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The sustainable hydrogen boost in the industrial cluster of the Sassuolo Ceramic District linked to the port of Ravenna

Relatore

Pierluigi Leone

Correlatore

Marco Cavana

Candidato

Luigi Marrazzo

Abstract

This thesis aims to provide an understanding of how the world's leading players are moving toward a new era in which the energy transition through the decarbonisation of entire sectors is something that is finally foreseeable and affordable. This important role belongs to several characters, each one has equal relevance and is able to communicate and collaborate with other parties. In this way, governments, investors, financers, companies, and customers can achieve the desired outcomes that bring revenues and welfare to everyone. From this starting point, the most recent energy and sustainable policies are illustrated to strengthen the targets set, with the responsibility and the wish to respect them. After that, new sustainable frontiers come up especially for the industrial sector, a hard-to-abate sector among the hardest to decarbonise and with a share of the final energy consumption of more than 30%. The industrial clusters are the answer to that as they involve many different activities located in a common area with many economic and social interests, all linked together. Actually, there are some unsolved matters, but many more studies and tangible evidence demonstrate the potential of these solutions that can make possible the net-zero challenge reachable within specific deadlines. The Ceramic District based in Emilia-Romagna, one of the major driving regions in Italy for the industry and the economy, is explored and explained as a case study of this thesis with the aim to overcome the use of fossil fuels, in particular natural gas, with the increasingly important energy vector, hydrogen. Hydrogen can be and will be one of the greatest and "greener" solution to make the ceramic industry, whose impact on environment is huge especially by thermal energy consumption, cleaner and more sustainable during the entire process with technologies already scaled up and commercially available. The port of Ravenna is the perfect energy hub and the cornerstone from which everything can begin and spread to make this energy transition more feasible than ever.

List of contents

LIST OF FIGURES

LIST OF TABLES

1. Introduction

The present work stems from the idea to develop an in-depth research, a detailed study and at last, a tangible resolution leading to this final draft showcased within this thesis. Each of the following chapters has the aim to firstly introduce and then analyze the most important topics that in an orderly manner build up the idea from which the thesis was conceived and what it wants to reach.

Hydrogen is the key player of the study, and it is the cornerstone through which significant investments in renewable energy systems, the establishment of industrial clusters involving multiple entities, the progression of energy transition, and the attainment of environmental benefits are interwoven and facilitated.

Globally, the industry sector stands as one of the most energy-intensive and hard-to-abate field, representing nearly one-third of the world's energy consumption and consequently contributing an almost equivalent share to greenhouse gas emissions. The forthcoming years emerge as critical for accelerating efforts in transitioning this sector towards sustainable practices.

From this perspective, the European Union and, looking in a more detailed way, numerous strong and innovative Italian entities, have embarked on a trajectory focused on swiftly achieving essential objectives in fighting climate change. This pathway underscores a significant energy transition towards renewable methods while preserving the robust tradition of high-quality mastery that distinguishes Italian industries as global frontrunners. Within this context, the Italian ceramic industry, particularly situated in the region of Emilia-Romagna, stands as a noteworthy exemplar. It has been studied and analyzed and placed side by side to the port of Ravenna, crucial source for the entire ceramic system. The hydrogen serves as a glue between these two important entities. Firstly, it comes out to be one of the major reasons for a substantial growth for the port, fostering economic investments and driving renewable energy production. More importantly, its paramount significance lies in serving green hydrogen as the optimal energy vector, proficiently limiting CO_2 emissions within the ceramic industry, a field notorious for its formidable challenge in transition towards sustainable practices. This sector's energy-intensive processes necessitate vast quantities of both electricity and thermal energy, making hydrogen the most viable avenue for ushering in 'green' methodologies. Calculations and results prove the feasibility of this study, showcasing green hydrogen as a prospective local product capable of enriching both the economic and social system while concurrently serving as an energy source within the industrial sector through integration into the existing gas network.

Although the requisite investments are substantial, the returns on investment present a considerably promising prospect.

The objective of this thesis is to present an overview of the accomplishments made while also paving the way for further discussions that might yield even more effective solutions in addressing the challenges posed by a complex system that is resistant to change. Despite its intricacies, the thesis remains anchored in firm and attainable objectives to be pursued.

2. Major worldwide and European guidelines and objectives

2.1 The EU Emissions Trading System

The European Union Emissions Trading System, also known as ETS, works on the ‘cap and trade’ principle.

A ‘cap’ represents a set limit on the total volume of greenhouse gas emissions permissible for the facilities and aircraft operators covered by the regulatory framework. This cap is progressively reduced on the annual basis in alignment with the EU’s climate objectives, contributing to a gradual reduction in emission overtime. The cap is quantified in terms of ‘emission allowances’, with each allowance granting the holder the right to emit one tonne of carbon dioxide equivalent (CO2-eq). Companies operating within the cap primarily acquire these allowances through the EU’s carbon market, while some allowances are allocated to them for free and they can also engage in allowance trading among themselves as needed. When installations or operators succeed in lowering their emissions, they have the option to retain surplus allowances for future or to sell them.

The EU ETS encompasses a range of greenhouse gases emitted from specific activities and carefully measured, verified, and reported like in the list below:

- **Carbon dioxide (CO_2)** from electricity and heat generation, involving energy-intensive industry sectors, including oil, refineries, steel works, and production of iron, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, and bulk organic chemicals. Aviation within the European Economic Area and departing flights to Switzerland and the United Kingdom. Maritime transport, specifically 50% of emissions from voyages starting or ending outside of the EU and 100% of emissions from voyages between two EU ports and when ships are within EU ports. [1]
- **Nitrous oxide (N_2O)** from production of nitric, adipic and glyoxylic acids and glyoxal. [1]
- **Perfluorocarbons (PFC_S)** from the production of aluminium. [1]

Participation in the EU ETS is compulsory for companies in these sectors, although there are certain expectations and criteria that in some sectors only operators exceeding a specified size are subject to inclusion and some small installations may be exempted from participation if governments implement alternative measures to reduce their emissions.

Since its inception in 2005, the EU ETS has played a pivotal role in achieving a 37% reduction in emissions from power and industrial facilities. [1]

Recently, a new and separate emissions trading system was created: Emissions Trading System 2 (ETS 2), covering the field of fuel combustion in buildings, road transport and additional sectors (mainly small industry sectors not covered by the existing EU ETS). [2]

From 2024, other new sectors such as installations for the incineration of municipal waste above a certain threshold are also required to monitor and report their emissions in the EU ETS. [3]

For all those new sectors, the ETS 2 works in tandem with other policies under the European Green Deal, including the Effort-Sharing legislation. Its primary goal is to facilitate cost-effective reduction of emissions and create equitable conditions for decarbonisation within these sectors. ETS 2 is designed as an upstream system, which means it focuses on regulating fuel suppliers rather than individual households and car drivers.

ETS 2 has been meticulously planned to ensure its operation is organised, seamless, and efficient with the following timeline [2]:

- 2025: monitoring and reporting of greenhouse gas emissions.
- 2026: introduction of the Social Climate Fund (SCF)[1].
- 2027: launch of ETS 2, with the incorporation of a market stability reserve in the initial years to maintain allowance prices stability.
- 2027: initiation of front-loading for the auctioning of allowances.
- 2030: ETS 2 attains a 42% reduction in emissions compared to 2005 baseline.

The price of allowance serves a dual purpose. It acts as an incentive for companies to curtail their emissions, while also determining the revenues generated by the EU ETS through the sale of these allowances. Since 2013, the EU ETS has gained over EUR 152 billion from revenues. These revenues primarily contribute to national budgets within the Member States. Member States, in turn, utilize these funds to support investments in renewable energy, enhance energy efficiency, and adopt low-carbon technologies, all of which further the reduction of emissions. Additionally, the sale of allowances provides vital resources for initiatives related

[1] **SCF**: the fund has the aim to help vulnerable households, micro-business and transport users counter the additional costs they may face when the EU ETS Directive is revised to cover these two sectors. The SCF will mobilise EUR 86.7 billion from 2026 to 2032. [4]

to low-carbon innovation and energy transition, such as the Innovation Fund[2] and the Modernisation Fund[3]. [1]

2.1.1 The Effort Sharing Regulation 2021-2030

Originally established in 2018, the Effort Sharing Regulation underwent an amendment in 2023. With the introduction of new national targets, Member States will collectively play a role in achieving a 40% reduction in emissions at the EU level within the Effort Sharing sectors, as compared to the 2005 levels. These national targets for reducing greenhouse gas emissions by 2030 encompass various sectors, including domestic transport but excluding aviation, buildings, agriculture, small industry, and waste. In the table below, can be found the specific emission reduction targets for each Member State relative to their 2005. [7]

Table 1 – The reduction targets established for greenhouse gas emissions for the year 2030. [7]

COUNTRY	***OLD TARGETS (2018)***	***NEW TARGETS (2023)***
Belgium	-35 %	-47 %
Bulgaria	-0 %	-10 %
Czechia	-14 %	-26 %
Denmark	-39 %	-50 %
Germany	-38 %	-50 %
Estonia	-13 %	-24 %
Ireland	-30 %	-42 %
Greece	-16 %	-22,7 %
Spain	-26 %	-37,7 %
France	-37 %	-47,5 %
Croatia	-7 %	-16,7 %
Italy	-33 %	-43,7 %
Cyprus	-24 %	-32 %
Latvia	-6 %	-17 %
Lithuania	-9 %	-21 %

[2] **Innovation Fund**: one of the world's largest funding programmes for the deployment of net-zero and innovative technologies. [5]

[3] **Modernisation Fund**: dedicated funding programme to support 10 lower-income EU Member States in their transition to climate neutrality by helping to modernise their energy systems and improve energy efficiency. [6]

Luxembourg	-40 %	-50 %
Hungary	-7 %	-18,7 %
Malta	-19 %	-19 %
Netherlands	-36 %	-48 %
Austria	-36 %	-48 %
Poland	-7 %	-17,7 %
Portugal	-17 %	-28,7 %
Romania	-2 %	-12,7 %
Slovenia	-15 %	-27 %
Slovakia	-12 %	-22,7 %
Finland	-39 %	-50 %
Sweden	-40 %	-50 %

The Regulation acknowledges the different capacities of Member States to take action by tailoring targets based to Gross Domestic Product (GDP) per capita.

In addition to setting emissions reduction goals, the Regulation also establishes yearly emission limits for the period spanning from 2021 to 2030. These annual emission limits are derived from a trajectory system designed to reach the 2030 emission reduction targets, coupled with a series of adjustments outlined in articles 4[4] and 10[5] of the Effort Sharing Regulation.

The Commission Implementing Decision (EU) 2020/2126 dated 16 December 2020, gives details of the outcomes of these calculations, assigning to each Member State the corresponding annual emission allocations, often referred to as AEAs (annual emission allocations), for each year between 2021 and 2030. In the table below are only shown data for the larger European Member States, starting from 2023. [8]

Table 2 - Annual AEAs, in tonnes of CO2, for the European larger counties. [8]

Member State	***Annual emission allocations in tonnes of CO_2-eq***							
	2023	***2024***	***2025***	***2026***	***2027***	***2028***	***2029***	***2030***
Germany	399142745	385061046	370979348	356897650	342815952	328734253	314652554	300570856
France	317286309	308066096	298845883	289625670	280405456	271185243	261965030	252744817
Italy	264027488	259289265	254551242	249813118	245074995	240336872	235598749	230860626

[4] **Article 4**: values set out in the Intergovernmental Panel for Climate Change 5th Assessment Report and listed in Annex to Commission Delegated Regulation (EU) 2020/1044. [8]

[5] **Article 10**: review conducted by the Commission, assisted by European Environment Agency, and constitutes reviewed greenhouse gas emissions data. [8]

Poland	201204624	198032420	194860216	191688012	188515807	185343603	182171399	17899 9195
Spain	196344088	194017170	191690253	189363335	187036418	184709500	182382583	18005 5665

On an annual basis, the Commission conducts an evaluation and issues reports regarding the progress made towards meeting the established targets. If any Member State is found to be falling behind their efforts, they will be mandated to submit an action plan to the Commission outlining the necessary corrective measures.

2.2 World and European climate change strategies

2.2.1 The Paris Agreement

To address the challenges of climate change and its adverse consequences, world leaders came to a historic agreement at the UN Climate Change Conference (COP21) in Paris on 12 December 2015, the Paris Agreement. This landmark accord establishes long-term objectives for all nations, which include:

- Significantly reducing worldwide greenhouse gas emissions to curtail the global temperature rise within this century to 2 degrees Celsius (℃), with the aim of pushing for even more ambitious efforts to limit the increase to 1.5 ℃.
- Conducting regular reviews of each country’s commitments every five years.
- Providing financial support to developing nations to aid in their climate change mitigation efforts, enhance their resilience and strengthen their capacity to adapt to climate-related impacts.
-

The Paris Agreement is a legally binding international treaty that officially came into force on 4 November 2016. Today, a total of 194 Parties, which includes 193 States along with the European Union, have become signatories to the Paris Agreement. [9]

Figure 1 - The 17th Sustainable Development Goals (SDGs) of the UN. [10]

2.2.2 The REPowerEU Plan

In response to the challenges and the disruption in the global energy market resulting from Russia's invasion of Ukraine, the European Commission initiated its REPowerEU Plan in May 2022. This Plan is aimed at assisting the European Union in several key accomplishments, including:

- Decreasing its reliance on Russian fossil fuels.
- Achieving energy savings of nearly 20%.
- Implementing a gas price cap and a global oil price cap.
- Doubling the deployment of additional renewable energy sources.

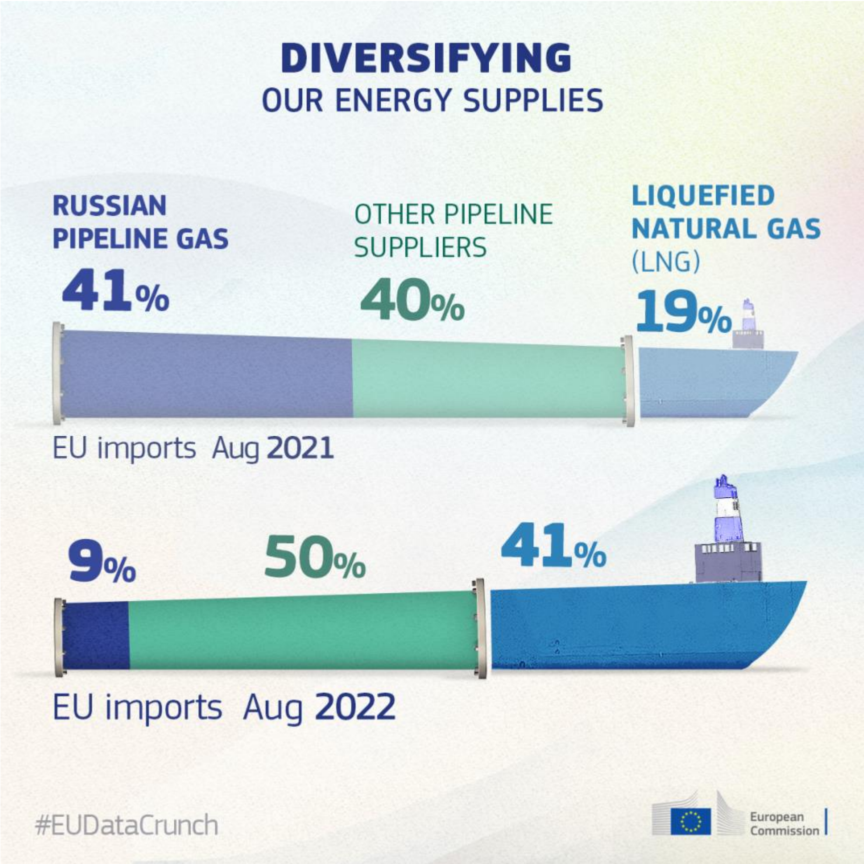

Figure 2 - The change of EU energy supplies. [11]

Saving energy is the most cost-effective, secure, and environmentally friendly method for reducing dependence on fossil fuels imports from Russia. Key achievements related to energy savings and renewable energy within the REPowerEU Plan include:

- All EU countries have committed to reducing their gas consumption by a minimum of 15%.
- From August 2022 to March 2023, there was an 18% reduction in gas demand, surpassing the established target.
- Member States extended the voluntary gas demand reduction target for an additional year in March 2023, as proposed by the Commission.

Investing in renewable energy yields multiple benefits, including mitigating climate change, enhancing the EU's energy independence, bolstering supply security, and fostering job creation within the EU. Notable outcomes achieved in the past year under the Plan include:

- For the first time, the EU generated more electricity from wind and solar sources than from natural gas.
- The installation of a record of 41 GW of new solar energy capacity.
- A 16 GW increase in wind capacity.
- Renewable sources now account for 39% of the EU's electricity generation.

The implementation of REPowerEU Plan necessitates substantial investments and reforms, mobilising nearly EUR 300 billion, with roughly EUR 72 billion allocated in grants and EUR 225 billion in loans. [11]

2.2.3 The Green Deal Industrial Plan

In February 2023, the European Commission unveiled the Green Deal Industrial Plan, which aims to boost the competitiveness of Europe's net-zero industry and facilitate a swift transition to climate neutrality. The Plan seeks to create a more supportive environment for the scaling up of the EU's manufacturing capacity for the net-zero technologies and products to meet ambitious targets. It builds upon prior initiatives and leverages the strengths of the EU Single Market, consisting of four key pillars [21]:

- **Predictable and simplified regulatory environment**: The Plan identifies objectives for net-zero industrial capacity and establishes a regulatory framework tailored for rapid ensuring deployment. This framework is complemented by the Critical Raw Materials Act[6], ensuring sufficient access to essential materials for manufacturing key technologies. Additionally, it involves a reform of the electricity market design to enable consumers to benefit from the lower costs associated with renewable sources.
- **Speeding up access to finance**: The Commission will engage in consultations with Member States regarding an amended Temporary State aid Crisis and Transition Framework[7]. It also involves revision

[6] **Critical Raw Material Act**: set of actions to ensure the EU's access to a secure, diversified, affordable and sustainable supply of critical raw materials. [27]

[7] **Temporary crisis and Transition Framework**: proposal, part of the Green Deal, that aims to boost investments for a faster roll-out of renewable energies as well as to support the decarbonisation of the industry and the production of equipment necessary for the net-zero transition. [12]

of the General Block Exemption Regulation (GBER)[8] in alignment with the Green Deal objectives.

- **Enhancing skills**: Recognizing that between 35% and 40% of all jobs could be influenced by the green transition, the Plan emphasizes the development of skills required for well-paying, high-quality jobs.
- **Open trade for resilient supply chains**: The Plan emphasizes global cooperation based on principles of fair competition and open trade, building on the EU's partnerships, and aligning with the work of the World Trade Organization to establish resilient supply chains.

The Green Deal Industrial Plan is rooted in the European Green Deal, introduced by the Commission on December 11, 2019, which sets the objective of making Europe the world's first climate-neutral continent by 2050.

2.2.4 The Net-Zero Industry Act

The Act is a crucial component of the first pillar of the Green Deal Industrial Plan, with a focus on bolstering the resilience and competitiveness of net-zero technology manufacturing within the EU. Its overarching objective is to enhance the security and sustainability of the energy system while creating an environment that is conductive to establishing net-zero projects in Europe and attracting investments. The ultimate aim is to ensure that the European Union's strategic net-zero technology manufacturing capacity approaches or achieves at least 40% of the Union's deployment requirements by 2030. The primary actions to drive investments in net-zero technology manufacturing include [22]:

- **Setting enabling conditions**: The Act places emphasis on prioritizing Net-Zero strategic projects that are considered vital for strengthening the resilience and competitiveness of the EU industry.
- **Accelerating CO2 capture**: The Act establishes an EU target to reach an annual injection capacity of 50 million tonnes (Mt) in strategic CO_2 storage sites within the EU by 2030. This significant capacity expansion aims to overcome a major barrier to the

[8] **GBER**: legislation setting out the terms and conditions of national aid which does not require prior Commission authorisation. [13]

development of economically viable CO_2 capture and storage solutions, especially for hard-to-abate, energy-intensive sectors.

- **Facilitating access to markets**: The Act mandates that public authorities take into account sustainability and resilience criteria for net-zero technologies in public procurement or auctions.
- **Enhancing skills**: The Act introduces new measures to ensure the presence of a skilled workforce supporting the production of net-zero technologies within the EU. This includes the establishment of Net-Zero Industry Academies.
- **Fostering innovation**: The Act establishes regulatory frameworks to pilot innovative net-zero technologies and promote innovation under flexible regulatory conditions.

Additionally, the Act establishes a "Net-Zero Europe Platform" designed to aid the Commission and Member States in coordinating actions, sharing information, and identifying financial requirements, bottlenecks, and best practices for projects across the EU. This platform plays a critical role in supporting investment and collaboration within the EU. [22]

Ursula von der Leyen, the President of the European Commission, stated, *"We need a regulatory environment that allows us to scale up the clean energy transition quickly. The Net-Zero Industry Act will do just that. It will create the best conditions for those sectors that are crucial for us to reach net-zero by 2050: technologies like wind turbines, heat pumps, solar panels, renewable hydrogen as well as CO2 storage."*, perfectly explaining what are the intentions and the efforts to put in them. [22]

2.2.5 The European Hydrogen Bank

Hydrogen is set to play an important role in the European Union carbon neutrality objective by 2050, while gradually reducing its dependency from fossil fuels as well as possible.
The European Hydrogen Strategy was introduced in 2020 and outlined one of its main objectives, corresponding to a large domestic production of renewable hydrogen within the EU. Then, in December 2022, a political agreement was reached to amend the EU ETS Directive, which includes the provision of free allowances for electrolysers involved in hydrogen production. This revision also increases the allowances allocated to the

Innovation Fund and allows for EU-wide auctions to be conducted under the Innovation Fund framework. [14] These acts are essential and are incentives to a hydrogen European structure development, that is still primordial and disjointed.

The recent establishment of the European Hydrogen Bank is geared toward addressing the investment gap and facilitating the connection between future renewable hydrogen supply and the EU's objective of achieving 20 million tonnes of renewable hydrogen production. The Hydrogen Bank aligns with the goals of the Green Deal Industrial Plan and the Net-Zero Industry Act. It will position European companies as key players in the emerging global hydrogen market.

However, the European hydrogen market faces a series of investment challenges. As of now, there is approximately 160 MW of installed electrolyser output capacity, whereas reaching the production target of renewable hydrogen would necessitate to scale up and add between 80-100 GW of manufacturing capacity. This, in turn, will require roughly an expansion of 150-210 GW of new hydrogen production capabilities for low-cost electricity production, making renewable hydrogen competitive with its fossil fuel counterparts in order to persuade new demand sectors. [14]

The total investment requirements for producing, transporting, and consuming 10 million tonnes of renewable hydrogen are estimated to be in the range of EUR 335-471 billion, with EUR 200-300 billion specifically needed for additional renewable electricity production.

Investments are needed in key hydrogen infrastructure categories by 2030, dealing with electrolysers capacity and their scale up (EUR 50-75 billion), European internal pipelines (EUR 28-38 billion), hydrogen storage (EUR 6-11 billion). [14]

These investments are crucial for the continued development and expansion of the renewable hydrogen sector in the EU. However, cooperation between European countries is essential for an efficient process that leads to the desired result, without wasting significant sums of funds.

There is currently a "green premium" associated with choosing hydrogen over fossil fuels due to higher costs, with a total economic value estimated in approximately EUR 90-115 billion for both domestic production and the import and expecting declining production costs and growing demand of renewable hydrogen. Since renewable hydrogen is not yet readily available on the global market, this green premium is essential to secure an annual production capacity. After the mid-2020s, the market premium is expected to decrease as production costs decline and the demand for green products produced with renewable hydrogen rises.

In the short term, additional resources at the EU level will be required to support hydrogen deployment and the scaling up of manufacturing of other crucial net-zero technologies. The Innovation Fund, with its provisions for EU-level competitive bidding auctions, offers a promising and cost-efficient approach to promote the expansion of renewable hydrogen and other strategic net-zero technologies within Europe.
It’s important to note that the majority of investments in the hydrogen sector will need to come from private capital. The climate taxonomy delegated act[9] is already facilitating the channelling of private funds toward activities related to the manufacturing of equipment for hydrogen production and utilization, as well as hydrogen storage. This private capital is instrumental in driving the growth of the renewable hydrogen sector.

The European Hydrogen Bank is built upon four fundamental pillars, encompassing a range of mechanisms and functions to advance the production of renewable hydrogen:

- **Two new financing mechanisms**: The Bank will introduce these mechanisms that are designed to bolster renewable hydrogen production within the EU and on an international scale.
- **Demand visibility**: The Bank serves to enhance it by establishing connections with off-takers, coordinating with parallel Member State initiatives, and tapping in existing data centres. This facilitates a more comprehensive understanding of and response to hydrogen project demands.
- **Coordination and blending**: The Bank assumes coordinates and facilitates blending with existing financial instruments, thereby providing support to hydrogen projects and ensuring they are effectively aligned with broader financial strategies and objectives.

[9] **Climate taxonomy delegated act**: classification system that defines criteria for economic activities that are aligned with a net zero trajectory by 2050 and the broader environmental goals other than climate. [15]

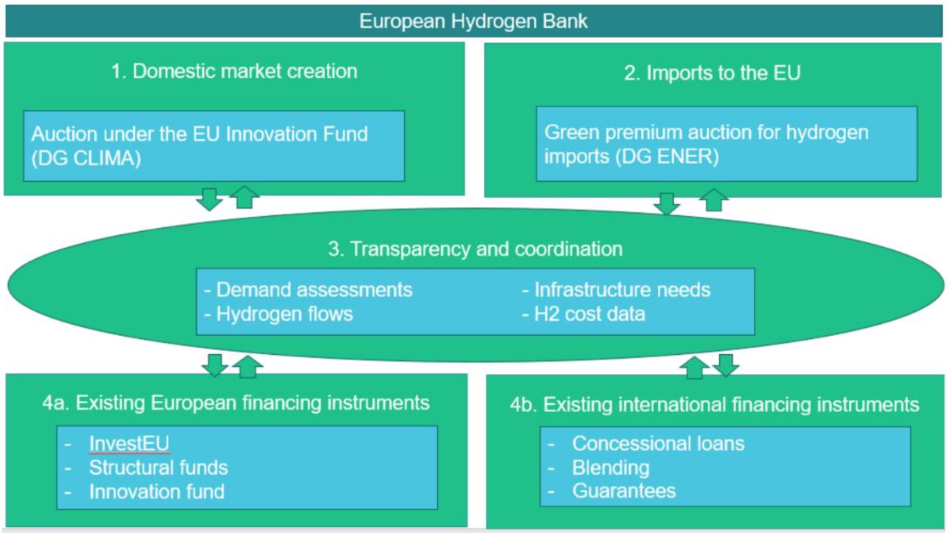

Figure 3 - The main solutions designed from the European Hydrogen Bank. [14]

The European Hydrogen Bank is going to play an important role in the renewable hydrogen sector by acting as a catalyst for private sector investment. It will contribute to the early development of markets and help discover price competitive pricing, all while enhancing investor confidence and supporting project-finance expertise within the private financing sector. The overarching objective is to reduce the cost gap and make renewable hydrogen more cost-competitive, to a point where private off-takers are both willing and financially able to support and invest in the sector. By fostering competition for financing and creating an environment that encourages private investment, the Bank aims to make renewable hydrogen projects economically viable and attractive to a broader range of investors. This, in turn, support the broader goals of transitioning to cleaner energy sources and achieving climate neutrality.

3. The pathway of Industrial Clusters for carbon-neutrality

Industrial clusters are geographic areas where co-located companies, representing either a single or multiple industries, providing opportunities for economies of scale, sharing of resources and risks, and the potential for optimizing demand.

Given that the industrial sector accounts for 30% of total global CO_2 emissions, industrial clusters are expected to play a crucial role in accelerating the transition to a net-zero carbon economy. Industrial CO_2 emissions are particularly challenging to reduce, making the role of clusters even more important. [16]

While there are various initiatives and research papers focused on reducing emissions within the industrial sector, often concentrating on specific technologies or industry segments, there is a need for a more integrated approach that transcends sector boundaries. Such an approach could provide a more comprehensive and effective strategy for tackling industrial emissions and advancing the goal of achieving the goal of net-zero emissions.

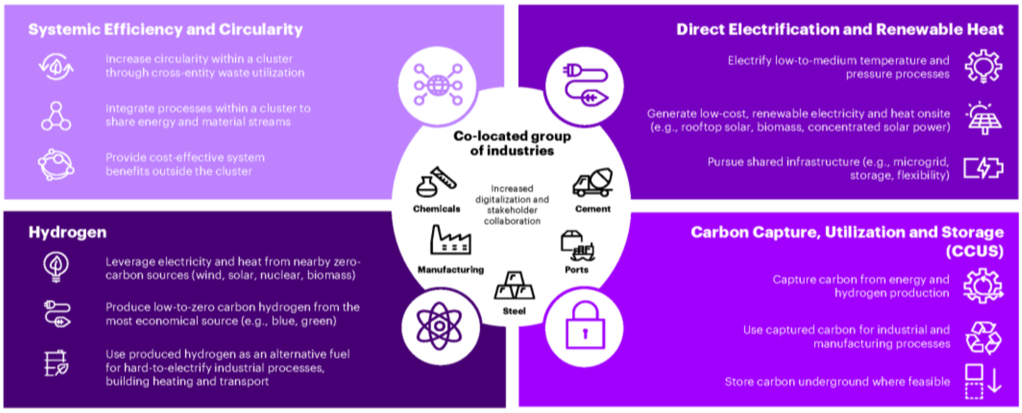

Figure 4 – Net-zero carbon emissions solutions for Industrial Clusters. [16]

Industrial clusters, through multi-stakeholder collaboration, offer the opportunity to create systematic value and deliver a range of benefits [16]:

1. **Emissions reduction**: The primary goal is to reduce emissions, contributing to global climate objectives.
2. **Economic benefits**: Beyond emissions reduction, industrial clusters also generate economic benefits. They create jobs and enhance local environmental quality, leading to improved public health.
3. **Business opportunities**: For industrial companies, emissions reduction not only helps avoid potential carbon taxes but also presents business opportunities. Developing a premium low-carbon products can enhance market competitiveness and profitability.
4. **Enhanced energy planning**: Energy companies can gain greater visibility into industrial energy demand, aiding in capital expenditure planning. This insight enables them to expand renewable energy installations, optimize demand, and provide integrated energy management services.
5. **Global leadership for Governments**: By taking decisive actions to achieve net-zero emissions target, Governments can export knowledge of effective policy frameworks, commercial models, and infrastructure for low-carbon technologies, showcasing their commitment to sustainability.
6. **R&D and Innovation**: Industrial clusters promote research and technological development (RTD) and digital services. They facilitate the release of patents, publication of academic literature demonstrating cost reduction and efficiency improvement for key technologies like electrolysers for renewable hydrogen production.

In summary, industrial clusters serve as hubs for collaboration and innovation, driving emissions reduction and delivering a range of economic, environmental, and technological benefits for various stakeholders.

Furthermore, financiers can also benefit from this collaborative approach by aligning with climate commitments, meeting shareholder expectations and, expanding the scope of ESG[10] asset class through investments in low-carbon infrastructure for emerging technologies such as Carbon Capture and Storage (CCS) and hydrogen.

To achieve these goals, a comprehensive collaboration within and across industries is imperative, coupled with a robust commitment of capital and willingness to share resources. Governments can contribute by allocating capital to support infrastructure development and by fostering business models that reduce risk for private industry. They can create financial environment conducive to achieving net-

[10] **ESG**: Environmental, Social and Governance.

zero targets through mechanisms such as subsidies and tax credits. On the other hand, energy companies and financiers play a crucial role by actively engaging in collaborative efforts to allocate capital and resources for the development of cross-sector, low-carbon infrastructure projects.

In addition to emissions reduction, systematic efficiency and circularity within industrial clusters represent vital frameworks to consider. Collaboration focused on enhancing efficiency and circularity can yield financial and environmental benefits within the cluster and the broader system, further contributing to sustainable and responsible industrial practices.

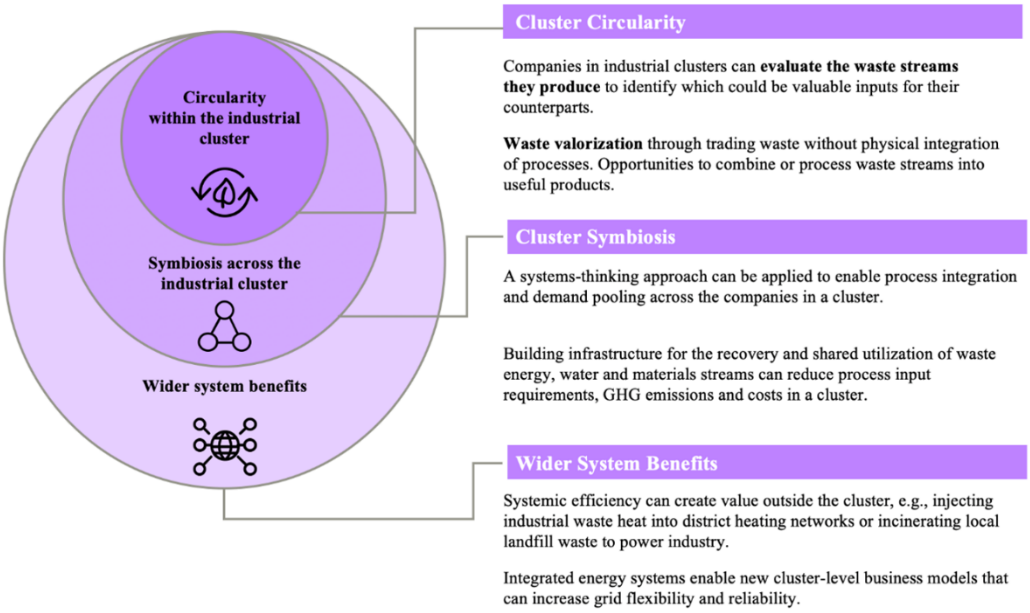

Figure 5 - Systematic efficiency and circularity for industrial clusters. [16]

Collaboration within industrial clusters is indeed essential for achieving common goals, but it comes with its share of challenges. However, proactive actions can be taken to pave the way for success:

1. **Cultivate strong partnerships**: building a culture of shared values and trust is fundamental for effective cooperation. Developing strong partnerships and mutual respect among cluster members is crucial.
2. **Align interests**: Joint decision-making can be slowed down by varying interests and incentives among cluster members. To overcome this challenge, it's essential to establish cluster-wide consortiums and agree on targets that align with individual interests, fostering a sense of collective purpose.

3. **Clear decision-making**: Appointing decision-making groups with well-defined responsibilities can help streamline the decision-making process within the cluster. This can help overcome delays caused by complex decision-making instruments.
4. **Manage investment risks**: Investment risks in industrial clusters can be substantial due to high upfront costs and long payback periods. Furthermore, policy cycles are often shorter than investment cycles, making capital allocation challenging. Public-private partnerships can offer external funding solutions that reduce capital outlay for the cluster and help de-risk investments.
5. **Value by-products and integration**: Within a cluster, companies may have varying production volumes and processes. Establishing obligations for input and output among partners and implementing a system value by-product is crucial. Companies should invest in process integration as part of their long-term strategies. Business models and flexible arrangements introduced by integration should also be developed to optimize resource use and reduce waste.

By addressing these challenges and taking proactive measures, industrial clusters can operate more efficiently, reduce emissions, and deliver on their environmental economic, and technological objectives.

3.1 Direct electrification and renewable energy

Electrification offers a practical pathway to reduce emissions across various industrial sectors. While direct electrification has faced challenges, it is becoming increasingly attractive due to several factors. The introduction of carbon pricing mechanisms encourages industries to reduce emissions, making electrification a more appealing option. The declining costs of renewable energy sources, such as wind and solar, have made electricity generation more cost-effective and environmentally friendly. Utilizing shared infrastructure (like microgrids), can enhance the feasibility of electrification by optimizing resource use and distribution. Stricter emissions reduction targets and policies can drive industries to eliminate the use of unabated fossil fuels, further promoting electrification.

To effectively reduce emissions, a key approach is to electrify low-to-medium temperature and pressure processes, while simultaneously generating low-cost, renewable electricity and heat onsite. This can be achieved through readily available technologies such as rooftop solar, biomass, CSP[11], along with the adoption of shared infrastructure (e.g., microgrid, storage).

Research from important institutions has shown that minor CO_2-intensive sectors, such as paper, wood, textiles, can be almost entirely electrified with technologies already developed. These industries accounted for a substantial portion of EU industrial emissions in 2015 and electrifying them could lead to a significant reduction of 36% of EU industrial emissions by 2050. [16]

In summary, it is technically feasible to electrify a wide range of industrial processes, including those in heavy industry. The adoption of commercially available technologies and the integration of renewable energy sources can significantly contribute to emissions reduction in various industrial sectors. The table 3 below summarizes key processes in various industries that can be electrified with commercially available technologies.

Table 3 - Electrification processes in hard-to-abate industries. [16]

Industries	**Electrifiable processes**	**Technologies**
All industries (including food and textiles)	Low-temperature process heat, i.e., cooling, drying, space heating, steam generation	• Compression heat pumps and chillers • Electric boilers • Mechanical vapor recompression
Wood	Curing	• Ultraviolet curing
Paper and pulp	Limestone calcination	• Electric kilns
Ceramics and glass	Firing ceramics, glass melting, annealing, and tempering	• Resistance furnace
Machinery	Process heat	• Induction furnace
Transport equipment	Process heat	• Induction furnace
Manufacturing	Process heat	• Resistance heating
Non-ferrous metals and secondary steel	• Melting • Smelting • Metals refining	• Induction furnace • Resistance furnace • Electric arc furnace

While there have been limited commercial examples of electrifying industrial heating processes, the activity in this field is growing due to technological maturity and the potential for broader productivity enhancements. Two concrete examples

[11] **CSP**: Concentrated Solar Power.

can illustrate the possibilities and benefits of electrification in industry. Electric Arc Furnaces (EAF) are established tools in secondary steel production, accounting for approximately 28% of global steel production. These furnaces use electricity to melt and recycle steel scrap, making the process more energy-efficient and environmentally friendly compared to traditional combustion-based methods. Another tangible example is the electrification in the Chemicals Industry, especially replacing steam turbines in the propylene purification units with electric motors and frequency inverters. This solution yields several significant benefits, in energy savings in the order of GWh, water savings for millions of litres and tonnes of CO_2 emissions reduction. [16]

The performances can also improve because of lower temperatures due to electrification, enhancing the control of reactions and other operations, contributing to increase the continuous plant operation without the normal required annual technical shutdowns.

These examples demonstrate that electrification in industry can lead to substantial energy and resource savings, reduced emissions, and improved operational efficiency. They serve as practical illustrations of the benefits that can be achieved through electrification in various industrial processes.

Cluster electrification plays a crucial role in advancing the transition to sustainable industrial practices. The key components of on-site and shared renewables, energy storage, and microgrids collectively contribute to achieving energy autonomy and reducing the risk associated with the variability of renewable sources like wind and solar. Here's how each of these elements contributes to the overall goal [16]:

1. **On-site renewables**: On-site renewable energy sources, such as rooftop solar panels or biomass facilities, allow industrial cluster to generate their own clean energy. This reduces their reliance on conventional energy sources and can provide a substantial portion of energy needed for industrial processes.
2. **Energy storage**: Energy storage solutions, such as batteries, enable industrial clusters to store excess energy generated during period of high renewable energy production. This stored energy can be used when renewable energy generation is low, ensuring stable and reliable energy supply.
3. **Microgrids**: Microgrids are localised energy distribution systems that can operate independently or in conjunction with the main grid. They enhance energy resilience and can increase flexibility to properly manage production based on peak price hours and lower ones, balancing energy supply and demand within an industrial cluster. This flexibility not only reduces energy costs but also provides an opportunity for industries to earn revenue by

offering grid flexibility services. Microgrids are particularly useful in areas with unreliable or unstable grid infrastructure.

4. **Renewable PPAs**[12]: When on-site renewables are insufficient to meet energy demand, industrial clusters can pool the demand and negotiate renewable power purchase agreements. These agreements involve buying electricity directly from renewable energy sources, promoting the growth of clean energy generation.

Renewable heat is another critical aspect to achieve almost entirely emissions reduction in the industrial sector, for both direct and indirect heat processes. These processes represent a significant portion of industrial energy demand, accounting for the half of 2019 global heat demand. Nevertheless, despite the potential, a small fraction, the 10% of industrial process heat is currently sourced from renewables. The majority of renewable heat in industry comes from bioenergy, primarily in industries dealing with biomass waste, such as paper, pulp and food. Certain industries, like cement production, are also exploring the use of municipal waste for bioenergy. Here's an overview of renewable heat sources with their advantages and constraints [16]:

- **Bioenergy**: Coming from biomass, biogas, syngas, and municipal solid waste, it is already extensively used in certain industries. Bioenergy can supply heat over a wide range of temperatures and is often used for cogeneration (combined heat and power). It is already extensively used in certain industries. The challenges come from the fact that bioenergy has a lower calorific value compared to fossil-based fuels, and its availability depends on biomass resources.
- **Solar thermal**: Technology includes flat plate collectors and heliostat tower systems. The major obstacles are due to high capital cost for system set-up and process integration and the fact that it is a renewable source that is highly location-dependant.
- **Geothermal heat**: Ground source heat pumps and hot sedimentary aquifer systems are common geothermal technologies. It has a low footprint above ground level and can provide continuous heat production. Commercial-scale geothermal systems may have limitations in achieving high temperatures, and suitable locations are essential.
- **Other sources**: Renewable electricity and hydrogen can also be used for heat generation but are going to be extensively explored for this purpose in the industrial sector in the next future.

[12] **PPA**: Power Purchase Agreement.

Important actions are required to overcome several challenges, such as the cost competitiveness, the cost of electricity is three times the cost of natural gas, making it a barrier to adoption; the capital investment for the high upfront costs for the installations; the limited productivity gains may not be significant; the technical complexity requiring upskilling of operators and process changes, which can be technically complex; the process disruption, replacing process equipment with electric alternatives; the stranded assets, causing the early retirement of long-life fossil-based assets and compromising return of investment. To overcome these challenges, various policy and industry actions can be considered including, carbon pricing, implementing carbon regulations with CO_2 footprint requirements for materials and CO_2-based tariffs; reducing electricity taxation and levies; sectoral agreements can help drive down costs and increase adoption; technology support schemes; retrofitting and hybrid technologies can help industries transition to renewable heat without entirely abandoning existing assets. [16]

In conclusion, a combination of technological advancements, supportive policies, and industry collaboration is essential to overcome the challenges and promote the adoption of renewable heat sources in industrial clusters. These sources can play a significant role in reducing emissions and advancing sustainability in the industrial sector.

3.2 Carbon capture, utilization, and storage (CCUS)

CCUS involves capturing carbon dioxide (CO_2) emissions from industrial processes and then either permanently storing the CO_2 avoiding the release into the atmosphere or repurposing it for other uses. Its projects depend on the economic viability to determine their feasibility and success. Although the environmental advantages are evident, the financial outlay for project initiation and ongoing operations represents a critical factor. It is needed a great ability to generate revenue through carbon utilization or secure storage because it is essential to balance costs and make this technology appealing to industries and potential investors.

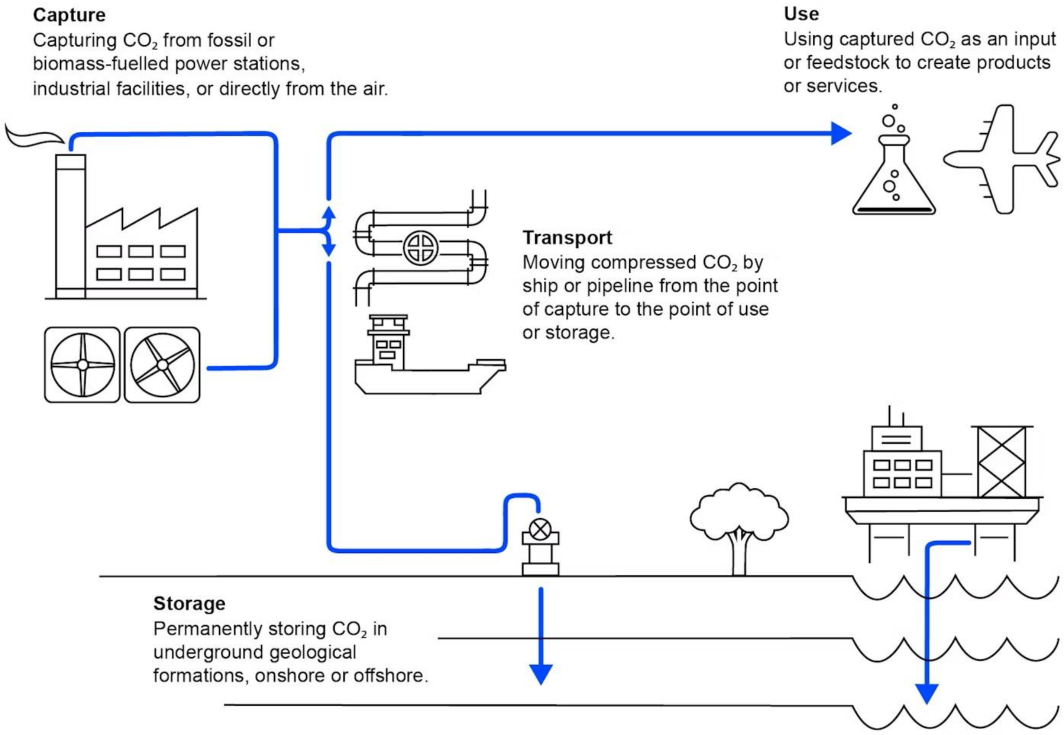

Figure 6 - General scheme of the CCUS technology. [17]

To have a better view it is useful to split the two technologies because of their different history and development. Carbon capture and storage (CCS) is emerging as a promising opportunity for hard-to-abate industry sector. To meet the requirements for climate change mitigation, a large number of CCS facilities must be deployed globally by 2040, estimating 2,000 of them. Currently, there are a limited number of operational, slightly more than 1% of the planned total. [16] To quickly improve this condition, industrial clusters are ideal locations for implementing CCS, as they can capture emissions from multiple sources within close proximity. The major barriers are related to the high costs for the equipment and the significant energy requirements, particularly in heavy industry sectors. Transportation of captured CO_2 necessitates specially designed and pressurized pipelines for condensed CO_2.

Carbon capture and utilization (CCU) has strategies focused on the transformation of captured CO_2 into valuable products like chemicals, fuels, or contruction materials. Offers various ways to use captured CO_2, with Enhanced Oil Recovery (EOR) being one of the most advanced applications in which CO_2 is injected into reservoir rock in existing oil or gas fields, where it is permanently stored while also increasing oil recovery. CCU suffers of technological issues regarding the repurpose of CO_2 and so the economical pathway is more difficult.

In conclusion, CCS and CCU are essential tools in the fight against climate change and carbon emissions reduction. The success of these technologies depends on supportive policies, technological advancements, and cost-efficiency measures to make them more widespread and effective in among many industrial sectors.

3.3 Hydrogen

Hydrogen, as an energy and feedstock, has emerged as a focal point of attention for hard-to-abate sectors, especially in industrial applications, representing a transformative solution with the potential to revolutionize the way industries produce, store, and utilize energy. To encourage the widespread deployment of low or zero-carbon hydrogen, it is important to demonstrate its cost competitiveness compared to fossil fuels and other decarbonisation methods like electrification. Industrial clusters prove to be highly conducive environments for harnessing the potential of hydrogen. Here, hydrogen production and consumption coexist within the same locale, reducing the necessity for extensive long-distance infrastructure.

Initially, the thesis explores the multifaceted role of hydrogen within industrial sectors, especially in the field of ports and their surroundings involving medium-high temperatures industries, such as the ceramic ones. It provides an overview of the general opportunities, challenges, and implications of adopting hydrogen technologies, as well as the evolving regulatory landscape and economic considerations to subsequently pass to the specific case study of Italian Ceramic District of Sassuolo and its intricate connection with the nearby port of Ravenna.

Through this exploration, the aim is to shed light on the transformative potential of hydrogen and its implications for industrial sustainability within the unique industrial and geographical context of the Italian Ceramic District.

Hydrogen is a versatile element that find applications in a wide range of industrial processes and energy production. Here’s an overview of its established and emerging uses:

Existing applications of hydrogen:

- **Refinery Hydrogenation**: In mineral oil refineries, removing impurities and improving the quality of petroleum.
- **Ammonia Production**: Crucial for the production of ammonia, a vital component for fertilizers supporting agricultural needs.
- **Methanol Production**: Serving as both a chemical feedstock and a fuel source, showing its adaptability across industries.

New and emerging applications of hydrogen:

- **Green Steel Production**: For primary steel, offering a sustainable way to reduce greenhouse gas emissions in the steelmaking process.
- **High-Value Chemical Production**: Hydrogen's versatility extends to producing high-value chemicals for clean chemical manufacturing.
- **Industrial Heat Generation**: Hydrogen is becoming a reliable source for generating heat in industrial processes, which enhances energy efficiency.

Figure 7 - Hydrogen demand asset. [19]

In 2020, Europe experienced a significant demand for hydrogen of 288 TWh (8.64 Mt), primarily driven by existing applications, such as refineries, ammonia, and methanol production, which collectively accounted for 84% of the total demand. [19]

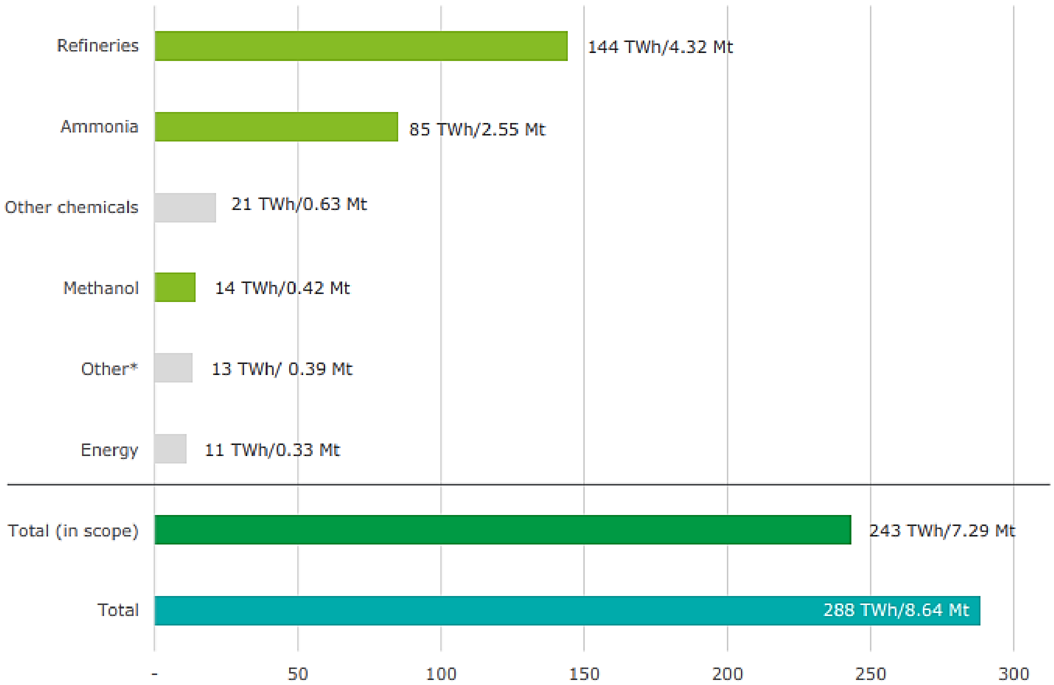

Figure 8 - Hydrogen demand by sector in 2020 in Europe (in TWh and Mt/year). [19]

The hydrogen production landscape can be categorised and viewed, considering three of the main types according to their carbon emissions. Here, the types of hydrogen included are “grey” hydrogen, “green” hydrogen, and “blue” hydrogen.

Grey hydrogen is primarily produced from natural gas or coal using methods such as steam methane reforming (SMR) or coal gasification. Currently, grey hydrogen production is predominant in Europe, with 95% of total production and is highly carbon-intensive, which makes these hydrogen technologies unsuitable for a route toward net-zero emissions. Overall, in 2020, there were 251 steam methane reforming plants (SMRs) in the EU+UK, with a total grey hydrogen production capacity of 245 TWh (7.35 Mt). [19]

Figure 9 - Steam methane reforming plants (SMRs) to produce grey hydrogen in Europe. [19]

Green or renewable hydrogen is produced in a climate-neutral manner. Renewable hydrogen is produced through water electrolysis, which uses electricity generated from renewable sources like solar, wind and hydropower. This method splits water molecules into hydrogen and oxygen, and when renewable electricity is used, the entire process is free from carbon. The advantages are evident since this net-zero route allows the exploitation of synergies from sector coupling, thus decreasing technology costs and providing flexibility to the power system. [18] The most valuable driver for green hydrogen deployment is the cost of electricity. Green hydrogen is becoming economically attractive due to the decreasing costs of solar and wind electricity production. The cost of electricity generated from solar photovoltaic (PV) and onshore wind sources has seen a remarkable reduction over the past decade, which prices now reach 56 USD/MWh for solar energy and 48 USD/MWh for onshore wind energy. Green hydrogen production costs have witnessed a significant decline, primarily attributed to a 60% reduction in the capital costs of electrolysis since 2010. This has led to a noteworthy drop in the cost of hydrogen, ranging from USD 10-15/kg down to as USD 4-6/kg. [18] Green hydrogen carries substantial advantages for the power system, particularly in the integration of VRE[13] sources into the grid. Electrolysers used for green hydrogen production can be designed as flexible assets, capable of responding rapidly to compensate for fluctuations in VRE output. Furthermore, green hydrogen can be stored for extended durations and employed when VRE sources are unavailable for power generation. [18] However, it’s essential to acknowledge the challenges that green hydrogen still faces. Notably, its production costs are still higher compared to grey hydrogen, often ranging from two to three times more expensive. Additionally, the adoption of green hydrogen technologies for end-uses can be costly. The lack of dedicated infrastructure is another impediment, highlighted by a mere 5,000 kilometres of hydrogen transmission pipelines worldwide and where pipelines are present, transporting hydrogen necessitates additional energy inputs, equivalent to 10-12% of the energy content of the hydrogen itself. The entire green hydrogen value chain exhibits notable energy losses. Equally significant is the absence of a recognized green hydrogen market and the failure to value the lower GHG emissions that green hydrogen can offer. [18] These issues collectively underscore the complexities that need to be addressed as we strive to fully leverage the potential of green hydrogen in the energy landscape. Green hydrogen represents a pivotal piece of the puzzle in the transition to a low or zero-carbon energy landscape. While significant strides have been made in reducing costs and recognizing its benefits for power systems, it remains crucial to address disparities in the areas mentioned above. The future of green hydrogen hinges on collaborative efforts across governments, industries, and the research community to unlock its full potential.

Blue hydrogen, also referred to as low-carbon hydrogen, occupies a critical niche within the hydrogen landscape, serving as a crucial bridge between high-carbon grey hydrogen and fully sustainable green hydrogen. It is produced through a

[13] **VRE**: Variable Renewable Energy.

similar process as grey hydrogen, using steam methane reforming plants (SMRs), but distinguishes itself through the incorporation of CO_2 capture units and subsequent CO_2 storage (CCS). [20] Blue hydrogen is widely recognized as a transitionary solution aimed at reducing carbon emissions from hydrogen production. It plays a vital role in the progression toward a hydrogen-based economy, particularly during the market ramp-up phase in the 2020s and 2030s. The technical potential of blue hydrogen is not bound by hydrogen demand but by the availability of natural gas and its relative price. While blue hydrogen holds a crucial position in the decarbonisation journey, its long-term is expected to diminish beyond 2035. This transition reflects the growing competitiveness of green hydrogen, which becomes increasingly economically attractive due to the declining costs of renewable energy sources. Blue hydrogen projects typically have a lifespan of approximately 25 years, and in their later stages, they may evolve into a supplementary and balancing resource to support green hydrogen. [19] In summary, blue hydrogen facilitates the transition to a more sustainable hydrogen-based economy, gradually decreasing emissions at the expenses of grey hydrogen production while green hydrogen gains the upper hand.

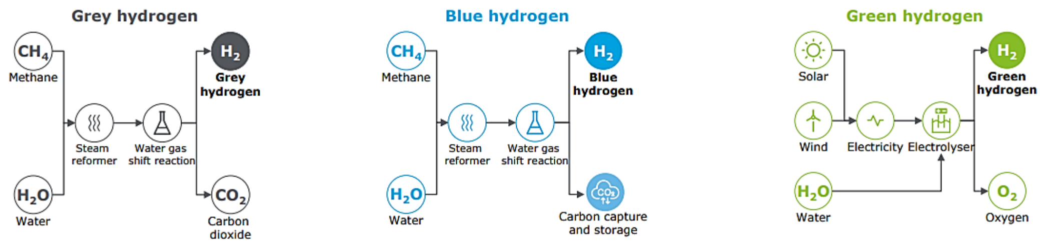

Figure 10 - Hydrogen colour spectrum based on production process. [19]

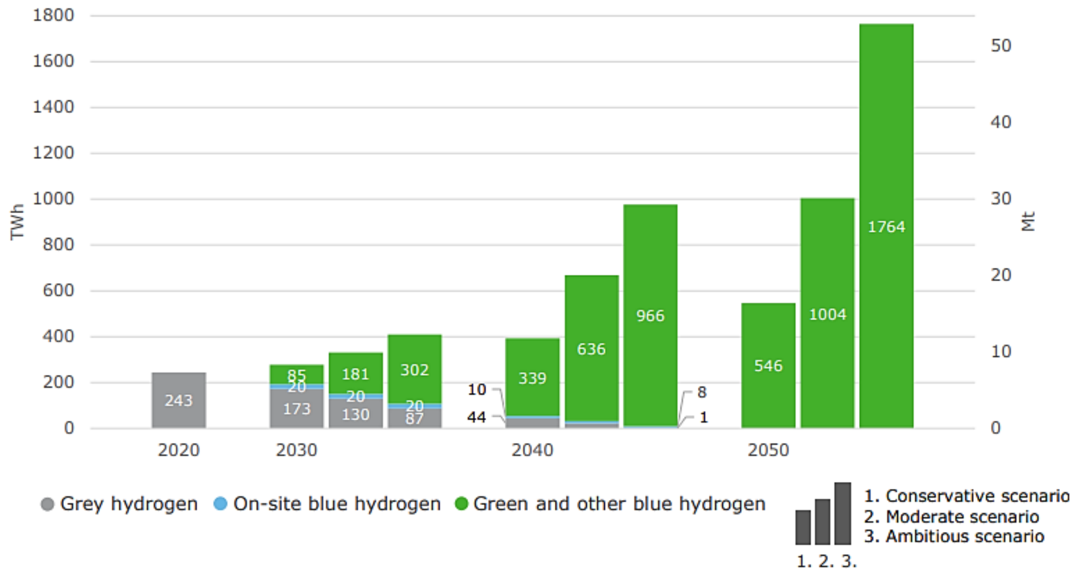

Figure 11 - Projected hydrogen annual supply in three different scenarios. [19]

3.3.1 Hydrogen implementation in European ports

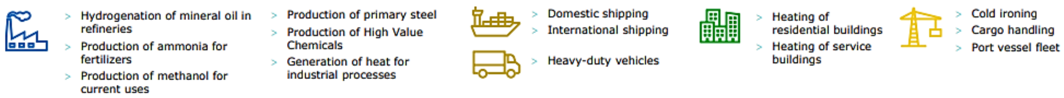

Figure 12 - Hydrogen demand asset. [19]

Port areas have emerged as central nodes in the evolving hydrogen landscape, incited by a convergence of industrial and transportation activities. Projections indicate that these regions will be focal points for hydrogen demand, with an estimated 50% of the total demand concentrated in these areas. [19]

Within or near port regions, industrial processes often hinge on hydrogen, relying on it as a fundamental feedstock or for various essential applications. Traditional sectors like refineries, chemicals, and steel production have long integrated hydrogen into their operations, illustrating its intrinsic importance.

Port regions, known for their significance as transportation hubs encompassing shipping and logistics, are witnessing a transformative shift. The maritime industry, in particular, is increasingly exploring hydrogen as a prospective zero-emission fuel to meet stringent environmental regulations and reduce carbon emissions.

Moreover, ports offer strategic advantages for hydrogen-related activities. They typically feature the necessary infrastructure, including hydrogen production facilities, pipelines, and storage facilities, making them attractive locations for a range of hydrogen-related operations.
Notably, certain ports are evolving into dynamic hydrogen hubs or clusters, optimizing their capabilities to efficiently serve local industrial and transportation sectors. These evolving hubs form interconnected ecosystems that facilitate the seamless flow of hydrogen-related activities and significantly contribute to the regional hydrogen economy.

Table 4 - Expected hydrogen related CO2-eq abatement by 2050. [19]

Category	Conservative scenario	Ambitious scenario
Industry	31%	64%
Transport	10%	34%
Urban areas	0%	20%
Port activities	4%	20%

Hydrogen has the potential to significantly reduce CO_2-eq emissions in Europe, with the potential to abate up to 655 Mt of emissions by 2050. This reduction represents approximately the 16% of all European CO_2-eq emissions. [19]
However, a comprehensive view about the existing challenges due to the enormous renewable capacity to install to satisfy green hydrogen production in Europe is essential. For a significant domestic production, a range of 160-720 GW of solar PV capacity, supplemented by 40-125 GW of wind onshore and 35-80 GW of wind offshore would be necessary. [19]
Importing a certain amount of hydrogen is inevitable. For this reason, the collaboration between, ports, industrial clusters, and the broader hydrogen supply chain is instrumental in building a sustainable and interconnected hydrogen infrastructure that can serve as a foundation for a more resilient system.
The classification of ports into four archetypes based on logistics and transport, urban, industrial, and bunkering criteria is a way to categorize and understand the roles and characteristics of different types of ports. These archetypes help in identifying the primary activities and functions of ports, which can be crucial for planning and implementing hydrogen supply and distribution networks. [19]
These archetypes and tiers help policymakers and industry stakeholders in identifying which ports are suitable for specific hydrogen-related activities, such as hydrogen production, storage, and distribution, based on the port's

primary functions and geographic context. It also assists in allocating resources and developing strategies for hydrogen deployment within the port areas to support the growing demand for hydrogen in various sectors.

Figure 13 - Map of European ports that can import hydrogen. [19]

3.4 Evaluation of life cycle assessment in the ceramic industry

From a chemical point of view, ceramics represent non-metallic and inorganic solids primarily derived from naturally occurring materials like bauxite, magnesite, and clay, which is particularly abundant. However, depending on the mixture, the final ceramic products can present several differences conditioning durability and performance. [23] Refractories, for instance, find crucial utility in extreme-temperature industrial processes due to their exceptional resistance to heat, mechanical stress, and chemical exposure while retaining their structural integrity. These applications are prevalent in industries such as metallurgy, cement, glass production, energy generation, and chemical processes. Technical ceramics, on the other hand, are known for their ability to withstand higher temperatures and mechanical loads, significantly extending the lifespan of various industrial components. They find application in products like insulators, engine components, catalyst carriers, biomedical implants, and filtration systems. Notably, most technical ceramics exhibit inert and non-toxic characteristics, contributing to a reduction in environmental pollution. They are increasingly replacing heavy metallic alloys in challenging applications across multiple industries, establishing ceramics as a fundamental component in advanced engineering materials. Advanced ceramics play a significant role in clean energy production, with applications ranging from piezoelectric systems for solar energy conversion, to solid oxide fuel cells, showcasing their significance in advancing sustainable energy solutions. [26]

The manufacturing process of ceramics typically involves the following steps: the acquisition of raw materials, addition of additives, powders, and water, followed by shaping into various forms, which are dried and fired in high-temperature kilns. [26]

The production process of ceramic tiles can be divided into two primary stages: shaping and the glazing. The shaping stage encompasses the acquisition of raw materials, preparation of the slurry, forming of the ceramic bodies, and subsequent drying. The glazing stage involves obtaining the necessary raw materials, preparing the glaze-frit, milling, depositing the glaze onto the ceramic bodies, and conducting the firing process with sinterization. Notably, the sintering or burning stage in the production of ceramic tiles is recognized as a critical step due to the high fuel consumption, primarily derived from non-renewable fossil fuels like natural gas. In instance when required, ceramic tiles undergo a finishing process that involves grinding and polishing before undergoing a selection process and final packaging. The choice of raw materials primarily includes clays, feldspars, and carbonates, which are transported to the ceramic tile factory and stored until they are needed. Within the factory, these raw materials and additives are mixed with water when a wet process is employed. Subsequently, atomization occurs, transforming the suspension into granular particles, known as "atomized powder". This atomized powder is then mechanically compressed to form the "green" ceramic bodies. After shaping, the ceramic bodies are dried, reducing the remaining water content to less than 1%, through exposure to higher temperatures inside the dryers, typically around 170 °C. [24]

Simultaneously, the preparation of glazes is carried out, involving the creation of glassy coatings applied to the surface of the floor or tile. The main primary input materials in this process include raw materials for

manufacturing, such as frits, kaolin, sand, various oxides, pigments, and water, which are ground to produce a glaze for application. [24]
Once the initial processes are completed, the ceramic bodies are glazed using various techniques including immersion, spraying, bell or disk application, curtain coating, dripping, and electrostatic application. The choice of technique depends on factors such as the shape, size, quantity, and structure of the pieces, as well as the desired appearance of the glazed surface. Following the reducing of humidity and the application of the enamel layer, the ceramic pieces are subject to heat treatment in kilns, typically ranging from 800 ℃ to 1700 ℃. After kiln firing, most ceramic tiles are removed, inspected, and prepared for distribution. The glazed tiles undergo a classification process based on various criteria, including whether the product is enamelled or non-enamelled, the shaping process used, water absorption groups, surface abrasion resistance classes, grades of resistance to staining, and surface appearance or visual analysis. Once classified, the ceramic tiles are packaged and prepared for sale. [24]

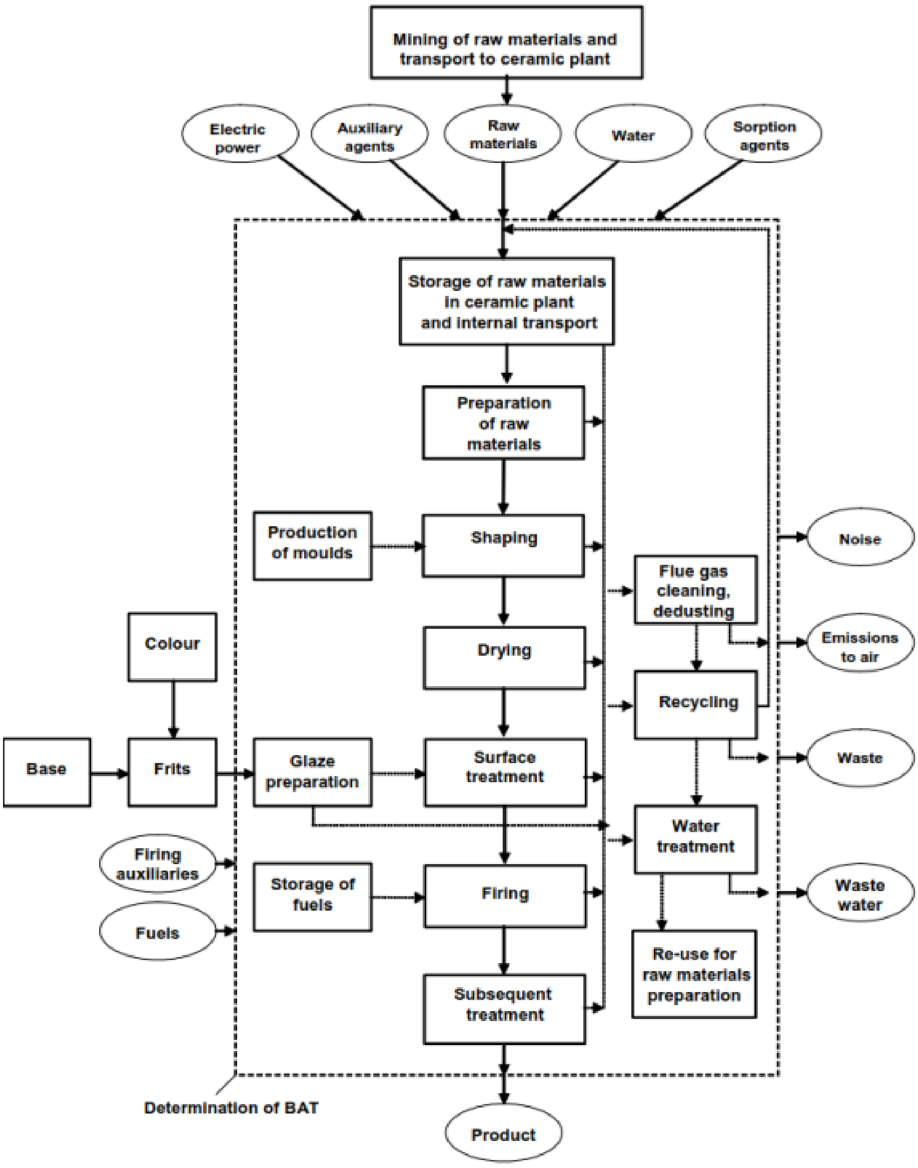

Figure 14 - Stages of ceramic manufacturing. [25]

The ceramic tile industry brings significant economic benefits; however, it is also associated with high energy consumption and the emission of pollutants that have adverse effects on the environment, human health, and the overall competitiveness of the products. Throughout the life cycle of ceramic tiles, multiple environmental impacts can emerge, spanning from the initial production stages to the final product and involving atmosphere pollutants, wastewater, energy consumption, noise and odour, soil contamination. [25]

Nevertheless, the most severe consequences arise from specific aspects, notably the substantial consumption of electricity (often derived from natural gas), emissions during the production process, which encompass particulate materials, gases, and polluting liquids, as well as the creation and management of waste materials.
Hence, the ceramic industry presents a complex environmental landscape with various factors impacting the sustainability of its operations. However, the industry has taken significant strides to mitigate these challenges. To drive to reduce energy consumption while enhancing energy efficiency is a paramount concern for the ceramic sector. This effort encompasses the exploration of innovative solutions, including the integration of renewable energy sources and the electrification of production processes, which hold the potential to reduce the industry's carbon footprint.

3.4.1 European ceramic industry

The European ceramic industry, with a total EU revenue of EUR 26 billion and over a third of its production volume exported outside the EU plays a pivotal role in the global market. [26] The European ceramic industries have collaborated to reduce emissions and have already made notable results. Between 1990 and 2020, the CO_2 emissions associated with producing clay blocks for one square metre of an external wall were reduced by an average of approximately 50%. In addition, the energy consumption for manufacturing one tonne of wall and floor tiles has seen a 47% reduction. This remarkable progress extends to the total CO_2 emissions in the ceramic industry in the EU, which have declined by over 45% since peaking in 2000. [26]
Cerame-Unie remains committed to advancing plans for enhanced efficiency and swift reductions in environmental impact. The ceramic industry is an integral part of a broader industrial ecosystem encompassing raw materials supply, energy sources, manufacturing facilities, and downstream users. [26] The collective efforts of the European ceramic industry reflect its dedication to environmental responsibility and sustainable production practices in the face of energy-intensive processes.

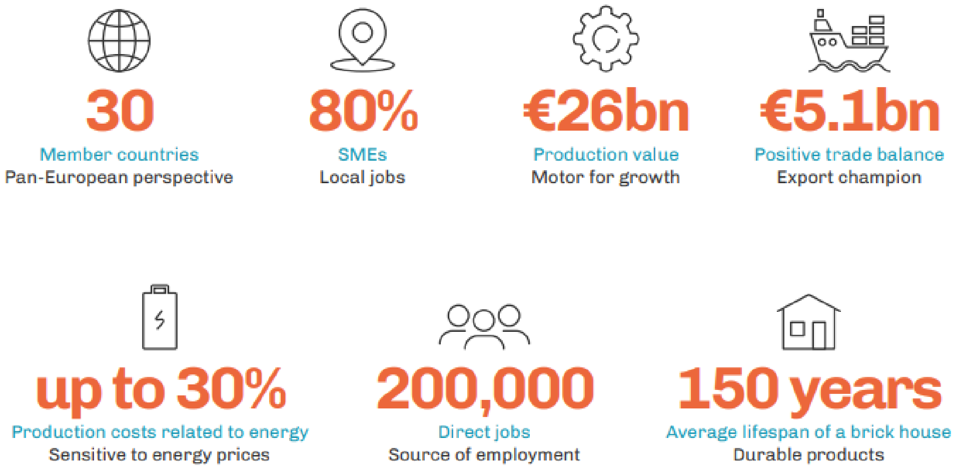

Figure 15 - European ceramic industry in numbers. [26]

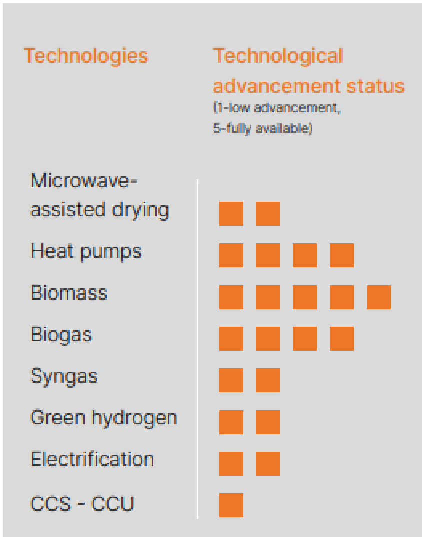

Figure 16 - Technological advancement status for the ceramic industry. [26]

In conclusion, the European ceramic industry has embarked on a journey of transformation, driven by its commitment to environmental responsibility, sustainability, and competitiveness. The industry's unique composition, characterized by a high number of small and medium-sized enterprises, necessitates innovative solutions and a collaborative approach.
Green hydrogen, green synthetic gas, and biofuels are key elements in the decarbonization of the power supply. Under this vision, the European ceramic industry envisions a future in 2050 with a significantly reduced

energy demand, marking a significant step toward a cleaner, more sustainable, and environmentally responsible industry.

While challenges persist, the European ceramic industry is well-positioned to continue its commitment to remaining a strong and reliable part of the European supply chain, along with its efforts to reduce emissions and improve efficiency.

4. Case study: port of Ravenna linked to the Ceramic District of Sassuolo

The thesis, now, gets into the core of the study, the analysis, and the methodology, connecting all the general informations and data seen so far to this specific area of case study. This write intends to bring to light something really important, enlightening readers and passionate people about many considerations, facts, ideas, attempts, results and conclusions for this crucial geographical region, inserted in a much wider and more complex context, which talks about people, workers, innovative perspectives, care of the environment and of the future, leaving a personal trace of what astonishing can be done.

The Italian ceramic industry comprises companies engaged in manufacturing tiles, ceramic slabs, sanitary ceramics, porcelain, tableware, refractory materials, technical ceramics, and bricks. It stands as a prominent pillar of the Italian sector, showcasing remarkable strength in penetrating international markets and enduring the challenges posed by the changing global scenario.

Everything starts from the objective to find the best solutions to reduce the greenhouse gas emissions of the hard-to-abate industry sector of the ceramics. In the region of Emilia-Romagna, Italian cornerstone for its geographical position well-suited and exploited for any kind of reason, it is present and consolidated one of the most dynamic and intellectual exchange of ideas coming from any direction.

In this relatively small piece of land, around Modena and with the administrative headquarter situated in Sassuolo, was born the Ceramic District, in which a group of entrepreneurs established the first society dedicated to the production of ceramics. Today, this District is one of the main ceramic's tiles manufacturers worldwide. In this context, the port of Ravenna is perfectly integrated. Without this strategical port, far only few kilometres from the entire ceramic production, the District wouldn't be the same since it is widely subject to the port operations. The port is source of raw materials, energy carriers, railways, highways, and maritime transports that bring with them every type of component or material useful to the final user that is the entire value chain of the ceramic industries cluster.

4.1 The port of Ravenna

Figure 17 - Top view of the port of Ravenna. [28]

The port of Ravenna is an important seaport located in the city of Ravenna, Italy. It's situated on the Adriatic Sea and has a long history dating back to ancient times. This port is known for its strategic location, connecting the Mediterranean Sea with the Po River, and providing access to the northern part of Italy and central Europe. It also plays a significant role in trade with the markets of the Middle and Far East, and the Black Sea. It serves as a hub for various types of cargo, including goods such as grains, and many other commodities.

The port facilities have undergone modernization and expansion over the years to accommodate the growing demands of trade and shipping. It's not just a commercial hub but also contributes to the economic development of the surrounding areas.

To give an insight into more specific details, the port of Ravenna stretches over 11 kilometres from the city centre to the city's Darsena. Noteworthy for its advancements in shipbuilding and the transportation of bulk solids, which make up approximately 66% of the port's overall traffic, it plays a pivotal role in maritime trade. Functioning as a canal port, it boasts 22 private terminals, 14 km of operational quays, and current depths of -10.50 meters (reaching -11.50 m in the Trattaroli area). In terms of infrastructure, the port's total warehouse capacity is 602,258 square meters, with 1,323,922 square meters designated for yards and over 1,256,298 cubic meters for tanks/silos. [29]

Managed under Legislative Decree no. 168/2016 by the "Autorità di Sistema Portuale del mare Adriatico Centro-Settentrionale", the port of Ravenna ensures accessibility from key Italian and European markets. Its advantageous location led to its designation as a core port in both Baltic-Adriatic Corridor (Corridor 1) and the Mediterranean Corridor (Corridor 3) through the new regulation for the TEN-T[14] networks by the European Community, as approved with European Regulation no. 1315/2013. [29]

Focusing on the traffic trends, during the initial seven months of 2023, the port of Ravenna managed a total of 15,572,366 tonnes, indicating a decline of 4.9% equivalent to over 800,000 tonnes less than the preceding year. In the ongoing trend, petroleum products are maintaining stability, while solid agrifood products are showing a robust growth of over 6%, and for fertilizers, indicating a remarkable surge of almost 16%. In contrast, there has been a notable decline in construction materials by nearly 21%, with a handling volume of 2.9 million tonnes. This decline is primarily attributed to the adverse trajectory of the ceramic raw materials, recording a substantial drop of 20.7% compared to July 2022. [30] This trend finds explanations in the altered conditions within the geopolitical and economic landscape, especially for the Ukraine conflict since the Nation is one of the largest exporters of clay. Hence, the aim is to simplify regulations, eliminating unnecessary burdens, freeing up resources for crucial new investments to support the ceramic sector.

[14] TEN-T: Trans-European Trasport Network policy, key element for the development of coherent, efficient, multimodal, and high-quality transport infrastructure across the EU. [34]

Figure 18 - Ceramic raw material in the port of Ravenna. [33]

The region of Emilia-Romagna, precisely for this purpose, has instituted the "Zona Logistica Semplificata" (ZLS), representing a novel economic policy tool. The zone is designed to provide assistance in realizing the development strategies outlined in the plans and programs of the Autorità di Sistema Portuale del mare Adriatico Centro-Settentrionale (the Authority). In precise terms, the ZLS is defined as "Geographically delimited and clearly identified area, consisting also of non-territorially adjacent areas that present an economic-functional nexus and that include at least one port area with the characteristics established by Regulation (EU) no. 1315 of 11 December 2013". [35] The primary aim of the ZLS is to foster the advancement of the regional production-industrial and logistics system. This is pursued by creating advantageous conditions for its growth, specifically through administrative simplifications, as well as through tax, customs, and financial incentives tailored for the companies already operating within it. An examination of the regional economic system reveals that its defining features are the manufacturing sectors, holding strategic significance due to their substantial contribution to the regional economy and their high level of foreign trade engagement. Specifically, there are eight specialized production sectors that collectively represent around the 37% of the turnover and the total regional added value. These sectors are agri-food, textiles and clothing, wood and furniture, ceramics, chemicals, and plastics, as well as pharmaceuticals and biomedical products. [35]

4.1.1. The future of the port between economic growth and green transition

Currently, the port of Ravenna is undergoing two important transformations that include two crucial objectives. A first transformation concerns the energy efficiency of the port buildings and terminals and the second transformation, directly linked to the first one, regarding the installation of renewable energy systems, from one side able to help for the first objective and, in addition, to produce energy to sell to the grid or to the companies nearby.
To succeed in this huge change, in response to the legislative amendments introduced by Law no. 84/1994 concerning energy sustainability, the Authority acknowledges the significant environmental impact it carries and actively addresses issues related to energy consumption and the resultant emission of greenhouse gases. This is accomplished through a dual approach: Firstly, by gauging and overseeing the trajectory of climate-altering emissions within the port system through the "Documento di pianificazione energetica ed ambientale del sistema portuale" (DEASP), and secondly, by executing targeted measures to enhance energy efficiency, reduce emissions, and advocate for the judicious use of energy resources. [33]

Table 5 - Electricity consumption and emissions related to the activities of the entire area of the port of Ravenna. [33]

Indirect energy consumption of the Authority headquarters and port				
	u.m.	**2019**	**2020**	**2021**
Electricity for the Authority headquarters	KWh	73.817	60.521	79.772
Electricity for the port		1.517.119	1.480.731	1.320.535
Total electricity		1.590.936	1.541.252	1.400.257
Indirect emissions in tonnes of CO_2 – location based				
Electricity for the Authority headquarters	t CO_2	20,40	16,72	22,03
Electricity for the port		419,18	409,13	364,86
Total electricity		439,58	425,85	386,89

Table 5 illustrates how, over recent years, there is a general positive trend for both the Authority headquarters and the port in reducing emissions and energy consumption. The year 2020 was heavily marked by the Covid-19 pandemic resulted in a decrease in both CO_2 emissions and electricity consumption, also a consequence of this inevitable factor. However, in 2021, the positive trend of total reduction in both fields is confirmed, except for the Authority headquarters that see an increment of CO_2 emissions and electricity consumption also compared to 2019 measurements. The energy consumption of the Authority can be attributed to both direct and indirect sources. Direct consumption is associated with service vehicles, while indirect consumption encompasses the use of electricity for lighting, office heating, and the operation of mechanical systems. In this regard, one of the strategies implemented by the Authority in the energy sector involves the generation of energy from renewable sources, in alignment with the goals of enhancing energy efficiency and mitigating climate-altering emissions. [33] The most impacting solutions were taken through the enhancement of the internal lighting system with new LED luminaries and the implementation of an automation control and management system. Moreover, a 30 kW photovoltaic system was installed on the roof of the Authority's headquarters. In the year 2021, this PV plant generated 39,530 kWh of electricity, preventing the release of 10.91 tonnes of CO_2 emissions. [33]

A predominant contributor to CO_2 emissions stems from port activities, especially navigation, operations conducted by port enterprises, and the transportation of goods within the port. Primary navigation, including freight and passenger traffic, together with navigation support, which encompasses operations conducted by tugs, moorers, and pilots are responsible for the 75% of total CO_2 emissions, accounting for approximately 87.100,00 tonnes of CO_2. [33] Indeed, the pollution associated with maritime transportation presents inherent complexities, particularly in the context of being one of the most challenging sectors to decarbonize. This difficulty is attributed to various factors since the maritime transport industry operates on a global scale with a vast fleet of ships, each with distinct propulsion systems, energy requirements, and operational patterns. New cleaner propulsion technologies such as biofuels and hydrogen fuel cells have been recently introduced but it is still a slow transition in the whole sector.

The new frontiers involve many innovative projects. Among the most important can be found:

- **FSRU (Floating Storage & Regassification Unit) project**: This project involves a floating storage and a regasification vessel "BW Singapore" acquired by Snam. This vessel boasts a continuous regasification capacity of approximately 5 billion cubic meters, and in addition, it offers a storage capacity of 170,000 cubic meters of liquefied natural gas (LNG). As part of the project, infrastructure will be developed to connect the ship to the existing gas transport network. This connection comprises approximately 8.5 km segment of offshore pipeline and an approximately 34 km section of underground onshore pipeline. The design prioritizes non-man-made areas, adhering to the preservation of protected areas and minimizing land use. [36]
- **Ravenna CCS project**: This project consists in a Carbon Capture and Storage (CCS) infrastructure designed to capture CO_2 emitted by the industrial districts in the area, including the Ceramic District. Carbon dioxide will be directly captured from industrial smokestacks, isolated from other emissions, and conveyed through underground pipelines to the upcoming Casal Borsetti pumping station. Subsequently, the captured CO_2 will be transported under pressure to offshore platforms and injected into depleted reservoirs that have been repurposed as permanent storage sites at 2,500 meters below the seabed. Starting from 2026, the project anticipates storing approximately 4 Mt of CO_2 annually. This significant storage capacity aims to play a crucial role in the decarbonization efforts of hard-to-abate industries in the Ravenna area and Northern Italy. [37]
- **Romagna 1&2 project**: This energy hub is a cohesive integration of multiple systems designed to synergistically facilitate the production of electricity from renewable sources and the generation of green hydrogen. Additionally, the hub incorporates battery storage systems to store electricity, establishing a true Hydrogen Valley. The potential of this project is demonstrated by some key numbers, including 750 MW of installed capacity at maximum output, featuring 75 offshore wind turbines, a floating photovoltaic park, and integrated storage systems collectively. Additionally, the project aims for the annual production of 8,000 tonnes of green hydrogen, resulting in a target installed capacity of 60 MW. Furthermore, 1700 GWh of electricity are expected to be generated from wind and solar plants, emphasizing its substantial impact on renewable energy production. [38]

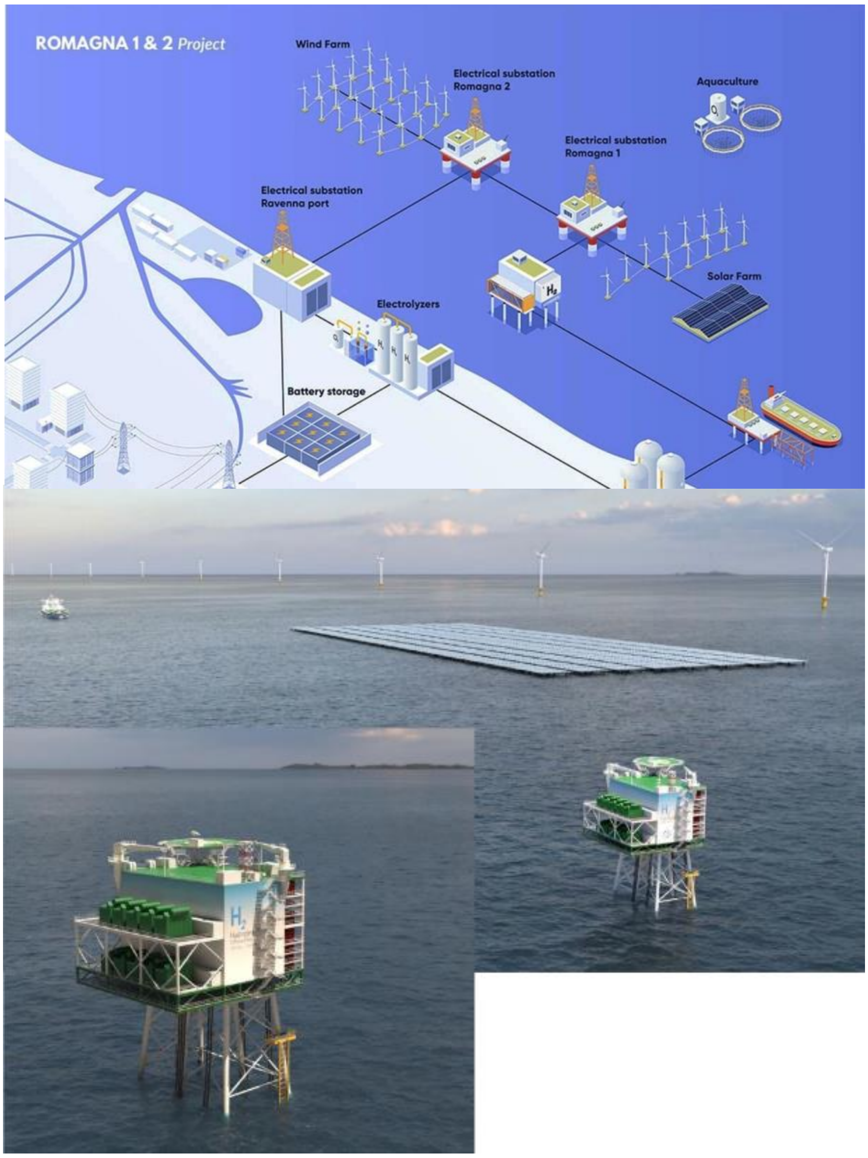

Figure 19 - Romagna 1&2 project by Agnes. [38]

Focusing on the hydrogen production, the plant is able to produce 1,160 kg/h or 12,900 Nm^3/h of pure hydrogen. It will be distributed among the various offtakers, including national natural gas network operator for blending, hydrogen vehicles for public and private mobility through

Hydrogen Refueling Stations (HRS), and distribution to companies and industries, particularly those classificated as hard-to-abate. [38]
This diversified distribution strategy highlights the versatility of hydrogen as an energy carrier, addressing both transportation and industrial applications.

Throughout this case study, the commitment to a sustainable footprint in the port of Ravenna and its surrounding area has been tangible and robust. The meaning of this thesis lies in the recognition that a strong alternative to the conventional systems reliant on fossil fuels is not only available but demonstrably present.

The description of the characteristics, trades, and projects within the port of Ravenna highlights the intricate web of coexistence and interdependence among various elements. Effective communication and cooperation between all working and social entities are essential for establishing a functional framework that benefits everyone involved.

The Ceramic District, which will be the focus of the upcoming section is this thesis, shares numerous connections with the port of Ravenna, creating a mutually beneficial relationship between the two. In the coming years, projects mentioned before, such as Carbon Capture and Storage and the substantial production of hydrogen from renewable sources within the port area are going to exert a significant influence on the ceramic industries of the District. This impact, in turn, presents an opportunity for the ceramic sector to enhance its production in a more sustainable manner, aligning with ETS, avoiding paying emissions taxes. This not only has the potential to boost revenues but also expands commercial trades for ceramics products, simultaneously enabling the industries to seek and receive increased quantities of raw materials, as consequence of a rise in production.

4.2 Union of Municipalities of the Ceramic District of Sassuolo

For years, the Italian ceramic industry sector has been an example of excellence at an international level in terms of high-quality production and management of critical environmental factors. Throughout this period, companies within the sector have engaged in extensive research activities fostering collaboration with local institutions and regulatory bodies. The primary goal has been to curtail the environmental and health impacts stemming from their operations. Notably, these accomplishments extend beyond environmental considerations and encompass social sustainability. The sector has actively embraced Corporate Social Responsibility and Corporate Welfare, initiating collaborative projects with educational institutions, including schools and universities to advance education and research in tandem with societal well-being. In this context of the executed and ongoing initiatives, companies within the ceramics sector have already established a favourable position in alignment with the objectives of the 2030 Agenda. This framework, inherently international in nature, mirrors the global markets that the sector serves. It serves as a valuable tool for highlighting efforts undertaken within a shared framework, encompassing not only major multinational corporations but also entire production chains and local businesses actively addressing these concerns.

Within the province of Modena lies the pivotal hub recognized both nationally and globally for the manufacturing of ceramic floor and wall tiles. This district hosts approximately 300 companies, providing employment to around 18,000 individuals. The concentration of these enterprises is primarily observed in the Sassuolo area, Formigine, and Fiorano. Collectively, these businesses, in conjunction with those situated in the province of Reggio Emilia, account for 80% of the country’s tile production, generating a turnover of 4 billion euros. [41]

Figure 20 - SDGs for the Italian ceramic industry objectives. [31]

The examination focuses on this specific ceramic sector because enlarging the view to the Italian industrial sector, the industry's energy consumption in Italy reached 1048 PJ, constituting approximately 20% of the overall final energy consumption. Additionally, carbon dioxide emissions from manufacturing and the process industry contributed to 20% of the total national emissions. [32] This few data already underscores the substantial role of the Italian industrial sector in the country's energy landscape and carbon emissions profile. This information serves as a foundation for further analysis and strategic planning aimed at enhancing energy efficiency and reducing carbon emissions within the Italian industrial landscape.

At a European level, total emissions from the ceramic industry amount to 19 million tonnes of CO_2 annually, which is roughly 1% of Europe's total industrial emissions covered by the EU Emissions Trading Scheme (ETS). On the other hand, being mostly composed of SMEs and small emitters, ceramic installations represent 10% of all industrial installations under the ETS. [26]

The manufacture of ceramics, indeed, is considered one of the hard-to-abate sectors belonging to the EU Emissions Trading System (ETS). The comprehensive roster of all the country ETS plants can be accessed through two sources: the EU ETS Italy platform provided by the Italian Ministry of the Ecological Transition, specifically for Italian industrial sites, and the deliberation 2003/87/CE for Italy. [32]

For the Italian ceramic manufacture, the plants under the EU ETS are 121. Each plant is represented by its specific characteristics, stretching through the precise location, the freely allocated allowances in tonnes of CO_2-equivalent, the estimated ceramics production, the yearly thermal and electricity consumption, and the total greenhouse gas emissions, as it can seen in the table 5 below.

Table 6 - List of the 121 ceramics plants in Italy under ETS.

City	Freely Allocated Allowances (t CO2-eq/a) - EU ETS Italy	Estimated Ceramics Production (t of ceramics/a)	Yearly Thermal Energy Consumption (GJ)	Yearly Electricity Consumption (GJ)	Total greenhouse gas emissions (t CO2-eq/anno)	Type of Emitter
SASSUOLO	39698,0	172505,6	839281,2	126162,0	59570,2	
FINALE EMILIA	10236,0	44480,0	216405,9	32530,5	15360,0	SMALL
FIORANO MODENESE	47993,0	208551,1	1014651,2	152523,8	72017,5	
SASSUOLO	39540,0	171819,0	835940,8	125659,8	59333,1	
FIORANO MODENESE	6074,0	26394,2	128414,4	19303,4	9114,5	SMALL
CASTELLARANO	15122,0	65711,9	319704,0	48058,4	22691,8	
FIORANO MODENESE	4135,0	17968,4	87420,7	13141,2	6204,9	SMALL
SASSUOLO	34672,0	150665,4	733023,3	110189,1	52028,2	
Viano	8535,0	37088,4	180444,0	27124,6	12807,5	
MORDANO	25610,0	111286,9	541437,6	81389,7	38429,9	
FIORANO MODENESE	50885,0	221118,1	1075792,8	161714,7	76357,2	
CASALGRANDE	23408,0	101718,2	494883,7	74391,6	35125,7	
FIORANO MODENESE	37289,0	162037,4	788351,0	118506,1	55955,3	
FINALE EMILIA	7642,0	33207,9	161564,5	24286,6	11467,5	
IMOLA	35546,0	154463,3	751501,1	112966,7	53339,7	
BORGO TOSSIGNANO	26171,0	113724,7	553298,1	83172,6	39271,8	
FAENZA	23993,0	104260,3	507251,6	76250,8	36003,5	
FINALE EMILIA	26714,0	116084,3	564778,0	84898,2	40086,6	
TOANO	24183,0	105086,0	511268,5	76854,6	36288,6	
FIORANO MODENESE	4574,0	19876,1	96701,9	14536,4	6863,7	
CASALGRANDE	31975,0	138945,7	676004,2	101617,9	47981,2	
CASALGRANDE	30705,0	133427,0	649154,3	97581,8	46075,4	

BORGO VAL DI TARO	4561,0	19819,6	96427,1	14495,1	6844,2	SMAL L
FIORANO MODENESE	6617,0	28753,8	139894,3	21029,1	9929,4	SMAL L
FIORANO MODENESE	8956,0	38917,8	189344,6	28462,6	13439,2	SMAL L
FIORANO MODENESE	26958,0	117144,6	569936,6	85673,7	40452,7	
PAVULLO NEL FRIGNANO	36444,0	158365,5	770486,3	115820,6	54687,3	
FIORANO MODENESE	10501,0	45631,5	222008,5	33372,6	15757,6	SMAL L
FIORANO MODENESE	13519,0	58746,1	285814,0	42964,0	20286,4	SMAL L
CASTELVETRO DI MODENA	14107,0	61301,2	298245,2	44832,7	21168,7	
FIORANO MODENESE	6867,0	29840,2	145179,7	21823,6	10304,5	SMAL L
CASTEL BOLOGNESE	6615,0	28745,1	139852,0	21022,8	9926,4	SMAL L
VETTO	7987,0	34707,1	168858,4	25383,0	11985,2	SMAL L
RUBIERA	9381,0	40764,6	198329,8	29813,2	14077,0	SMAL L
VIANO	9343,0	40599,5	197526,4	29692,5	14020,0	SMAL L
SCANDIANO	34416,0	149552,9	727611,0	109375,5	51644,1	
CASTELVETRO DI MODENA	20524,0	89186,0	433911,2	65226,2	30798,0	
FINALE EMILIA	3028,0	13158,0	64016,9	9623,1	4543,8	SMAL L
PAVULLO NEL FRIGNANO	39294,0	170750,0	830740,0	124878,0	58963,9	
SAVIGNANO SUL PANARO	21706,0	94322,3	458900,6	68982,6	32571,7	
SAN CLEMENTE	23477,0	102018,1	496342,5	74610,9	35229,2	
MARANELLO	21067,0	91545,5	445391,1	66951,8	31612,8	
CASTELLARANO	19178,0	83337,0	405454,5	60948,5	28778,2	
CASTELLARANO	7495,0	32569,1	158456,7	23819,4	11246,9	SMAL L
RUBIERA	29937,0	130089,7	632917,5	95141,1	44923,0	
GONZAGA	11629,0	50533,2	245856,2	36957,5	17450,3	SMAL L
SAN MARTINO IN RIO	17283,0	75102,4	365391,1	54926,1	25934,6	
CASTELVETRO DI MODENA	45522,0	197813,5	962410,1	144670,9	68309,6	
TERRE DEL RENO	15391,0	66880,8	325391,1	48913,3	23095,5	
CASALGRANDE	24724,0	107436,8	522706,1	78573,9	37100,4	
CASTELLARANO	5647,0	24538,7	119386,9	17946,4	8473,8	SMAL L
SASSUOLO	15789,0	68610,3	333805,5	50178,1	23692,7	
SASSUOLO	24268,0	105455,3	513065,5	77124,8	36416,2	
CASTELLARANO	20111,0	87391,3	425179,7	63913,6	30178,2	
FIORANO MODENESE	6476,0	28141,1	136913,3	20581,0	9717,8	SMAL L
CASTELVETRO DI MODENA	14572,0	14003,5	308076,1	32208,0	4201,0	
SERRAMAZZONI	25345,0	110135,4	535835,1	80547,5	38032,3	

CORREGGIO	9584,0	41646,8	202621,6	30458,4	14381,6	SMAL L
CASTELVETRO DI MODENA	4341,0	18863,6	91775,9	13795,9	6514,0	SMAL L
CASTELVETRO DI MODENA	9554,0	41516,4	201987,3	30363,0	14336,6	SMAL L
CASTELLARANO	12935,0	56208,4	273467,2	41108,0	19410,1	SMAL L
FINALE EMILIA	11132,0	48373,5	235348,8	35378,0	16704,5	
CASTELLARANO	10441,0	10033,6	220740,0	23077,4	3010,1	
CASTEL BOLOGNESE	26251,0	114072,3	554989,4	83426,8	39391,8	SMAL L
CASTELLARANO	5241,0	42266,1	118345,2	11411,9	6762,6	
RUBIERA	24254,0	195596,8	547671,0	52811,1	31295,5	SMAL L
CAMPOSANTO	4151,0	33475,8	93732,3	9038,5	5356,1	
CAMPOSANTO	61700,0	497580,6	1393225,8	134346,8	79612,9	
MARANELLO	20707,0	89981,2	437780,1	65807,7	31072,6	
SERRAMAZZONI	13344,0	57985,7	282114,2	42407,8	20023,8	
PRIGNANO SULLA SECCHIA	4568,0	36838,7	103148,4	9946,5	5894,2	SMAL L
FIORANO MODENESE	31732,0	255903,2	716529,0	69093,9	40944,5	SMAL L
FIORANO MODENESE	13620,0	109838,7	307548,4	29656,5	17574,2	
FRESAGRANDINARIA	9001,0	39113,4	190296,0	28605,6	13506,8	
MARANO SUL PANARO	8642,0	37553,4	182706,1	27464,6	12968,0	SMAL L
GONZAGA	15827,0	68775,4	334608,9	50298,9	23749,7	
SASSUOLO	12405,0	53905,3	262262,2	39423,6	18614,7	SMAL L
FIORANO MODENESE	16958,0	73690,1	358520,1	53893,3	25446,9	SMAL L
ALFONSINE	15891,0	69053,5	335961,9	50502,3	23845,8	SMAL L
BAISO	8089,0	35150,3	171014,8	25707,2	12138,2	SMAL L
FRASSINORO	9448,0	41055,8	199746,3	30026,2	14177,5	SMAL L
CASALGRANDE	11152,0	48460,4	235771,7	35441,5	16734,5	SMAL L
CASALGRANDE	10968,0	47660,9	231881,6	34856,8	16458,4	SMAL L
VIANO	4178,0	33693,5	94341,9	9097,3	5391,0	SMAL L
SCANDIANO	4753,0	38330,6	107325,8	10349,3	6132,9	SMAL L
PRIGNANO SULLA SECCHIA	7820,0	63064,5	176580,6	17027,4	10090,3	SMAL L
CASTELVETRO DI MODENA	2852,0	23000,0	64400,0	6210,0	3680,0	SMAL L
GUSPINI	1310,0	10564,5	29580,6	2852,4	1690,3	SMAL L
FAENZA	4419,0	19202,5	93424,9	14043,8	6631,1	SMAL L
CASTELVETRO DI MODENA	10311,0	83153,2	232829,0	22451,4	13304,5	SMAL L
MASSERANO	8317,0	67072,6	187803,2	18109,6	10731,6	SMAL L

ROSIGNANO MARITTIMO	12187,0	98282,3	275190,3	26536,2	15725,2	
CAMBIANO	38959,0	314185,5	879719,4	84830,1	50269,7	SMAL L
TODI	2197,0	17717,7	49609,7	4783,8	2834,8	
Bevagna	3024,0	24387,1	68283,9	6584,5	3901,9	SMAL L
AVIGLIANO UMBRO	10450,0	84274,2	235967,7	22754,0	13483,9	
MARSCIANO	11465,0	49820,6	242389,0	36436,3	17204,2	
MONFUMO	13053,0	56721,1	275961,9	41483,0	19587,1	SMAL L
POSSAGNO	5897,0	25625,1	124672,3	18740,9	8848,9	SMAL L
POSSAGNO	6870,0	29853,2	145243,1	21833,2	10309,0	SMAL L
POSSAGNO	14476,0	13911,2	306046,5	31995,8	4173,4	SMAL L
POSSAGNO	1863,0	8095,6	39386,9	5920,7	2795,6	SMAL L
FELTRE	3597,0	29008,1	81222,6	7832,2	4641,3	
GATTINARA	4544,0	4366,7	96067,7	10043,4	1310,0	
TERNI	8842,0	38422,4	186934,5	28100,3	13268,2	
MORDANO	6669,0	28979,8	140993,7	21194,4	10007,4	
NOALE	6977,0	30318,2	147505,3	22173,2	10469,6	SMAL L
CASTIGLION FIORENTINO	4321,0	18776,7	91353,1	13732,3	6484,0	SMAL L
VALENZA	6299,0	27372,0	133171,2	20018,5	9452,2	SMAL L
LOREGGIA	6529,0	28371,4	138033,8	20749,4	9797,3	SMAL L
ISOLA VICENTINA	3740,0	16252,0	79069,8	11885,9	5612,2	SMAL L
RONCO ALL'ADIGE	10763,0	46770,1	227547,6	34205,3	16150,8	SMAL L
CASIER	4161,0	18081,4	87970,4	13223,8	6243,9	SMAL L
GIACCIANO CON BARUCHELLA	8701,0	37809,7	183953,5	27652,2	13056,6	SMAL L
GENZANO DI LUCANIA	11306,0	91177,4	255296,8	24617,9	14588,4	
RUBIERA	13371,0	107830,6	301925,8	29114,3	17252,9	SMAL L
TREVISO	8784,0	70838,7	198348,4	19126,5	11334,2	SMAL L
FIORANO MODENESE	8712,0	70258,1	196722,6	18969,7	11241,3	
TREVISO	19230,0	155080,6	434225,8	41871,8	24812,9	SMAL L
BORGO VALBELLUNA	3624,0	29225,8	81832,3	7891,0	4676,1	
TERAMO	10441,0	84201,6	235764,5	22734,4	13472,3	

4.3 Methodology

The objective is to ensure the success of this case study by highlighting the primary characteristics of the area under examination, namely the port of Ravenna and the Ceramic District of Sassuolo, and the broader provinces of Modena and Reggio Emilia. Key focal points include the energy production, distribution, and utilization, along with critical infrastructures, all studied extensively to devise a cohesive solution at bolstering energy efficiency and significantly reducing greenhouse gas emissions, particularly CO_2, in the near future.

Hydrogen assumes a pivotal role in this thesis case study, serving as the linchpin in consolidating the envisioned framework, as illustrated below.

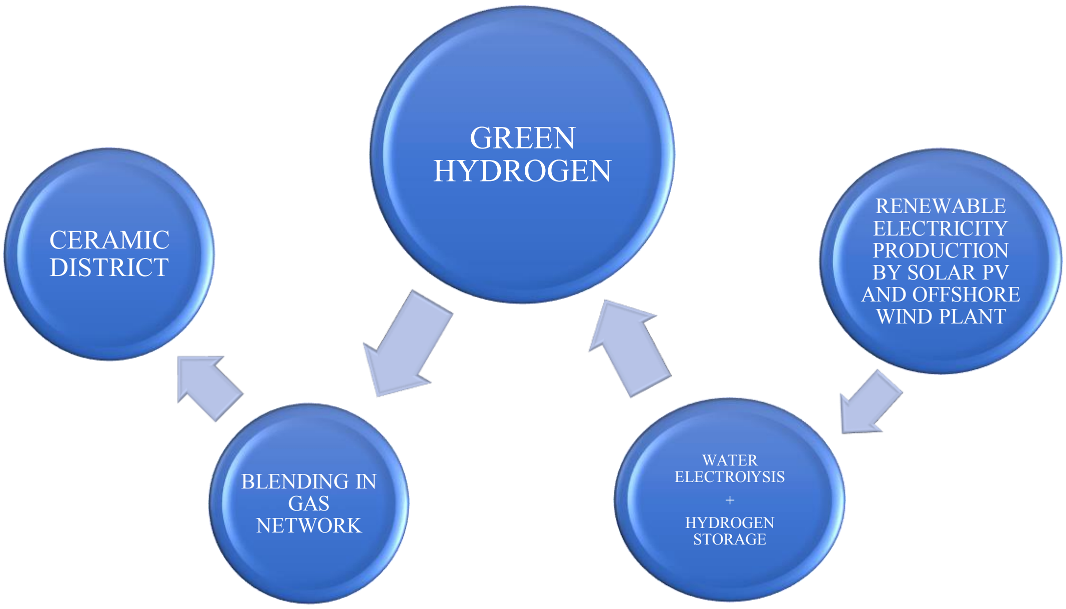

Figure 21 - Functional scheme of the adopted methodology.

The foundation of this endeavour is robust. Multiple arrows emanate from and converge toward hydrogen, forming a functional scheme aimed at achieving a realistic and simplified depiction. This schematic design endeavours the study's concept more accessible and feasible. The goal is highly promising, giving the vast potential it holds, contingent upon collaborative efforts from all stakeholders involved. A successful outcome would yield mutual benefits for each party involved.

The Ceramic District can be described as a cluster within a 25 km radius encompassing nearly three-fourths (71,1%) of all Italian ceramic facilities. Here, there are 86 plants out of 121 under EU ETS, as detailed in table 6 from the preceding section, and account for the majority of Italian ceramic production.

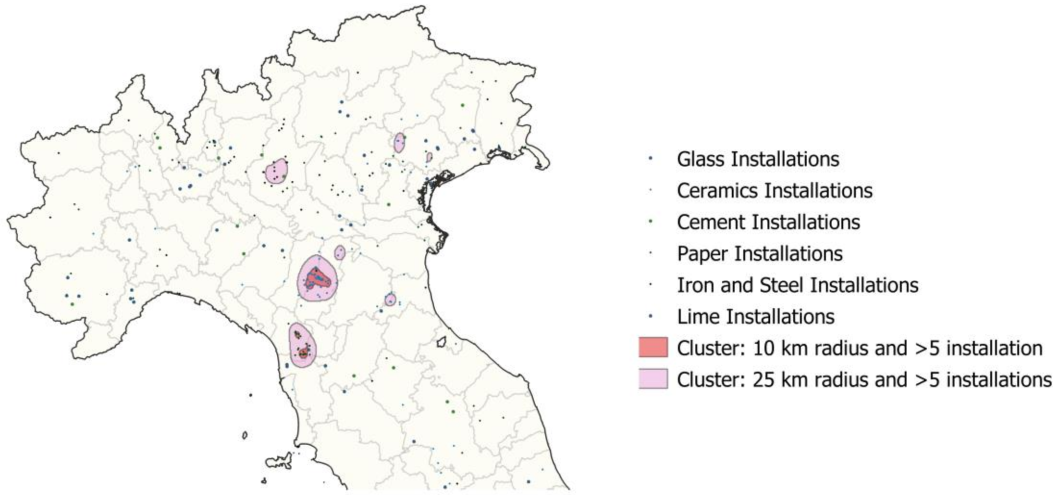

Figure 22 - Focus on the industrial cluster of the Ceramic District, the biggest one on the map. [32]

Consequently, these operations demand substantial energy inputs. Annually, this sector produces approximately 6,910,631.23 tonnes of ceramics, consuming around 4,620,553 gigajoules (GJ) of electricity and 31,924,228 GJ of thermal energy. This production activity results in total CO_2-equivalent emissions amounting to 2,196,014 tonnes per year, with EU ETS covering ‘only’ 1,501,395 tonnes of CO_2-eq emissions annually. Despite 45% of these plants being categorized as “small”, with the exception of two, none adhere to the limits imposed by the EU ETS, as detailed in the graphic below. The EU ETS, an instrument established by the European Union, allows industries to emit a set quantity of CO_2. Any emissions surpassing this cap incur a penalty, which currently stands at EUR 100 per tonne of CO_2 over the limit. Given the discrepancy between the actual CO_2 emissions and the permissible limits, the entire district faces an annual burden of approximately 69,5 million euros. This situation gets worse considering that each year, the EU ETS reduces the cap on CO_2-eq emissions, thereby escalating the financial strain on ceramic companies within the district.

The operations within the ceramic industry encompass various tasks (e.g., mechanical compression, drying, etc.) carried out by electrical machines involved in pre-heating and post-heating processes. It is reasonable to infer that the entirety of electricity consumption within these processes is sourced from the electrical grid. The sintering or burning stage primarily takes place in kilns, a process that, as of now, cannot be feasibly electrified. Therefore, natural gas serves as the primary energy source for this specific phase. Consequently, the entire thermal energy consumption within each ceramic facility is attributes to the combustion of natural gas obtained from the gas network.

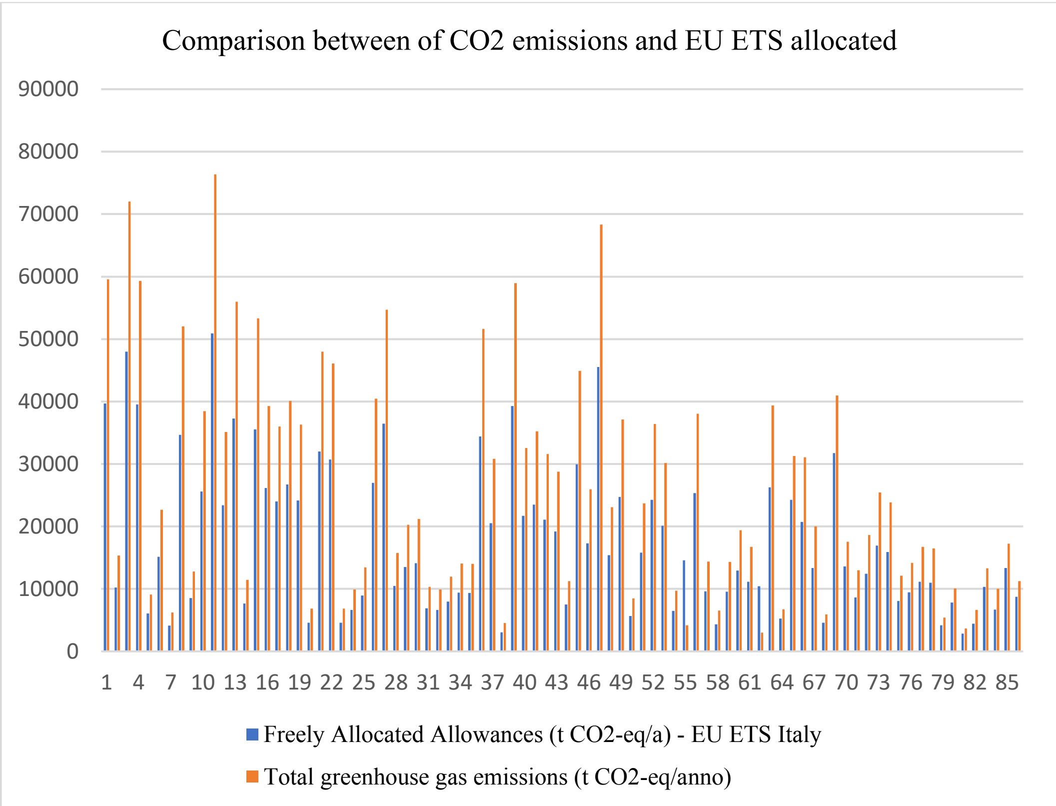

Figure 23 - The 86 ceramic facilities in the district with their CO2 emissions and ETS allowed.

The concept that arises it to improve the energy efficiency of these ceramic plants by introducing a blended mixture of pure hydrogen and natural gas in the existing network. This pure hydrogen can be supplied by an extended production from renewable energy systems situated in the port of Ravenna, made possible by the Agnes project "Romagna 1 &2".

A blend of natural gas and hydrogen can be successfully achieved by adhering to gas interchangeability guidelines, ensuring that the introduction of 'new' gases, in this case hydrogen, into an existing natural gas network doesn't necessitate any modifications to final appliances. There are three crucial parameters to consider:

- **Wobbe index**: This index was introduced after the realization that, at fixed pressure, the thermal supply in a burner is proportional to its volumetric heating value and the gas flow in the burner that is inversely proportional to the squared root of specific gas density (specific to the air density),

$$WI = \frac{HHV}{\sqrt{\rho}} \left[\frac{MJ}{Nm^3}\right]$$

- **Higher heating value**: This parameter refers to the total amount of heat released by combustion.
- **Specific gas density**: Also called gas gravity, this is the ratio between density of the gas being considered and that of air $\left(\rho_{air} = 1{,}225 \frac{kg}{m^3}\right)$,

$$GG = \frac{\rho_{CH_4}}{\rho_{air}}$$

In Italy, the Ministerial Decree May 18, 2018, regarding the technical regulation for fuel gas, has set specific ranges for these three parameters me. Any gas or gas mixture must not exceed these established values, otherwise without any treatment, would impede the transportation, storage, and utilization within the existing gas infrastructure.

Table 7 - Italian gas network boundaries by SNAM for gas mixtures, and methane and hydrogen single values. [40]

	Acceptable values	Methane	Hydrogen
HHV (MJ/S$\mathbf{m^3}$)	34.95 – 45.28	39.13	12
Wobbe index (MJ/S$\mathbf{m^3}$)	47.31 – 52.33	53.43	45.83
Gas gravity	0.555 – 0.800	0.536	0.068

Certainly, in this particular case study focusing on gas properties relevant to Italy's natural gas network, the primary gas in consideration is methane (CH_4), constituting the majority of the natural gas flowing through the network. Alongside methane, the study encompasses the properties of hydrogen (H_2) due its potential integration into the network as part of a blended mixture.

Table 8 - Composition of the natural gas injected in Italian gas network. [42]

Composition	**Unit of measurement**	**Tarvisio Import (Russian gas)**	**Passo Gries Import (North Europe)**	**Mazara del Vallo Import (Algerian gas)**	**Gela Import (Libyan gas)**	**Panigaglia Import (GNL)**
Methane	%MOLE	94,579	93,075	85,501	86,394	90,169
Ethane	%MOLE	3,157	4,120	9,481	6,063	7,879
Propane	%MOLE	0,644	0,710	1,342	1,886	1,131
Iso Butane	%MOLE	0,099	0,185	0,091	0,279	0,077
Normal Butane	%MOLE	0,103	0,121	0,117	0,420	0,074
Iso Pentane	%MOLE	0,023	0,046	0,023	0,095	0,063
Normal Pentane	%MOLE	0,019	0,024	0,019	0,062	0,029
Hexanes +	%MOLE	0,028	0,047	0,019	0,016	0,001
Nitrogen	%MOLE	0,713	1,019	1,216	3,965	0,552
Carbon dioxide	%MOLE	0,635	0,629	2,091	0,743	0,001
Helium	%MOLE	0,000	0,024	0,100	0,077	0,000
Oxygen	%MOLE	-	-	-	-	0,024
HHV	kWh/m3	10,766	10,859	11,160	10,979	11,291
LHV	kWh/m3	9,716	9,804	10,091	9,926	10,204
Wobbe Index	kWh/m3	14,016	14,031	13,914	13,727	14,449
Volumetric mass	kg/m3	0,72302	0,73402	0,78836	0,78388	0,74837
Relative density		0,59002	0,59900	0,64334	0,63969	0,61071
Compressibility factor (Z)		0,99777	0,99771	0,99739	0,99753	0,99753
Molecular weight	kg/kmol	17,06	17,32	18,59	18,49	17,65

Table 9 - Composition of natural gas injected in Italian gas network, section 2. [42]

Composition	Unit of measurement	Ravenna Sea Input (National gas)	Falconara Input (National gas)	Interconnection GNL Edison Minerbio	OLT Livorno Import (GNL)	Slovenian Import (Gorizia)	TAP Import Trans Adriatic Pipeline
Methane	%MOLE	99,629	99,303	93,223	95,967	94,860	94,198
Ethane	%MOLE	0,066	0,018	5,920	3,426	3,101	3,290
Propane	%MOLE	0,018	0,002	0,189	0,352	0,560	1,261
Iso Butane	%MOLE	0,005	0,001	0,019	0,068	0,083	0,241
Normal Butane	%MOLE	0,002	0,001	0,027	0,062	0,085	0,334
Iso Pentane	%MOLE	0,005	0,003	0,005	0,012	0,019	0,113
Normal Pentane	%MOLE	0,004	0,004	0,006	0,003	0,017	0,088
Hexanes +	%MOLE	0,001	0,000	0,001	0,001	0,017	0,063
Nitrogen	%MOLE	0,229	0,514	0,521	0,085	0,664	0,211
Carbon dioxide	%MOLE	0,041	0,152	0,067	0,009	0,576	0,180
Helium	%MOLE	0,000	0,002	0,022	0,015	0,018	0,021
Oxygen	%MOLE	-	-	-	-	-	-
HHV	kWh/m3	10,469	10,418	10,934	10,835	10,744	11,123
LHV	kWh/m3	9,434	9,389	9,870	9,776	9,694	10,046
Wobbe Index	kWh/m3	14,028	13,939	14,245	14,258	14,020	14,365
Volumetric mass	kg/m3	0,68248	0,68458	0,72192	0,70771	0,71956	0,73468
Relative density		0,55694	0,55865	0,58913	0,57753	0,58720	0,59954
Compressibility factor (Z)		0,99800	0,99801	0,99773	0,99781	0,99779	0,99763
Molecular weight	kg/kmol	16,10	16,15	17,03	16,70	16,98	17,33

This table, separated in two sections, considers the parameters HHV, LHV, WI expressed in kWh/m^3 25 °C, combustion reference temperature equal to 25 °C, m^3 referred at 15 °C and 1.01325 bar (standard condition). [42]

Understanding the distinct properties of methane and hydrogen is essential for assessing their interchangeability and compatibility within the existing infrastructure. Methane, being the predominant component in the natural gas supply, and hydrogen, which might be introduced into this network, have varying characteristics concerning combustion, energy content, density, and other critical factors that influence their use and mixing capabilities within the network. Analysing these properties is crucial to ensure the effective blending of hydrogen with methane while meeting regulatory and operational requirements.

Table 10 - Properties of methane compared to hydrogen. [39]

	Methane	Hydrogen
Formula	CH_4	H_2
Molecular weight (g/mol)	16.04	2.016
Density (kg/$\mathbf{m^3}$)	0.668	0.084
Energy density (MJ/kg)	55.5	142
Energy density (MJ/$\mathbf{m^3}$)	37.3	12
Flame speed (m/s)	0.39	3.06
LFL[15] (%)	5.3	4
HFL[16] (%)	15	75
Flame adiabatic temperature (°C)	1953	2129
Autoignition temperature (°C)	600	577

To ensure the viability of this study, it is essential to explore how hydrogen can be effectively integrated into the existing natural gas network. The adoption of green hydrogen holds significant importance for facilitating the sustainable transition of the ceramic district in the provinces of Modena and Reggio Emilia. In this context, the port of Ravenna plays a pivotal role, hosting ongoing projects that aim to establish substantial pure hydrogen production in the near future. Of particular focus in this study is the Agnes project, specifically "Romagna 1 & 2", as initially outlined. The Agnes project aims to supply 8,000 tonnes of pure hydrogen, in the amount of 1,160 kg/h or 12,900 $\mathrm{Nm^3/h}$ starting from 2026 [38]. As part of the project's plan, this quantity of green hydrogen is addressed for distribution across various channels: integration into the national natural gas network for blending, utilization in hydrogen-powered vehicles through Hydrogen Refuelling Stations (HRS), and distribution to industries, particularly those categorized as hard-to-abate. The attainment of this ambitious objective necessitates substantial investments in renewable energy systems, encompassing the installation of 750 MW capacity at maximum output. This setup includes 75 offshore wind turbines, a floating photovoltaic park, and integrated storage systems [38]. A comprehensive analysis was conducted to verify the feasibility of this production scale, especially concerning its consistency in supply, as it relies on variable electricity production inherent in renewable energy. Hence, relying on a ongoing project devised by

[15] LFL: Low Flammable Level, minimum concentration of a flammable gas in a mixture with air to produce fire in the presence of an ignition source.

[16] HFL: High Flammable Level, maximum concentration of a flammable gas in a mixture with air to produce fire in the presence of an ignition source.

prominent and well-established companies within the sector, which has been fully approved, the area under consideration is being examined from naturalistic perspective. The findings reveal that the Ravenna Sea area boasts considerable potential for generating a significant quantity of electricity through offshore wind farms and the floating photovoltaic system.

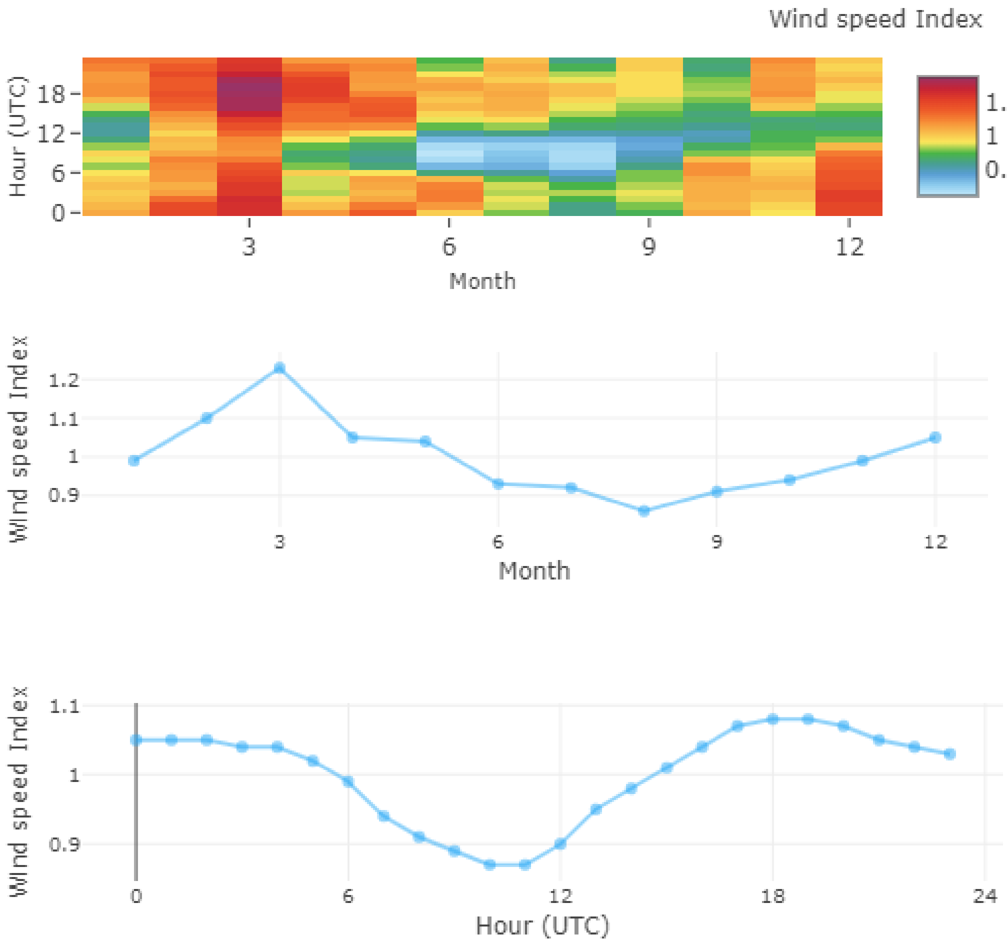

Figure 24 – Wind speed variability during months and daily. [43]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5						0						
5 - 6				0	2	4	2	0				
6 - 7			0	5	11	13	12	7	3	0		
7 - 8		1	8	16	23	26	25	20	14	7	1	
8 - 9	3	10	21	29	35	39	38	34	27	17	7	3
9 - 10	11	20	32	39	46	49	50	45	38	26	16	9
10 - 11	18	28	41	47	53	57	58	54	45	32	20	15
11 - 12	22	33	46	51	57	60	62	58	49	36	23	20
12 - 13	24	36	48	52	58	61	63	59	50	37	23	21
13 - 14	22	34	46	49	54	58	60	56	46	33	21	17
14 - 15	16	28	38	42	47	51	54	49	38	25	15	10
15 - 16	7	19	28	32	37	42	44	38	28	16	6	4
16 - 17	1	8	17	21	26	30	32	26	16	4	0	0
17 - 18		0	4	9	14	18	18	13	4			
18 - 19				1	4	7	7	2	0			
19 - 20					0	1	0					
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	125	217	329	395	468	515	526	462	357	233	131	99

Figure 25 – Average hourly profiles of the total photovoltaic power output in MWh. [44]

The data presented in Figures 24 and 25 indicate a significant complementary relationship between wind and solar energy sources in this specific area. Analysis reveals that wind speed, and consequently the power generated by wind turbines, tends to be lower during the summer months and in the central hours of each day. Conversely, solar power output exhibits higher levels precisely during the summer months and particularly in the most irradiated of each day. This observed pattern suggests a compensatory relationship between these renewable energy sources. When one source experiences limitations in providing the required power for electricity generation, it can be compensated for by the other renewable source. This dynamic allows for an almost consistent power supply, facilitating the production of green electricity and subsequently green hydrogen through water electrolysis in the coastal area of Ravenna. Furthermore, in instances where both wind and solar plants are unable to meet the required power demand, the system is well-implemented with a hydrogen storage capacity of 16.7 tonnes stored at 300 bars [38]. This reserve stands ready for utilization, offering a strategic backup solution to ensure a continuous and reliable energy supply.

4.4 Calculations based on various blending scenarios

Building upon the assumption of a reliable hydrogen supply integrated into the gas network, this thesis aims at investigating three distinct scenarios involving the blending of hydrogen with natural gas. Each scenario explores the feasibility and implications of supplying the ceramic district with varying percentages of hydrogen admixed with natural gas, specifically at levels of 5, 10 and 15%.

To determine the volume of natural gas required for a year's operation in the ceramic district, the thermal demand acquired, accounting for 31,924,228 GJ, can be related to the energy density of methane (37.3 MJ/m^3). Given these two values, converting the thermal energy to megajoules (MJ) for consistency:

$$31{,}924{,}228\ GJ\ x\ 1{,}000\ \frac{MJ}{GJ} = 31{,}924{,}228{,}000\ MJ$$

Now, to find the volume of natural gas (in cubic meters) needed for a year's operation, the formula needed is:

$$\frac{Total\ energy\ required\ (MJ)}{Energy\ density\ of\ methane\ \left(\frac{MJ}{m^3}\right)} = Volume\ of\ natural\ gas\ (m^3)$$

The volume of natural gas results in 855,877,426.3 m^3. Hence, approximately 856 million cubic meters of natural gas are required for the year's operations within ceramic district.

In determining the volume of hydrogen needed to blend 5% of hydrogen with natural gas to fulfil the total energy demand in the ceramic district, specific steps have been followed. Firstly, the energy supplied by the 5% of hydrogen for meeting the entire energy demand was calculated.

$$Energy\ provided\ by\ 5\%\ hydrogen = 0.05\ x\ 31{,}924{,}228{,}000\ MJ =$$

$$= 1{,}596{,}211{,}400\ MJ$$

Subsequently, the energy yet to be supplied by natural gas following the incorporation of energy from hydrogen is calculated.

$$Remaining\ energy\ from\ natural\ gas = 31{,}924{,}228{,}000\ MJ - 1{,}596{,}211{,}400\ MJ =$$

$$= 30{,}328{,}016{,}600\ MJ$$

The next step involves computing the revised volume of natural gas needed to meet this remaining energy demand.

$$Volume\ of\ natural\ gas\ (m^3)\ for\ 95\%\ of\ energy\ demand =$$

$$= \frac{Remaining\ energy\ from\ natural\ gas}{Energy\ density\ of\ methane} = 813{,}083{,}555\ m^3$$

As a result, the volume of hydrogen required to achieve the 5% blend:

$$Volume\ of\ hydrogen\ (m^3) = \frac{Energy\ provided\ by\ 5\%\ hydrogen}{Energy\ density\ of\ hydrogen}$$

The energy density of hydrogen is 12 MJ/m^3. Therefore, to fulfil the energy demand of the ceramic district with a 5% hydrogen blend, approximately 133, 017,617 cubic meters of hydrogen, in addition to 813,083,555 cubic meters of natural gas, would be necessary. The total amount of needed cubic meters turns out to be 946,101,172 m^3, representing an increase from the initial requirement of 855,877,426.3 m^3 when hydrogen wasn't integrated. This escalation finds explanation in the fact that the energy density of hydrogen is lower in comparison to the methane one. Consequently, a larger volume of hydrogen is needed to substitute the same energy quantity as methane, leading to a higher total volume of the gas blend.

Similar calculations can be conducted for scenarios involving 10% and 15% hydrogen blending. In these scenarios, it is expected that, obviously, a greater amount of natural gas will be replaced by an increased injection of hydrogen to cover the required thermal energy. At the same time, an increment in the total volume of the gas mixture is foreseeable compared to the scenario using only natural gas.

The calculations for these additional scenarios of 10% and 15% are conducted based on the same approach.

$$Energy\ provided\ by\ 10\%\ hydrogen = 0.10\ x\ 31{,}924{,}228{,}000\ MJ$$

$$Energy\ provided\ by\ 15\%\ hydrogen = 0.15\ x\ 31{,}924{,}228{,}000\ MJ$$

Where, 31,924,228,000 MJ is the annual thermal energy required by the ceramic district.

For the scenario of 10% hydrogen blend, the results are summarised in Table 11 below.

Table 11 - Results for a blending with 10% of hydrogen.

Energy provided by 10% hydrogen	3,192,422,800 MJ
Remaining energy of natural gas	28,731,805,200 MJ
Volume of natural gas	770,289,984 m^3
Volume of hydrogen	266,035,233 m^3
Total volume of mixture	1,036,325,217 m^3

Indeed, the expectations were met, proving that as the portion of hydrogen increased in the blend with natural gas, there was a reduction in volume of natural gas required. However, this reduction was coupled with an increase in the total volume of fuel needed to satisfy the thermal energy demand specified by the ceramic plants.

In the scenario of a 15% hydrogen blend, Table 12 below shows the values achieved.

Table 12 - Results for a blending of 15% of hydrogen.

Energy provided by 15% hydrogen	4,788,634,200 MJ
Remaining energy of natural gas	27,135,593,800 MJ
Volume of natural gas	727,495,812 m^3
Volume of hydrogen	399,052,850 m^3
Total volume of mixture	1,126,548,662 m^3

Once more, the outcomes demonstrate a reduction in the energy provided by natural gas alongside a decrease in its volume, compensated by a larger quantity of hydrogen required in terms of both volume and energy output.

The emission factor (EF) is now introduced and established based on the carbon content of the fuel. This emission factor, related to weight, enables the derivation of the emission factor in tonnes CO_2/ TJ (terajoules) based on energy density or in tonnes CO_2/m^3 considering the density. [45]

These calculations were done to consequently calculate how much is the reduction regarding CO_2 emissions. The reduction in CO_2 emissions resulting from the decreased use of methane due to the inclusion of hydrogen in the blend can be determined by considering the emission factor for methane and the difference in volumes of methane used in the scenarios with and without hydrogen blending.

Initially the study focused on the EF, which stands at approximately 56.1 kg CO_2/GJ for each unit of methane burned. [45] Given the volume of natural gas without hydrogen blend for the ceramic district equal to 855,877,426.3 m^3, as calculated earlier for the total energy demand, and considering the volume of natural gas with hydrogen blend, substantial results about CO_2 emissions are achieved.

Starting from the blending of 5% hydrogen, the volume of burned natural gas equals to 813,083,555 m^3. The difference in volumes of methane is the volume of methane removed, equal to 855,877,426.3 m^3 - 813,083,555 m^3 = 42,793,871.3 m^3. In the next step, the calculation of CO_2 emissions reduced is done by replacing this volume of methane by using the energy density and then the emission factor (EF).

$$Volume\ of\ methane\ removed\ (MJ) =$$

$$= Volume\ of\ methane\ displaced\ (\mathrm{m}^3)\ x\ Energy\ density\ of\ methane\ \left(\frac{MJ}{\mathrm{m}^3}\right)$$

The methane removed, expressed in energy terms, is equal to 1,596,211,399 MJ, then converted in 1,596,211.4 GJ. The CO_2 emissions reduction comes from the relation between this last term and the EF.

$$CO2\ emissions\ reduction = Volume\ of\ methane\ displaced\ x\ EF\ for\ methane$$

In conclusion, in this first case scenario, the CO_2 reduction for removing the specified quantity of natural gas from the energy supply to the ceramic district accounts for 89,547,459.5 kg or 89,547.5 metric tonnes.

However, the decrease in natural gas consumption led to a large use of hydrogen, in terms of volume. With 133, 017,617 cubic meters of burned hydrogen in the case of 5% blending, the equivalent value in kilogram is found through hydrogen density (0.084 kg/m^3), accounting for 11,173,479.8 kg of H_2.

Before specifying the calculations made to evaluate the CO_2 equivalent emissions corresponding to the use of green hydrogen, the carbon footprint is expressed. This term, per kg of generated green hydrogen, is based on an estimated electrolyser power consumption ranging from 48 to 58 kWh/kg H_2 [46]. It is important to note that these calculations do not include emissions arising from hydrogen transportation, compression, or any subsequent conversion into hydrogen derivatives. Additionally, emissions originating from the manufacturing of electrolysers and related equipment, along with emissions linked to deployment of electrolyser facilities, have been excluded as well. Numerous studies have examined the emission factor associated with green hydrogen, yielding a range between 1.0 kg of CO_2-eq to 4.9 kg CO_2-eq per kg of H_2[46]. Subsequently, an average value accounting for 2.5 kg of CO_2-eq per kg of H_2 can be considered.

Reclaiming the first case scenario of 5% blending, 133,017,617.0 m^3 of hydrogen are used instead of 42,793,871.3 m^3 of natural gas. This volumetric term, corresponding to 11,173,479.8 kg of H_2, is now multiplied for 2.5 kg of CO_2-eq per kg of H_2. The result is that 27,933,699.6 kg of CO_2 or approximately 27,933.7 metric tonnes are emitted by using that specified amount of hydrogen in the ceramic district.

Consequently, the total quantity of CO_2 emissions reduction is decreased compared to the initial value found from the removal of a part of natural gas. From 89,547.5 metric tonnes of CO_2 spared by removing 42,793,871.3 m^3 of natural gas, it is crucial to subtract the metric tonnes of CO_2 generated by green hydrogen.

$$Final\ CO_2 \text{ saved for 5\% hydrogen blend} = 89{,}547.5 \text{ tonnes} - 27{,}933.7 \text{ tonnes} =$$

$$= 61{,}613.8 \text{ tonnes}$$

Therefore, through the substitution of the calculated volume of methane with a 5% hydrogen blend, an approximate reduction of 61,613.8 tonnes in annual CO_2 emissions would benefit the ceramic district. This change allows for sustained ceramics production while concurrently boosting revenues by reducing natural gas consumption. Additionally, this shift results in decreased carbon taxes, aligning with the EU ETS annual limit and alleviating the financial burden incurred of surpassing these limits.

Similar calculations can be conducted for scenarios involving 10% and 15% hydrogen blending. The results are summarised in Table 13 below.

Table 13 - Results of CO2 reduction from the less use of methane in both cases 10% and 15% of blending.

	Removed volume of natural gas	Removed energy of natural gas	CO_2 emissions reduction
10% H_2	85,587,442.3 m^3	3,192,411.6 GJ	179,094.3 tonnes
15% H_2	128,381,614.3 m^3	4,788,634.2 GJ	268,642.4 tonnes

These results do not define the final CO_2 reduction. The same steps taken for the scenario of 5% blending have been done for calculating the production of CO_2 emissions deriving by the consumption of green hydrogen.

Table 14 - Values regarding hydrogen consumption in both scenarios of 10% and 15% of blending.

	Volume of hydrogen used	Corresponding hydrogen value in kg	Tonnes of CO_2-eq emitted
10% H_2	266,035,233.0 m^3	22,346,959.6	55,867.4
15% H_2	399,052,850.0 m^3	33,520,439.4	83,801.1

In conclusion, the final CO_2 reduction was found for both scenarios, 10% and 15% respectively. In the scenario of 10% hydrogen blend, the emissions of carbon dioxide removed from from the ceramic district account for 123,226.9 metric tonnes. For the latter scenario of 15% hydrogen blend, the net removal of CO_2 equals 184,841.3 metric tonnes.

4.5 Discussion and conclusions

The objectives of this thesis were based on finding a realistic and feasible solution to reduce CO_2 emissions of the ceramic district of Sassuolo. This was pursued by proposing the integration of green hydrogen into the natural gas mix, serving to fulfil the thermal requirements of the district's plants.

The main results are inserted in two tables (Table 15 and Table 16), showing respectively the trend of volumes of both fuels, methane, and hydrogen, in the three distinct scenarios. The second table shows the variations of CO_2 emissions.

Table 15 - Results for volumes variations in the three scenarios in addition to the base one.

	Volume of CH_4 [Mm^3]	Volume of H_2 [Mm3]	Total Volume [Mm3]	% of volume increased
Base scenario	855,9	0	855,9	0,0
5% H_2	813,1	133,0	946,1	10,5
10% H_2	770,3	266,0	1036,3	21,1
15% H_2	727,5	399,1	1126,6	31,6

Table 16 - Results for CO2eq emissions in the three scenarios in addition to the base one.

	ton of CO_2eq of CH_4	ton of CO_2eq of H_2	ton of CO_2eq of the mixture	% of reduction of CO_2eq
Base scenario	1790949	0	1790949	0
5% H_2	1701402	27930	1729332	3,44
10% H_2	1611854	55860	1667714	6,88
15% H_2	1522307	83811	1606118	10,32

The key outcome derived from Table 15 revolves around the percentage increase in the total volume of fuel required to meet the thermal demand of the ceramic district. This calculation was performed considering the limitations regarding the existing gas network, concerning an increase in volume of gas flowing through pipes and, in addition, the related volumetric flow rate.

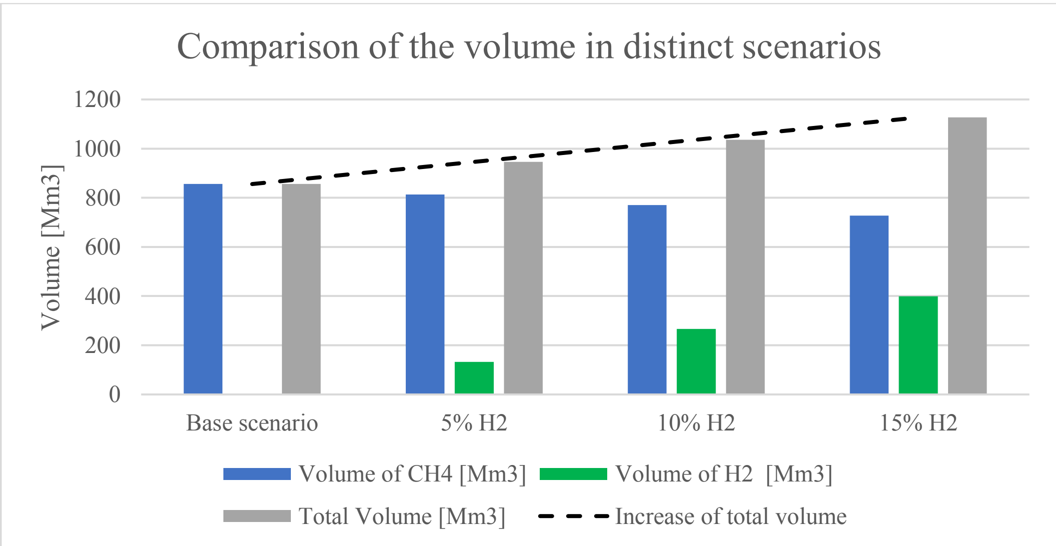

Figure 26 - Graph showing the difference of total volume applied and the trend of the increased total volume.

In the region of Emilia-Romagna, where both the Ceramic District of Sassuolo and the port of Ravenna are situated, the yearly consumption of thermal energy amounts to approximately 347,504,400 GJ. Particularly, the natural gas consumption of the region accounts for around 9,32 billion cubic meters in a year [47]. Based on these assumptions, the average volumetric flow rate of natural gas within gas pipes of Emilia-Romagna can be estimated. This is computed by dividing the total volume of natural gas injected in a year by the overall annual hours (8760 h), resulting in an average volumetric flow rate of 1,063,524 m^3/h. Considering the specifics of the case study, the increased volumetric flow rate would be associated with the larger volume of the fuel mixture injected into the ceramic plants within the district over the course of a year. In this case study, the scenario with the largest total volume involves the greatest blending of hydrogen (15%). This increased blending portion results in a 30% rise in the original required volume when only natural gas is utilised. Hence, the larger total volume belongs to the scenario where 15% hydrogen is blended with natural gas, leading to an expanded overall fuel volume due to hydrogen lower energy density compared to methane. In the region of Emilia-Romagna, the pipelines' capacity relevant to this context amounts to 79,469,140 m^3. Consequently, the average flow rate within these pipelines is calculated as 3,311,214 m^3/h [48]. Based on this fundamental assumption and given that the total volume to inject in the scenario involving the 15% hydrogen blend amounts to 1126.6 million cubic meters, the corresponding volumetric flow rate for this specific case can be calculated. The operational nature of the ceramic district's plants running continuously allows a flow rate to be supplied that can be spread across the total hours in a year. This calculation yields a flow rate of 128,607 m^3/h, a value comfortably within an acceptable range.

These considerations were essential for assessing the feasibility of injecting of a specific quantity of hydrogen into the existing natural gas network. The analysis took into account the network's complexity, capabilities, and constraints. Therefore, each scenario considered in this thesis holds the potential within the current conditions of the gas grid. This approach ensures that all scenarios explored are realistically aligned with the existing infrastructure's capabilities and limitations.

The framework, now, revolves around the intricate dynamics of reducing CO_2 emissions within the context of operations within the ceramic district. This comprehensive analysis delves into the integration of hydrogen into the existing natural gas network, aiming to curtail carbon emissions while sustaining the district's thermal energy requirements. By examining Table 16 and delving into the CO_2 emissions associated with the operations within the ceramic district, a detailed examination offers evidence showcasing the achievement of emission reduction goals.

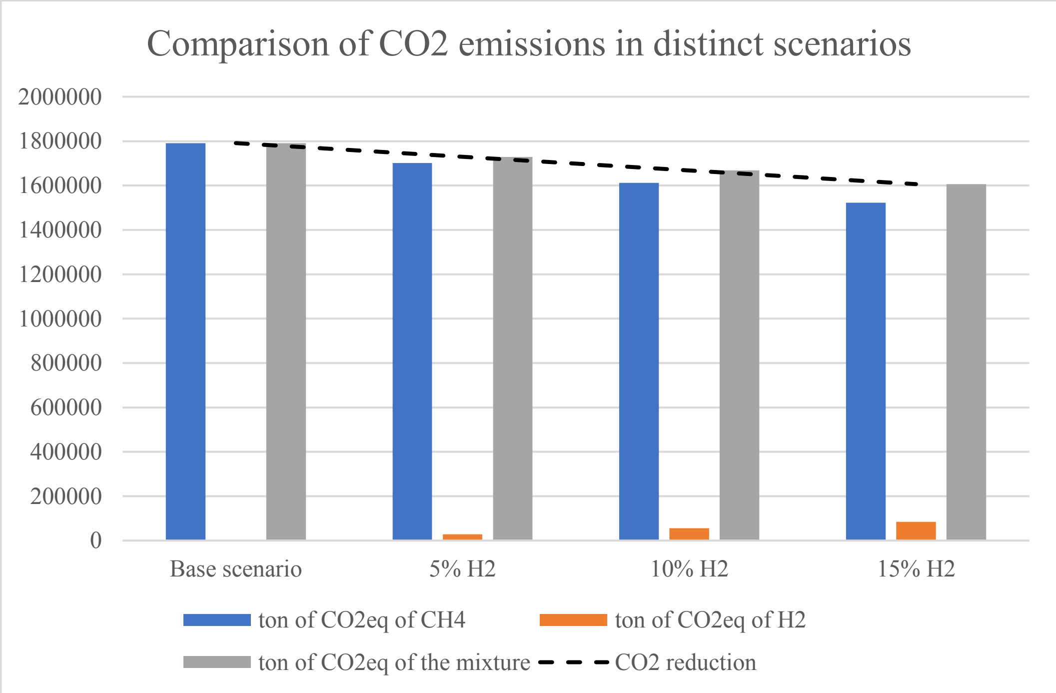

Figure 27 - Graphic representation of the CO2 emissions of the distinct scenarios, showing their gradually reduction with more integrated hydrogen.

Figure 27 serves as a valuable visual aid in elucidating the pathway toward achieving a reduction in CO_2 emissions within the ceramic district. While it outlines the potential avenues for emission reduction, particularly evident in scenarios involving significant blending, it also highlights a crucial point: even in the instances of major blending, emissions remain relatively high. This observation underscores the necessity for further efforts and interventions to achieve substantial reductions in CO_2 emissions within the district.

However, the analysis focusing on the trend of CO_2 reduction percentages present positive outcomes, showcasing a notable achievement. Specifically, it illustrates a 10% reduction in CO_2 emissions concerning the total emissions when considering the scenario of exclusively utilising natural gas within the district.

In conclusion, the outcomes derived from this thesis can be regarded as courageous. The concepts, projects, and implementations discussed within this study have garnered substantial attention and interest within the community. There exists an active and sustained commitment towards achieving significant and impactful results. Since its inception, this thesis aimed at demonstrating the interconnection prevailing at global scale. It emphasized the role of the European Union as a pivotal force, offering support and incentivising governments and companies. Indeed, this support encourages them to channel efforts and resources into addressing challenges within this wide landscape, encompassing a spectrum of guidelines and regulations, feasibility studies and economic incentives. Moreover, it incorporates a learning process from past failures and emphasizes tangible results that often surpass initial expectations. This comprehensive approach underscores the multifaced nature of addressing complex global challenges and highlights the continuous evolution and progress witnessed within this sphere.

The thesis remarks upon the crucial steps essential for the feasibility and success of the case study, initially delving into the broader concept of a general industrial cluster before zooming in on the specific area. It highlights the pivotal role of ports within the complex value chain, starting from the acquisition of raw materials and reaching at providing substantial energy quantities to many industrial sectors. Moreover, the thesis conducts a detailed analysis of the ceramic industry, aiming to gain deeper insights into optimizing efficiency and reducing emissions throughout various operational phases. Finally, it concentrates on the case study of the specific Italian area including the port of Ravenna and the Ceramic District within the provinces of Modena and Reggio Emilia, finalized at studying and creating the best conditions to achieve the desired results.

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