

Introduction

Over 90% of the Sun is composed of hydrogen, which is not only the lightest, but it is also the most abundant element in the universe. A single proton orbited by a single electron constitute the hydrogen atom, that on Earth usually joins another atom to form a hydrogen molecule (H_2). Largely due to its simple structure, H_2 is mostly found in compounds with other molecules, such as water (H_2O), being thus difficult to isolate from other elements. But why should we try to isolate hydrogen from the compounds it can be found in? This question is key to contextualise our work, as hydrogen can be a critical enabler of the energy transition paradigm.

While economies and societies keep evolving and energy demand at the global level continues to grow, the need to enhance the decoupling of economic growth from (mostly fossil) energy use is increasingly pressing. Given higher energy prices, supply disruptions and fear of repeated supply shortages in the last three years after the pandemics and the resurgence of different regional armed conflicts, global energy intensity improvements - defined as the percentage decrease in the ratio of total energy supply per unit of gross domestic product (GDP) - have slowed down. At the same time, however, energy and climate policies, particularly those of the European Union (EU), have been relaunched with new and highly ambitious decarbonisation targets, aiming to make Europe the first climate neutral continent by mid-century¹.

¹ Becoming «climate neutral» means reducing greenhouse gas emissions as much as possible, but it also means compensating for any remaining emissions. This is how a net-zero emissions balance can be achieved (Council of the European Union, 2019).

Although the EU currently represents only about 6 % of global GHG emissions (European Commission 2024), the proposal of the European Commission presented in early 2024 to set an emission reduction target of 90% by 2040 compared to the 1990 levels (European Commission, 2024), is only the latest example of an enhanced ambition to decarbonise all sectors. Decarbonisation strategies must however be integrated in the well-known «energy trilemma», which involves trade-offs and opportunity costs between security of energy supply, competitiveness and sustainability issues. Along with the implementation of energy efficiency measures, the installation of new renewable capacity is currently the main driver of decarbonisation efforts, which remain nonetheless subject to renewables' intermittency (if we exclude hydropower and geothermal energy) and seasonality in their production profiles. Therefore, realising the ambitious energy and climate agenda requires both stability and predictability. While the latter can be guaranteed by a comprehensive and future-proof regulatory framework that is able to simplify bureaucratic procedures and attract private capital investments, stability requires different technological solutions capable of enabling the phase-out of fossil fuels.

While EU energy policies in the previous decade were almost exclusively concentrated on developing and deploying renewable power technologies like solar and wind and encouraging massive electrification of end-use applications and production processes, the policy framework introduced with the Fit-for-55 - and the subsequent adoption of the REPowerEU plan in 2022 - has been carving out an important role for clean molecules in enabling decarbonisation where the penetration of electricity is not possible, thus avoiding reliance on traditional fossil fuels. Clean molecules include low-emission gases (e.g. biogas and biomethane), abated fossil gases (thanks to carbon capture and storage), renewable and emission-negative gases, that are likely to both directly substitute unabated gas in some cases and to gain a market share in new applications previously served by other non-gaseous energy vectors, like diesel or electric cars. One of such molecules is hydrogen, the development of which has not only become a critical pillar of the EU's decarbonisation strategy, but it also represents an important component of Europe's industrial policy. Indeed, several Member States within the Union are home to world-class industrial players along the hydrogen and fuel-cell value chains, thus potentially making the EU one of the most advanced global hubs in the manufacturing of H₂ technologies. From an energy point of view, hydrogen can support decarbonisation as it produces zero carbon emissions at the point of its use (either as a feedstock or as a fuel) and it can also be combined with other molecules, such as CO₂ to produce so-called «synthetic fuels», that help reduce emissions by displacing fossil fuels both in industry and transportation.

Given the technological, economic, regulatory and political implications of hydrogen development and deployment at the EU level, this thesis attempts to analyse the integration of H₂ into the European energy system from an economic policy perspective along four different chapters. While the analysis on how and why hydrogen can prove crucial for decarbonisation will be addressed

repeatedly based on the specific context of each chapter, the question of whether hydrogen integration would be actually feasible and economically viable will be the backbone of our discussion.

The effective decarbonisation of the energy system is only possible if both final uses and the entire energy supply chain are low- or zero-emission. That is why Chapter 1 will address and compare the different hydrogen production methods that currently exist, from the most to the least polluting, and assess their cost-effectiveness. While being relatively easy to produce, hydrogen can be difficult to transport, as it is extremely light and flammable, and it has a low energy density in terms of volume compared to natural gas, for example, thus requiring greater transport capacity for the same amount of energy. Therefore, finding the most efficient transport mode for H₂ and evaluating its storage needs is critical to assess its potential market development. Lastly, we will briefly mention the potential hydrogen end-uses, so as to prepare the ground for the different concrete cases addressed in the following chapters.

Chapter 2 will thus examine the policy and regulatory landscape at the EU level that can support the development of an integrated hydrogen market, while estimating the investment needs to enable the creation of H₂ production hubs, transmission networks and regional demand centres. Despite the early adoption of an EU Hydrogen Strategy (in 2020) that has provided a roadmap for new policy and investment measures, not all EU Member States have been keeping the pace of the EU's agenda, both because of their different political and economic priorities, and because of the structure of their national energy systems, which varies significantly from one EU country to the other.

Out of the EU's top three economies, Italy is the last one to have adopted a national hydrogen strategy, while countries like France and Germany (and also Spain) have already consolidated their national roadmaps with a view to upscaling hydrogen in their energy mixes and potentially importing it from neighbouring countries. Indeed, import proves essential to achieve the H₂ targets set at the EU level, as these significantly outpace the means available to the EU countries to produce hydrogen at present. Therefore, in Chapter 3 we will analyse the potential creation of several «hydrogen supply corridors» that would be needed to meet the expected renewable and low-carbon hydrogen demand in the EU, with Germany as the main demand driver, up to 2040-50. In this context, Italy could potentially become one of the major hydrogen producers and importers in the EU, mainly thanks to its extensive gas network and interconnections, and its geographic location, which is naturally projected into the southern Mediterranean, thus giving access to both ample renewable resources and potential low-cost hydrogen imports from North African countries.

As the development of the currently small hydrogen market requires the simultaneous transition of both supply (including import) and demand, in Chapter 4 we will examine a concrete use case related to hydrogen use in hard-to-abate industries in Italy. These sectors are indeed characterised by their technical inability to electrify their production processes and energy uses, thus currently continuing to consume large amounts of fossil fuels, mostly natural gas. Here,

hydrogen can prove to be a game-changer, by enabling the replacement of those high-emitting energy inputs, and complementing the energy uses that are already electrified. The significance of H₂ for decarbonising hard-to-abate sectors is underlined by the newly adopted EU rules on hydrogen, by several Member States' national H₂ strategies as well as by the industry itself, with a view to supporting the energy transition and develop a European (and Italian) value chain for cutting-edge hydrogen technologies.

The work that will be carried out in the next four chapters is inspired both to the courses taken during the master's degree, in particular the «Energy, Environment and European Security» course, to the specialised trainings on natural gas and hydrogen completed at the Florence School of Regulation within the European University Institute, as well as to the traineeship experiences at the European Energy Forum and at the Delegation of Confindustria to the European Union. This dissertation benefited from the scientific support of the Istituto Affari Internazionali (IAI) in the context of the “Eni Sustainable Energy Scholarship” part of the IAI-ENI Strategic Partnership².

² <https://www.iai.it/en/ricerche/iai-eni-strategic-partnership>