

# Conclusion

In this thesis we have conducted a comprehensive analysis of hydrogen production, transmission, and end-uses, with a specific focus on H<sub>2</sub> integration into the European energy system and its potential role in enhancing Italy's contribution to the EU's energy transition goals, both externally (to enable the import of clean hydrogen from neighbouring countries) and domestically (to decarbonise hard-to-abate and energy-intensive sectors). In order to outline the relevant implications of this work, our key findings will be divided into the three main components of the hydrogen value chain: generation, transport and utilisation. Observations on the element of H<sub>2</sub> storage will be also included, as storage needs are linked to both H<sub>2</sub> production and end-use.

## Hydrogen generation

As emerged from the examination of hydrogen production methods, the steam methane reformation (SMR) process is still the predominant mode of H<sub>2</sub> generation at a global, European and Italian level. This is not only due to the large availability of natural gas as a source for producing hydrogen via SMR, but it is given mainly by the existing challenges in reducing the cost of the technologies (i.e. electrolyzers) for producing green hydrogen. The cost of electrolytic H<sub>2</sub> generation is greatly influenced by the electrolyser capital cost, as well as by the electrolyser's current low load factor (i.e. the average generation over peak

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generation within a specific period). On the contrary, the SMR's high efficiency leads to larger hydrogen yield per unit of feedstock (methane) employed. This is also why there are currently less than 200 MW of electrolyser installed capacity in the EU, while the European hydrogen industry estimates that no less than 100 GW would be needed if the Union wants to achieve the REPowerEU target of 10 million tonnes (Mt) of domestic renewable H<sub>2</sub> production per year by 2030.

However, where the electrolysis is not powered by renewable energy, the hydrogen produced cannot be recognised as renewable under EU rules. Therefore, to achieve the above electrolyser capacity, approximately twice the capacity in terms of installed renewables is required at the EU level. Indeed, we have seen that 10 Mt of hydrogen have an energy value of around 330 terawatt hour (TWh), but if we consider that the capacity factors of renewable energy sources such as wind and solar PV are lower than 30% (which correspond to 2000-3000 hours in a year), this means that 330 TWh of hydrogen would require around 500 TWh of renewable power production. This in turn suggests that around 150-200 GW of new renewable installed capacity should be only dedicated to the production of green hydrogen in the EU.

For this reason, major financial efforts are needed to decarbonise the still largely fossil-based hydrogen generation, while the competitiveness of clean hydrogen production also depends on the cost of renewable electricity. As reported in Chapter 1, several economic analyses of mature alkaline electrolyser technologies in Europe have shown that one major driver of the higher cost for renewable hydrogen is the cost of the electricity. The use of power purchase agreements (PPAs) - contracts signed between a producer and a consumer of electricity that fix a certain price - can help insulate the counterparts from market price volatility. In instances where part or all renewable generation is sold to electrolyser operators through PPAs, hydrogen from renewable electricity could create a new downstream market for renewable power, facilitating the integration of high levels of variable renewable energy (e.g. solar, wind) into the energy system, because the electricity consumption of electrolysers can be adjusted to follow renewable generation.

Regarding electricity and hydrogen production, the recently revised EU regulatory framework encourages the signing of PPAs with renewable generators, but it imposes strict criteria for recognizing the production of H<sub>2</sub> as renewable (RFNBO). Such requirements range from additionality, i.e. the need to match the production of green hydrogen with electricity generated by new (additional) renewable installed capacity, to spatial and temporal correlation, ensuring that the additional renewables are located in the same area where H<sub>2</sub> is produced and that renewable electricity generation and hydrogen production coincide temporally. The EU Delegated Acts on renewable H<sub>2</sub> also define a 70% threshold for GHG emission savings during the RFNBO production process. Although Europe hosts more than one third of proposed hydrogen investments globally, the vast majority of H<sub>2</sub> projects is still at a planning stage. This is due partly to the uncertainty in the ability to comply with the EU's new criteria and to the lack of demand visibility. This is part of the so-called «chicken-or-egg» dilemma,

whereby the demand from customers will not materialise until there are no appropriate infrastructures (including production facilities and renewable power plants) that ensure cheap hydrogen supply, but without that demand, investors will not finance hydrogen projects, which in turn means zero demand.

The EU has been attempting to solve such dilemma by channelling different EU revenue sources (e.g. the EU Emission Trading System, EU bonds, the Multi-annual Financial Framework) through the European Hydrogen Bank, Next Generation EU, and the IPCEI (which imply direct State aid) to encourage European hydrogen production projects while linking the future estimated European H<sub>2</sub> demand with international hydrogen supplies. The key element that must be considered in such a process is the identification of potential hydrogen off-takers, who can drive demand in different sectors, since setting specific supply targets is not enough of an incentive. In addition, the recently adopted definition of «low-carbon hydrogen» by the EU could enable blue H<sub>2</sub> to serve as a bridge technology, facilitating the uptake of hydrogen in different demand sectors. Low-carbon can be exploited especially in areas not particularly favourable to the development of renewable sources - both because of geographic characteristics and scarce land availability. Blue hydrogen could carve out a role in the EU's H<sub>2</sub> demand, at least until green H<sub>2</sub> has become cost-competitive, and in the short-to-medium term especially because of the requirement for a largely decarbonised electricity grid, to which currently almost no Member State is able to comply.

Among the EU countries, we have seen that although the emission intensity of Italy's electricity system is expected to remain above the RFNBO threshold also by 2030, this situation could change if we consider the development of renewable energy installed capacity at a regional level. Given that Italy's electricity market is split into different bidding zones - contrary to most EU countries whose entire national territory corresponds to one large bidding zone - the requirements for producing renewable hydrogen could materialise in the bidding zones where large new renewable power plants will be built, which are mainly in Italy's southern regions. According to the analysis we carried out in Chapter 4, we could see in the future over 90% of the electricity mix covered by renewables in Italy's South and islands, a condition which can enable the production of renewable hydrogen by taking electricity directly from the grid. Even prior to this, such bidding zones could become «low-carbon», thus needing to meet the spatial and temporal correlation criteria set out in the RFNBO Delegated Acts, which means that the electrolyzers must be located in the same bidding zones as the renewable power plants, thereby creating the need for hydrogen transport from the production areas in the South towards the main demand centres in the North, where most of Italy's (hard-to-abate) industries are located.

### Hydrogen transmission

Hydrogen transport infrastructure is indeed essential to enable the hydrogen market to reach its maturity. Due to uncertainty about future hydrogen demand in each country, the architecture of the H<sub>2</sub> transport infrastructure is highly

context-dependent. We have seen that pipelines (transporting compressed H<sub>2</sub>) remain the cheapest option up to a distance of around 2000 km, thus being potentially suitable, for instance, to transport green H<sub>2</sub> from southern to northern Italy. We have also seen that hydrogen projects - despite being for the most part at the «less advanced» stage - represent the highest share of infrastructural projects included in the Ten-Year Network Development Plan (TYNDP) developed by ENTSO-G, thus showing the willingness of project promoters to commit to the creation of an EU hydrogen market. This is also why initiatives such as the European Hydrogen Backbone have been involving several natural gas transmission system operators (TSOs) in designing an almost 60 000 km-long interconnected hydrogen grid in Europe by 2040. This future H<sub>2</sub> network could consist of approximately 70% repurposed pipelines, as we have demonstrated that both the upfront investment cost and the levelised cost of hydrogen transmission (LCOT) are significantly lower for repurposed lines than for new ones. However, while pipelines are being reconverted to carry H<sub>2</sub>, operators need to simultaneously ensure the security of natural gas supply. As we saw in Chapter 2 when considering the EU's gaseous fuels consumption, by 2040 no less than 160 billion cubic metres (bcm) of natural gas will still be used in the EU, of which around 35 bcm in Italy.

The creation of a hydrogen infrastructure network is currently on the political agenda of both EU institutions and the largest Member States. In early 2024 the EU adopted the new Hydrogen and Decarbonised Gas Markets Package, consisting of the revised Gas Directive and Gas Regulation. One major aim of these new legislative measures is to ensure a more integrated network planning between electricity, gas and the future hydrogen network, as emphasised by the EU Strategy for Energy System Integration, that was released in 2020 together with the EU Hydrogen Strategy. The simultaneous publication of both strategic documents by the European Commission was not a coincidence, as (green) hydrogen can play an important role in «sector coupling». Power-to-hydrogen (P2H) technologies, like electrolyzers, can serve the double purpose of converting curtailed electricity into renewable (or low-carbon) hydrogen (depending on the type of electricity used) for storage or direct use, and even into natural gas (after methanisation). This is why we have stressed the need for improved cooperation between the electricity and gas TSOs in each country, with the development of joint scenarios that cover electricity, natural gas and hydrogen network planning, thus making it possible to identify potential synergies in the system and save on investments in the networks. Currently, in the Italian case, we have seen that Terna (the electricity TSOs) and Snam (the gas TSO) jointly develop the Scenario Description Document every 2 years, covering energy scenarios for gas and electricity, but when planning the development of both networks, they draw up separate documents that do not identify potential synergies between different energy sources and vectors.

Addressing the issues related to the creation of a European hydrogen network is crucial, but the EU and its Member States will not manage to achieve the renewable hydrogen production targets only by relying on the EU's renew-

able capacity. We have seen (in Chapter 3) that due to higher costs, limited space for installing renewable power plants and the slow pace of new hydrogen capacity projects in Europe,  $H_2$  imports (also in form of its chemical derivatives) can appear more attractive. This was demonstrated as we looked at the  $H_2$  production cost (LCOH) in Latin America and North Africa, where in both cases the LCOH is lower than 2  $\$/kg_{H_2}$ , whereas the cost in Europe - depending on the specific country or region - can be as high 10  $\$/kg_{H_2}$  or more, but nowhere in the EU is the LCOH lower than 3-5  $\$/kg_{H_2}$ . Therefore, in the long term, both Latin America and North Africa could become established green hydrogen suppliers to the EU, but in order to meet the Union's short-to-medium term needs, the cheapest - and closest - option among those considered is the export of  $H_2$  via pipeline from North Africa. This import route is indeed one of the three hydrogen supply corridors mentioned in the REPowerEU Communication, the other two being the North Sea route (with Norway and the UK as major suppliers) and the Eastern European (Ukrainian) route. The key feature that these three corridors have in common is the  $H_2$  transport mode, namely pipelines. As with gas pipelines instead of LNG deliveries, hydrogen pipelines do not involve conversion, liquefaction, reconversion and regasification costs, that add up to the transport cost.

In Chapter 3 we evaluated six potential European hydrogen import corridors, which include the above three and which are all planned to end in Germany, whose economy is driving the EU's renewable hydrogen demand across different sectors. In this scenario, we explored the potentially strategic role that the EU's second largest manufacturer, Italy, could play in enabling the import and integration of renewable hydrogen into the EU's energy system. From an economic point of view, the North Africa-Italy  $H_2$  supply corridor could give the EU access to the cheapest green hydrogen available in all corridors by 2040, together with the south-western corridor, which however suffers from a significant lack of energy (electricity and gas) interconnections between the Iberian Peninsula and the rest of Europe. Nonetheless, the limited renewable energy infrastructure and the low renewable penetration in the energy systems of the North African countries constitutes a significant obstacle. Although countries like Tunisia and Algeria have been taking part in some renewable and hydrogen development projects and they are already interconnected to Italy via a single pipeline (the TransMed), the flow of hydrogen towards Europe largely depends on the repurposing of pipelines connecting Algeria and Tunisia and on their respective financing. Moreover, the North African region is currently affected by severe political instability, that can significantly raise the cost of investment and hinder the establishment of energy partnerships.

Despite the above-mentioned obstacles, the Italian gas TSO Snam has already started to carry out the first feasibility studies for the so-called «Italian Hydrogen Backbone», a 2300 km-long corridor, with a view to its commissioning immediately after 2030. The project, that is part of a wider initiative aimed at creating a hydrogen corridor from North Africa to Germany, can serve a dual purpose: on the one hand, the  $H_2$  backbone can enable future green  $H_2$  flows to

reach the demand centres in northern and central Europe; on the other hand, it can facilitate the decarbonisation of Italian hard-to-abate industries (mainly located in the North of the country) by transporting renewable hydrogen produced in southern Italy both because of the higher renewable potential in this part of the country and because of the above mentioned EU rules that impose strict criteria for defining hydrogen as renewable.

### Hydrogen utilisation

This leads us to the analysis we developed on the current and potential hydrogen end-uses, for which we can conclude that hard-to-abate industrial sectors should be, and in some cases already are, the primary off-takers, both at the EU and Italian level. Some of the EU's newly approved pieces of legislation, such as the Hydrogen and Decarbonised Gas Markets Package and also the Net-Zero Industry Act, identify hard-to-decarbonise sectors as priority sectors for the uptake of clean H<sub>2</sub>. In addition, as we showed in Chapter 4, hydrogen projects and feasibility studies for H<sub>2</sub> use in industrial processes, as well as statistical projections at the EU level show that industry will drive the increase in hydrogen demand at least up to 2050. Also, based on the «clean hydrogen ladder» presented in Chapter 1, we learned that H<sub>2</sub> use in steel and chemical industries, for instance, is almost unavoidable, if those sectors aim to be part of a net-zero future. Long-term electricity storage, long-haul aviation and shipping are also included in the upper part of the ladder, meaning that hydrogen use needs to be scaled up in those sectors as well. Some other uses, such as domestic heating, urban and short-range transport are in the bottom part of the ladder mainly because of the current lack of proper infrastructure (like distribution lines or hydrogen refuelling stations) and the presence of more efficient electricity solutions (e.g. heat pumps), thus entailing higher overall costs in adopting hydrogen - not to mention renewable H<sub>2</sub>. Any type of policy initiative should therefore focus on stimulating the use of H<sub>2</sub> where it can represent the most efficient application.

Indeed, according to the latest (2024) version of the Italian National Energy and Climate Plan (NECP), around 0,25 Mt (or 9 TWh) of green hydrogen are expected to be used in the Italian industry and transport sectors by 2030. As our case study on hard-to-abate sectors showed, more than 0.5 Mt of unabated hydrogen are currently used in industry (mostly as a feedstock for chemicals and refineries). However, if we compare this number with the targets for renewable hydrogen included in the Italian NECP, we can clearly conclude that those targets are not ambitious enough to achieve the 42% renewable hydrogen (RFNBO) target in industry by 2030 foreseen by the EU's Renewable Energy Directive (RED III). Indeed, Italy's NECP provides for 0,115 Mt of renewable H<sub>2</sub> to be used in industry, which however correspond to just around 22.4% of the total amount used in refining and chemicals today (0.514 Mt). A 42% renewable hydrogen target would instead require an almost double quantity (0.215 Mt) compared to what is currently indicated in the NECP for industry (0.115 Mt).

On a broader perspective, Italy's newly adopted National Hydrogen Strategy claims that H<sub>2</sub> contribution to the national energy mix could rise from the current 1% to 2% by 2030, and up to 20% by 2050 (in the high-diffusion scenario), even though no specific form of hydrogen is mentioned. In Chapter 3 we clearly showed that only if we consider unabated (grey) H<sub>2</sub> in the future mix, we could see an increase up to over 2% of hydrogen in Italy's energy mix. The above-mentioned renewable hydrogen consumption expected by 2030 (8 TWh) indeed corresponds to barely 0.7% of Italy's final energy demand, whereas by adding the current grey H<sub>2</sub> consumption (19 TWh), we see that hydrogen contribution to the national energy mix increases to around 2.3%, in line with the Preliminary Guidelines' targets.

As to the financing component, the bulk of public support for the development of hydrogen projects in Italy has been delivered through the National Recovery and Resilience Plan (NRRP), with an initial amount of around €3.6 billion, which is just a small part compared to what is envisaged by the National Hydrogen Strategy. Based on the estimated need for 15–30 GW of electrolyser capacity, according to the Strategy cumulative investments are projected to range between €8 and €16 billion. Since there is no specific form of hydrogen mentioned, but given the importance accorded by the Italian Government to the principle of technological neutrality, we could add another €10 billion to account for other hydrogen production technologies, such as steam methane reforming (grey H<sub>2</sub>) or CCS (blue H<sub>2</sub>). Notwithstanding the increase in the amount of public support (€500 million) for Hydrogen Valleys (aimed at creating local clean hydrogen markets and whose projects are mostly located in southern Italy), the initial €2 billion foreseen by the NRRP for the uptake of renewable H<sub>2</sub> in hard-to-abate sectors have been reduced to €1 billion.

In general, the 2024 Italian National Hydrogen Strategy remains largely silent on the financial dimension of implementation. This lack of detailed financial planning makes it difficult to assess the feasibility of the proposed targets, to estimate the scale of private and public funding needed, and to monitor progress over time. Consequently, while the Strategy is valuable as a policy framework and roadmap, it falls short of providing a concrete, actionable financial plan that would allow stakeholders and policymakers to gauge the economic requirements for the effective deployment of hydrogen in Italy.

Therefore, to avoid stranded investments and an inefficient allocation of public resources to uncertain hydrogen projects, initial efforts in Italy should be on decarbonising the current unabated fossil-based hydrogen consumption, by setting precise financial and investment targets. This is especially true when trying to boost the production and use of renewable hydrogen. Since its production process involves the consumption of significant amounts of renewable electricity, there is an opportunity cost involved in using that electricity to produce hydrogen or using it to electrify or decarbonise other sectors (e.g. transportation). That is why the additionality rule imposed by the new RED Delegated Acts on RFNBOs is crucial to prevent the different EU and national decarbonisation initiatives from competing for the same renewable electricity. Nevertheless, un-

subsidised renewable hydrogen typically remains uncompetitive with fossil H<sub>2</sub>, thus requiring targeted public support.

The case study on the uptake of clean hydrogen in the Italian ceramics sector has shown that there can be an advantage in installing a dedicated renewable power plant at the ceramics site to feed an electrolyser, provided that the cost of electricity is not higher than the energy market price. However, since the ceramics industry would need a constant supply of hydrogen if it were to use H<sub>2</sub> instead of natural gas to provide the heat needed, having one single renewable (intermittent) power plant could be a problem in terms of load factor. We saw that with only one solar plant (located either on the ceramics facility roof or in an area nearby), the load factor is between 25 and 39%, meaning that the electrolyser would be largely under-utilised if compared to a potential load factor of 63%, corresponding to 5500 hours per year. Therefore, to guarantee a renewable electricity supply for a greater number of hours, either more renewable power capacity must be installed at the ceramics site, or the electrolyser must be connected to the electricity grid (using a PPA). In most cases, and mainly due to the strong impact of the CAPEX and also limited space for installing new renewable power plants, the grid option is preferable. While most renewable energy generation potential is in southern Italy, the bulk of ceramic manufacturing plants are located in the North of the country, in the provinces of Reggio Emilia and Modena. This example, like with other hard-to-abate industries, further shows that the installation of electrolysers in areas with greater renewable potential (in the South) could create a significant demand for centralised hydrogen production and the subsequent development of a transport network towards end-use sites.

The 2024 Italian hydrogen strategy acknowledges the ceramic industry among the hard-to-abate industrial sectors where hydrogen could play a role in long-term decarbonisation, mainly as a substitute for natural gas in high-temperature thermal processes. The document provides indicative estimates of hydrogen consumption in the ceramic sector under long-term scenarios, thereby implicitly recognising its technical relevance within the Italian industrial landscape. However, the Strategy remains largely high-level and generic in its treatment of the ceramic industry. In particular, it does not clearly differentiate between renewable (green) hydrogen and hydrogen produced from fossil sources, nor does it explicitly link the envisaged hydrogen uptake in the ceramic sector to specific decarbonisation pathways, technology readiness levels, or cost and infrastructure constraints.

This lack of distinction risks overestimating the decarbonisation potential of hydrogen deployment, as the climate benefits critically depend on the production pathway of the hydrogen used. Moreover, the Strategy does not clarify whether hydrogen use is expected to be transitional or structural in the long term. As a result, while the Strategy signals a potential role for hydrogen in the ceramic sector, it falls short of providing a robust, technology-specific and climate-consistent framework for its effective and sustainable deployment.

This notwithstanding, before being able to play a significant role in the European strategy for upscaling hydrogen, Italy should clearly define a more am-

bitious and long-term industrial investment vision. This could lead to useful actions and could create a competitive advantage for national industrial supply chains. Implementing the regulatory framework, which the EU has already put in place, and identifying specific financial incentives to stimulate investment in renewable and low-carbon hydrogen infrastructures is essential.