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Florence School of Regulation: Cost-effective decarbonisation study 2022

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List of Acronyms

Badische Anilin- und SodaFabrik – BASF
Billion – Bn
Capital expenditure – CAPEX
Carbon border adjustment mechanism – CBAM
Carbon capture and storage – CCS
Carbon capture, utilisation and storage – CCUS
Carbon contracts for difference – CCfD
Carbon dioxide – CO_2
Emissions Trading System – ETS
Energy Efficiency Directive – EED
Energy efficiency first – EEF
Euro – Eur
European Union – EU
European University Institute – EUI
Florence School of Regulation – FSR
Greenhouse gas – GHG
Guarantee of origin – GO
Hydrogen – H2
Important Projects of Common European Interest – IPCEI
Intergovernmental Panel on Climate Change – IPCC
International Energy Agency – IEA
Kilogram – KG
Kilowatt hour – kWh
Megawatt hour – MWh
Methane – CH4
Million – Mn
Million tonnes – Mt
National energy and climate plan – NECP
Oil and Gas Methane Partnership – OGMP
Operational expenditure – OPEX
Per annum – p.a.
Photovoltaic – PV
Projects of Common Interest – PCI
Renewable Energy Directive – RED
Renewable energy sources – RES
Renewable energy sources of electricity – RES-E
Renewable fuels of non-biological origin – RFNBO
Research and development – R&D
Research and development and demonstration – R&D&D
Sixth Assessment Report – AR6
Steam methane reforming – SMR
Technology readiness level – TRL
Terawatt hour – TWh
Tonne – t
United States Dollar – USD

1. Introduction

Aims of the study update

In 2020, the Florence School of Regulation (FSR) published a comprehensive study peer reviewing major analyses in the area of energy decarbonisation with the aim of giving a coherent interpretation of their findings.[1] These data were the basis for further investigation of some key metrics for assessing the cost-effectiveness of different decarbonisation options with a view to informing targeted policy on this issue at the level of the European Union (EU).

Just over one year on, much has changed, both in the world of energy and more widely. This short follow-up to the original and more comprehensive cost effectiveness study aims to take stock and frame developments in the past months in the context of EU energy policy, and to reassert some of the key messages from the 2020 publication that remain relevant. In so doing, the authors have updated key cost and capacity information according to some of the latest relevant publications, and have reflected on some of the challenges and opportunities presented by wider developments.

The purpose of the study is not to propose a specific answer or trajectory regarding the balance of policies to decarbonise the energy sector. Instead, the aim is to highlight some key information relevant to policymakers charting the next energy sector decarbonisation steps.

EU energy aims in context

The EU has consistently identified three core energy policy objectives: sustainability, competitiveness, and security of supply.[2] In theory, these are considered equally important and are attributed equal weight in policymaking considerations. However, in reality at different points in time the three priorities have been given different levels of focus. Prior to the 1992 Kyoto Protocol, the primary concerns were arguably security of supply and competitiveness with the development of the internal energy market and initiatives to develop infrastructure, notably to ensure that all Member States could access multiple suppliers of natural gas. Since 2009, the priority has unequivocally shifted towards sustainability and achieving the EU's environmental commitments.[3] Core EU mechanisms such as the European Union Emissions Trading System (EU ETS) and the Renewable Energy and Energy Efficiency Directives (RED & EED) are statements of this intent.

The authors of this study would like to underline from the outset that they fully agree with this prioritisation. The Intergovernmental Panel on Climate Change's (IPCC's) Sixth Assessment Report (AR6) released earlier this year stated that "it is unequivocal that human influence has warmed the atmosphere, ocean and land."[4] This was the first time that one of these landmark IPCC publications had made such a clear assertion. To avoid global warming of 1.5°C above pre-industrial levels massive reductions in greenhouse gas (GHG) levels are required in a very short time frame, with the majority of the IPCC AR6 scenarios envisaging warming in excess of 2.0°C by the end of the century. Every fraction of a degree that can be avoided will potentially avert significant cost and suffering. As a key driver of emissions, the energy sector must reach carbon neutrality as quickly as possible to support the avoidance of further warming. This is unquestionably the greatest energy challenge the EU has faced, and it is likely to remain so until at least 2050.

1 Piebalgs, Jones, Dos Reis, Soroush, Glachant (2020). Cost-effective decarbonisation study, Florence School of Regulation, https://fsr.eui.eu/publications/?handle=1814/68977

2 European Parliament (2021). Energy policy: general principles, Fact Sheets on the European Union, https://www.europarl.europa.eu/factsheets/en/sheet/68/energy-policy-general-principles

3 Most pertinently now the commitments under the Paris Climate Agreement and the EU Green Deal.

4 Intergovernmental Panel on Climate Change (IPCC) (2021). Headline Statements from the Summary for Policymakers (IPCC AR6), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Headline_Statements.pdf

Seen from this perspective, the EU concluded that its initial energy and climate targets[5] of a 40% reduction in GHG emissions by 2030 and a renewable energy target of 32% were inadequate. The 2019 Green Deal[6] adopted a target of at least a 50% GHG cut by 2030 and carbon neutrality by 2050. Last year the GHG target was upgraded to a binding 55% reduction. This was followed by the 'Fit for 55' package, which aims to put the EU on course to achieve these aims.[7]

Decarbonising the economy will involve massive structural changes and investments, requiring decades to complete. It is therefore important to start early and to ensure that financial commitments can be sustained, not least because mitigating warming in the second half of the century depends on emissions being reduced now.

However, the decarbonisation objective cannot be seen in isolation, the EU's other energy policy aims of competitiveness and security are also crucially important. These aims do not need to be in competition. A well-executed decarbonisation of the energy sector can bring with it affordable, reliable and more domestically sourced energy. Nevertheless, achieving the appropriate balance among the objectives will require careful forward planning as it may be difficult to retain public support for decarbonisation, particularly during the first years of the transition, if it comes at the cost of competitiveness and security. The cost aspect of this transition has in some instances been referred to recently as 'Greenflation'.[8]

The cost of energy is an essential element of competitiveness for many companies, particularly for energy-intensive industries such as chemicals, steel, metals, and cement, where energy typically represents 20-40% of the total cost.[9] This is also equally important for industries which operate with tight margins, such as car manufacturers. It is counterproductive to increase energy costs in the EU for such enterprises to the extent that they relocate outside Europe where GHGs are not so strongly regulated, as this would almost certainly increase the overall GHG emissions resulting from their operations. The ETS is the key EU mechanism to curb industrial emissions, and the Commission's proposal of a Carbon Border Adjustment Mechanism (CBAM)[10] aims to address this problem, or 'carbon leakage,' albeit with limitations.

Equally, electricity and gas costs have increased for EU citizens in recent years, with exceptional price rises in recent months. The total electricity price for household consumers[11] was much higher in the second half of 2021 than it was in 2008, with an overall gradual increase in energy costs between these dates when adjusted for inflation. In some Member States this increase has been significantly greater than in others.[12] Support for the EU's decarbonisation agenda nevertheless remains strong. A recent Eurobarometer survey indicated that 93% of EU citizens consider climate change a serious problem and 57% of citizens consider the EU the most responsible actor to address this issue.[13] However, social responses to sharp energy price increases in the past, such as the 'gilet jaunes'[14] movement in France, demonstrate that EU citizens remain sensitive to energy price changes.

5 European Commission (2021). Clean energy for all Europeans package, https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

6 European Commission (2021). A European Green Deal, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

7 European Council (2021). Fit for 55, https://www.consilium.europa.eu/en/policies/eu-plan-for-a-green-transition/

8 Blas (2022). Greenflation Is Very Real and, Sorry, It's Not Transitory, https://www.bloomberg.com/opinion/articles/2022-01-10/greenflation-is-a-crucial-step-in-the-energy-transition-central-banks-take-note

9 Energy Star (2013). Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making, https://www.energystar.gov/sites/default/files/buildings/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2028_08_2013%20Final.pdf

10 European Commission (2021). Carbon Border Adjustment Mechanism: Questions and Answers, Press Corner, https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661

11 I.e., including all taxes and levies.

12 Eurostat (2021). Electricity and gas prices in the first half of 2021, https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20211020-1

13 European Union (2021). Special Eurobarometer 513: Climate Change, https://europa.eu/eurobarometer/surveys/detail/2273

14 Chrisafis (2018). Who are the gilets jaunes and what do they want?, The Guardian, https://www.theguardian.com/world/2018/dec/03/who-are-the-gilets-jaunes-and-what-do-they-want

In order to meet the EU's Green Deal objectives, at least €1 trillion of public investment will be required in the period 2021-2030, with further financing required from the private sector.[15] At a time when many third countries are failing to take robust action to mitigate their emissions, limiting increases in energy prices for citizens remains important. A rapid and sustained increase in electricity and gas prices not seen in other countries is likely to challenge public support for the decarbonisation agenda. For this reason, it is especially important to ensure clear communication about the origin of price rises[16] to avoid citizens attributing them to decarbonisation initiatives when it is not the case. The exceptionally high energy prices experienced in the second half of 2021 should serve to further emphasise the need to end European reliance on imported fossil fuels, and therefore accelerate the transition to a renewable and more independent energy future.

Security of energy supply also remains a vital issue for EU citizens. The transition must therefore be undertaken in a manner that continues to guarantee robust energy security. The challenges in this respect are changing rapidly, with grid stability and cybersecurity rising on the agenda, and having renewed relevance in the geopolitics of gas deliveries. The next stage in the EU's energy decarbonisation agenda will probably only bring further change. Policy will need to be prepared to adapt.

In 2020 the Commission published its Energy Sector Integration,[17] Methane[18] and Hydrogen Strategies,[19] which have now been followed with numerous initiatives in the Fit for 55 package[20] and recent legislation on methane,[21] hydrogen and decarbonisation of the gas sector.[22] These initiatives in the context of the Green Deal[23] will set the basis for the EU's energy system for the next decades. The manner in which they will be implemented in practice will form the basis of the next stage of the EU energy transition and is likely to have a profound effect on energy prices and competitiveness. Keeping energy affordable, secure and competitive while aggressively pursuing decarbonisation will be challenging.

Lessons from the past

The EU is currently at the beginning of a new 'energy technology cycle' with widespread retirement of coal generation, a phase-down of nuclear power in some Member States, rapidly increasing renewable electricity capacity, and the emergence of a decarbonised gas sector.

As we have learned through developing wind and solar photovoltaic (PV) markets, ensuring the correct balance of investment and subsidies between different decarbonisation options and technologies at any given stage in the process is far from simple and can have huge effects in terms of energy cost. It is vital to strike the optimum balance between research, development and demonstration (R&D&D) of new technologies at lower costs[24] on the one hand and creating demand through production subsidies etc. on the other hand.[25]

15 European Commission (2020). The European Green Deal Investment Plan and Just Transition Mechanism explained, https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_24

16 Market pressures, weather conditions, delays in repair work, etc.

17 European Commission (2020). Powering a climate-neutral economy: An EU Strategy for Energy System Integration COM(2020) 299 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0299&from=EN

18 European Commission (2020). EU strategy to reduce methane emissions, https://ec.europa.eu/energy/sites/ener/files/eu_methane_strategy.pdf

19 European Commission (2020). A hydrogen strategy for a climate-neutral Europe COM(2020) 301 Final, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

20 European Council (2021). Fit for 55, https://www.consilium.europa.eu/en/policies/eu-plan-for-a-green-transition/

21 European Commission (2021). Regulation on methane emission reductions in the energy sector, COM(2021)805 final, https://ec.europa.eu/energy/sites/default/files/proposal-methane-emission-reductions-regulation.pdf

22 European Commission (2021). Hydrogen and decarbonised gas market package, https://ec.europa.eu/energy/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en

23 European Commission (2021). A European Green Deal, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

24 'technology push'

25 'market pull'

Over the last few years, the EU has spent roughly €70Bn per annum (p.a.) on renewable energy subsidies.[26] If this could have been reduced by even 20% considerable resources would have been available for other priorities. With the benefit of hindsight, a more cost-effective development of the renewable electricity market could have been achieved by investing roughly €10Bn in R&D&D for wind and PV from 2008 to 2012 before increasing production subsidies. This is not to criticise the EU's policy. Citizens should be proud of EU leadership in driving down costs in this sector. Nevertheless, experience in wind and solar should inform policy moving forward where appropriate.

Regarding the future hydrogen and renewable gas markets, developing an approach that ensures optimal timing and value of 'technology push' and 'market pull' tools will be crucial. On the one hand, the EU's gas system must be zero-carbon by 2050, but it must also support wider decarbonisation aims, for example regarding its relationship with energy system integration and circular economies. As will be explained in greater detail below, there are indicators that decarbonised hydrogen technologies are not yet established and mature enough to warrant a 'technology-specific' approach. Therefore, there is reason to believe that technology neutrality and trust that market mechanisms will determine the approach to production subsidies remain important if a cost-effective decarbonisation policy is to be pursued.

2. The 2020 objectives and the challenge of the Green Deal

First movers

The first-generation cross-cutting climate and energy policy from the EU came in the form of the '20-20-20' objectives, referring to a 20% reduction in GHG emissions, a 20% improvement in energy efficiency relative to 1990 levels, and 20% of energy originating from renewable sources, all by 2020.[27] At the time of their announcement, these aims were broadly considered highly ambitious by the global community.

However, in 2020 the GHG emission reduction target was surpassed with a reduction of 31% relative to 1990 levels. The targeted renewable energy share was also surpassed with a final share of 21.3%. Despite signs that it might be missed, the 20% energy efficiency goal was also narrowly achieved[28] – although probably due largely to the temporary drop in overall energy consumption in 2020 as a result of the COVID-19 pandemic.[29]

Any qualification of the outcomes of the '20-20-20' objectives must start by acknowledging that these aims provided the EU with the foundations needed to meet the ambitions of the Green Deal. The establishment of a well-functioning ETS system has delivered meaningful emission reductions, with an enhanced role moving forward as proposed in the Fit for 55 package. The renewable energy industry now employs roughly 1.6 million Europeans, with a greater proportion of women and young people than in traditional energy sectors.[30]

The European Commission stresses the 'Energy Efficiency First' principle as the priority in energy sector decarbonisation policy, with good reason. However, it is the area where the EU has had the most difficulty in delivering. The COVID-19 pandemic artificially depressed energy demand in 2020 but it has since quickly rebounded to above pre-pandemic levels in line with the economic recovery, representing a disappointing overall trend. Similarly, during the 2009-2020 period the EU experienced relatively little

26 Commission's Staff Working Document, COM(2019)1 final Part 1/4, accompanying the report on "Energy prices and costs in Europe", p.216, figure 164, https://ec.europa.eu/energy/sites/ener/files/documents/swd_-_v5_text_6_-_part_1_of_4.pdf

27 European Commission. 2020 climate and energy package, https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2020-climate-energy-package_en

28 European Environment Agency (2021). EU achieves 20-20-20 climate targets, 55% emissions cut by 2030 reachable with more efforts and policies, https://www.eea.europa.eu/highlights/eu-achieves-20-20-20

29 In 2019 the EU was roughly 10% behind the 20% energy efficiency target. See here.

30 European Commission (2021). Energy sector economic analysisTop of Form, Bottom of Form https://ec.europa.eu/jrc/en/research-topic/energy-sector-economic-analysis

economic growth,[31] which contributed to lower energy consumption. There is also significant variation between Member States regarding improvements in energy efficiency. Certain Member States such as Lithuania, Greece and Denmark have made significant reductions in their overall energy consumption, while nine Member States achieved less than a 5% decrease by 2020 relative to 1990 levels. Poland even increased its overall consumption since the EU-wide peak in 2006.[32, 33]

The energy system changes required to achieve the 20-20-20 aims have come at considerable economic cost.[34] Early support schemes were often characterised by overconsumption and a national-based system of RES-E support, meaning that capacity was often situated in sub-optimal geographical locations.[35] This experience must be considered in future energy policy.

Such comments are easy to make with the benefit of hindsight, and renewable support schemes, now mostly based on tenders, are now far more efficient and deliver competitive prices. Moreover, the energy efficiency objective recently became legally binding at the EU level through a revision of the Energy Efficiency Directive (EED), with a benchmarking system for Member States to set their indicative national contributions.[36] Today, renewable energy is competitive with fossil fuel generation worldwide, typically representing the most cost-effective form of new capacity.[37, 38] These global cost reductions are to some extent direct consequences of efforts under the EU's 20-20-20 framework. Seen in this light, the initiative has contributed to indirect GHG savings and RES-E installations far greater than the 31% GHG reduction and 21.3% RES-E share seen in the EU. European citizens should be proud of the leadership their Union has shown here.

Nonetheless, it is important to note that the decarbonisation efforts up to 2020 were just the beginning of efforts to decarbonise the EU's economy, and in many respects represent 'low hanging fruit.' Continued support by all EU citizens will be dependent on a cost-effective sustained long-term transition.

Energy security and competitiveness in the context of climate focused policy

During the period 2010-2020 the EU focused on diversifying sources of gas supply, especially for the countries largely or completely dependent on a single supplier. The EU adopted a new infrastructure planning approach, with EU funds for energy infrastructure projects of common interest (PCIs). This has proved a very successful initiative. The number of gas suppliers increased between 2012 and 2018 for all Member States located in southern, central and northern European regions. All Member States now have multiple supply options, which will further increase once additional ongoing projects are completed. This has had a positive effect on the relative competitiveness of gas supplies in countries previously characterised by limited liquidity options. The average import price for southern, central and northern Member States was 13% higher than for western Member States in 2013. This reduced to 5% in 2018[39] and is continuing to narrow, notwithstanding recent global market conditions.

31 World Bank (2020). GDP (current US$) – European Union, World Bank national accounts data and OECD National Accounts data files, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=EU

32 Eurostat (2021). Energy saving statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_saving_statistics#Final_energy_consumption_and_distance_to_2020_and_2030_targets

33 These national level indicators may also be a reflection of evolving trends in the (re)location of energy intensive industries, for example.

34 Commission's Staff Working Document, COM(2019)1 final Part 1/4, accompanying the report on "Energy prices and costs in Europe," p.216, figure 164 https://ec.europa.eu/energy/sites/ener/files/documents/swd_-_v5_text_6_-_part_1_of_4.pdf

35 Linden, et al. (2014). Electricity tariff deficit: Temporary or Permanent Problem in the EU?, https://ec.europa.eu/economy_finance/publications/economic_paper/2014/pdf/ecp534_en.pdf

36 European Commission (2021). Commission proposes new Energy Efficiency Directive, https://ec.europa.eu/info/news/commission-proposes-new-energy-efficiency-directive-2021-jul-14_en

37 International Renewable Energy Agency (2021). Renewable Power Generation Costs in 2020, https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

38 Nevertheless, care should be taken when making such calculations to take into account the more limited operating hours of intermittent solar and wind capacity, and relevant system costs – notably storage and balancing.

39 Eurostat (2021). Natural gas price statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics

As domestic renewable electricity and decarbonised gases occupy an increasing share of the energy mix, concern over the security of gas supplies should continue to decrease moving forward.[40] Again, EU citizens can be satisfied with what EU energy policy has delivered on this issue.

Renewed ambition

Achieving the Green Deal objective of a 55% GHG cut by 2030 represents a step change in terms of ambition compared to the 20-20-20 objectives. If renewable electricity objectives[41] need to increase in proportion to the increased GHG reduction ambition (from a 40% reduction to a 55% reduction) then renewable electricity will need to satisfy around 67% of EU electricity demand by 2030, compared to around 30% today.[42] This will require the level of newly installed wind and PV capacity per annum to double in the 2020-2030 period compared to 2010-2020.

Member States' current national energy and climate plans (NECPs) are not on a trajectory to achieve this level of renewable installation, and without a far higher level of effort and urgency this target will not be achieved.[43] At the same time, a far higher share of intermittent generation in the mix will require much more balancing and storage. Scaling up grid infrastructure in parallel with generation will be key to maximising the effective capacity of renewable installations and avoiding significant increases in electricity prices. This merits careful planning and attention. Equally, energy efficiency will need to reach 36% or more, something which has been reflected in the recently amended and now legally binding EED targets.[44, 45] This is also a huge challenge and again will require a level of commitment by Member States not currently demonstrated in their national plans. Put simply, unless Member States significantly increase their level of ambition, and more importantly concrete action, the 2030 and 2050 objectives will not be met.

This analysis of the renewable electricity and energy efficiency objectives needed to achieve the Green Deal target of 55% is to a certain extent a simplistic extrapolation based on existing estimates for the original 2030 target. Nevertheless, it is a reasonable illustration of the scale of the challenge ahead for the EU. It also underlines the importance of integrating cost-effectiveness in the Commission's preparation of its energy policy overall, and legislation on hydrogen and decarbonisation of the gas sector in particular.

40 Although the EU will probably not reach peak gas import levels for several years.

41 Established on the basis of the pre-Green Deal. 40% GHG cut by 2030.

42 Eurostat (2020). Archive: Electricity generation statistics – first results, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_generation_statistics_–_first_results&oldid=498612

43 It is worth noting that according to the IEA Member States are on track to reach the current renewable installation targets as outlined in the NECPs. These are likely to be upgraded before 2030 and their ambition will need to aggressively increase to come close to the 67% level outlined here.

44 Upgraded target of 36% from previous target of 32.5%.

45 European Commission (2021). Proposal for a recast Directive on energy efficiency COM(2021) 558 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558

3. Expected costs and capacity of renewable electricity technologies

Levelised costs of different renewable energy technologies

This study analyses the known and forecast costs of renewable electricity of different origins at various points in the timeline of decarbonisation by peer-reviewing a cross-section of available literature on the topic.[46]

Figure 1: Levelised costs of renewable electricity sources, present, 2030, 2050*[47]

Technology	Levelised cost **today**** [EUR/MWh]***	Levelised cost **2030** [EUR/MWh]	Levelised cost **2050** [EUR/MWh]
Utility scale solar	18 – 125	25 – 110	15 – 90
Rooftop scale solar	62 – 186	60 – 110	49 – 90
Onshore wind farm	22 – 142	25 – 115	15 – 95
Offshore wind farm	50 – 180	40 – 140	20 – 75

KEY: Colour coding (only for illustrative purposes): High price low price
NOTE:
* Data from reference list 1 [Agora Energiewende (2021b). European Commission (2020). IEA (2021b). IRENA (2021). BNEF (2021). Zachmann, et al. (2021)]
** The year reported relates to the estimate, not to the publication year of the source. Grid costs excluded.
*** Euros per megawatt hour of electricity produced

Figure 1: Reflections

- Both onshore wind and utility-scale solar PV are currently competitive with fossil generation in terms of the cost of electricity delivered to the grid, with rooftop solar and offshore wind competitive in favourable circumstances.
- The average levelised costs of utility-scale solar, onshore wind and offshore wind are expected to continue to fall by 2030 and further again by 2050.
- Offshore wind shows perhaps the most significant potential for cost reduction, from one of the most expensive sources of RES-E today to potentially the cheapest in 2050. Key drivers of this cost reduction are lower CAPEX costs due to technology improvements delivering higher capacity factors.
- Significant uncertainty remains regarding the final price of electricity from these sources, particularly in the upper ranges of prices. This has potential implications for when capacity is to be installed in increasingly unfavourable weather conditions with exponentially higher marginal costs.
- These figures do not factor in the additional network costs resulting from higher balancing and storage capacity.

Projected renewable energy potential

The following table provides an overview of total renewable energy generation potential estimations. These are theoretical estimations based on the availability of appropriate conditions and do not take into account permitting issues and competition for land use, which can be meaningful barriers.

46 A full list of sources can be found in the reference list.

47 The numbers in the 2020 version of the study are as follows but they do not take into account the cost of financing, which reduces the values relative to the 2021 numbers, which do include these costs (all expressed in EUR/MWh). Utility scale solar: (today) 11.2 – 160, (2030) 10 – 38.5, (2050) 10 – 18.7. Rooftop scale solar: 55 – 190. Onshore wind farm: 16.9 – 92, 17 – 45, 14 – 28. Offshore wind: 42 – 133, 36 – 96, 35.

Figure 2: Total realistic energy potential of cumulative installed capacity for renewable electricity in the EU, present, 2030, 2050*

Technology	Technical potential: **Today** [TWh/yr]**	Technical potential: **2030** [TWh/yr]	Technical potential: **2050** [TWh/yr]
Solar PV	126	300	1,300
Wind	367	800	3,400
Solar PV + Wind	493	1,100	4,700
EU electricity demand	2,851 (2019)	3,200	3,570 – 4,826

KEY: Colour coding (only for illustrative purposes): *Insufficient capacity* *Sufficient capacity*
NOTE:
* Data from reference list 1 [IEA WEO, 2021. Belmans, Vingerhoets, 2021. EUROSTAT, 2020. EU Member State National Energy and Climate Plans (NECPs), EU EC SWD(2020)176 MIX scenario.]
** Terawatt hours per year.

Figure 2: Reflections

- The technical potential of renewable electricity from solar and wind in the EU is set to more than double by 2030 and to continue to increase very strongly by 2050.
- Potential electricity use is projected to increase considerably by 2030 and 2050. This is due to a general drive towards electrification and the potentially significant growth of electricity as feedstock for synthetic fuel conversion (e.g. hydrogen).
- Covering this growing demand is likely to be very challenging in the coming decades, although it is technically possible by 2050, when potential installed capacity could more feasibly catch up with demand.
- Deployment of renewable capacity is to a considerable extent dependent on external factors such as permitting processes and competition for land use, such as for carbon offsetting or urban and agricultural development. These may end up being more influential factors than minor variations in price competitiveness, for example in the wind sector. Permitting for onshore wind is becoming more restrictive in many cases, while offshore wind potential is contingent on Member State maritime spatial planning, which requires compromises with fishing, military, and other environmental priorities.
- The likelihood of renewable energy scarcity in the coming decades highlights the need to limit energy demand where possible and to be efficient. Due to energy losses in converting electricity into other energy vectors (e.g. renewable hydrogen), direct electrification should be favoured wherever practicable.

As was touched on previously, an important potential factor constraining the increase in RES-E capacity is grid issues, notably the challenge of increasing network capacity quickly enough and where required (e.g. from far offshore to urban centres). This, coupled with the intermittent nature of wind and PV, is likely to increase grid costs and could lead to expensive curtailments. For example, in Germany €1.2 Bn in system costs were incurred in 2019 to deal with curtailment as grid capacity was insufficient to carry peak renewable electricity production, although it should be noted that these costs are decreasing.[48] In the first half of 2021, 41% of Germany's electricity was sourced from renewables whereas even in the 40% 2030 GHG cut scenario Germany aims at approximately a 65% share of renewables in its electricity system.[49] To minimise these costs as far as possible during the scale-up of RES-E capacity there needs to be an equally strong focus on cross-border grid balancing, grid planning and cost-effective storage as there is on maximising overall production potential.

As part of this study, the FSR has reviewed the literature in an attempt to determine scenarios and forecasts of balancing and storage costs for renewable electricity but we have failed to identify sufficient data to draw reliable conclusions. This is in itself an important observation, and additional work needs

48 Bundesnetzagentur (2019). Bericht: Quartalsbericht Netz- und Systemsicherheit - Gesamtes Jahr 2019, https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Berichte/2020/Quartalszahlen_Gesamtjahr_2019.pdf?__blob=publicationFile&v=5

49 Eurostat (2021). Share of energy from renewable sources, https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_ren&lang=en

to be completed on this issue so that the EU can quickly adopt a forward-looking and cost-effective approach to ensuring that infrastructure/storage options exist in time to prevent curtailment.

In the view of the authors, these findings give rise to an important conclusion. Apart from energy efficiency, which must remain the EU's highest energy priority, it is clear that renewable electricity will form the backbone of the EU's decarbonised energy system. Achieving the required levels of renewable installation will require the elimination of infrastructure and other bottlenecks that are likely to constrain the cost-effective production and use of renewable electricity moving forwards. These efforts to streamline the growth of the renewable energy sector will have to be well coordinated with other decarbonisation and land use initiatives, which highlights the need for a holistic centrally coordinated approach.

4. Building a clean hydrogen economy

Together with renewable electricity, the hydrogen and wider decarbonised gas sector is arguably the most important area for achieving the EU's energy aims in the coming decades. During the term of this Commission the EU will set the framework for the development of the EU's future low and zero-carbon hydrogen market. Ensuring that this policy is established based on objective data and with respect to the considerable uncertainties surrounding its basis will be crucial to build a resilient, decarbonised and competitive gas system.

Definitions of hydrogen types

In this study, the terminology 'grey,' 'blue,' 'green' and 'turquoise' hydrogen is used. Grey hydrogen is produced from natural gas via steam methane reforming ('SMR') and the resultant CO_2 is vented into the atmosphere unabated.[50] This is currently the most common form of hydrogen production both in the EU and globally. Blue hydrogen follows the same chemical process as grey hydrogen, but with the application of carbon capture and storage (CCS) to abate much (but not all) of the emissions. To further decarbonise the SMR process it is possible to use biomethane feedstock[51] rather than fossil methane. Green hydrogen is produced by electrolysis of water with renewable electricity. This process releases only hydrogen and oxygen so it is considered to have zero direct emissions.[52] Turquoise hydrogen is produced through pyrolysis[53] of a methane feedstock (either bio or fossil methane) and produces hydrogen and solid carbon as outputs. Like electrolysis, pyrolysis uses electricity to drive the chemical reaction and therefore when this energy is renewably sourced there are also no process emissions.[54]

Researchers at the FSR have peer-reviewed a wide selection of different studies that estimate the future costs and cost components of green, blue and turquoise hydrogen. The resulting data presented below represent a coherent approach based on these studies. In this manner, we attempt to provide an objective illustrative picture of average industry and academic predictions of some of the key data that can serve as inputs for the EU in policy considerations. We recognise the imperfection of the approach and its sensitivity to variables but maintain that it is nevertheless a worthwhile exercise and valuable reference point.

50 Grey hydrogen can also refer to auto thermal reforming (ATR) of methane. However, as it is the predominant method of production in this study we use grey hydrogen to refer only to unabated SMR.

51 I.e., methane produced through the decomposition of organic matter, such as agricultural waste products.

52 It should be noted that there can be considerable upstream emissions associated with the production of green hydrogen, through the installation of infrastructure for example. These may also vary between different energy inputs, such as offshore versus onshore wind or solar.

53 Pyrolysis refers to a type of chemical processes in which feedstocks are heated to very high temperatures to drive a reaction.

54 Nevertheless, it is important to keep in mind that due to the methane feedstock used there is scope for significant supply chain emissions. There are other comparable methods in development such as photocatalysis, which uses renewable energy to power photons that breakdown a methane feedstock.

Hydrogen cost projections

The data here reflect long-term historical and projected trends and as such do not take into account the exceptionally high energy commodity prices experienced in the second half of 2021. This is important to keep in mind as it remains to be seen where prices will restabilise following these recent developments. Even a 20% difference in the electricity or gas price can have very meaningful implications for the competitiveness of different hydrogen technologies, and therefore the policy instruments that can be best applied to support the decarbonisation of the sector. Nevertheless, the authors of this study follow the data and assumptions of major existing analyses, with the caveat that the conclusions here do not assume lasting disruption to commodity prices.

The following table presents an assessment of the current technological maturity of green, blue and grey hydrogen based on observations from industry and technological guidelines. Technologies are considered 'commercial' when there is evidence of at least one project operating in a commercial environment, with a distinction between 'established' commercial technologies (i.e. those relatively widely adopted by industry) and 'early' commercial ventures, which are fewer and less well established. Estimations of levelised costs[55] are also provided based on reputable independent analyses[56] and some values from industry where data are lacking.[57]

Figure 3: Minimum and average levelised costs of low and zero carbon hydrogen of different origins: present, 2030, 2050*

Scenario	Current Technological Maturity	Levelised cost assumption	EUR/kgH_2** **today**	EUR/kgH_2** **2030**	EUR/kgH_2** **2050**
Domestic green H_2: Utility scale solar	Commercial (established)	Minimum	2.6	1.3	0.9
		Average	6.9	3.6	2.7
Domestic green H_2: Offshore wind	Commercial (established)	Minimum	3.6	1.8	0.9
		Average	6.9	4.8	3.0
Domestic blue H_2	Commercial (established)	Minimum	0.9	0.9	1.0
		Average	1.8	2 [6.8***]	2.0
Domestic turquoise H_2	Commercial (early)	Minimum	-	0	0
		Average	-	3 [4.1***]	3 [4.1***]

KEY: Colour coding (only for illustrative purposes): High price – low price
NOTE:
** Data from reference list 1 [IEA (2021a). IEA (2021b). IRENA (2021). H Quest via Collins (2021). BNEF (2021). BASF, Monolith Materials, Argonne International Laboratory, Universidad Politécnica de Madrid, via Conti, et al. (2021). Zachmann, et al. (2021)]*
*** Euros per kilogram of hydrogen*
**** Including use of non-crop 'sustainable biomethane' for upper end estimations. A blend of natural gas and biomethane is also possible. Every 10% of biomethane blended would add roughly 10% to the overall feedstock cost by 2030, although this is not infinitely scalable. Biomethane prices vary enormously. Company reported data are included in these estimates.*

55 The ratio between the total cost of production and the total hydrogen output, normalised per unit of hydrogen kilo.

56 IEA, IRENA and BloombergNEF, Bruegel, DIW Berlin, Columbia University, Energy Transitions Commission, Argonne National Laboratory, Universidad Politécnica de Madrid, together with the energy cost assumptions in the previous section.

57 BASF, Monolith Materials.

Figure 3: Reflections

- Consistent with the observations on electricity price forecasts, green hydrogen from offshore wind shows the greatest potential for cost reductions over the long term, but with considerable uncertainty. Utility-scale solar PV is the most competitive of the green hydrogen options at present, but with greater scalability limitations than offshore wind for domestic production.
- The cost of green hydrogen is based on production cost estimates for RES-E. However, in the event that renewable electricity remains scarce or constrained it will be available for hydrogen only at the overall electricity market price, not the production cost.
- In the context of the drive to electrify fossil-powered sectors (e.g. transport) and the parallel phase-out of coal for electricity generation and decrease in nuclear capacity, it is very unlikely that there will be 'excess' renewable electricity in the EU until at least 2040. On this basis, and while no certain predictions can be made, there are reasonable grounds to expect that the upper rather than lower cost estimates for green hydrogen are likely to be realised during this period.
- Blue hydrogen from natural gas is typically the most cost-effective decarbonised hydrogen source for the next decade. This will, however, be dependent on the future gas price, with consistently high prices favouring the competitiveness of electrified hydrogen technologies such as electrolysis and pyrolysis.
- In the case of blue and turquoise hydrogen, the role of methane emissions in the production process must be factored in. Biomethane could be used to 'offset' these emissions.
- Methane pyrolysis is the least mature of the production methods here, and certainly there are the least data available to assess its future cost and emission trajectory. Nevertheless, it has the potential to be a carbon sink and to support cross-sectoral decarbonisation aims in the process.
- Pyrolysis uses less than 15% of renewable electricity to produce hydrogen relative to electrolysis. This means that it is less sensitive to the cost of RES-E and therefore becomes relatively more competitive than electrolysis the higher the cost of RES-E.
- The range and diversity of key data/predictions of future costs in the literature is in itself an important finding, as they demonstrate the high level of uncertainty surrounding future hydrogen cost trends.

The following table shows the different EU ETS prices required to substitute grey hydrogen with domestic low and zero carbon alternatives of different origins. The data here provide a more granular breakdown of energy inputs, also considering the difference between fossil and bio-based methane feedstocks for blue hydrogen.

Figure 4: European Union Emission Trading System (EU ETS) prices to substitute grey hydrogen with low and zero carbon hydrogen of different origins, present, 2030, 2050*

Scenario	Levelised cost assumption	ETS price of substitution of **grey hydrogen: today** [EUR/tCO_2]**	ETS price of substitution of **grey hydrogen: 2030** [EUR/tCO_2]**	ETS price of substitution of **grey hydrogen: 2050** [EUR/tCO_2]**
Domestic green H_2 (Solar PV)	Average	220	90	20
	Minimum	45	0	0
Domestic green H_2 (Offshore wind)	Average	320	120	45
	Minimum	70	5	0
Domestic blue H_2: Natural gas feedstock	Average	70	26	25
	Minimum	0	0	0
Domestic blue H_2: Sustainable biomethane	Average	300	350	260
	Minimum	50	50	32
Domestic turquoise hydrogen	Average	-	40****	25****
	Minimum	-	0*** / ****	0*** /****

KEY: Colour coding (only for illustrative purposes): High price *low price*
NOTE:
** Data from reference list 1 [IEA (2021c). Agora (2021a). Burgess & Watson (2021). Engie (2021). Global CCS Institute (2021). Zachmann, et al. (2021)]*
** Euros per tonne of carbon dioxide emissions
*** Whenever the resultant ETS switching costs are negative, implying cost-competitiveness conditions even in the absence of carbon pricing, a value of zero is reported above.
**** Company reported data
The IEA WEO 2021 NZE scenario anticipates carbon prices of 220 EUR/tonne in advanced economies, 175 EUR/tonne in major and developing economies and slightly lower elsewhere by 2050 (p. 103).

Figure 4: Reflections

- The only low carbon production source that can currently be competitive at scale with grey hydrogen through carbon pricing is blue hydrogen with natural gas as feedstock.
- By 2030 it is likely that carbon prices will be over 100 EUR/t and green hydrogen will be widely competitive with grey hydrogen, assuming step change improvements in efficiency and cost reduction of electrolysers. However, this also assumes the availability of renewable electricity at production cost rather than market value.
- Turquoise hydrogen may not require any carbon price to be competitive. The biggest variable for this technology is arguably the value of the carbon co-product. At minimum, carbon black can be used as a stable and permanent form of carbon storage, and also as a soil improver in the agricultural sector. At high enough qualities, carbon black can be made into valuable and often critical products such as carbon nano tubes and graphene.

Figure 5 below offers an EU ETS threshold for substituting natural gas with domestic low and zero carbon hydrogen of different origins. This covers, for example, the use of hydrogen as a substitute for natural gas in heating or electricity generation. Nevertheless, the comparison between hydrogen and natural gas is made on a direct MWh basis and therefore does not take into account the lower volumetric energy density of hydrogen relative to methane.

Figure 5: European Union Emission Trading System (EU ETS) prices for substitution of natural gas with hydrogen of different origins, present, 2030, 2050* [58], [59]

Scenario	Levelised cost assumption	ETS price for substitution of **natural gas** combustion: **today** [EUR/tCO_2]**	ETS price for substitution of **natural gas** consumption: **2030** [EUR/tCO_2]**	ETS price for substitution of **natural gas** consumption: **2050** [EUR/tCO_2]**
Domestic green H_2 (Solar PV)	Average	725	460	240
	Minimum	80	15	0***
Domestic green H_2 (Offshore wind)	Average	725	510	280
	Minimum	210	80	0
Domestic blue H_2: Natural gas feedstock	Average	105	195	320
	Minimum	0	0	0
Domestic turquoise H_2	Average	-	280	280
	Minimum	-	0***/*****	0***/****

KEY: Colour coding (only for illustrative purposes): High price — low price
NOTE:
** Data from reference list 1 [IEA (2021c). Agora (2021a). Burgess & Watson (2021). Engie (2021). Global CCS Institute (2021). Zachmann, et al. (2021)]*
*** Euros per tonne of carbon dioxide emissions*
****Whenever the resultant ETS switching costs are negative, implying cost-competitiveness conditions even in the absence of carbon pricing, a value of zero is reported above.*
***** Company reported data*

Figure 5: Reflections

- Switching from natural gas to hydrogen can be expected to be broadly uncompetitive until significantly after 2030, even with relatively high carbon prices. This should give cause for careful thought, for example regarding the cost implications of mandatory offtake quotas.
- Switching from natural gas to low and zero carbon hydrogen is likely to require demand-side support such as very high subsidies for key sectors (e.g. steel and cement) or supply-side support such as guarantees of origin (GO) to derive a premium from the final product.
- These switching costs do not factor in the infrastructure/investment cost for energy-intensive industry switching from natural gas to hydrogen (new cement kilns, steel furnaces, etc.). Therefore, the real switching costs for energy-intensive industry to move from natural gas to hydrogen will be far higher.
- CCUS has the potential to play an important role in the interim period, subject to it being rolled out rapidly (so that it can be amortised by 2050) and at sufficient scale to be cost-effective and readily available to retrofit to existing energy-intensive industry infrastructure.
- The numbers in Figure 5 are to a very considerable extent dependent on the natural gas price and the relationship of natural gas prices to electricity prices. We assume natural gas and electricity prices to be within the 'typical' range, but in the light of recent market developments it is also possible that prices restabilise at different levels. In this event, also depending on the level of entanglement of electricity prices with gas prices, they can make a significant impact on the switching thresholds, potentially reducing them considerably.

58 These numbers are based on the calculated energy switching cost. They do not therefore take into account the cost of modifying plants and equipment (e.g. converting steel furnaces to hydrogen. Therefore, they are likely to appreciably under-estimate the real switching costs required). Moreover, the calculations only take into account process emissions, assuming 0 for green hydrogen, between 1 and 2kg for blue and 0-2kg for turquoise hydrogen. While there are some supply chain emissions associated with the infrastructure and maintenance of green hydrogen, the supply chain emissions of methane-based hydrogen are invariably much higher due to methane leakage. This increases with the amount of methane required (i.e. more for blue than turquoise). As a result, including full supply chain emissions of blue hydrogen might involve even higher emissions than continuing to use natural gas, for example in the following scenario. An assumed emission methane leak rate of 3.5% across the supply chain, full CCS including flue gases (CO2 capture rate 85%/ SMR CCS capture rate of 65%) = total emissions of 19.13kg CO2eq./kg h_2 (486kg CO2eq./MWh). The ETS would in this case support continued use of natural gas rather than blue hydrogen from fossil methane.

59 The methodology for calculating the ETS price required for switching is as follows. H_2 and natural gas equivalent MWh prices (per kg price of H2 x 25.4), an assumed natural gas emission factor of 200 kg/MWh, an assumed emission factor of green/turquoise H2 = 0, an assumed emission factor for blue H2 = 50.8kg /MWh. Subtract the emission factor of H2 from the emission factor of natural gas, calculate the result as a factor of 1,000 (KG) and multiply the resulting factor by the difference between the MWh price of energy inputs to get the ETS price required for switching.

From the above data and complementary information, we draw the following conclusions about some of the key variables and conditions that might shape the development of a clean hydrogen economy in Europe.

Key factors in the development of a clean hydrogen economy

A) Technological maturity

Low and zero-carbon hydrogen production methods remain relatively immature, with considerable variation between technologies. Electrolysis is arguably the most mature, with some commercial projects in operation. The International Energy Agency (IEA) classifies the most mature forms of electrolysis at a technology readiness level (TRL) of 9.[60] CCS technology has been applied at commercial scale in other sectors with varying levels of success, but it remains uncommon in the hydrogen sector. Nevertheless it has a TRL of 8-9.[61] Among the processes explored here, pyrolysis is the least developed, TRL 6-8[62], with the very first commercial operations installed only recently, but many more are likely to follow.[63] In this context, we can have the highest level of certainty about projected electrolyser and CCS development and cost trajectories, with potentially significant but nevertheless uncertain developments still to come in pyrolysis.

It remains to be seen how quickly the cost and efficiency of these technologies will change moving forwards, and also their capacities to operate at scale and in harmony with wider decarbonisation and land use objectives. Based on the data in this study, we expect a combination of technologies to be required at different points in the coming decades.

B) Future energy costs and availability

Unlike renewable electricity, which is a CAPEX-driven business model (wind and sunshine being free), low and zero-carbon hydrogen production is an OPEX-dominated business, as the production cost is driven to a considerable extent by the price of the energy input (gas, electricity).[64] Any prediction regarding the future cost of low and zero-carbon hydrogen therefore requires assumptions of the costs of RES-E and natural gas/biomethane, and the commodity prices of products required to develop the corresponding infrastructure.[65] In the case of renewable hydrogen, it also requires assumptions as to the number of hours a year that cost-effective RES-E is available to build in electrolysis plant capacity factors.

Many estimations that renewable hydrogen will be competitive with blue or turquoise hydrogen in the medium term rely on ambitious price reductions and load factor increases. The IEA, for example, estimates that for green hydrogen to be competitive with blue or turquoise hydrogen by 2030, renewable electricity supplies will be required at €10-20 MWh for 4000 hours p.a.[66] Such load factors and prices of EU-generated electricity will be very challenging.[67] Imports of green hydrogen may be a partial solution in the future, but this will take time and could pose fresh energy security challenges.[68]

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60 International Energy Agency (2021). ETP Clean Energy Technology Guide, https://www.iea.org/articles/etp-clean-energy-technology-guide

61 International Energy Agency (2021). ETP Clean Energy Technology Guide, https://www.iea.org/articles/etp-clean-energy-technology-guide

62 International Energy Agency (2021). ETP Clean Energy Technology Guide, https://www.iea.org/articles/etp-clean-energy-technology-guide

63 Monolith Materials (2021). https://monolith-corp.com/

64 For example, roughly 60% of the current cost of blue hydrogen is the cost of the natural gas feedstock. See here.

65 For example, the IEA found that "since the beginning of 2020, prices for PV-grade polysilicon more than quadrupled, steel has increased by 50%, aluminium by 80%, copper by 60%, and freight fees have risen six-fold. Compared with commodity prices in 2019, we [IEA] estimate that investment costs for utility-scale solar PV and onshore wind are 25% higher." (p.17)

66 IEA "World Energy Outlook 2020" and IEA "Future of Hydrogen" (2019). All rights reserved.

67 The European Clean Hydrogen Alliance (ECHA) is targeting green hydrogen costs of 5eur/kg in 2024 and 3eur/kg in 2030.

68 World Energy Council (2021). Decarbonised hydrogen imports into the European Union: challenges and opportunities, https://www.worldenergy.org/assets/downloads/WEC_Europe_Hydrogen_study.pdf?v=1635515415

Finally, as was mentioned above, estimations regarding the future cost and quantity of renewable hydrogen that can be supplied to the EU market also require assumptions regarding the availability of sufficient quantities of renewable electricity. If a new green or turquoise hydrogen plant buys renewable electricity in the market, this reduces the renewable electricity available for other purposes but increases the overall demand. If the marginal electricity supplier is gas or coal, the net result of green or turquoise hydrogen production is the additional fossil fuel electricity generation to cover the additional capacity required. The emissions associated with the resulting hydrogen, would be even higher than grey hydrogen in this scenario.[69] Addressing this issue of 'additionality' is therefore key to decarbonisation of the sector. There are, however, potential solutions, for example requiring new electrified hydrogen plants (electrolysis, pyrolysis etc.) to source 'additional' renewable electricity based on corporate power purchase agreements or direct lines that do not count towards renewable electricity targets.[70]

This is one of the issues that the Commission will need to address when designing a robust accounting and compliance system (e.g. based on GOs) for renewable energy and wider hydrogen guarantees of origin. The FSR has a dedicated paper with recommendations on this.[71]

C) Physical challenges and constraints

Conversation on a potential future decarbonised hydrogen economy is often quite abstract and based on theoretical assumptions about what is possible at a given cost and level of technological maturity. Although this is useful and important, numerical forecasts (such as those in this study) can add to this abstraction. It is important to frame theory within the boundaries of tangible physical constraints. For the decarbonised hydrogen economy, four of the most important and interconnected of these boundaries are (i) access to fresh water, (ii) weather conditions, (iii) geological conditions and (iv) competition for land.

With current technology, electrolysers require uncontaminated fresh water to function at a high level of efficiency. The availability of this resource often does not closely correlate with the weather conditions required for cheap and abundant RES-E, particularly solar PV.[72] Installing large quantities of electrolyser capacity in areas with freshwater scarcity could contradict the EU taxonomy requirement to 'do no significant harm', for example.[73] Further study is required as to how significant the issue of water scarcity is, and whether this will be a limiting factor for renewable hydrogen production in areas with favourable energy conditions, such as southern Europe and north Africa (in the case of imported hydrogen).[74]

One alternative is to desalinate sea water for use in electrolysers. Estimates suggest[75, 76] that this requires little additional electricity (~0.1%), thus limiting competition for scarce renewable electricity while adding little cost to the final hydrogen product (~€0.01/KG). Nevertheless, desalination will increase the physical footprint of the infrastructure required, potentially adding to competition for land use and the impact on biodiversity, and also creating challenges and limitations in the location of electrolysers. It

69 Belmans, Dos Reis, Vingerhoets (2021). Electrification and sustainable fuels: competing for wind and sun, https://cadmus.eui.eu/handle/1814/71402

70 The resultant certified renewable hydrogen would count towards any renewable energy targets. Nevertheless, it is worth noting that even the allocation of 'additional' dedicated RES-E capacity would still compete with grid RES-E for land, and potentially for budgetary support.

71 Pototschnig (2021). Renewable hydrogen and the "additionality" requirement: why making it more complex than is needed?, https://fsr.eui.eu/publications/?handle=1814/72459

72 European Environment Agency (2021). Use of freshwater resources in Europe, https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-3/assessment-4

73 European Commission (2021). EU taxonomy for sustainable activities, https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

74 It is worth noting that current fossil hydrogen production requires large quantities of water, which would no longer be required in a decarbonised hydrogen economy, thus offsetting the total 'additional' requirement.

75 ACS Energy Lett. (2021). Does the Green Hydrogen Economy Have a Water Problem?, 6, 3167-3169, https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.1c01375

76 Khan, et al. (2021). Seawater electrolysis for hydrogen production: a solution looking for a problem?, https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee00870f

remains to be seen whether it will be possible to perform cost-effective electrolysis using salt water[77] or to establish supply chains to desalinate water cheaply without emissions and at scale.

According to the data in this study, SMR with CCS is likely to be the most cost-effective form of low-carbon hydrogen in the coming years. Nevertheless, CCS requires certain geological conditions to store CO_2 long term or a pipeline network to transport large quantities of CO_2 to a location with suitable geology.[78] At present, the EU does not have an extensive CO_2 transportation network, and a large amount of the SMR infrastructure in place is not well correlated with the availability of local geological storage.[79] Repurposing existing natural gas infrastructure could play a role here in transporting CO_2 and hydrogen as required.[80]

The kinds of very practical considerations briefly touched on here are just as important as the theoretical cost and maturity of a product or process and should not be lost in the debate.

D) Customer inertia and demand trends

Long-term projections regarding the future demand for low and zero-carbon hydrogen are relatively unknown, with different predictions originating from different notions of suitable energy choices across sectors.[81]

Existing demand for hydrogen comes almost entirely from oil refining and ammonia production.[82] However, predicting future demand in existing areas of use is difficult, for example regarding projected oil demand and the requirement for artificial fertiliser in an evolving EU agriculture sector.[83] The use of hydrogen in new applications (e.g. as an energy vector and in heating, transportation etc.) are also challenging to predict, with a range of technologies still vying for a share of these markets. The outcome of this competition will not only be decided by cost-effectiveness or other objective criteria but also by the willingness of consumers to adopt different technologies.[84, 85] Any hydrogen policy should attempt to take into account these uncertainties.

77 Khan, et al. (2021). Seawater electrolysis for hydrogen production: a solution looking for a problem?, https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee00870f

78 International Panel on Climate Change (2018). IPCC Special Report on Carbon Dioxide Capture and Storage, 197-265, https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter5-1.pdf

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