ENERGY POLICY GROUP

Clean Hydrogen in Romania

ELEMENTS OF A STRATEGY

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Clean Hydrogen in Romania

Elements of a Strategy

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Contents

List of abbreviations

AEP – Annual Energy Production

ATR - Autothermal Methane Reforming

CAPEX – Capital Expenditure

CCfD – Carbon Contract for Difference

CCGT – Combined Cycle Power Plant

CCS – Carbon Capture and Storage

CCUS – Carbon Capture Utilisation and Storage

CfD – Contracts for Difference

CNG – Compressed Natural Gas

DCF – Discounted Cash Flow

DRI – Direct Reduced Iron

EGD – European Green Deal

ETS – Emissions Trading System

FLH – Full Load Hours

GHG – Greenhouse Gas

GO – Guarantee of Origin

HDV – Heavy-duty Vehicles

H-EMU – Hydrogen Electric Multiple Units

LCOE – Levelized Cost of Energy

LCOH – Levelized Cost of Hydrogen

LNG – Liquefied Natural Gas

LOHC – Liquid Organic Hydrogen Carrier

NECP – National Energy and Climate Plan

NRRP – National Recovery and Resilience Plan

PEM – Proton Exchange Membrane

PPA – Power Purchasing Agreement

PSA – Pressure Swing Adsorption

PtL – Power-to-Liquid

RED – Renewable Energy Directive

RES – Renewable Energy Sources

RFNBO – Renewable Fuels of Nonbiological Origin

SAF – Sustainable Aviation Fuel

SMR – Steam Methane Reforming

List of figures

List of tables

Executive Summary

Decarbonising the EU economy will most of all require direct electrification of over 60% of end-uses, based on energy efficiency considerations. However, this will not always be technically possible or cost-efficient. Decarbonised molecules, such as hydrogen, will also contribute to eliminating 'stubborn emissions' in hard-to-abate sectors such as high-temperature heat and feedstock in industry, aviation and long-haul shipping, and possibly large-scale district heating and long-term electricity storage, thus increasing the flexibility and resilience of the energy system.

There seems though to be a level of confusion among domestic actors about the role that hydrogen is to play in decarbonisation. In Romania, hydrogen is portrayed as a silver bullet towards a decarbonised future in sectors looking to find their place in a landscape shaped by the European Green Deal. However, as argued in the present report, its real impact will greatly depend on the country's economic strategy and costs of technology.

In Romania, the most promising hydrogen uses are in industry (steel, ammonia, fertilisers, refineries, and high value chemicals), transport (long-haul aviation, maritime shipping, HDVs and some railway segments), existing district heating systems and, potentially, long-term or seasonal energy storage beyond 2030. Other uses, such as gas blending or green hydrogen use in CCGTs are rather a waste of economic value, given the comparatively high costs of producing hydrogen.

The Romanian authorities announced the intention to release a national hydrogen strategy in 2022. This will be an opportunity to make informed and comprehensive decisions regarding the future of hydrogen, including on uses, as opposed to the current patchwork of uncoordinated and poorly designed initiatives. The strategy should be developed based on the active involvement of public and private stakeholders, with targets and potential funding sources.

Finding economically viable opportunities for sector integration based on best practices in R&D cooperation and commercial projects will be imperative to the development of a Romanian hydrogen industry. From the outset, there ought to be a solid business case for the hydrogen value chains that are set to expand once funding opportunities become available and technology costs decrease.

Based on considerations regarding carbon intensity, cost and availability, green (a.k.a. clean or renewable) hydrogen is the most promising for delivering the goals of decarbonisation on the long term. Pink hydrogen also promises near-zero GHG emissions, but factoring in the cost aspect, green hydrogen is on a clear path to significant cost reductions that render it competitive with fossil-based hydrogen by 2030. Therefore, the study argues that clean hydrogen should be the focus of the Romanian national hydrogen strategy.

Today there is still a cost gap between fossil-based and clean hydrogen. However, electrolyser CAPEX is expected to decrease from €1,060/kW (PEM) to €375/kW (PEM), and as low as €100/kW (alkaline). The current cost differences between the two electrolyser types in terms of cost and performance are likely to narrow in time as innovation and widespread deployment of various technologies will boost convergence towards similar cost structures. However, the cheaper alkaline electrolysers expected to be available by 2030 will likely be supplied by Chinese manufacturers, while the European hydrogen value chain will focus more on PEM electrolysers. Either way, by 2030, producing clean hydrogen will no longer be a CAPEX intensive business. The price of renewable energy becomes the main cost component, especially at medium to high electrolyser load factor. Coupled with the decreasing cost of renewable energy, higher carbon price and elimination of free allocation of CO_2 allowances, this will allow clean hydrogen to breakeven with fossil alternatives between 2028 and 2032 based on local renewable potential.

Two modelling scenarios analysed for this report, based on the Fit for 55 package proposals regarding the use of clean hydrogen in industry and transport, show that between 1,470 MW and 2,350 MW of electrolyser capacity will need to be installed in Romania by 2030. This amounts to 3.7% and 6%, respectively, of the EU electrolyser capacity by 2030 targeted in the European Commission's Hydrogen Strategy. When factoring in the additionality principle, this will require between 3 and 4.5 GW of new renewables to be installed besides the capacities included in the current National Energy and Climate Plan.

Based on an electricity price of €50/MWh, a reasonable if not conservative assumption for Romania in 2030, given the RES potential and expected cost reductions, the resulting levelized cost of hydrogen (LCOH) for alkaline electrolysis is between €2.21/kgH_2 and €2.3/kgH_2, while for PEM electrolysis it ranges from €2.34 to €2.73/ kgH_2, depending on load factor. The LCOH can go down to as much as €1.38/kgH_2 for alkaline electrolysis and €1.59/ kgH_2 for PEM electrolysis in 2030 for an electricity price of €25/MWh. The only way of ensuring a stable and predictable source of low-cost electricity for the electrolysis units is long-term Power Purchase Agreements (PPAs) with multiple RES producers, or wholesale purchasing of electricity that comes with Guarantees of Origin (GOs). To respect the additionality principle, a temporal and geographical connection between the electrolyser and renewable capacity would also be needed.

Key strategic choices will have to be made in the upcoming strategy regarding hydrogen production pathways, location of sites, end-uses, and transport infrastructure. This report offers arguments about cost, carbon intensity, and availability for the Romanian authorities to focus on clean hydrogen, and to prioritise large-scale investments in renewable and electrolyser capacities. This would be fully compliant with the European pathway enshrined in the EU Hydrogen Strategy and Fit for 55 package provision and will help Romania capitalise on the major opportunities of developing new value chains as part of the energy transition.

Key policy recommendations

It is imperative to develop a national hydrogen strategy. The strategy must identify the drivers in the sector and set priorities for production and identify pathways for use, costs, and deployment targets for 2030 and 2050. It ought to include a timeline for market development, a clear regulatory framework, and financial measures to support the development of the hydrogen sector and the associated value chains. The strategy should:

- **Prioritize clean hydrogen** from renewable electricity, since there is a clear cost-efficient pathway up to 2030, besides being optimal in terms of carbon intensity, availability, and sectorial EU renewable targets. The government ought to choose solutions in line with a net-zero GHG emissions by 2050 trajectory.
- **Target the most promising uses** for hydrogen: industry (feedstock, reduction agent, high temperature heat) and transport (maritime shipping, heavy-duty vehicles, long-haul aviation, and some railway segments), and long-term energy storage. Direct combustion of hydrogen should be avoided, given the low energy efficiency of the process. Therefore, the potential for hydrogen in the heating of buildings is expected to be limited, as it is not cost-effective for use in individual households.
- **Involve public and private stakeholders to outline a strategic roadmap** with targets and potential funding sources. Explore economically viable opportunities for sector integration based on best practices for international cooperation in R&D and commercial projects.
- **Include a component dedicated to hydrogen for the transport sector**, with clarifications regarding modes of transport, the role of the state, and the ways to finance that infrastructure. The role of synthetic fuels produced from clean hydrogen should also be included.
- **Outline measures to develop the hydrogen value chain in Romania**, particularly for electrolyser manufacturing. The education and R&D sectors should also be prioritised. Based on the initial development for the domestic market, Romania can aim to become an exporter of equipment and know-how to neighbouring markets. The national hydrogen strategy should be followed by a national industrial decarbonisation strategy and roadmap.

Romania should support the proposals for hydrogen deployment in the Fit for 55 package, especially those from the revised Renewable Energy Directive. The proposals are to achieve 40% RES by 2030, partly through a binding obligation on industry to cover 50% of feedstock and energy needs through RFNBOs, with a similar target of 2.6% RFNBOs proposed for the transport sector. Yet, as shown in this report, the 2030 ambitions for clean hydrogen can be higher, especially in the industrial sector. On the same basis, **the additionality principle should be endorsed by the Romanian authorities as part of the delegated acts for the Renewable Energy Directive to be proposed by the European Commission.**

Romania should implement a favourable legal and regulatory framework for investments in renewable energy sources. This is paramount for tapping into Romania's potential to produce cost-competitive clean hydrogen, which will require access to renewable electricity. In addition, Romania's offshore wind potential should be thoroughly assessed, followed by the creation of a fair investment framework. The destination of financial support should reflect the high probability that **by 2030, hydrogen production will transform from a CAPEX-intensive to an OPEX-intensive process**, with the cost of electricity having the highest share in the cost structure of clean hydrogen. It will be more efficient to incentivize renewable power generation assets and capital expenses for electrolysis units, both being upfront costs.

The government should introduce **mechanisms allowing electrolysers to combine multiple electricity sources** (through direct PPAs and/or Guarantees of Origin) to reach a sufficiently high load factor, and thus a more affordable clean hydrogen production.

- **Lead-market creation instruments must be implemented**, such as carbon contracts for difference (CCfD), hydrogen supply contracts, a Power-to-Liquid (PtL) quota for the aviation sector or a labelling system for climate-friendly basic materials.
- Given the country's very good renewable energy potential, hence the significant potential to produce cost-efficient clean hydrogen, a **strategic choice must be made between exporting clean hydrogen or using it locally** to further develop downstream industries, such as green steel production. Romania should engage in "hydrogen diplomacy" to seize the opportunities for international hydrogen trading.
- **Dobrogea must become a clean hydrogen valley**. On the short term, it can become a local, medium-scale and industry-focused hydrogen valley, with potential for local clean hydrogen projects with several industrial off-takers as anchor load and potentially transport off-takers, replacing grey hydrogen supply, or more carbon intensive industrial processes. In the long-term Dobrogea can grow into a larger-scale, international and export-focused hydrogen valley, with the Port of Constanța as its centrepiece.

Sumar executiv

Decarbonarea economiei Uniunii Europene va necesita, în primul rând, electrificarea directă a peste 60% din consumul final de energie, dar acest lucru nu va fi întotdeauna posibil din punct de vedere tehnic sau economic. Moleculele decarbonate, cum ar fi hidrogenul, vor contribui, de asemenea, la eliminarea emisiilor dificil de înlăturat în sectoare cum ar fi încălzirea la temperaturi înalte și materiile prime din industrie, aviația și transportul maritim pe distanțe lungi și, eventual, încălzirea urbană la scară largă și stocarea energiei electrice pe termen lung, sporind astfel flexibilitatea și reziliența sistemului energetic.

Se pare, totuși, că există un grad de confuzie în rândul actorilor naționali cu privire la rolul pe care hidrogenul trebuie să îl joace în decarbonare. În România, hidrogenul este descris drept o soluție universală pentru un viitor fără emisii de carbon în sectoarele care își caută locul în peisajul Green Deal-ul european. Cu toate acestea, după cum arată prezentul raport, impactul real al hidrogenului va depinde în mare măsură de strategia economică a țării și de costurile tehnologiei.

În România, cele mai promițătoare utilizări ale hidrogenului sunt în industrie (oțel, amoniac, îngrășăminte, rafinării și produse chimice de mare valoare), transporturi (aviație pe distanțe lungi, transport maritim, vehicule de mare tonaj și unele segmente feroviare), sistemele existente de încălzire urbană și, potențial, stocarea energiei pe termen lung sau sezonieră după 2030. Alte utilizări, cum ar fi amestecul de gaze sau folosirea hidrogenului verde în centrale cu ciclu combinat (CCGT) reprezintă mai degrabă o risipă de valoare economică, având în vedere costurile relativ ridicate de producție a hidrogenului.

Autoritățile române au anunțat intenția de a publica o strategie națională privind hidrogenul în 2022. Aceasta va fi o bună ocazie de a lua decizii informate și cuprinzătoare cu privire la viitorul hidrogenului, inclusiv cu privire la utilizări, spre deosebire de actuala abordare prin inițiative necoordonate și superficiale. Strategia trebuie să fie elaborată pe baza implicării active a părților interesate din sectorul public și privat, cu obiective clare, cu estimarea costurilor și cu identificarea potențialelor surse de finanțare.

Soluțiile viabile din punct de vedere economic pentru integrarea sectoarelor, bazate pe cele mai bune practici de cooperare în domeniul cercetării și dezvoltării și pe proiecte comerciale, vor fi imperative pentru dezvoltarea unei industrii românești a hidrogenului. Încă de la început, va fi necesară o argumentare comercială solidă pentru lanțurile valorice ale hidrogenului, care urmează să se extindă odată ce sursele de finanțare vor deveni disponibile iar costurile tehnologiei vor scădea.

Pe baza considerațiilor privind intensitatea carbonului, costul și disponibilitatea surselor regenerabile de energie, hidrogenul verde (numit și hidrogen curat sau regenerabil) este cel mai promițător pentru realizarea obiectivelor de decarbonare pe termen lung. Hidrogenul roz (nuclear) promite, de asemenea, emisii de gaze cu efect de seră aproape de zero dar, ținând cont de costuri, hidrogenul verde este pe o tendință clară de eficientizare care îl va face competitiv cu hidrogenul pe bază de combustibili fosili până în 2030. Prin urmare, prezentul studiu susține că hidrogenul curat trebuie să fie punctul central al strategiei naționale românești privind hidrogenul.

În prezent, există încă o diferență de cost între hidrogenul de origine fosilă și cel curat. Cu toate acestea, se preconizează că CAPEX-ul electrolizoarelor va scădea de la 1.060 EUR/kW (PEM) la 375 EUR/kW (PEM) și până la 100 EUR/kW (alcalin). Diferențele actuale de cost și performanță dintre cele două tipuri de electrolizoare vor scădea probabil în timp, pe măsură ce inovația și implementarea pe scară largă a diferitelor tehnologii vor stimula convergența către structuri de cost similare. Dar electrolizoarele alcaline mai ieftine ce vor fi disponibile până în 2030 vor fi probabil furnizate de producătorii chinezi, în timp ce lanțul valoric european al hidrogenului se va concentra mai mult pe electrolizoarele PEM. În orice caz, până în 2030, producerea de hidrogen curat nu va mai necesita investiții mari de capital. Prețul energiei regenerabile va deveni principala componentă a costurilor, în special la un factor de încărcare mediu spre ridicat al electrolizorului. Împreună cu scăderea costului energiei regenerabile, cu prețul mai mare al carbonului și cu eliminarea alocării gratuite a cotelor de CO_2, acest lucru va permite hidrogenului curat să ajungă la pragul de rentabilitate față de alternativele fosile între 2028 și 2032, pe baza potențialului local de energie regenerabilă.

Două scenarii de modelare analizate în acest raport pe baza propunerilor din pachetul *Fit for 55* privind utilizarea hidrogenului curat în industrie și transporturi arată că, până în 2030, în România va trebui să fie instalată o capacitate de electroliză între 1.470 MW și 2.350 MW, ceea ce reprezintă 3,7%, respectiv 6% din capacitatea de electroliză din UE până în 2030 stabilită în Strategia privind hidrogenul a Comisiei Europene. Dacă se ia în considerare principiul adiționalității, va fi nevoie de instalarea a 3 GW până la 4,5 GW de noi surse regenerabile de energie, pe lângă capacitățile incluse în actualul Plan Național Integrat pentru Energie și Schimbări Climatice (PNIESC).

Pe baza unui preț al energiei electrice de 50 EUR/MWh, o ipoteză rezonabilă, chiar conservatoare pentru România în 2030, având în vedere potențialul RES și reducerile de costuri preconizate, costul actualizat al hidrogenului (LCOH) rezultat pentru electroliza alcalină este cuprins între 2,21 EUR/kgH_2 și 2,3 EUR/kgH_2, în timp ce pentru electroliza PEM variază între 2,34 EUR/kgH_2 și 2,73 EUR/kgH_2, în funcție de factorul de capacitate. LCOH poate scădea până la 1,38 EUR/kgH_2 pentru electroliza alcalină și 1,59 EUR/kgH_2 pentru electroliza PEM în 2030, pentru un preț al energiei electrice de 25 EUR/MWh. Singura modalitate de a asigura o sursă stabilă și previzibilă de energie electrică la costuri reduse pentru unitățile de electroliză este dată de contractele de achiziție pe termen lung (PPA) cu mai mulți producători de energie regenerabilă sau de achiziția angro de energie electrică însoțită de garanții de origine. Pentru a respecta principiul adiționalității, ar fi necesară, de asemenea, o legătură temporală și geografică între electrolizor și capacitatea de energie regenerabilă.

În viitoarea strategie vor trebui făcute alegeri fundamentale în ceea ce privește modalitățile de producție a hidrogenului, amplasamentele, utilizările finale și infrastructura de transport. Prezentul raport oferă argumente privind costul, intensitatea carbonului și disponibilitatea, astfel încât autoritățile să se concentreze asupra hidrogenului curat și să acorde prioritate investițiilor pe scară largă în capacitățile regenerabile și în electrolizoare. Acest lucru este pe deplin în acord cu traiectoria europeană prezentată în Strategia UE privind hidrogenul și de propunerile din pachetul *Fit for 55*, ajutând guvernul să valorifice șansele majore de dezvoltare a unor noi lanțuri valorice ca parte a tranziției energetice.

Recomandări

Este necesară elaborarea strategiei naționale privind hidrogenul. Strategia trebuie să identifice factorii determinanți din acest sector, să stabilească priorități pentru producerea de hidrogen și să identifice modalitățile de utilizare, costurile și țintele de dezvoltare pentru 2030 și 2050. Aceasta ar trebui să includă un calendar pentru dezvoltarea pieței, un cadru de reglementare clar și măsuri financiare pentru a sprijini dezvoltarea sectorului hidrogenului și a lanțurilor valorice asociate. Strategia ar trebui:

- **Să acorde prioritate hidrogenului curat** obținut din energie electrică din surse regenerabile, deoarece există o tendință clară de reducere a costurilor până în 2030. În plus, aceasta este soluția optimă din punctul de vedere al emisiilor de carbon, al disponibilității și al obiectivelor sectoriale ale UE în materie de energie regenerabilă. Guvernul trebuie să aleagă soluții în conformitate cu o traiectorie de neutralitate climatică până în 2050.
- **Să vizeze cele mai promițătoare utilizări ale hidrogenului**: industria (materie primă, agent de reducere, căldură la temperaturi ridicate), transporturile (transportul maritim, vehiculele grele, aviația pe distanțe lungi și unele segmente feroviare) și stocarea energiei pe termen lung. Arderea directă a hidrogenului ar trebui evitată, având în vedere eficiența energetică scăzută a procesului. Prin urmare, se preconizează că potențialul de utilizare a hidrogenului pentru încălzirea clădirilor va fi limitat, deoarece nu este rentabil pentru utilizarea în gospodăriile individuale.
- **Să implice părțile interesate din sectorul public și privat** pentru a defini o foaie strategică de parcurs cu obiective și potențiale surse de finanțare. Trebuie vizată explorarea abordărilor viabile din punct de vedere economic de integrare a sectoarelor pe baza celor mai bune practici internaționale de cooperare în domeniul cercetării și dezvoltării și al proiectelor comerciale.
- **Să includă o componentă dedicată hidrogenului pentru transporturi**, cu clarificări privind tipurile de transport, rolul statului și modalitățile de finanțare a acestei infrastructuri. De asemenea, ar trebui luat în considerare rolul combustibililor sintetici produși din hidrogen curat.
- **Să evidențieze măsurile de dezvoltare a lanțului valoric al hidrogenului în România**, în special în ceea ce privește producția de electrolizoare. De asemenea, ar trebui să se acorde prioritate sectoarelor educației și cercetării și dezvoltării. Pe baza dezvoltării inițiale a pieței interne, România poate avea ca obiectiv să devină un exportator de echipamente și know-how către piețele vecine. Strategia națională privind hidrogenul ar trebui să fie urmată de o strategie națională de decarbonare a industriei și de o foaie de parcurs.

România trebuie să susțină propunerile pentru implementarea hidrogenului din pachetul *Fit for 55*, în special cele din Directiva Revizuită privind Energia din Surse Regenerabile (RED). Propunerile vizează atingerea unui procent de 40% de surse regenerabile de energie până în 2030, parțial printr-o obligație impusă industriei de a acoperi 50% din necesarul de materii prime și energie prin RFNBO (combustibili regenerabili de origine nebiologică), un obiectiv similar de 2,6% RFNBO fiind propus pentru sectorul transporturilor. Totuși, după cum se arată în prezentul raport, ambițiile pentru 2030 în ceea ce privește hidrogenul curat pot fi mai mari, în special în sectorul industrial. Pe aceeași bază, **principiul adiționalității trebuie susținut de autoritățile române ca parte a actelor delegate pentru Directiva privind Energia din Surse Regenerabile,** care urmează a fi propuse de Comisia Europeană.

România trebuie să implementeze un cadru legal și de reglementare favorabil pentru investițiile în sursele de energie regenerabilă. Acest lucru este esențial pentru valorificarea potențialului României de a produce hidrogen curat la preț competitiv, ceea ce va necesita acces la energie electrică din surse regenerabile. În plus, potențialul eolian offshore al României ar trebui să fie evaluat în detaliu, urmat de crearea unui cadru de investiții echitabil și competitiv. Destinația sprijinului financiar ar trebui să reflecte probabilitatea ridicată ca, până în 2030, **producția de hidrogen să se transforme dintr-un proces cu costuri de capital ridicate într-un proces dependent de costurile operaționale**, costul energiei electrice având cea mai mare pondere în structura costurilor hidrogenului curat. Vor fi mai eficiente investițiile în producerea energiei regenerabile și cheltuielile de capital pentru unitățile de electroliză, ambele fiind costuri inițiale.

Guvernul ar trebui să introducă **mecanisme care să permită electrolizoarelor să combine mai multe surse de energie electrică** (prin intermediul unor PPA-uri directe și/sau garanții de origine) pentru a atinge un factor de capacitate suficient de ridicat și, astfel, o producție de hidrogen curat mai accesibilă.

- **Trebuie implementate instrumente de creare a piețelor-pilot**, cum ar fi contractele de carbon pentru diferență (CCfD), contractele de furnizare a hidrogenului, o cotă de *Power-to-Liquid* (PtL) pentru sectorul aviației sau un sistem de etichetare pentru materialele cu emisii scăzute de carbon.

- Având în vedere potențialul foarte bun al țării în materie de energie regenerabilă și, prin urmare, potențialul semnificativ de a produce hidrogen curat în mod eficient din punct de vedere al costurilor, **este necesară o alegere strategică între exportul de hidrogen curat și utilizarea acestuia la nivel local** pentru a dezvolta în continuare industriile din aval, cum ar fi producția de oțel cu emisii scăzute de carbon. Mai mult, România ar trebui să se angajeze într-o „diplomație a hidrogenului” pentru a valorifica oportunitățile oferite de comerțul internațional cu hidrogen.

- **Dobrogea trebuie să devină un pol de dezvoltare a hidrogenului curat.** Pe termen scurt, Dobrogea poate deveni o vale a hidrogenului la scară locală, de dimensiuni medii, axată pe industrie, cu potențial pentru proiecte locale de hidrogen curat, cu multipli consumatori industriali ca punct de plecare și, eventual, consumatori din transporturi, înlocuind aprovizionarea cu hidrogen gri sau procesele industriale cu emisii mai mari de carbon. Pe termen lung, Dobrogea poate deveni o vale a hidrogenului la scară mai mare, de anvergură internațională și axată pe exporturi, având ca element central Portul Constanța.

1. Introduction

In view of the upcoming hydrogen strategy that the Romanian authorities have committed to in the National Recovery and Resilience Plan (NRRP), this report seeks to establish some key principles. A comprehensive strategy should set the national priorities in terms of hydrogen supply, end-uses, transportation, as well as broad legal and regulatory framework. With a short timeframe for decarbonisation, production methods with the highest potential for greenhouse gas (GHG) emissions reductions and the highest value and efficient end-uses should be prioritised.

This report outlines the most important theoretical and practical considerations that need to be considered when establishing these priorities. Cost and volume estimations for the production of clean hydrogen[1] in Romania by 2030 have been made, aligned with decarbonisation pathways.

1.1 Hydrogen in the European context

The objectives of the Romanian hydrogen strategy should be aligned with the broader targets of the European Green Deal (EGD) and overall EU decarbonisation efforts. The EGD offers a vision for a clean and climate neutral EU to be reached in the next three decades, with ambitious intermediate steps including 55% GHG emissions reductions by 2030. Thus, rather than being a footnote concern, climate change mitigation becomes a primary organisational principle for the entire EU economy. Energy, transport, industrial and agricultural policies will be shaped according to the necessity to reduce their carbon footprint. The flagship initiative of EGD, the new 'Climate Law,' has it that as of 2050 any remaining GHG emissions in the EU economy shall be balanced by carbon sinks.

The emissions reduction needed for these ambitions will rely on a combination of uptake in renewable energy, improvements in energy efficiency, large-scale shifts to decarbonised fuels, promotion of circular economy, decarbonisation of industrial processes, material substitution, and changes in individual behaviour. Crucially, decarbonising the EU economy will require the direct electrification of over 60% of end-uses, to cover an increasing amount of the energy needed in the transport, industry, and heating and cooling sectors.

This is clearly established by the Commission's Energy System Integration Strategy (EC 2020a), which aims at raising efficiency and minimising the transition costs to a renewables-dominated energy system, aligned with the climate neutrality objective. The strategy acknowledges that there will be limits for direct electrification, which is not always technically possible or cost-efficient. Decarbonised molecules, such as hydrogen, will also contribute to eliminating 'stubborn emissions' in hard-to-abate sectors such as high-temperature heat and feedstock in industry, aviation and long-haul shipping, and possibly large-scale district heating and long-term electricity storage, thus

[1] According to the European Commission's Hydrogen Strategy, *clean hydrogen* refers to renewable hydrogen.

increasing the flexibility and resilience of the energy system. This assumes a spectacular growth of the hydrogen market, from currently ca. 2% of the EU final energy consumption, mostly as chemical feedstock in the production of ammonia and methanol in some oil refineries, with 85% of present production happening at the point of consumption. Moreover, 95% of hydrogen is currently produced from fossil fuels and will therefore need be decarbonised, mostly by replacement with hydrogen produced from renewables.[2]

To kick-start the hydrogen economy, the European Commission published in 2020 the Hydrogen Strategy (EC 2020b), with an ambitious roadmap for the deployment of clean hydrogen.[3] The milestones are 6 GW of electrolysers by 2024 and 40 GW by 2030. The focus is on the deployment of renewable hydrogen, including the domestic capacity to manufacture electrolysers. Steam methane reforming (SMR) with carbon capture may play a limited role in decarbonising part of today's hydrogen production, as highlighted in the strategy's terminology, which exclusively labels renewable hydrogen as 'clean.' The strategy also envisions a role for low-carbon hydrogen produced from non-renewable electricity, which has a low carbon intensity and can thus bring emissions reductions. The European Clean Hydrogen Alliance, announced by the Commission's Industrial Strategy (EC 2020c), will be an important promoter of projects and investments to achieve the targeted electrolyser rollout.

The long-term goal is to expand from initially restrained clusters to a pan-European liquid and liberalised hydrogen market. This will require infrastructure investments, market-based support schemes for producers, as well as lead market creation mechanisms, including consumption quotas for final consumers. The latter would in part be implemented according to the proposals of the Fit for 55 package.

The increased ambitions set in the revised Renewable Energy Directive (EC 2021a), aiming to achieve 40% RES by 2030, would partly be achieved through a binding obligation on the industrial sector to cover 50% of feedstock and energy needs with *renewable fuels of nonbiological origin* (RFNBOs). A similar target of 2.6% for RFNBOs is proposed for the transport sector, while the ReFuelEU Aviation initiative sets the objective by 2030 at 5% sustainable aviation fuels (SAFs), 0.7% coming from RFNBOs (to be increased to 64% and 28% respectively by 2050). In practice, RFNBO targets will mostly have to be met using hydrogen. Such fuels need to be produced from renewable sources other than biomass, including the direct use of clean hydrogen, as well as other fuels such as ammonia and synthetic hydrocarbons, which in practice would also have to be produced from renewable hydrogen. Given the important role foreseen for hydrogen, robust criteria are needed for ensuring its positive climate impact.

The current version of the Renewable Energy Directive (RED II) sets the GHG savings requirement for renewable hydrogen at 70% compared to fossil fuel-based alternatives, while the EU Taxonomy

[2] Decarbonised hydrogen could also be produced from other sources. Pyrolysis of natural gas, electrolysis with nuclear energy and steam methane reforming of biomethane with carbon capture, which could even deliver negative emissions if sustainable biomass is used. However, the Commission's hydrogen strategy strictly defines 'clean hydrogen' as hydrogen produced from electrolysis using renewable energy.

[3] See Footnote 3.

(EC 2020d) for sustainable activities imposes an emissions limit of 3 tCO_2/tH_2 for hydrogen to be classified as clean. These requirements are crucial, as it is estimated that electrolytic hydrogen can only have lower emissions than SMR-based hydrogen if the carbon intensity of electricity is under 190 gCO_2/kWh (IRENA 2021a). According to Bruegel (2021), the current average carbon intensity of the European electricity grid is 285 gCO_2/kWh. Only hydrogen produced with electricity from the French, Lithuanian and Swedish grids would meet the limits imposed by the taxonomy, as pointed out by Bellona (2021).

One way to ensure the climate credentials of electrolytic hydrogen is to only power the electrolyser with renewable electricity alone. At the same time, though, the RES capacities used for hydrogen production must not displace the use of renewable electricity in other sectors with fossil fuel-generated power, as this would increase CO_2 emissions elsewhere in the economy. With a hard cap on emissions set through the EU ETS, this should be manageable on the long run. Nonetheless, to address current concerns about potential cannibalisation of renewable electricity that would better serve the direct electrification of end users, the principle of additionality establishes that only new RES capacities that would not have otherwise been installed should be used for clean hydrogen production.

To that purpose, a connection is needed between the new RES installation and the electrolyser. There are multiple ways in which this may be achieved. A physical connection is one option. Alternatively, a virtual connection may link the electrolyser to the grid if it was in the same bidding zone as the new RES capacity with which it either has a PPA or from which it purchases RES electricity proven by guarantees of origin.[4] To avoid displacement of existing RES capacities, the electrolyser would only be allowed to produce hydrogen while the connected renewables produce electricity – a temporal connection to be proven every 15-minutes. A laxer 'system-level matching' alternative is also considered: RES and electrolyser capacities would have to be matched at system level, with no direct or indirect connection requirements. Electrolysers would produce hydrogen only at times when more renewables are fed into the grid than on average. However, there are concerns regarding the ability of a system-level matching framework to adequately implement the additionality principle and ensure the climate benefits of renewable hydrogen. Therefore, it is expected that the Commission will impose stricter requirements for geographical and temporal connection.

This debate will be settled in the delegated acts that the European Commission will publish by the end of year for the implementation of Article 27(3) of the new Renewable Energy Directive. The acts will provide the criteria based on which RFNBOs, hence also hydrogen, can be considered renewable in the transport sector. With the new proposed quota for RFNBOs in the industrial sector, the conditions set in the delegated acts are expected to become the general standard for classifying hydrogen as renewable. The methodology that will be presented by the Commission will determine the sustainability criteria for hydrogen and, ultimately, the eligibility of electrolysers for subsidies. All these factors must be considered in the development of national plans for hydrogen deployment.

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[4] There are also some proposals for including existing renewable capacities, as long as they no longer receive any subsidies.

The Hydrogen and Decarbonised Gas Package, to be released on December 14, is expected to also acknowledge the role of low-carbon hydrogen, which will require a separate certification framework.

1.2 Hydrogen in the national context

While hydrogen-based technologies were tackled in the NECP, it was only from a general perspective, insufficient for establishing the priorities of a national hydrogen strategy. Aside from calling for a general assessment of the potential of hydrogen in the Romanian energy mix, the NECP set no clear targets or measures, and certainly no roadmap for sector integration.

The hydrogen conversation in Romania was boosted especially as part of the recovery planning, which created the circumstances for transformational changes in the EU energy and industry sectors. These will be based, among other things, on sector integration and value chains for clean hydrogen. Growing signals from public and private stakeholders, as well as politicians, indicate an awakening to the opportunities likely to arise in the following period, in a striking departure from the conservative approach to the energy sector of the past years.

In the power generation sector, there are plans for investments in at least 1.6 GW of gas-fired power generation in the next five years. Such assets, along with any new piece of gas infrastructure, will be designed to blend into a decarbonized gas industry of the future. Enabling them to also work based on hydrogen is deemed, contrary to economic analysis, to reduce their risk of turning into stranded assets. One such initiative is the recent plan to build a gas-fired power plant alongside wind and solar PV capacities to power the country's largest steel plant in Galați, a project due to transit to hydrogen use in a later phase.

While this sudden interest for hydrogen in Romania is welcome, proposals of isolated and poorly conceived projects show a lack of a robust foundation in economic and policy analysis and planning. Instead, this hydrogen hype seems to be coupled to the momentum that the topic has received internationally. Indeed, other European countries such as France, Germany and Norway have already published national hydrogen strategies, as have Australia, Japan, and Korea. Alarmingly, there seems to be a level of confusion among domestic actors about the role that hydrogen is to play in decarbonisation based on its technically feasible and most cost-efficient applications. Hydrogen is portrayed as a silver bullet towards a decarbonised future in sectors looking to find their place in a landscape shaped by the EGD. However, as argued in the present report, its real impact will greatly depend on the country's economic strategy and costs of technology.

The Romanian authorities announced the intention to release a national strategy in 2022. This will be an opportunity to make informed and comprehensive decisions regarding the future of hydrogen, as opposed to the current patchwork of uncoordinated and poorly designed initiatives.

Finding economically viable opportunities for sector integration based on best practices in R&D cooperation and commercial projects will be imperative to the development of a Romanian hydrogen industry. From the outstart, there ought to be a solid business case for the hydrogen value chains that are set to expand once funding opportunities become available and technology costs decrease. A national hydrogen strategy should be developed based on the active involvement of public and private stakeholders, with targets and potential funding sources.

Hydrogen in the Romanian National Recovery and Resilience Plan

In the successive NRRP drafts, various types of investments in hydrogen were considered, in particular two projects based on CCGTs ready to use renewable hydrogen and equipped with CCS. However, the final version revealed a widely reconsidered approach to hydrogen, emphasising its likely role in the energy and transport sectors.

The NRRP's energy component addresses the challenges of the Romanian energy sector in terms of decarbonisation and air pollution, aiming *to accelerate the decarbonisation of the energy sector by phasing-out lignite and coal fired-power plants by 2032 and by facilitating the deployment of renewables and alternative energy sources, such as green hydrogen.* Reform 4 (*Developing a favourable legislative and regulatory framework for future technologies, in particular hydrogen and storage solutions*) aims to create the needed legislative and regulatory framework and to remove any administrative obstacles to developing renewable hydrogen, with focus on transport, as well as the gas and electricity sectors.

As part of this reform, Romania will develop a National Hydrogen Strategy and a Strategy Action Plan that will define a set of policies to guide, coordinate and mobilise public and private investment in the areas of production, storage, transport, and use of hydrogen. The deadline is 31 March 2023. The reform also states as mandatory the use of hydrogen-ready appliances and equipment by end-users by 1 January 2026, thought what is meant by this needs to be further clarified. Investment 2 – *Distribution infrastructure of renewable gases (using natural gas in combination with green hydrogen as a transitional measure) as well as green hydrogen production capacities and/or its use for electricity storage* – is meant to contribute to the deployment of green hydrogen in line with the EU Strategy for hydrogen. It has two sub-investments:

- Building at least 1,870 km of network for the distribution of green hydrogen in the Oltenia region that shall carry at least 20 % of renewable hydrogen (by volume) when commissioned by 30 June 2026, and 100% renewable hydrogen and/or other renewable gases in 2030.
- Installing green hydrogen production capacities of at least 100 MW in electrolysers, producing at least 10,000 tonnes of hydrogen from renewable sources by 31 December 2025.

On the Sustainable Transport side, 12 H-EMU (Hydrogen Electric Multiple Units) are expected to become operational by Q2 2026. Hydrogen is not included in any industry related reforms or investments.

2. Hydrogen basics: production, transport, and use

Hydrogen is an energy carrier. Given its molecular structure, it has the capacity to convert, store, and release energy. It can be stored, moved, and utilised in different ways, and above all be produced in a variety of ways. Indeed, hydrogen can be produced from fossil fuels and renewables alike, with the latter having a significant potential to decarbonise hard-to-abate sectors such as industry and long-distance transport. Hydrogen may also serve as an energy storage vector. It is thus important to first establish what the likely sources of demand for hydrogen will be.

2.1 Demand for hydrogen in end-use sectors

As a guiding principle in the pathway to climate neutrality by 2050, direct electrification should be prioritised along with energy efficiency. This is also established in the European Commission's Energy System Integration Strategy (EC 2020a), given the conversion losses that occur each time an energy vector is converted. Such an approach is compatible with the 'energy efficiency first' principle. However, in hard to abate sectors, where alternatives are either not technically possible or too costly, hydrogen could offer solutions for various processes in industry, transport, and heating, with potential use in the energy sector as well. (Aurora 2021, Agora 2021)

Industry

Certain industrial applications cannot be decarbonised through direct electrification. The demand for clean hydrogen will be driven by the need to decarbonise the feedstock in the steel industry and petrochemical applications, as well as replacing fossil fuels for producing high temperature heat. It is estimated that 70-95% of these hard to abate industrial sectors can be decarbonized using hydrogen by 2050, providing the highest value for renewable hydrogen in the future. The most promising uses for clean hydrogen in the industrial sector are likely to be the following:

- Feedstock in the production of high value chemicals, ammonia, and in certain refinery processes
- Steel production: reaction agent in direct reduced iron (DRI)
- High temperature heat

In Romania, the most suitable applications for medium-term use are ammonia production at the Azomureș fertilisers plant, production of high value chemicals at Chimcomplex, and use in refineries (OMV Petrom, Petromidia, Lukoil). In addition, the Liberty Steel plant in Galați has already announced a plan to produce green steel using renewable hydrogen. (Liberty Steel 2021)

Transport

Batteries offer a pathway to the electrification of certain transport modes. Their energy density, though, poses a significant challenge especially for freight transportation. While most road transport and even short distance aviation may be decarbonised through direct electrification, long-haul aviation, maritime shipping, HDVs and some railway segments (where direct electrification makes no technical or economic sense) can be decarbonised either directly with hydrogen, or through ammonia and other hydrogen-derived synthetic fuels.

In Romania, transport is the only sector with rising GHG emissions. The shipping sector is a key candidate for rapid uptake of hydrogen in transport, with the Danube being an important transport corridor, while the port the Port of Constanța is a potential hydrogen hub. In addition, Romania also hosts important long-distance freight corridors that require decarbonisation solutions. Use of hydrogen and other RFNBOs in long-haul aviation is expected to increase, with the ReFuelEU Aviation already setting SAF targets for 2030. According to the NRRP, Romanian authorities also plan to use hydrogen in rail transport on some existing lines, and possibly in the future on new lines where electrification makes no economic or environmental sense.

Heating of buildings

Although not expected to provide considerable growth opportunities for hydrogen by the end of the decade, the heating sector, particularly the existing district heating systems, represents another potential application. Hydrogen is a viable solution for decarbonisation especially in countries of Eastern Europe, with cold winters and numerous cities with old large-scale district heating systems, in cases where a massive deployment of heat pumps – a generally more efficient solution – is not technically feasible.

Power sector

The expansion of variable renewable energy sources significantly increases the need for adding flexibility to the energy systems. Battery storage systems are currently regarded as the go-to solution to flexibility issues, but their use is generally limited to short-term storage. Transforming electricity into hydrogen opens the way for long-term energy storage solutions for the entire energy system, yet to avoid significant efficiency loss from multiple conversions, alternatives to re-electrifications should also be considered. Meanwhile, other uses, such as gas blending or renewable hydrogen use in CCGTs are a waste of economic value, given the comparatively high costs of producing hydrogen.

Romania’s renewable energy outlook for 2030 and beyond rests on significant investors’ interest in both onshore and offshore capacities that can well make a case for long-term or seasonal energy storage. The national availability of underground storage solutions such as salt caverns makes this option worthwhile exploring.

2.2 Hydrogen production

IEA (2021) and IRENA (2021) along with other actors in the energy sector classify hydrogen through a color-coding scheme, based on the source fuel used to produce the hydrogen. An overview of the various shades of hydrogen is summarized in Table 1.[5]

Fossil-fuel based hydrogen

Grey, blue, and turquoise colour codes refer to hydrogen that comes from fossil fuels, while green hydrogen is derived from power generated by renewable energy sources or biomass. Pink and yellow hydrogen involve hydrogen production based on grid power, with pink referring to the use of nuclear power, and yellow indicating the use of various other sources.

Grey hydrogen generally refers to hydrogen obtained using coal, lignite, natural gas, or even oil. The most widely used methods are steam methane reforming and partial oxidation. In steam methane reforming (SMR), high-temperature steam (700-1000°C) is used to produce hydrogen from methane sources, typically natural gas. Methane reacts with the high-temperature steam under high pressure (3-25 bar), which in the presence of a catalyst results in hydrogen, carbon monoxide, and a small amount of CO_2 (DOE 2021). Additional water is added to the mixture, converting carbon monoxide into CO_2, producing more hydrogen as a result. The hydrogen is subsequently isolated through pressure swing adsorption (PSA), serving as a molecular sieve of sorts (Assemblée Nationale 2021). Though less common, partial oxidation can also be used to produce grey hydrogen. In a process similar to pyrolysis and combustion, the methane reacts with small amounts of oxygen, creating a syngas that chiefly contains hydrogen and carbon monoxide, as well as a small amount of CO_2. Analogous to SMR, the carbon monoxide reacts with water to form carbon monoxide and more hydrogen, in a water-gas shift reaction.

Blue hydrogen uses the same production methods as grey hydrogen, i.e., SMR and partial oxidation, in a facility equipped with CCS technology, capturing and storing the CO_2 emitted in the production process. Autothermal methane reforming (ATR), which uses oxygen and either CO_2 or steam in reaction with methane to form syngas, could be more suitable for future use with CCS, given its more concentrated CO_2 stream.

Turquoise hydrogen, also requiring natural gas as a source fuel, is produced by breaking down gas through methane pyrolysis, i.e., thermal decomposition at high temperatures in an inert atmosphere. Specifically, in methane pyrolysis the methane is split into hydrogen and solid carbon.

[5]Although less commonly used, there are other colour codes for hydrogen in use today. Black and brown are often used to refer to the production of hydrogen from coal and lignite respectively. White hydrogen infers that the hydrogen is a by-product of industrial processes.

Electricity-based hydrogen

Green hydrogen, called clean hydrogen in European Commission documents, is the term that applies to the production of hydrogen from water electrolysis using electricity generated from renewable energy sources (mostly solar and wind). Electrolysers induce an electromechanical reaction, splitting water into its two components, hydrogen and oxygen, without emitting any CO_2 in the process.

Analogous to green hydrogen, **pink hydrogen**[6] is also produced through electrolysis, but based on nuclear power. The nuclear reactors' high temperatures may be used in other hydrogen production techniques by producing steam for a more efficient electrolysis or SMR.

Yellow hydrogen refers to hydrogen in which the electrolysis is powered using grid electricity. Grid electricity is typically of mixed origin, composed of power coming from both fossil fuels and renewables, with the emissions level tied to the carbon intensity of the mix in the respective grid.

Green hydrogen can be produced in two distinct manners. On the one hand, electricity generated by renewables can power the electrolysis process. Concretely, wind, solar, or hydro sources generate carbon-free electricity that powers an electrolyser, which involves breaking the water molecules into dihydrogen and oxygen by means of electric currents in the electrolyser. The process starts by pumping clean water into the electrolyser, which enables the split of hydrogen and oxygen using an electric charge. Oxygen is subsequently released into the atmosphere or else utilised, separating and thus producing hydrogen.

At the moment, there are two main electrolysis technologies considered for large scale use: alkaline and Proton Exchange Membrane (PEM). Historically, alkaline electrolysers were developed first, starting in the 1920s. They are now the most mature technology in this field, ready to be deployed at almost any scale (limited by the number of stacked electrolysers) and setting the benchmark in terms of commercial availability and maturity. PEM electrolysers were first used in the 1960s and came with certain advantages: improved energy efficiency, in some cases higher production rates, better safety, everything packed in a more compact design. Improvements are also expected in terms of commercial maturity, system size and capital investment costs.

On the other hand, green hydrogen can be produced through another technique called pyro-gasification, which involves heating organic matter (i.e., different types of biomass) and various other types of carbon-containing waste (e.g., wastewater, non-recyclable plastic) to high temperatures of between 900-1200°C, in the presence of a limited quantity of oxygen. This method results in the extraction of a complex gas, which contains hydrogen molecules (Engie 2021). Nevertheless, this technique is still quite nascent, making electrolysis the economically and technically more viable option.

[6] Pink hydrogen is also referred to as purple or red hydrogen.

The European Commission's hydrogen classification

With the goal of homogenizing the terminology within the EU, the European Commission presented its own "hydrogen taxonomy" covering production pathways, greenhouse gas (GHG) emissions, and relative competitiveness. The Commission identifies the following types of hydrogen, as shown in Table 1.

Table 1 European Commission's hydrogen production pathways

Electricity-based hydrogen	Produced through the electrolysis of water (in an electrolyser powered by electricity), regardless of the electricity source. The life-cycle GHG emissions of electricity-based hydrogen production depend on how the electricity is produced.
Renewable hydrogen	Produced through the electrolysis of water with the electricity stemming from renewable sources. The life-cycle GHG emissions of renewable hydrogen production are close to zero. Renewable hydrogen may also be produced through the reforming of biogas instead of natural gas, or biochemical conversion of sustainable biomass.
Clean hydrogen	Refers to renewable hydrogen
Fossil-based hydrogen	Produced through a variety of processes using fossil fuels as feedstock, mainly SMR or coal gasification. This represents the bulk of hydrogen produced today. The life-cycle GHG emissions of fossil-based hydrogen production are high.
Fossil-based hydrogen with carbon capture	A subpart of fossil fuel-based hydrogen, but where GHG emitted in hydrogen production are captured. The GHG emissions of fossil-based hydrogen production with carbon capture or pyrolysis are lower than fossil-fuel based hydrogen, but the variable effectiveness of GHG capture (up to 90%) needs to be considered.
Low-carbon hydrogen	Encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle GHG emissions compared to existing hydrogen production.
Hydrogen-derived synthetic fuels	A variety of gaseous and liquid fuels based on hydrogen and carbon. For synthetic fuels to be considered renewable, the hydrogen part of the syngas must be renewable. Synthetic fuels include for instance synthetic kerosene in aviation, synthetic diesel for cars, and various molecules used in the production of chemicals and fertilisers. Synthetic fuels can be associated with very different levels of GHG emissions, depending on the feedstock and process used. In terms of air pollution, burning synthetic fuels produces similar levels of air pollutant emissions as fossil fuels.

It is likely that Romania will accelerate the development of the hydrogen sector with the mounting pressures to meet the 2030 and 2050 decarbonisation targets. Therefore, even if only small projects are expected to be developed and implemented in the following years, the strategic planning for large scale deployment should envisage larger time horizons. Based on current hydrogen production costs, there is still an investment window for hydrogen based on fossil fuels. However, this will be short-lived as climate policies, financing options and investment opportunities will solidify the business case for green hydrogen by the end of the decade. Indeed, both Agora (2021) and BNEF (2021) indicate that by 2030 green hydrogen in markets with above-average renewable energy potential, such as Romania, will be cheaper than blue hydrogen – the only alternative when factoring in climate concerns. Fossil fuel-based assets will have a narrow economic lifetime and require early replacement, ultimately exposing the sector to a lock-in risk.

2.3 Assessing the suitability and potential of different types of hydrogen

To determine the suitability of each type of hydrogen and its potential contribute to decarbonisation, the following three key elements should be observed: carbon intensity, pricing, and availability.

Carbon intensity

The lifecycle emissions of hydrogen production presented in Figure 1 point to the fact that hydrogen produced through electrolysis, supplied by green hydrogen has, by far, the lowest emissions compared to other options:

- Grey hydrogen: 13.2-15.8 $kgCO_2eq/kgH_2$
- Blue hydrogen: 4.1-6.9 $kgCO_2eq/kgH_2$
- Green hydrogen: 0.6 $kgCO_2eq/kgH_2$

Although green hydrogen generates the lowest level of carbon emissions, one should bear in mind that the carbon intensity of electrolytic hydrogen, which includes pink and yellow hydrogen, can vary greatly depending on the source of the electricity used. A country that has a high carbon intensity of its power mix, such as Romania, still has to account for significant carbon emissions in grid-powered electrolysis. Only when electrolysis relies entirely on renewable power can it really contribute to a decarbonized hydrogen economy. For green hydrogen produced from biomass, it is difficult to determine the sustainability of the used biomass (e.g., wood, agricultural waste, wastewater, etc). Green hydrogen from biomass even has the potential to be carbon negative if the biochar produced is returned to the soil (Assemblée Nationale 2021). Moreover, green hydrogen, or an electricity mix with a high-enough share of decarbonised electricity, are the only production pathways compliant with the EU Taxonomy for Sustainable Finance that sets the benchmark at 100 $gCO_2eq/kWh\ H_2$. Like electrolytic hydrogen, turquoise hydrogen's carbon intensity depends on the origin of the electricity used for pyrolysis.

Although deemed a solution for building up the hydrogen market, blue hydrogen has recently come under scrutiny for its GHG emissions when considering its full life cycle. A recent study from Cornell University (2021) indicates that blue hydrogen emissions are 20% higher than burning natural gas or coal for heat, leading to the conclusion that its use is difficult to justify when aiming for reduced emissions. Such estimations, however, vary greatly based on the fugitive emissions of the respective methane supply chain. In any event, methane emissions have a significant impact (86 gCO_2eq/gCH_4 over 20 years) and must be accounted for when assessing the climate implications and the economic opportunity to develop blue hydrogen.

With emissions as low as 0.6 tCO_2eq/tH2, renewable hydrogen is compliant with the threshold set by the taxonomy, which also leaves headroom for electrolytic hydrogen produced from a renewable-intensive grid mix. The same applies for nuclear hydrogen, which is comparable with renewable hydrogen in terms of lifecycle GHG emissions.

The 3 tCO_2eq/tH_2 threshold set by the taxonomy leaves out grey hydrogen, which comes with emissions between 13.2 and 15.8 tCO_2eq/tH_2. With life-cycle emissions ranging between 4.1 and 6.9 tCO_2eq/tH_2, blue hydrogen would have met the TEG recommendation, but clearly does not qualify as sustainable under the Taxonomy.

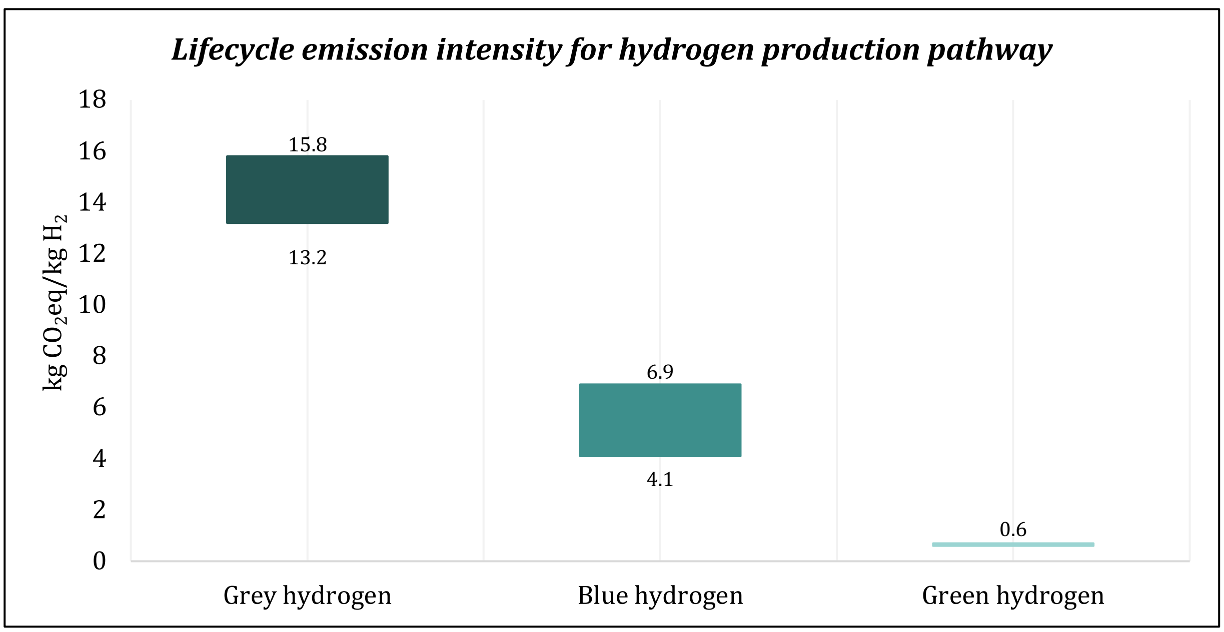


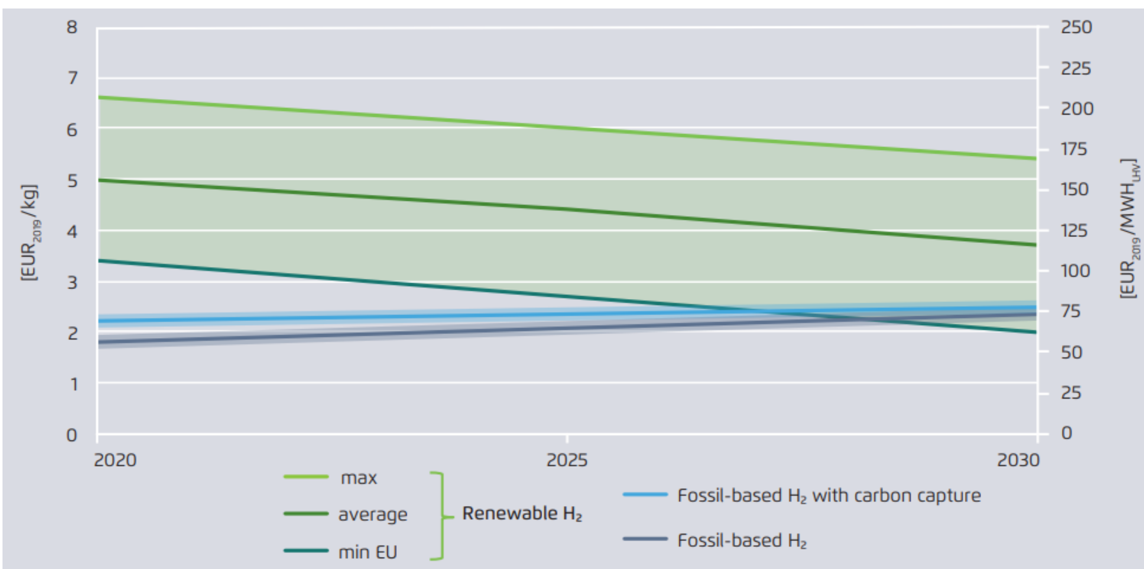
Figure 1 Lifecycle emission intensity for hydrogen production pathways (Source: Agora 2021, Energy Policy Group)

Cost

As of today,[7] there still is a significant cost gap between each type of hydrogen, as shown in Figure 2. At a cost of €1.4/kgH_2, or €1.8/ kgH_2 including the cost of carbon of about €50/ton,[8] grey hydrogen is still the most competitive type of hydrogen. Blue hydrogen has a similar cost structure to grey hydrogen, though somewhat more expensive, factoring in the price of CCUS technology. Currently, the cost of blue hydrogen amounts to about €2.1/ kgH_2, or € 2.2/ kgH_2 when a CO_2 cost of €50/ton is included (Agora 2021).

The cost of grey hydrogen mainly depends on the price of the fossil fuel used in the SMR process. As the lion's share of grey hydrogen relies on a steady supply of natural gas, the price of grey hydrogen mainly depends on the gas price. As price levels of natural gas have started to rise significantly, the costs of grey and blue hydrogen are likely to move closer towards the lower range of green hydrogen's cost. Furthermore, being a more mature type of hydrogen, grey hydrogen also has the benefit of scale, while existing facilities can be retrofitted with CCUS.

Comparatively, green hydrogen has a more wide-ranging cost, as it depends on variable renewable sources. Estimates point to a cost of RES hydrogen between €3.4/ kgH_2 and €6.6/ kgH_2, resulting in a cost gap of approximately €3/ kgH_2 between grey and green hydrogen.



Guidehouse based on BNEF (2021), Prognos et al. (2020), Hydrogen Europe (2020), Gas for Climate (2020), Agora Energiewende and AFRY Management Consulting (2021)

The price range for fossil-based H_2 reflects an implicit carbon price of €50/tCO_2 in 2020 increasing to €100/tCO_2 in 2030. For natural gas, a price of €20/MWh is assumed. The capture rate for fossil-based H_2 with carbon capture is assumed to be around 75%.

Figure 2 Production cost of clean hydrogen compared to fossil-based hydrogen, with and without carbon capture (Source: Agora 2021)

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[7] Not accounting for the steep increase in gas prices.
[8] At the time of this report's writing, the ETS price has exceeded €70/ton.

Availability

As of today, most of hydrogen globally comes from fossil fuels, making grey hydrogen the prevalent shade. Out of the 90 Mt of hydrogen produced at present, about 79% comes from dedicated fossil fuel-based plants. More specifically, 59% comes from natural gas without CCUS, 19% from coal, and less than 1% from oil. The remaining 21% is hydrogen produced as a by-product. Hydrogen produced from renewables or fossil fuel plants equipped with CCUS account together for less than 1% of total global production (IEA 2021). Specifically for green hydrogen, the availability of renewable capacities is important. Today, the installed capacities are not sufficient for both delivering energy to the grid and powering the electrolysers but given the planned RES expansion in Europe and the cost reductions, the EC intends to address this through the principle of additionality.

Blue hydrogen has raised interest in Romania, as the country is the second in the EU, after the Netherlands, in terms of natural gas reserves and production, with an annual production of 8.5 Mtoe (BP 2020). Blue hydrogen could feed the industries that require a steady flow of hydrogen. Nevertheless, it is important to bear in mind that blue hydrogen has financial and environmental drawbacks, such as increased costs for CO_2 transport and storage, and the fact that CCS capture rates reach 85-90% at best (IRENA 2020).

Turquoise hydrogen, relying on the nascent and still to be proven technology of pyrolysis, combines the use of natural gas as a feedstock without the production of CO_2 as a by-product. Pyrolysis renders the carbon from the methane into solid carbon black, for which a market already exists, potentially providing additional revenue streams for stakeholders looking to develop turquoise hydrogen in Romania (Monolith 2020)

Table 2 Types of hydrogen based on colour code (Source: Energy Policy Group)

Shade	Grey (blue if CCS)	Turquoise	Green	Pink/yellow
Source	Fossil fuels (mostly natural gas)	Natural gas	• RES + water • Organic matter	Grid electricity (Pink if electricity is from nuclear power)
Technology	• SMR • Partial oxidation	• Pyrolysis	• Electrolysis • Thermolysis	Electrolysis
Status	Mature	Nascent	Mature	Mature
Carbon intensity (kg CO2eq/kg H2)	• Grey: 13.2-15.8 • Blue: 4.1-6.9	• Depends on the power source • Can range from negative to 4 (Assemblée Nationale 2021)	• Electrolysis: 0.6 • Thermolysis: low, zero, or negative	Depends on the source of electricity used in the mix

Cost in 2021 (€/kg H2)	• Grey: 1.4 • Blue: 2.1 With carbon cost: • Grey: 1.8 • Blue: 2.2 (Not accounting for the current gas prices)	1.6[9]	3.3-6.6 (electrolysis)	4.6[10]

Based on all the above considerations, green hydrogen is the most promising for delivering the goals of decarbonisation on the long term. Pink hydrogen also promises near-zero GHG emissions, but factoring in the cost element, green hydrogen is on a clear path of cost reductions that will render it competitive with fossil-based hydrogen. This is because pink hydrogen is heavily dependent on the cost of nuclear energy, about €140/MWh for new capacities. Therefore, clean hydrogen should be the main pathway for the Romanian national hydrogen strategy.

2.4 The economics of clean hydrogen production

By 2030, it is estimated that electrolyser CAPEX will reach €100-375/kW (BNEF 2021). To put this in perspective, in 2021 the electrolyser CAPEX was estimated at between €175/kW (alkaline) and €1,060/kW (PEM). Cost reduction expectations are not the same for all electrolysis technologies. Alkaline and PEM electrolysers are the most technologically mature and commercially available. Alkaline electrolysers have the lowest installation costs, while PEM electrolysers have an advantage in flexibility, physical footprint, and output pressure, which may eliminate the need for a compressor or significantly reduce the additional energy input required for the compression stage, given that hydrogen storage or transport generally require high pressure.

IRENA (2021) estimates that the current cost differences between the two electrolyser technologies in terms of cost and performance are likely to narrow in time as innovation and widespread deployment of various types of technologies will boost convergence towards similar cost structures – which is also confirmed by BNEF (2021). However, it is worth mentioning that the cheaper alkaline electrolysers expected to be available by 2030 will likely be supplied by Chinese manufacturers, while the European hydrogen value chain will focus more on PEM electrolysers.

The cost of RES energy has been constantly decreasing over the past decade, with solar PV reaching a record low in 2020. In the most favourable locations at global level, involving solid policy support and adequate financing, solar power can be generated at or even under €20/MWh. Regions with high

[9] Data on pyrolysis-based hydrogen production are still scarce.
[10] Calculated for an LCOE of new nuclear capacities of €140/MWh

levels of solar irradiation are expected to enjoy the strongest solar cost reductions, effectively reducing the production cost of hydrogen on account of cheaper electricity.

As more large-scale hydrogen projects are planned, electrolyser utilisation will increase over time. This can be attributed to a more efficient mix of renewables and integrated design optimisation. Generally, the higher the load factor for the electrolyser, the lower the hydrogen production costs.

Beyond on these three key elements, the higher CO_2 costs and the elimination of free allocation could allow clean hydrogen to breakeven with fossil alternatives between 2028 and 2032 based on local renewable potential. Of course, this projection will depend on the dynamics of CO_2 certificates commercialised through the EU Emissions Trading System. Clean hydrogen is expected to undergo comparable learning curves to those witnessed for renewable sources such as solar and wind energy, for which, over time, costs have dropped to the point that in some European countries, bids are below the wholesale electricity prices (IRENA 2019).

2.5 Hydrogen transport and storage

A key advantage for using hydrogen as a solution for decarbonisation is its transport and storage versatility. It can be stored in large quantities for long periods of time in salt caverns and other forms of underground storage. This flexibility can allow the partial decoupling of energy production and consumption, thus bringing system-level benefits.

Hydrogen can be transported in various ways and over long distances with limited losses, which enables cross-border trade. This can be achieved either through reconversion of existing gas infrastructure or through new dedicated pipelines, as well as ships. Besides, hydrogen can be transported through other established alternative carriers, such as ammonia, methanol, and liquid organic hydrogen carrier (LOHC). In Romania, transport and storage infrastructure is still incipient. Reliance on the existing gas infrastructure is not sufficient. Large capital-intensive investments would need to be deployed for new dedicated hydrogen infrastructure as well.

Hydrogen will require significant developments in terms of transport infrastructure to attain the level of penetration in the energy mix that governments aim for in their quest for decarbonisation. Delivering hydrogen demands an extensive and complex infrastructure and poses challenges due to potential hydrogen embrittlement of steel pipelines and welds, permeation and leaks, as well as the high costs of the available compression options (DOE 2021b). To transport hydrogen from production facility to consumption centre, such as heavy industry, power generators, or fuel stations, a network of pipelines, storage facilities, liquefaction plants, compressors and dispensers is needed.

Transport and packing methods

As hydrogen is a versatile energy vector, it has the potential to be shipped and delivered in different forms, which are also referred to as *packing mode*.[11] Currently, three main packing modes exist for hydrogen.

1. Hydrogen can be delivered in the form of a *highly compressed gas*, generally using positive displacement compressors or centrifugal compressors, to up the pressure of the hydrogen molecules.
2. Hydrogen can be *liquefied* in for transport over long distances. This is achieved by cooling the hydrogen molecules to below −253°C, a process analogous to natural gas liquefaction.
3. Transporting hydrogen can be done by means of *different chemical carriers*, such as ammonia, methanol, and liquid organic hydrogen carriers (LOHC).

Hydrogen packing takes place in compression or liquefaction facilities or in chemical reactors, as in the case of LOHC hydrogenation and ammonia synthesis. The packaged form is then transported to its destination, after which it will be unpacked. The unpacking process consists of extracting and/or processing hydrogen using compressors, pumps, evaporators, dehydrogenation reactors (in the case of LOHC) or ammonia cracking plants. Purification systems and pressure meters are also of particular importance so as to deliver the hydrogen in a state that allows it to meet the purity and pressure requirements of the end-user.

Nonetheless, there are significant conversion losses related to the requires compression of hydrogen – up to 13% of the total energy content of hydrogen; the percentage reaches 40% for liquified hydrogen (Bossel 2004). At present, liquid hydrogen, liquid organic hydrogen carriers (LOHC) and ammonia are the carbon-neutral solutions that enjoy the most traction.

Modes of transport

There is no universal transport solution for hydrogen. The right mode of transport will depend on distance, terrain, and end-use. In general, there are three modes of hydrogen transport: pipelines, trucks, and ships. For shorter- and medium-range distances, retrofitted pipelines are the most viable option, as they allow for low transportation costs. For longer distances, new and retrofitted (subsea) transmission pipelines provide cheaper at-scale transport than shipping. In case of lack of pipeline infrastructure, hydrogen can be transported overland using trucks or by sea using special-purpose ships equipped with hydrogen storage tanks.

Pipelines are widely considered to be the main pathway for hydrogen transport. As such, three ways can be pursued to deliver hydrogen to the end-user:

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[11] Hydrogen packing refers to the form in which hydrogen is being transported or delivered. It can refer to the liquefaction, compression, or conversion to a chemical carrier.

1. Hydrogen can be injected and blended, along with natural gas into the gas grid. From a technical viewpoint, blending compressed gaseous hydrogen into existing natural gas pipelines is feasible up to a concentration of 15% at best. Nevertheless, the maximum possible concentration of hydrogen in natural gas pipelines is heavily affected by pressure fluctuations, structure, and existing defects, which lower the possible level of blending.

   Current assumptions point to a blending percentage of 2-10%, if certain adaptions are made. This is crucial, as hydrogen's energy density is about a third of that of that of natural gas, which means that when blended, the energy content of gas would incur a significant reduction. As such, a 3% hydrogen blend in natural gas pipelines could potentially reduce the energy delivery of the pipeline by about 2% (Haeseldonckx 2007).

   The volume of hydrogen that would be blended in the gas grid would be variable, following the nature of its production, meaning that the hydrogen concentration would vary in time, adversely impacting the grid. Natural gas pipelines and equipment are usually made so that they only allow a limited range of gas mixtures (Abbot 2012). Moreover, end-users may not be able to accommodate much or any hydrogen content. A feasibility study would be needed about how the blending of hydrogen would affect the natural gas grid of Romania (AEI 2021), though its scope will likely be very limited. Blending a higher value molecule such as hydrogen with methane would only make it lose value and raise costs for end consumers, with limited climate benefits.

2. Retrofitting existing natural gas pipelines to noncorrosive and nonpermeable pipelines,[12] and developing a dedicated hydrogen network with a conversion of existing gas infrastructure combined with new hydrogen-only infrastructure. Retrofitting would entail both an upgrade of existing gas transport infrastructure that would allow the injection of certain amounts of hydrogen into the grid, as well as repurposing gas pipelines for hydrogen transport.

   In Romania, retrofitting may be considered the economically more sensible option, as there are over 13,000 km of natural gas pipelines in Romania. Retrofitting would allow hydrogen to be shipped to all major urban centres in the country, as well as the port of Constanța, over already existing routes.

3. Producing synthetic methane through methanation, that is converting captured CO_2 into methane through hydrogenation. The synthetic methane thus produced would then be injected into the natural gas grid.

For long-haul transport, maritime transport may also be a viable option. Nevertheless, the specific size and type of fleet would depend on the packaging modes, which are themselves in different stages of technological viability. Liquefied hydrogen needs to be transported in large carriers, similar to the liquefied natural gas (LNG) carriers, while compressed hydrogen will be delivered in tanker ships similar to those transporting compressed natural gas (CNG). LOHC can be transported in conventional oil tankers, and ammonia can be transported in refrigerated chemical tankers.

[12] Materials including polyethylene, fiber-reinforced polymer pipelines

Currently, though, hydrogen is generally transported by means of pipelines or overland using cryogenic liquid tanker trucks or gaseous tube trailers.

Costs

Transport costs of hydrogen depend on both the form in which the hydrogen is transported, as well as the mode of transport. To assess the cost of hydrogen delivery, four key elements must be pondered:

- The amount of hydrogen transported
- The distance between supplier and consumer
- The modes of transport
- The packing method.

For short and medium ranges, when using retrofitted pipelines, transportation costs can go as low as €0.09/kg up to 500 km. However, such low costs are only possible for existing pipelines and, if suitable, for retrofitting. When it comes to lower or fluctuating demand, or when it is necessary to develop a full pipeline system, trucking hydrogen, gaseous or liquefied, tends to be the most attractive option, reaching costs of around €1.05/kg per 300 km.

In terms of long-distance transmission costs, the IEA (2019) estimates that it would cost about €0.9/kg H_2 to transport gaseous hydrogen for a distance of 1,500 km. Much like natural gas, the cost of transporting hydrogen by pipeline increases for longer distances. Maritime shipping is the long-distance option when pipelines are not available.

Upon arrival to the demand location, hydrogen enters the local distribution system. Like international transport, the cost and efficiency of local distribution depends on whether hydrogen is transported in pure form or as an energy carrier such as ammonia or LOHCs. Furthermore, the price depends on volume, distance, as well as the final user's requirements.

A study from Hydrogen Council (2021) indicates that by 2030, the cost of dispensed hydrogen generally doubles the cost of hydrogen production, factoring the costs of preparing the hydrogen for transport (compression, liquefaction, or storage), distribution, and fuel station. Therefore, it is generally preferable for electrolytic hydrogen to have transport of electricity than of molecules, meaning that the electrolyser should be located close to the point of demand.

Hydrogen storage

The low volumetric density of hydrogen makes storage challenging. Since hydrogen is the lightest element in the periodic table, it requires large volumes to store a limited amount of energy value. For example, at atmospheric pressure, for one kilogram of hydrogen, a storage volume of about $11m^3$ is needed. (Air Liquide 2021)

Hydrogen can be stored in three states: gaseous, liquid, and solid. Until now, hydrogen has generally been stored in gaseous or liquid form for small-scale or local use. Most production currently happens on-site where consumed, usually in refineries, ammonia plants, methanol, and hydrogen peroxide production plants. This type of consumption accounts for about two thirds of hydrogen production (FCH-JU 2020). Larger-scale use, however, will require storage in larger quantities and for longer periods of time.

Romania will require both short-term (hours or days) and long-term (weeks or months) storage options. Short-term storage is a prerequisite for trade. Ports require flexible short-term storage capacity to facilitate the storage of hydrogen and hydrogen carriers when loading and unloading transport vessels. In the transport sector, short-term hydrogen storage is also crucial for vehicle refuelling stations. Long-term supply solutions help to decouple supply and demand and avoid mismatches between the two. Longer-term storage solutions may contribute to overcoming large and abrupt power supply changes related to seasonal weather variations (Hydrogen Council 2017). Storage options include:

- **High pressure storage in gaseous form.** Much like natural gas, hydrogen has a molecular structure that allows it to be compressed and stored in tanks. Nevertheless, hydrogen's volume is significantly larger than that of hydrocarbons, requiring a significant compression for practical handling purposes. Hydrogen is kept under high pressure to maintain the high storage density.
- **Very low temperature in liquid form.** Similar to natural gas, the process of liquefaction for hydrogen occurs by reducing its temperature to -253 °C, which is an extremely low temperature, while LNG which is stored at -162 °C. From a technical point of view, storing liquefied hydrogen is a complex and expensive matter, hence being less used.
- **Geological storage** mainly consists of salt caverns, depleted oil or gas reservoirs and aquifers, especially suitable for large-scale and long-term hydrogen storage (HyUnder 2014). Such storage is already used for natural gas and could provide a wide range of advantages, including economies of scale, high efficiency, low operational costs and low costs of land (IEA 2019). Given hydrogen's low energy density, natural geological storage is likely to be one of the cheapest storage solutions. This type of storage is advantageous in the long run to guarantee, for example, a backup supply. Romania's geological storage potential in salt caverns has been evaluated by the HyUnder project, which identified three clusters where this can be used for hydrogen storage.

3. Modelling results for a renewable hydrogen by 2030 pathway for Romania

Understanding the scale of hydrogen deployment required for reaching the 2030 targets is crucial for designing the national hydrogen strategy. This chapter presents the results of a modelling exercise based on two scenarios for the uptake of renewable hydrogen in Romania by 2030 in terms of hydrogen demand, electrolysis and RES capacities, as well as hydrogen cost estimations.

The current hydrogen demand in Romania comes almost entirely from the industrial sector – ammonia, refineries, chemicals, with the largest demand in the steel and glass sectors. FCH-JU (2021) estimated the total yearly hydrogen demand in Romania to be 184,506 tons, based on market research, consultation with industry and discussions with stakeholders. While such a methodology cannot ensure a perfect level of accuracy, the figure reveals the order of magnitude Romanian authorities should consider.

Table 3 Current hydrogen demand in Romania (Source: FCH-JU 2021)

Transport	**Ammonia**	**Refinery**	**Methanol**	**H_2O_2**	**Other chemicals**	**Energy**	**Other**	**Total (tH_2/year)**
0	92,765	55,821	30,926	3	0	4,808	183	**184,506**

As mentioned in the previous chapter, the main applications of renewable hydrogen by 2030 will be in industry and transport. Based on the current policy debates, two hydrogen demand scenarios were analysed in this study for 2030:

- **Scenario I, *Fit for 55***: 50% of current hydrogen demand in the industrial sector and 2.6% of total energy demand from the transport sector, amounting to a total of 154,950 tH_2/year.
- **Scenario II, *Full clean hydrogen***: 100% of current hydrogen demand in the industrial sector and 2.6% of total energy demand from the transport sector, for a total of 247,203 tH_2/year.

Table 4 Hydrogen demand scenarios in Romania by 2030 (Source: Energy Policy Group)

Scenarios	**Industrial (tH2/year)**	**Transport (tH_2/year)**	**Total (tH_2/year)**
Fit for 55	92,253	62,697	154,950
Full clean hydrogen	184,506	62,697	247,203

The emission reduction potential of switching from fossil to clean hydrogen in the industrial sector alone by 2030 would result in yearly savings of 1.282 Mt CO_2 in the Fit for 55 scenario, and 2,654 Mt CO_2 in the Full clean hydrogen scenario.

The yearly electricity demand for electrolysis in the two scenarios is 7.44 TWh in Scenario I and 11.87 TWh in Scenario II – the equivalent to the yearly output of the existing 3 GW of onshore wind installed in Romania for Scenario I, and significantly more than the yearly output of the 4.5 GW of the existing onshore wind and photovoltaic capacities in high production years for Scenario II.

When factoring in the additionality principle, the required electricity demand for electrolysis will need to come from additional renewable capacities to those already foreseen in the NECP. Based on several studies (Agora 2021, BNEF 2021), producing electrolytic clean hydrogen starts being cost-effective at more than 5,500 full load hours a year. Therefore, it can be estimated that the needed electrolyser capacity is 1,470 MW in the Fit for 55 scenario, and 2,350 MW for Full clean hydrogen. This amounts to 3.7% and 6%, respectively, of the EU electrolyser capacity by 2030 targeted in the European Commission's Hydrogen Strategy (EC 2020b). These capacity estimations require a minimum of 5,500 full load hours to meet the assumptions of hydrogen demand for each scenario. For a lower number of full load hours, Romania would have to either produce fossil fuel-based hydrogen, or import. Alternatively, higher load factors would result in surplus production, ready for export.

Based on these estimations of electrolysis capacity, a Discounted Cash Flow (DCF) model was used to calculate the Levelized Cost of Hydrogen (LCOH) in Romania in 2030. To account for the technological progress and cost reductions expected in the following decade, 2030 projections were used for technical and economic indicators. Based on estimations from BNEF (2021), the 2030 CAPEX used was €100/kW for alkaline electrolysis and €375/kW for PEM electrolysis, along with a fixed OPEX of 2% of CAPEX. The model accounts for the stack replacement, included in the fixed OPEX for alkaline technology, while for PEM it adds a 20% to CAPEX in year 10 of the total 20 years' lifetime. The cost of water[13] is €0.3/m^3. For the rest of the assumptions used in the model, see Annex I.

The model also accounts for the economic value of by-products such as residual heat and oxygen, given that both PEM and alkaline electrolysis output is of very high purity, suitable for a wide range of industrial and medical applications. The model output reflects production costs and does not factor in other costs resulting from transport, conversion/reconversion, and storage. A sensitivity analysis for the two scenarios was done to calculate the LCOH depending on two variable parameters: the price of electricity supplied to the electrolysers, ranging between €25-50/MWh, and the number of full load hours a year.

[13] According to the IEA (2021), electrolysis requires approximately 9 kg of water for every kg of hydrogen while other ways of producing hydrogen require even more (13-18 kg of water for SMR with CCS and between 48-85 kg of water for coal gasification). For significant electrolysis capacities and hydrogen output, the total water consumption needs to be considered. Using desalinised seawater from coastal areas is an alternative that would add up to €0.02/kg H_2.

Results

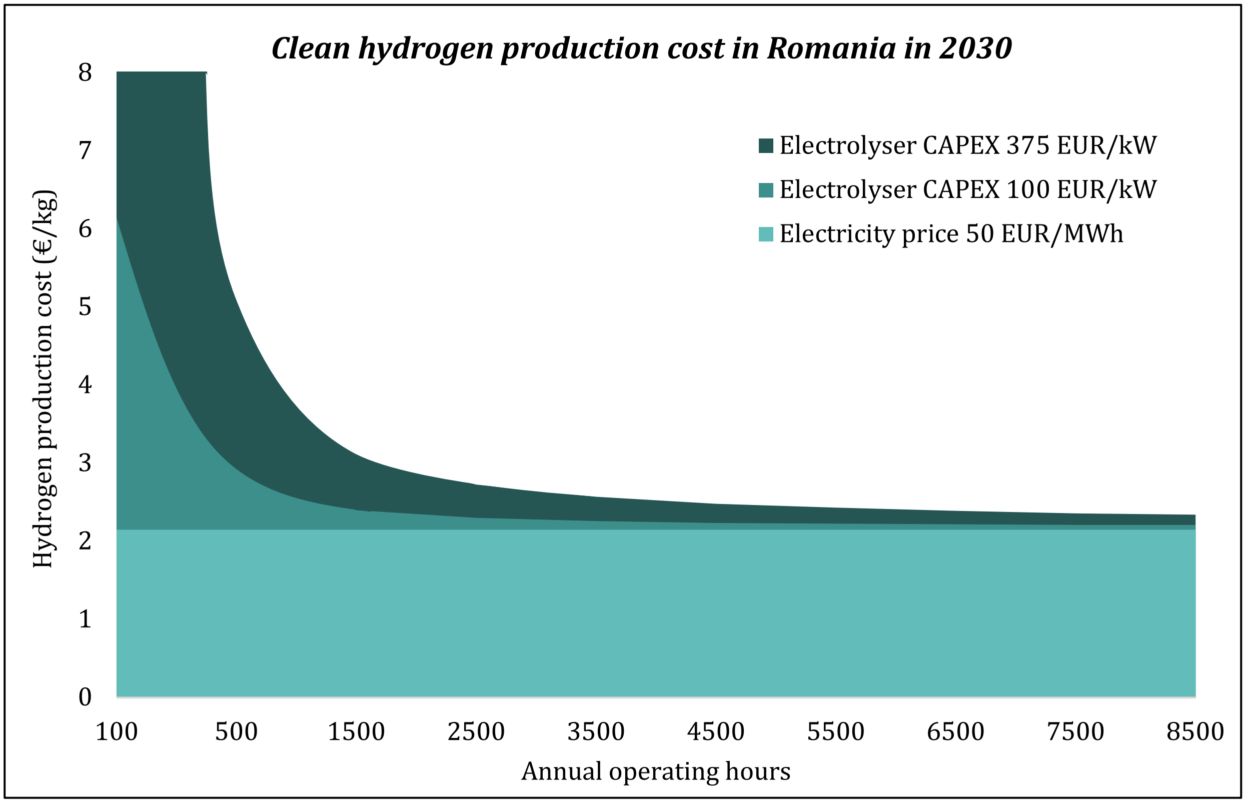

Figure 3 Clean hydrogen production cost in Romania in 2030 depending on electrolyser load factor, for an electricity price of €50/MWh (Source: Energy Policy Group)

The results reveal that for sufficiently large electrolyser capacities and accounting for technology progress in terms of efficiency and costs by 2030, producing clean hydrogen will no longer be a CAPEX intensive business case at more than 1,500 load hours. The price of the renewable energy becomes the main cost component. For an electricity price of €50/MWh, a reasonable if not even conservative prospect for Romania in 2030 given the country's RES potential and expected cost reductions, the resulting LCOH for alkaline electrolysis is between €2.21/kgH_2 and €2.3/kgH_2, while for PEM electrolysis it ranges from €2.34 - 2.73/kgH_2, depending on the number of load hours (from 2,500 to 8,500), as shown by Figure 3.

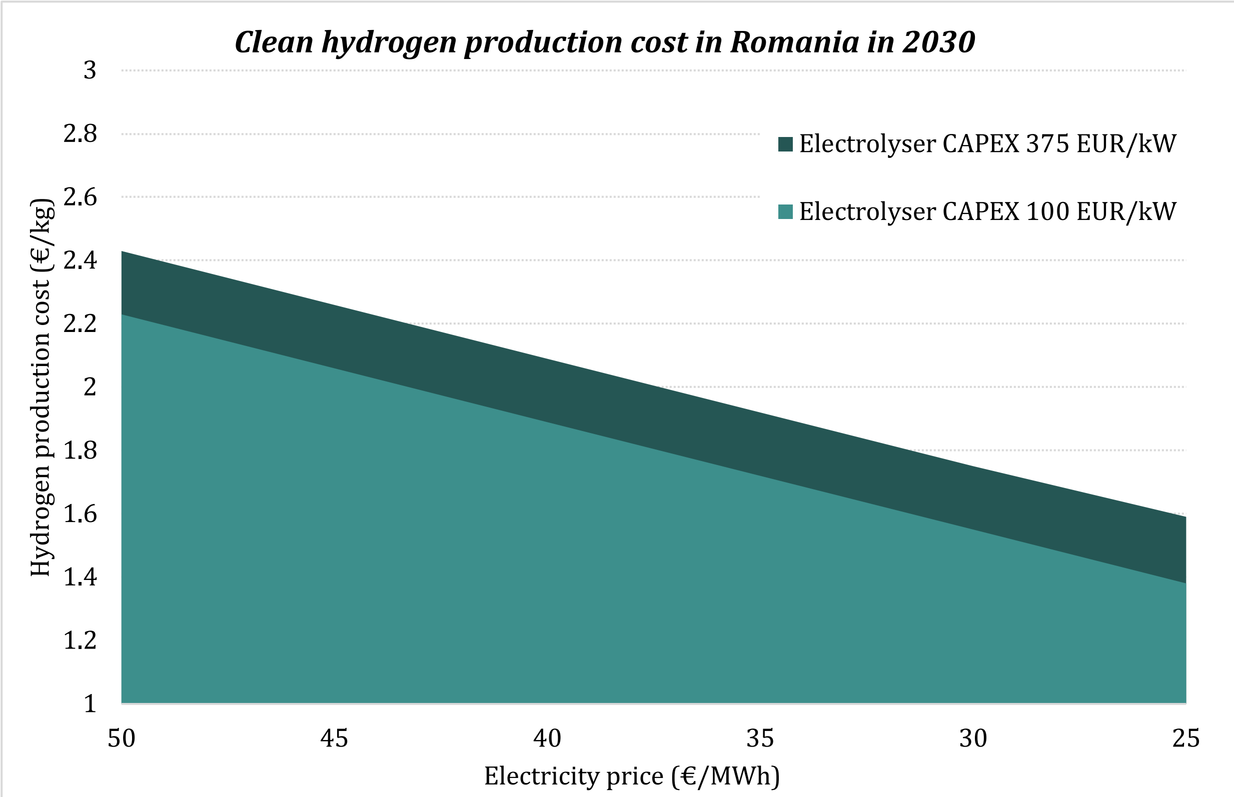

Figure 4 Clean hydrogen production cost in Romania in 2030 depending on the price of electricity, for 5,500 electrolyser FLH (Source: Energy Policy Group)

A sensitivity analysis for the price of electricity supplied to the electrolysers for 5,500 full load hours (FLH) reveals that the LCOH can go down to as much as €1.38/kgH_2 for alkaline electrolysis and €1.59/kgH_2 for PEM electrolysis in 2030 at an electricity price of €25/MWh, as shown by Figure 4. The way of ensuring a stable and predictable source of low-cost power for electrolysers is to close long-term Power Purchase Agreements (PPAs) with multiple renewable capacities, or through wholesale purchasing of electricity that comes with Guarantees of Origin (GOs). Solitary renewable installations in Romania cannot meet a high enough number of FLH to power electrolysers for a sufficient number of hours that would lead to a low LCOH. Solar PV would offer around 1,500 FLH, onshore wind between 2,500 and 3,000 FLH, while offshore wind might reach up to 4,000 FLH (EPG 2020), but at a higher electricity cost.

According to Agora (2021), the cost of fossil-based hydrogen (grey and blue) is expected to reach approximately €2.5/kgH_2 by 2030 for a natural gas price of €20/MWh and a carbon price of €100/tCO_2. Under such circumstances, clean hydrogen is a more cost competitive pathway than blue hydrogen even with PEM electrolysers and at a relatively conservative renewable electricity price of €50/MWh, which would result in an LCOH of around €2.4/kgH_2.

For an average LCOE of new[14] nuclear energy of €140/MWh (Lazard 2021), our model reveals that producing nuclear-based hydrogen (pink) using alkaline electrolysers would lead to an LCOH of €4.6/kgH_2 starting with 2030, almost double the cost of clean hydrogen in a conservative scenario, while also not contributing to the targets proposed in the revised RED II directive.

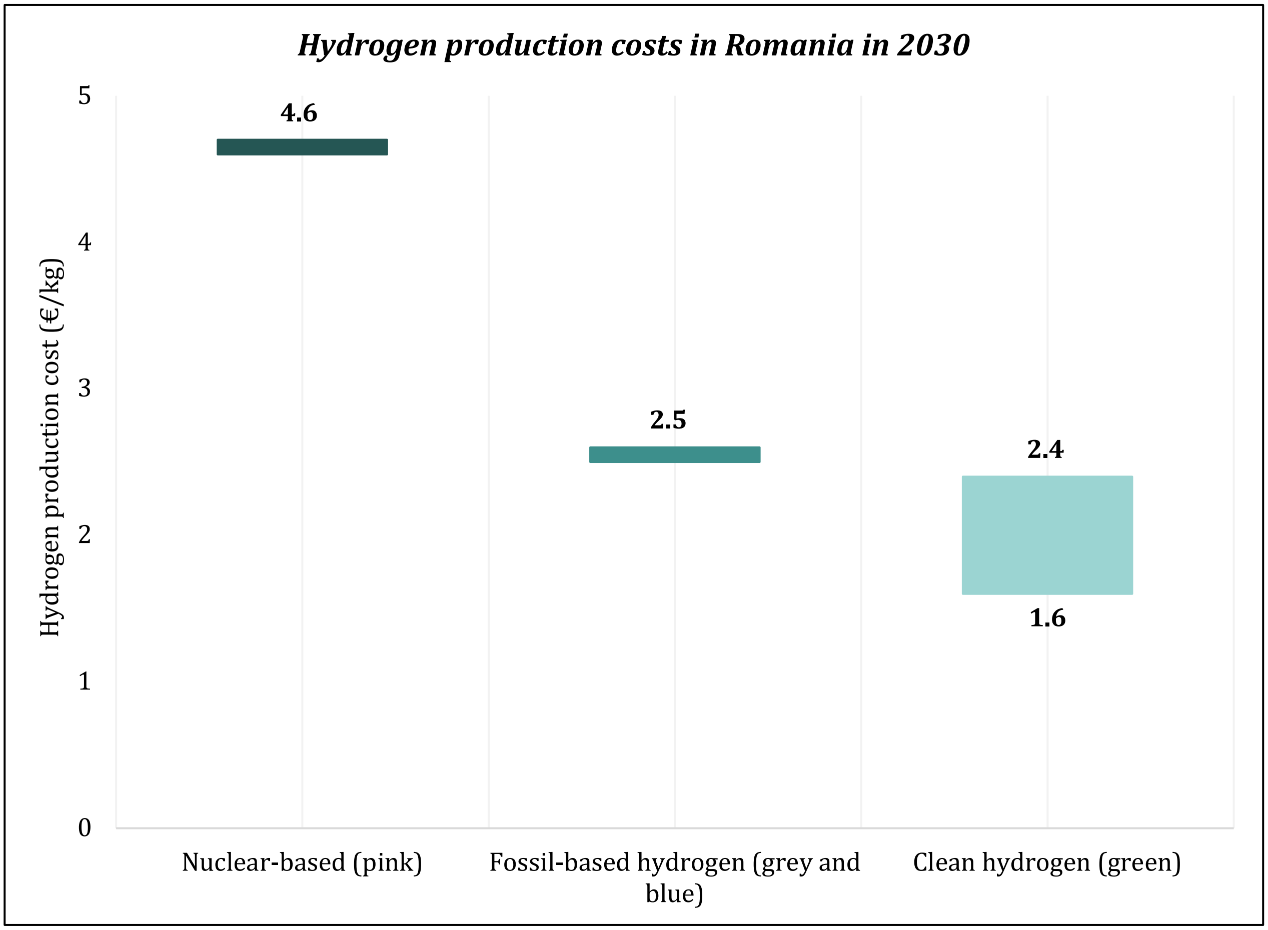

Figure 5 Hydrogen production costs in Romania in 2030 (Source: Energy Policy Group)

[14] Only new electricity production capacities are considered in this discussion since Romania is already facing a severe electricity generation deficit, with direct implication on the electricity prices. This aspect is particularly relevant when referring to baseload capacities, such as nuclear.

4. Way forward and recommendations

4.1 The elements of a hydrogen strategy

IEA (2021) points out that 16 countries have already published hydrogen strategies worldwide, with more than 20 others announcing that they are actively developing one. The preferred hydrogen production method depends on the available natural resource and renewable potential, but also on the climate commitments that each country has made. However, the strategies of EU countries favour electrolysis, mostly based on renewable energy sources, with only the Netherlands, Hungary and Norway also considering natural gas with CCUS by 2030. Similarly, most of the European strategies focus on using hydrogen in sectors such as industry and transport, with Germany, Hungary, the Netherlands, Portugal, and Spain also considering a potential use in the electricity production sector.

Apart from national specifics, there are elements that the strategies published by now have in common (WEC 2021) and that compose a non-exhaustive list of what the Romanian hydrogen strategy should also include:

- Identifying the main driver behind developing the hydrogen sector
- Prioritising production and use pathways
- Setting hydrogen cost targets
- Deploying targets for 2030 and beyond, including a timeline for market development
- Adopting clear legislative, regulatory, and financial measures to support the development of the hydrogen sector
- Deciding and accordingly preparing for hydrogen imports and exports
- Developing a hydrogen value chain in Romania.

4.2 Lead-market creation

Agora (2021b) presents several instruments that would contribute to the creation of a hydrogen market and can be considered part of Romania's hydrogen strategy and action plan:

Carbon contracts for difference

A carbon contract for difference (CCfD) is a contract between a private entity and a public counterparty. A CCfD contractually mandates a public entity to pay the difference between the negotiated strike price and the market price of ETS allowances, whenever the level of the strike price is higher than the market price. The payments go the other way whenever the market price of ETS is above the strike price. The private entity pledges to invest in measures that aim for the conversion of its production to hydrogen-based technologies. The contractually set strike price itself should be aligned to the actual abatement costs for carbon in order to generate the required investment incentive for hydrogen-based technologies.

H_2 supply contracts

H_2 supply contracts are sourced at auctions involving the purchase and resale of green hydrogen, serving as contracts to purchase hydrogen from a producer. H_2 supply contracts are concluded between an intermediary and the producer that offers the lowest cost at an auction for the supply of a specific quantity of green hydrogen per period (e.g., monthly delivery) over a fixed period (x years). The intermediary sells the acquired green hydrogen further at an auction to an end-user at the highest price possible. The green hydrogen producer then receives a compensation from the intermediary, in addition to the sales price to the intermediary. This compensation covers the difference between the bid of the hydrogen producer (buying-in price) and the bid of the end consumer (sales price). The approach ties in with the concept of Contracts for Difference (CfD).

PtL quota for aviation

An EU-wide quota that increases over time for the admixture of power-to-liquid (PtL) fuel in the form of synthetic e-kerosene up to a maximum share of 50%. Quota-obligated actors are producers and distributors of fossil kerosene that are expected to shift towards the e-kerosene business. The additional costs for this green are to be borne by airlines and airline customers.

General H_2 Quota

A quota for a virtual or actual admixture of green hydrogen to natural gas in the existing gas grid (blending). The blending would be in the range of 3 - 5%.

Labelling system for climate-friendly basic materials

Labelling of products as having a certain reduced level of embedded carbon or GHG in total owing to the specific production processes involved in the green hydrogen production process. The labelling can take various forms, using a rating system (scale), a figure (e.g., the CO_2 emissions "within" the product) or a binary "Yes" or "No" (compliance with product standard XY for green products). The labelling ought to be mandatory by law.

4.3 The geopolitical role of green hydrogen

As the world is turning away from fossil fuels in its pursuit of climate neutrality, hydrogen appears to be set to take the role that oil & gas currently have in geopolitical discussions. As IRENA (2021b) points out, while fossil fuel resources are geographically concentrated, every country on the planet has a potential to produce clean hydrogen, although not necessarily evenly distributed. Clean hydrogen is a less asymmetric commodity compared to natural gas, and it is not likely to achieve the same level of reciprocity as cross-border electricity trading. Nonetheless, if rightly planned and executed, the shift to clean hydrogen may lead to a more democratic approach to energy resources.

The drivers for a more democratic and decentralized global hydrogen energy landscape are technology and production costs, enabling infrastructure, and future market structures.

Currently, hydrogen is a localized industry, with approximately 85% being produced and used on site (IRENA 2019b). Some countries have already adopted hydrogen strategies that clearly state their intentions. Germany focuses on hydrogen imports, while Australia and Chile intend to use their significant energy production potential and position themselves as major hydrogen producers and exporters. Expectedly, frontrunners and first movers are likely to gain significant advantages in terms of creating value chains that will lead to exporting not only hydrogen, but also technology.

One can expect a delicate balance between green hydrogen importing and exporting countries. The countries' strategies should be implemented by means of carefully planned industrial policy measures. Clearly, exporter countries would benefit from an advantage in terms of RES potential, both as resource availability and a spatial spread. A certain dynamic is to be expected, though, as importers will also be able to consider producing locally, as business models evolve and impact costs.

As hydrogen will start being used on larger scale, new trade routes and dependencies will be created. This makes it even more important that the hydrogen strategy be backed by a robust energy and industrial action plan. Otherwise, in case of disorderly transition, a possibly swift and unexpected shift from net energy exporter to net energy importer may pose economic challenges, potentially leading to instability.

A recent study (Van de Graaf 2020) identifies key questions that countries should consider in their strategic planning. To position itself not only on the geoeconomic and geopolitical map, but also on the global hydrogen value chain, Romania should address the following questions:

a. How will hydrogen be mainly produced – clean or fossil?

b. Will the country mostly rely on local or imported hydrogen?

c. How will hydrogen be handled – pure or derivate?

d. How will hydrogen be used – by selected applications or in the broader framework of a hydrogen economy?

e. Where will hydrogen be mostly consumed – export or focus on domestic industrial use?

Given the good RES potential of Romania, and thus the significant potential to produce cost-efficient clean hydrogen, a strategic decision will have to be made between exporting cheap green hydrogen or using it locally to further develop downstream industries, such as the steel industry. After adopting a hydrogen strategy, Romania will also have to establish a "hydrogen diplomacy," to ensure it takes advantage of hydrogen trade opportunities.

The hydrogen value chain is and will continue to be on medium-term dependent on public investments, support policies and subsidies. Therefore, it is only natural that governments use this as leverage in the geopolitical landscape. As the overall European hydrogen ambitions are enshrined in the EU Hydrogen Strategy, national roadmaps and investment plans should also converge into more regional plans.

4.4 Dobrogea – Clean Hydrogen Valley

Hydrogen valleys are a concept aiming to enable the emergence of locally integrated hydrogen ecosystems typically comprising of multi-million-euro investments across a defined geographic area and cover a substantial part of the hydrogen value chain, from hydrogen production, storage, and transport to its use in sectors like industry, mobility, and energy, with numerous examples being set up across Europe.

Roland Berger (2021) identifies in its report four essential elements for defining a hydrogen valley:

- Large scale – multi-million investment projects that go beyond pilot and demonstration stages
- Supply of more than one sector or application in the mobility, industry, or energy sector
- High value chain coverage – from production and dedicated renewables production to storage, transport, and off-take
- Geographically defined scope – hydrogen ecosystems that cover a specific geography.

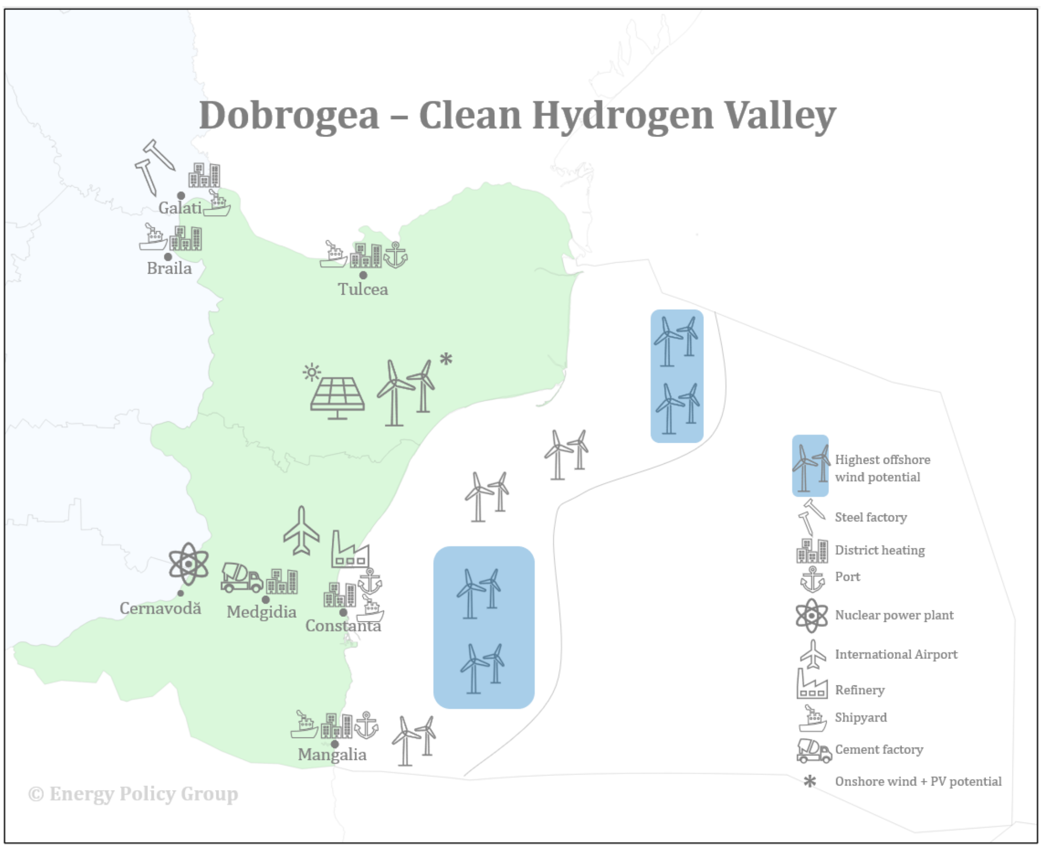

Figure 6 Dobrogea Clean Hydrogen Valley concept (Source: Energy Policy Group)

The Dobrogea region in particular owns all the prerequisites for hosting a pole for hydrogen development, as it has both outstanding capacity to produce clean hydrogen (onshore and offshore renewable energy), and potentially significant demand from existing refineries and steel making industry, use in district heating, decarbonising port activities, and maritime transport.

Dobrogea is Romania's renewable energy pole, with most of the country's 3 GW of onshore wind installed there and more to come by 2030 and beyond, when we can also expect offshore wind capacities to come online. Besides, 1.4 GW from the Cernavodă nuclear power plant's two nuclear reactors are operational in the region, with two additional reactors planned for the next decade, to the effect of almost doubling the installed capacity in an area with limited local energy demand. This will cause serious grid congestion issues. Creating demand for clean hydrogen at regional and then at national level will help ease the difficulties of evacuating the electricity produced in Dobrogea. In addition, if Romania makes efficient use of the available EU financial instruments for clean energy development, it could even become a premier producer of clean hydrogen in SEE, and even grow into a regional exporter.

As pointed out in a previous EPG (2020) study, Romania has a significant offshore wind potential in the Black Sea, with an estimated total potential natural capacity of 94 GW leading to a total Annual Energy Production (AEP) of 239 TWh. While the actual technical potential is of course more limited, with the recent technology cost reductions and EU's push for offshore wind to become the main source of renewable energy by 2050, the premises are set for a significant development of this resource in the Black Sea. This will facilitate an accelerated decarbonisation of key sectors such as transport and industry, either through direct RES-based electrification, or through the use of hydrogen. This will also help ease the difficulties of evacuating the electricity produced by offshore wind farms out of the region, setting solid foundations for Dobrogea to become a green hydrogen valley.

Significant hydrogen demand can come from industry, especially the local refinery of Petromidia, the integrated steel making plant of Liberty Galați, the cement factory of LaFarge Medgidia, the municipal district heating systems (e.g., Constanța), and the transport sector – especially maritime shipping (Ports of Constanța, Tulcea, and Mangalia) and civil and military aviation (Mihail Kogălniceanu International Airport). The Port of Constanța can become a true gateway for hydrogen export. Indeed, it represents one of the most valuable assets for this vision. By synergising the offshore wind and hydrogen value chains, it could grow into a regional pole of decarbonisation for the entire Black Sea basin. The shipyards in Constanța, Mangalia, Tulcea, Brăila and Galați can also contribute by building or retrofitting ships to run on clean hydrogen, and hosting refuelling stations.

Therefore, Dobrogea fits the second archetype identified by Roland Berger (2021) for a local, medium-scale and industry focused hydrogen valley:

- potential for local green hydrogen production projects
- several industrial off-takers as anchor load and potentially transport off-takers, replacing grey hydrogen supply or more carbon intensive industrial processes
- most investments to be led by the private sector.

Moreover, with the right strategic decisions, mainly focusing on efficiently tapping into Romania's cheap renewable energy potential, there is long-term potential for Dobrogea to fit into the third archetype, that is, a larger-scale, international and export-focused hydrogen valley.

The regulatory barriers identified by Roland Berger (2021) for developing hydrogen valleys across Europe apply to Dobrogea, too: lack of expertise and procedures from the permitting authorities, grid connection fees, taxes and levies on renewable electricity, missing safety regulations and standards, and legal uncertainties surrounding the implementation of European strategies and regulations (for example, the additionality principle).

4.5 The hydrogen value chain in Romania

According to the EU Hydrogen Strategy (EC 2020b), the share of hydrogen in the European energy mix will increase from less than 2% today to around 13-14% in 2050, generating investments between 180 and 470 billion euro. Between 2020 and 2024, over 6 GW of renewable hydrogen electrolysis production capacity will be installed, with a production of up to 1 million tonnes, which is a significant opportunity for the development of this industry at national level.

Between 2025 and 2030, the installed electrolysis capacities will be at least 40 GW, which corresponds to a production of up to 10 Mt of renewable hydrogen, which will gradually become cost competitive. Also, electrolysers will be used to balance energy systems and to increase their flexibility. After 2030, RES hydrogen-based technologies will reach maturity and be widely developed to help hard-to-decarbonise sectors. Romania can attract major investments at EU level by 2030, totalling €24 - 42 billion for electrolysers, and €220 - 340 billion for power generation capacities to ensure the supply of electrolysers with renewable energy. Investments in hydrogen transportation, distribution and storage in the EU will total €65 billion by 2030.

For electrolysers manufacturing, the authorities should aim to attract producers of PEM (Proton Exchange Membrane) electrolysers. Compared to the alkaline ones, they are more efficient and more flexible, being more suitable for an energy system with a large share of variable energy sources. Another aspect to consider is the fierce competition from Asian alkaline electrolysers manufacturers; they offer much lower prices compared to European and North American manufacturers.

To capitalize on the opportunity to relocate part of the hydrogen value chain to Romania, joining the European Clean Hydrogen Alliance (EC 2021b) must be a priority for the government, together with the project proposal for IPCEI on Hydrogen.

Systems of hydrogen production by PEM electrolysis are complex, with numerous components. Their assembly and configuration require advanced technical know-how, among others, in the mechanical, electrical, hydraulic and electrotechnical fields.

The IEA (2021) estimates that the number of jobs created in production and development for every €1 million spent along the hydrogen production value chain will be 7.2.

While hydrogen technologies are steadily becoming mature, there is still significant road ahead for progress, therefore the R&D sector should be a key component of the future hydrogen value chain in Romania. Initiatives such as the National Center for Hydrogen and Fuel Cells, part of ICSI Rm. Valcea, should be encouraged and expanded also in other research centres, aiming to create a stronger link between R&D activities and the actual development of the market. In addition, educational programs in all hydrogen-related aspects should be developed at university levels to create the necessary critical mass of specialists required for a powerful sector.

As both the availability and the cost of green hydrogen is ultimately heavily dependent on renewable energy sources, the development of the hydrogen value chain must synergise with the development of the renewable value chain in Romania, which is already supported by initiatives such as RESinvest (RWEA 2021).

Annex I

FINANCIAL ASSUMPTIONS			
Project lifetime (years)	20	Taxes	25%
Loan Interest (%)	5%	Workforce cost (€/year)	1,000,000
Inflation (% annual)	1.5%	Land cost (€/year)	200,000
Loan years	10	Water cost (€/m^3)	0.3
Finance (% total investment)	70%	Oxygen price (€/Tn)	10
Depreciation (%)	95%	Heat price (€/MWh)	2
Other CAPEX (% main equipments)	12%	Discount rate	5%

TECHNICAL ASSUMPTIONS		
Electrolysis	**Alkaline**	**PEM**
Efficiency (kWh/Nm^3 H_2)	4.32	4.32
Output pressure (bar)	10	30
Water consumption (liter/kg H_2)	13.3	13.3
CAPEX (€/kW)	100	375
Fixed OPEX (% year)	2%	2%
Stack replacement	Included in Fixed OPEX	Year 10
Replacement cell stack cost / total electrolyser cost (%)	0%	20%
Stack degradation (% per 1,000 hours)	0.1%	0.1%

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