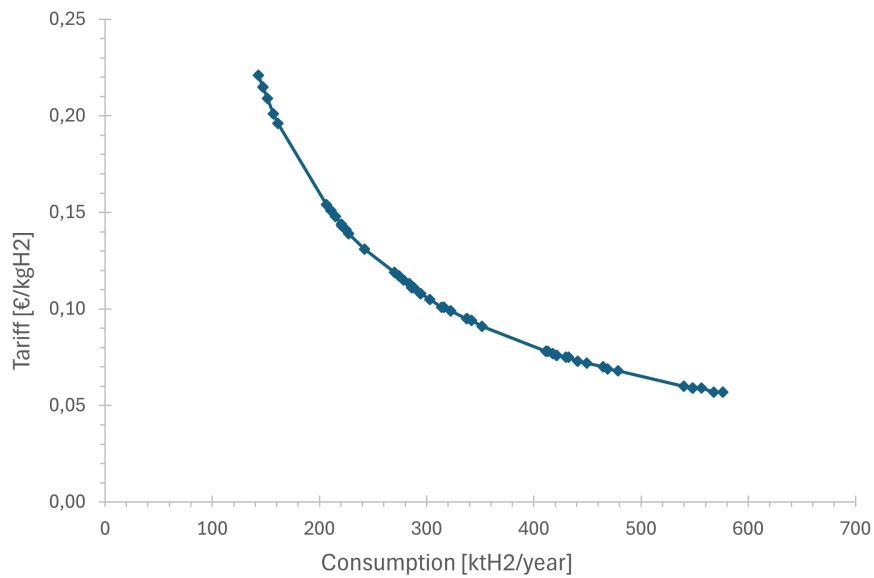


Figure 4.9: Initial usage tariff variation with total consumption.

As for the investment, CAPEX will depend only of the compression power installed, since the diameter of the pipe is always the same (explained why in [subsection 4.2.3](#)). In [Figure 4.10](#), it is shown this variation. The distinction between two lines comes from the fact that the requirement of compressors in more than one section increases the costs significantly. However, it is important to remember that this network is projected to work on extreme scenarios and that it was always considered the functioning in redundancy to ensure continuous operation. Therefore, the full load hours will be averagely low, decreasing the cost-efficiency of the system.

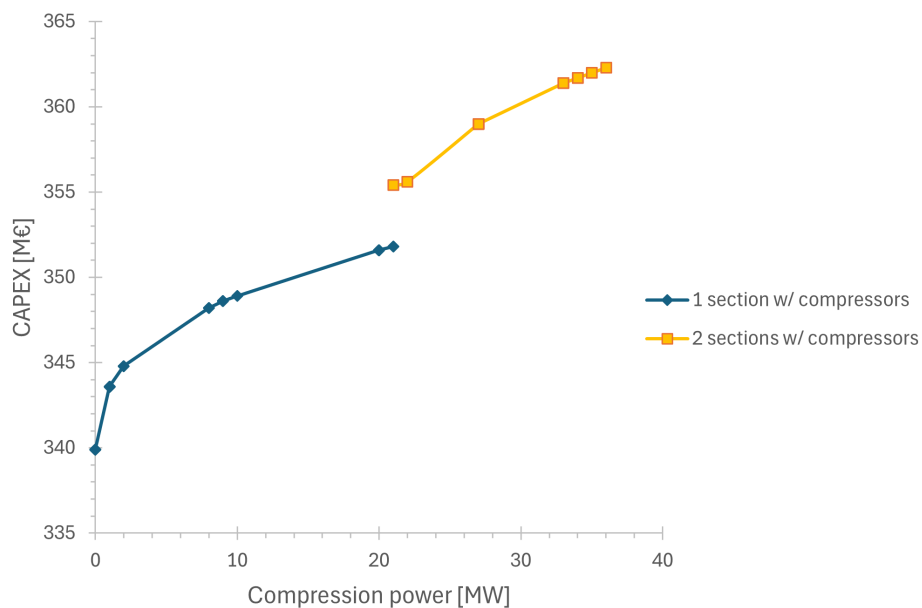


Figure 4.10: CAPEX variation with required compression power.

### 4.2.3 Results Discussion and Validation

The first thing that stands out about the results is the fact that the optimized diameter is the same for all scenarios and equal to 500 mm. This can be justified by the restrictions imposed on the network, considering the assumptions made in this case study. Due to the project's uncertainty, it was considered a very conservative scenario, where the network is prepared for very critical situations. In this case, it is considered that even in the future, after the evolution of the market and transportation levels increase, there is still a possibility of all the production being made in Figueira da Foz. Therefore, the search sees no point in assigning a diameter higher than 500 mm (the diameter considered in A), since the capacity of the network would be limited by that diameter. In future adaptations, more realistic and informed decisions about possible developments on production sites selection should be considered, and the optimal diameter will probably be higher.

Consequently, the second-moment tariff ( $t_2$ ) is practically the same across all scenarios since the network's maximum capacity is also constant (it depends on the diameter and maximum velocity). As a result, both the consumption considered (85% of the maximum) and the compression power required will remain the same.

In addition, the results show that CAPEX values range between 340 and 362 M€. These values are lower compared to the predicted investment of CelZa, already mentioned to be 414 M€. This difference can be mainly justified by the following factors (some already pointed out):

- The function used for CAPEX calculations is based on a study conducted in 2010. Even with the considered upper limit for material costs, the impact of inflation is not negligible and, therefore, the function may underestimate the investment.
- OPEX is calculated using a fixed percentage of CAPEX and, therefore, simplifies the variable costs of operation relative to the compressors' electricity consumption. Depending on the source of this energy, there is a possibility of a considerable increase in total costs.
- The diameter obtained for all scenarios is lower than the one predicted for CelZa (500 mm compared to 700 mm). A smaller pipe requires less investment in materials and labour.
- It was considered a null investment for the conversion of natural gas pipelines, reflecting the impact on total costs through an increased OPEX. Although this approach may not affect the value of the tariff (depending on its accuracy), it decreases the CAPEX value.

To assess this last factor's impact on the accuracy of the results, the total cost of the pipeline can also be calculated using [7], where the cost of repurposing is estimated. For a 20" repurposed onshore pipe, it is estimated a CAPEX of 0.54 M€/km. If it is considered this initial investment with an operational cost similar to a new pipeline (2.5% of CAPEX per year), the total cost of the repurposed pipeline between Cantanhede and Mangualde throughout the 40 years lifetime would be 135 million euros. Considering the assumption indicated in [subsubsection 4.1.2.6](#), the total cost would be 200 M€.

As it was verified, the method used actually overestimates the costs compared to considering an initial investment for repurposing using the functions developed by EHB.

Using [84] to estimate the CAPEX of the CelZa new pipeline, the value obtained was 245 M€. This function is estimated for the year of 2009, so it should be higher now due to inflation. Estimating using the 1.8 M€/km value from [7], it is obtained an investment of 292 M€.

The function used (Equation 4.3) estimates the investment in the new pipeline at 240 million euros, which is very close from the first approximation. As it is visible, there is a considerable uncertainty when estimating the costs through developed functions. Despite that, the value predicted in [7] is based on the most recent data, compared to the other references. As it is based on European-wide data, it is possible that it overestimates the costs when applied to the Portuguese case, due to differences regarding labour costs. Considering this information, the values provided by Equation 4.3 can be considered acceptable.

Moreover, the impact of inflation on the tariff was not considered, but it is not negligible and, therefore, should be considered in future analysis. Report [7] shows that the increase in costs relative to the EHB's previous study can be attributed to inflation. However, it also concludes that it does not affect the previous conclusions, stating it is more cost-efficient to install electrolyzers close to renewable power generation and then use pipelines to transport hydrogen to the point of consumption, than it is to install electrolyzers close to hydrogen demand and, consequently, power electrolyzers through the electricity grid. This conclusion comes from the fact that inflation has a similar impact on the electricity transmission infrastructure.

An important note regarding cost estimation is that most functions are based on European-wide data (or at least on a wide data set). While it can be appropriate for pan-European grid calculations due to pipeline diversity, it may not accurately reflect individual project costs due to regional variations in terrain, population density, and economic structure. Limited empirical data on hydrogen transmission pipelines introduces uncertainties, despite efforts to extrapolate from gas pipeline data and reduce bias. Material and labor costs, which constitute 70% to 80% of expenses, are subject to fluctuations in steel and energy prices, inflation, and workforce dynamics. Therefore, the calculation of costs using generic functions can result in potential errors and should be used with caution.

Although the initial prediction for 2030 in EN-H2 was of an electrolysis capacity of 2.5 GW [11], the current National Plan for Energy and Climate ([60]) sets a goal for the same year of 5.5 GW. To understand how much hydrogen production can be translated from this capacity it is necessary to know the capacity factor (CF) of electrolysis.

Based on International Renewable Energy Agency (IRENA) and Hydrogen Council reports, [85] and [86] respectively, the capacity factor can be estimated around 50%, considering a hybrid PV-wind plant.

An electrolysis capacity of 5.5 GW, with a CF of 50%, can produce approximately 24 TWh of hydrogen per year (a little over 600 ktH<sub>2</sub>). This exceeds the hydrogen consumption considered in all 54 scenarios for 2030 (ranging from 143 to 576 ktH<sub>2</sub>/year) during this methodology's application, although it would also support other projects beyond Celza. Based on this data, one

can assume that using one-third of the expected electrolysis capacity (approximately 200 ktH<sub>2</sub> per year), the project's financial viability may be secured (considering the 0.15€/kgH<sub>2</sub> criteria).

While this brief analysis provides a simple estimate for comparing the production required to meet internal consumption scenarios with the actual H<sub>2</sub> production capacity in Portugal, it falls outside the scope of this work. Nonetheless, it underscores the importance of evaluating the real market demand for green hydrogen in Portugal and aligning governmental goals for installed capacity with production capacity predictions.

Lastly, an important consideration that could be made is the impact of the repurposing of natural gas infrastructure on the Portuguese economic structure and energetic system. The net value of the national gas transportation network assets is, in 2024, of more than nine hundred million euros [87]. Considering the predicted evolution of natural gas consumption, if there is no repurpose, natural gas consumers may experience a price increase due to low consumption and high amortization values. Additionally, there is even a possibility that, if natural gas consumption gets too low, the taxpayers may have to pay for the rest of the assets with zero benefit. The conversion of this part of the national gas transportation network for the ENTH<sub>2</sub> allows the asset value to be charged through the network usage tariff, being paid by the ones who directly benefit from this H<sub>2</sub> transportation. However, this complex analysis is out of this dissertation's scope and is suggested for future works regarding methodologies for infrastructure repurpose.

Ultimately, this conversion will mainly benefit those avoiding the electrification, especially in hard-to-abate industries, or sectors where hydrogen is used as feedstock (like the production of ammonia, methanol, or SAFs). Other positive impacts should be analyzed regarding the electric system balance, transportation or domestic applications, for example.

## Chapter 5

# Conclusions

The proposed methodology outlined in this work is intended to serve as a proof-of-concept for network planning based on a strategic approach. It raises significant questions about the future of the energy sector, where the challenges are rapidly increasing. As efforts to transform energy production and ensure quality of life for future generations intensify, the design challenges of energy systems can benefit from the greatest evolutionary leap since the discovery of petroleum: Artificial Intelligence. AI is poised to dramatically alter human lives, with those who adapt quickly reaping the greatest benefits. This evolution is crucial for energy systems design, where project planning urgently needs to shift from analytical methods to AI-driven technology. This reflection is explored further in a subsequent section.

In addition to serving as a proof-of-concept, this work is primarily motivated by Portugal's ambition to play a significant role in the future green hydrogen market, aligning with European goals and contributing to a future characterized by independence, cooperation, and sustainability. The application of the developed methodology using CelZa not only provides valuable insights for project development but also exemplifies the critical information that should guide government and TSOs steps towards the implementation of hydrogen networks. The value of this type of work lies in the fact that current literature related to the subject is not yet very deepened compared with other energy systems design challenges, since it is a relatively recent problem.

Furthermore, as this dissertation aims to be a valuable tool for TSOs, its industrial implementation requires specific guidelines, which will be discussed in this chapter. Given the limited timeframe in which this work was developed, the primary goal was to support future adaptations and improvements. Consequently, several ideas for the evolution of the methodology will be proposed.

## 5.1 Main Conclusions of the Dissertation

- The methodology developed in this work, focused on hydrogen network planning, addresses a subject that is still scarcely covered in existing literature. This process considers the specific drivers of H<sub>2</sub>, combining several factors, such as geographic characteristics, production and consumption uncertainty, energy system integration, and financial viability. **The demand-side approach aims to address the market-driven nature of hydrogen, emphasizing the dependency on market existence for the successful implementation of hydrogen infrastructures.**
- This method was divided into three algorithms, **intending to be applicable to a vast number of problems and serve as support for future improvements, adaptations, or inspired methodologies.** The architecture of the three algorithms is designed to ensure that each can be used independently, expanding their potential industrial applications. Furthermore, the use of a genetic algorithm for the optimization process facilitates easier future adaptations due to its versatile nature.
- Using both DSS and CMA methods, it was possible to understand the possible national consumption for a future connection with CelZa. The results clearly show the challenges derived from CelZa's location, which is characterized by areas of low consumption and few relevant players in the industrial sector in comparison with other regions of the country. Nevertheless, it is also shown that there is sufficient consumption to ensure the project's viability, as long as exportation is considered or a large number of new players get involved. **The values obtained for possible internal hydrogen consumption, based on current data, range from 3.1 to 7.7 TWh per year.** Across all scenarios considered, **the average CO<sub>2</sub> emissions reduction was approximately one megatonne per year, representing 12.5% of the best-scenario target for 2030 (EN-H2).**
- The GA results demonstrate that **LCOHT has a decreasing tendency as consumption increases**, even though there is an increase in compression necessity and, therefore, in CAPEX. **The maximum investment obtained was 362 million euros**, considerably below the current prediction of 414 M€. This discrepancy is mainly due to the developed method not accounting for the initial investment needed to repurpose natural gas pipelines but instead reflecting the cost through increased OPEX.
- Results from the optimization methodology's application in CelZa show that **the project's economic viability may be achieved with one-third of the predicted electrolysis capacity for 2030 (5.5 GW according to [60]).** Considering that only consumers within a radius of 5 km from the network can be converted, the minimum scenario where this economic viability is ensured corresponds to converting half the natural gas, propane, and butane consumption in that region, balancing half the curtailment of electricity from renewables, and exporting at least 10 TWh of hydrogen per year to Spain.

## 5.2 Hydrogen: Proposed Solutions and Emerging Opportunities

### 5.2.1 Industrial Implementation of the Methodology

The developed methods intended to have the maximum industrial use possible, both by direct use of the algorithms or implementation of an adapted methodology. Even though there was a major concern in generalizing the algorithms, its implementation depend on specific project information and variables and, therefore, should be adapted in each case. In order to do so, some guidelines are provided below:

- This project was developed using Google Colab, which is a platform from Google that allows for an easy implementation of Python code. However, the algorithms can be implemented in any software that reads Python, with the required adaptations.
- Even though all algorithms can be implemented independently with some minor adaptations, in this case the DSS algorithm and the GA were developed to always work together, meaning that the GA's architecture requires some variables definition through DSS. Regarding CMA, it is already fully prepared to work independently.
- Both CMA and DSS algorithms functioning depend on the inputs provided, especially on the files format. Careful attention should be provided to the content format in the Excel files, ensuring that the tables are organized in the same way it is read by the code. Minor adaptations of those files may be required. For example, to use the DGEG consumption files, the pivot table has to be altered, changing the municipalities list from a filter to a row.
- The locations' coordinates are obtained via an API key provided freely by Google Maps. There is a possibility that this key expires and a new one should be generated. As an alternative, other APIs can be used to perform the same function.
- The algorithms work for other countries rather than Portugal, although the coordinates search should be modified for the specific intended country.
- Regarding the genetic algorithm there is a very high degree of adaptation required to ensure optimal functioning. The penalty calculation through hydraulic modelling should follow the same steps, but is extremely dependent of the project specifications and methodology assumptions. Moreover, the population generation process and genetic operations are also dependent of the representation of the solutions chosen and, consequently, of the optimization variables identified. Results display and manual calibration would also need modifications. Therefore, any adaptation of the algorithm should be done with extreme caution, requiring considerable programming knowledge.

As for the methodology itself, it can be used freely in any context and its adaptation in future works will allow the near-optimal implementation of hydrogen infrastructures.

### 5.2.2 Analytical vs AI

The optimization technique employed and discussed throughout this work, the genetic algorithm, falls under the category of intelligent search algorithms. This technique, a specific form of artificial intelligence, was initially developed around 1975 [45]. As highlighted, its application in this methodology serves several purposes, including setting a proof-of-concept for the application of AI-based methods in the specific context of hydrogen network planning. Although there is extensive literature on the application of intelligent search in various network planning scenarios, current approaches still favor analytical methods.

Conversely, intelligent search methodologies have been increasingly implemented due to the rising complexity in the design variables. This complexity arises from synergies between different sectors as global organizations strive for more sustainable, efficient, and integrated energy systems, driven significantly by the electrification process.

The deployment of a hydrogen market introduces several challenges and complexities. However, it also offers significant benefits, leveraging the transformative period we are currently experiencing. The recent advancements in generative AI, exemplified by tools such as ChatGPT, are poised to drastically impact the world and coincide perfectly with the escalating challenges in the energy system. A study by McKinsey & Company [88] assesses the potential impact of generative AI on the global economy, predicting it could contribute between \$2.6 trillion and \$4.4 trillion annually. The study also indicates that generative AI is expected to have the most significant impact on knowledge work, particularly activities involving decision-making and collaboration, which previously had the lowest potential for automation. Previous generations of automation technologies, such as genetic algorithms, excelled in automating data management assignments like data collection and processing. The natural language capabilities of generative AI considerably increase the possibility for automation in these operations, resulting in better-informed decisions.

Ultimately, the transition by TSOs from analytical methods to the implementation of objective and non-biased optimization techniques is crucial for the future management of energy systems. This shift aims to ensure the preservation of natural resources for future generations while optimizing system efficiency and sustainability.

### 5.2.3 Future Works

The following future works are proposed:

- Adaptation of the methodology to include consumption profiles in the scenarios, allowing the modelling of the flow variation with time. With this improvement the compressors' cost of operation can take into account the use factor of the compressors, allowing for a more realistic optimization and cost estimation. Considering this time variation, it may even be possible to perform a continuous evaluation of the costs, compared to the current solution of two specific moments.

- In addition to the ones analyzed, several other network parameters can be included as optimization variables, such as storage, network flexibility and pipeline layout. The last one can take into account the potential of production and the consumption profiles by region.
- Inclusion of other variables to calculate the costs. There are several possibilities, for example taking into account the inflation, support mechanisms like guarantees of origin and funding through EU programs, remuneration fees with margin for profit, etc.
- In CelZa's specific case, some improvements should also be performed. Some simplifications may be addressed, for example using the real diameter between Mangualde and Celorico da Beira or changing the assumptions regarding production sites, reducing uncertainty and avoiding similarly extreme scenarios. The diameter of the new pipe between Figueira da Foz and Cantanhede should be considered an optimization variable in future adaptations. In addition, some "out of the box" solutions may be investigated, like parallel or redundant piping, for example.
- Other optimization algorithms can be used and compared in terms of accuracy (for example Tabu Search, Memetic Algorithms or Simulated Annealing). Ultimately, generative AI should be integrated to achieve the full potential of intelligent search.
- An user-friendly interface can be added to allow for quick and more intuitive use of this tool.
- This type of methodology can be adapted in the future for distribution networks, adding another degree of complexity due to the meshed characteristics of the network. In addition, geographical data should have a higher resolution to support such method.
- It is also proposed the development of a methodology for the repurposing of the natural gas network, assessing specific details such as operational lifetime, tariff impact or consumers benefit regarding assets amortization.

**Note:** The author plans to publish an article detailing the developed methodology and its application in the case study. Currently, an article based on the deep literature review conducted during the State of the Art chapter is in the submission process.



## **Appendix A**

# **Overview of EU's Hydrogen Infrastructure Projects**

Table A.1: European partners' current consumptions and future perspectives regarding 100% hydrogen infrastructures.

Country	Operators	Current gas network extension	Final energy consumption w/o household (TWh/year)	Natural Gas consumption (TWh/year)	N° 100% H2 infrastructure projects	Expected date of first commissioning	References
Austria	GCA and TAG	1 700 km	211	50	3	2030	[89], [90], [91]
Belgium	Fluxys	4 000 km	268	97	2	2026	[92], [93], [94]
Bulgaria	Bulgartransgaz	3 380 km	90	13	1	2029	[26]
Croatia	Plinacro	2 500 km	52	12	1	2040	[95]
Czech Rep.	NET4GAS	4 000 km	199	55	2	2030	[96], [97]
Denmark	Energinet	1 250 km	105	16	3	2030	[98], [99], [100]
Estonia	Elering	977 km	20	2	1	2030	[101]
Finland	Gasgrid Finland	1 300 km	204	7	3	2030	[101], [102], [103]
France	GRTgaz and Teréga	37 000 km	1110	287	8	2027	[54], [55]
Germany	ONTRAS, OGE, GASCADE and Gasunie	40 000 km	1548	590	19	2025	[104], [63], [105]
Great Britain	National Gas Transmission	7 630 km	-	-	1	2030s	[106]
Greece	DESFA	1 456 km	129	14	1	2030s	[27]
Hungary	FGSZ	5 874 km	141	60	2	2030	-
Ireland	GNI	2 477 km	97	21	1	2040	[107]
Italy	Snam	32 500 km	940	371	1	2030	[108]
Latvia	Conexus Baltic Grid	1 190 km	32	3	0	-	-
Lithuania	Amber Grid	2 285 km	44	7	1	2030	-
Luxembourg	Creos	2 175 km	30	6	1	2027	[109]
Netherlands	Gasunie	16 000 km	359	161	3	2025	[61]
Norway	Gassco	9 000 km	179	4	1	2030	[110]
Romania	Transgaz	14 000 km	186	63	1	-	[29]
Slovakia	EUSTREAM	2 200 km	84	28	2	2030	[96]
Slovenia	Plinovodi	1 195 km	43	6	1	2029	-
Spain	Enagás	11 000 km	740	145	3	2030	[50], [51]
Sweden	Nordion Energi	-	281	6	2	2030	[103], [102]
Switzerland	Transitgas AG and FluxSwiss SAGL	512 km	-	-	0	-	[111], [112]
Ukraine	TSO of UA	-	-	-	1	2030	[96]

Table A.2: European partners' 100% hydrogen infrastructure projects (corridors A, B and C).

Project	Corridor	Operators	Planned investment	Capacity (GWh/day)	First CoD	Repurposed pipelines (%)	Ref.
Italian Hydrogen Backbone (part of SouthH2 Corridor and Sunshyne Corridor)	A	Snam	-	450 import; 170 export	2030	73%	[108], [113]
H2 Readiness of the TAG Pipeline System (part of SouthH2 Corridor and Sunshyne Corridor)	A	TAG	-	168	2030	100%	[108], [113], [90]
H2 Backbone WAG + Penta West (part of SouthH2 corridor)	A	Gas Connect Austria	-	150	2030	40%	[108], [89]
H2 Backbone Murfeld	A	Gas Connect Austria	-	33	-	0%	[91]
Slovenian Hydrogen Backbone - Central Region	A	Plinovodi	-	33	2029	-	-
Spanish Hydrogen Backbone	B	Enagás	4,9 B €	-	2030	-	[51], [52]
HySoW (Hydrogen South-West corridor of France)	B	Teréga	-	44	2030	28%	[55]
BarMar (part of H2Med corridor)	B	GRTgaz, Teréga, Enagás	1 B € (Spain)	215	2030	0%	[52], [50]
HY-FEN	B	GRTgaz	-	200	2030	-	[114]
Hydrogen Network Netherlands	C	Gasunie	1,5 B €	240 - 360	2025	85%	[61], [62]
Danish-German Hydrogen Network	C	Gasunie, Energinet	-	240	2028	-	[98]
H2T (Hydrogen Offshore Transport)	C	Gassco	2,6 - 4,7 B €	430	2030	-	[110]
AquaDuctus	C	GASCADE, Fluxys	-	480	2030	0%	[92]

Table A.3: European partners' 100% hydrogen infrastructure projects (corridors D, E and Germany).

Project	Corridor	Operators	Planned investment	Capacity (GWh/day)	First CoD	Repurposed pipelines (%)	References
Nordic-Baltic Hydrogen Corridor	D	Amber Grid, Conexus Baltic Grid, Elering, Gasgrid Finland, Ontras, Gaz System Poland	-	-	2030	-	[101]
The Nordic Hydrogen Route - Bothnian Bay	D	Gasgrid Finland, Nordion Energi	3,5 B €	-	2030	0%	[102]
Baltic Sea Hydrogen Collector	D	Nordion Energi, OX2, Gasgrid Finland, Copenhagen Infrastructure Partners	-	810	2030	0%	[103]
Interconnector Bornholm-Lubmin	D	GASCADE, Energinet	-	240	2027	-	[99]
Central European Hydrogen Corridor CEHC	E	TSO of UA, EUSTREAM, NET4GAS, OGE	1-1,5 B €	144	2030	90%	[96]
Flow - Making Hydrogen Happen	Germany	Ontras, GASCADE	-	480	2025	-	[63]
H2ercules	Germany	OGE	3 B €	-	2030	> 50%	[104]
Czech-German Hydrogen Interconnector (CGHI)	Germany	GASCADE, NET4GAS, OGE	-	144	2030	90-100%	[97]
doing Hydrogen	Germany	ONTRAS	-	-	2027/2028	60%	[115]
Green Octopus Mitteldeutschland	Germany	ONTRAS	-	-	2027	60%	[116]
Hyperlink 3	Germany	Gasunie	-	60-200	2028	-	[117]

## **Appendix B**

# **EHB Projects Map**

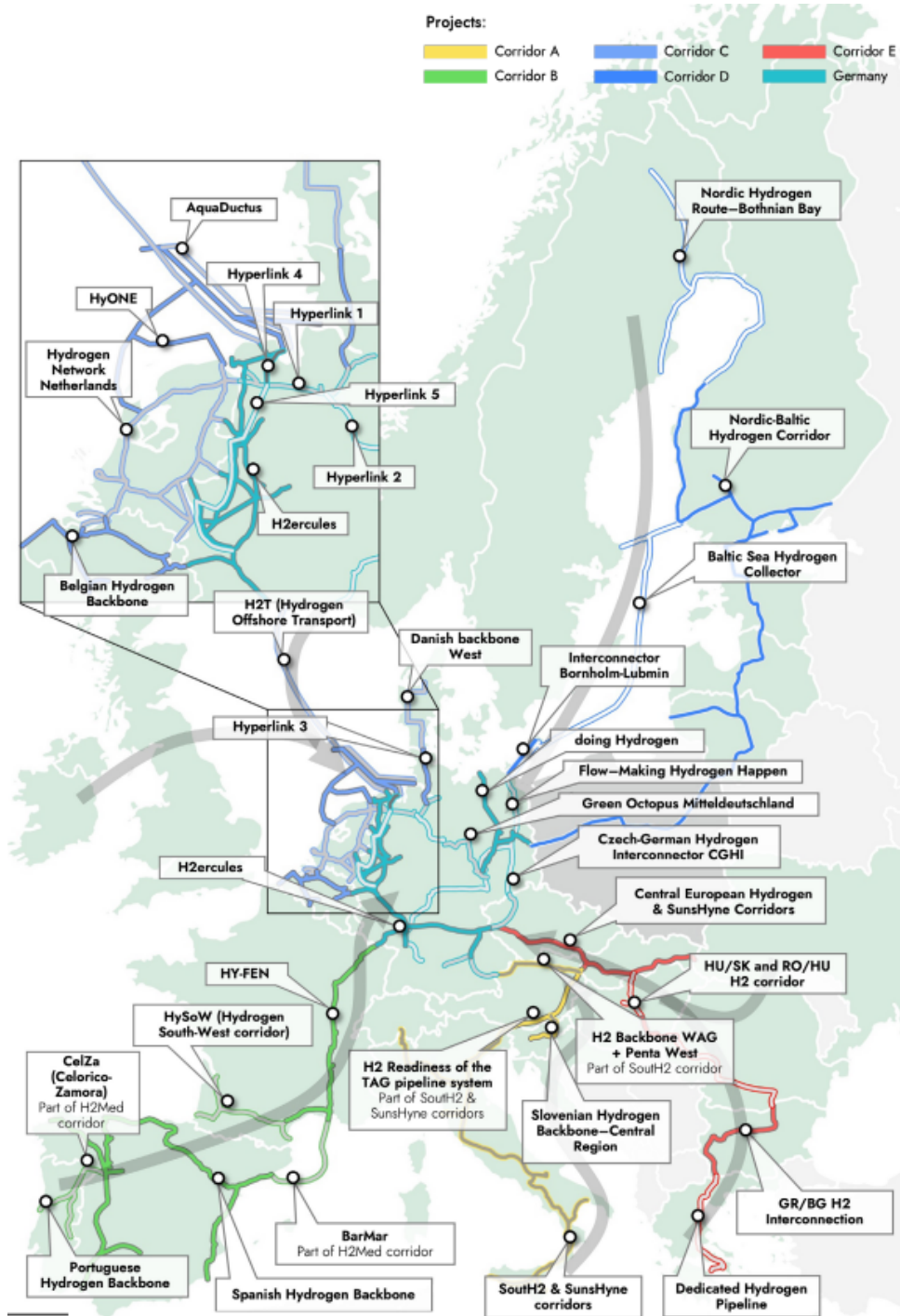


Figure B.1: Detailed map of the EHB infrastructure projects [7].

## Appendix C

# Germany's Hydrogen Infrastructure Projects

Table C.1: Germany's projects overview.

Project	Capacity (GWh/day)	Final Length (km)	First CoD	References
<b>Flow - Making Hydrogen Happen</b>	480	1100	2025	[63]
<b>H2ercules</b>	-	2000	2025	[104]
<b>Czech-German Hydrogen Interconnector</b>	-	-	2030	[97]
<b>doing Hydrogen</b>	-	-	2027/28	[115]
<b>Green Octopus Mitteldeutschland</b>	-	305	2027	[116]
<b>Hyperlink</b>	-	1000	2026	[118]
<b>RHYn</b>	20	100	2028	[54]
<b>MosaHYc</b>	6	90	2027	[54]
<b>Central European Hydrogen Corridor</b>	144	1225	2030	[96]
<b>Aquaductus</b>	480	400	2030	[92]
<b>H2T</b>	430	-	2030	[110]
<b>Interconnector Bornholm-Lubmin</b>	240	140	2027	[99]
<b>HyPipe Bavaria – The Hydrogen Hub</b>	-	300	2030	[66]
<b>Energiepark Bad Lauchstädt</b>	-	25	2025	[58]
<b>H2 North-South Corridor</b>	-	400	2028	[58]
<b>H2 East-West Corridor</b>	-	320	2032	[58]
<b>H2Coastlink</b>	-	240	2027	[119]
<b>H2EU+Store</b>	220	-	2030	[120]
<b>TH2ECO</b>	-	42	2025	[64]



## Appendix D

# Search Space Calculations

Equation D.1 and Equation D.2 were developed to allow a general calculation of the search space of the problem, using the suggested methodology. The first one is used to calculate the number of different genotypes that can be considered. If there is no consideration of repeated solutions, it is required to remove the cases where the genotype is indeed different, but represent the same phenotype (real-world representation of the network), using the second equation.

$$(N_d)^p \times \left[ \sum_{k=0}^s \binom{s}{k} \cdot \frac{s!}{(s-k)!} \cdot (N_c)^k \right]^2 \quad (\text{D.1})$$

$$(N_d)^p \times \left[ \sum_{k=0}^s \binom{s}{k} \cdot (N_c)^k \right]^2 \quad (\text{D.2})$$

In the equations above,  $p$  represents the number of new pipelines,  $s$  the number of pipeline sections,  $N_d$  the number of available diameters, and  $N_c$  is the number of available compression powers.

Both equations takes into account the possible values for the pipeline diameters across all new pipelines projected,  $(N_d)^p$ . The difference relies in the calculation of possibilities for the compression stations.

In Equation D.1 for each possible number of compressors  $k$  it is used the binomial coefficient  $\binom{s}{k}$  to calculate the number of ways to choose  $k$  compressors from  $s$  possibilities (one in each section, see subsection 3.2.4), times the number of ways to arrange  $k$  compressors in  $s$  positions  $\left(\frac{s!}{(s-k)!}\right)$ , times the possibilities for compression power available  $(N_c)^k$ .

In Equation D.2, the calculation differs in the fact that the number of ways to arrange  $k$  compressors in  $s$  positions  $\left(\frac{s!}{(s-k)!}\right)$  is neglected, to reject solutions that represent the same phenotype.

Utilizing both equations it is possible to obtain the values indicated in subsection 3.2.4 for the search space provided as example and shown in Figure 3.7:

$$(3)^1 \times \left[ \sum_{k=0}^2 \binom{2}{k} \cdot \frac{2!}{(2-k)!} \cdot (3)^k \right]^2 = 2,883$$
$$(3)^1 \times \left[ \sum_{k=0}^2 \binom{2}{k} \cdot (3)^k \right]^2 = 768$$







## **Appendix F**

# **Mapping of National Regions Decarbonization Potential**

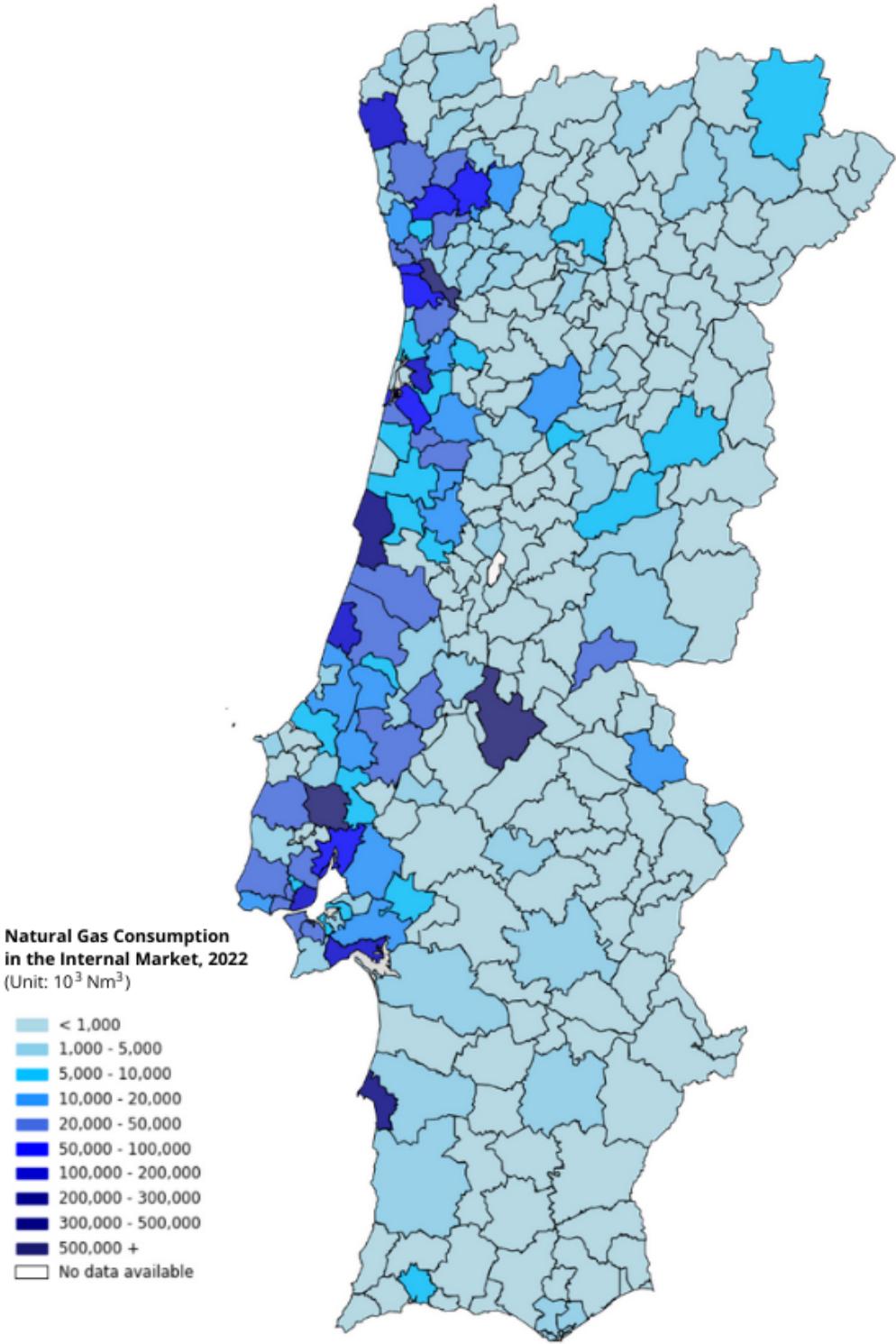


Figure F.1: Portuguese natural gas consumption by region in 2022.

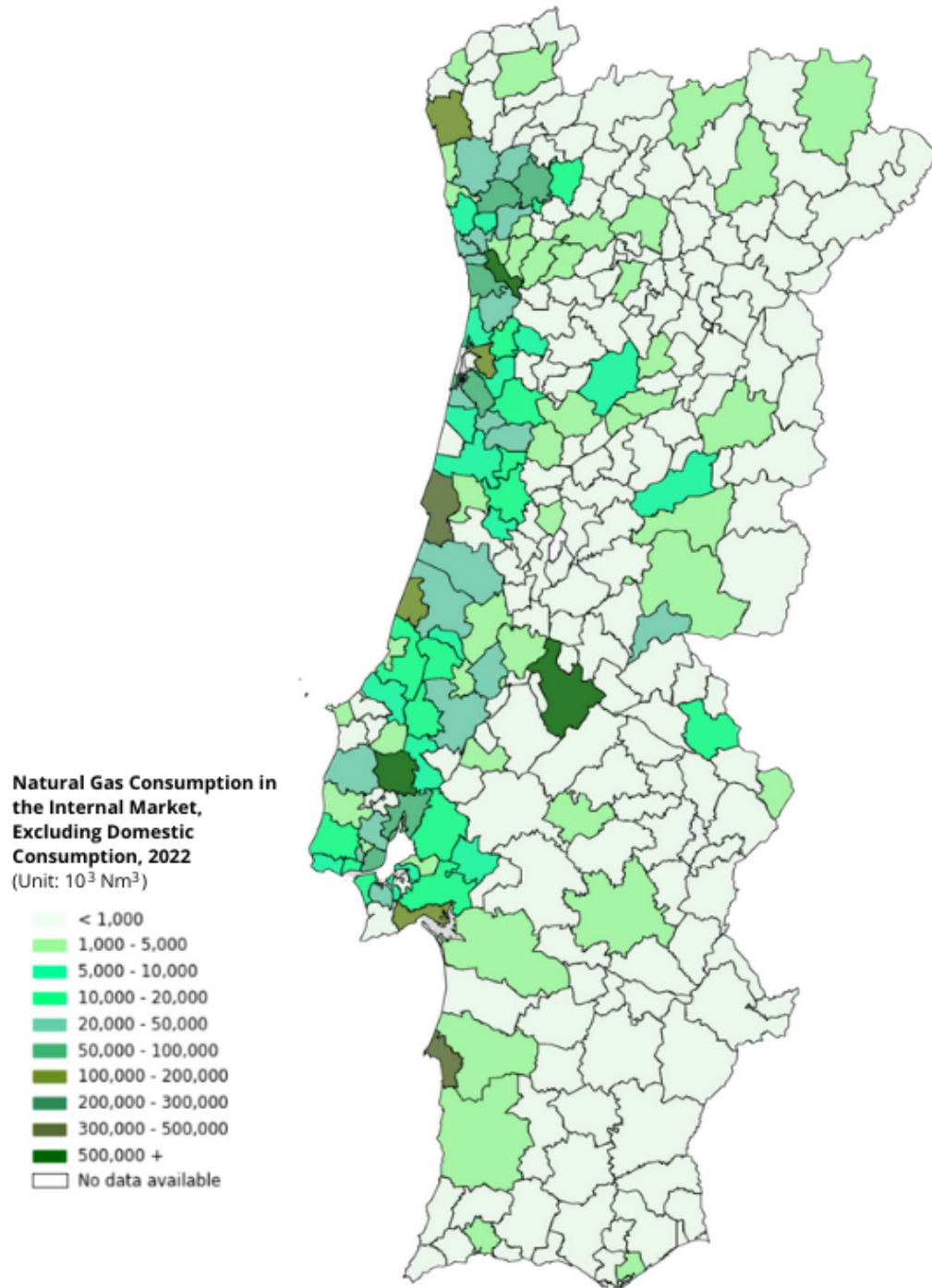


Figure F.2: Portuguese natural gas consumption by region in 2022, excluding the domestic sector.

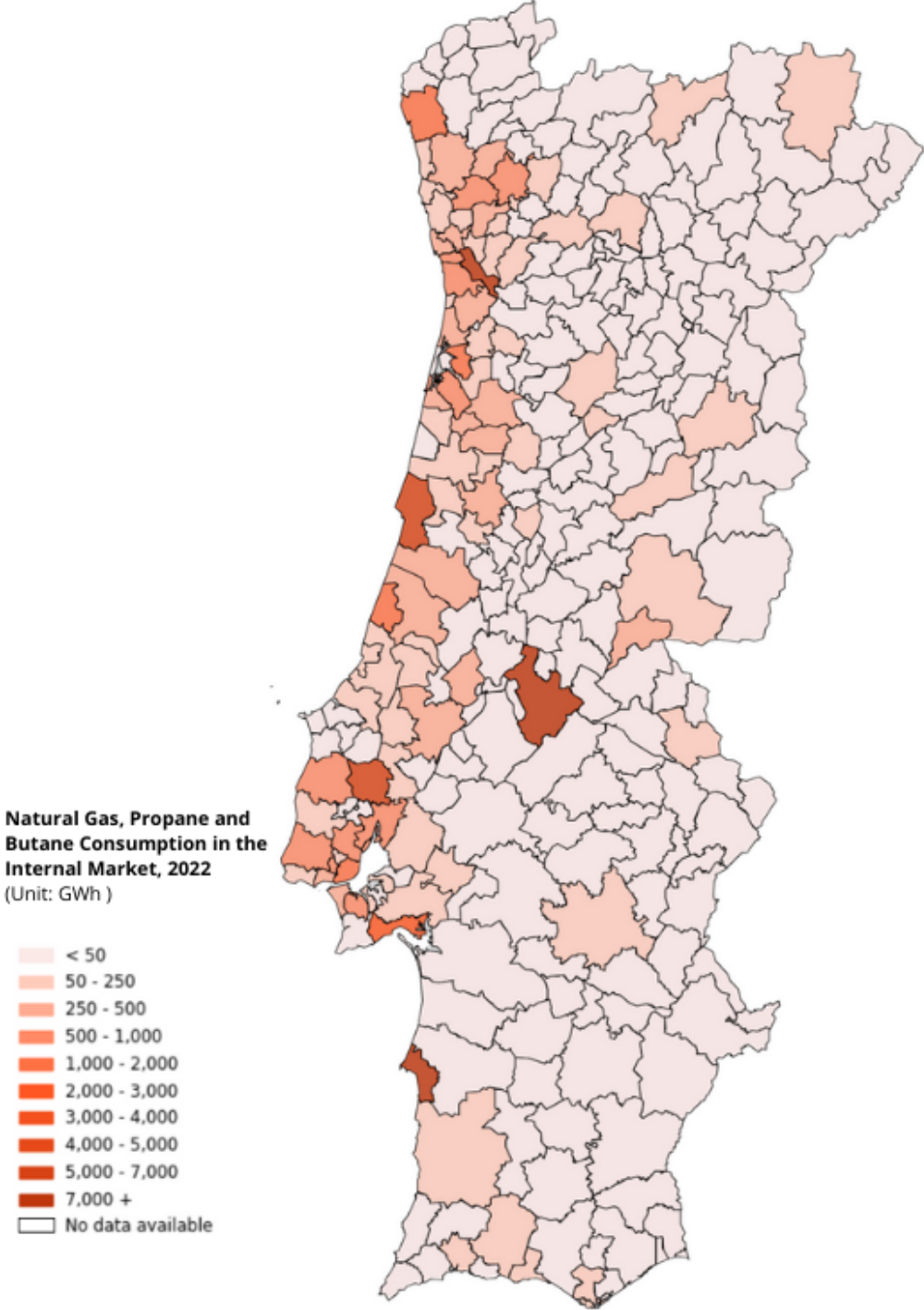


Figure F.3: Portuguese natural gas, propane and butane consumption by region in 2022.

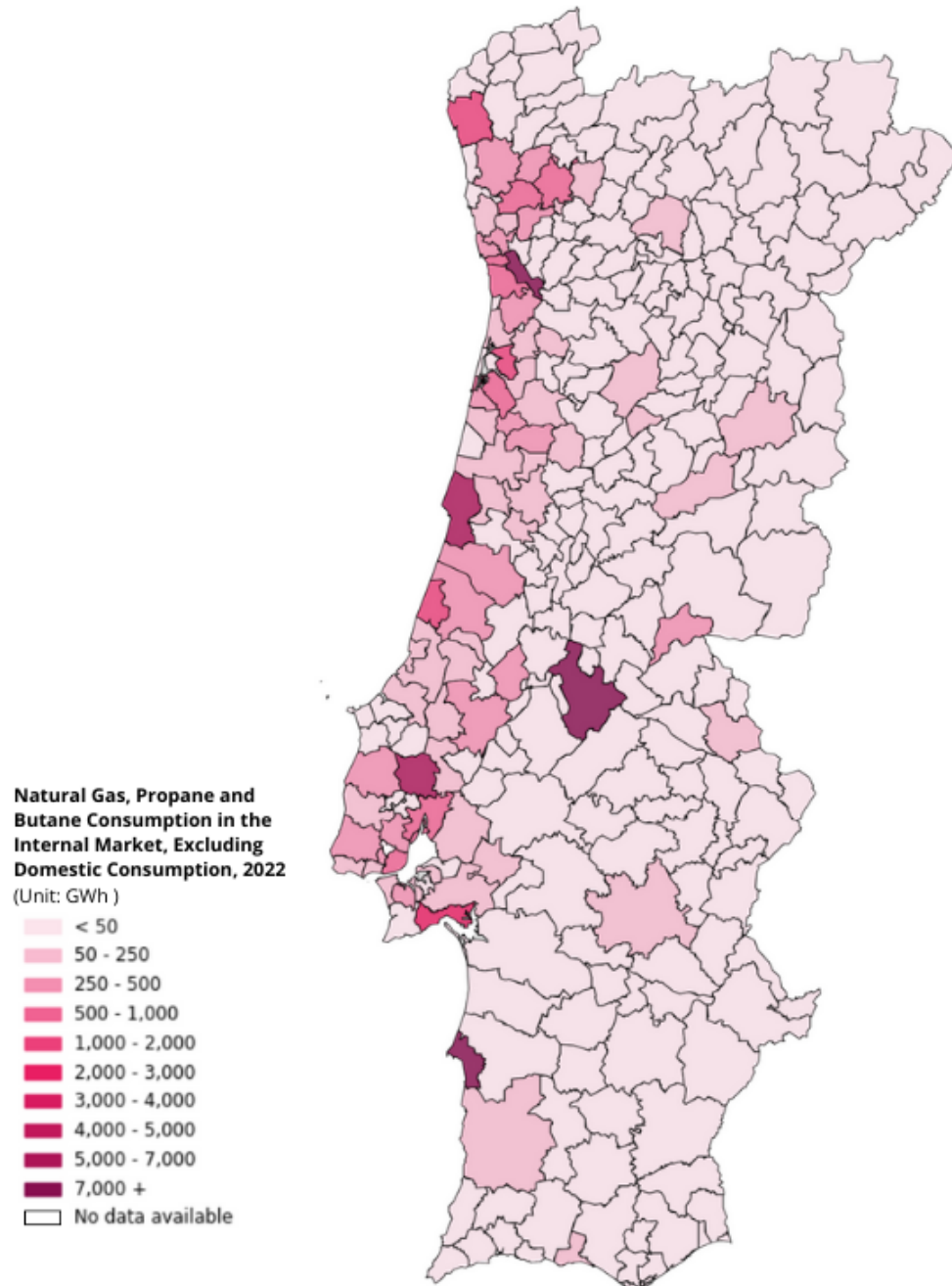


Figure F.4: Portuguese natural gas, propane and butane consumption by region in 2022, excluding the domestic sector.



## Appendix G

# Portugal's Population and Company Density

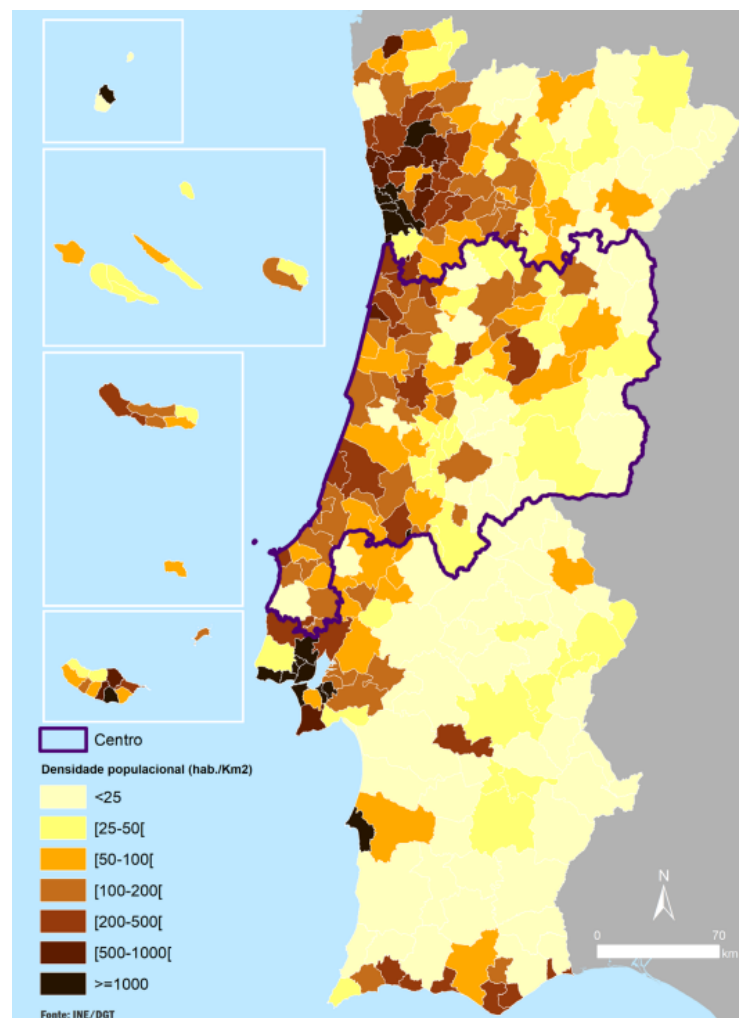


Figure G.1: Population density in Portugal, 2021 [121]. Unit: [residents/km<sup>2</sup>].

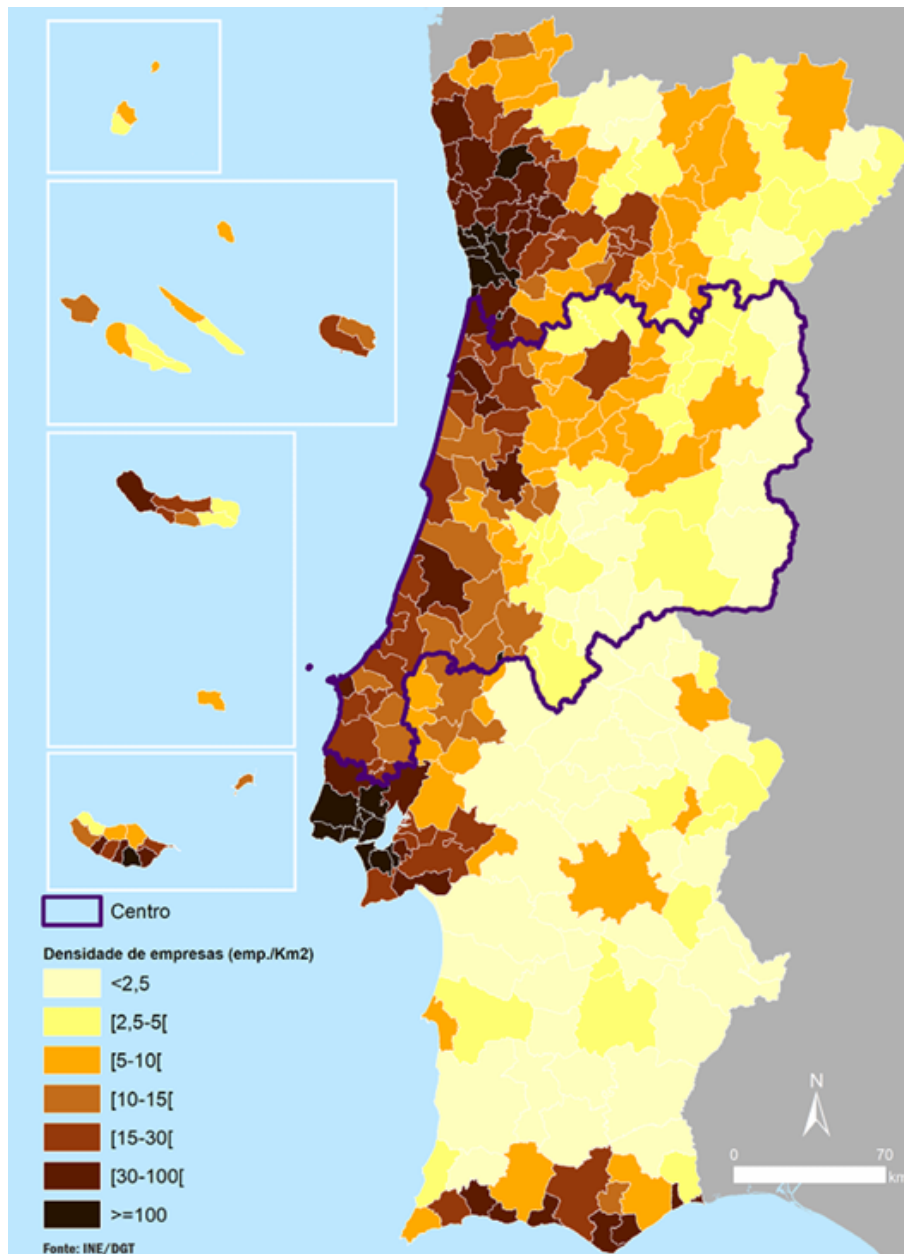


Figure G.2: Company density in Portugal, 2021 [121]. Unit: [companies/km<sup>2</sup>].

## Appendix H

# DSS Results for Consumption Inside Respective Areas of Influence

Table H.1: Natural gas, Propane and Butane consumption in a 5-kilometer radius of CelZa.

<b>Municipality</b>	<b>Total consumption</b>	<b>Domestic consumption</b>	<b>Total consumption w/o domestic</b>
<b>Anadia</b>	358	8	350
<b>Belmonte</b>	3	2	1
<b>Cantanhede</b>	144	30	114
<b>Castelo Branco</b>	81	36	45
<b>Celorico da Beira</b>	5	2	3
<b>Covilhã</b>	107	28	79
<b>Figueira da Foz</b>	5098	72	5026
<b>Fornos de Algodres</b>	3	1	2
<b>Fundão</b>	40	10	30
<b>Guarda</b>	94	32	62
<b>Macedo de Cavaleiros</b>	15	8	7
<b>Mealhada</b>	138	6	132
<b>Mortágua</b>	63	6	57
<b>Nelas</b>	65	5	60
<b>Portalegre</b>	146	14	132
<b>Santa Comba Dão</b>	16	7	9
<b>Tondela</b>	36	11	25
<b>Vila Nova de Foz Côa</b>	5	2	3
<b>Viseu</b>	239	113	126
<b>Total</b>	6656	393	6263

Table H.2: Natural gas, Propane and Butane consumption in a 10-kilometer radius of CelZa.

<b>Municipality</b>	<b>Total consumption</b>	<b>Domestic consumption</b>	<b>Total consumption w/o domestic</b>
<b>Anadia</b>	358	8	350
<b>Belmonte</b>	3	2	1
<b>Cantanhede</b>	144	30	114
<b>Carregal do Sal</b>	7	2	5
<b>Castelo Branco</b>	81	36	45
<b>Castelo de Vide</b>	3	0	3
<b>Celorico da Beira</b>	5	2	3
<b>Covilhã</b>	107	28	79
<b>Figueira da Foz</b>	5098	72	5026
<b>Fornos de Algodres</b>	3	1	2
<b>Fundão</b>	40	10	30
<b>Gouveia</b>	10	3	7
<b>Guarda</b>	94	32	62
<b>Macedo de Cavaleiros</b>	15	8	7
<b>Mangualde</b>	46	9	37
<b>Mealhada</b>	138	6	132
<b>Meda</b>	3	0	3
<b>Mortágua</b>	63	6	57
<b>Nelas</b>	65	5	60
<b>Nisa</b>	7	5	2
<b>Portalegre</b>	146	14	132
<b>Santa Comba Dão</b>	16	7	9
<b>Tondela</b>	36	11	25
<b>Torre de Moncorvo</b>	6	4	2
<b>Trancoso</b>	7	2	5
<b>Vila flor</b>	5	3	2
<b>Vila Nova de Foz Côa</b>	5	2	3
<b>Vimioso</b>	5	3	2
<b>Viseu</b>	239	113	126
<b>Vila Velha de Ródão</b>	260	0	260
<b>Total</b>	7015	424	6591

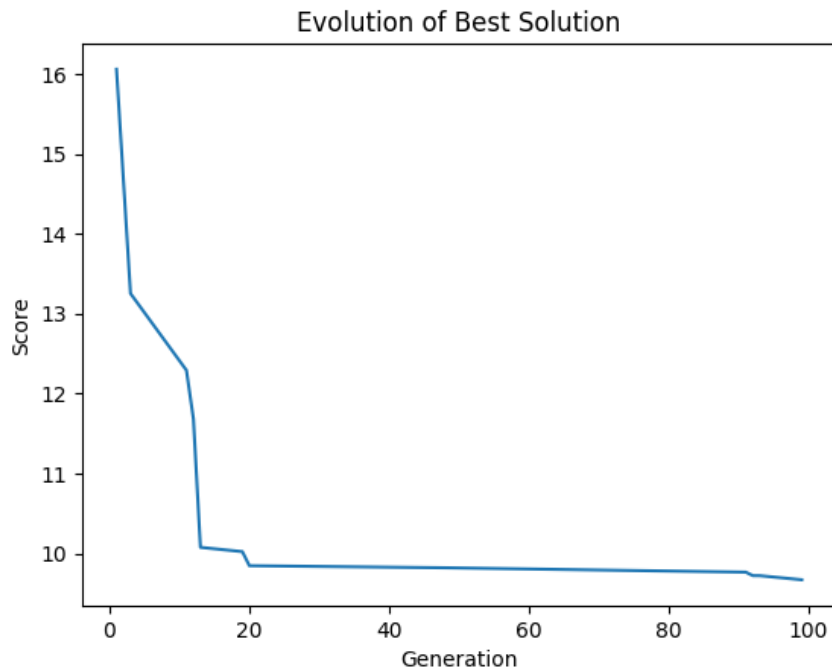
Table H.3: Natural gas, Propane and Butane consumption in a 20-kilometer radius of CelZa.

<b>Municipality</b>	<b>Total consumption</b>	<b>Domestic consumption</b>	<b>Total consumption w/o domestic</b>
Águeda	257	23	234
Alfândega da Fé	3	1	2
Anadia	358	8	350
Belmonte	3	2	1
Cantanhede	144	30	114
Carregal do Sal	7	2	5
Castelo Branco	81	36	45
Castelo de Vide	3	0	3
Celorico da Beira	5	2	3
Covilhã	107	28	79
Crato	4	2	2
Figueira da Foz	5098	72	5026
Fornos de Algodres	3	1	2
Fundão	40	10	30
Gouveia	10	3	7
Guarda	94	32	62
Macedo de Cavaleiros	15	8	7
Mangualde	46	9	37
Manteigas	3	1	2
Marvão	2	1	1
Mealhada	138	6	132
Meda	3	0	3
Mira	16	4	12
Mirandela	40	17	23
Monforte	1	1	0
Montemor-o-Velho	69	9	60
Mortágua	63	6	57
Nelas	65	5	60
Nisa	7	5	2
Oliveira do Bairro	416	6	410
Penacova	5	4	1
Penalva do Castelo	4	0	4
Portalegre	146	14	132
Santa Comba Dão	16	7	9
Seia	32	11	21
Tábua	8	3	5
Tondela	36	11	25
Torre de Moncorvo	6	4	2
Trancoso	7	2	5
Vila flor	5	3	2
Vila Nova de Foz Côa	5	2	3
Vimioso	5	3	2
Viseu	239	113	126
Arronches	0	0	0
Vila Velha de Ródão	260	0	260
<b>Total</b>	<b>7875</b>	<b>507</b>	<b>7368</b>



## **Appendix I**

# **Results Output of the Genetic Algorithm**



Optimal solution found on generation 99  
 Best Solution: ['500' '1' 'B' '0' '0' '5' '0' '0' '3' 'B' 'A' 'C' '21' '8' '24']  
 Best Score: -9.669065534700387  
 New pipeline diameter: 500 mm  
 Initial stage:  
   Need for compressors? - Yes  
   How many? - 1 ; Where? - B  
   Compression solution for pipeline B: 5 MW  
 Final stage:  
   Need for additional compressors? - Yes  
   How many? - 3 ; Where? - ('B', 'A', 'C')  
   Compression solution for pipeline B: 21 MW  
   Compression solution for pipeline A: 8 MW  
   Compression solution for pipeline C: 24 MW  
 Did it violated any restriction? - No  
 Penalty: 0  
 Tariff in phase 1: 0.112 €/kgH2  
 Tariff in phase 2: 0.057 €/kgH2  
 Total estimated CAPEX: 353.2 M€  
 CAPEX 1: 320.3 M€  
 CAPEX 2: 32.8 M€  
 Maximum consumption allowed: 720 ktH2/year  
 Initial H2 production capacity required: 285 ktH2/year  
 H2 production capacity required to fill 85% of the pipeline: 612 ktH2/year  
 Expansion capacity: 2.5 times the initial consumption.  
 Immediate national decarbonization impact: 538 ktoe

Figure I.1: Example output of the GA.

## **Appendix J**

# **Optimal Network Parameters for the 54 Scenarios**

The results are divided in two tables ([Table J.1](#) and [Table J.2](#)), due to the extension of the data <sup>1</sup>.

---

<sup>1</sup>"Consump." refers to "consumption", "CS" means "compression stations", while "comp." replaces "compression".

Table J.1: Results of the GA implementation for all scenarios (part 1).

Scenario	Initial consump. [TWh/year]	Internal consump. [GWh/year]	External consump. [GWh/year]	CAPEX [M €]	Tariff 1 [€/kgH2]	Tariff 2 [€/kgH2]	DN [mm]	Initial CS locations	Initial comp. power [MW]	CS locations in 2nd phase	Comp. power in 2nd phase [MW]
I-A	11,263	6263	5000	343,6	0,111	0,056	500	B	1	A, B	30, 25
I-B	11,591	6591	5000	343,6	0,108	0,056	500	B	1	A, B	30, 25
I-C	12,368	7368	5000	343,6	0,101	0,056	500	B	1	A, B	30, 25
II-A	16,263	6263	10000	351,6	0,078	0,056	500	B	20	A, B	30, 25
II-B	16,591	6591	10000	351,6	0,076	0,056	500	B	20	A, B	30, 25
II-C	17,368	7368	10000	351,6	0,073	0,056	500	B	20	A, B	30, 25
III-A	21,263	6263	15000	361,4	0,060	0,057	500	A, B	11, 22	A, B	30, 25
III-B	21,591	6591	15000	361,4	0,059	0,057	500	A, B	11, 22	A, B	30, 25
III-C	22,368	7368	15000	362	0,057	0,057	500	A, B	13, 22	A, B	30, 25
IV-A	5,632	3132	2500	339,9	0,221	0,056	500	0	0	A, B	30, 25
IV-B	5,796	3296	2500	339,9	0,215	0,056	500	0	0	A, B	30, 25
IV-C	6,184	3684	2500	339,9	0,201	0,056	500	0	0	A, B	30, 25
V-A	8,132	3132	5000	343,6	0,154	0,056	500	B	1	A, B	30, 25
V-B	8,296	3296	5000	343,6	0,151	0,056	500	B	1	A, B	30, 25
V-C	8,684	3684	5000	343,6	0,144	0,056	500	B	1	A, B	30, 25
VI-A	10,632	3132	7500	348,2	0,119	0,056	500	B	8	A, B	30, 25
VI-B	10,796	3296	7500	348,2	0,117	0,056	500	B	8	A, B	30, 25
VI-C	11,184	3684	7500	348,2	0,113	0,056	500	B	8	A, B	30, 25
VII-A	11,599	6599	5000	344,8	0,108	0,056	500	B	2	A, B	30, 25
VII-B	11,927	6927	5000	344,8	0,105	0,056	500	B	2	A, B	30, 25
VII-C	12,704	7704	5000	344,8	0,099	0,056	500	B	2	A, B	30, 25
VIII-A	16,599	6599	10000	351,6	0,076	0,056	500	B	20	A, B	30, 25
VIII-B	16,927	6927	10000	351,6	0,075	0,056	500	B	20	A, B	30, 25
VIII-C	17,704	7704	10000	355,4	0,072	0,057	500	A, B	1, 20	A, B	30, 25
IX-A	21,599	6599	15000	361,7	0,059	0,057	500	A, B	12, 22	A, B	30, 25
IX-B	21,927	6927	15000	361,7	0,059	0,057	500	A, B	12, 22	A, B	30, 25
IX-C	22,704	7704	15000	362,3	0,057	0,057	500	A, B	14, 22	A, B	30, 25

Table J.2: Results of the GA implementation for all scenarios (part 2).

Optim

Scenario	Initial consump. [TWh/year]	Internal consump. [GWh/year]	External consump. [GWh/year]	CAPEX [M €]	Tariff 1 [€/kgH2]	Tariff 2 [€/kgH2]	DN [mm]	Initial CS locations	Initial comp. power [MW]	CS locations in 2nd phase	Comp. power in 2nd phase [MW]
X-A	8,699	4949	3750	339,9	0,143	0,056	500	0	0	A, B	30, 25
X-B	8,945	5195	3750	339,9	0,139	0,056	500	0	0	A, B	30, 25
X-C	9,528	5778	3750	339,9	0,131	0,056	500	0	0	A, B	30, 25
XI-A	12,449	4949	7500	348,6	0,101	0,056	500	B	9	A, B	30, 25
XI-B	12,695	5195	7500	348,6	0,099	0,056	500	B	9	A, B	30, 25
XI-C	13,278	5778	7500	348,9	0,095	0,056	500	B	10	A, B	30, 25
XII-A	16,199	4949	11250	351,8	0,078	0,056	500	B	21	A, B	30, 25
XII-B	16,445	5195	11250	351,8	0,077	0,056	500	B	21	A, B	30, 25
XII-C	17,028	5778	11250	355,6	0,075	0,057	500	A, B	1, 21	A, B	30, 25
XIII-A	5,800	3300	2500	339,9	0,215	0,056	500	0	0	A, B	30, 25
XIII-B	5,964	3464	2500	339,9	0,209	0,056	500	0	0	A, B	30, 25
XIII-C	6,352	3852	2500	339,9	0,196	0,056	500	0	0	A, B	30, 25
XIV-A	8,300	3300	5000	343,6	0,151	0,056	500	B	1	A, B	30, 25
XIV-B	8,464	3464	5000	343,6	0,148	0,056	500	B	1	A, B	30, 25
XIV-C	8,852	3852	5000	343,6	0,141	0,056	500	B	1	A, B	30, 25
XV-A	10,800	3300	7500	348,6	0,117	0,056	500	B	9	A, B	30, 25
XV-B	10,964	3464	7500	348,6	0,115	0,056	500	B	9	A, B	30, 25
XV-C	11,352	3852	7500	348,6	0,111	0,056	500	B	9	A, B	30, 25
XVI - A	8,300	3300	5000	343,6	0,151	0,056	500	B	1	A, B	30, 25
XVI - B	8,464	3464	5000	343,6	0,148	0,056	500	B	1	A, B	30, 25
XVI - C	8,852	3852	5000	343,6	0,141	0,056	500	B	1	A, B	30, 25
XVII - A	13,300	3300	10000	351,6	0,095	0,056	500	B	20	A, B	30, 25
XVII - B	13,464	3464	10000	351,6	0,094	0,056	500	B	20	A, B	30, 25
XVII - C	13,852	3852	10000	351,6	0,091	0,056	500	B	20	A, B	30, 25
XVIII - A	18,300	3300	15000	359	0,07	0,057	500	A, B	5, 22	A, B	30, 25
XVIII - B	18,464	3464	15000	359	0,069	0,057	500	B, C	22, 5	A, B	30, 25
XVIII - C	18,852	3852	15000	359	0,068	0,057	500	B, C	22, 5	A, B	30, 25



# References

- [1] Xianlong Ge, Yuanzhi Jin, and Jingzheng Ren. A data-driven approach for the optimization of future two-level hydrogen supply network design with stochastic demand under carbon regulations. *Journal of Cleaner Production*, 365, 2022.
- [2] Peter Kotek, Borbála Takácsné Tóth, and Adrienn Selei. Designing a future-proof gas and hydrogen infrastructure for Europe – a modelling-based approach. *Energy Policy*, 2023.
- [3] A. Ajanovic, M. Sayer, and R. Haas. The economics and the environmental benignity of different colors of hydrogen. *International Journal of Hydrogen Energy*, 2022.
- [4] Bruno Henrique Santos, João Peças Lopes, Leonel Carvalho, Manuel Matos, and Inês Alves. Public policies to foster green hydrogen seasonal storage: Portuguese study case model until 2040. *Energy Strategy Reviews*, 2024.
- [5] IEA. The Future of Hydrogen - seizing today's opportunities, 2019.
- [6] The European Hydrogen Backbone (EHB) initiative. <https://www.ehb.eu/>.
- [7] European Hydrogen Backbone. Implementation roadmap-cross border projects and costs update, 2023.
- [8] Anthony Wang, Jaro Jens, David Mavins, Marissa Moultak, Matthias Schimmel, Kees Van Der Leun, Daan Peters, and Maud Buseman. European Hydrogen Backbone - Analysing future demand, supply, and transport of hydrogen, 2021.
- [9] Enagás. H2med and the Spanish Hydrogen Backbone, included in the list of Projects of Common Interest of the European Commission. <https://www.enagas.es/en/press-room/news-room/press-releases/h2med-spanish-hydrogen-backbone-pci/>.
- [10] REN. Gases renováveis. <https://www.ren.pt/pt-pt/atividade/gases-renovaveis>.
- [11] REN. PDIRG 2024-2033. 2023.
- [12] H2med. The H2med project - Supplying Europe with affordable carbon-free energy. <https://h2medproject.com/the-h2med-project/>.
- [13] Young Bin Woo and Byung Soo Kim. A genetic algorithm-based metaheuristic for hydrogen supply chain network problem with two transportation modes and replenishment cycles. *Computers Industrial Engineering*, 2019.

- [14] Jonathan Hanto, Philipp Herpich, Konstantin Löffler, Karlo Hainsch, Nikita Moskalenko, and Sarah Schmidt. Assessing the implications of hydrogen blending on the european energy system towards 2050. *Advances in Applied Energy*, 2024.
- [15] Fabian Neumann, Elisabeth Zeyen, Marta Victoria, and Tom Brown. The potential role of a hydrogen network in europe. *Joule*, 2023.
- [16] Gregor Brändle, Max Schönfisch, and Simon Schulte. Estimating long-term global supply costs for low-carbon hydrogen, 2020.
- [17] Min Ju Chae, Ju Hyun Kim, Bryan Moon, Simon Park, and Young Soo Lee. The present condition and outlook for hydrogen-natural gas blending technology, 2022.
- [18] Dengji Zhou, Siyun Yan, Dawen Huang, Tiemin Shao, Wang Xiao, Jiarui Hao, Chen Wang, and Tianqi Yu. Modeling and simulation of the hydrogen blended gas-electricity integrated energy system and influence analysis of hydrogen blending modes. *Energy*, 2022.
- [19] T. Klatzer, U. Bachhiesl, S. Wogrin, and A. Tomasgard. Ramping up the hydrogen sector: An energy system modeling framework. *Applied Energy*, 2024.
- [20] Department for Energy Security and Net Zero. Hydrogen blending into GB gas distribution networks: a strategic policy decision. <https://www.gov.uk/government/consultations/hydrogen-blending-into-gb-gas-distribution-networks>, 2023.
- [21] Gas Networks Ireland. Injecting green hydrogen blends into Ireland's gas network - Technical and safety feasibility study, 2022.
- [22] HyDeploy - Project phases. <https://hydeploy.co.uk/project-phases/>.
- [23] HH2E. HH2E and Gascade pipeline grid connection agreement for hydrogen. <https://shorturl.at/cjqv7>.
- [24] Sara Bellocchi, Marcello De Falco, Marco Facchino, and Michele Manno. Hydrogen blending in italian natural gas grid: Scenario analysis and lca. *Journal of Cleaner Production*, 2023.
- [25] Snam and hydrogen. [https://www.snam.it/en/hydrogen\\_challenge/snam\\_hydrogen/](https://www.snam.it/en/hydrogen_challenge/snam_hydrogen/).
- [26] Bulgartransgaz. Bulgartransgaz has joined the European Hydrogen Backbone initiative. <https://shorturl.at/ltuP7>.
- [27] Michael Thomadakis. Building up the Greek Hydrogen Value Chain - "The role of infrastructure in enabling the development the H2 value chain". 2022.
- [28] FGSZ - Possibilities of hydrogen transportation studied in joint project by FGSZ and the University of Miskolc. <https://shorturl.at/lFX19>.
- [29] Transgaz. Proposal NTS backbone for hydrogen transport.
- [30] Filipe M. Quintino, Nuno Nascimento, and Edgar C. Fernandes. Aspects of hydrogen and biomethane introduction in natural gas infrastructure and equipment. *Hydrogen (Switzerland)*, 2021.

- [31] Jukka Lassila, Tero Kaipia, Juha Haakana, and Jarmo Partanen. Concept of strategic planning in electricity distribution business, 2011.
- [32] Weifeng Yao, C. Y. Chung, Fushuan Wen, Mingwen Qin, and Yusheng Xue. Scenario-based comprehensive expansion planning for distribution systems considering integration of plug-in electric vehicles. *IEEE Transactions on Power Systems*, 2016.
- [33] Kai Liu, Lorenz T. Biegler, Bingjian Zhang, and Qinglin Chen. Dynamic optimization of natural gas pipeline networks with demand and composition uncertainty. *Chemical Engineering Science*, 2020.
- [34] Jinyu An and Shini Peng. Layout optimization of natural gas network planning: Synchronizing minimum risk loss with total cost. *Journal of Natural Gas Science and Engineering*, 2016.
- [35] Hong Liu, Chao Xiang, Zhengyang Xu, Shaoyun Ge, and Chenghong Gu. Synergetic planning method for energy stations, pipeline networks, and demand response. *Sustainable Energy Technologies and Assessments*, 2023.
- [36] Alireza Kabirian and Mohammad Reza Hemmati. A strategic planning model for natural gas transmission networks, 2007.
- [37] André Hugo, Paul Rutter, Stratos Pistikopoulos, Angelo Amorelli, and Giorgio Zoia. Hydrogen infrastructure strategic planning using multi-objective optimization. *International Journal of Hydrogen Energy*, 2005.
- [38] LNEG. Geoportal Energia e Geologia. <https://geoportal.lneg.pt/mapa/?mapa=AtlasH2Verde>.
- [39] Teresa Ponce De Leão, Sofia Simões, Teresa Simões, Lídia Quental, Justina Catarino, Filipa Amorim, Teresa Brás, Pedro Patinha, Tiago Lopes, Carlos Rodrigues, Susana Machado, Carmen Rangel, Francisco Gírio, and Ana Picado. Atlas Nacional do H2 Verde Sustentável. [https://www.lneg.pt/wp-content/uploads/2022/10/AtlasH2Portugal\\_Apresentacao5maio2022\\_Distribuir.pdf](https://www.lneg.pt/wp-content/uploads/2022/10/AtlasH2Portugal_Apresentacao5maio2022_Distribuir.pdf).
- [40] Hidalgo Gonzalez and Uihlein Andreas. High-resolution energy atlas - European Commission, 2023.
- [41] Portgás. Plano Diretor da Infraestrutura 2022.
- [42] Khalil Ben Safta and Jolando M. Kisse. Hydrogen pipeline network design: An optimization-based planning method considering the existing natural gas network, 2022.
- [43] Philip M. Gerhart, Andrew L. Gerhart, and John I. Hochstein. *Munson, Young and Okiishi's Fundamentals of Fluid Mechanics*. 8th edition.
- [44] Helena Gaspar. Project Net Present Value estimation under uncertainty. *Central European Journal of Operations Research*, 2017.
- [45] Carlos C. António. *Optimization of Mechanical Systems*. 2021.
- [46] Mohamed Abdel-Basset, Laila Abdel-Fatah, and Arun Kumar Sangaiah. *Metaheuristic algorithms: A comprehensive review*. Elsevier, 2018.

- [47] Sheila Samsatli, Iain Staffell, and Nouri J. Samsatli. Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in great britain. *International Journal of Hydrogen Energy*, 2016.
- [48] European Commission. Database - Eurostat. <https://ec.europa.eu/eurostat/web/main/data/database>.
- [49] The European Commission. Commission Delegated Regulation (EU) 2024/1041 of 28 november 2023 amending regulation (EU) 2022/869 of the European Parliament and of the Council as regards the Union list of projects of common interest and projects of mutual interest. *Official Journal of the European Union*, 2024.
- [50] GRTgaz. Barmar-H2med. <https://www.grtgaz.com/en/our-energy-transition/hydrogen-transport/barmar>.
- [51] Enagás. A transmission network to supply hydrogen. <https://www.enagas.es/en/energy-transition/gas-network/energy-infrastructure/hydrogen-transmission/>.
- [52] Enagás. The results of the Call For Interest carried out by Enagás confirm the hydrogen transport infrastructures submitted to the Projects of Common Interest (PCI). <https://www.enagas.es/en/press-room/news-room/press-releases/second-hydrogen-day/>.
- [53] Enagás. Enagás has successfully concluded the first phase of the Call For Interest for the Spanish Hydrogen Backbone Network. <https://www.enagas.es/en/press-room/news-room/press-releases/close-call-for-interest-hydrogen-backbone/>.
- [54] GRTgaz. Hydrogen projects. <https://www.grtgaz.com/en/our-energy-transition/hydrogen>.
- [55] Teréga. Hysow: A hydrogen transport and storage infrastructure project. <https://shorturl.at/pBWX1>.
- [56] Teréga. Return of the Call for Expression of Interest: H<sub>2</sub> and CO<sub>2</sub>.
- [57] GRTgaz, HDF Energy, Soladvent, Storengy, Teréga, TotalEnergies, and Elogen. The role of hydrogen transport and storage infrastructure: An opportunity for industrial competitiveness, 2021.
- [58] FNB Gas. Hydrogen Core Network. <https://fnb-gas.de/en/hydrogen-core-network/>.
- [59] Ralf Dickel. Decarbonizing Germany’s heating sector. *The Oxford Institute for Energy Studies*, 2024.
- [60] Governo Português. Plano Nacional Energia e Clima 2021-2030 (PNEC 2030), 2023.
- [61] Gasunie. Hydrogen network Netherlands. <https://www.gasunie.nl/en/projects/hydrogen-network-netherlands>.
- [62] Gasunie. King Willem-Alexander marks the start of construction of Gasunie’s national hydrogen network. <https://shorturl.at/bklzV>, 2023.

- [63] Flow-making hydrogen happen. <https://www.flow-hydrogen.com/en/home-en/>.
- [64] TH2ECO. <https://www.th2eco.de/>.
- [65] GET H2 Nukleus. <https://www.get-h2.de/en/implementation/>.
- [66] Hypipe Bavaria – The Hydrogen Hub. <https://www.hypipe-bavaria.com/en/>.
- [67] DGEG. Consumos por município e por setor de atividade. <https://www.dgeg.gov.pt/pt/estatistica/energia/gas-natural/consumos/>.
- [68] Paulo Coelho. *Tabelas de Termodinâmica*. 4th edition, 2017.
- [69] Hydrogen Analysis Resource Center. Hydrogen density at different temperatures and pressures. <https://h2tools.org/hyarc/hydrogen-data/hydrogen-density-different-temperatures-and-pressures>.
- [70] National Institute of Standards and Technology. Isobaric properties for hydrogen - nist chemistry webbook. <https://webbook.nist.gov/>.
- [71] Galp. Eletricidade e gás natural da Galp. <https://www.galp.com/pt/pt/empresas/eletricidade-e-gas/Apoio-ao-Cliente/Centro-de-Informacao/Eletricidade-e-Gas-Natural-da-Galp>.
- [72] Repsol. Ficha de dados de segurança - propano comercial, 2020.
- [73] Repsol. Ficha de dados de segurança - butano comercial, 2022.
- [74] HyJack. Sizing and costing. <https://hyjack.tech/components>.
- [75] T. D. Eastop and A. McConkey. *Applied Thermodynamics for Engineering Technologists*. 1993.
- [76] Sylvestre Baufumé, Fabian Grüger, Thomas Grube, Dennis Krieg, Jochen Linssen, Michael Weber, Jürgen Friedrich Hake, and Detlef Stolten. Gis-based scenario calculations for a nationwide german hydrogen pipeline infrastructure. *International Journal of Hydrogen Energy*, 38, 2013.
- [77] T O Khan, M A Young, and C B Layzell. The techno-economics of hydrogen pipelines, 2021.
- [78] Simonas Cerniauskas, Antonio Jose Chavez Junco, Thomas Grube, Martin Robinius, and Detlef Stolten. Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a germany case study. *International Journal of Hydrogen Energy*, 45, 2020.
- [79] Brian D. James, Cassidy Houchins, Jennie M., and Daniel DeSantis. Final report: Hydrogen storage system cost analysis, 2016.
- [80] NREL. Hydrogen station compression, storage, and dispensing technical status and costs: Systems integration, 2014.
- [81] DGT. Carta Administrativa Oficial de Portugal-CAOP2023 (Continente). <https://dados.gov.pt/pt/datasets/carta-administrativa-oficial-de-portugal-caop2023-continente/>.

- [82] Repsol. Cumprimento do dever de informação dos comercializadores de energia ao consumidor. 2022.
- [83] Agência Portuguesa do Ambiente. Fator de emissão da eletricidade-2023, 2023.
- [84] T O Khan, M A Young, and C B Layzell. The techno-economics of hydrogen pipelines, 2021.
- [85] IRENA. Green hydrogen cost reduction : scaling up electrolyzers to meet the 1.5° C climate goal. 2020.
- [86] Hydrogen Council. Path to hydrogen competitiveness - A cost perspective. 2020.
- [87] ERSE. Proveitos e ajustamentos 2024-2025, 2024.
- [88] Michael Chui an Eric Hazan, Roger Roberts, Alex Singla, Kate Smaje, Alex Sukharevsky, Lareina Yee, and Rodney Zimmel. The economic potential of generative AI. *McKinsey & Company*, 2023.
- [89] Project description - h2 backbone wag + penta-west. <https://h2backbone-wag-pw.at/en/project-description/?lang=en>.
- [90] H2 Readiness of the TAG pipeline system. <https://h2-readiness-tag.at/en/about/>.
- [91] Project description - About "H2 Backbone Murfeld". <https://h2backbone-murfeld.at/en/project-description/?lang=en>.
- [92] Fluxys Belgium. Aquaductus Project. [https://www.fluxys.com/en/press-releases/fluxys-group/2023/230123\\_press\\_gascade\\_fluxys\\_aquaductus](https://www.fluxys.com/en/press-releases/fluxys-group/2023/230123_press_gascade_fluxys_aquaductus).
- [93] Fluxys Belgium. Information Memorandum for H2 infrastructure. [www.climat.be](http://www.climat.be), 2022.
- [94] Fluxys Belgium. Hydrogen, the all-rounder for a climate-neutral economy. <https://www.fluxys.com/en/hydrogen#/>.
- [95] Ministry of Economy and Sustainable Development. Hydrogen Strategy of the Republic of Croatia until 2050, 2022.
- [96] Central European Hydrogen Corridor. <https://www.cehc.eu/>.
- [97] CGHI vision. <https://www.cghi.eu/cghi-project/>.
- [98] Energinet. Energinet and Gasunie agree on next steps towards a cross-border green hydrogen infrastructure. <https://shorturl.at/muv27>.
- [99] Gascade. Bornholm-Lubmin hydrogen pipeline to realize renewable ambitions in Baltic Region. <https://shorturl.at/quEI2>.
- [100] Energinet. Danish Backbone West and Hyperlink 3. [https://energinet.dk/media/khujfjny/energinet\\_presentation\\_hydrogen\\_maturation\\_project.pdf](https://energinet.dk/media/khujfjny/energinet_presentation_hydrogen_maturation_project.pdf).
- [101] Nordic-Baltic Hydrogen Corridor - Elering. <https://elering.ee/en/nordic-baltic-hydrogen-corridor>.

- [102] Gasgrid. Nordic Hydrogen Route. <https://gasgrid.fi/en/projects/nordic-hydrogen-route-en/>.
- [103] Baltic Sea Hydrogen Collector. <https://balticseahydrogencollector.com/>.
- [104] OGE. A H2erculean task: Hydrogen infrastructure at the core of the ramp-up in Germany. <https://oge.net/en/press-public-information/oge-policy-impulse/2023/hydrogen-a-h2erculean-task>.
- [105] ONTRAS. Hydrogen infrastructure. <https://www.ontras.com/en/hydrogen>.
- [106] Gas Transmission and Metering. Project Union Launch Report. 2022.
- [107] GNI. Researching a cleaner energy future. <https://www.gasnetworks.ie/renewable/hydrogen/research/>.
- [108] South2 - The initiative. <https://www.south2corridor.net/south2>.
- [109] Mosahyc. <https://grande-region-hydrogen.eu/en/projects/mosahyc/>.
- [110] Gassco and dena. German-Norwegian Energy Cooperation Joint Feasibility Study. 2023.
- [111] Transport-System – Transitgas AG. <https://www.transitgas.ch/en/transport-system/>.
- [112] FluxSwiss. Transitgas pipeline. <https://www.fluxys.com/en/about-us/fluxswiss/transitgas-pipeline>.
- [113] Sunshyne corridor. <https://www.sunshynecorridor.eu/sunshyne-project/>.
- [114] GRTgaz. HY-FEN. <https://www.grtgaz.com/en/our-energy-transition/hydrogen-transport/hyfen>.
- [115] ONTRAS Gastransport GmbH - doing hydrogen. <https://www.doinghydrogen.com/en/partner/ontras/>.
- [116] Green Octopus Mitteldeutschland | ONTRAS Gastransport GmbH. <https://www.ontras.com/en/go>.
- [117] Hyperlink 3. <https://www.hyperlink-gasunie.de/en/about-hyperlink/hyperlink-3>.
- [118] Hyperlink. <https://www.hyperlink-gasunie.de/en/about-hyperlink>.
- [119] GTG Nord. H2COASTLINK: Import and onward transport at high pressure. <https://gtg-nord.de/en/hydrogen-grid/>.
- [120] H2EU+Store - Project Map and Timetable. <https://www.h2euplusstore.com/en/project/project-map-and-timetable.html>.
- [121] Pedro Chamusca and António Bento-Gonçalves. *Os Desafios (Geográficos) da Governação Territorial*. UMinho Editora/CECS, 2023.