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REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL

Progress on competitiveness of clean energy technologies

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1. INTRODUCTION

Russia's unprovoked and unjustified military aggression against Ukraine has massively disrupted the world's energy system. It has shown the EU's over-dependency on Russian fossil fuels and emphasised the need to enhance the resilience of the EU's energy system, which had already been challenged by the COVID-19 crisis[1]. The all-time high energy prices and the risk of supply shortages across the EU have made it even more urgent to accelerate the twin green and digital transition under the European Green Deal[2] and to ensure a more secure, affordable, resilient, and independent energy system.

The year 2022 has been marked by the REPowerEU plan[3], a crucial element of the EU's policy response to the unprecedented crisis. The plan is a roadmap to phase out the EU's dependency on Russian energy imports as soon as possible through measures on energy saving, the diversification of energy supplies, and the accelerated roll-out of renewable energy.

Furthermore, with the "Save gas for a safe winter" Communication[4], the Commission has put forward a plan to reduce gas use in the EU by 15% until next spring. The Council has adopted two regulations on storage and coordinated demand reduction measures for gas respectively[5]. In September 2022, the Council agreed on the Commission proposal for a "Regulation on an emergency intervention to address high energy prices"[6] to alleviate the impact of energy prices on the EU's consumers, while also addressing the unprecedented volatility and uncertainty in EU and global energy markets. In particular, this intervention includes a reduction of electricity consumption, a revenue cap for inframarginal power generation, and a temporary, mandatory, solidarity contribution from fossil fuel companies.

Delivering on the REPowerEU objectives will require an additional cumulative investment of EUR 210 billion between now and 2027 in addition to the investment already needed to reach climate neutrality by 2050[7]. This investment will support the massive scaling-up and speeding-up of the deployment of clean energy technologies (e.g. solar photovoltaic, wind, heat pumps, energy saving technologies, biomethane and renewable hydrogen), which is of critical importance to face the double energy and climate urgency. Overcoming the related technological and non-technological challenges will also require a strong and competitive EU clean energy sector.

The REPowerEU plan confirmed the commitment to achieve the European Green Deal's long-term goal of making the EU climate-neutral by 2050, and to fully implement the Fit for 55 package presented in July 2021[8]. Delivering on the European Green Deal objectives will

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1 COM(2021) 952 final and SWD(2021) 307 final ('Progress on competitiveness of clean energy technologies').
2 COM(2019) 640 final ('The European Green Deal').
3 COM(2022) 230 final ('REPowerEU Plan').
4 COM(2022) 360 final ('Save gas for a safe winter').
5 OJ L 173, 30.6.2022. Regulation (EU) 2022/1032 of the European Parliament and of the Council of 29 June 2022 amending Regulations (EU) 2017/1938 and (EC) No 715/2009 with regard to gas storage; OJ L 206, 8.8.2022. Council Regulation (EU) 2022/1369 of 5 August 2022 on coordinated demand-reduction measures for gas.
6 COM(2022) 473 final ('Proposal for a Council Regulation on an emergency intervention to address high energy prices').
7 COM(2021) 557 final ('Amendment of Directive 2018/2001, Regulation 2018/1999 Directive 98/70/EC as regards the promotion of energy from renewable sources').
8 COM(2021) 550 final ('Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality').

require the EU to develop, implement and scale-up innovative energy efficiency and renewable energies solutions. Half of the greenhouse gas emissions reductions expected by 2050 will require technologies that are not yet ready for the market[9], so research and innovation (R&I) activities are a crucial component to increase the EU's technological sovereignty and global competitiveness.

Within this framework, and in line with previous editions, this third annual competitiveness progress report[10] presents the current and projected state of play for different clean and low carbon energy technologies and solutions[11]. It also maps the research, innovation and competitiveness aspects of the EU's clean energy system as a whole[12].

The 2021 edition was important for the assessment of the COVID-19 economic recovery, because it highlighted how improvements in competitiveness can mitigate the pandemic's economic and social impact in the short and medium terms.

This year's report must take into account the EU's call for the higher roll-out of clean energy technologies and the impact of the energy crisis on the sector. Against this backdrop, the report builds on available data to provide insights into ways of reinforcing EU's competitiveness in strategic energy value chains, while also increasing the penetration of the EU's clean energy technologies. At the same time, ongoing and fast-changing geopolitical, energy and climate developments mean that the most up-to-date quantitative data is not always able to reflect the unprecedented situation adequately. Therefore, this report focuses on progress made until the end of 2021, building on the consolidated data available until then. More recent data have been indicated when available and reliable. However, these are scarce and therefore cannot yet fully reflect the impact of the current energy crisis on the competitiveness of clean energy technologies. Wherever possible, and in order to take into account the recent challenges faced by the clean energy sector and their impact on it, the analysis builds on the already visible implications and qualitative assessments for the year 2022; however the full impact can only be assessed in next year's progress report.

Competitiveness is a complex and multifaceted concept which cannot be defined by a single indicator[13]. This report therefore assesses the competitiveness of the EU's clean energy system as a whole (Section 2), and of specific clean energy technologies and solutions (Section 3) by analysing a defined set of indicators (Annex I). As of this year, the

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9 European Commission, Directorate-General for Research and Innovation, *Research and innovation to REPower the EU*, Publications Office of the European Union, Luxembourg, 2022, https://data.europa.eu/doi/10.2777/74947.

10 Report from the Commission to the European Parliament and the Council on '*Progress on Competitiveness of clean energy technologies*' (first edition: COM(2020) 953 final; second edition: COM(2021) 952 final).

11 These include: Solar Photovoltaics, Offshore and Onshore Wind, Heat Pumps for building applications, Batteries, Renewable Hydrogen production through water electrolysis, Renewable Fuels, Smart technologies for energy management, Hydropower, Ocean Energy, Geothermal, Carbon Capture Utilisation and Storage (CCUS), Bioenergy, Concentrated Solar Power and Heat (CSP), Nuclear.

12 In this report, the clean energy system covers three market segments:
(1) renewable energy, including manufacturing, installation and generation;
(2) energy efficiency and management systems that include technologies and activities such as smart meters, smart grids, storage and renovation of buildings; and
(3) electric mobility, which includes components such as batteries and fuel cells essential for electric vehicles and charging infrastructures.

13 Based on the conclusions of the Competitiveness Council of 28 July 2020.

Commission's Clean Energy Technology Observatory (CETO) will carry out the in-depth evidence-based analysis underpinning this report[14].

This report is published in accordance with Article 35(1)(m) of the Regulation on the Governance of the Energy Union and Climate Action[15] and accompanies the State of the Energy Union report[16].

2. OVERALL COMPETITIVENESS OF THE EU CLEAN ENERGY SECTOR

2.1 Setting the scene: recent developments

2.1.1 Energy prices and costs: recent trends

As stated in previous competitiveness progress reports, industrial electricity and gas prices have been higher in the EU than in most non-EU G20 countries during the last decade. The unjustified and unprovoked Russian invasion of Ukraine has increased the already all-time high prices observed in 2021 in the EU and many other regions of the world. Wholesale gas prices in Europe were five times higher in the first quarter of 2022 than a year earlier and in August 2022 reached an historical high point, before falling to lower levels. Due to gas power plants often being a price-setter in European markets, this has resulted in a similar trend for wholesale electricity prices[17]. They have also affected manufacturing costs for some sectors, in particular, energy-intensive industries. The price of commodities has also been increasing. The fifth Energy Prices and Costs report[18], which is due for adoption at the end of 2022, will provide updated quantitative data and analysis.

The EU and Member States have already taken several measures since 2021 to help mitigate the impact of high energy prices[19]. The Commission's proposal for a Regulation on an Emergency Intervention to Address High Energy Prices, as agreed by the Council in September 2022, includes tools to reduce the use of gas to generate power by around 4% over the winter, thereby reducing pressure on prices, and a proposal to raise more than EUR 140 billion for Member States to help alleviate the impact of high energy prices on consumers[20].

Although the impact of this trend on the clean energy technologies' value chain remains mixed, it may indicate an improvement in their competitiveness, in particular as compared to non-renewable alternatives[21]. For example, solar photovoltaic electricity generation is already the cheapest generation source in a growing number of countries. In the production of renewable hydrogen through water electrolysis, however, the cost of electricity is one of the main factors affecting the economic viability of electrolysers.

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14 https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en.

15 OJ L 328, 21.12.2018. Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action.

16 COM(2022) 547 final ('State of the Energy Union 2022').

17 European Commission, Directorate-General for Energy, Market Observatory for Energy, *Quarterly Report on European gas markets,* Vol. 15.

18 Previous 2020 edition: COM(2020) 951 final ('Energy prices and costs in Europe').

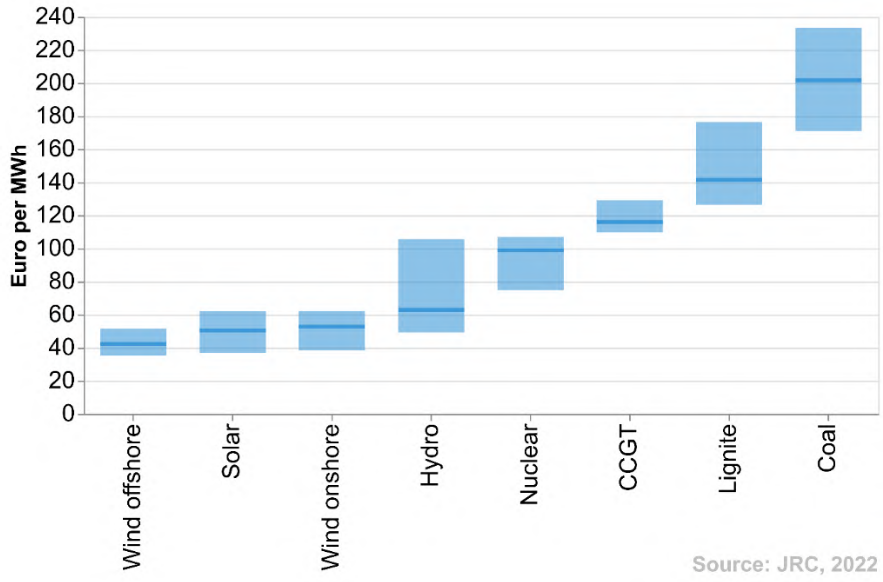
19 Measures include the Commission's Communication COM(2021) 660 final ('Tackling rising energy prices: a toolbox for action and support'*)*, and Communication COM(2022) 138 final ('Security of supply and affordable energy prices').

20 COM(2022) 473 final ('Proposal for a Council Regulation on an emergency intervention to address high energy prices').

21 The International Renewable Energy Agency (IRENA), *World Energy Transitions Outlook 2022: 1.5°C Pathway*, Abu Dhabi.

Figure 1 provides more insights into the costs of clean energy technologies. It gives a snapshot of levelised cost of electricity (LCOE) calculations for the year 2021 for a range of representative conditions[22] across the EU. The results indicate that technology fleets with low variable costs (including variable operational costs and fuel costs) have been highly cost-competitive in 2021. This finding is most robust for solar- and wind-powered generation which have LCOE in the range of EUR/MWh 40 to 60. Furthermore, the Combined Cycle Gas Turbine (CCGT) fleet appears to have been more competitive on average in 2021 than coal-fired generation. CCGT benefited from preferred dispatch during the first three quarters of 2021, while the fuel switch only became important in the fourth quarter of 2021. This allowed for significantly higher capacity factors for CCGT in 2021[23]. The rise of gas prices continued to support gas-to-coal switching during the first quarter of 2022, despite the increase in carbon prices. However, the high coal prices at the beginning of the second quarter of 2022 started to close the gap, and recent announcements by some Member States to temporarily increase the use of coal-fired plants have led to expectations that coal prices will rise further in the coming months.

*Figure **1**: Snapshot of technology-fleet specific levelised costs of electricity (LCOE) for the year 2021. The light blue bars display a range across the EU27. The thick blue lines denote median.*



Source: Joint Research Centre METIS model simulation, 2022[24]

The very high energy prices have generated large financial gains for electricity producers with lower marginal costs (e.g. those operating in the wind and solar energy sectors). The Commission therefore proposed a regulation on an emergency intervention to address high energy prices[25], which was politically agreed at the extraordinary meeting of the Energy

[22] Data points are shown for first to third inter-quartile range to filter for outliers.
[23] The modelled capacity factors could overestimate actual fuel switching and thus differences in capacity factors to some extent (see section 2.1 in Kanellopoulos, K., De Felice, M., Busch, S. and Koolen, D., *Simulating the electricity price hike in 2021*, JRC127862, EUR 30965 EN, Publications Office of the European Union, Luxembourg, 2022).
[24] JRC127862 Kanellopoulos, K., De Felice, M., Busch, S. and Koolen, D., Simulating the electricity price hike in 2021, EUR 30965 EN, Publications Office of the European Union, Luxembourg, 2022.
[25] COM(2022) 473 final ('Proposal for a Council Regulation on an emergency intervention to address high energy prices').

Council on 30 September. This regulation includes the temporary capping and redistribution of the inframarginal technologies revenues to alleviate difficulties for energy consumers and society in general. It also includes a mandatory temporary solidarity contribution applying to the profits of businesses active in the crude petroleum, natural gas, coal and refinery sectors, which have significantly increased by comparison with previous years. The current energy/fossil fuel crisis is the latest reminder of the need for a change in paradigm in order to ensure future stability.

The REPowerEU plan calls for a massive scaling-up and speeding-up of renewable energy in power generation, industry, buildings and transport - not only to accelerate the EU energy independence, and give a boost to the green transition, but also to lower electricity prices and reduce fossil fuel imports over time[26]. Measures will include boosting renewable energy which will require an electricity infrastructure that is fit for purpose. To deliver on the REPowerEU objectives, renewable energy deployment needs to be combined with energy-saving and energy efficiency measures[27].

2.1.1 Global resources and materials supply chains: vulnerabilities and disruptions

Together with concerns about the reliability of existing supply chains, and in particular the supply of natural gas, both the COVID-19 pandemic and the current geopolitical context have led to disruptions in some global supply chains of materials and resources, and have therefore affected the clean energy sector. The EU heavily relies on supplies from third countries and the twin green and digital transition will be fuelled by access to raw materials. The recent trends in the global supply chains of materials and resources have highlighted the urgency to strengthen the EU's resilience and its energy supply security through materials and resources independence, and technology sovereignty.

The availability of materials and the resilience of supply chains is a prerequisite for delivering on REPowerEU, because the increased demand for clean technologies goes hand in hand with a higher demand for resources such as metals and minerals. Technologies that are heavily reliant on imported raw materials, or components containing these materials include wind (permanent magnets, rare earth elements), solar PV (silver, germanium, gallium, indium, cadmium, silicon metal), and batteries (cobalt, lithium, graphite, manganese, nickel)[28]. The International Energy Agency (IEA) forecasts that the total global demand for minerals, due to the announced renewables rollout, is set to double or even quadruple by 2040[29].

Surging raw material prices affect the costs of clean energy technologies. The prices of commodities needed for these technologies, like lithium and cobalt, more than doubled in 2021, while those for copper and aluminium increased by around 25% to 40%[30]. In the same year, the decade-long trend of cost reductions for wind turbines and Solar PV modules was

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26 See Section 3, Page 6 COM(2022) 230 final ('REPowerEU Plan').
27 COM(2022) 360 final ('Save gas for a safe winter').
28 European Commission, *Critical materials for strategic technologies and sectors in the EU - a foresight study*, 2020, https://ec.europa.eu/docsroom/documents/42882.
29 IEA, *The Role of Critical Minerals in Clean Energy Transitions*, revised version in May 2022.
30 Kim, T., *Critical minerals threaten a decades-long trend of cost declines for clean energy technologies*, IEA website, May 2022.

reversed: compared to 2020, their prices increased by 9% and 16% respectively. Battery packs will be at least 15% more expensive in 2022 than in 2021[31].

An emerging challenge is to avoid replacing fossil fuel dependency with a dependency on imported raw materials and the technological expertise for their processing and for manufacturing components. For instance, China has a near monopoly in mining and processing the rare earth elements crucial for clean energy technologies, combined with a strong market position within their production chain.

The resource dependency challenge comes in three parts. Firstly, the EU faces an increased competition for access to critical raw materials as other countries increase their own efforts to build up their capacity and potentially restrict their exports. Half of the 30 Critical Raw Materials listed by the EU[32] are imported in proportions above 80% in volume, which is especially concerning when supply is concentrated in very few countries.

Secondly, despite the significant progress made in terms of circular economy and recycling rates (more than 50% of some metals[33] are now recycled, covering more than 25% of their consumption[34]), secondary raw materials alone will not be sufficient to address high - and still growing - demand. Secondary raw materials also present additional challenges (e.g. higher recycling costs for some materials, technical feasibility and the insufficient availability of end-of-life assemblies). However, the economics of recycling will improve as the cost of primary sourced materials and the volume of available end-of-life assemblies increase. Secondary raw materials will therefore be an important source of supply after 2030 - provided that the necessary investment starts now. Innovative recyclability design is also very important.

Thirdly, there is theoretical potential to cover between 5 and 55% of Europe's 2030 needs by extracting raw materials from European soils[35]. However, fostering domestic mining capabilities faces obstacles due to long permitting procedures and environmental concerns, insufficient refining capacity, and a lack of skilled labour and expertise. The new proposal for a Battery Regulation[36] is an example of a flagship initiative which will help Europe to become a leader in the circular economy of batteries - starting with sustainable mining and ending with recycling.

Scarcity of resources, such as land and water – whether for siting of solar, wind or bioenergy, or for water electrolysis to produce renewable hydrogen – could constrain the further deployment of clean energy technologies at the desired level in the EU. Facilitating multiple uses of space such as agri-PV (combining agriculture and solar PV production) and designating sites in maritime spatial planning for simultaneous activities such as fisheries and offshore renewable energy can help in overcoming these constraints. At the same time, taking

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31 IEA, *The Role of Critical Minerals in Clean Energy Transitions*, revised version of May 2022.

32 COM(2020) 474 final, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*.

33 Iron, zinc or platinum.

34 European Commission, Directorate-General for Energy: Guevara Opinska, L., Gérard, F., Hoogland, O., et al., *Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis : final report*, Publications Office of the European Union, Luxembourg, 2021, https://data.europa.eu/doi/10.2833/946002

35 KU Leuven, *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge*, 2022.

36 COM(2020) 798 final, ('Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020').

into account water availability is of outmost importance for Member States to consider when designing the energy mix.

An effective approach to the EU's dependency on imports of the raw materials required for the manufacturing of clean energy technologies will be crucial to ensure the sector's future competitiveness (in terms of costs, technology sovereignty and resilience) and to deliver on the twin green and digital transition. The Commission published an action plan in 2020[37] to alleviate supply risk. This included actions to diversify sourcing outside the EU (e.g. through strategic raw materials partnerships); fostering the circular economy (e.g. through eco-design, R&I or mapping the availability of critical raw materials in the urban mine or tailings); and enabling domestic potential (e.g. using earth observation technology). In addition to securing supply, the EU may also have to build up strategic reserves where supply is at risk. The President of the European Commission therefore announced a European Critical Raw Materials Act in her State of the Union address on 14 September 2022.

2.1.2 Impact of COVID-19 and recovery

COVID-19's mixed economic impact was a major threat to the EU's clean energy sector in 2020-2021.

On the one hand, with a turnover of EUR 163 billion in 2020 and a gross value added (GVA) of EUR 70 billion, the EU's renewable energy industry increased by 9% and 8% respectively by comparison with 2019 figures. Overall, it generated approximately four times more value added per euro of turnover[38] than the fossil fuel industry, and nearly 70% more than the EU's overall manufacturing sector[39]. However, this ratio worsened slightly in 2020, indicating an increased leakage (e.g. in the form of imports).

In 2021, the EU's manufacturing[40] of most clean energy technologies and solutions largely increased, reversing the trend seen in 2020. The EU's production of batteries had a bumper year with production value quadrupling by comparison with 2020 values as more capacity came online. Heat pump, wind and solar PV production grew by 30% in 2021 (heat pumps had a record year; wind bounced back to pre-pandemic levels; and solar PV reversed the declining trend seen since 2011). Production of biofuels, mainly biodiesel, grew by 40% and increased widely across Member States, while production of bioenergy (e.g. pellets, starch residues and wood chips) increased by 5%. Hydrogen production[41] rose by nearly 50% as the Netherlands more than doubled its production in 2021.

The simultaneous increase of prices that started in 2021 may nevertheless give an overly positive picture of production growth. In addition, some technologies experienced an increase of imports to meet the growing demand in the EU. For example, 2021 was the year with the greatest relative increase in the EU trade deficit in heat pumps (EUR 390 million in 2021 as

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[37] COM(2020) 474 final ('Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability').

[38] The fossil fuel industry's gross value added per euro of turnover is less than EUR 0.10 (Eurostat Structural Business Statistics).

[39] The GVA to turnover ratio for manufacturing (NACE C) in the EU is about EUR 0.25 (Eurostat SBS_NA_IND_R2 data).

[40] This refers to production value in monetary terms (EUR).

[41] This includes all hydrogen, irrespective of production route.

compared with EUR 40 million in 2020, with 2020 being the first year in which the EU trade surplus turned into a deficit), followed by biofuels (EUR 2.3 billion in 2021; EUR 1.4 billion in 2020) and solar PVs (EUR 9.2 billion in 2021; EUR 6.1 billion in 2020). Nonetheless, the EU maintained a positive trade balance in wind energy technology (EUR 2.6 billion in 2021; EUR 2 billion in 2020) and in hydropower technology, despite a decreasing trend observed since 2015 (EUR 211 million in 2021; EUR 232 million in 2020).

The EU's economic recovery policies, such as the Recovery and Resilience Facility (RRF) within the NextGenerationEU[42], are a key driver for refocusing and enhancing investments in the clean energy sector. In October 2022, the Council agreed[43] on the European Commission proposal[44] to add a dedicated REPowerEU chapter into Member States' Recovery and Resilience Plans (RRPs) in order to finance key investments and reforms which will help achieve the REPowerEU objectives[45].

The reforms and investments proposed by the Member States in their RRPs have exceeded both the climate and digital expenditure targets so far (at least 37% and 20% of the RRPs' expenditure respectively)[46]. In the 26[47] RRPs approved by the Commission by 8 September 2022, measures worth approximately EUR 200 billion have been dedicated to the climate transition and EUR 128 billion to digital transformation [48], representing 40% and 26% of the total allocation of these Member States (grants and loans) respectively.

42 COM(2020) 456 final ('Europe's moment: Repair and Prepare for the Next Generation').

43 https://www.consilium.europa.eu/en/press/press-releases/2022/10/04/repowereu-council-agrees-its-position/

44 COM(2022) 231 final, ('Proposal for a regulation of the European Parliament and Council amending Regulation (EU) 2021/241 as regards REPowerEU chapters in recovery and resilience plans and amending Regulation (EU) 2021/1060 , Regulation (EU) 2021/2115, Directive 2003/87/EC and Decision (EU) 2015/1814').

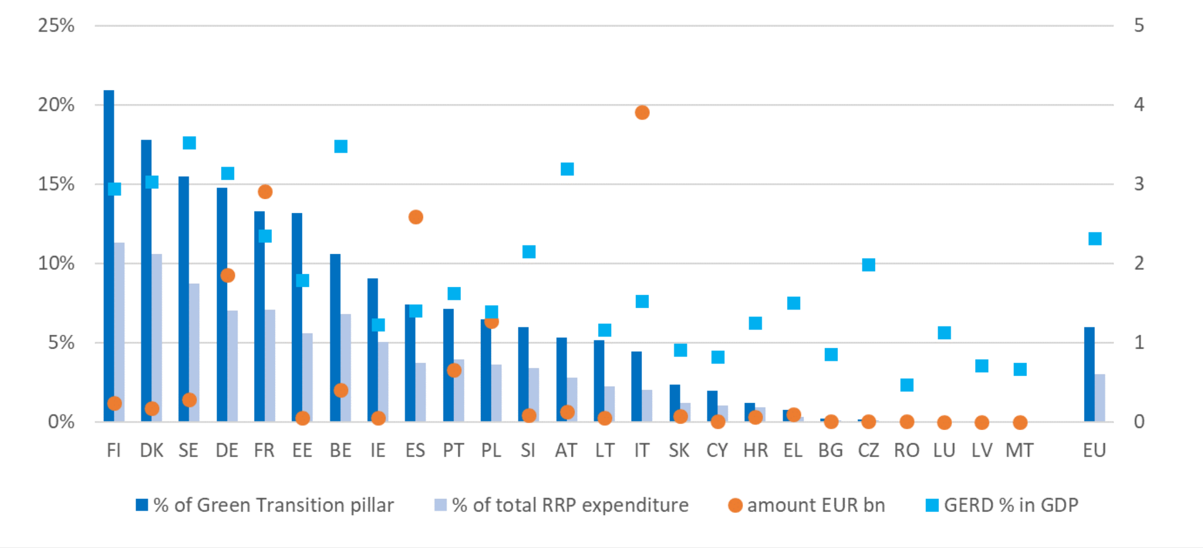
45 The proposal includes additional EU budgetary reallocations to complement the still available EUR 225 billion of RRF loans and calls for an increase in funds for the RRF. The European Commission has initiated bilateral discussions with Member States to identify reforms and investments that could potentially be eligible for financing under the new REPowerEU chapters. The EU funding complements other available public and private financing, which will play a key role in delivering the investments needed for REPowerEU.

46 Progress in implementing the RRP's can be followed live on the Recovery and Resilience Scoreboard, an online platform set up by the Commission in December 2021.

47 AT, BE, BG, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, IE, IT, LT, LU, LV, MT, NL PL, PT, RO, SE, SI, SK.

48 The RRPs had to specify and justify to what extent each measure contributes fully (100%), partly (40%) or has no impact (0%) on the climate objective. The contribution to the climate objective has been calculated using Annex VI of the RRF Regulation, respectively. Combining the coefficients with the cost estimates of each measure makes it possible to calculate to what extent the plans contribute to the climate target.

Figure 2: R&D&I in green activities in the RRPs as a share (left axis) and absolute amount (right axis). The R&D intensity vs GDP (right axis) is also given for comparison.



Source: JRC based on DG ECFIN data

The 25 RRPs approved by the Council 8 September 2022 include measures related to R&I for a total budget of EUR 47 billion[49] (including both thematic and horizontal investments[50]). Within this figure, EUR 14.9 billion have been allocated to investments in Research, Development and Innovation (R&D&I) in green activities (Figure 2).

2.1.3 Human capital & skills

The latest data on worldwide **human capital** show that, while the clean energy sector has been resilient during the COVID-19 pandemic, skills gaps and shortages increased in 2021 and are expected to continue in 2022.

Employment in the EU's broader clean energy sector[51] reached 1.8 million in 2019, with an average annual growth of 3% since 2015[52] and representing 1% of total EU employment. By comparison, employment in the overall economy grew by 1% a year on average[53], while

[49] The figures are based on the pillar tagging methodology for the Recovery and Resilience Scoreboard and correspond to the measures allocated to the policy areas 'R&D&I in green activities', 'digital-related measures in R&D&I' and 'R&D&I" as primary or secondary policy areas. The Council has not yet adopted the NL RRP, and therefore no data is yet available under the pillar tagging methodology. More information on the Recovery and Resilience Scoreboard is available at https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/

[50] Thematic R&I investments include those targeted at the green transition, digital technologies and health, while horizontal R&I investment involve cross-cutting measures that e.g. strengthen innovation ecosystems, upgrade research infrastructure and support business innovation.. For more information, the Recovery and Resilience Scoreboard is available at: https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/.

[51] The clean energy sector figures in the report refer to data based on Eurostat EGSS (categories 'CREMA13A', 'CREMA13B' and 'CEPA1'). 'CREMA13A' (production of energy from renewable resources) includes the manufacturing of technologies needed to produce renewable energy. CREMA 13B (heat/energy saving and management) includes heat pumps, smart meters, energetic refurbishment activities, insulation materials, and parts of smart grids. CEPA1 (protection of ambient air and climate) includes electric and hybrid cars, buses and other cleaner and more efficient vehicles, and charging infrastructure that is essential for the operation of electric vehicles (this also includes components such as batteries, fuel cells and electric power trains that are essential for electric vehicles.

[52] Eurostat [env_ac_egss1].

[53] Eurostat [lfsi_emp_a].

employment in the fossil energy industry declined by 2% on average in the last decade[54]. China ranked first in the world in 2020 (39%) followed by the EU (11%)[55] in worldwide employment in the "Renewable Energy" sector, which in total accounted for 12 million jobs[56].

The composition of jobs in the EU broader clean energy sector has changed in several ways[57]. The heat pump industry[58] is overtaking the solid biofuels[59] and wind energy sectors, as the largest employer. This is mainly due to the increase in installation of heat pumps. This trend is likely to continue with the REPowerEU plan and new product offerings available for the renovation sector[60]. In addition, the clean energy sector is 20% more productive than the overall economy on average. Since 2015, labour productivity has been increasing faster in the clean energy sector (2.5% annually) than in the overall economy (1.8% annually). This increase has been driven by the e-mobility sector (5% annually) and renewables (4% annually), with different trends observed depending on the technologies.

However, nearly 30% of EU businesses involved in electrical equipment manufacturing[61] have experienced **labour shortages** in 2022, reaching even higher levels than in 2018. This is mainly due to the overall economic recovery from the pandemic combined with the clean energy sector's slowness in building the skills capacities required by the green and digital transition[62]. With over 70% of EU businesses involved in electrical equipment manufacturing facing materials shortages in 2022, these trends show the growing risk of clean energy supply chain disruptions (Figure 3).

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[54] Eurostat [sbs_na_ind_r2].

[55] International Renewable Energy Agency (IRENA) and International Labour Organization (ILO), *Renewable Energy and Jobs – Annual Review 2021*, Abu Dhabi and Geneva.

[56] This includes direct and indirect employment.

[57] EurObserv'ER. *The State of Renewable Energies in Europe – Edition 2021 20th EurObserv'ER Report*, 2022. This figure includes heat pumps.

[58] Heat pumps accounted for 24% of all jobs in renewables, whereas solid biofuels and wind energy each contributed 20%. Based on: EurObserv'ER. *The State of Renewable Energies in Europe – Edition 2021 20th EurObserv'ER Report,* 2022.

[59] Methodological revisions have affected especially biofuel data, which is updated based on project data from the Horizon 2020 project ADVANCEFUEL.

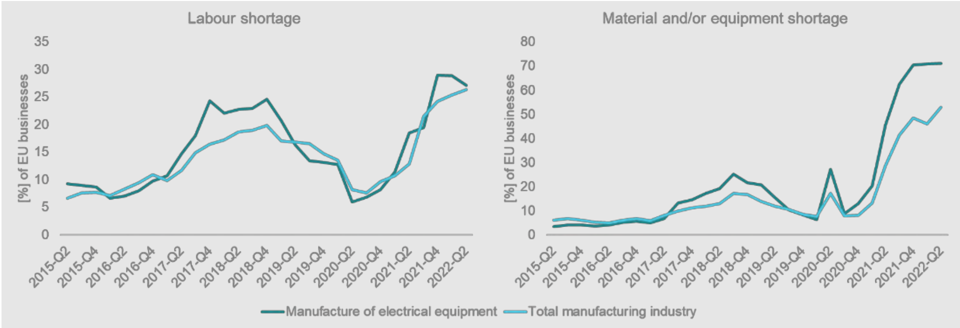
[60] European Heat Pump Association (EHPA). *European Heat Pump Market and Statistics Report 2021,* 2022.

[61] The NACE '27 – Manufacture of electrical equipment' code is used as a proxy for clean energy manufacturing industry as many clean energy technologies fall under this category. It is also used as a proxy for the renewables industrial ecosystem in the EU's industrial strategy [COM(2020)108 final and its recent update COM(2021)350 final].

[62] The slowness is due to various job misalignments (e.g. spatial, sectoral, occupational and temporal). The fast-paced change towards green and digital contrasts with the time to build skills capacity. See, for example:

- Czako, V., *Skills for the clean energy transition,* 2022. (forthcoming);
- Asikainen, T., Bitat, A., Bol, E., Czako, V., Marmier, A., Muench, S., Murauskaite-Bull, I., Scapolo, F. and Stoermer, E., *The future of jobs is green*, Publications Office of the European Union, Luxembourg, 2021, doi:10.2760/218792, JRC126047;
- Cedefop (European Centre for the Development of Vocational Training), *An ally in the green transition – VET, especially apprenticeship, can provide the skills needed for greening jobs – and in turn help shape them,* Publications Office of the European Union, Luxembourg, 2022, http://data.europa.eu/doi/10.2801/712651.

Figure 3: Labour and material shortages experienced by EU electrical equipment manufacturers and by the EU's total manufacturing sector [%].



Source: JRC based on Business Survey data from DG ECFIN[63]

The REPowerEU plan calls for increased efforts to overcome the skilled labour shortages in various segments of clean energy technology. To this end and building on already existing activities within the EU[64], the plan announces support for skills through ERASMUS+[65] and the Joint Undertaking on Clean Hydrogen[66]. The EU solar energy strategy also proposes specific actions[67]. The 2022 Clean Energy Industrial Forum (CEIF) adopted the Joint Declaration on Skills[68], undertaking to take concrete steps to address the skilled labour shortages that have been identified[69]. In 2022, the Council also adopted a recommendation inviting Member States to adopt measures which address the employment and social aspects of climate, energy and environmental policies[70]. The European Commission proposed on 12 October 2022 to make 2023 the European Year of Skills in order to make the EU more attractive for skilled workers[71].

Gender imbalances in the energy sector's workforce and in the energy-related research and innovation continue, although consistent and continuous gender-disaggregated data is largely lacking[72]. The under-representation of women in the decision-making of energy companies and in higher education in science, technology, engineering, and mathematics (STEM) sub-fields is reflected in a lower share of patent applications with women inventors (only 20% in all patent classes in 2021[73] and just over 15% for climate change mitigation technologies[74]), a lower share of start-ups founded or co-founded by women (less than 15% in the EU in

63 Business and consumer survey data [industry_subsectors_q8_nace2]
64 For example, the 2020 European Skills Agenda, its flagship Pact for Skills and its partnerships with industrial ecosystems, and the Just Transition Mechanism.
65 Erasmus + https://www.erasmusskills.eu/eskills/
66 Clean Hydrogen Joint Undertaking, *Strategic Research and Innovation Agenda 2021–2027*, https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf.
67 COM(2022) 221 final ('EU Solar Energy Strategy').
68 Joint Declaration on Skills in the Clean Energy Sector, published 16 June 2022. Available at: https://ec.europa.eu/info/news/clean-energy-industrial-forum-underlines-importance-deploying-renewables-2022-jun-16_en.
69 For example, it is estimated that 800 000 workers will need to be trained to work in the batteries value chain to meet the REPowerEU goals. About 400 000 workers will have to be trained and upskilled in the heat pump value chain, not including those experts currently working in heat pumps and facing retirement in the next few years (see footnote 69).
70 2022/C 243/04, Council Recommendation on ensuring a fair transition towards climate neutrality.
71 COM(2022) 526 Final
72 COM(2020) 953 final, COM(2021) 952 final ('Progress on competitiveness of clean energy technologies').
73 For those inventions where at least one inventor is based in Europe. Figures based on European Patent Office 2022.
74 International Energy Agency, https://www.iea.org/commentaries/gender-diversity-in-energy-what-we-know-and-what-we-dont-know.

2021)[75] and lower amounts of capital invested in women-led companies (only 2% in all-female start-ups and 9% in mixed teams in the EU in 2021[76]).

The EU is stepping up its efforts to ensure a balanced and equal ecosystem. Initiatives include the gender equality strategy for 2020-2025[77], the Women TechEU initiative launched in 2022[78], the new eligibility criterion included under Horizon Europe[79], and the concrete target measures in the 2022 New Innovation Agenda[80]. Bridging the gender gap will not only help address the EU's jobs and skills challenges in order to achieve the twin green and digital transition, but will also support the inclusion of women in these work fields and thus address societal challenges.

2.2 Research and innovation trends

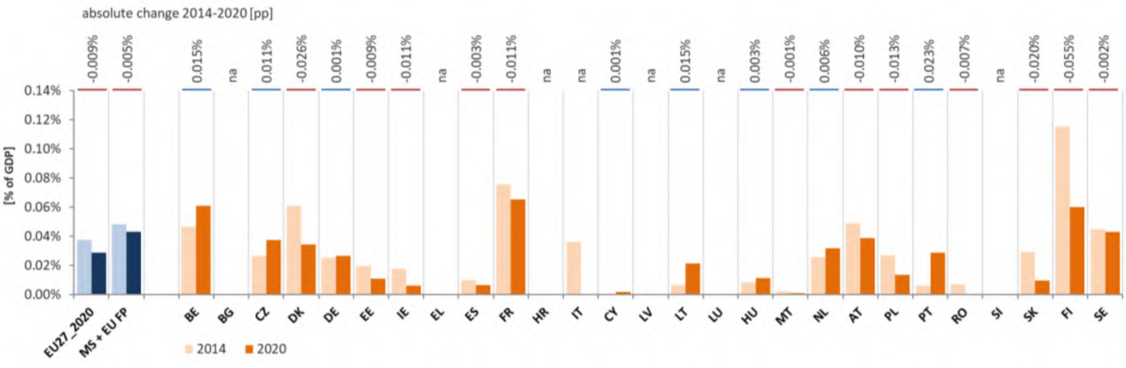
The rising environmental, geopolitical, economic and social instability in the world requires an agile EU R&I policy that can effectively respond to a crisis situation and at the same time ensure the implementation of the European Green Deal.

The EU's R&I policy shapes the direction of innovation and the portfolio of clean energy technologies. The world's largest R&I programme, Horizon Europe (with its budget of EUR 95.5 billion dedicated to R&I in 2021-2027), and other EU funding programmes (e.g. the innovation fund and the cohesion policy funding) are intended to strengthen the EU R&I's ecosystem and help achieve the EU's policy objectives [81]. Together with joint and coordinated efforts across the Member States (notably through the Strategic Energy Technology Plan (SET Plan))[82], R&I activities increase the resilience of the EU's clean energy sector.

Most EU Member States increased their public R&I investments in the EU Energy Union priorities in 2020[83,84], with more than EUR 4 billion reported so far. The final total figures for 2020 are expected to be comparable with pre-financial crisis values in absolute terms. Nonetheless, when measured as a proportion of Gross Domestic Product (GDP), investment in public R&I, at the national and EU levels, remains below 2014 levels (Figure 4).

75 European Innovation Council and SMEs Executive Agency (EISMEA), 2022.
76 IDC European Women in Venture Capital report, 2022.
77 European Commission, gender equality strategy.
78 European Innovation Council and SMEs Executive Agency (EISMEA), 2022. https://eismea.ec.europa.eu/programmes/european-innovation-ecosystems/women-techeu_en.
79 Horizon Europe has a new eligibility criterion where research organisations applying for funding must have an actionable Gender Equality Plan, with a target for a gender balance of 50% in all Horizon Europe related decision-making bodies and evaluators. More information available at: https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/democracy-and-rights/gender-equality-research-and-innovation_en#gender-equality-plans-as-an-eligibility-criterion-in-horizon-europe.
80 COM(2022) 332 final ('The New Innovation Agenda').
81 European Commission, Directorate-General for Research and Innovation, Science, Research and Innovation *Performance of the EU report 2022*, Publications Office of the European Union, Luxembourg, 2022.
82 The SET plan is the EU's main tool to align policies and funding on clean energy technologies R&I at EU and national level and to leverage private investments.. For more information: : https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en.
83 Renewables, smart system, efficient systems, sustainable transport, CCUS and nuclear safety, COM(2015) 80 final ('Energy Union Package').
84 JRC SETIS https://setis.ec.europa.eu/publications/setis-reseach-and-innovation-data_en.

Figure 4: *Public clean energy R&I investments in EU Member States as a share of GDP since the start of Horizon 2020*[85].



Source: JRC based on IEA[86] *and own work*[87].

In 2020, Horizon 2020 funds supporting Energy Union R&I priorities added EUR 2 billion to the Member States' national programmes' contributions. While national contributions alone remain low among major economies, with the inclusion of Horizon 2020 funds, the EU ranked second among major economies in public clean energy R&I investment in 2020 (Figure 5)[88], both in absolute spending (EUR 6.6 billion, with the US leading at EUR 8 billion) and as a share of GDP (0.046%, with Japan leading with 0.058%, but just ahead of the US and South Korea[89]).

According to global assessments, the corporate sector invests on average at least three times as much in clean energy R&I as the government sector[90]. Investment by the EU's business sector accounts for 80% of the R&I spending in the Energy Union R&I priorities. In 2019, estimated private R&I investment in the EU amounted to 0.17% of GDP (Figure 5), and 11% of the business and enterprise sector's total R&D spending. Estimates for the EU show that investment in absolute terms (EUR 18-22 billion per year) has been comparable with the US and Japan since 2014. In terms of percentage of GDP, however, despite the EU's investment being above the US, the EU remains lower than other major competing economies (Japan, South Korea, and China).

85 'EU FP' means the EU Framework Programme; and 'na' refers to countries which did not provide any data

86 Adapted from the 2022 edition of the IEA energy technology RD&D budgets database.

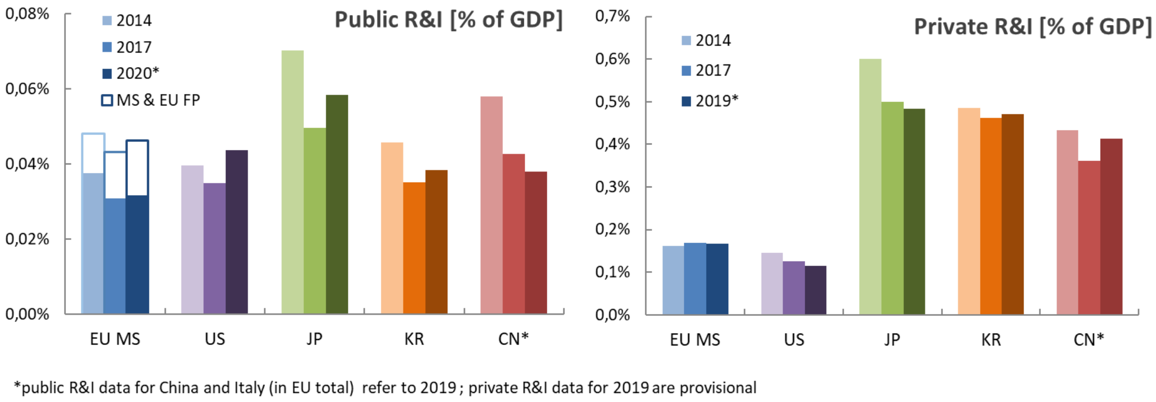
87 JRC SETIS https://setis.ec.europa.eu/publications/setis-reseach-and-innovation-data_en.

88 The graph overlaps the first two categories of Figure 4 for the EU. The values in the two figures are slightly different, as the figure for Italy in Figure 5 is an estimate.

89 These figures include Member States and EU framework programme funds. Last year's report only referred to Member States funds, which are also shown in Figure 5 and remain below other major economies' funds as a share of GDP.

90 IEA, *Tracking clean energy innovation - A framework for using indicators to inform policy*, 2020.

Figure 5: Public and private R&I financing in Energy Union R&I priorities in major economies as a share of GDP



Source: JRC based on IEA[91], MI[92], own work.

Since 2014, half of the EU Member States have increased their **patenting activity** in line with the Energy Union R&I priorities, with green innovation champions such as Germany and Denmark performing strongly both in absolute numbers and in the share of green patents in their overall innovation portfolio. The EU remained the top worldwide patent applicant in the fields of climate & environment (23%), energy (22%) and transport (28%).

Worldwide, there were slightly fewer **scientific publications** addressing low carbon energy technologies in 2020 than in 2016-2019. In the EU, this number increased more modestly in 2016-2019 (when compared to the global average), and declined more strongly in 2020. The EU contributed just over 16% of scientific articles worldwide, but did continue to produce more than twice the global average number of publications per head of population[93].

This trend is mostly due to the increasing number of scientific publications in other domains and to the fact that high-income economies no longer seem to dominate in topics related to clean energy and innovation[94]. The EU was leading in energy research 10 years ago, but the massive improvement in the quantity and quality of Chinese output in energy research has pushed the EU down into second position. Chinese researchers are in the lead when it comes to the most cited publications related to energy (with a 39% share)[95]. Nonetheless, EU scientists collaborate and publish internationally in clean energy topics, to a degree that is well above the global average and there is a higher level of collaboration between the public and private sectors in the EU. The Horizon 2020 R&I framework programme, the European Regional Development Fund and the seventh framework programme for R&I were ranked

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91 Adapted from the 2022 edition of the IEA energy technology RD&D budgets database.

92 Mission Innovation Country Highlights, 6th MI Ministerial 2021, http://mission-innovation.net/wp-content/uploads/2021/05/MI_2021v0527.pdf.

93 European Commission, Directorate-General for Research and Innovation, Provençal, S., Khayat, P., Campbell, D., *Publications as a measure of innovation performance in the clean energy sector*: assessment of bibliometric indicators, Publications Office of the European Union, Luxembourg, 2022

94 Schneegans S., Straza, T., and Lewis, J. (editors), UNESCO Science Report: the Race Against Time for Smarter Development, UNESCO Publishing, Paris, 2021.

95 European Commission, Directorate-General for Research and Innovation, Science, Research and Innovation, *Performance of the EU report 2022*, Publications Office of the European Union, Luxembourg, 2022.

among the global top 20 acknowledged funding schemes supporting clean energy science in the period 2016-2020[96].

The need to improve the monitoring of public and private clean energy R&I activity and the quantitative assessment of competitiveness was highlighted in the last edition of the report[97] and has since become even more crucial. The review of the SET Plan and the planned update of the National Energy and Climate Plans (NECPs)[98] due in June 2024[99], are together creating the momentum to reinforce the dialogue on clean energy R&I and competitiveness between the EU and its Member States.

2.3 The global clean energy competitive landscape

Worldwide, the urgent commitment to accelerate the energy transition has led to the development of many clean energy solutions, ranging from niche technologies to global industry and international value chains. It is estimated that global markets will be worth EUR 24 trillion for renewable energy and EUR 33 trillion for energy efficiency by 2050[100].

The EU's leadership in science, its strong industrial base and its ambitious clean energy framework conditions provide a good technology base for the anticipated market development of several clean energy technologies. The EU has maintained its good position in **internationally protected patents** since 2014, thus confirming the trend highlighted in last year's report[101]. The EU remains second only to Japan in high-value inventions[102], it leads in renewables, and shares the lead with Japan in energy efficiency, thanks mainly to the EU's specialisation in materials and technologies for buildings. The EU's patenting data also show its leadership in renewable fuels; batteries and e-mobility; and carbon capture, storage and utilisation technologies.

Most new investments in clean energy technologies are expected to take place outside the EU and necessary raw materials are traded internationally[103]. This makes the EU's strong presence and performance in global value chains and its access to third country markets essential. The increase in measures taken by third country governments (introducing market access barriers, local content requirements and other discriminatory measures or practices) can nevertheless distort **international trade and investment dynamics**. These measures can have a negative impact on EU jobs, growth and tax base, and undercut the benefits that the EU would normally reap from being a first mover in this area. They also create a clear risk of "contamination", because they can prompt other third countries to take similar measures which create inefficiencies in international supply chains and in the longer-term affect

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96 Elsevier, Pathways to Net Zero:The Impact of Clean Energy Research, 2021. Available at: https://www.elsevier.com/__data/assets/pdf_file/0006/1214979/net-zero-2021.pdf. Publications are counted as net-zero energy research if they advance knowledge about clean energy research and innovation and the pathway toward achieving a net-zero future. The data is sourced from Scopus database.

97 COM (2021) 952 final and SWD(2021) 307 final ('Progress on competitiveness of clean energy technologies')

98 Further details on NECPs: https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en.

99 OJ L 328, 21.12.2018. Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action sets out the regular revision of NECPs to align them with latest policy developments. The draft NECPs are expected by June 2023.

100 IRENA, *Global energy transformation: a roadmap to 2050*, Abu Dhabi, 2019.

101 COM(2021) 952 final ('Progress on competitiveness of clean energy technologies').

102 High-value patent families (inventions) are those containing applications to more than one office (i.e. they are applying for protection in more than one country or market).

103 International Energy Agency, *Net Zero by 2050 - A Roadmap for the Global Energy Sector*, 2021.

incentives to invest in the sector. This would in turn increase costs for the transition overall and could erode the general public's ongoing commitment to global decarbonisation.

Concern also persists and is increasing throughout the world about the impact of state- and subsidy- backed technology domination; closed markets; different intellectual protection (IP) rules; innovation and competitiveness policies in the sector especially those implemented by China, as well as other third countries. The current geopolitical crisis has also affected competition in the global clean energy market, and it remains to be seen how new national measures on accelerating the domestic roll-out of clean energy technologies (e.g. the US inflation reduction act[104]) might negatively impact the global competitive clean energy landscape.

Within this framework, **international cooperation in R&I** will not only further accelerate the clean energy transition, but will also counteract disruption of the global energy market. EU programmes and policies, such as Horizon Europe and Erasmus+, have consistently supported R&I cooperation with trusted global partners. The Commission's Communication on "The global approach to research and innovation"[105] provides an improved framework for developing international cooperation. The Commission's Communication on "EU external energy engagement in a changing world"[106] envisages the intensification of such cooperation and the development of partnerships to support the green transition on crucial topics such as renewable and low carbon hydrogen, and access to raw materials and innovation. In addition, the Commission's Communication "A new ERA for research and innovation"[107] calls for the guiding principles for knowledge valorisation to be updated and developed. A code of practice for the smart use of IP is expected by the end of 2022[108]. The Commission is helping to advance international cooperation on energy innovation and technology by continuing to engage in Mission Innovation[109] and the Clean Energy Ministerial. Furthermore, the new EU global connectivity strategy, the Global Gateway[110], the Commission's Communication "Trade policy review"[111] and the International Just Energy Transition Partnership with South Africa[112] underline the importance of deepening international cooperation and trade relations in order to leverage the competitiveness of clean energy technologies in synergy with the openness and the attractiveness of the EU's single market.

International research cooperation, technology transfer, trade policy and energy diplomacy will need to work together to ensure undistorted trade and investment in the technologies, services and raw materials that are needed for the transition both inside and outside the EU. The EU will also need to further exploit its potential to upscale innovation in order to avoid the risk of increasing its dependency on other major economies for imported technologies needed in the energy transition and in the new energy system architecture.

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104 FACT SHEET: The Inflation Reduction Act Supports Workers and Families | The White House
105 COM(2021) 252 final ('Europe's strategy for international cooperation in a changing world').
106 JOIN(2022) 23 final ('EU external energy engagement in a changing world').
107 COM(2020) 628 final ('A new ERA for Research and Innovation').
108 A new guide is already available on the valorisation of results from Horizon Europe at: https://data.europa.eu/doi/10.2826/437645.
109 http://mission-innovation.net/. After first five successful years, MI 2.0 was launched with a new set of 'missions'.
110 JOIN(2021) 30 final ('The Global Gateway'), Joint Communication from the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank.
111 COM(2021) 66 final ('Trade Policy Review - An Open, Sustainable and Assertive Trade Policy').
112 Just Energy Transition Partnership with South Africa (europa.eu).

2.4 The innovation funding landscape in the EU[113]

Climate tech solutions[114] are fostering the EU's competitiveness and technology sovereignty. Together with the adoption of more mature generation technologies, they will play a crucial role in achieving carbon neutrality by 2050[115].

The EU climate tech domain has over the last 6 years attracted an increasing amount of venture capital (VC) investment[116] that is at the forefront of innovation. Climate tech can require long lead times before reaching maturity, so there is a crucial need for a significant amount of capital throughout start-ups' funding lifecycles; investments in R&I[117]; government action to de-risk the development of climate tech solutions, and further encouragement for private sector participation.

Worldwide, VC investment in the **climate domain** has shown impressive resilience to the pandemic, with already higher levels of investments in 2020 (EUR 20.2 billion) and new all-time highs in 2021 (EUR 40.5 billion, a 100% increase compared to 2020[118]). Within this figure, EU-based climate tech start-ups and scale-ups attracted EUR 6.2 billion of VC investment in 2021, more than double the 2020 level[119]. This accounts for 15.4 % of global climate tech VC investment. 2021 was also the first year in which later-stage investments in EU-based climate tech were higher than in China[120]. However, early-stage investment reached new highs in the US and China in 2021, but peaked in the EU (Figure 6).

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113 The analysis presented in this section is based on Pitchbook data. PitchBook currently identifies more than 2 750 venture capital companies in its Climate Tech vertical (compared with more than 2 250 at the time of publication of the 2021 edition of the CPR report). The figures for historical VC capital investment in the CPR 2020 and 2021 reports are therefore not directly comparable.

114 PitchBook's climate-tech vertical is a selection of 2 760 companies that are developing technologies intended to help mitigate or adapt to the effects of climate change. Most companies in this vertical are focused on mitigating rising emissions through decarbonisation technologies and processes. Applications within this industry vertical include renewable energy generation; long duration energy storage; electrification of transportation; agricultural innovations; industrial process improvements; and mining technologies.

115 The section was developed in close collaboration with the European Commission's Clean Energy Technology Observatory: Georgakaki, A. et al, Clean Energy Technology Observatory Overall Strategic Analysis of Clean Energy Technology in the European Union – 2022 Status Report, European Commission, 2022, JRC131001.

116 Venture capital deals are defined as early-stage deals (including pre-seed, accelerator/incubator, angel, seed, series A and B occurring within 5 years of the company's founding date) and later-stage deals (usually series B to series Z+ rounds and/or occurring more than 5 years after the company's founding date, undisclosed series and private equity growth/expansion).

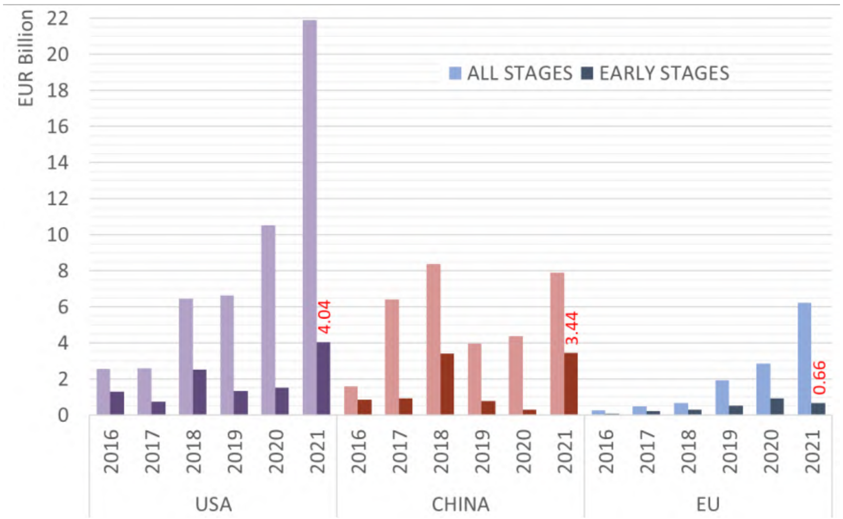
117 This gives rise to the notion of deep-green start-ups (i.e. start-ups that use cutting-edge technologies to address environmental challenges such as green battery manufacturing and electric aircraft). Deep green is at the intersection between climate-tech and deep tech (deep tech is the application of scientific discoveries in engineering, mathematics, physics, and medicine. It is characterised by long R&D cycles and untested business models).

118 This accounts for 5.2% of total VC funding in 2021 according to JRC elaboration based on PitchBook data (4.6% in 2020).

119 COM(2021) 952 final ('Progress on competitiveness of clean energy technologies').

120 The sole investments in Swedish EV Battery developer Northvolt have a significant impact on the overall VC investment trends in EU Climate Tech firms over the past years. As the company transitioned towards later investment stages, early-stage investments in EU Climate Tech firms decreased in 2021 while later stage investments increased to reach for the first time a higher value than reported in China.

Figure 6: Venture capital investments in climate tech start-ups and scale-ups



Source: JRC elaboration based on Pitchbook data.

The **energy domain** accounted for 22% of global climate tech VC investments in 2021 (clean energy generation[121] and grid technologies[122] accounted for 13.2% and 8.7% respectively). With levels almost four times higher (x 3.8) than in 2020[123], the energy domain remains behind the Mobility and Transport domain (46%), but has for the first time overtaken the Food and Land use domain (19.6 %).

In the EU, VC investments in energy firms confirmed the sustained growth seen over the past 4 years (up by 60% on 2020). Despite this good performance, the relative share of the EU's VC investments in energy halved in 2021. With 10% of VC investment in energy firms, the EU ranks third, far behind the US (62%) and China (13.3%), which both displayed outstanding 2021 investment levels driven by megadeals in clean energy generation.

Despite the positive VC funding dynamics in the EU and the attraction of EU-based climate tech for VC investors, structural barriers and societal challenges[124] are still holding back EU-based climate tech scale-ups by comparison with other major economies. The EU taxonomy for sustainable activities nevertheless provides a framework to facilitate durable investment and defines environmentally sustainable economic activities. In addition, the EU's innovation policy has expanded over the years and the institutional landscape has changed with it[125].

Horizon Europe's pillar III on "Innovative Europe" has provided tools to support start-ups, scale-ups and Small and Medium-Sized Enterprises (SMEs). Within this context, the European Innovation Council (EIC) is, with its EUR 10.1 billion budget between 2021 and

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[121] Including solar, wind, nuclear, waste-to-energy, ocean and hydro and geo-thermal energy.

[122] Including long-duration energy storage, grid management, analytics, battery technology, smart grid and clean hydrogen production.

[123] Investments in clean energy generation technologies are the main driver of this growth. Pushed by significant large investments in nuclear fusion in the US and wind in China, it has increased 2.4 times faster than investment in grid technologies and climate-tech VC investments in general.

[124] COM(2020) 953 final ('Report on Progress of Clean Energy Competitiveness'), and COM(2022) 332 final ('The New Innovation Agenda').

[125] COM(2022) 332 final ('The New Innovation Agenda').

2027, the EU's flagship innovation programme for identifying, developing and scaling-up breakthrough technologies and game-changing innovations. Horizon Europe also supports the European Innovation Ecosystems initiative and the European Institute of Innovation and Technology (EIT). EIT InnoEnergy has built the largest sustainable energy innovation ecosystem in the world and is also spearheading the move to a decarbonised EU by 2050 through the leadership of three industrial value chains (the European Battery Alliance, the European Green Hydrogen Acceleration Centre and the European Solar Initiative).

As regards **EU funding programmes**, the Innovation Fund is one of largest in the world[126] for demonstrating clean innovative technologies and deploying them at an industrial scale. The InvestEU programme is a major element of the EU's recovery plan, supporting access to, and availability of, finance for SMEs, mid-caps and other enterprises. The cohesion policy provides large scale and long-term investments, especially for SMEs, in innovation and industrial value chains in order to boost the development of renewable and low-carbon technologies and business models. Moreover, the European Investment Bank (EIB) and the European Investment Fund (EIF), effectively support the deep-tech development that the EU needs to achieve its sustainability goals. Other funding programmes, such as the Modernisation Fund and the proposed Social Climate Fund[127], aim at helping to funnel revenues from climate-related policies in support of the energy transition.

These programmes and other EU initiatives, such as the capital market union (CMU)[128], aim to further mobilise private investors in the funding of climate tech and deep[129] climate-tech start-ups. For instance, the pioneering partnership between the European Commission and Breakthrough Energy Catalyst[130] is another example on how to boost investments in critical climate technologies bringing together the public and private sectors.

Creating synergies between EU programmes and instruments and increasing cohesion between the EU's local innovation ecosystems can help the EU to become a global leader in climate tech, thus closing the scale-up gap between the EU and other major economies by leveraging its diverse talents, intellectual assets and industrial capabilities. The 2022 European Innovation Scoreboard[131] highlights the importance of establishing a pan-European innovation ecosystem, and the 2022 Commission Communication "the New European Innovation Agenda"[132] represents already a step forward because it aims at leveraging the strengths of the EU innovation ecosystem[133].

126 EUR 38 billion of support from 2020 to 2030, assuming a carbon price of EUR 75/tCO2.
127 https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/social-climate-fund_en
128 https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/capital-markets-union_en
129 Deep-tech start-ups build on scientific knowledge and typically have long R&D cycles and untested business models. Deep-climate-tech start-ups are companies that use cutting edge technology to address environmental challenges.
130 Commission and Breakthrough Energy Catalyst partnership (europa.eu): https://ec.europa.eu/commission/presscorner/detail/en/IP_21_2746
131 European Commission, European innovation scoreboard 2022, Annual Report, 2022.
132 COM(2022) 332 final ('The New Innovation Agenda').
133 The Communication states that the EU will take forward concrete measures to improve access to finance for EU start-ups and scale-ups; improve rules to allow innovators to experiment with new ideas; help create 'regional innovation valleys'; attract and retain talent in the EU; and improve innovation policy-making through clear terminology, indicators and data sets as well as policy supports to Member States.

2.5 Impacts of systemic change

To achieve the twin green and digital transition and deliver on the European Green Deal and Fit for 55 objectives, the EU clean energy sector needs to accelerate a paradigm-shift already in motion: the need to break down the silos between sectors and to strengthen cooperation in horizontal areas (e.g. the critical role of raw materials, the digitalisation of the energy system and the interaction of different technologies in industrial processes, individual buildings, and cities). Examples of this systemic transformation include: building-related clean energy technologies; digitalisation of the energy system; and energy communities and sub-national cooperation.

Building-related clean energy technologies: compulsory solar PV installations on roofs and doubling the current rate of deploying individual heat pumps[134] will help to achieve climate and energy targets. Achieving these targets will also require the building sector to integrate a broad set of complementary solutions for new buildings, such as efficient insulation methods and control systems, but also resource efficient measures. This should go hand in hand with increasing the renovation rate and fostering deep renovation. On-site energy storage (batteries) is another important element to enable higher shares of heat pumps and avoid extreme peaks in electricity generation and transmission/distribution. In addition to product availability, installation skills and operational services for the different technologies is crucial for the EU's clean energy sectors and its competitiveness.

Digitalisation of the energy system: digitalisation is expanding exponentially: internet traffic has tripled in the last 5 years alone, and around 90% of the data in the world today were created over the last 2 years[135]. Decentralisation of energy - at the generation level as well as through millions of connected smart appliances, heat pumps and electric cars - is transforming the local energy system. An assessment for Hamburg (Germany) indicated a significant cost savings potential: investing EUR 2 million in smart charging to decrease peak demand can avoid the need to invest EUR 20 million for the necessary grid reinforcement to cater for a share of 9% of electric vehicles in the city[136]. Without intelligent management of local energy needs, capacity limits in distribution networks can slow clean energy transformation. However, some digital solutions may increase energy consumption and GHG emissions without appropriate efficiency measures, like recovering heat waste from data centres.

Energy communities and sub-national cooperation: at least two million European citizens have engaged in more than 8 400 energy communities and carried out over 13 000 projects since the year 2000[137]. Energy communities represent an important test bed and application field for clean energy technologies and solutions. The total renewable capacities installed by energy communities in Europe is currently estimated to be at least GW 6.3 (i.e. around 1-2%

[134] COM(2022) 230 ('The RePowerEU plan').

[135] International Energy Agency, Digitalization and Energy, 2017, https://iea.blob.core.windows.net/assets/b1e6600c-4e40-4d9c-809d-1d1724c763d5/DigitalizationandEnergy3.pdf.

[136] Stromnetz Hamburg, *Elektromobilität – Netzausbaustrategie und Restriktionen im Hamburger Verteilnetz,* Hamburg, 2018,https://www.hamburg.de/contentblob/10993526/1f90214d9b07e4de6323c078ff779d9d/data/d-anlage-13-pra%CC%88sentation-snh-20180504-energienetzbeirat-snh.pdf.

[137] Schwanitz, V. J., Wierling, A., Zeiss, J. P., von Beck, C., Koren, I. K., Marcroft, T., and Dufner, S. , *The contribution of collective prosumers to the energy transition in Europe - Preliminary estimates at European and country level from the COMETS inventory*, August 2021, https://doi.org/10.31235/osf.io/2ymuh.

of installed capacity at national level). Solar PV constitutes the lion's share of installed capacity. Onshore wind comes next. Developing participatory models for more clean energy technologies, in particular targeted for lower income households, can trigger the development of more energy communities across the EU and, at the same time, contribute to addressing energy poverty.

Enhancing the interaction across horizontal areas, while factoring in the interdependencies between different sectors both at Member States and EU level is key for accelerating the deployment and upscale of clean energy technologies and for strengthening the EU's competitiveness in the global clean energy market[138].

3. FOCUS ON KEY CLEAN ENERGY TECHNOLOGIES AND SOLUTIONS

This section presents the competitiveness assessment of a range of clean energy technologies and solutions that are key for energy generation, storage and system integration. It also provides insights into how the technology and the market are evolving to meet the European Green Deal and REPowerEU objectives. This section includes an analysis of solar photovoltaics, wind, heat pumps for building applications, batteries, hydrogen production through electrolysis, renewable fuels, and digital infrastructure. It also provides an overview of other important technologies[139]. This evidence-based analysis - based on the indicators listed in Annex I - was performed within the framework of the Commission's in-house Clean Energy Technology Observatory (CETO), which is executed by the Joint Research Centre. The in-depth technology-specific reports are available on the CETO web site[140].

3.1. Solar photovoltaics[141]

Solar Photovoltaics (PV) has been the fastest growing power generation technology in the world over the last decade. All the scenarios towards a climate neutral energy system[142] assign a central role to PV. The recent European solar energy strategy communication[143] calls for about 450 GWac of new photovoltaic system capacity between 2021 and 2030. Given the current trend of installing a DC capacity 1.25 to 1.3 times the AC capacity to optimise the use of the grid connection[144], this would bring the total nominal PV capacity in the EU to approximately 720 GWp. The EU solar energy strategy addresses the main bottlenecks and barriers to investment with a view to accelerating deployment, ensuring security of supply and maximising the socio-economic benefits of PV energy throughout the value chain[145]. The

[138] SAPEA (Science Advice for Policy by European Academies), *A systemic approach to the energy transition in Europe*, Berlin, 2021, https://doi.org/10.26356/energytransition.

[139] Hydropower, Ocean energy, Geothermal energy, Concentrated solar power and heat, Carbon capture utilisation and storage, Bioenergy, Nuclear energy

[140] https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en

[141] Evidence-based analysis from CETO (Chatzipanagi, A. et al, Clean Energy Technology Observatory: Photovoltaics in the European Union 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, doi: 10.2760/812610 JRC130720) unless otherwise noted.

[142] Most notably, the scenarios projected by non-governmental organisations such as Greenpeace, the Energy Watch Group, Bloomberg New Energy Finance, the International Energy Agency, the International Renewable Energy Agency, as well as by PV industry associations.

[143] COM(2022) 221 final ('EU Solar Energy Strategy').

[144] Kougias I. et al, The role of photovoltaics for the European Green Deal and the recovery plan, 2021,(doi: 10.1016/j.rser.2021.111017). AC: Alternating Current; DC: Direct Current.

[145] The flagship actions announced in the EU's solar energy strategy include the EU solar rooftops initiative; the Commission's permitting package – including a legislative proposal, recommendations and guidance; the EU's large-

European Solar PV Industry Alliance, one of the concrete initiatives of the EU solar energy strategy**,** was formally endorsed by the Commission in October 2022, and it aims at scaling up manufacturing technologies of innovative solar photovoltaic products and components[146].

Technology analysis: The average efficiency of silicon cell-based modules has increased from 15.1% in 2011 to 20.9% in 2021[147]. This is thanks to the use of larger cut wafers and higher efficiency solar cells, including multi-junction cells designs. Europe has notable expertise and a lead in the promising perovskites technology, for which several EU companies such as Evolar (Sweden), Saule Technologies (Poland) and Solaronix (France) are currently setting up production lines.

The EU's solar strategy[148] aims to reverse the declining trend observed in public and private funding in the PV industry [149]. The EU remains nonetheless a strong innovator in the field, with a significant number of publications and patent applications recorded in 2017-2019. Germany alone ranks fifth in the world in the patenting of high-value inventions in PV.

Value chain analysis: Both production data and new investment projects confirm the dominance of Asia, and in particular China, in the PV manufacturing landscape. All of the additional polysilicon manufacturing capacity of 80 000 t announced at the beginning of 2021 (to be added to a total capacity of ~650 000 t in 2020), as well as the 118 000 t already under construction, is being built in China[150]. Silicon solar cells, which are mostly produced in China, represent over 95% of worldwide production. The EU nonetheless retains a considerable share in the production equipment (50%) and inverter (15%) manufacturing segments of the PV value chain.

Global market analysis: Worldwide investment in new solar generation increased by 19% in 2021 to reach USD 205 billion (EUR 242.5 billion[151]). However, 2021 saw a further deterioration of the EU's trade balance, because its imports increased while its exports remained stable, representing 13% of global exports. Higher material costs experienced in many industrial sectors in 2021 and 2022 led to an exceptional and unprecedented increase in production costs for cells and modules, reversing a decade-long cost reduction trend. Nevertheless, the competitiveness of PV further improved by comparison with non-renewable electricity sources[152]. The number of countries where photovoltaic electricity

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scale skills partnership for onshore renewable energy, including solar energy; and the EU solar PV industry alliance). In particular, the EU solar rooftops initiative would make the installation of rooftop solar energy compulsory for (i) all new public and commercial buildings with useful floor area greater than 250 m² by 2026; (ii) all existing public and commercial buildings with useful floor area greater than 250 m² by 2027; and (iii) all new residential buildings by 2029. It is expected that these measures will in combination significantly increase investment in PV assets and increase PV manufacturing capabilities in the EU.

146 https://ec.europa.eu/info/news/commission-kicks-work-european-solar-photovoltaic-industry-alliance-2022-oct-11_en

147 VDMA, *International Technology Roadmap for Photovoltaic (ITRPV),* 2022.

148 It particularly aims to develop a solar energy R&I flagship in the next Horizon Europe work programme, establish an R&I pillar in the proposed EU Solar Photovoltaics Industry Alliance, and develop a joint R&I agenda on solar energy with Member States in the European Research Area framework.

149 Latest figures available for 2018 and 2019.

150 Jäger-Waldau, Arnulf (2022) Overview of the Global PV Industry. In: Letcher, Trevor M. (eds.) Comprehensive Renewable Energy, 2nd edition, vol. 1, pp. 130–143. Oxford: Elsevier. Doi. 10.1016/B978-0-12-819727-1.00054-6

151 Using the average exchange rate of EUR 1.1827 for USD 1 over the year 2021. See https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html

152 This is because natural gas, oil and coal prices have risen much faster over the same period. See https://www.iea.org/reports/renewable-energy-market-update-may-2022.

generation is the cheapest source is therefore growing. Increases in fossil fuel prices due to natural disasters, accidents or international conflicts, can only reinforce this trend.

In conclusion, the latest available data for 2021 and 2022 confirm the previously observed trend[153]. The EU has confirmed its position as one of the largest markets for PV and as a strong innovator especially in emerging PV technologies and applications (such as agri-PV, building-integrated PV and floating PV). However, the EU is heavily dependent on imports from Asia for several crucial components (wafers, ingots, cells and modules), and retains significant presence only in the production equipment and inverter manufacturing segments (which are currently facing a bottleneck due to the shortage of chips[154]). Additional bottlenecks due to affordability limitations (especially for low-income households and SMEs), excessively long waiting times (e.g. linked with insufficient skilled PV installers) are already impacting the large deployment of PV. The measures and flagship actions announced in the EU's solar energy strategy provide the main opportunities to invest in PV assets and develop PV manufacturing capacities in the EU, as well as the diversification of imports. In parallel, continuous technological advances towards more efficient and sustainable cell designs and manufacturing processes have made it possible to further improve the competitiveness of PV technologies by comparison with non-renewable energy sources – even though raw material costs have risen. These elements strengthen the business case for boosting both production and deployment in the EU, including innovative applications.

3.2. Offshore and onshore wind[155]

Wind energy has a central role in the EU's climate and energy policy, as the acceleration of wind energy deployment is essential to deliver on the European Green Deal, the Fit for 55 and the REPowerEU objectives. REPowerEU calls for the faster installation of wind energy capacities, with 510 GW of wind to be installed by 2030[156], projected to correspond to a 31% share of EU installed power production capacities[157].

The EU has been a worldwide leader in wind energy R&I since 2014, with public spending accounting for EUR 883 million in the period 2014-2021, and it currently hosts 38% of all innovating companies, with the biggest pool of start-ups and innovating corporates. In 2021, however, only 11 GW of wind energy (10 GW onshore wind; 1 GW offshore wind) was installed in the EU, and perspectives for 2022 are still below the pace needed to achieve the REPowerEU targets. China is currently leading in terms of cumulative wind energy installations, with a capacity of 338 GW, mainly due to increased deployment rates in 2021. In the same year, the EU reached about 190 GW of cumulative installed capacity.

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153 COM(2021) 952 final ('Progress on competitiveness of clean energy technologies').

154 EU Chips survey report. European Chips Report | Internal Market, Industry, Entrepreneurship and SMEs (europa.eu).

155 Evidence-based analysis from CETO (Telsnig, T. et al , Clean Energy Technology Observatory: Wind Energy in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, doi:10.2760/855840, JRC130582.) unless otherwise noted.

156 SWD(2022) 230 final ('Implementing the REPower EU Action plan: investment needs, hydrogen accelerator and achieving the bio-methane targets'). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN.

157 SWD(2022) 230 final ('According to PRIMES modelling projections of the net installed power capacity in REPowerEU in 2030'), Figure 3: Net installed capacity in REPowerEU in 2030 (GWe). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN.

To deliver on the REPowerEU objectives, speeding- up wind energy deployment will be crucial and will require clear investment pipelines and translating political objectives into actual implementing measures, including the enactment of commitments to facilitate permitting for wind farms.

Technology analysis: Total global installed onshore wind capacity was 769 GW in 2021, almost three times higher than a decade earlier[158], with 72 GW capacity installed in 2021 alone. 2021 was also a record year for offshore wind, with 21 GW of new capacity installed globally, more than triple the previous record in 2020. Total global installed capacity accounted for 55 GW in 2021[159]. China led the increase in the global installed capacity with 30.6 GW of onshore wind capacity and 16.9 GW offshore wind capacity installed in 2021.

The EU had a total installed onshore wind capacity of 173 GW and total installed offshore wind capacity of about 16 GW at the end of 2021. Total wind capacity was equivalent to about 14% of the EU's total electricity consumption. 2021 also saw the second highest annual contribution by onshore wind capacity in the EU since 2010 (10 GW annual deployment[160]). However, only 1 GW of offshore wind was deployed in the EU in 2021[161]. Industry players highlight the granting of permits as one of the main bottlenecks to the continuing and massive deployment of wind energy, because it causes delays and fewer completed projects. This in turn puts pressure on supply chain profitability. The Commission has made legal proposals and a guidance to accelerate permitting as part of the REPowerEU package.

Value chain analysis: The wind energy sector has developed into a global industry with about 800 manufacturing facilities. Most of these are in China (45%) and Europe (31%)[162]. The EU has kept the lead in terms of high-value patents in wind energy technologies: its share of high-value inventions was 59% in 2017-2019. EU turbine manufacturers continue to lead in terms of quality, technological development and investment in R&I. The EU's wind industry also has high manufacturing capabilities for high-value-added components (e.g. towers, gearboxes and blades) and for devices that can also be used by other industrial sectors (e.g. generators, power converters and control systems). The EU's manufacturing value chain for offshore wind mainly sources its components from EU manufacturers. For onshore wind, by contrast, the EU's original equipment manufacturers (OEMs) source their components from many different foreign suppliers.

Many of the raw materials for generators are imported mostly from China. Potential difficulties in increasing raw materials production output to reach the 2030 targets could pose challenges for the EU wind industry. The increase in resources' prices in 2021 and supply uncertainties also constitute an obstacle. The industry has also raised environmental concerns with respect to the recycling of composite blades. Both national and EU research programmes in wind energy therefore focus increasingly on circularity.

Global market analysis: The EU has**,** over the last decade**,** maintained a positive trade balance with the rest of the world, ranging between EUR 1.8 billion and EUR 2.8 billion. However,

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158 *Renewable Capacity Statistics 2022*, IRENA, Abu Dhabi, 2002.

159 *Renewable Capacity Statistics 2022*, IRENA, Abu Dhabi, 2002.

160 Wind Energy in Europe: 2021 Statistics and the outlook for 2022-2026, WindEurope, Belgium, 2022.

161 Wind Energy in Europe: 2021 Statistics and the outlook for 2022-2026, WindEurope, Belgium, 2022.

162 Followed by India (7%), Brazil (5%) and North America (4.5%). See also: WindEurope/Wood Mackenzie, *Wind energy and economic recovery in Europe*, Belgium, 2020.

the EU has had negative trade balances with China and India since 2018. Chinese OEMs for the first time overtook their EU counterparts in terms of global market share in 2020. The EU's leading markets, nevertheless, host a substantial number of domestic manufacturers[163].

In conclusion, the EU's wind sector remains a world leader in terms of R&I and high-value patents. This is thanks to the manufacturing capacity, workforce and skills at its disposal. However, the industry will have to more than double the current annual rate of capacity installation in the EU in order to achieve the 2030 targets.

The implementation of the Renewable Energy Directive[164], the recent proposal for its amendment[165] as well as the respective 2022 Commission recommendation and guidance[166], are expected to overcome the main permit-related barriers to deployment. Clear advance indication of the Member States' wind installation plans will also allow for the timely preparation of future capacities. In parallel, R&I on circularity will move the industry forward by addressing environmental concerns and supply disruptions, thus improving the competitiveness of the EU's wind energy sector.

3.3. Heat pumps for building applications

At EU level, heat pumps are increasingly supported within the framework of the European Green Deal, the Fit for 55 package, and by the REPowerEU plan[167]. The REPowerEU plan calls for a doubling of the current deployment rate of individual heat pumps, which would result in a total deployment of 10 million heat pumps over the next 5 years and 30 million by 2030, and would be matched by the scaling-up of the EU's manufacturing capacity. It also calls for faster deployment of large heat pumps in district heating and cooling networks. The widespread joint deployment of both rooftop PV (and solar thermal) and heat pumps, with smart controls responding to grid load and price signals, would contribute to heating decarbonisation and reduce grid integration challenges.

<u>Technology analysis:</u> Heat pumps for building applications are commercially available products. They can be classified according to the source from which they extract thermal energy (air, water or ground), the medium to which they transfer heat (air or water), their purpose (space heating or cooling a space, domestic water heating) and market segments (commercial or residential buildings, and networks).

As regards heat pumps that are mainly used for space and sanitary water heating, the installed stock measured for this sector reached nearly 17 million units in Europe at the end of 2021, while sales reached 2.18 million units in 2021, a compound annual growth rate of 17% over the last 5 years, and 20% over the last 3 years[168].

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163 WindEurope/Wood Mackenzie, *Wind energy and economic recovery in Europe*, 2020.

164 OJ L 328, 21.12.2018. Directive (EU) 2018/2001 of 11 December 2018 on the promotion of the use of energy from renewable sources.

165 COM(2021) 557 final ('Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652').

166 SWD(2022) 0149 final ('Guidance to Member States on good practices to speed up permit-granting procedures for renewable energy projects').

167 COM(2022) 230 final (*'REPowerEU Plan')*.

168 European Heat Pump Association (EHPA), 2022, https://www.ehpa.org/market-data/.

R&I activities for individual heat pumps are driven by the demand for more efficient, compact and silent units; larger ambient temperature operating ranges; digitalisation for optimal integration with energy grids; and local energy generation and storage. They are also driven by evolving EU regulations for more energy efficiency and lower life-cycle environmental impact, including materials circularity and low global warming potential (GWP) refrigerants. R&I on commercial heat pumps addresses, for example, the integration of simultaneous supply of heat and cold with thermal storage.

The EU's R&I position is strong and improving. It leads in patents for 'mainly-heating' heat pumps for building applications. In 2017-2019, 48% of patents for 'high-value inventions' were filed in the EU, followed by Japan (12%), the United States (8%), Korea (7%) and China (5%)[169]. In 2014-2022, Horizon 2020 provided a total of EUR 277 million in funding for projects on heat pumps for building applications.

<u>Value chain analysis:</u> Turnover for heat pumps manufacturing, installation and maintenance activities in the EU amounted to EUR 41 billion in 2020, and has grown at an average annual rate of 21% over the last 3 years. Direct and indirect jobs amounted to 318 800 in 2020, an average annual growth of 18% over the last 3 years. These data include all types of heat pumps, including air-to-air heat pumps used for cooling and/or heating[170].

Heat pumps do not require critical raw materials for their production, but they are affected by the current worldwide shortage of semiconductors.

<u>Global market analysis:</u> In the EU, the 'mainly heating' heat pump value chain consists of many SMEs and a few large players. The proportion of heat pumps that are imported is increasing and the trade deficit reached EUR 390 million in 2021, in contrast to the surplus of EUR 202 million recorded 5 years earlier[171]. Imports from China doubled in 2021 to reach EUR 530 million.

In conclusion, the deployment of heat pumps is already proceeding rapidly, but needs to accelerate still further in order to meet the REPowerEU objectives. EU-based suppliers need to ramp up production in order to partake in the EU's growing demand for heat pumps. Some industry associations argue that a faster phasing-out of high GWP refrigerants would slow down the ramping-up for specific applications, but the prohibition dates in the proposal to amend the F-Gas regulation[172] are designed to give industry sufficient time to adapt. A lack of trained installers and high upfront cost may slow deployment in the EU.

Industry is calling for a 'Heat Pump Accelerator' platform that would bring together the Commission, Member States and the sector itself. The platform would be supported by clear and sustained policy signals that would create confidence in long-term planning; ensure a favourable regulatory framework; drive down costs through more cooperation and R&I; and develop a pact for skills focussed on heat pumps. As part of the REPowerEU plan, the Commission will support the Member States' efforts to pool their public resources via

[169] Lyons, L. et al, Clean Energy Technology Observatory Heat Pumps in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets, 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, JRC130874

[170] Based on EurObserv'ER data, 2020

[171] COMEXT, code 841861.

[172] COM(2022) 150 final ('Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014').

potential Important Projects of Common European Interest (IPCEIs) focused on breakthrough technologies and innovation along the heat pumps value chain; and to establish a large-scale skills partnership under the pact for skills.

3.4.Batteries

Batteries will play a crucial role in achieving the European Green Deal objectives and implementing the REPowerEU plan[173], because they can reduce dependency on fuel imports in transport as well as ensure maximum use of renewable electricity and reduce curtailments. Over 50 million electric vehicles (EVs) are expected to be operating on the EU's roads by 2030[174] (with at least 1.5 TWh of batteries) and over 80 GW/160 GWh of stationary batteries[175]. The EU is gradually moving towards zero-emission new cars by 2035, in line with the objective of an EU entire car fleet of 270 million vehicles that should be zero-emission (mostly electric) by 2050. E-mobility is the main driver of demand for batteries. Lithium-ion batteries are expected to dominate the market well beyond 2030, but other technologies are being developed in parallel.

Technology analysis: Despite chip and magnesium supply disruptions, the deployment of battery technology in the EU has reached historic highs: 1.7 million new EVs were sold in 2021, reaching 18% of the market (compared to 3% in 2019 and 10.5% in 2020[176]) and surpassing China (16%). National EVs sales ranged from 1.3% in Cyprus to 45% in Sweden. The stationary EU battery market is also growing rapidly and is forecast to reach 8GW/13.7GWh by the end of 2022[177]. However, further acceleration is needed to reduce dependency on gas peaking plants, in line with the objectives of REPowerEU.

In 2021, the average battery price fell by 6% to around EUR/kWh 116[178] in the global market and to around EUR/kWh 150 in the EU market. This continues a long-term trend. However, with prices rising in 2022 due to supply-side shocks, the trend is now reversing (for example, in spring 2022 the price of lithium carbonate was up by 974% on 2021[179]). Battery packs will be at least 15% more expensive in 2022 than in 2021[180]. The system cost of grid-scale Li-ion applications was around EUR/kWh 350 in 2021[181] and, for home storage systems, roughly twice that.

Value chain analysis: Almost all the EU's 2021 mass-production of lithium-ion batteries was still carried out by Asian manufacturers established in the EU (Hungary and Poland). The construction of new gigafactories means that the EU (particularly Germany and Sweden) is

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173 COM(2022) 230 final ('REPowerEU Plan').

174 Policy scenarios for delivering the European Green Deal, European Commission, 2021. Available at: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en.

175 Policy scenarios for delivering the European Green Deal, European Commission, 2021. Available at: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en.

176 European Automobile Manufacturers' Association (ACEA), February 2022, https://www.acea.auto/fuel-pc/fuel-types-of-new-cars-battery-electric-9-1-hybrid-19-6-and-petrol-40-0-market-share-full-year-2021/

177 European Market Monitor on Energy Storage, sixth edition (EMMES 6.0), https://ease-storage.eu/publication/emmes-6-0-june-2022/

178 BNEF, Battery Pack Prices Fall to an Average of $132/kWh, November 30, 2021. Exchange rate of EUR .8826 for USD 1 on 30 November 2021/11/2021.

179 Energy Storage News, 'BloombergNEF predicts 30% annual growth for global energy storage market to 2030', 4 April 2022.

180 IEA, *Global EV outlook 2022*, 2022.

181 Based on Aurora Energy Research 21 April 2022 webinar 'How high can battery costs get?'

set to gradually gain importance on the market. Swedish Northvolt produced its first battery cell made with 100% recycled nickel, manganese and cobalt at the end of 2021, and started commercial deliveries in 2022. It states to have a highly efficient recycling process with recovery of up to 95% of battery metals[182].

The EU is expected to reach over 75 GWh[183] installed production capacity by the end of 2022 (compared to 44 GWh in mid-2021). The projects currently underway show that the EU is on track to meet 69% of demand for batteries by 2025 and 89% by 2030[184]. This is largely thanks to the European Battery Alliance's initiatives[185].

The upstream raw materials segment remains the least resilient in the battery value chain. Despite several EU initiatives, the supply gap for battery raw materials increased in 2021[186]. Spent batteries are still mostly sent to Asia for recycling[187].

The EU is rapidly advancing in Li-ion technology (notably the highest performing NMC[188] strand), but it is progressing too slowly in stationary battery technologies based on abundant raw materials (e.g. flow batteries and sodium-ion batteries – the latter also have good EV potential given developments in China among other factors). The EU is also slower in embracing cheaper Lithium (ion) Iron Phosphate (LFP) technology, which are increasingly used in Asia and less dependent on critical raw materials.

Global market analysis: China controls 80% of the world's Li-ion battery raw material refining capacity, 77% of cell production capacity and 60% of battery component manufacturing capacity[189]. The EU's trade deficit in Li-ion batteries continued to grow in 2021 and reached EUR 5.3 billion[190] (up 25% on 2020). The EU carries out roughly 19% of global EV production[191], but it has very little of the upstream supply chain (with the exception of cobalt processing). Electric bus production and deployment in the EU (7 356 e-buses were in circulation at the end of 2021) is insignificant compared to China, which has over 90% of the global stock of 670 000 e-busses[192].

In conclusion, the EU is increasingly building up the highly needed technological capability in cheaper storage/longer-term storage (e.g. technologies for sodium-ion; zinc based; flow batteries) and is strong in final products (especially EV production and deployment, with the exception of the electric buses segment). It is also quickly catching up in cell manufacturing when it comes to Li-ion technology and is on track to becoming nearly self-sufficient in battery production by 2030. The lack of domestic raw materials and advanced materials production is a persistent problem despite current ongoing initiatives. The EU aims to

182 NorthVolt.com, *'Northvolt produces first fully recycled battery cell'*, 12 November, 2021.
183 Including LG Chem (Poland): 32 GWh; Samsung SDI (Hungary): 20 GWh; Northvolt (Sweden): 16 GWh; SK Innovation (Hungary): 7.5 GWh (Benchmark Minerals: Europe's EV gigafactory capacity pipeline to grow 6-fold to 789.2 GWh to 2030 - Green Car Congress). Other producers, e.g. SAFT, MES and Leclanché contribute with smaller scale capacities, but are increasing their production volumes.
184 EIT InnoEnergy, *Contribution for High-Level ministerial meeting on batteries*, February 2022.
185 European Battery Alliance (europa.eu)
186 EIT Innoenergy, *Contribution for High-Level ministerial meeting on batteries*, February 2022.
187 EBA250, the industrial development programme of the European Battery Alliance, https://www.eba250.com/.
188 NMC = Nickle Manganese Cobalt.
189 Willuhn M., *National lithium-ion battery supply chains ranked*, PV Magazine, 16 September 2020.
190 COMEXT 2022 data.
191 Based on Prodcom 2021 production data for EU, and IEA data on 2021 global sales of EVs.
192 2022 IEA EV Outlook.

increase its effort to address-these challenges from extraction to refining, from processing to recycling with e.g. the announced European Critical Raw Material Act.

3.5. Renewable hydrogen production through water electrolysis

Renewable hydrogen[193] has a great potential to contribute to the EU's climate and energy objectives. It can be used as fuel for sectors that are difficult to electrify (e.g. long-distance and heavy-duty transport); as chemical feedstock (e.g. fertilisers and other chemicals); and in industrial processes (e.g. steel or cement production). Hydrogen and its derivatives are forecast to represent 12% of the global energy mix in 2050[194], yet renewable hydrogen using water electrolysis represents currently only 0.1% of the overall EU production.

REPowerEU has further strengthened the policy objectives of the 2020 hydrogen strategy[195], setting the 2030 targets for renewable and low carbon hydrogen to 10 Mt of domestic production and 10 Mt of imports (partly in the form of ammonia). The setup of a European Hydrogen Bank will accelerate the production and the use of renewable hydrogen and help develop the necessary infrastructures in a coordinated manner[196].

The Commission and leading EU electrolyser manufacturers committed themselves to increasing manufacturing capacity tenfold to 17.5 GW in hydrogen output by 2025[197]. In addition, the Member States' RRPs allocate around EUR 10.6 billion to hydrogen technologies and two IPCEIs were approved by the Commission in 2022 (July and September), for EUR 5.4 and 5.2 billion of investments, involving 15 and 13 Member States respectively.

Technology analysis: Out of a worldwide capacity of 300 MW in 2020[198], Europe (including the UK and the EFTA countries) accounted for 135 MW of installed capacity in 2021. Proton Exchange Membrane (PEM) and alkaline electrolysers make up 55% and 44% of the installed capacity deployed on European territory respectively (including EFTA and the UK)[199].

The levelised cost of electricity is the main factor impacting the economic viability of the electrolysers' investments and rising electricity prices remain one of the key challenges for the economic viability of a competitive production of electrolyser hydrogen.

The cost of European hydrogen production using renewable sources varies from a (2020) median of EUR/kgH_2 6.8 (Solar PV-based production), to a median of EUR/kgH_2 5.5 in (wind-based production)[200]. Costs of electrolysers are expected to fall due to high

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193 The EC defines renewable hydrogen as hydrogen that is produced using renewable electricity or that is obtained from biomass which meets 70% of the CO_2 emissions reductions (as compared to fossil fuels). The EC has defined a threshold for the 'low carbon hydrogen' in the Gas and Hydrogen Decarbonisation Package of 15 December 2021 (COM(2021) 803 final).

194 IRENA, *Geopolitics of Energy Transformation: the Hydrogen Factor*, Abu Dhabi, 2022.

195 COM(2020)301 ('A hydrogen strategy for a climate neutral Europe').

196 As announced in the 2022 State of the Union Address on 14 September 2022. https://ec.europa.eu/commission/presscorner/detail/ov/SPEECH_22_5493

197 Joint Declaration of 5 May 2022, https://ec.europa.eu/documents/50014/.

198 *Global Hydrogen Review*, IEA, 2021.

199 *The Clean Hydrogen Monitor*, Hydrogen Europe, 2021.

200 *The Clean Hydrogen Monitor*, Hydrogen Europe, 2021.

temperature electrolysis: from 2130 EUR/kW in 2020 to 520 EUR/kW in 2030. The 2030 cost targets for PEM and alkaline electrolysers are at EUR/kW 500 and 300 respectively[201].

Value chain analysis: The 2021 manufacturing capacity for water electrolysers has been estimated at 2.5 GW/y in Europe[202]. Global manufacturing capacity was estimated at around 6-7 GW/y (about two thirds alkaline and one third PEM for both European and global markets)[203].

Manufacturing volumes in Europe are lower than in China and the United States. It is estimated that Chinese companies have half of the world's alkaline electrolysis manufacturing capacity, and that American companies have most of the world's PEM electrolysis manufacturing. Europe leads in terms of number of manufacturing companies and in Solid Oxide electrolysis but depends on countries such as China, Russia and South Africa for the supply of necessary critical raw materials, and it is able to source only 1-3% of them domestically[204].

Water consumption (currently around 17 l/kgH_2) associated with the roll-out of more renewable hydrogen production will increase stress on freshwater resources, so new electrolyser locations should comply with the Water Framework Directive[205] to also safeguard against water-related production bottlenecks.

Global market analysis: Only 0.2% of the European total annual (non-renewable) hydrogen demand of 8.4 M tonnes is supplied via international trade[206]. Even though international hydrogen trading is still not a reality, there are significant trade opportunities in the future supply of renewable hydrogen for the EU as identified in the REPowerEU plan.

In conclusion, without bigger assembly systems, more automation and economies of scale, the EU cannot compete with China in alkaline technology.

Currently high electricity prices and reliance on imports of critical raw materials concentrated in a few suppliers are fundamental weaknesses of the EU electrolysers' value chains. Long-term cooperation agreements are needed. There is also a need for dedicated research into alternatives to the rare metals and other critical raw materials that are currently necessary for water electrolysis. Furthermore, long-term success depends on sustainable water supply and sufficient recycling capacity in the EU as well as a comprehensive approach to pull demand and supply. The support of EU regulatory and funding frameworks, as well as large investments through the recovery funding, IPCEIs, cohesion policy, Horizon Europe, the Clean Hydrogen Joint Undertaking[207] and the Innovation Fund are crucial for the competitiveness of the EU renewable hydrogen industry.

[201] *Strategic Research and Innovation Agenda 2021-2027*, Clean Hydrogen partnership.
[202] Joint Declaration of the European Electrolyser Summit Brussels, 5 May 2022.
[203] BNEF, 2021. Note that Different sources provide varying estimates of annual production capacity.
[204] Dolci, F. et al, Clean Energy Technology Observatory: Hydrogen Electrolysis -- 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, JRC130683.
[205] OJ L 327, 22.12.2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy
[206] Hydrogen Europe, Clean Hydrogen Europe, 2021. The yearly hydrogen demand includes Iceland, Norway, Switzerland and the UK.
[207] The Clean Hydrogen Joint Undertaking has allocated EUR 150.5 million, the Horizon 2020 programme made EUR 130 million available, and the Innovation Fund supported four projects with EUR 240 million until mid-2022.

3.6.Renewable fuels

Renewable fuel technologies can significantly contribute in the short term to the decarbonisation of transport, and ensuring the security of energy supply and energy diversification. The REPowerEU plan[208] identifies, in particular, biomethane[209], as key to diversify EU gas supplies by increasing its production twice above the EU 2030 target, thus putting biomethane on top of renewable energy priorities.

The Fit for 55 legislative proposals[210] would introduce a significant demand for renewable energy in the transport sector in 2030, considerably above the targets for the shares of advanced biofuels and renewable fuels of non-biological origin set in the revised RED II proposal[211]. This is due to the greenhouse gas (GHG) saving target of 13% in transport (which is not likely to be met by electrification alone), and the higher GHG saving targets of 40% and 61% in the revised proposals for the Efforts Sharing Regulation[212] and the Emission Trading System Directive[213] respectively (if these are to be met with equal contributions from transport). The REPowerEU plan proposes to further increase required renewable fuel quantities. Contrary to road transport, whose decarbonisation is expected to rely for a large part on electricity and hydrogen,[214] the RefuelEU Aviation and FuelEU Maritime proposals project that renewable fuels will supply 5% and 6.5% of the EU's total jet and shipping fuel consumption in the aviation and maritime sectors[215, 216].

Technology analysis: Commercial pathways do exist (e.g. anaerobic digestion to biomethane, hydrogenated vegetable oil and lignocellulosic ethanol production), but there is little installed capacity (0.43 Mt/y) and planned production is limited (1.85 Mt/y). A variety of innovative technologies (e.g. biomass gasification to Fischer-Tropsch synthetic fuels, pyrolysis-derived fuels and biomethanol production) have been demonstrated in industrial environment and are ready to take-off. Noticeable progress is being made with several next generation technologies. The EU focuses its actions on advanced biofuels, mainly based on non-recyclable waste and residues, and limits its support for biofuels based on food and feedstock.

Technologies for other renewable synthetic fuels (solar fuels, 2nd generation microbial fuels and micro-algae fuels) are mostly still at lab-scale. Even for electro-fuels, the most advanced technologies are not yet commercial because of still existing technological challenges,

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208 COM(2022) 230 final (*'REPowerEU Plan').*

209 Especially when produced from organic waste and residues, thus resulting in an advanced biofuel when used in the transport sector.

210 COM(2021) 550 final ('Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality').

211 COM(2021) 557 final ('Amendment of Directive 2018/2001, Regulation 2018/1999 Directive 98/70/EC as regards the promotion of energy from renewable sources').

212 COM/2021/555 final ("Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement").

213 COM/2021/551 final ("Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757").

214 The main policy drivers in the sector are CO2 emissions standards and Alternative Fuels Infrastructure Regulation (AFIR) proposed as part of the 'Fit for 55' package.

215 SWD(2021) 633 final, ('Impact assessment accompanying the Proposal for a Regulation of the European Parliament and the Council on ensuring a level playing field for sustainable air transport').

216 COM(2021) 562 final ('Proposal for a Regulation on the use of renewable and low-carbon fuels in maritime transport').

currently high electrolysis costs, high conversion losses (50%) and high transportation and distribution costs[217].

Value chain analysis: The main challenge for the market uptake of advanced biofuels is their competitiveness with existing conventional biofuels derived from food crops. The cost of advanced biofuels is estimated at 1.5 to 3 times the market price of traditional biofuels such as biodiesel and bioethanol (set at 50-100 €/MWh). Advanced biofuels also have high capital expenditures (up to EUR 500 million for a single plant) and are linked to the availability of sustainable biomass feedstock. There is significant potential to cut capital costs by 25-50% and feedstock costs by 10-20%, namely through R&I, large scale deployment and co-processing in existing plants.

Private R&I Venture Capital biofuels funding[218] was on average EUR 250 million per year in 2010-2021. The US and Canada dominated (albeit with different definitions of biofuels), while the EU's share has been only 6% in the last 5 years. However, the EU is in the lead with twice as many high-value patents as the US. China holds most low innovation patents and EU's patent applications are increasing in US and China.

Global market analysis: The EU has roughly 7% of the global biofuel market worth (i.e. about EUR 105 billion in 2020) and is mostly generated from first-generation biodiesel. Turnover peaked at EUR 14.4 billion in 2018[219] with most being generated in France, Germany and Spain. 250 000 direct and indirect jobs were created along the value chain in the EU. The EU is also home to 29% of the world's innovation companies, while the US and Japan have the most.

The advanced biofuels sector is only just emerging. The number of commercial plants is still quite low and international trading is very limited. The EU is the world leader with 19 of the 24 operational commercial advanced biofuels plants. Sweden and Finland have the most (12 between them)[220].

All biofuels can be traded internationally. International trade is lower than for its fossil counterparts, and barely exists for advanced biofuels. The EU's biofuel imports have been constantly increasing since 2014. It had a biofuel trade deficit of more than EUR 2 billion in 2021, with imports mainly coming from Argentina, China and Malaysia. The Netherlands and Germany are the biggest EU producers and global biofuel exporters.

In conclusion, although the installed and planned renewable fuels production capacity for 2030 is minimal and the potential of advanced biofuels from sustainable feedstock in the EU is limited, this sector can nevertheless contribute to the Fit for 55 GHG emission savings targets and sufficiently cover any transport electrification lag. Some technical and economic risks must still be overcome in order to fully realise the potential of renewable fuels in

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217 50% for electro-fuels. Today's electro-fuel costs of 7 EUR/litre are expected to decrease to 1-3 EUR/litre until 2050, due to economies of scale, learning effects and anticipated reduction in the renewable electricity price.

218 Private investments include venture capital, angel and seed, and grants. 57% of the investment since 2010 was in the US, 28% in Canada and only 10% in the whole EU (JRC CETO 2022 Advanced Biofuels report).

219 Advanced Biofuels reports that France had the highest turnover in 2020 (just over EUR 2 500 million), followed by Germany and Spain (around EUR 1 500 million each) and Hungary, Romania and Poland (a little less than EUR 1 000 million each) (see Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,, JRC130727).

220 Sweden has 8 plants, Finland has 4, Spain and Italy each have 2, and France and the Netherlands each have 1. Outside the EU, the US has 2 and China, Indonesia, Japan and Norway each have 1 (JRC CETO 2022 Advanced Biofuels report).

transport. The cost of all renewable fuels and, in particular, of synthetic ones, are still high because they rely on renewable energy and hydrogen prices. Nevertheless, advanced biofuels rely on local sustainable biomass resources and short supply chains that create a large number of skilled jobs, reduce energy poverty and drive industrial competitiveness. The EU is the clear market leader in operational commercial advanced biofuels plants and high-value innovations. EU companies are currently among the world's top ten but they risk losing their technological leadership due to the lack of private funding. Therefore, besides the energy domestically produced, the export potential of underlying European technologies should also be considered.

3.7. Smart technologies for energy management

EU and national policymaking have clearly recognised the importance of smart electricity grids in recent years. The 2020 EU strategy for energy system integration[221] acknowledged the importance of smart grids in achieving the EU's energy and climate policy objectives. The 2022 revised Trans-European Energy Infrastructure Regulation[222] refers to smart electricity deployment as a priority thematic area[223]. In their Recovery and Resilience Plans (RRPs), Member States recognised the potential of digital solutions to upgrade the smartness of electricity grids[224]. Electrification and smartening of the grid are progressing, but more is needed to reinforce the electricity infrastructure in order to implement the REPowerEU plan. The challenges include reduction, data-sharing between different players, flexibility, interoperability and technology readiness. The EU's action plan on digitalising the energy system[225] presents a series of measures to overcome these barriers.

Given the large number and wide range of smart energy technologies, this section focuses on presenting an assessment of the relevant technological and market developments for just three key technologies: i) advanced metering infrastructure; ii) home energy management systems; and iii) smart electric vehicle charging.

i) Advanced Metering Infrastructure (AMI)

AMI systems[226] offer many advantages for both energy service providers and consumers, including reduced electricity bills through better consumption management; better grid observability and therefore better outage management; reduced costs for grid updates due to better management of electricity peaks; and better customer control through the use of advanced customer infrastructure (i.e. smart applications and web portals)[227].

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221 COM (2020)299 final ('Powering a climate-neutral economy: An EU Strategy for Energy System Integration').

222 OJ L 152, 3.6.2022. Regulation (EU) 2022/869 of the European Parliament and the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013.

223 The Regulation requires that smart grid projects contribute to at least two of the following criteria: (i) security of supply; (ii) market integration; (iii) network security, flexibility and quality of supply; and (iv) smart sector integration.

224 European Commission, *Recovery and Resilience Scoreboard. Thematic Analysis: Digital public service*s, December 2021.

225 COM (2022)552 final, Digitalising the energy system – EU action plan

226 AMI systems are comprised of different components. Smart meters are the core part, and are complemented by communication networks and data management systems.

227 Advanced Metering Infrastructure and Customer Systems, *Results from the Smart Grid Investment Grant Program*, Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, https://www.energy.gov/sites/prod/files/2016/12/f34/AMI%20Summary%20Report_09-26-16.pdf.

The roll-out of intelligent metering systems is progressing in the EU, although it needs to further accelerate. In 2020, only 43% of consumers had been equipped with a smart electricity meter (corresponding to about 123 million units in the EU and UK)[228]. Functionalities offered by AMI vary: in most countries, they offer detailed information via a meter interface about consumption data (e.g. consumption level/date/time) and/or information on cumulative consumption data.

Exploiting AMI's full potential will require further integration with home energy management systems and smart appliances (including smart EV charging) as well as with new energy services.

ii) Home energy management system (HEMS)

The increasing roll-out of smart appliances[229] indicates that HEMS should become the hub for data aggregation, optimisation and externalisation to third parties (e.g. energy brokers and service providers). The Commission is preparing a code of conduct for energy smart appliances manufacturers, which will define interoperability requirements and the principles for data sharing between appliances; home and building automation systems; EV chargers; aggregators; and distribution system operators[230].

Current home energy management solutions range from direct-to-customer energy monitoring applications to white-label software platforms for utility customers, which can later be rolled out to end-users. In addition to "traditional" companies with track records in energy and/or electronics[231], large software companies such as Google, Apple, and Cisco now distribute HEMS products[232]. This trend emphasises the increasing role of software engineering in Internet of Things (IoT) devices.

Demand for HEMS is expected to grow significantly in the coming years. For example, the German market, which is the biggest national HEMS market in the EU, is expected to grow to nearly USD 460 million (EUR 544 million[233]) by 2027, and the French HEMS market could have a compound annual growth rate (CAGR) of 20.3% between 2021 and 2027[234]. This reflects global trends. The global HEMS market was estimated at USD 2.1 billion in 2021 (EUR 2.5 billion[235]), and could grow to USD 6 billion (EUR 7 billion[236]) by 2027 (with

[228] Estonia, Spain, Italy, Finland and Sweden: 90%; Denmark, France, Luxembourg, Malta, the Netherlands and Slovenia: 70-90%; Latvia and Portugal: 50-70%; Greece, Austria and the UK: 20-50% (Vitiello, S., Andreadou, N., Ardelean, M. and Fulli, G., Smart Metering Roll-Out in Europe: Where Do We Stand? Cost Benefit Analyses in the Clean Energy Package and Research Trends in the European Green Deal, Energies, Vol. 15, p. 2340, 2022, https://doi.org/10.3390/en15072340.

[229] Examples include smart thermostats, smart plugs, smart lighting, as well as distributed energy appliances like solar PV, EVs.

[230] Support on the development of policy proposals for energy smart appliances | JRC Smart Electricity Systems and Interoperability (europa.eu)

[231] e.g. Fortum (FI), ENEL X (IT), Bosch (DE), NIBE (SE) and Schneider Electric (FR). HEMS vendors were presented in detail in the Commission's 2021 competitiveness report (SWD(2021) 307 final, Staff Working Document).

[232] Google's Home, Apple's Siri, and Cisco's energy management service are examples of HEM services.

[233] An average exchange rate of EUR 1.1827 for USD 1 over the year 2021 is used in this paragraph. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

[234] Delta-EE, https://www.delta-ee.com/research-services/home-energy-management/.

[235] An average exchange rate of EUR 1.1827 for USD 1 over the year 2021 is used in this paragraph. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

a CAGR of 16.5% during 2022-2027)[237]. At this stage, however, it remains unclear whether HEMS will only help consumers in optimising their consumption and comfort or whether they will also enable demand response and flexibility at scale.

iii) Smart EV charging

Smart EV charging will be key to maximising synergies between EVs, renewable energy generation and grid services. The pace of EV roll-out means that EVs are not expected to create a power-demand crisis in the short to medium-term[238], but they could reshape the load curve[239]. The impact of smart EV charging can be bigger in regions and local areas where a high EV concentration meets less robust grid infrastructure. Smart EV charging techniques can potentially provide balancing services for the grid and reduce renewable curtailment, thus reducing the need for grid upgrades.

Smart charging includes a range of pricing and technical charging options, and comes in three forms: unidirectional vehicles-to-grid (V1G), bidirectional vehicles-to-grid (V2G), and vehicle-to-home or building (V2H-B). Key players in the smart EV charging market include ABB (Sweden/Switzerland), Bosch Automotive Service Solutions Inc. (Germany), Schneider Electric (France), GreenFlux and Alfen N.V. (Netherlands), Virta (Finland), Driivz and Tesla (US).

The global smart EV charging market is clearly taking off, with an estimated value of USD 1.52 billion (EUR 1.77 billion[240]) in 2020 and a compound annual growth rate (CAGR) of 32.42% between 2021 and 2031[241]. However, unlike more mature V1G solutions, V2G and V2H-B have not yet reached the broad market deployment stage, although the number of pilots and demonstrations is growing.

Rolling out smart charging infrastructure at scale will bring two challenges: firstly, standardisation of communication interfaces among charging points, EVs and the distribution grid will need to be consolidated; secondly, an increasing demand for raw materials will need to be met[242].

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236 An average exchange rate of EUR 1.1827 for USD 1 over the year 2021 is used in this paragraph. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

237 IMARC group: Home Energy Management System Market Size and Share 2022-2027, https://www.imarcgroup.com/home-energy-management-systems-market?msclkid=5440b237b02f11ecae445030f049ab37.

238 Distribution grid simulations in Germany show that grid upgrade requirements are rather low until EVs reach around 20% of all vehicle stock (Vertgewall, C.M. et al., *Modelling Of Location And Time Dependent Charging Profiles Of Electric Vehicles Based On Historical User Behaviour*, CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution, 2021).

239 McKinsey&Company, McKinsey Center for future mobility, *The potential impact of electric vehicles on global energy systems*, 2018

240 An average exchange rate of EUR 1.1827 for USD 1 over the year 2021 is used in this paragraph. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

241 Transparency market research, *Smart EV Charger Market: 2021 – 2031*, 2021

242 Raw materials such as stainless steel, copper, aluminium, polycarbonates, elastomers, and thermoplastics polyurethanes are used for manufacturing critical components of EV charging stations (enclosures, cables, connectors, cable insulation and jacketing, and flexible conduits). Silicon and germanium are crucial raw materials for the manufacture of electronic circuits and boards.

AMI systems, HEMS and EV smart charging are expected to make further progress. The deployment of AMI systems has been slower than initially envisaged. Further integration with HEMS and smart appliances is required to fully exploit the opportunities of AMI systems. The increasing presence of smart appliances should result in a significant increase in demand for HEMS. The global market for smart EV charging should also take off, but challenges will need to be overcome.

3.8. Main findings on other clean energy technologies

The above sections focus on those clean energy technologies and solutions analysed in 2021[243]. The other main clean energy solutions presented in this section are covered in the accompanying CETO reports[244]. These technologies are at different development stages and are evolving in diverse contexts. This means that they each have their own sets of competitiveness challenges and opportunities.

Hydropower[245], for example, has been substantially deployed across the EU. Installed capacity was 151 GW in 2021, a +6 GW increase compared to 2011, corresponding to about 12% of the EU's net electricity generation. The EU's 44 GW of pumped hydropower represents nearly all the EU's electricity storage capacity and ensures flexibility to the electric grid and water storage capacity. With an aging fleet, sustainable refurbishment of existing hydropower capacity steadily gains importance, as well as an opportunity to make the hydropower fleet more resilient to climate and market changes. The EU is a leader in R&I, holding 33% of all high-value inventions globally (2017-2019) and hosting 28% of all innovative companies. In a globally expanding market, it also held 50% of all global exports in hydropower, to a value of EUR 1 billion in 2019-2021. However, fully exploiting its potential will require the EU to overcome challenges linked to social acceptance and environmental impacts of new installations and reservoirs. The effects of climate change also impact hydropower in Europe in various ways and hydropower reservoirs may play a role mitigating some of these effects. It is essential to recognise the additional benefits (beyond energy generation) of multi-purpose hydropower reservoirs and to incentivise more sustainable (i.e. less impacting) hydropower technologies and measures.

A growing number of deployments of **ocean energy**[246] are taking place. In the long term, considering the resource potential, ocean energy can contribute up to 10% of the EU energy needs. The 2020 EU offshore renewable energy strategy[247] proposed specific capacity targets for ocean energy with the long-term objective of at least 40 GW by 2050. EU companies are leading the ocean energy sector with most companies hosted in EU countries. Deployments inside and outside the EU are increasing in terms of installed capacity. Individual devices are

243 COM(2021)952 final ('Progress on competitiveness of clean energy technologies').
244 https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en.
245 Quaranta, E. et al,, Clean Energy Technology Observatory, Hydropower and Pumped Hydropower Storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, JRC130587.
246 Including wave, tidal salinity gradient and ocean thermal energy conversion technologies.
247 COM(2020) 741 final ('An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future').

already contributing to the grid for longer periods of time[248]. However, continuing cost reductions and ensured sustainability are needed for wave and tidal energy technologies to be established in the electricity market and to be competitive with other renewable energy sources. Further funding dedicated to testing and market uptake is also necessary to allow their large-scale deployment.

Geothermal[249] energy has experienced growth both for power plants, and for district heating and cooling, although at a slow rate compared to other clean energy technologies. In 2021, two additional geothermal power plants were commissioned in Germany, with a capacity of 1 MWe and 5 MWe[250] - thus, bringing the EU's total capacity to 0.877 GWe – while total global installed capacity was around 14.4 GWe. In 2021, total installed geothermal district heating and cooling capacity reached 2.2 GWth in the EU, with over 262 systems. The largest growth is happening in France, the Netherlands and Poland. Enhanced geothermal systems (EGS) still face several innovation challenges that will require further R&I. Lowering the risk of investing in geothermal energy projects is crucial for tapping into the huge potential of geothermal energy. In the EU, the main challenges concern cost-efficiency and environmental performance.

Concentrated solar power and heat[251] (CSP) can substantially contribute to electricity generation in locations with high direct insolation, but only a fraction of its potential has been harnessed so far. In 2021, worldwide installed capacity was approximately 6.5 GW, with 2.4 GW installed in the EU. There is also a large EU market for industrial process heat, which can be partly exploited by concentrated solar heat systems. Exploring this potential for power and process heat with financial and other support measures would allow the EU to better face international competition. This is particularly important as Chinese organisations are emerging as international CSP project developers, a field where EU companies have traditionally been leaders. CSP has shown considerable progress in terms of cost reduction and in establishing itself as a reliable option. European organisations play a leading role in research and technological development. EU researchers are top publishers of scientific papers and authors of high-value patents increasing efficiency and reducing cost, as set out in the CSP implementation plan of the Strategic Energy Technology Plan (SET Plan)[252]. R&I will play a key role here and concrete support will continue to be provided at EU level as announced in the EU's new solar energy strategy.

Carbon Capture Utilisation and Storage (CCUS) progress has sped up over the past years but still only a small number of installations are operating in the EU. France, Germany and the Netherlands are the leaders in public and private R&I investment and in top patenting companies. There are some continuing barriers to the development of CCUS, mostly as

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248 Meygen 1A tidal energy (UK) has been running since April 2018, Mutriku wave energy (ES) since July 2011 and Shetland tidal since 2016.

249 Bruhn, D. et al, *Clean Energy Technology Observatory: Deep Geothermal Energy in the European Union- 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, European Commission. 2022, JRC130585

250 European Geothermal Energy Council, *2021 EGEC Geothermal Market Report*.

251 Taylor, N. et al, Clean Energy Technology Observatory: Concentrated Solar Power and Heat in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, doi. , 2022, doi: 10.2760/080204, JRC130811.

252 https://setis.ec.europa.eu/implementing-actions/csp-ste_en

regards regulatory implementation[253], economics, risk and uncertainties, and public acceptance. 11 large-scale CCS and CCU projects have been selected for EU support from the Innovation Fund.

Bioenergy[254] currently represents almost 60%[255] of the renewable energy supply in the EU. Bioenergy remains important for the transition of several Member States' energy sectors, because it helps decarbonise the economy while increasing energy security and diversification. The projected increase of biomass means it is important for the EU to ensure that bioenergy is sourced and used sustainably, and to avoid negative impacts on biodiversity and carbon sink and stocks. The revision proposal of the Renewable Energy Directive includes stronger sustainability criteria for bioenergy and introduces a requirement for Member States to apply the cascading principle in their financial support schemes. Sustainably produced biomethane, based on organic waste and residues, in particular, can contribute to the REPowerEU goal of reducing EU dependency on imported fossil fuels. The obligation to separately collect organic waste by 2024 represents a major opportunity for the sustainable biogas production in the coming years. Bioenergy provides flexible power generation, balancing the electricity grid and plays a key role in enabling high shares of variable renewable energies, such as wind and solar, in the electricity grids.

Nuclear energy, with 103 power reactors (101 GWe) in the EU in 2022, generates about a quarter of the EU's electricity, and provides about 40% of the EU's low-carbon electricity[256]. Alongside renewables, nuclear power is included in the EU strategic long-term plan for a climate neutral economy by 2050. The REPowerEU plan further recognises the role of nuclear-based hydrogen in substituting natural gas in the production of fossil-free hydrogen. The potential contribution of nuclear to the future low carbon energy mix relies on research and innovation, aiming at ever safer and cleaner nuclear technologies (both conventional and advanced ones). Several utilities and research organisations from at least seven EU Member States have shown interest in new Smaller and Modular nuclear Reactors[257] (SMRs) linking them to decarbonised electricity and non-electric energy production such as industrial and district heating and hydrogen production. Interested EU industrial and state actors are driving a process towards a European industrial model for SMR deployment in the early 2030s.

4. CONCLUSION

The rapid development and deployment of home-grown clean energy technologies in the EU is key to a cost-effective, climate friendly and socially fair response to the current energy crisis.

In response to unprecedentedly high energy prices, the EU has swiftly put forward a set of measures that will **protect consumers and businesses**, including vulnerable households and clean energy technology industry players, while ensuring the achievement of the 2030 and 2050 climate and energy targets.

253 For example the ratification of the London protocol.
254 Motola, V. et al, Clean Energy Technology Observatory: Bioenergy in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets, European Commission, 2022, JRC130730.
255 This figure includes biofuels, accounting for about 7%.
256 World Nuclear Association, *Nuclear Power in the European Union*, table "EU nuclear power", website accessed on 14 October 2022.
257 European Commission, Small Modular Reactors and Medical Applications of Nuclear technologies, Publications Office of the EU, Luxembourg, 2022.

In parallel, the EU should continue its efforts to **reduce its dependency on, and effectively diversify its sourcing of, raw materials**, as their surging prices severely affect the competitiveness of clean energy technologies. The announced European Critical Raw Materials Act[258] aims at contributing to achieve these ambitions. The EU also needs to **deepen international cooperation**, and **overcome the shortage of skilled labour** in various clean energy technology segments, while also ensuring a gender- balanced and equal environment. The proposal to make 2023 the European Year of Skills represents a step towards the increase of skilled workers.

More public and private investments in clean energy research and innovation, scale-up and affordable deployment are of pivotal importance. The EU's regulatory and financial frameworks have a crucial role to play here. Together with the implementation of the New European Innovation Agenda, EU funding programmes, **enhanced cooperation** between Member States, and a continuous **monitoring of national R&I** activities, are crucial to design an impactful EU R&I ecosystem, and to bridge the gap between research and innovation and market uptake, thus reinforcing EU competitiveness.

This report confirms[259] that the **EU has remained at the forefront of clean energy research**, and that R&I investment is steadily growing (albeit below pre-financial crisis levels). At global level, the EU remains a leader in 'green' inventions and high-value patents, being the top worldwide patent applicant in the fields of climate & environment (23%), energy (22%) and transport (28%). The EU's global share of scientific publications has fallen, but EU scientists collaborate and publish internationally in clean energy topics at a rate that is well above the global average. Additionally, the EU exhibits a higher level of public-private collaboration.

Turnover and gross value added of the EU renewable energy sector have continued to increase since 2019, and the EU's production of most clean energy technologies and solutions showed the same trend in 2021. Although the EU has maintained a positive trade balance in a number of technologies, such as wind, its trade deficit has increased for others, such as heat pumps, biofuels and solar PV. This overall trend is partly due to the EU's increasing demand for such technologies.

On specific clean energy technologies, the report shows that the EU's **wind** sector remains a world leader in R&I and high value patents in 2022, and maintains a positive trade balance. Competition remains fierce, however, and the wind industry will need to overcome the current unfavourable context also due to the increasing global demand for rare earth materials and supply chain disruptions. The sector will need to double its current annual installation capacity in order to achieve the REPowerEU targets. The EU has also confirmed its position in 2022 as one of the largest markets for **PV** as well as a strong innovator, especially in emerging PV technologies. From the value chain perspective, the EU is still lagging behind Asia, with a strong dependence on several crucial components. Innovative solutions and continuous technological advances offer additional opportunities for deployment in the EU.

[258] As announced by the President of the European Commission in her State of the Union address on 14 September 2022. https://ec.europa.eu/commission/presscorner/detail/ov/SPEECH_22_5493.

[259] As in the previous edition: COM (2021) 952 final and SWD(2021) 307 final ('Progress on competitiveness of clean energy technologies').

The EU is at a crossroads for several technologies. Several challenges still need to be overcome to fully exploit them. The **heat pumps** sector will have to accelerate its already fast-growing deployment and ensure systems affordability (especially for low-income households and SMEs), and EU suppliers will have to ramp up production in order to maintain their market share by comparison with third countries. With regards to **battery production**, the EU is on track to almost achieving self-sufficiency by 2030, but a lack of domestically sourced raw materials and advanced materials production capacity continue to pose challenges. Further attention is needed to increase recycling capacity and establish technological capability in cheaper storage/longer-term storage. On **hydrogen production through electrolysis,** the EU benefits from its strong comprehensive approach to pull demand and supply. The EU's value chain position varies (e.g. it leads in Solid Oxide electrolysis, but does not compete in alkaline technology). Surges in electricity prices and reliance on critical raw materials are some of the main challenges. The EU is the clear market leader in operational commercial plants of **renewable fuels** and high-value innovations. Although with limited installed and planned production for 2030, renewable fuels can contribute to all Fit for 55 emission saving targets, if certain technical and economic risks are addressed. Innovation in the EU's **digital energy infrastructure** will be key to ensuring that the electricity grid is fit for the future energy system. Demand for HEMS and smart EV charging is taking off and expected to grow and the roll-out of an intelligent metering system is progressing in the EU (albeit at a slower pace than envisaged).

Overall, despite the promising positive trends observed in the EU innovation ecosystem, further efforts are needed to address structural barriers and societal challenges holding back the EU-based climate-tech start-ups and scale-ups more than in other major economies. To exploit its potential to become a global leader in the climate-tech and deep-tech domains, the EU needs to leverage its diverse talents, intellectual assets and industrial capabilities, and to get private investors to participate more actively in the funding of climate-tech and deep-climate-tech start-ups.

The Commission will continue to monitor the clean energy sector's progress and will further develop its methodology and data collection in cooperation with the Member States and stakeholders. Within this context, the Commission will update its evidence-based methodology for future editions of the Competitiveness Progress Report. This will inform policy decisions and help make the EU competitive, resource efficient, resilient, independent, and climate-neutral by 2050.

ANNEX I: METHODOLOGICAL FRAMEWORK FOR THE ASSESSMENT OF THE EU'S COMPETITIVENESS[260]

Part 1: Overall Competitiveness of the EU clean energy sector	Part 2: Clean energy technologies and solutions		
Macro-economic analysis (aggregated, per MS and per clean technology)	1. Technology analysis Current situation and outlook	2. Value chain analysis of the energy technology sector	3. Global market analysis
Recent developments - energy prices and costs: recent trends - sustainability and circularity challenges of clean energy technologies; (critical) raw material dependency of the EU clean energy sector and impacts on the EU competitiveness. - impact of the Covid-19 and Recovery - human Capital and Skills	**Capacity installed, generation/production** (today and in 2050)	**Turnover**	**Trade (imports, exports)**
Research and innovation trends - public and Private R&I investments - patenting and High-Value patents EU and per MS	**Cost / Levelised Cost of Electricity (LCoE)[261]** (today and in 2050)	**Gross value added growth** Annual, % change	**Global market leaders vs. EU market leaders** (market share)
The global clean energy competitive landscape	**Public R&I funding (MS and EU)**	**Number of companies in the supply chain, incl. EU market leaders**	**Resource efficiency and dependence[262]**
The innovation funding landscape in the EU (versus major economies)	**Private R&I funding**	**Employment in value chain segment**	
The role of **systemic change on the clean energy sector** (e.g. digitalisation, buildings, energy communities and sub-national cooperation)	**Patenting trends** (incl high value patents)	**Energy intensity / labour productivity**	
	Level of scientific publications	**Community production** Annual production values	

260 The assessment was made in close collaboration with the European Commission's Clean Energy Technology Observatory: Details for Part 1 are reported in Georgakaki, A. et al, Clean Energy Technology Observatory Overall Strategic Analysis of Clean Energy Technology in the European Union – 2022 Status Report, European Commission, 2022, JRC131001. For Part 2 the individual technology reports are available at https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en

261 And –if available- Levelised Cost of Storage (LCoS).

262 Segments of the value chain that depend on critical raw materials.