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What is special about green innovation? Policy insights from green hydrogen, electric vehicles and carbon-emissions reducing steel production

TIP meeting, 18-19 June 2024.

This document discusses the concept of green innovation. It explores green innovation trends with a comparative focus on green hydrogen, electric vehicles and carbon-emissions reducing steel production. The objective is to identify implications for innovation policy aimed at supporting green transitions.

This document is part of the 2023-24 TIP project "Making technology investments succeed: What should STI policies do for skills and capabilities?" [see DSTI/STP/TIP(2013)14/REV1 for the latest project description].

This is a preliminary draft that will be complemented with additional research and insights gathered during the round of interviews with experts that will be conducted in the coming months. A revised version will be produced for the 64th TIP Meeting in December 2024.

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Executive Summary

What is green innovation?

1. Green innovations are new or improved products or processes (or a combination thereof) that lead to environmental improvements compared to alternatives.

2. Green innovations include innovations enabling the reduction in greenhouse gas emissions and in air, water, soil or noise pollution generated by specific products or processes, the more efficient use of resources (e.g. raw materials, energy, water) during the production or use of certain products, as well as solutions to protect and restore biodiversity, or improve reuse, recycling and waste management processes.

3. These innovations may take place across various economic sectors, can be both technological and non-technological innovations and differ in their degrees of novelty and impact.

4. Major differences of green innovations compared to other innovations include the following:

- There is the unpriced environmental cost of pollution. This reduces the effective demand for green innovations and increases larger unappropriated benefits of spillovers from green innovation.
- Green inventions require multi-disciplinary and collaborative ventures, resulting in potentially higher production costs.
- Path dependencies and technological lock-ins in existing, environmental harmful technologies can impede the diffusion of these technologies.

What is the evidence on green innovation?

5. Patents are widely used proxies to gather quantitative information on green innovation activities. Green patents account for about 12% in overall patenting activity worldwide.

6. The evolution of green patenting indicates a more sustained growth than overall patenting from the mid-1990s to the mid-2010s, with an average annual growth more than three times as high as that of overall patents (27% against 8%) but with a decrease in the growth rate of green patents and in the gap since then (Probst et al., 2021[1]; OECD, 2023[2]).

7. Trademark and venture capital data point to diffusion and commercialisation of green innovations from 2010 to 2020 (OECD, 2023[3]).

How do green innovations dynamics vary in the fields of green hydrogen, green steel and electric vehicles?

8. Green innovations in industry, power generation, and transport can have a crucial impact on environment, as these sectors respectively generated 24%, 23%, and 15% of global greenhouse gas (GHG) emissions in 2019 (IPCC, 2022[4]).

9. Representative of these sectors' innovation potential for decarbonisation and consequent prominence are green hydrogen, electric vehicles and carbon-emission-reducing steel production.

- Green hydrogen is produced through water electrolysis using renewable energy and could be used as substitute for grey hydrogen in the chemicals and refinery sectors, and in sectors that are hard to decarbonise with alternative green innovations.
- Electric vehicles (EVs) are powered by an electric motor and use a rechargeable battery as primary power source, in place of combustion engines using fossil fuels and emitting greenhouse gases.
- Green steel aims at mitigating the carbon emissions that are generated as a by-product of steel production processes through the use of breakthrough technologies.

10. The green technologies in these three sectors differ in their level of maturity. While green hydrogen and green steel are not available at a commercial scale yet, electric vehicles are mature technologies with a significant level of market uptake.

11. Green innovation activity in the three sectors does not stem only from sectoral incumbents, but newcomers often play an important role (e.g. technology providers in green steel) and can challenge incumbents on the market (e.g. novel EV-only car manufacturers and digital companies in the case of electric vehicles).

12. As regards barriers to technology development and diffusion, the three sectors face high production costs compared to existing (more polluting) alternatives, confront concentrated supply chains for critical resources and materials, and require significant infrastructure investments (e.g. charging stations for EVs).

13. Green hydrogen and green steel diffusion is also constrained by the lack of market demand for these products. Additionally, the sectors experience specific technical or market hurdles. For green hydrogen, which is an inflammable gas, the development of transport infrastructures comes with safety concerns. For green steel, the current global excess steelmaking capacity exerts downward pressures on prices and may disincentivise green producers to enter the market.

What are relevant policy levers and STI policy actions?

14. Regarding policy levers, countries have implemented supply-side measures to support the development and deployment of these green innovations, notably as part of large industrial policy investment strategies (such as the US Inflation Reduction Act). These include:

- Public investments in technology development and diffusion programmes (e.g. the Hydrogen Headstart Program in Australia),
- Establishment of public-private partnerships (e.g. the EU Clean Steel Partnership),

- Use of other financial instruments (public loans, guarantees and government venture capital).

15. Demand-side measures are less developed in the case of green hydrogen and green steel than for electric vehicles, which have been widely adopted in some countries first in the form of incentive schemes for electric vehicles' purchase and through investments in charging infrastructures. Hydrogen valleys work as local demonstrators of the use of hydrogen by various industries, and act as first real-life cases for piloting hydrogen markets.

16. Going forward, more demand-side instruments are important, including embedding specific requirements into public procurement (e.g. share of low-carbon steel used to build public infrastructures), and setting other policy targets and regulatory requirements to provide incentives to create markets that currently do not exist.

17. STI policies also play a crucial role in bolstering supply-side conditions for the development and deployment of green innovation. Massive industrial policy investments are already being made in the fields of electric mobility and green hydrogen, among other sectors that deemed critical for national competitiveness and resilience. Public-private partnerships are critical given the magnitude and long-term sustainability of investments needed.

18. Reinforcing supply-side conditions also involves building the necessary skills and capabilities to develop and deploy green innovations, which span different education levels and stages of the innovation cycle.

19. Additional considerations for policy making aimed at building comprehensive STI policies for the green transition are the following:

- Comprehensively assessing the full environmental and societal footprint of the life cycle of "green" innovations is relevant to understand best ways forward for innovation to support green transitions.
- Policies need to build on robust and timely technology and sector-specific intelligence, using latest data and expert assessments.
- Coordination of efforts across policy areas is equally critical to maximise impacts of public funding and stimulate citizen and business behaviours that align with green transition objectives.

1. Introduction

20. The urgency of climate change raises the need for rapid green innovations, including alternative ways of producing energy, transportation and industrial production, an important priority on STI policy agendas [DSTI/STP/TIP(2023)10]. These new or improved products or processes (or a combination thereof) that lead to environmental improvements compared to existing products and processes encompass a broad spectrum of technological and non-technological innovations (OECD, 2010[5]). This includes aiming for reductions in greenhouse gas emissions for energy generation, transport and in industry production. The burning of fossil fuels for power generation and transportation is the largest contributor to CO_2 emissions (accounting for 2/3 of the total in 2019) (IEA, 2023[6]; Cervantes et al., 2023[7]).

21. This paper explores green innovation dynamics in three green innovation areas within the energy, transport and emission-intensive industry sectors: green hydrogen, electric vehicles and carbon emissions reduction in the steel sector. The focus is on STI ecosystem characteristics and core policy levers. Aside from outlining the innovation dynamics within those sectors, the objective is to provide a better understanding of green innovation compared to innovation in general. The sectors were selected based on their innovations' potential environmental impacts, with energy generation, road transport and steel production representing 23%, 10% and 5% of global greenhouse gas (GHG) emissions respectively (IEA, 2023[8]; IPCC, 2022[4]), the substantive investments underway to boost these innovation ecosystems, and relatedly their prominence in green policy agendas and investments.

22. The draft paper has been developed in the context of the 2023-24 project "Making technology investments succeed" of the OECD Working Party for Innovation and Technology Policy (TIP). It builds on existing analyses conducted by the International Energy Agency (IEA, 2024[9]; IEA, 2023[10]; IEA, 2023[8]), the OECD Committee for Industry, Innovation and Entrepreneurship (CIIE) (Cammeraat, Dechezleprêtre and Lalanne, 2022[11]; Dechezleprêtre et al., 2023[12]), the OECD Steel Committee (OECD, 2022[13]; OECD, 2024[14]; OECD, 2024[15]; OECD, 2023[16]) and the OECD Committee for Scientific and Technological Policy (CSTP) in collaboration with CIIE (OECD, 2023[3]; Cervantes et al., 2023[7]).

23. The focus of this paper is on uncovering comparatively the innovation ecosystem characteristics of those three sectors (green hydrogen, electric vehicles and decarbonisation of steel) and consequently on developing innovation policy implications. The approach adopted, which consists in bringing together the quantitative and qualitative evidence, is similar to the one adopted for the TIP work conducted on digital innovation across diverse sectors (Paunov and Planes-Satorra, 2019[17]).

24. The paper benefitted from insights gathered through different workshops organised by the OECD Working Party on Innovation and Technology Policy (TIP) in 2023 and 2024. This includes the expert workshop "STI for biodiversity: Harnessing technology and innovation partnerships" that took place on 29 February – 1 March 2024, co-organised by the Italian National Biodiversity Future Center (NBFC) and the OECD Working Party on Innovation and Technology Policy (TIP), and hosted by the Institute of Marine Sciences (ISMAR-CNR) in Venice (OECD, 2024[18]); as well as the workshop "What makes co-creation work for transitions" co-organised by the TIP and the Japanese Ministry of Economy Trade and Industry (METI) in 24-26 May 2023 (OECD, 2023[19]). The paper also builds on past TIP work on co-creation for green innovation (de Silva et al., 2023[20]) as well as on innovation policies for the green and digital transitions (Arnold et al., 2023[21]).

25. Going forward, the paper will be complemented with insights from experts gathered via interviews and workshops. TIP delegates are invited to provide suggestions on experts that can contribute insights into the innovation ecosystem of these sectors.

26. This paper is structured as follows: Section 2 introduces the concept of green innovation and discusses its scope. Section 3 explores green innovation dynamics in the energy production, transport and emission-intensive industry sectors focusing on the examples of green hydrogen, electric vehicles and carbon-emission reducing steel production. Section 5 discusses policy implications.

2. Green innovation: what is it?

2.1. Definition and key characteristics

27. In broad terms, green innovation can be defined as the creation of new or improved products or processes (or a combination thereof) that lead to environmental improvements compared to alternatives. This includes innovations enabling the reduction in air, water, soil or noise pollution generated by specific products or processes, the more efficient use of resources (e.g. raw materials, energy, water) during the production or use of certain products, as well as solutions to protect and restore biodiversity, or improve reuse, recycling and waste management processes. These may take place across various economic sectors from agriculture to transportation and energy and involve both technological and non-technological innovations. Examples are renewable energy technologies, green mobility solutions, environmentally friendly materials, sustainable agricultural practices, or sustainable waste management and recycling solutions.

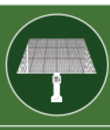
28. Green innovations differ in their degrees of novelty and impact, from incremental to radical or breakthrough. As regards novelty, many sectors require important advances in innovations, for instance, where current technologies do not allow scaling greener solutions or where these solutions are not green enough to result in emission-reduction goals. The IEA estimates that over 35% of the reduction in energy-related CO_2 emissions needed to achieve net-zero carbon emissions by 2050 is to come from technologies that are not yet commercially available (IEA, 2023[22]). As regards impact, the widespread adoption of green innovations would result in substantive socio-economic changes, such as major changes associated with shifting from producing vehicles using combustion engines to electric motors.

29. While environmental improvements are currently mostly associated with reducing carbon emissions, it regards a much wider set of issues, including environmental degradation and biodiversity. Innovation strategies and investments tackling the green transition focus on achieving net-zero carbon emissions targets. However, greener innovations are broader and also include those reducing environmental degradation and biodiversity loss – which refers to the decrease in the variety of living species on Earth, including plants, animals, bacteria and fungi (United Nations, 1992[23]) (OECD, 2024[24]) (OECD, 2023[19]). While biodiversity provides vital ecosystem services, including food and clean water, flood protection, water filtration and pollination, it is declining (OECD, 2021[25]). The global population of wild species has fallen by 60% over the last 40 years, and over one million plant and animal species – constituting a quarter of the world's species – are at risk of extinction (Brondizio et al., 2019[26]).

30. Evaluating the environmental improvements of green innovations requires assessing also their production's environmental footprint and full life cycle and not only the end product. The installation of renewable energy infrastructures, such as solar or wind

farms, is an illustrative and much-debated example. While they are critical for the transition to clean energy systems, such infrastructures can have negative impacts on biodiversity, for example through direct species mortality (e.g. from collision or electrocution), habitat loss and degradation, barrier effects on species movement and ecosystem services impacts (Figure 1) (OECD, 2024[27]). Another example are electric vehicles (EVs). While they do not emit CO_2 emissions and other pollutants, EVs have a much higher CO_2 production footprint than traditional combustion engine vehicles, mostly due to the materials and energy needed to produce EV batteries (McKinsey & Company, 2023[28]). The end-of-life management of batteries also poses environmental challenges.

Figure 1. Overview of potential biodiversity impacts from renewable power infrastructures

		
Direct wildlife mortality and morbidity	• Avian collision with panels or mirrors • Burning of birds and insects (CSP) • Drowning or poisoning in evaporation ponds (CSP)	• Avian and bat collision with turbines • Secondary entanglement of marine species with cables and anchors (floating offshore)
Habitat loss and degradation	• Vegetation clearance • Change in surface-water flows • Impacts on freshwater habitats in water-scarce areas (CSP)	• Vegetation clearance or disturbance for foundations, access roads etc. (onshore) • Loss of benthic habitat from anchors, foundations and cables (offshore)
Habitat fragmentation and barrier effects	• Physical barrier from fences • Potential edge effects	• Barrier effects for birds and bats
Habitat alteration / creation (potentially positive or negative)	• Microclimatic changes due to solar panels • Nesting sites/shelter for birds, arthropods and plants	• "Reef effect" of wind turbine foundations (offshore)
Behavioural changes, species displacement & physiological changes	• Avoidance during construction or operation • Attraction to solar panels (e.g. aquatic insects and birds)	• Avoidance during construction or operation • Attraction to wind facilities • Physiological stress from operation of facilities
Potential impacts from invasive alien species	• IAS introduced during construction • IAS colonisation and dispersal due to vegetation clearance, mowing etc.	• IAS introduced during construction • IAS colonisation and dispersal due to roads, offshore turbine foundations etc.
Ecosystem service impacts (potentially positive or negative)	• Aesthetics and recreation • Carbon sequestration, nutrient and water cycles • Pollination	• Aesthetics and recreation • Carbon sequestration
Indirect impacts (potentially positive or negative)	• Displacement of agriculture and associated pressures • Displacement of GHG intensive energy sources • Alternative livelihoods in developing countries	• Displacement of fisheries and associated pressures (offshore) • Displacement of GHG intensive energy sources • Alternative livelihoods in developing countries
Cumulative and population-level impacts	• Cumulative impacts on populations of sensitive species • Cumulative impacts on ecosystems, e.g. desert and xeric shrubland	• Cumulative impacts on populations of sensitive bird and bat species due to collision • Cumulative impacts on marine species and ecosystems (offshore)

Note: This figure provides examples of potential impacts based on empirical evidence and inference. Mitigation measures can avoid or reduce the severity of these impacts. CSP = Concentrated Solar Power. IAS = invasive alien species. RoW = right of way
Source: (OECD, 2024[29])

31. The circularity of the economy is another often overlooked aspect of relevance to green innovation. The circular economy concept refers to products and their materials being reused, repaired or recycled at end of use rather than disposed of at the end of the product lifecycle. This reduces environmental impacts by reducing waste disposal and reduces requirements for product input materials. Shifting to such a model requires systemic changes across industries and supply chains.

2.2. Some evidence on green innovations

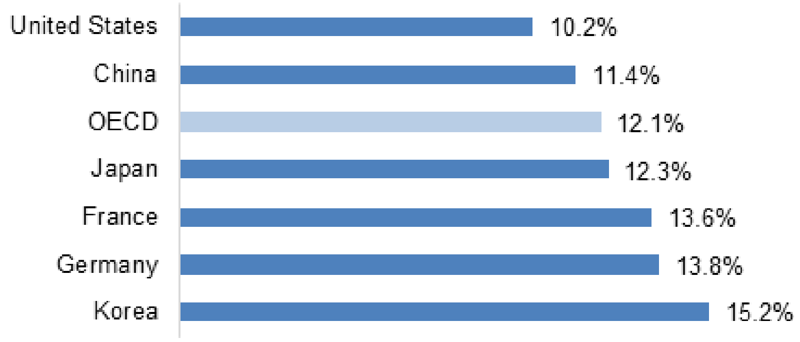
32. As is the case of any innovation indicator, our evidence on green innovations largely stems from measures that are proxies of green innovation activities. This section covers information from patent, trademark and venture capital data.

33. Since patent data provide very granular information on the invention to be protected, they have been widely used to identify green patents (see the Annex). The following observations can be made using green patent data – measured by the OECD Env-Tech classification or based on y-codes.

34. First, the share of environmental-related inventions in total inventions as measured by patent applications is currently around 12% in the OECD total (Figure 2). It is also the case for the top six inventor countries (2016-2021) as measured in number of environment-related inventions as % of environment-related inventions worldwide, with the exception of Korea.

Figure 2. Green patenting has a low share in overall patenting activity in top 6 countries (2016-2021)

Number of environment-related inventions as % of all domestic inventions (in all technologies)

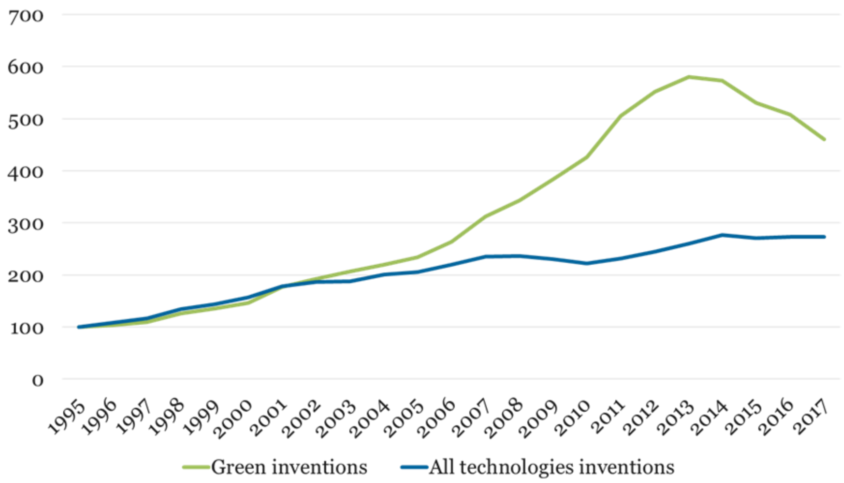


Note: Green patents identified based on OECD Env-Tech classification. Average % for period 2016-2021.
Source OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats.

35. As regards trends, the number of green patent applications increased from the mid-1990s onwards, peaking in 2013 and declined afterwards (Figure 3) (Probst et al., 2021[1]; OECD, 2023[2]), as is also echoed in trademark applications and venture capital investments data. Figure 4 illustrates these trends of green patent applications peaking in the early 2010s for the United States and Germany.

36. OECD countries dominate in green patenting (80% in 2019, OECD (2022[30])). Top countries in the past decade are Japan, the United States, Germany, Korea, and China (Figure 5) (Elliott, Jabbour and Su, 2023[31]) (Probst et al., 2021[1]). This largely reflects the strengths these countries have in innovation and in patenting, which can also be seen by geographic data that show that green patenting takes place where patenting is important. Figure 6 gives the example of the United States and Germany.

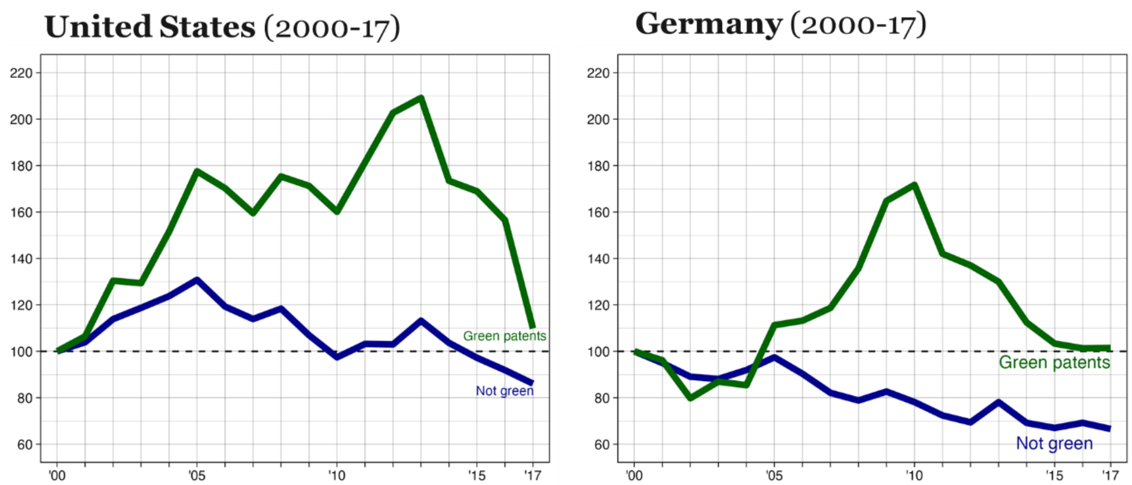
Figure 3. Worldwide green patenting peaked in the mid-2010s



Note: 100 = 1995. International patent families. Green patents identified based on y-codes.

Source: Probst et al. (2021[1])

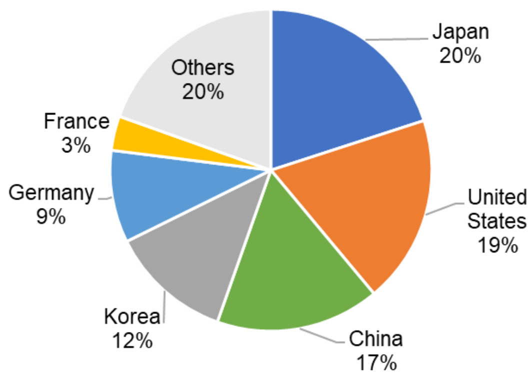
Figure 4. Green patenting peaked in the mid-2010s in Germany and the United States



Note: Own calculations. 100 = 2000. Triadic patents only. Green patents identified based on y-codes. Data source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, Oct 2023.

Figure 5. Top six inventor countries (2016-2021)

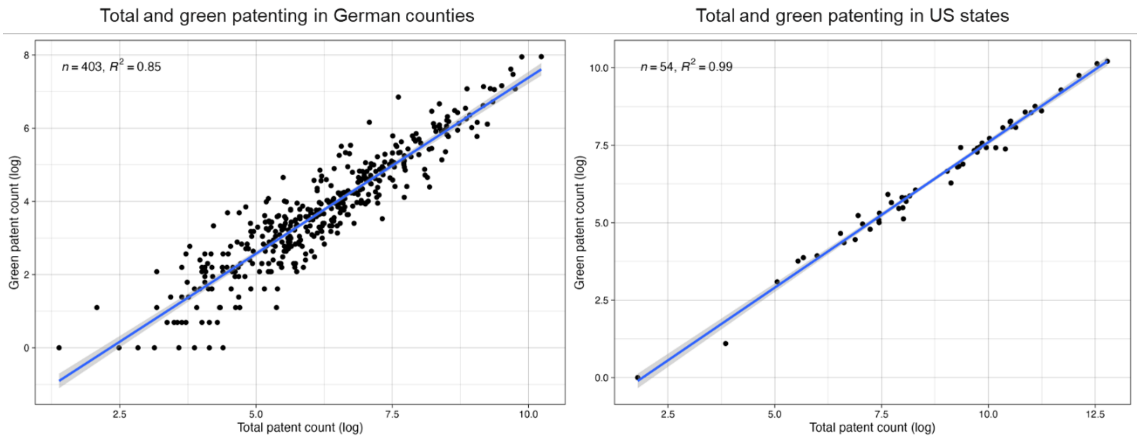
Number of environment-related inventions as % of environment-related inventions worldwide.



Note: Green patents identified based on OECD Env-Tech classification. Average % for period 2016-2021.

Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats.

Figure 6. Green patenting is regionally dispersed, with high patenting regions also leading in green patenting.



Note: Own calculations. Triadic patents only. Green patents identified based on y-codes. Years: 2000-17.

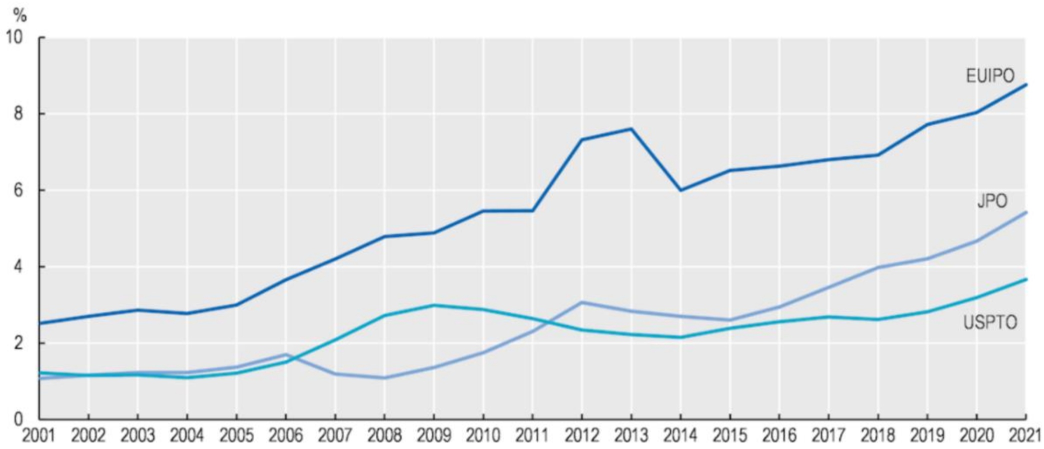
Data source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, Oct 2023.

37. Moreover, trademark data suggests increased diffusion and commercialisation of green products over the past two decades. The share of trademark applications for climate-related goods and services increased significantly in the last two decades. Especially in Europe, the share quadrupled from 2% to over 8%, in the United States it tripled from 1% to more than 3%, and in Japan it increased rapidly from around 1% to more than 5% between 2001 and 2021 (Figure 7).

38. Finally, available data show venture capital (VC) for green start-ups has surged globally in the latest decade. Private investments funding has grown sixfold since 2010, growing from around USD 3 billion to USD 18 billion in 2020 (Figure 8). Investors primarily focus on mature technologies with low-carbon mobility start-ups receiving the largest amounts of investments between 2014 to 2020. However, the share of VC in green start-ups in total VC has remained stable over the last decade, indicating that the growth in

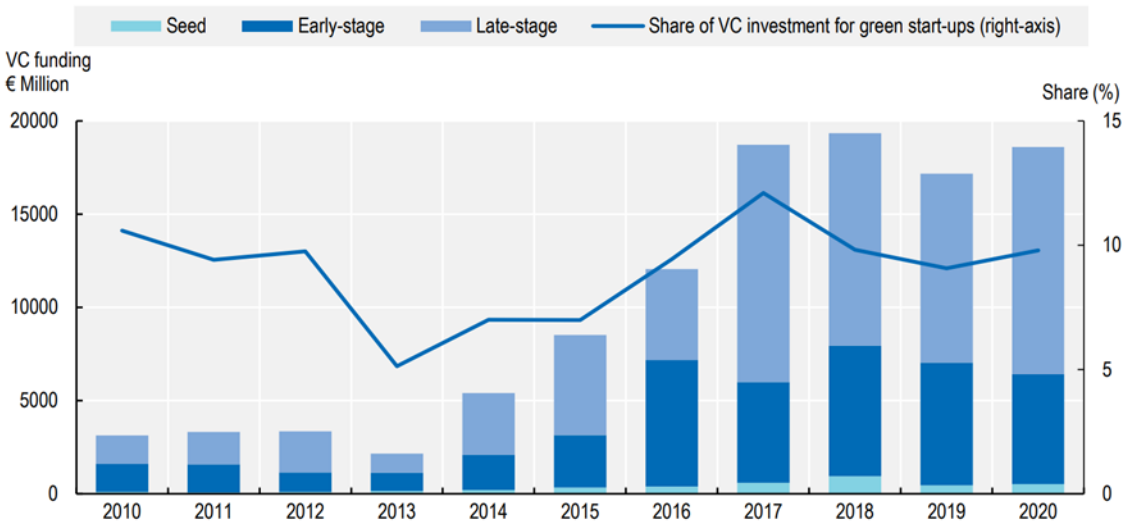
green VC investments (partly) reflects the total growth in global VC across all sectors and industries (OECD, 2023[3]; OECD, 2022[30]).

Figure 7. Trademark applications for climate-related goods and services as % of total applications



Note: Green-related trademarks are identified using sets of climate-related keyword search on the goods and services description of the trademarks. EU Intellectual Property Office (EUIPO), the Japan Patent Office (JPO) and the US Patent and Trademark Office (USPTO). Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, December 2022. OECD (2021[32]).

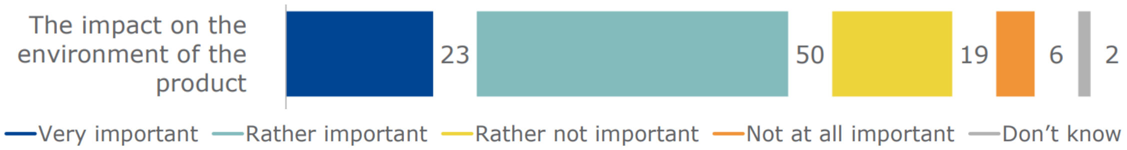
Figure 8. VC investments in green start-ups in OECD countries (in EUR million)



Note: Clean-tech start-ups are identified using information on their sector of operation (e.g., renewable energy) and on the textual description of their activity using natural language processing (NLP) methods, based on a climate change-related vocabulary. Source: (OECD, 2023[3]).

39. As to consumer's demand for environmental products, survey results for the EU-27 countries reveal that more than 70% of consumers consider the impact of a product on the environment is 'very important' or 'rather important' when making a buying decision (Figure 9).

Figure 9. Eurobarometer on consumer attitudes towards environmental impacts of products



Note: The following question was asked: "How important are the following aspects when making a decision on what products (goods or services) to buy?" (% EU27)

Source: Flash Eurobarometer FL535: The EU Ecolabel (v1.00). (2023). [Data set]. European Commission, Directorate-General for Communication. http://data.europa.eu/88u/dataset/s3072_fl535_eng.

2.3. Specificities of green innovations

Under-investment challenges

40. Several features of green innovation result in under-investment in their development and diffusion, with less private capital invested in them than would benefit sustainability goals.

41. First among these factors is that inventors cannot fully appropriate the returns to their inventions. This is a general feature of many innovations that provides justification for public support that is amplified in the case of green innovation. This is due to the nature of innovations, with empirical research showing the gap between public benefits and private returns is larger than in the case of other innovations and impacts a broader range of subsequent technologies (Dechezleprêtre and Mohnen, 2014[33]; Popp and Newell, 2012[34]; Barbieri, Marzucchi and Rizzo, 2020[35]). Higher public returns also result from higher complexity and risk of these innovations compared to others. The higher risk increases the private cost for funding those innovations (Howell, 2017[36]; Popp, 2019[37]; Ghisetti et al., 2017[38]).

42. Moreover, environmental improvements have public good features in that all benefit while those contributing to improvements and to reducing environmental damages are not compensated for. The incentives to invest in the development as well as in the adoption of green innovations are consequently lower. Much will depend on public policy creating incentives by, for instance, pricing carbon emissions, or by committing to international agreements that build more stability (Table 1). Building consumer demand for these products and increasing public procurement are additional demand measures relevant in that regard and can help bring down the costs of green innovations.

Supply-side factors for green innovation

43. Supply factors are, in many regards, similar for green and non-green innovations, with first the need of actors with skills and capacities to support these innovations. Specificities concern, however, the issue of stronger needs for multi-disciplinary and collaborative ventures where major radical innovations in the field are needed. Critical infrastructures also play a role to advance on green innovation, as illustrated by GreenLab in Denmark – a green industrial park that provides a testing ground for green energy solutions (de Silva et al., 2023[20])–, as well as to deploy and diffuse them. This requires coordinated changes across the full value chain without which these innovations will be stalled (as none can advance without the other).

Table 1. Overview of drivers of the creation and diffusion of green innovation

Supply side determinants	• Green invention requires **strong skills and capabilities** to be created and/or adopted. Green innovation stands out due to the **higher complexity and novelty** of knowledge inputs compared to regular inventions. • The cognitive and interpersonal **skills set** required for green occupations exceeds that of non-green jobs, reflecting the heightened complexity of green innovations. • International collaborations and open innovation channels allow effective knowledge sourcing for the creation and adoption of green innovation. • Cost of green technologies and investments in key **infrastructures** to advance research, demonstration and deployment of green innovations. • **Coordination** across the whole value chain is necessary for effective deployment of green innovations
Demand side determinants	• Consumer **preferences, attitudes and awareness** stimulate demand for green products and hence drive the creation and diffusion of green innovation. • Price of green technologies relative to existing alternatives. • **Expectations of revenues from green innovation investments, shaped also by governmental decisions creating markets**. • Demand of the public sector through green **public procurement** can play an important part in the diffusion phase of green innovations.
Policy and regulation	• Policy and regulation play a pivotal role in incentivizing the creation and diffusion of green innovations • Supply side instruments foster the development and diffusion of green innovations through measures like subsidies on green R&D or feed-in-tariffs. • On the demand side, policies create markets for green products and technologies through tools such as environmental taxes or green public procurement.
International agreements and action	• They incentivize green innovative activities and encourage knowledge sharing among signatory countries. • They also mitigate investment uncertainty and thus enable the creation and diffusion of green technologies.

Source: (Johnstone, Haščič and Popp, 2009[39]; Barbieri, Ghisetti and Gilli, 2017[40]; Corrocher and Mancusi, 2021[41]; Barbieri, Marzucchi and Rizzo, 2020[35]; De Marchi, 2012[42]; Wagner, 2007[43]; Consoli et al., 2016[44]; Mealy and Teytelboym, 2022[45]; Horbach, 2008[46]; Kesidou and Demirel, 2012[47]) (Dekker et al., 2012[48])

Path-dependency and lock-ins

44. Green innovation can furthermore be impeded by path dependencies and technological lock-ins in existing, environmental harmful technologies. Depending on a technology type, economic agents establish routines, accumulate knowledge, develop skills, build networks and relations. This creates a certain path or trajectory the agents operate along when deciding oninvestments, new technology adoption or innovation activities. This path is reinforced and strengthened over time by increasing returns through learning-by-doing and feedback loops withconsumers and suppliers for instance.

45. Additionally, infrastructure is built to support the current technology path, markets are established, regulatory frameworks are implemented and large sunk investments are made. This can create lock in situations where an incumbent technology dominates and prevents a potentially superior technology from emerging. Hence, breaking with a non-green trajectory to develop or adopt green technologies can be very challenging. Countries with a history of creating and adopting green innovations are more likely to continue on this path and diversify into new green technologies (Aghion et al., 2016[49]; Mealy and Teytelboym, 2022[45]).

Public engagement and green innovation

46. The public support for green innovations has changed substantially over the past years as the recognition of the urgency of climate change has risen globally. Reasons

include climate activism of civil society actors, the proliferation of climate shocks and the wider global commitments many governments have adhered to, such as the 2015 Paris Agreement. As regards the STI ecosystem, the shift away from an exclusive growth focus towards a vision of STI in support of society, has also resulted in a wider focus on supporting green innovations.

47. The current geo-political tensions have affected political commitments to green transitions. On the one hand, they have strengthened political commitment to developing renewable energy sources among countries relying on energy imports to meet energy needs. On the other hand, the stronger need for critical minerals for green innovations presents a more complex picture of the resilience-sustainability nexus.

3. Green innovation ecosystem features across sectors

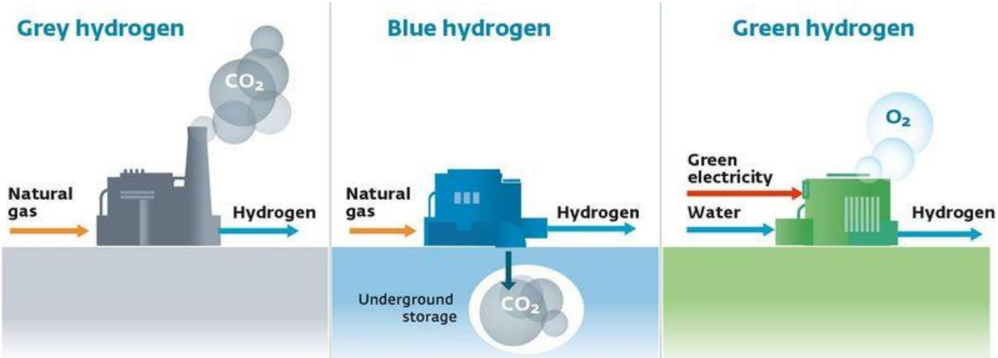
3.1. Green hydrogen

Description and relevance in clean energy innovations

48. Hydrogen naturally occurs in compound forms with other elements, such as in water (H_2O), natural gas, coal, or petroleum. It is produced or separated from these compounds, typically from water, fossil fuels, or biomass. Once produced, hydrogen can store and deliver usable energy, i.e. hydrogen is an energy carrier. Hydrogen is currently mostly produced on-site and used to process oil in refineries, produce methanol for use in plastics, and produce industrial ammonia, the main ingredient in artificial fertilisers.

49. Green hydrogen is produced through a process called electrolysis, which consists in breaking down water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity generated from renewable sources such as wind, solar, or hydropower. The process does not emit greenhouse gases or other pollutants – but requires the availability of large amounts of renewable energy and water.

Figure 10. Types of hydrogen



Note: The production of grey hydrogen releases carbon dioxide (CO_2) as a byproduct, contributing to greenhouse gas emissions. Most industry uses today use grey hydrogen. "Blue hydrogen" is also produced from natural gas, but most of the CO_2 emissions generated are sequestered (stored in the ground) using Carbon Capture, Utilisation and Storage (CCUS). Capturing the CO_2 instead of releasing it into the atmosphere makes blue hydrogen a low-carbon alternative but not a carbon-free one.

Source : (University of Calgary, 2023[50])

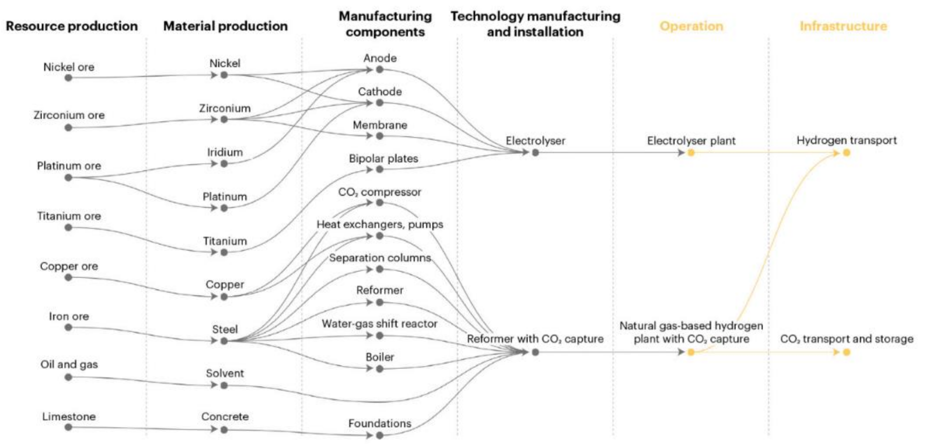
50. Most hydrogen produced today, however, is grey hydrogen using fossil fuels such as coal and natural gas, which releases CO_2 as a byproduct (Figure 10). In 2022, low-

emission hydrogen production (including green and blue hydrogen) accounted for less than 1% of global hydrogen production (IEA, 2023[10]).

51. Green hydrogen has many potential end-uses. The most immediate one is as substitute for grey hydrogen, which is currently mainly used in the chemicals and refinery sectors and in other sectors that are hard to decarbonise in other ways, including the steel sector we discuss in section 3.3. Further potential also exists for uses in the transportation sector, especially international shipping and heavy-duty road transportation. Uses in other sectors, such as aviation, light-duty vehicles and heating, face technical challenges (e.g. safety risks, challenges of transportation and storage) that currently make them less viable and efficient compared to other green innovation alternatives (e.g. batteries in the case of electric cars).

52. Innovation in the field of green hydrogen comprises many technologies that are necessary to produce, transport, store and consume such hydrogen. Key elements along its value chain include resource and material production, manufacturing of components, technology manufacturing and installation as well as operation and infrastructure deployment (Figure 11).

Figure 11. Key elements for each step in the low-emission hydrogen supply chain



Source: (IEA, 2023[51])

53. Other main green innovation areas in the energy supply sector include: i) renewable energy technologies, such as solar, wind, and geothermal energy technologies, ii) energy storage technologies such as batteries, iii) carbon capture, utilisation and storage (CCUS) technologies, and iv) innovations to enhance energy efficiency in the generation, transmission and distribution of energy (Table 2).

Table 2. Green innovation areas in the energy supply sector

Green innovation areas
Renewable energy technologies Technologies that enable the production of energy using renewable energy sources (i.e. natural sources that are replenished at a higher rate than they are consumed), such as solar energy (through the use of photovoltaic and thermal technologies), wind energy (through the use of land-based and offshore wind turbines), hydropower, geothermal energy, wave and tidal energy, and biomass.
Energy storage technologies Technologies that allow storing energy and delivering it for future use. Research and innovation activities in this field focus particularly on batteries (e.g. lithium-ion batteries, solid-state batteries, sodium-ion batteries), but also other technologies for mechanical energy storage (e.g. in pressurized fluids) and thermal energy storage.
Green hydrogen Hydrogen is an energy carrier that must be produced – or separated – from another substance. Hydrogen is considered green when it is produced from water using renewable energy sources, through a process called electrolysis. A variety of technologies are necessary to produce, store, transport, and use (green) hydrogen.
Carbon capture, utilisation and storage [CCUS] Combination of technologies that capture CO_2 from the gases discarded by industry or power generation and then transport it to utilize it for other purposes or safely store it underground in suitable geological formations (e.g. depleted oil and gas reservoirs, saline aquifers).
Energy efficiency Improvements in the efficiency of the generation, transmission, and distribution of energy, as well as in enabling technologies such as energy storage solutions. Digital innovations play a key role (e.g. use of industry 4.0 technologies and data analytics to monitor energy use and identify opportunities for efficiency gains).

Source: Own elaboration based on (Samseth et al., 2021[52]), (IEA, 2023[51]), (IEA, 2020[53]), (Deloitte, 2024[54])

Technology maturity and key actors in the sector

54. Innovation in green hydrogen technologies is led by industry. According to patent data, automotive companies and equipment suppliers are key innovators in this field, with top patent applicants located in Japan and Korea. European chemical companies are top innovators in the field of grey hydrogen technologies, while progressively diversifying into emerging technologies (such as CCUS) to produce low-carbon hydrogen. Start-ups and universities and public research institutions are important sources of innovation in this field.

55. Regarding the level of technology and market maturity, the value chain for green hydrogen is not fully developed at commercial scale at present. Technologies necessary to produce, transport, store and consume green hydrogen are at different stages of maturity, facing different technical challenges. Reaching commercial scale requires addressing challenges linked to efficiency, cost, manufacturing capacities to produce these technologies for green hydrogen production. There is also a need for innovations regarding its distribution and end-use (European Commission, 2022[55]).

56. Several technical and market barriers currently prevent the widespread production and use of green hydrogen. The reliance on large scale availability of renewable energy for its production is a central one, others including safety risks, high infrastructure and coordination costs to deploying hydrogen value chains, and lack of global certification standards. Table 3 below provides further details.

Table 3. Green hydrogen: overview of trends in technology development and diffusion

Who are the innovators?	• **Industry** is an important player in green innovation. Patent data suggest innovation in green hydrogen technologies (electrolysers and fuel cells) is dominated by **automotive companies and equipment suppliers**[1]. Top patent applicants are Japanese and Korean companies. • Innovation in established (grey) hydrogen technologies is dominated by **European chemical companies** with experience producing and handling grey hydrogen. They are also diversifying into emerging technologies (such as carbon capture, usage and storage) enabling the supply of low-emission hydrogen. • **Start-up creation** has increased since 2000. Most start-ups that filed international patent applications related to hydrogen in 2011-2020 were located in Europe (51%) and the United States (33%). Low-emissions hydrogen accounted for about approximately 10% of global early-stage VC investments in clean energy start-ups in 2021, up from 5% in 2020. • **Young firms (<5 years)** file more original/radical patents in the field of hydrogen production and storage than older firms. This does not hold for fuel-cells related patents. • **Universities and public research** institutions generated 13.5% of all hydrogen-related international patents filed in 2011-2020, with Korean and European institutions in the lead. They focus on low-emissions hydrogen production methods (e.g. electrolysis).
Barriers to technology diffusion / market upscale & supply conditions	Regarding all types of hydrogen (incl. green): • **Energy losses in production**: There is no natural source of hydrogen on earth. Hydrogen is bound up with other molecules like those of fossil fuels, biomass, or water, requiring the use of energy to obtain hydrogen. Therefore, hydrogen production implies either significant carbon emissions (in the case of grey hydrogen) or the use of renewable energy (in the case of green hydrogen). This conversion as well as transporting and storing hydrogen has inherent inefficiencies where some of the input energy is lost. Hydrogen should be hence used in applications that most effectively reduce overall energy consumption and emission. • **Important infrastructure costs and coordination challenges to deploy hydrogen value chains***:* Transporting and storing hydrogen is currently very expensive, and would require the construction of dedicated pipelines, upgrading natural gas pipelines that are no longer needed, and building shipping and port infrastructures and grid connection. Currently, green hydrogen needs to be used where it is produced. • **Safety concerns**: The transportation and storage of hydrogen poses safety risks as it is a highly flammable element. A few technologies exist for large hydrogen leakage detection but lack the speed and sensitivity to measure smaller leaks. Regarding green hydrogen: • **High production cost**: Green hydrogen remains more expensive than grey hydrogen (around 3 times more in 2021). Cost reductions depend on reduced costs of electrolysers and other infrastructure components and availability of large volumes of cheap renewable electricity. • **Dependent on the availability of abundant and low-cost renewable energy and abundant water resources**: The expansion of green hydrogen depends on the availability of large volumes of renewable energy and water resources. This would require upscaling the installation of renewable energy production infrastructures. • **Socio-economic concertations**: The most appropriate use for such electricity for green hydrogen needs to be decided on (prioritizing its use for green hydrogen production implies lower availability for other direct uses). To illustrate, if green hydrogen provided energy to the chemicals and steel sectors only by 2050, this would – with the current state of technologies' capacities - require total electricity amounts close to the world's entire electricity production in 2020.
Demand conditions	• **Limited market demand:** Demand for hydrogen remains so far concentrated in traditional uses in refining and the chemical industry and is mostly met by hydrogen produced on-site from unabated fossil fuels. • **Limited policy support to stimulate demand**: Despite the refining and chemical sectors accounting for practically all the demand for hydrogen today, the policies to create demand for low-emission and green hydrogen in these sectors is very low. • **Lack of global certification standards**: There are no internationally agreed ways to guarantee the origin and quality of hydrogen (i.e. distinction between green and grey) to consumers, which prevents the establishment of a transparent market. Multiple ongoing efforts aim at developing such standards (see **Error! Reference source not found.** below).
Technology diffusion through trade	Today, hydrogen trade flows are limited to a few existing hydrogen pipelines connecting industrial areas in Belgium, France and the Netherlands, and to a few pilot projects to demonstrate hydrogen trade by ship. Building transport and storage infrastructure would be an important enabler for trade.

Note: [1] Despite its limitations, patent data is considered a good indicator of innovation in the field of hydrogen, characterized by relatively risky and long development cycles (e.g. compared to the ICT sector). This prompts innovators to file patents to ensure they can benefit from these investments if the technologies successfully enter the markets. This is more so the case of start-ups, for which patents can be used as a proof of innovation when aiming to raise venture capital funding, a signal of value and even collateral against debt.
Source: Own elaboration based on (Cammeraat, Dechezleprêtre and Lalanne, 2022[11]), (EPO and IEA, 2023[56]), (European Commission, 2022[55]), (IEA, 2023[10]) and (IRENA, 2022[57]).

Policies in support of green hydrogen

57. Countries have been very active in developing dedicated hydrogen strategies and roadmaps, as well as green STI and industrial policies with significant emphasis on green hydrogen. As of September 2023, 41 governments world-wide had a hydrogen strategy in place. Policy goals and targets set in such strategies and action plans, especially if accompanied by public investment commitments, are key drivers of public but importantly also private investments, as they reduce market uncertainty by signalling long-term directionality of public investments.

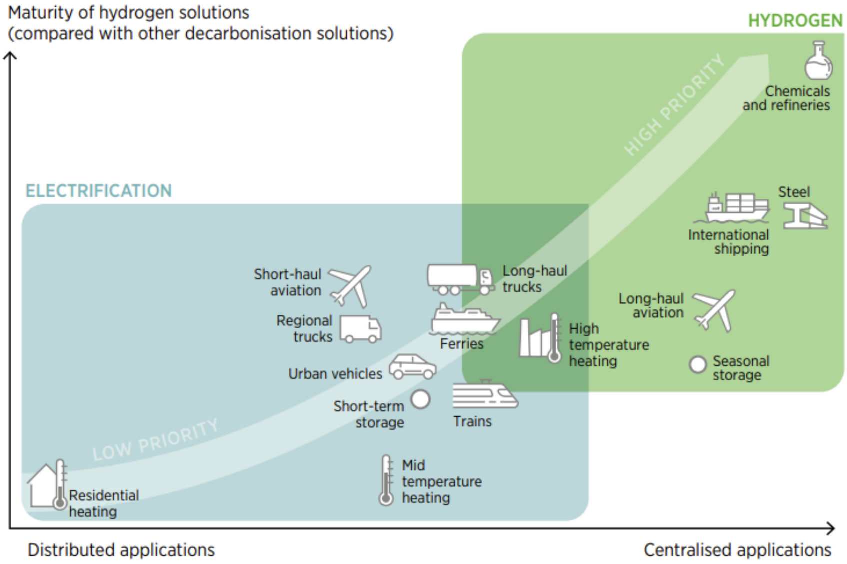
58. STI policies can support the development of innovation in green hydrogen with tailored supply and demand-side instruments. Policy efforts are ongoing in many countries, as discussed in Table 4. Policy levers in support of green hydrogen

59. Regarding supply-side support, significant efforts have focused on the development of hydrogen valleys (green hydrogen regional hubs). These projects are placed in geographical areas where multiple hydrogen users or potential users are co-located, and work as local demonstrators of the use of hydrogen by various industries. These are key support instruments for real-life piloting of hydrogen markets in controlled environments, where risks for hydrogen producers are low as demand is identified upfront and transport infrastructure needs are minimised.

60. A range of other financial support instruments are used to de-risk investments in green hydrogen innovation and demonstration, such as loans, guarantees, and public venture capital. Public-private partnerships, such as the Clean Hydrogen Joint Undertaking in the EU, are also critical in this context, as well as instruments to support the development of skills across the hydrogen value chain.

61. Regarding support for demand, efforts to support the emergence of a market for green (and low-carbon) hydrogen requires establishing clear definitions and certification schemes for green hydrogen, ideally at global scale, as otherwise there are limited incentives for innovation in currently much costlier green hydrogen. Currently limited efforts are dedicated to stimulating demand for green hydrogen from sectors that currently use grey hydrogen (refineries, chemical sectors) and from hard-to-decarbonise sectors that stand to benefit most from the current options offered by the technology compared to alternatives and that have been advised as core priority fields (see Figure 12 for examples).

Figure 12. Green hydrogen policy priority



Note: On the x-axis the end users are placed according to the estimated average daily hydrogen demand for industry, refuelling stations and combustion devices, with a power relationship. On the y-axis, the end uses are placed according to the differences between the technological readiness levels of hydrogen-based vs electricity-based solutions.

Source: (IRENA, 2022[58])

Table 4. Policy levers in support of green hydrogen

Strategies and public funding	• **Policy strategies and roadmaps:** As of September 2023, a total of 41 governments world-wide had a hydrogen strategy in place, including some early movers that are already updating their original strategies with higher ambitions (e.g. Belgium, Germany, Japan, Korea) (IEA, 2023[10]). Moreover, many countries have recently adopted new industrial strategies that place significant emphasis on hydrogen technologies, such as Japan's Green Growth Strategy (2020) and Green Transformation Promotion Act (2023), the US Inflation Reduction Act (IRA) (2022) and the proposed EU Net Zero Industry Act. Policy goals and targets set in green STI or (green) hydrogen strategies and action plans, especially if accompanied by public investment commitments, are key drivers of public but importantly also private investments, as they reduce market uncertainty by signaling long-term directionality of public investments. • **Public-private partnerships to support green hydrogen projects:** In some cases, large-scale investments also involve the private sector in public-private partnerships. An example here is the Clean Hydrogen Joint Undertaking in the EU - a public-private partnership supporting research and innovation activities in hydrogen technologies, aimed at scaling up the development and deployment of the European value chain for green hydrogen technologies. This also includes support for green hydrogen valleys (see below). Another example is the Midwest Alliance for Clean Hydrogen in the United States to establish regional clean hydrogen hubs.

Table 5. Policy levers in support of green hydrogen (continued)

Strategies and public funding (continued)	• **Public investments in green hydrogen projects and key infrastructures:** For example, the EU has created the European Hydrogen Bank to de-risk hydrogen project investments, which includes the launch of auctions that award a subsidy to hydrogen producers in the form of a fixed premium per kg of hydrogen produced for a maximum of 10 years of operation. Other support schemes are Australia's Hydrogen Headstart Program (2023) (a total of AUD 2 billion in the form of grants to support large-scale hydrogen production projects), the US 45V Clean Hydrogen Production Tax Credit (which provides USD 3 per kilogram of hydrogen to projects with low GHG emissions) and the UK Low Carbon Hydrogen Production Business Model (also providing revenue support to hydrogen producers to overcome the operating cost gap between low carbon hydrogen and high carbon fuels). A notable example of investments in key infrastructures are the EU Important Projects of Common European Interest on hydrogen (which are ambitious, cross-border, integrated projects funded by the EU deemed strategic to achieve EU objectives but where private investments fail to materialize due to significant investment risks of such projects).
Hydrogen valleys / regional hubs	• **Hydrogen valleys**, geographical areas where multiple hydrogen users or potential users are located, are an important support mechanism. These reduce the risks for hydrogen producers as demand is identified upfront, large-scale production reduces costs, and co-location minimizes transport infrastructure needs. These projects work as local demonstrators of the use of hydrogen by various industries, and act as first real-life cases for piloting hydrogen markets. Hydrogen valleys have been supported by the Clean Hydrogen Mission, a programme launched in June 2021 by Mission Innovation (MI)– a global initiative of 23 countries and the EU aimed at accelerating global clean energy innovation, launched in 2015. Examples for hydrogen valleys around the globe are collected on the "Mission Innovation Hydrogen Valley Platform". In the United States, the Regional Clean Hydrogen Hubs Program (H2Hubs) launched in 2022 by the Office of Clean Energy Demonstrations will allocate up to USD 7 billion to establish 6 to 10 regional clean hydrogen hubs across the country to be deployed over approximately 8-12 years depending on the size and complexity of the H2Hubs. The award period will include the planning, development, and construction of the H2Hub as well as 2-4 years of operations.
Other supply side measures to support research and innovation	• **Development of skills for industries at all steps of the hydrogen value chain**. Skills are critical for developing new hydrogen technologies but also to effectively implement them across different sectors, including technical skills obtained through vocational training programmes. There is strong demand for engineering skills, as well as those in designing, operating and maintaining hydrogen infrastructure and vehicles. For example, the Hydrogen Society Roadmap for South Africa 2021 pays specific attention on the impacts of the transition to green hydrogen on existing jobs, calling for reskilling programmes and scaling up dedicated training. Some programmes have also been launched to help SMEs benefit from innovation in the field of green hydrogen. In Germany, the International Hydrogen Ramp-up Programme supports SMEs identify, prepare and implement pilot projects for the production and use of green hydrogen. • **Unlock private investments on research, innovation and demonstration projects.** Public financial instruments, such as public loans, guarantees and government venture capital, can be used to partly de-risk green hydrogen innovation and demonstration projects, allowing to crowd in private investment. • **Support innovation efforts to reduce the use and dependence of green hydrogen technologies on critical raw materials**.

Table 6. Policy levers in support of green hydrogen (continued)

Demand side support measures	• **Harmonisation of international standards and regulations to create a market for green hydrogen**. Regulations on hydrogen's environmental attributes and associated regulatory standards (e.g. on purity, origin, safety) and certification schemes are critical to establish well-functioning hydrogen markets that are transparent and reduce safety risks. Notably, referring to the emissions intensity of hydrogen production in regulation and certification – based on agreed methodology – can enable mutual recognition and facilitate market and regulatory interoperability. Several countries have taken steps in that direction (see Table 6.4 in (IEA, 2023[10]), e.g.: - In 2022, the Netherlands became the first European country to issue guarantees of origin for green hydrogen produced in the country, certifying that hydrogen is produced from green electricity. - The European Union is working on low-carbon thresholds and standards for production facilities, as well as on a comprehensive terminology and EU-wide criteria for the certification of low-carbon and green hydrogen. A Roadmap on Hydrogen Standardisation, published in 2023 by the European Clean Hydrogen Alliance, lines out gaps, requirements, challenges and recommendations on standardisation needs. - Japan has introduced a number of strict safety regulations and standards for the production, storage and transportation of hydrogen such as the High Pressure Gas Safety Act. • **Supporting demand of sectors with highest potential use cases.** Despite the chemicals and refining industries accounting for practically all the demand for hydrogen today, policies to stimulate demand for green hydrogen in these sectors remain very low. The introduction of mandatory targets on hydrogen demand in those and other hard-to-abate sectors (e.g. steel) could boost demand and accelerate the development of more efficient technologies.

Source: Own elaboration based on data elaborated by (Cammeraat, Dechezleprêtre and Lalanne, 2022[11]), (EPO and IEA, 2023[56]), (European Commission, 2024[59]) (IEA, 2023[10]), (IEA, 2022[60]), (Weichenhain et al., 2022[61]).

3.2. Electric vehicles

Description and relevance for green transport

62. Electrification is a key trend driving green innovation in the transportation sector, with electric vehicles (EVs) being the main area of innovation. The other three trends driving green innovation in the transportation sector are the expansion of new mobility modes, the development of sustainable fuels and the greening of the sector's production processes and end-products (Table 7).

63. The level of technological maturity of innovations under each of these areas differ. Some are very mature and with significant levels of market uptake (e.g. electric vehicles, electric micro-mobility, platform-based mobility services), others are in demonstration stage (e.g. ships capable of running on hydrogen, ammonia and methanol) and others are in early stages of conceptual design and prototyping (e.g. hybrid electric aircrafts, aircrafts running on hydrogen).

64. Green innovations in the transport sector are relevant in view of the sector emitting 15% of global GHG emissions in 2019 (IEA, 2023[8]; IPCC, 2022[4]). From 1990 to 2022, total CO_2 emissions increased at an annual growth rate of 1.7% in the transport sector. This is faster than any other end-use sector except for industry, which has experienced similar growth rates (IEA, 2024[62]). The IEA predicts the need of an annual CO_2 emissions reduction of more than 3% per year until 2030 to get on track with the Net Zero Emissions by 2050 scenario.

Table 7. Green innovation trends in the mobility sector

Trends driving green innovation in the mobility sector	Examples of green innovation areas
Electrification Use of electric motors across different modes of transport to replace combustion engines powered by fossil fuels.	All-electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (fuelled by green hydrogen) Electric heavy-duty road vehicles Electric trains Electric ships (e.g. electric and hybrid electric ferries, hydrogen-based propulsion systems for ships)
New mobility modes Change towards new modes of transportation, especially in urban areas, that are environmentally-friendlier than equivalent existing alternatives, with potential of reducing individual car ownership.	Electric micro-mobility (e.g. e-bikes, e-scooters) New forms of shared mobility / platform based on-demand mobility services, e.g.: - Car sharing (members can access - potentially electric - vehicles owned by car sharing companies as part of a shared fleet) and micro-mobility sharing (e.g. e-scooters) - Ride sharing (an online app helps connect people to travel together to the same or similar destinations)
Sustainable fuels Development of alternative fuels that have a lower carbon footprint to substitute fossil fuels. Their potential lies primarily in decarbonizing hard-to-abate sectors like aviation or heavy-duty vehicles, in which electrification is challenging.	Biofuels (produced from biomass) Green hydrogen Synthetic fuels (e.g. ammonia, methanol)
Greening of production processes and products Improvement of design and production process in the transportation sector (e.g. automotive sector) to become more environmentally friendly. Digital innovations can critically contribute to optimizing processes.	Greening production processes, e.g. by: – Increase energy and resource efficiency – Increase share of renewable energy used – Responsible sourcing of raw materials (e.g. for batteries) – Materials longevity, reuse, recycling, and sustainable disposal Greening end-products, e.g.: – Improvements in design of vehicles, ships and aircrafts to reduce fuel requirements – Alternative battery chemistry to reduce intensity of critical metals (e.g. nickel, lithium) – Improvements in end-of-life battery management and recycling – Repair, resource recovery, and recycling of products and materials

Source: Own elaboration based on (IEA, 2023[8]), (IRENA, 2021[63]), (McKinsey, 2023[64]), (McKinsey, 2022[65]), (OECD/ITF, 2023[66]).

65. Within electric vehicles, three different types exist, ranging from fully electric vehicles (EVs) to hybrid electric vehicles and much less explored fuel-cell electric vehicles, which utilize hydrogen-powered electric engines.

66. EVs are considered a key technology to decarbonise road transport. Road transport accounted for 10% of world GHG emissions in 2019 (IEA, 2023[8]; IPCC, 2022[4]) Traveling by private car represents the prevalent mode of transport with a share of 45% in the worldwide mobility split in 2022 (McKinsey, 2023[67]).

Technology maturity and key actors in the sector

67. EVs (including batteries and charging infrastructures) are mature technologies, with a growing number of models (including more affordable ones) increasingly available. Alternative battery chemistries are being developed to reduce their environmental impacts and dependence on critical minerals supply chains. Battery recycling is being developed to provide another source for materials, reducing dependence on critical minerals and waste.

Fast and ultra-fast charging technologies are also being developed to increase the convenience of travel and reduce range anxiety.

68. Main innovators in the field of EVs are traditional car makers (including equipment suppliers) and new market players, including firms coming from the ICT sector (Table 8). Policy requirements initially drove electrification of traditional car manufacturers, which then increased efforts to remain competitive amidst rising competition from new entrants, particularly from China and emerging economies (IEA, 2024[9]).

69. China, Europe and the USA have mature markets for EVs, and jointly account for 95% of global sales in 2023. Uptake has been enabled by advancements in battery technologies and their decreasing costs over the past 20 years. The share of electric cars in global cars sales is growing rapidly, reaching 18% in 2023 (up from 14% in 2022, 9% in 2021 and less than 5% in 2020) (IEA, 2024[9]).

70. Trade in EVs and batteries is also increasing, with China being the lead exporter in both products in 2023. The increasing numbers in cheap Chinese EVs led to the introduction and increases in import taxes on EVs, including the case of the United States (increasing from 25% to 100% in May 2024) or the EU (at 10% as of May 2024). The recent increase in US tariffs on EVs might only cause small shifts in global trade as EV imports from China are neglectable small (only 12,000 EVs in 2023) (IfW, 2024[68]). For the EU, the picture is a little different as the EU is the biggest importer of Chinese EVs (500,000 vehicles in 2023, almost one third of Chinese total exports). Dynamics in tariffs and their implications on trade may also shape the trajectory of global innovation, affecting technology transfer, research collaboration as well as competition dynamics (IEA, 2024[9]).

Table 8. Electric vehicles: overview of trends in technology development and diffusion

Who are the innovators?	• **Automotive companies**, including equipment suppliers, OEMs, remain large innovators for EV technologies. Incumbents are facing significant competitive pressures given changes in market demands (shift towards EVs and increasing importance of digital components of vehicles) and entry of new market players (e.g. novel EV-only car manufacturers, firms in the ICT sector entering the EVs market). Traditional car manufacturers only accounted for 40% of global EV sales in 2022 (vs. 55% in 2015). EV-only manufacturers are constantly increasing their market shares, with Tesla and BYD accounting for more than 30% of global sales in 2022.This is pushing incumbents to invest in internal skills and capabilities to remain competitive in the EVs market segment. • **China** is the main player in battery supply chain and EV component trade. 85% of global battery cell production capacity is located in China. • Leading applicant countries for EV patents are **Japan, USA, Germany, Korea and China** (2016-2019). • EV patents of **young firms (< 5 years old)** increased at a faster rate than in the case of older firms (2000-2016). Young firms play a vital role in bridging academia and industry, focusing primarily on core emerging technologies, while older firms specialize in integrating these technologies into vehicles. • **Universities and research institutes** are more important players than in ICE vehicles innovation. EV patents have a higher share of citations to university patents and to academic literature compared to ICE technologies (2000-2019). • **VC investments in start-ups** developing EV and battery technologies are booming, reaching nearly USD 2.1 billion in 2022, a 30% increase relative to 2021. Investments especially rose in batteries and critical minerals. • Global investments in EV batteries increased eightfold between 2018-2023, with USD 115 billion of total investments in 2023. China, Europe and the United States account for over 90% of this spending with highest investments taking place in China.

Table 9. Electric vehicles: overview of trends in technology development and diffusion (continued)

Barriers to technology diffusion / market upscale & supply conditions	**Policies have been key in stimulating supply.** These include policy requirements and regulations (e.g. CO_2 emission standards for vehicles, future bans on ICE vehicles) and policy instruments supporting investments in manufacturing capacities in batteries and EVs (e.g. public equity investments in new battery plants, tax credits linked to investments – see Table 10**Error! Reference source not found.** below). Some **barriers** to technology diffusion and market upscale remain: • **High purchasing cost:** EV still tend to be more expensive than equivalent ICE vehicles, although more affordable models are increasingly entering the market. Uncertainty about the evolution of energy prices might reduce consumers' incentives to purchase EVs. • **Dependent on deployment of charging infrastructures:** The expansion and standardization of publicly accessible chargers is a key condition to provide the same level of convenience and accessibility as for refuelling conventional vehicles. • **Concentrated supply chains for critical materials needed to produce batteries:** Building sustainable, resilient and secure supply chains as well as reducing the use of critical minerals will be key due to the variability in their prices and their availability. Also, innovation in alternative battery chemistry as well as end-of-life battery use and battery recycling is needed.
Demand conditions	Demand for EVs is mainly driven by **changes in consumer preferences**, mainly due to (a mix of): • Increased consumer demand for more sustainable transportation solutions, in view of raising awareness about emissions and air pollution generated by cars and their impact on health (particularly in urban areas) and the environment. • Purchasing incentives and subsidies for EVs provided by governments, making them an attractive greener alternative to internal combustion engine (ICE) vehicles. • Reduced price gap between ICE cars and EVs over time. Volatility of fossil fuel prices, although uncertainty also exists regarding electricity prices.
Technology diffusion through trade	• EVs: Chinese exports grew steeply in 2023, up 60% relative to 2022, making China the world's largest exporter despite high import taxes (e.g. 100% in the USA and 10% in the EU). • International trade for used EVs is expected to grow as the stock of EVs ages. Trade flows are expected to follow used ICE trade routes such as from the US to Middle and Central America. • Batteries: China was the world's largest EV battery exporter in 2023, with around 12% of its EV batteries being exported. The share of EV battery imports remains relatively large in Europe (20% of demand) and the USA (30% of demand).

Note: OEMs stands for original equipment manufacturers.
Source: Own elaboration based on data elaborated by (Dechezleprêtre et al., 2023[12]) in chapter 4 covering patent data and resulting innovation trends in the automotive ecosystem, and insights by the (IEA, 2024[9]) on venture capital (see section "finance, venture capital and trade" and chapter "Trends and development in EV markets") and (NNCTA, 2023[69]), (Paunov and Planes-Satorra, 2019[17]), (OECD, 2022[70]), (PWC, 2021[71]), (IEA, 2024[72]).

Policies in support of electric vehicles

71. The number of national and multilateral initiatives and pledges focusing on electromobility has increased rapidly in the last decade (IEA, 2023[73]). Governments worldwide, including those outside major markets, are implementing policies to support EV adoption. Common policies and regulation include fuel economy standards, zero-emission vehicle mandates, purchase incentives, and bans on internal combustion engine vehicles.

72. Many governments are adopting industrial policies to support the development of manufacturing capacities in EVs and/or batteries (Table 10). In the USA, the Inflation Reduction Act (IRA) (2022) has led to the introduction of the Clean Vehicle Tax Credit, which benefits consumers purchasing EVs that comply with several requirements (incl. final assembly occurring in North America, and critical mineral and component requirements) and the supply-side Advanced Manufacturing Production Tax Credits, which provides subsidies for domestic battery production. The Green Deal Industrial Plan in the

EU is another example. Additionally, some emerging and developing economies are developing specific industrial policies to bolster battery and EV production, aiming to enhance domestic manufacturing capabilities (IEA, 2024[9]).

73. Demand-side policies have significantly shaped corporate strategies and consumer adoption, especially through incentives like purchase rebates. While early adopters like China, Europe, and the United States initiated EV markets with demand-boosting policies, many countries are now gradually reducing incentives as the market becomes more mature and focusing on segments like heavy transport and charging infrastructure.

74. On the supply side, common instruments are the support for R&D activities especially on battery technologies, demonstration programs (e.g. on EV infrastructure) as well as support for transitioning manufacturing-related skills from ICE to EVs.

Table 10. Policy levers in support of electric vehicles

Type of instrument	Examples
Strategies and roadmaps	• **Industrial policies supporting the expansion of manufacturing capacities in key strategic technologies for the green transition, incl. in batteries and EVs***:* Examples include the US Inflation Reduction Act (IRA), adopted in 2022, and the Green Deal Industrial Plan. Such policies also aim at reducing dependence on critical minerals supply chains and increasing the countries' resilience to supply chain disruptions. They are often accompanied by significant funding commitments and support schemes. • **Strategies and roadmaps for the automotive and battery industries.** Korea has been particularly active, with strategies that include the 2030 K-Battery Development strategy, the Global Strategy for the Automotive Industry (2022-2030), and the Innovation Strategy for the Rechargeable Battery Industry (2022-2030). Australia announced a National Battery Strategy in 2023 to support the development of a domestic battery manufacturing industry. Other countries that implemented national strategies on batteries are, for example, Finland, Sweden, Hungary or Norway.
Supply side support measures	• **Support for R&D activities.** Examples include the US funding for electric vehicles battery research provided by the Department of Energy, and the Electric Vehicles for American Low-carbon Living, provided by ARPA-E. The UK provided over GBP 30 million of funding through the Automotive Transformation Fund for research in batteries and hydrogen vehicles**.** The Advanced propulsion centre UK supports R&D activity along the EV supply chain through collaborative research and development competitions, matching public and private investments. • **Support for demonstration activities**. Examples include Canada's electric vehicle infrastructure demonstrations programme (2016-2024), which supports demonstration of innovative EV charging and hydrogen refueling infrastructure. • **Skills development.** Support for transitioning manufacturing-related skills from ICE to EVs. This also covers building up skills on battery technologies and production. For example, the EU Net-Zero Industry Act foresees the introduction of Net-Zero Industry Academies to roll out up-skilling and re-skilling programmes in strategic industries, including in the field of batteries.

Table 11. Policy levers in support of electric vehicles (continued)

Demand side support measures	• **Incentive schemes for the purchase of EVs:** While these have been very important to stimulate demand over the past decade, in major EV markets like China and European countries like Norway, Germany or UK subsidies are declining or phasing out. • **Investments in public and private charging infrastructures:** In countries with more developed EV markets, the policy focus shifts from subsidizing the purchase of EVs towards supporting the deployment and standardization of mainly public but also private chargers. The Québec Electric Vehicle Charging Strategy sets a target of 6,700 fast-charging and 110,000 public charging stations by 2030 supported by a budget of CAD 514 million for the 2023–2028 period and amendments to building standards.
Regulations / framework conditions	• **Standards and regulations, both for EVs and ICE vehicles** such as fuel economy standards, zero-emission vehicle mandates, and bans on internal combustion engine vehicles. For example, CO_2 standards adopted March 2023 by the European Union require 55% in emission reduction of new cars by 2030 (compared to 2021). California adopted zero-emission vehicle mandates in 2023 that all new cars, trucks and SUVs sold in the state will be zero-emission by 2035. • **Standards and regulation for batteries** on recycling and end of life-of-life strategies as well as battery supply chainsThe 2023 EU Battery Regulation includes mandatory recycling targets for specific battery types and the 2023 EU Critical Raw Materials Act (CRM)with clear targets for domestic capacities and diversified supply chains.

Source: Own elaboration based on (EC-OECD, 2024[74]), (IEA, 2023[73]) (ISI, 2024[75]).

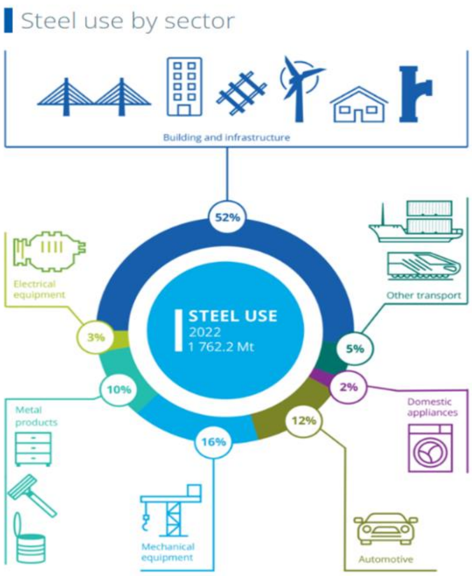
3.3. Carbon-emission-reducing steel production

Description and relevance for the decarbonisation of the manufacturing sector

75. Steel is a ferrous alloy consisting primarily of iron and is used as an essential material for building and infrastructure (representing more than half of global steel use) and for producing machines, medical equipment, household, and metal goods that contribute to people's lives and well-being (Figure 13). Steel is also necessary to build the renewable power infrastructure (e.g. wind turbines or solar panels), thus enabling significant emission reductions in other sectors and applications (OECD, 2023[16]). However, the steel sector ranks as one of the most emitting industry sectors, accounting for around 30% of worldwide industrial carbon emissions. To comply with the Paris Agreement objective of limiting global warming to 1.5 °C, direct emissions from the steel sector must decline by 90% from 2020 levels by 2050 (OECD, 2022[13]; OECD, 2024[14]).

76. Steel can mainly be produced in two different ways: either through the reduction of iron ore from coal in blast furnaces heated at very high temperatures by burning fossil fuels (BF-BOF route, also coined as primary route) or through the direct reduction of iron ore with an oxidant agent (e.g. natural gas), which is then smelted in an electric arc furnace where it can be mixed with scrap metal (DRI-EAF route). The quality of steel produced through the BF-BOF route is higher, as tramp elements embodied in the scrap lower the purity of the steel produced in the EAF route (Algers and Åhman, 2024[76]). However, the BF-BOF route is characterised by a higher CO_2 emission intensity (2.32 tonnes CO_2/ tonne of crude steel against 1.37 tonnes CO_2/tonne of crude steel) and represents the largest share of the global steel production (more than 70%) (Somers, 2022[77]; Algers and Åhman, 2024[76]).

Figure 13. Steel use by sector



Source: worldsteel.org, World Steel in Figures 2023

77. The decarbonisation of steelmaking will depend on efforts towards the development of green innovations along different strands. In the BF-BOF route, the technologies involve principally performance improvements such as energy-efficiency or processes optimisations (e.g. partial substitution of coal with biomass, hydrogen and CCUS). In the DRI-EAF route, the CO_2 produced by direct reduction of iron using natural gas could be captured and stored with CCUS technologies, natural gas could be substituted for green hydrogen which would prevent carbon emissions, and the electric arc furnaces could be powered with renewable electricity. Finally, a low carbon production route is under development around iron ore electrolysis (OECD, 2023[16]; Devlin et al., 2023[78]) (see Table 12).

Table 12. Green innovation areas in the steel sector: some examples

Green innovation areas
Improved performance (energy efficiency and processes optimisation) Improved performance encompasses technologies relevant for different production routes: for instance, it can concern the partial substitution of coal with biomass or hydrogen in a traditional blast furnace or the use of renewable electricity to power an EAF.
Circular economy Steel can be produced from scrap melted in an electric arc furnace. Improving the quality of scrap inputs in the EAF route would allow the production of higher quality secondary steel products.
Green hydrogen-based technologies Green hydrogen can be used for the direct reduction of iron instead of natural gas and thus prevent carbon emissions.
Carbon capture, utilization and storage [CCUS] CCUS enables the capture, transport and storage of CO_2 emissions in geological formations. The technology is particularly attractive for large emission sources with a high CO_2 concentration, and this explains why current CCUS pilot projects target blast furnaces and direct reduction plants.
Iron ore electrolysis Iron ore electrolysis consists in reducing the ore using an electric current to obtain pure iron, without emitting greenhouse gases. The pure iron is then fed into an electric arc furnace (EAF), where it can be mixed with scrap metal.

Sources: Own elaboration based on (OECD, 2023[16]; IEA, 2023[51]; Somers, 2022[77]).

Technology maturity and key actors in the sector

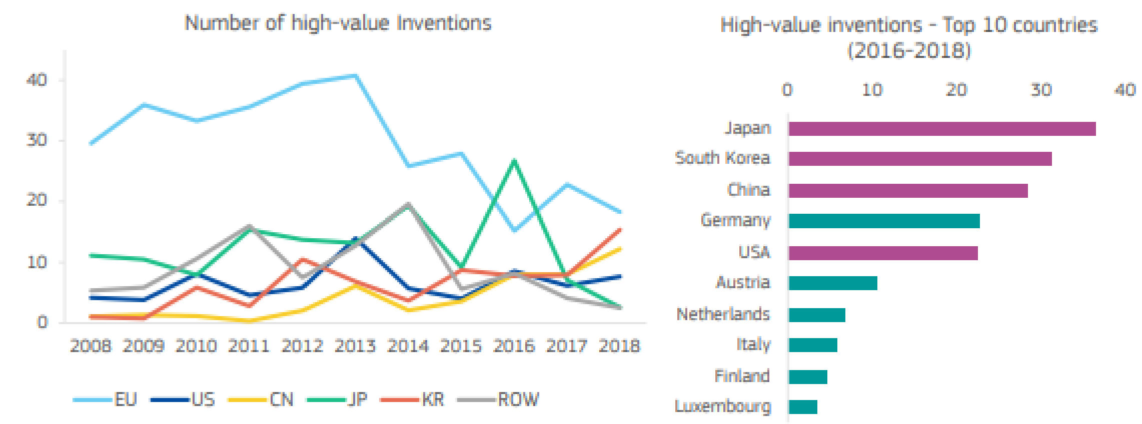
78. The G7 economies, China and India account for 70% of global steel production. The share of G7 economies has been declining in past years, while emerging economies have experienced growing shares of production: China manufactures around half of the world's steel and by 2050, India's share is expected to reach almost 20%, compared to around 5% today (IEA, 2023[51]; IEA, 2020[79]; OECD, 2023[16]).

79. In 2021, firms with net-zero targets accounted for 30% of global steel production. Projects focussing on near-zero emission production routes are rapidly developing, but they still need to reach higher levels of industrial maturity and to ensure production at commercial scale: the current production of near-zero emission steel represents less than 0.05% of the global steel production, with 1 million of metric tons (mmt) in 2022 for a global steel production of 1,890 mmt (OECD, 2023[16]; IEA, 2023[8]).

80. Countries differ widely in the structure of their steel industries, in technologies used, and in the innovations they seek, with some industries focusing on available technologies whereas others invest in carbon mitigation Research and Development (R&D) to improve production processes and products (OECD, 2023[16]).

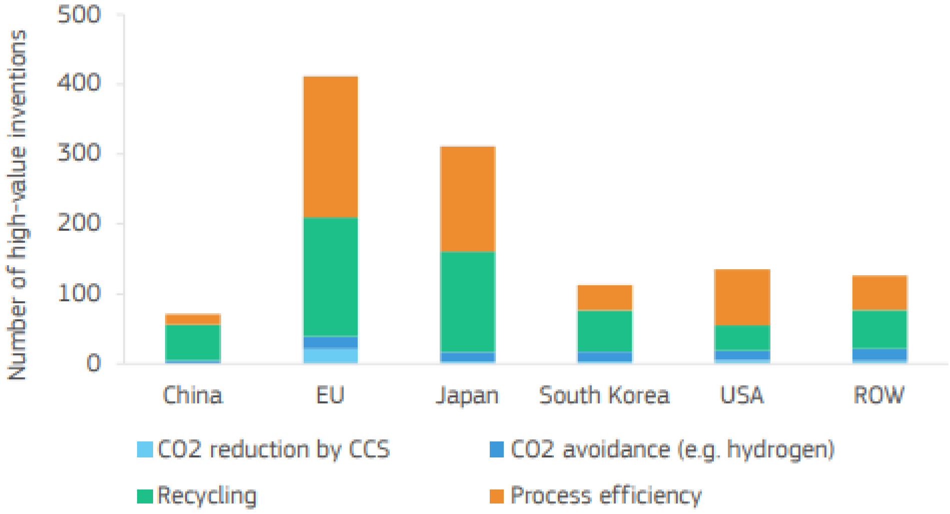
81. Patenting in carbon-emissions-reducing steel production technologies was led by the European Union (EU) from 2008 to 2015. From 2015 onwards, the yearly number of EU patents for low carbon steel has been declining. Over the 2016-2018 period, most high-value patents have been filed by Japan, followed by Korea (Figure 14). The areas of innovation mostly relate to recycling and process efficiency activities, and those linked to the use of hydrogen or CCUS in steelmaking represent only a fraction of the total patenting activity. Within that subset, twice as many hydrogen-related patents were filed as for CCUS. Inventions on avoiding CO_2 (e.g. using hydrogen) are spread across all countries, while most CCUS patents are in the EU (Figure 15) (Somers, 2022[77]).

Figure 14. Inventions related to decarbonisation breakthrough steel technologies (2008-2018) and top-10 countries (2016-2018)



Note: For the graph on the right, green stands for EU countries and purple represents non-EU countries.
Source: JRC using EPO's PATSTAT (Somers, 2022[77]).

Figure 15. Patenting of decarbonisation technologies related to metal processing



Source: JRC using EPO's PATSTAT (Somers, 2022[77]).

82. The different technologies supporting carbon-emissions-reducing steel production have different maturity levels. Some could technically be deployed today (DRI with natural gas as reducing agent), while others are still at an early development stage (iron ore electrolysis) (see Table 13Table 13). Scaling-up these technologies will require overcoming several economic and technical barriers to their diffusion (see Table 13Table 13).

Table 13. Carbon-emissions-reducing steel production: overview of trends in technology development and diffusion

Who are the innovators?	• Leading applicant countries for carbon-emissions-reducing steel production technology patents are **Japan, Korea, China, Germany, and USA** (2016-2018). • Patenting activity is driven by **steelmaking companies** in Japan and Korea (e.g. JFE Steel or Posco), while in the EU, it is led by **technology providers or other players along the steel value chain** (SMS Group, Siemens, Primetals Technologies). • Some **start-ups** also have a prominent role, like Boston Metals and Electra Steel in the United States which are developing iron ore electrolysis technologies and H2GreenSteel in Sweden.
Technology maturity	• The technologies have **different maturity levels**. Emirates Steel Industries operates in the United Arab Emirates the **first plant using DRI-EAF with CCUS** and **already produces** carbon-emissions-reducing primary steel. • The **first hydrogen-based DRI plants** are expected to **operate at a commercial-stage in the 2025-2026 period** in the EU, with two projects in Sweden (one led by the start-up H2GreenSteel and the Hybrit project involving SSAB). • **Iron ore electrolysis** is still at the **pilot stage** but could have considerable growth potential: several projects are aiming for commercial deployment in the late 2020s (Boston Metal and Electra Steel in the USA and ArcelorMittal with the Siderwin project in France). • **Investments**: Global announced investments for green steel projects exceed USD 104 billion, out of which around USD 56 billion concern projects at full scale and USD 47 billion R&D partnerships. In terms of technology, green H2-DRI-EAF accounts for nearly USD 67 billion of total investments.

Barriers to technology diffusion / market upscale & supply conditions	**General barriers regarding all green steel technologies** • **Large up-front capital costs**: Major capital expenditures investments are required to either replace blast furnace-based steelmaking plants, to build new plants or to adapt existing plants, and also to construct auxiliary facilities (e.g. renewable energy or CCUS infrastructure).The projected cumulative capital investment needed by 2050 to convert the current route to carbon-neutral production in the EU has been estimated at between EUR 70 billion and around EUR 100 billion, non-including the investments need for additional auxiliary facilities • **Long investment cycles and carbon lock-in**: The investment cycles of steelmaking assets are long, with blast furnaces having operating lives of up to 20 years before they need relining, and a typical lifetime of around 50 years. The switch to carbon-emissions-reducing technologies is more likely to occur in companies with emission intensive steelmaking assets approaching the end of their technical life. For companies with more recent asset, there is an accrued risk of locking in CO_2 emissions. To date, most green steelmaking capacity announced is based in jurisdictions with the oldest BOFs, like the EU, Canada and Korea. • **Global steel excess capacity and low exit of emission intensive plants**: Global steel excess capacity drives steel prices down, reduces firms' profitability and exacerbates competitive pressure. This could damage the financial health of potential green suppliers and their ability to invest in these capital-intensive new production technologies. Moreover, if new green steel plants do not replace existing blast furnace-based plants, they will contribute to feed the problem of global steel excess capacity, making the market entry of new actors even harder. • **Resource availability**: The deployment of green steel technologies depends on the availability of resources that are unevenly distributed across steel-producing countries (renewable energy, scrap, green hydrogen and iron ore). Some steelmaking companies have therefore adopted new location strategies, like the Korean steel producer POSCO which will invest in a facility to produce hydrogen in Australia or the Swedish startup H2GreenSteel which plans to open a hydrogen plant and iron reduction plant on the Iberian Peninsula. • **Social aspects**: For regions where the steel sector strongly contributes to the economy, steel decarbonisation may involve large social transitions, including the need to upskill or reskill the workforce, since the DRI-EAF production route is less labor-intensive than the BF-BOF route at a commercial scale. However, steelmaking companies' ability to plan the upskilling and reskilling of the workforce is impaired by the dependency of the decarbonisation timeline of steelmaking on other technologies. **Regarding circular-economy based technologies** • **Lacking lifecycle approach:** The whole life cycle of steel is not significantly considered by producers such as insufficient integration of recycled steel in the manufacture of new products and insufficient attention paid to recyclability of the products. • **Recycling challenges:** There is a need to invest significantly in modern scrap sorting technologies, as sorting still relies mainly on visual inspections, sometimes aided with a sport analysis. Some technologies are available to the market, but recyclers do not see the economic benefits of using them as there is low market demand for high quality recycled steel at a higher price. **Regarding green hydrogen-based technologies (see also section 3.1.)** • **Production capacity and infrastructure development**: Producing 2 million tons of hydrogen-based steel requires a green hydrogen amount of 144,000 tons. Hence, the timeline for commercial availability of steel production technologies based on green hydrogen will depend on prior provision of large production capacities and infrastructure for green hydrogen.
Demand conditions	• **Creation of markets for carbon-emissions-reducing steel production:** Investors and producers aiming to bring these technologies to market require certainty about early market demand. Voluntary markets for green steel are slowly emerging: some automotive companies are announcing they will use low-CO_2 steel in their vehicle manufacturing. For instance, the car and truck maker Daimler Mercedes-Benz has partnered with both Swedish startup H2GreenSteel and with Swedish steelmaker SSAB to introduce green steel into their vehicles. • **Creation of standardised methodologies to calculate the embodied emissions of steel products:** The lack of standards could constitute an important non-cost barrier to creating markets for climate-neutral products. Some standard and certification initiatives have been led by the industry: the World Steel Association has published a lifecycle GHG inventory methodology based on ISO standards for calculating steel plant GHG emissions.
Technology diffusion through trade	• There is no established international market for green steel yet. • Net exporters of non-green steel are China (51.1 Mt), Japan (26.4 Mt), Russia (16.6 Mt) and Korea (11.8 Mt). The EU and the USA are net importers (resp. 22.0 Mt and 20.6 Mt) (2022)

Sources: Own elaboration based on (OECD, 2023[16]; Somers, 2022[77]; IEA, 2023[51]; Algers and Åhman, 2024[76]; Hoffman, 2020[80]; OECD, 2024[15]; OECD, 2024[14]; Worldsteel, 2023[81]).

Policies in support of carbon-emissions-reducing steel production

83. Policy towards the development of carbon-emissions-reducing steel production has been enhanced through the definition of national low carbon strategies and their declination into roadmaps for national steel sector in some countries, such as Sweden. This policy directionality is also reinforced by international cooperation, as exemplified by the launch of the Steel Breakthrough at COP26 in 2021, a global platform including major steelmaking nations that will aim to support the development of a global market for low carbon steel.

84. Governments support the production of innovation for carbon-emissions-reducing steel production through numerous research and innovation funding programmes. Some programmes focus on the early-stage development of the technologies, while others aim to foster first-of-a-kind demonstration and commercial deployment. Examples are the EU ULCOS programme, which helped the early development of several of the key decarbonization technologies considered by the European steel industry and the EU Innovation Fund, which was implemented to encourage commercial demonstration (see Table 14). The production of innovation can also be incentivised by the introduction of carbon price schemes, though the current price levels are insufficient to make carbon pricing a key driver of the steel sector decarbonization (OECD, 2022[13]).

85. The demand for innovations can be enhanced through the introduction of public procurement rules surrounding green steel purchase for public buildings and infrastructure, as done for instance in the Buy Clean Initiative in the United States. The harmonization of international standards and regulations could also help to create an international market for green steel.

86. Promoting resource efficiency and circular economy measures in the steel sector as well as in downstream sectors is the subject of several government strategies. Recycled steel can partly replace the use of primary steel and reduce environmental impacts associated with primary steel production (ie. iron ore extraction or carbon emissions generated as a by-product of iron ore reduction with coal). Examples are Canada's National Vehicle Scrappage Programme in Canada or the Korean circular economy (CE) 9 policy, which promotes the use of AI to improve the scrap selection stage for EAF steelmaking.

Table 14. Policy levers in support of carbon-emissions-reducing steel production

Definition of low carbon strategies and roadmaps	• **Introduction of net-zero-emissions targets**: 90% of global steelmaking capacity and crude steel production are in countries that have announced a net-zero target. These net-zero pledges are directed to the whole economy, but they imply a fundamental shift in steel production modes (and industrial production in general) to bring it on a net-zero pathway. • **Sectoral and firm-level roadmaps**: in several countries, roadmaps for decarbonising the steelmaking sector have been drafted. An example is the Swedish steel industry roadmap, elaborated in the context of the Fossil Fuel Free Initiative launched in 2015, which targets at fossil-free steel production at a 2045 horizon. Most of the largest steel companies have also adopted decarbonisation roadmaps, including target setting and project announcements. • **International cooperation**: The Steel Breakthrough was launched at COP26 as part of the Breakthrough Agenda, and joined by 25 countries and the EU, including major steelmaking nations like the United States, India, Korea, India, and Japan. It aims to catalyse the use of near-zero emission steel in global markets and sets targets to track global progress in near-zero emission steel production capacity, investment in R&D and cost.

Table 15. Policy levers in support of carbon-emissions-reducing steel production (continued)

Supply-side measures supporting research and innovation	• **Early-stage R&D funding:** R&D programmes played an important supporting role in the early development of carbon-emissions-reducing steel production. For instance, several of the key decarbonisation technologies being considered by the steel industry were developed via the EU's ultra-low CO_2 steelmaking (ULCOS) programme, a project that associated 47 partners across the steel industry and research landscape. • **Demonstration and commercial deployment support**: Major investments are still needed. The EU Innovation Fund represents one of the world's largest funding programmes targeting the commercial demonstration of innovative low-carbon technologies, including projects in the steel industry. It will, for example, provide funding for the demonstration plant of the Swedish Hybrit project, whose initial R&D stages were partly funded by the Swedish government. • **Public-private partnership**: R&D funding can involve the participation of the private sector. An example is the EU Clean Steel Partnership which associates the European Commission and the European Steel Technology Platform and aims to bring a range of breakthrough technologies for clean steel production up to large-scale demonstration by 2030. Out of the estimated R&D investment needs of EUR 2.6 billion, the EU will contribute by EUR 700 million.
Demand-side support measures	• **Public procurement**: Public procurement could play a key role in generating early demand for low carbon steel. Governments purchase large quantities of steel for building and infrastructure construction. The United States' Federal Buy Clean Initiative promotes the use of low-carbon construction materials, including steel, in federal procurement and federally funded projects. The Swedish Transport Authority has also developed a methodology to integrate life-cycle accounting into its procurement decisions, which can promote low-emission material purchases. • **Harmonisation of international standards and regulations:** The harmonisation would help to create an international market for green steel.
Measures related to the circular economy	• **Enhanced resource efficiency and circularity in downstream sectors:** Governments have developed strategies aiming at promoting resource efficiency and circularity in sectors that may have impacts on the steel industry, like construction and buildings and automobile. Examples are the National Vehicle Scrappage Programme in Canada and the Japanese Construction Recycling Act. • **Improving steel recycling and scrap quality:** Some Asian countries – China, Japan, Korea – have invested in the use of AI to overcome scrap-specific challenges. For instance, with the circular economy (CE) 9 policy, Korea promotes the use of AI to both improve the scrap selection stage for EAF steelmaking and prevent leakage of domestic scrap.
Measures related to carbon pricing/framework conditions	• **Carbon pricing schemes:** Carbon pricing schemes provide a broad signal for the steel sector to shift towards lower-emission technologies. In 2021, carbon pricing covered only around 20% of global steelmaking capacity and production, without taking potential exemptions into account. • **Carbon contracts for difference (CCfDs)**: By providing higher certainty on the evolution of carbon prices and de-risking decarbonisation investments, CCfDs can support the switch from fossil fuels to renewables and the transition to hydrogen-based production in industrial sectors such as steelmaking. The German government launched in March 2024 the first bidding round of a pilot CCfD programme to help decarbonise the energy-intensive industry, including the steelmaking sector. • **Carbon border mechanisms (CBM):** CBMs aim at countering the risk of carbon leakage, namely the relocation of industrial activities to countries with less stringent regulations. Since October 2023, the EU has introduced a carbon border adjustment mechanism, that will require an equivalent purchase of carbon emission allowances on the ETS for import of carbon intensive products, including steel. Many other jurisdictions such as Australia, Canada and the United Kingdom are equally considering adopting CBMs.

Sources: Own elaboration based on (OECD, 2023[16]; Somers, 2022[77]; IEA, 2023[51]; IEA, 2020[79]; OECD, 2024[14]; OECD, 2024[82]).

4. Preliminary considerations for STI policy

87. This section provides some preliminary considerations for STI policy, based on the comparative analysis of sectors explored in section 3.

4.1. Quick sectoral comparison

88. Table 16 below presents key dimensions influencing green innovation dynamics in the three sectors of focus, allowing to identify key similarities and differences technology development. Electric vehicles enjoy advanced technologies and strong market presence, driven by both established and emerging automakers. By contrast, green hydrogen is still developing, with significant innovations required in production, storage, infrastructure, transport and regulation, led by the chemical and automotive industries. Steel production technologies to reduce carbon emissions are in early stages, predominantly advanced by Asian steelmakers and European technology providers, yet lack robust regulatory support.

4.2. Tackling demand-side challenges

89. Several demand-side challenges and conditions affect green innovation across sectors. Key takeaways from the analysis include the following: First, **the lack of market demand, and hence downward pressure on the prices, remains the main challenge for advancing the technology readiness of green innovations in some sectors.** These in turn hamper the wider deployment of those technologies for their environmental impacts. STI policy efforts aimed at supporting demonstration of those technologies and the functioning of related markets are critical to de-risk investments in innovation in those areas and accelerate the development of more advanced solutions. Hydrogen valleys are a case in point, which work as local demonstrators of the use of hydrogen by various industries, and act as first real-life cases for piloting hydrogen markets. Supporting the creation of hydrogen markets would require the establishment of clear definitions and certification schemes for green hydrogen, ideally at global scale.

90. Second, **citizens play different roles in influencing demand and steering green innovation directions across sectors**. While citizen behaviours directly shape demand for green mobility solutions (e.g. they can decide to purchase an electric vehicle or use shared mobility solutions instead of personal ICE cars), they have limited direct influence in shaping innovation trends in the field of green hydrogen or the decarbonisation of the steel sector. Citizen awareness and mobilisation regarding the climate and environmental impacts of fossil-fuel based economies, however, can play a key role by pushing regulations and policy action that support green research and innovation and the deployment of new technologies and processes to decarbonise industry.

91. Third, **tailored demand-side instruments can be further leveraged to stimulate industry to engage in green innovation efforts**. In the field of green hydrogen, there is limited policy focus on stimulating demand from hard-to-abate sectors, such as steel. Investments in key infrastructure is also critical to upscale adoption of some green technologies, such as investments in EV charging stations. Embedding specific requirements into public procurement (e.g. share of low-carbon steel used to build public infrastructures) can also help stimulate demand. Policy and regulatory requirements can also provide the right incentives to create markets that currently do not exist, such as building standards and certification schemes for green hydrogen to create such markets.

Table 16. Preliminary comparison

	Green Hydrogen	Electric vehicles	Carbon-emissions-reduced steel production
Technology readiness	The value chain is not fully developed at commercial scale and innovations are still needed regarding distribution and end use of green hydrogen	Mature technologies (incl. batteries and chargers) with significant levels of market uptake	The value chain is not developed at commercial scale yet for most of the technologies
Main innovators	Chemical companies dominate innovation in grey hydrogen; automotive companies and equipment suppliers dominate innovation in green hydrogen	Traditional car manufacturers and suppliers; new market players, e.g. novel EV-only car manufacturers and ICT firms with increasing market shares	Steelmaking companies (mostly from Asia) and technology providers and other players along the steel value chain (mostly from Europe).
Role of citizens	Limited, but public support would be crucial for the extension of the renewable energy production grid and the construction of green H2 transport infrastructures	Changes in consumer preferences (regarding mobility habits) towards greener transport mode can influence the diffusion of the technology	Limited, but public can push policy action that support the decarbonization of the manufacturing sector.
Infrastructure investments	Large investments in the construction of transport and storage infrastructures (e.g. EU IPCEI)	Investments for the deployment of charging infrastructures (extension of the network and standardization of chargers)	Large investments needed in renewable energy, green hydrogen production capacities and CCUS infrastructures to enable low carbon steel production
Role of regulations	Global certification standards could help the creation of a transparent international market, but they are currently lacking	Regulations (e.g. on CO_2 emissions of vehicles, bans on ICE vehicles) and standards (e.g. EV chargers) have supported the creation of a market for EVs	Regulations (standardization and harmonization) could help the creation of a market for green steel, but they are currently lacking
Demand vs supply-side measures	Current focus on supply-side measures (RD&D, public financial instruments).	Supply-side measures (RD&D, tax and financial incentives) and demand-side measures are in place (purchasing incentives or subsidy for EVs)	Current focus on supply-side measures (RD&D, public investments) complemented with some demand-side instruments (e.g. public procurement)
Resource availability, resilience and the circular economy	Circular economy challenges related to re-use of water. The heavy use of electricity may impose constraints esp. if electricity is to be generated by sustainable resources.	The supply chain of critical minerals needed for batteries production is concentrated. Improvements in the end-of-life management of EVs and battery recycling can respond to challenges and reduce toxic waste. Successful alternative battery chemistry solutions to reduce resource dependencies could address resource and increase resilience.	Primary steel production requires iron ore that is unevenly distributed across the globe. Enhancing steel recycling can increase resource availability for green steel production and resilience.

Source: Own elaboration

4.3. Improving supply-side conditions

92. Several policy avenues can help support build the right supply-side conditions for the development and deployment of green innovations. **Funding to facilitate riskier investment that may otherwise not be undertaken** is a first policy choice. Currently, massive industrial policy investments are underway, specifically in sectors countries identify as critical for their competitiveness and resilience. Major initiatives such Japan's Green Growth Strategy (2020) and Green Transformation Promotion Act (2023), the US

Inflation Reduction Act (IRA) (2022) and the Green Deal Industrial Plan in the EU. Electric mobility and green hydrogen feature prominently. These are de-risking private investments in innovation in those areas. Public-private partnerships are critical given the magnitude and long-term sustainability of investments needed.

93. Second, **infrastructure investments are essential for developing and deploying green innovations**. Investments in the deployment of EV charging stations to ensure wide geographical coverage is essential for EVs to be adopted at scale. Similarly, upscaling the use of green hydrogen would require significant investments in transportation infrastructures. Such large-scale investments require co-ordination across value chains and between industry and across government. The timing is critical here as, on the one hand, investing in infrastructures when technologies are still not mature risks creating new technology lock-ins, hampering future investments in (potentially better) alternative technology paths. Delaying infrastructure investments, on the other hand, could slow down green innovation efforts and adoption of new solutions, therefore delaying their positive environmental impacts and the competitive first-mover advantage of countries deploying and consequently experimenting more with those technologies.

94. Third, **standards and regulations can stimulate the development and scaled deployment of green innovations across sectors**. The establishment of international regulations and global certification standards on green hydrogen and green steel production, which are currently lacking, would also help stimulate the creation of global transparent markets for these technologies, induce more demand (see above) and attract industry investments on the supply side.

95. Fourth, **support the development of skills and capabilities needed to develop and deploy green innovations, which span different education levels and stages of the innovation cycle**. STEM (science, technology, engineering, mathematics) skills are critical for the development of cutting-edge green technologies, but skills required for their deployment extend far beyond. This regards all levels of education. Approaches will differ depending on the reskilling opportunities of those already operating in the industry, such as the skills needs for moving from the production of combustion engine vehicles towards electric vehicle production processes.

4.4. Building comprehensive STI policies for green innovation

96. **Comprehensively assessing the full environmental and societal footprint of the life cycle of "green" innovations** is relevant to understand best ways forward for innovation to support green transitions. This regards understanding environmental impacts as encompassing carbon emissions, environmental degradation and biodiversity loss. Adopting a comprehensive definition of green innovation is important as climate change and biodiversity loss are intrinsically intertwined, each exacerbating the impacts of the other. The adverse effects of climate change, such as extreme weather events, longer periods of droughts and wildfires, contribute to biodiversity loss. Conversely, biodiversity loss and ecosystem degradation reduce the natural resilience of ecosystems, undermining their ability to absorb and regulate greenhouse gases (GHGs). This cycle amplifies the severity of both climate change and accelerates the loss of biodiversity (European Commission, 2021[83]).

97. It also regards, however, the societal implications where changes are more radical, as public support for green transitions in democratic societies is essential. This illustrates the importance of societal engagement in innovation processes, including in finding ways to engage with at a disadvantage from transitions and ways to compensate those losses (Arnold et al., 2023[21]). Moreover, the need for societal endorsement and behavioural

changes for green innovations' diffusion further demands considering societal implications.

98. Production factors and products' after-life also have environmental impacts that are best integrated upfront to see how to best advance sustainability innovations. This is relevant when it comes to deciding on the focus for research and innovation efforts. Advances in production processes or end-of-life management as well as ways to mitigate biodiversity loss when deployed can enrich investigations and give a wider approach towards sustainable development (e.g. research efforts in reducing reliance on critical metals in batteries relative to research focused mainly on battery performance).

99. Moreover, **policies need to build on robust and timely technology and sector-specific intelligence**. Green innovation trends differ significantly across sectors and countries, with complex constraints affecting technology development, upscale and market adoption, particularly as massive investments promise rapid change. For policy to provide timely support, it needs to be informed with latest data and expert assessments. The National Network for Critical Technology Assessment (NNCTA) in the USA is a pilot initiative that showcases the importance of integrating multidisciplinary expertise and methods to inform technology and innovation policy decisions (OECD, 2024[84]). This also requires the capacity to scale up and down successes and failures, a challenge that requires adequate institutional settings.

100. **Coordination of efforts across policy areas is equally critical.** Research and innovation policies should be coordinated with efforts in other policy areas in order to maximise impacts of public funding and accelerate the green transition. For instance, moving towards greener mobility systems requires innovations in electric mobility solutions but also the deployment of needed infrastructure (e.g. green public mobility options, EV charging points).

101. Finally, **policies can be critical to stimulate citizen and business behaviours that align with green transition objectives**. Technology and innovation alone will not be sufficient to transition towards greener economies and societies. Changes in patterns of production and consumption are also needed. To mobilise citizens, communication and awareness raising efforts are important. For instance, transitioning towards greener mobility systems relies critically on changes in user behaviours that lead to a reduced dependency on individual car usage where possible, to prioritise green public mobility and other shared mobility options. Similarly, the greening of industrial processes requires technological advances but also measures that incentivise businesses to change their practices (e.g. requirements to make businesses account for climate and environmental impacts of their activities, minimize the use of natural resources and the generation of waste). The latter relies on market building support and long-term commitments to green transitions.

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Annex. Green patent classifications

102. To identify green patents, the codes of technology classes of patents can be utilized. Patents are classified into different technology classes following the International Patent Classification (IPC) or Cooperation Patent Classification (CPC). These codes can be utilized to identify green patents as done by the Y02/Y04 codes by the European Patent Office (EPO), the IPC Green Inventory by the World Intellectual Property Organization (WIPO), and the ENV-TECH list of environmental technology codes by the OECD. Comparative studies show that the different methodologies are complements rather than substitutes (Favot et al., 2023[85]). A second approach is to apply key word searches (e.g., PV panels) to the title and abstract of a patent.

103. The OECD developed a search strategy for environment-related patents referred to as **ENV-TECH** (Haščič and Migotto, 2015[86]). ENV-TECH allows the classification of green patents through IPC and CPC codes. The first strategy was published in 2012 and was updated in 2016, 2020, and 2022. The latest version from 2022 covers the following ten categories (OECD, 2022[87]):

- General environmental management
- Climate Change Mitigation, including:
    - Climate change mitigation technologies related to energy generation, transmission, or distribution
    - Climate change mitigation technologies related to production or processing of goods
    - Climate change mitigation in information and communication technologies
    - Capture, storage, sequestration or disposal of greenhouse gases
    - Climate change mitigation technologies related to transportation
    - Climate change mitigation technologies related to buildings
    - Climate change mitigation technologies related to wastewater treatment or waste management
- Climate change adaptation technologies
- Sustainable ocean economy

104. The EPO introduced the **Y02/Y04S classification scheme** as an additional category of CPC codes to identify climate change mitigation and adaptation technologies. The Y02 and Y04 subclasses cover the following areas: adaptation to climate change, greenhouse gases, climate change mitigation technologies related to buildings, energy, manufacturing, transportation, and waste-management, and smart grids. These subclasses are further divided into more granular groups, with overall 1300 different Y-tags for green technologies.

105. The WIPO, the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) collaborated to create the **IPC Green Inventory** overview that lists IPC codes related to environmental sound technologies. The inventory covers the following topics: alternative energy production, transportation, energy conservation, waste management, agriculture/forestry, administrative, regulatory or design aspects, nuclear power generation.