European Commission

# TOWARDS A GREEN & DIGITAL FUTURE

## Key requirements for successful twin transitions in the European Union

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## Key requirements for successful twin transitions in the European Union

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# EXECUTIVE SUMMARY

**The European Union aims to be sustainable, fair, and competitive.**
To keep the planet liveable and seize economic opportunities, the European Union is engaging in a swift and inclusive transition towards environmentally sustainable lifestyles and economies. The green transition aims to achieve sustainability, and combat climate change and environmental degradation. At the same time, the growing significance of digital technologies is transforming societies and economies. In the digital transition, the European Union aims to harness digital technologies for sustainability and prosperity, and to empower citizens and business. Successfully managing the green and digital 'twin' transitions is the cornerstone for delivering a sustainable, fair, and competitive future. There is no time to waste, and the twin transitions must be achieved together. To unlock their potential and to prevent negative effects, the green and digital transitions require a proactive and integrated management.

**This study examines how the European Union can ensure that the green and the digital transitions mutually reinforce each other.** This study analyses how current and future digital technologies could become key enablers for the green transition by 2050, which is when the European Union aims to be climate neutral. It also examines tension points between the twin transitions, such as how digital technologies might bring additional environmental burdens with them. It assesses how economic, social, and political factors will impact the twin transitions. The study takes a closer look at five economic sectors that are among the highest greenhouse gas emitters in the EU: 1) agriculture, 2) buildings and construction, 3) energy, 4) energy-intensive industries, and 5) transport and mobility. On this basis, the study derives key requirements for a successful management of the twin transitions.

**Digital technologies provide functions that can catalyse the green transition.** *Monitoring and tracking* can provide real-time information and be a catalyst for the circular economy. *Simulation and forecasting* can improve efficiency, for example in the form of Digital Twins that can simulate the entire life cycle of a product or process. *Virtualisation* of production and consumption changes sectors and reduces environmental impact by moving economic activities online, especially if the digital technologies are energy-efficient and circular. Using digital technologies, *systems management* can cope with an increasing complexity while optimising operations, for example in smart cities. Lastly, digital *information and communication* technologies enable new levels of interaction. Data and data analysis will be the backbone of the green and digital transitions. Modern information and communication technologies, such as sensors, can help to collect and disseminate such data.

See also Chapter 5 on page 16 >>

**Digital technologies can support the green transition in different ways depending on the sector.** In the *agriculture sector*, better systems management can increase agricultural productivity through more accurate applications of feed, water, energy, fertilizers, and pesticides. In the *buildings and construction sector*, virtualisation can entirely eliminate certain space needs, for example through remote meetings or online shopping. In the *energy sector*, digital information and communication technologies facilitate communication between stakeholders and technical elements in an increasingly complex energy system. In *energy-intensive industries*, monitoring and tracking provides information on the parts and materials used in products to enable better maintenance, increased recycling, and reuse. Lastly, in the *mobility and transport sector*, simulation and forecasting can help optimise traffic flows to limit congestion and pollution. For each of the five sectors, the study presents two examples of specific solutions that link the green and digital transitions (i.e. green-digital solutions).

See also Chapter 6 on page 21 >>

Successfully managing the green and digital ‘twin’ transitions is the cornerstone for delivering a sustainable, fair, and competitive future.

**Russia’s military aggression against Ukraine has a strong impact on the green and digital transitions in all sectors covered in this study.** It is driving up food prices and threatening food security globally. It is leading to price increases and supply issues in the construction sector. It is reinforcing the change in energy security, calling for a stronger emphasis on energy independence and the safety of critical energy infrastructures. It is threatening gas-reliant energy-intensive industries with a potential halt of Russian gas exports. The military aggression is also increasing the cost of transport. The war could either accelerate the twin transitions by reducing dependency on Russian energy and material imports, or, it could

A just transition is crucial for widespread acceptance of green-digital solutions. Social awareness could avoid rebound effects, such as increased consumption as a result of efficiency gains and cost savings.

reduce the financing available to invest in the twin transitions due to defence investments and increased energy and food prices.

**While green and digital technologies will play a major role in the 'green transition', their implementation will depend on several economic, social, and political factors**. The twin transitions depend on a range of contextual factors that must be carefully considered. *Economic factors* include the costs of the twin transitions, the economic opportunities created by the twin transitions, the shift of jobs between growing and declining sectors, and the financing of the necessary investments. *Social factors* include acceptance, fairness, and behavioural change. *Political factors* include regulatory frameworks, standards and geopolitical aspects. The green and digital technologies necessary for the twin transitions can only be rolled out at scale if these contextual factors are managed appropriately.

See also Chapter 4 on page 11 >>

**This study establishes key requirements that need to be met to succeed in managing the twin transitions.** There are key social, technological, environmental, economic, and political barriers to overcome for the twin transitions. The twin transitions rely on interoperable technologies and the willingness to share data, which is why data privacy and security are crucial. Research ecosystems are important for the development and improvement of technologies. Without an adequate infrastructure, the roll out of new technologies cannot take place. Moreover, societal commitment to the need to change is fundamental for the success of the twin transitions. A just transition is crucial for widespread acceptance of green-digital solutions. Social awareness could avoid rebound effects, such as increased consumption as a result of efficiency gains and cost savings. The labour force requires new skills for the green and digital transitions, while markets should internalise the environmental costs of products. The presence of small- and medium-sized companies is essential for a competitive and innovative market of green-digital solutions. Finally, there is a need for policy coherence and increased investment into green-digital solutions, and the financing of innovation that reduces their environmental footprint. The following table presents these key requirements in more detail.

See also Chapter 7 on page 73 >>

**This study is the result of an eight-month participatory foresight process.** It takes the goals of the twin transitions as a starting point and examines technologies that could be developed and combined to get there. It also looks at the obstacles that might arise. This foresight process included a thorough literature review and continuous expert engagement in discussions and workshops. The results of this process have been validated through further workshops and conferences with a wide range of stakeholders from academia, civil society, public administration, and industry. In total, over 200 experts participated in the foresight process.

## Key requirements for the twin transition

| | |
|---|---|
| **Social** | **Ensure just transitions**<br>Society at large has to benefit from the twin transitions, for example by overcoming the digital divide and avoiding subsidies that do not benefit vulnerable groups of society.<br>**Increase societal commitment to the need to change**<br>Awareness and inclusive societal debates are needed to change common behaviours and values in favour of the twin transitions.<br>**Ensure privacy and ethical use of technology**<br>Create willingness to share data by protecting privacy through anonymization, limiting data collection to strictly necessary data, and empowering end users to understand how their data is used and benefit from it. |
| **Technological** | **Implement innovation infrastructure**<br>Research ecosystems are needed for the development and improvement of green-digital technologies. Furthermore, enabling technologies require an adequate infrastructure for their roll out.<br>**Build a coherent and reliable technology ecosystem**<br>Technology interoperability and the reliability of technologies will be crucial in an increasingly complex and interconnected system.<br>**Ensure data availability and security**<br>Data governance regulations must ensure clarity about who owns data and who has access to it. It must protect stakeholders and make sure that data is secure. |
| **Environmental** | **Avoid rebound effects**<br>Awareness raising, adequate governance systems, and market mechanisms that avoid market failures can mitigate unintended side effects of the implementation of green-digital solutions.<br>**Reduce the environmental footprint of green-digital technologies**<br>Resource consumption, emissions, and pollution of green-digital solutions have to be reduced throughout their entire life cycle. |
| **Economic** | **Create enabling markets**<br>Markets have to internalise the environmental costs of products to give long-term investment incentives for green-digital solutions and overcome stranded assets and sunk costs.<br>**Ensure diversity of market players**<br>The market for green-digital solutions should not be dominated by a few big players but should be a healthy ecosystem that also includes small- and medium-sized companies and start-ups to ensure competition and innovation.<br>**Equip labour with relevant skills**<br>Education and training has to ensure that labour is equipped with the skills they need to handle green-digital technologies and that a sufficient amount of experts are available to drive innovation. |
| **Political** | **Implement adequate standards**<br>Standards should ensure the interoperability of different technologies, keep entry barriers low, and avoid that technologies become obsolete before their end of life.<br>**Ensure policy coherence**<br>Regulations should be consistent in the long-term across different government levels and regions to have a stable framework that facilitates cooperation and innovation while avoiding unnecessary complexity.<br>**Channel investments into green-digital solutions**<br>Regulations have to unlock public and private investments into green-digital solutions. |

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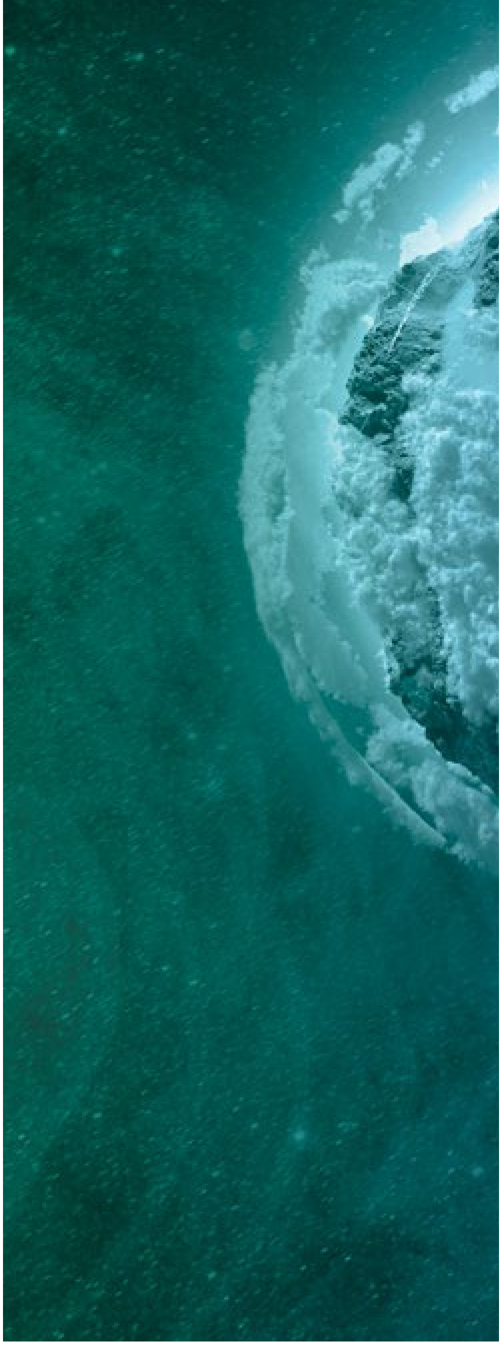

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# CONTENTS

# 1. INTRODUCTION

**We are living in a time of multiple crises that challenge our worldview.** The European Union and the rest of the world has been experiencing disruptions that were once considered to be at the edge of plausibility. The ongoing COVID-19 pandemic is still disrupting the normality of life as we know it. The Russian invasion of Ukraine, the military aggression, and hybrid threats raise geopolitical questions about the post-World War II world order. Europe has experienced multiple extreme weather events, including from devastating floods, wildfires, and violent storms at an unprecedented scale. They make it clearer than ever that the impacts of the climate crisis also affect Europeans. The world is showing its vulnerabilities.[1]

1 See European Commission (2020a), European Commission and Copernicus Climate Change Service (2022)

**The COVID-19 pandemic is still affecting the economy of the European Union.** The recovery of the world economy from the pandemic is fragile, with many countries facing economic burdens due to high healthcare costs and investment in crisis responses. Occasional local lockdowns are disrupting global supply chains, with many shortages of products and components. The pandemic is also impacting logistics capacities and challenging the integrated, efficiency-optimised global supply chains. Commodity markets are in turmoil, mainly affecting countries with low purchasing power, but also commodity-intensive industries, such as energy-intensive industries and construction. At the same time, the pandemic has demonstrated the adaptability of societies in such challenging times. For example, digital technologies supported and facilitated the rapid adaptation to new challenges.

**The Russian war of aggression against Ukraine highlights the need for a transition towards sustainable energy.** Dependence on fossil fuels has become a geopolitical issue with implications for the strategic autonomy of several Member States of the European Union. It calls for an accelerated energy transition towards renewable energy sources, for increased energy efficiency and savings, and for a diversification of energy imports already in the short term. This ambition is at the heart of the REPowerEU plan.[2] Many countries risk food shortages because of the expected loss of Ukrainian crop yields due to the war, and loss of Russian crop imports due to boycotts. It has triggered a rethinking of European food and energy security and sustainability, for example with respect to livestock feed imports and food production capacity.[3]

**The green transition is necessary to mitigate the consequences of climate change and environmental degradation, and it can decrease the European Union's dependence on energy imports.** Scientific evidence about the destructive impacts of the climate crisis points to a bleak long-term outlook and calls for bold, immediate action.[4] Climate mitigation and adaptation policies have been institutionalised at the international level with the

2 European Commission (2022a)
3 See discussion on open strategic autonomy, e.g. Joint Research Centre (2021a), European Commission (2021a)
4 IPCC (2022)

This study explores how the green and digital transitions can reinforce each other.

The focus is on how digital technologies can contribute to fighting climate change and environmental degradation.

2015 Paris Agreement,[5] and at the European level with the European Green Deal[6] and its related policy initiatives. At the same time, emerging environmental movements such as 'Fridays for Future' are gaining attention within society. The green transition is a term that refers to making the European Union more sustainable by reducing environmental impacts, modernising its economy, and increasing its autonomy by becoming less dependent on energy and raw material imports.[7]

**The digital transition is an ongoing process that continues to transform the way we live.** The digital transition has the potential to further transform dominant practices in the economy and in society.[8] For example, digitalisation changes how people communicate, receive information, or learn. It changes how businesses create value and how supply chains are managed. Unlike the green transition, the digital transition is not primarily being pushed by necessity, but is driven by the vast new opportunities it creates. It helps to solve crucial challenges of today's society. For example, it can facilitate the management of more complex energy grids, thereby enabling higher shares of renewable energy. However, the digital transition also poses its own challenges, such as the 'digital divide' between those that have the means to benefit from it and those that do not. This is why European policy has made it a priority to shape Europe's digital future in a way that aims to benefit everyone.[9]

**This study explores how the green and digital transitions can reinforce each other.** The focus is on how digital technologies can contribute to fighting climate change and environmental degradation. The goal is to gain a better understanding of the variety of interlinkages between the digital and green transitions, their synergies, tension points, and unintended effects. This study takes a long-term perspective of the green and digital - the twin - transitions up to 2050. It looks at the technologies required for these twin transitions and how they interact. This study also looks at social, economic, and political contextual factors that will play a role in successfully implementing the twin transitions.

**The European Commission's 2022 Strategic Foresight Report has been informed by this study.** The foresight exercise of this study underpins the Commission Communication '*2022 Strategic Foresight Report: Twinning the green and digital transitions in the new geopolitical context*'[10]. Building on a close collaboration, the Communication combines the policy implications of this study with additional insights from across the European Commission.

**The overarching research question of this study is: "How can the green and digital transitions reinforce each other?"** To answer such an overarching research question and cover the necessary scope, the report breaks it down into sub-questions. The structure of this study mirrors these sub-questions.

5 UN (2015a)
6 European Commission (2019a)
7 Joint Research Centre (2021a)
8 European Commission (2020b)
9 European Commission (2022b)
10 COM(2022) 289

# 2. RESEARCH APPROACH

**This study summarises the insights of an eight-month foresight process.**
The foresight process included a thorough literature review and expert engagement. The results of this process were validated through eleven workshops with the participation of a wide range of stakeholders from academia, civil society, public administration, and industry. In total, over 200 participants were involved in the process. The foresight process underlying this study enabled a transdisciplinary learning process, bringing together insights from different backgrounds. Multiple viewpoints were taken on board to better understand prospects and impacts of the interlinkages of the digital and green transitions.

**Our assessment takes a long-term perspective on how to reach a climate-neutral Europe by 2050.** The European Green Deal proposes ambitious targets and measures for a sustainable European Union. It encompasses measures in various areas, such as pollution, energy efficiency, biodiversity, and food production. One of the key objectives is to achieve climate neutrality in the European Union by 2050, and the time horizon of this study is aligned with this goal.[11]

**This analysis includes five sectors that are deemed important for the green transition.** To keep the focus on the most relevant parts of the European Union's economy, this study focuses on the most polluting sectors. The sectors included are: agriculture, buildings and construction, energy, energy-intensive industries, and transport and mobility.

**Contextual factors are a crucial horizontal issue for the green and digital transitions.** Specific contexts determine how any theoretical change will play out in real life. This is why contextual factors will be crucial for the European Union to implement the technological solutions needed for the twin transitions. This study also looks into these factors and how they influence the potential uptake of green-digital solutions. The authors have divided contextual factors into economic, social, and political factors. Paired with an analysis of green-digital technologies, key requirements for successful twin transitions have been identified.

**Digital technologies provide solutions that can be applied across different sectors.** This study provides an overview of the transformative potential of digital technologies in the short- and long-term. Furthermore, it presents functions enabled by digital technologies and their relevance for the green transition. Exploring combinations of digital technologies with green ones provides insights into innovative solutions. These areas of cross-sector innovation plot out where digital and green technologies provide future synergies and highlight avenues for new research areas.

**This study backcasts how green and digital technologies can help achieve the goals of the twin transitions.** The political commitment of a net-zero carbon Europe by 2050 is used as a normative guiding principle to identify green-digital technology innovation timelines. This is a goal-oriented backcasting approach[12] that looks at sector-specific green technology roadmaps of emerging and evolving technologies from today up to 2050. Furthermore, this study assesses the drivers and megatrends[13] that influence the different sectors.

**Ten case studies serve as concrete examples of green-digital solutions.** The case studies were chosen to show a variety of different possible green-digital solutions and describe how their successful implementation by 2050 could support the green transition. This report does not asses the likelihood of such a successful implementation. The green-digital solutions in the case studies address different interaction types, tackle various value creation phases, and raise a spectrum of social, institutional, and ethical issues that require political attention. The ten case studies look at practical considerations and examine future perspectives and transition dynamics for specific green-digital solutions. Each case study also presents an analysis of environmental, economic, and social sustainability. Future snapshots provide an idea of how green and digital technologies might play out in 2050, by using a 'what if' perspective. It should be noted that these are examples and successful twin transitions will require a much larger portfolio of solutions.

**Key requirements for successful twin transitions were identified through anticipation of future challenges.** The case studies look into the potential challenges of rolling out green-digital solutions. A systematic analysis of these challenges provides strategic insights for action to enable the green and digital transitions. These insights are laid out in the key requirements presented in Chapter 7.

11 European Commission (2019a)
12 Bibri (2018)
13 Joint Research Centre (2022a)

# 3. GOALS OF THE TWIN TRANSITIONS

**The green and digital transitions are two main trends that will shape the future of the European Union.**

Both are at the top of the political agenda; therefore it is imperative to consider how these two trends will interact and what the possible tension points are. The term 'twin transitions' refers not only to two concurrent transformational trends (the green and digital transitions); the term also refers to uniting the two transitions, which could accelerate necessary changes and bring societies closer to the level of transformation needed. To succeed with the green and digital transitions, a better understanding of the possibilities to link them is fundamental, especially when it comes to knowing what must be done most urgently.

## The green transition

**The climate crisis and the loss of biodiversity are clearly linked to human activities.** The consequences of this crisis pose an existential threat globally.[14] Some of these changes are already felt today and will be felt even more in the future. With the active engagement of the European Union, international commitments for climate action and sustainability have been made, such as the Paris Agreement and the UN's Sustainable Development Goals.[15] Efforts continue, and a majority of countries have pledged to reduce greenhouse gas emissions, to help those who are already affected to adapt to climate change, and to provide financing for action.[16] It is a call for immediate action to avert a climate catastrophe.[17]

**The way out lies in a swift and inclusive transition to environmentally sustainable lifestyles and economies.** The green transition refers to the fundamental shift in production and consumption patterns to allow us to live within planetary boundaries.[18] It means mitigating climate change by introducing climate-friendly lifestyles and taking environmental costs into account. It includes addressing the loss of biodiversity[19] and its multiple ecosystem services that are crucial to healthy living and to resilient societies.[20] At the same time, the green transition must be fair and inclusive.

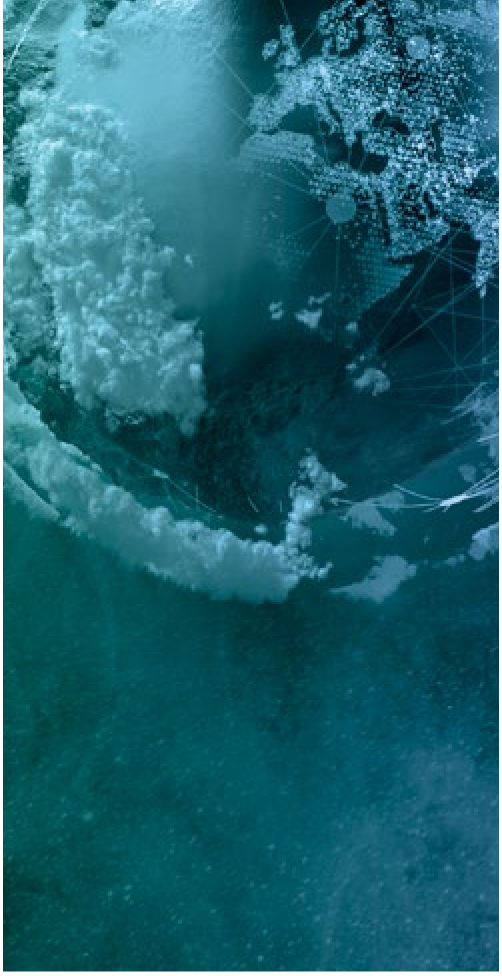
**The European Union is a leader in climate and environmental action.** The European Union was the first global player to present a long-term vision that aims for climate neutrality by 2050.[21] In 2019, the European Commission presented the European Green Deal, which sets out a new sustainable growth strategy and addresses some of the most important environmental and climate-related challenges. It sets the goal of transforming the European Union into a modern, circular, resource-efficient, and competitive economy, in line with the goals of competitive sustainability[22].[23] Following this blueprint, the European Union has adopted a European Climate Law[24] to establish the legally binding target of reaching net zero greenhouse gas emissions in the European Union by 2050. The European Commission has also proposed a legislative package to reach an increased climate ambition by 2030.[25] Furthermore, the Commission has adopted several strategies in support of its environmental targets, such as the Farm to Fork Strategy, the Sustainable Blue Economy Strategy, the Climate Adaptation Strategy, and the New Action Plan on Circular Economy.[26] The goals of the green transition have been maintained while responding to the COVID-19 pandemic and the Russian invasion of Ukraine through the Recovery and Resilience Facility[27] and REPowerEU[28].

**The green transition is an opportunity to unlock economic and societal benefits.** Green technologies can provide economic and environmental win-win situations for both societies and economies. The green transition is an opportunity to transform today's unsustainable activities towards a just future. One that overcomes societal challenges such as growing disparities, and opens up avenues for competitive advantages of economic activities that provide solutions without exceeding the planetary boundaries.

## The digital transition

**The digital transition is an ongoing process that is shaping the future of societies and economies.** The changes triggered by the digital

14 IPCC (2021), World Economic Forum (2021a), IPCC (2022)
15 UN (2015a), UN (2015b)
16 UN (2021a)
17 UN (2021b)
18 Rockström et al. (2009)
19 Mace et al. (2018)
20 Vysna et al. (2021).
21 European Commission (2018a)
22 The ability for the EU's economy, its industrial ecosystems and companies to move towards a sustainable economic model, enabled by digital and clean technologies, making Europe a transformational frontrunner and a competitive first-mover at global level. See European Commission (2019a).
23 European Commission (2019a)
24 European Union (2021)
25 European Commission (2021b)
26 European Commission (2020c), European Commission (2021c), European Commission (2021d), European Commission (2020d)
27 European Commission (2022c)
28 European Commission (2022a)



transition have the potential to increase prosperity and solve many societal challenges. At the same time, increasing digitalisation entails many risks, for example social disruptions and polarisation of opinions, increasing inequality, security risks, or mis- and disinformation.[29] Today, the European Union faces risks stemming from its dependence on non-European technologies and service suppliers, and globally there is a reliance on a few big technology companies.[30] Much of the data produced in the European Union is stored and processed elsewhere, which poses both a security risk and a potential loss of the value of European data. At the same time, the reach of digital innovation is expanding and could transform our society and economy even further.[31] Emerging technologies such as advanced robotics, automated mobility, or digitally-enabled biotechnologies are crossing digital, physical, and biological spheres.

**To make the digital transition a success, the European Union needs to establish a secure, trustworthy, and resilient digital infrastructure.** It needs a strong digital education and training ecosystem, so that the European Union's citizens and workforce are fully equipped for the digital age. The digital transition requires policies that harness the benefits of technologies, reduce the negative impacts of technological change, and avoid falling behind global competitors. The European Commission has presented a strategy to harness the benefits of the digital transition. The Digital Decade Compass outlines targets for 2030 and sets a path towards empowering "people and businesses to seize a human-centred, sustainable, and more prosperous digital future".[32] Furthermore, the European data strategy[33] aims to take the opportunity of increased data availability to address individual needs and create value for society and the economy. These initiatives aim to introduce a fully functioning Digital Single Market, an efficient European Cloud, global leadership in trustworthy Artificial Intelligence, and a secure digital identity for all. In this way, the European Union aims to make sure that digital tools enable citizens' rights and freedoms and strengthen democracies.

### The importance of linking the green and digital transitions

**While both transitions will transform our societies and economies, they are different in nature and in their dynamics.** The green transition is driven by the need to reach the aims of climate neutrality and sustainability, and to reach them quickly. It will not happen on its own and requires a political and societal push. In contrast, the digital transition is an ongoing process of technology-driven change, with the private sector as one of the primary drivers. Therefore, steering and support are important to make sure that the digital transition becomes a powerful instrument for achieving a fair and just green transition.

**In many areas, the green and digital transitions can reinforce each other, but they do not necessarily always align.** Digital technologies can be key enablers for reaching the European Green Deal objectives. For example, cities are responsible for approximately 75 % of global

29 European Commission (2020b)
30 European Commission (2020e), Joint Research Centre (2021a)
31 European Commission (2020b)
32 European Commission (2021e)
33 European Commission (2020f)

$CO_2$ emissions.[34] Smart cities and communities[35] are possible solutions to reduce these emissions and show how the twin transitions can take place in a holistic, systemic manner. Information and Communication Technology-based solutions could reduce commuting by 15-20 % and cut greenhouse gas emissions by 10-15 %,[36] while local Digital Twins[37] could significantly improve cities' ability to simulate or model the impact of policies. At the same time, there are areas where the two transitions can hamper each other. For example, the expansion of digital infrastructure will need to be kept in line with the aims of the green transition, particularly regarding the energy consumption and the environmental footprint of such digital infrastructure.

**Taking an integrated approach to the challenges of reaching successful twin transitions is essential to avoid the traps of pushing two agendas separately.** The green and digital transitions run in parallel, but linking them could allow us to benefit from synergies and manage the risks. Given the wide-reaching nature of these transitions, it is essential to examine their complexity and possible outcomes and consequences of their interactions. The future will be defined by how much of a success we make of the green and the digital transitions. It is therefore essential to optimise our efforts by linking the transitions effectively.

Taking an integrated approach to the challenges of reaching successful twin transitions is essential to avoid the traps of pushing two agendas separately. The green and digital transitions run in parallel, but linking them could allow us to benefit from synergies and manage the risks.

34 Wang and Moriarty (2019)
35 A smart city or community offers digitally enabled services that contribute to a better quality of life and improve conditions for business. These smart services can help to better manage resources like energy or water, to monitor and reduce local traffic and pollution, or to light and heat buildings more sustainably.
36 McKinsey Global Institute (2018)
37 Digital Twins are virtual representations of the real world that allow for example a more efficient development of innovations or an optimisation of processes. See Joint Research Centre (2020a).

# 4. CONTEXTUAL FACTORS FOR THE TWIN TRANSITIONS

**The green and digital transitions are about profound changes in our way of life.**

The factors influencing the green and digital transitions are multifaceted and often interconnected. Their influence is difficult to predict. As in past transitions, technology will play a role, but it is unlikely that the changes needed to succeed with the twin transitions will be solely technology-driven. For example, massive changes in behaviour and social norms are needed for many innovations, such as moving from owning a car to car-sharing. How any theoretical change plays out in real life is heavily dependent on the specific context (for example personal practicality, cost, fairness). There are many contextual factors that will determine the outcomes of the twin transitions.

**Many enabling technologies that would support a green transition are close to being ready, but their widespread implementation depends on contextual factors.** The technologies still face significant challenges to reach wide deployment and the uptake needed to unlock their full potential for the twin transitions.[38] Such factors are of particular importance when acknowledging the speed with which these technologies and solutions need to be put in place. There are a variety of existing frameworks to present the drivers and factors of transitions more systematically beyond the technology dimension.[39] The STEEP framework is often used in foresight and this study draws on this framework.[40] The acronym covers factors in the categories of: society, technology, environment, economy, and politics.

**This study has evaluated the role of contextual factors relevant for the green and digital transitions.** It applies the STEEP framework to look at these contextual factors in a holistic and systematic manner. Factors related to technology and environment are central to this study and are assessed in detail in chapters 5 and 6. This chapter (Chapter 4) focuses on the remaining categories of the STEEP framework. Social issues include social acceptance, behavioural change, and a just and fair transition. Economic issues include markets, supply chains, infrastructure, financing, human capital, and innovation capacity. Lastly, political issues include policymaking, governance systems, and the regulatory environment.

## Social factors

**The twin transitions require the buy-in and support of people.** Citizens will not only feel the effects of the transitions, they are for a large part the key players in them. European citizens are well aware that climate change is a serious problem and agree with the target of a climate-neutral European economy by 2050.[41] At the same time, the actions to meet this goal will take many forms, and a lack of social acceptance of them has the potential to be a serious barrier. Acceptance is the precondition for societal commitment and behavioural change, and both commitment and change are required in many areas for the green and digital transitions. For this study, social acceptance is deemed to cover three dimensions, namely socio-political, market, and community acceptance. Socio-political acceptance indicates that citizens and policymakers need to be convinced and have the will to act. Market acceptance refers to the openness to adopt new technologies, or the willingness-to-pay of businesses, consumers, and investors. Finally, community acceptance is the acceptance of local communities regarding new technologies and innovations. Community acceptance often depends on whether communities feel that they can trust the information and the intentions behind proposed changes.[42] The openness of the decision-making process, the involvement of all stakeholders, and a perception of fair sharing of costs and benefits are crucial factors for promoting community acceptance.

38 McKinsey & Company (2021a)
39 Geels (2010), Geels (2011), Köhler et al. (2019)
40 Hammoud and Nash (2014)
41 European Commission (2021f)
42 Wüstenhagen, Wolsink, and Burer (2007)

Acceptance is the precondition for societal commitment and behavioural change, and both commitment and change are required in many areas for the green and digital transitions.

**A central challenge for the twin transitions is to make sure that the transitions are fair, inclusive, and just.** This means protecting the people that may be adversely affected by the necessary shifts. It also means making the benefits of the twin transitions accessible to all to ensure social justice.[43] A perception of fairness and transparency is a significant factor in social acceptance. For example, a successful digital transition requires that connectivity is accessible to all, regardless of location, income, education-level, or age. The just transition also encompasses ethical concerns related to the twin transitions. For example, there are ethical concerns about the use of Artificial Intelligence, such as a lack of transparency, its capacity to replicate biases, or whether it can be held accountable for decisions in the public sector.[44]

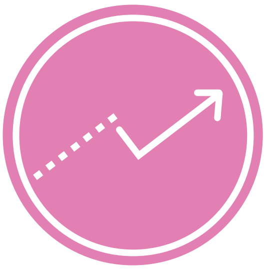
**Technology acceptance is a determining factor for successful green-digital solutions.** Looking at the digital transition and at the information society, researchers have examined technology acceptance to analyse and predict the potential acceptance or rejection of a technology.[45] The key variables identified are whether potential users believe that a technology will improve their lives and require little effort to use. These assessments of the potential user are in turn affected by the user's demographics, personality, and past experiences. The willingness of people to take up and learn new methods and technologies may also depend on their habits, lifestyle, culture and community. Such factors are essential to consider when assessing workable solutions and policies for the twin transitions.

**Solutions and policies need to take possible unintended consequences into account.** Unintended or unexpected consequences of new solutions or technologies are also referred to as 'rebound effects'.[46] Rebound effects are for example when reduced energy costs due to energy efficiency improvements lead to increased consumption in other areas. Or when people use electric vehicles more extensively due to lower operating costs. These kinds of behavioural effects need to be considered when designing technologies and policies at the level of the citizen and user, but also at the wider level of society. Otherwise, there is a risk of cancelling out savings on emissions in one area with increased emissions in another. Digital technologies have the potential to help address this issue by increasing citizens' awareness of their behaviour and of available alternatives,[47] or by changing their role in the decision-making process, for example through automation.

**The twin transitions call for high ambitions that are in the interest of society.** Societies all over the world are working on formulating ambitions and adapting norms along the lines of sustainability and positive change. The shift towards a sharing economy, or the de-coupling of economic growth from resource consumption and emissions, are two examples of

43 ETUC (2016), WWF (2019)
44 Rodrigues (2020), Joint Research Centre (2018a)
45 Lee, Kozar, and Larsen (2003), Marangunić and Granić (2015)
46 European Environment Agency (2019), Vivanco et al. (2016)
47 EIT Digital (2022)

these ambitions. The shifts in behaviour that can help to realise the twin transitions can be achieved in many ways. For example, the narrative of the twin transitions being necessary and in everyone's best interests is a crucial factor to mobilise society. Clear evidence-based communication of this narrative can help to overcome misperceptions, such as the feeling that the twin transitions come at the cost of well-being.



## Economic factors

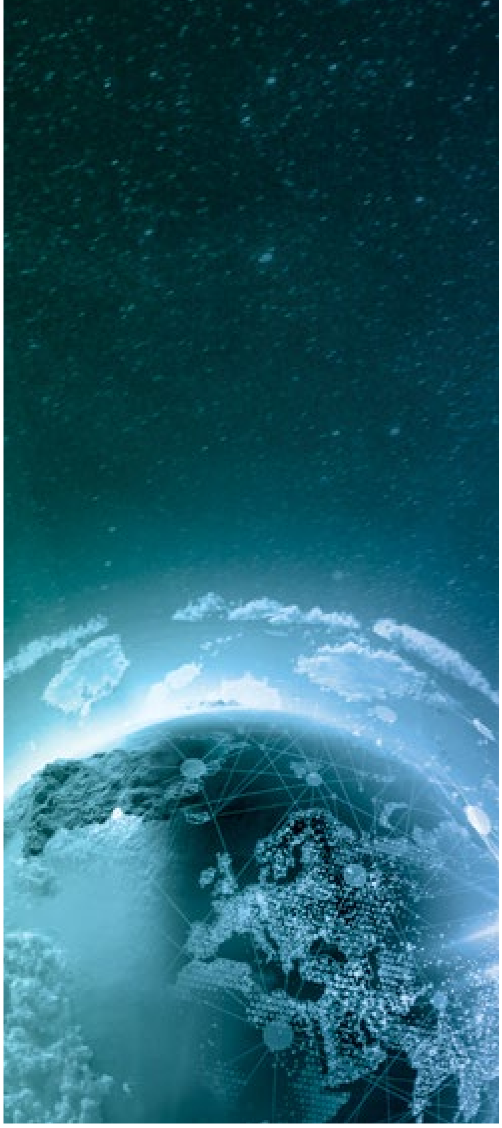
**The costs associated with the twin transitions can be a significant barrier to change.** In many areas, there are significant sunk costs[48] associated with the transformation of sectors. For example, businesses may be reluctant to abandon the infrastructure, or the methods (e.g. established procedures) that they have invested in. These create path dependencies and lock-ins, which give existing technologies an advantage over new technologies. To move beyond this path dependency, financing of the changes needed in the economy should be linked to the long-term potential in the context of the twin transitions.[49]

**Technological innovation can create new economic opportunities.** As the transitions progress, increasing returns from economies of scale and scope[50] for green and digital technologies could create new markets.[51] With green and digital technologies becoming more widespread, they can open up new development paths and lead to more innovation. Industry networks can expand activities around a green-digital solution through supply chains, infrastructure, and complementary technologies. This expansion can lead to new business opportunities.[52] The expected shifts between sectors because of the twin transitions indicate how the economy could adapt. For example, the electrification of the economy is expected to generate up to 2.0 % additional jobs in the electricity sector.[53]

**The impact of the twin transitions on employment and skills needs are also central issues.**[54] In the European Union, the green transition is estimated to lead to a net increase of up to 884,000 more jobs by 2030.[55] Each economic sector will be impacted differently, and many of the new technologies and methods require skills and labour that is not readily available in today's economy. Examples of skill gaps are digital skills, or building renovation skills. Some sectors may lose jobs (e.g. coal, oil and gas) and some regions of the European Union will be more affected than others. Reskilling is therefore an essential factor to bring workers into new or changing sectors.

**Financing is an essential steppingstone for the twin transitions.** Financing can be the determining factor for whether green-digital solutions see the light of day. Many of the technologies and solutions needed have reached 'technological readiness', but will need various complimentary funding sources and mechanisms to succeed. Investments are being directed towards the green and digital economy today, but much capital still flows into the old economy. This is in part due to investment incentives that follow market prices, which do not account for social and environmental long-term costs.[56] Sustainable finance has the potential to drive the green transition. The EU taxonomy for sustainable activities acknowledges this fact and provides definitions and standards for environmentally sustainable economic activities.[57]

48 Sunk costs are past investments in existing methods and infrastructure that is to be decommissioned before the end of its lifetime.
49 Joint Research Centre (2021b)
50 Economies of scale is when the average costs per unit of output decreases with the increase in the scale or magnitude of the output being produced. Economies of scope exist when it is cheaper to produce two products together than to produce them separately.
51 Klitkou et al. (2015)
52 European Environment Agency (2019)
53 Joint Research Centre (2021b)
54 Bruegel (2017)
55 Joint Research Centre (2021b)
56 European Environment Agency (2019)
57 European Commission (2021g)



## Political factors

**Policymakers and governing institutions are main players in the green transition.** Policies and political targets are strong drivers of the progress towards net-zero emissions and environmental protection. Policies, standards, and regulations are influencing the development and use of digital tools and technologies, and have the potential to do so even more in the future. As digital tools develop and expand, the political frameworks need to keep up to ensure that citizens and businesses can benefit from them. The European Commission's sector inquiry into the Internet of Things and the role of competition policy are examples of how political frameworks are being adapted to new developments.[58] The political factors of transitions involve not only policymakers and governments, but also local organisations, non-governmental organisations, and the private sector.[59]

**The global and geopolitical dimension of the twin transitions is of the utmost importance.** Global cooperation is necessary for achieving the goals of the green transition and, to a slightly lesser degree, of the digital transition.[60] Similarly, the twin transitions will be influenced by global developments. As examined in the context of the European Union's open strategic autonomy, there are many factors to consider, for example dependence on raw materials.[61] The twin transitions are an opportunity to diversify and strengthen Europe's energy sources, and to build a higher capacity and independence in data storage and processing in Europe. The aspect of energy independence plays a particularly important role when considering Russia's military aggression, which has provided yet another reason to accelerate the phase-out of fossil fuels. Moving forward it will be equally important to build and maintain resilient critical infrastructure, including digital infrastructure.

58 European Commission (2022d)
59 McKinsey & Company (2021a)
60 Joint Research Centre (2021a)
61 Joint Research Centre (2021a)

# 5. DIGITAL TECHNOLOGIES IN THE CONTEXT OF THE TWIN TRANSITIONS

**The digital transition is an ongoing process that influences much of human activity.**

Digital technologies are essential to everyday life in many societies, and the global economy relies on digital technologies in many ways. Across almost all fields, research and development draws on digital technologies for analysis, mapping, and much more. The term 'digital transition' is used here in this broad sense, as digital technologies that affect politics, businesses, habits, and social issues.[62] The term digitisation refers to the process of converting analogue information into digital form, while digitalisation is the integration of digital technology and infrastructures (e.g. into business, governance, or education).[63]

62 Reis et al. (2018)
63 Autio (2017)

Solutions and innovations may lie in the combination of digital technologies. Digital technologies are not independent of one another, there are several connections and interdependencies between them.

**The digital economy is crucial for the competitiveness of the European Union and can help to drive the green economy.** There is a strong political commitment to deliver on Europe's 'digital decade' by harnessing the full potential of the digital transition. However, new policies will be required to steer this process and align it with the goals of the green transition. A thriving digital economy is instrumental not only for the competitiveness of the European Union, but also for the green transition. Digital technologies can be an enabler for the transition towards a green economy, which is sustainable, fair, and inclusive. It is essential to keep building on the global momentum and rethinking policies for a digital and green economy.[64]

## Digital technologies and their development

**The digital technology landscape has been rapidly evolving over the past three decades.** The main drivers of the digital transformation are companies, particularly in the computing and internet sectors. These companies are mostly located outside of the European Union. Their growth and development are, to a large extent, driven by advancements in computing power, data storage capacity, and algorithms. The evolution of digital technologies is driven on one the hand by a technology push to improve the performance of electronics and on the other hand by the demand from users for digital technologies.[65] To indicate the scope of digital technologies considered in this study, an overview of key digital technologies can be found in Appendix 1.

**Emerging digital technologies have a lot of future potential for the green transition.** Looking towards 2050, DNA-based digital data storage offers the possibility of storing data much more efficiently, with information densities ten million times higher than the storage options available today.[66] For the green transition, this efficiency coupled with lower cooling requirements of DNA-based data storage results in a much lower energy consumption. Quantum computing and novel approaches to computing promise computing power far beyond the capabilities of current computers. This leap in computational power opens up new possibilities and could allow for the optimisation of many current practices. It can, for example, compute and simulate molecular behaviour to find viable options to create next generation batteries or more efficient processes to produce nitrogen-based fertilisers, which are needed for the agriculture sector.[67] Quantum computing can provide simulations of large complex molecules, which could, for example, lead to discoveries of new and more efficient catalysts for carbon capture.[68] The twin transitions can also help European Union Member States to meet their commitments to develop climate resilient and low-carbon health systems.

**Solutions and innovations may lie in the combination of digital technologies.** Digital technologies are not independent of one another, there are several connections and interdependencies between them. In fact, the combination of different digital technologies and tools could in itself be an impactful innovation for greening. The Internet of

64 Nordic Council of Ministers (2021)
65 AENEAS, ARTEMIS-IA, and EPOSS (2021)
66 European Innovation Council (2022)
67 Boston Consulting Group (2020)
68 World Economic Forum Annual Meeting 2019 (2019), TechUK (2021), Boston Consulting Group (2020)

Things is an example of the combination of several different digital technologies with breakthrough potential. Here, devices, sensors, and wearables have been adapted following the mass usage of smartphones and other devices that are now used as a gateway to connect to the internet. This change is fuelling the uptake of Internet of Things-connected devices, which is projected to exceed 75 billion already by 2025.[69] The Internet of Things thus relies on smartphones, geolocation technology, and constant and secure internet connectivity. It is therefore important to look not only at emerging digital technologies, but also at new combinations and applications of the existing digital technologies available to us already today.

**Contextual factors such as regulation, trust, and behaviour can determine the future of digital technologies.** Policies, legislation, and regulations are being put in place to ensure data protection, and digital platforms are receiving more oversight from governments in many countries. Data sharing and analysis can be enabled by standards for data collection and processing. Such political measures are needed to help build a digital landscape that society can trust and that reflects their fundamental values. Secure data governance is also vital to prevent cybercrime and cyberattacks. Social factors also need to be considered to assess the future paths of digital technologies. Examples of these factors include those described in Chapter 4, as well as hesitation towards digital technologies due to a lack of knowledge or trust from users, or willing changes in human behaviour. A similar hesitation can exist for businesses, where a lack of knowledge can often mean that the benefits of digital solutions are not understood. Relevant geopolitical factors include the stability of global supply chains, and access to the components and materials needed to build digital technology and infrastructure.

**Digital technologies have to be adapted to be useful in a variety of different circumstances.** The potential contribution of digital technologies to the green transition depends on the context and the maturity of the technology. Digital technologies will need to be adapted to fit the setting in which they are applied, considering for example the country, region, demography, or skill level of users. The digital divide and gaps in access and connectivity are hurdles to be overcome. For example, providing assistance for improving digital literacy and support with digital tools available at the community level would facilitate a better use of digital technologies across society.

## Functions of digital technologies in enabling the green transition

**Digital technologies provide functions that can catalyse the green transition.** To understand in practical terms which roles digital technologies could play to facilitate the green transition, Figure 1 outlines typical functions of digital systems and their impact on the environment. The focus here is on the basic capabilities with which digital technologies could support or speed up the green transition.[70] The overview is non-exhaustive, given the ongoing rapid development of digital technologies. There are synergies, overlaps, and combinations of capabilities between the different functions. As an example, cybersecurity and the reliability of the digital systems is fundamental to all of these functionalities.

69 Alam (2018)
70 WBGU (2019), Deloitte (2020), AENEAS, ARTEMIS-IA, and EPOSS (2021), IIASA (2019)

**Figure 1: Functions of digital technologies**

| | |
|---|---|
| **Monitoring and tracking** | **Monitoring and tracking can provide precise knowledge in real-time**<br>Digital technologies enable the monitoring of emissions, ecosystem statuses, and material flows. In a circular economy, digital tracking is an enabler for reuse and recycling. Examples include material passports or digital building logbooks. The combination of digital technologies, such as smart and communicating sensors, with data analytics, provides a nearly real-time understanding of the state of the environment (e.g. air or water quality). Accessible and interoperable data, combined with digital infrastructure and Artificial Intelligence solutions, can facilitate evidence-based decisions and expand capacities to understand and tackle environmental challenges.[71] Data, algorithms, and insights from analysis can provide information on the state of the environment that fosters sustainable development.[72] |
| **Simulation and forecasting** | **Simulation and forecasting can improve efficiency**<br>Knowledge about the whole life cycle of products can be gained through digital simulations. Such knowledge enables the identification of options to improve the environmental footprint, of fracture points that lead to obsolescence, and of ways to improve reparability and upgradability. For example, computer models for buildings can test alternative cooling approaches to reduce energy consumption during their life cycle. Forecasting of developments (e.g. weather or electricity demand) can be used to balance demand and supply in energy grids, prevent interruptions, and be prepared for crisis events. In predictive maintenance, the analysis of material wear can indicate when repair is needed and avoid downtime of machines. For the heating of buildings, self-learning thermostats can understand user habits and optimise heating cycles. For traffic management, Digital Twins with real-time data can optimise routes according to current conditions. |
| **Virtualisation** | **Virtualisation is changing sectors and reducing their environmental impact**<br>Virtualisation covers new approaches to solving underlying needs through digital alternatives, such as ebooks, videoconferences, virtual reality experiences, or digital prototypes. Extended reality technologies, such as augmented reality and metaverses, have the potential to move more services, production, or consumption activities online. Virtualisation also covers other developments, such as increasing online shopping, events, and concerts. Taking retail as an example, the demand for physical shops may reduce. On the other hand, transport for delivery and return of goods is increasing.[73] A successful virtualisation of production and consumption is based on the willingness of people to change their behaviour and adapt to new solutions. Such digital technologies have to be both energy-efficient and circular to ensure a positive environmental impact. |
| **Systems management** | **Systems management using digital technologies helps to cope with increasing complexity**<br>Successful uptake of Artificial Intelligence technologies by European industry could help to make production processes more efficient and less resource intensive. Digital Twins with real-life data could be used as enablers for smart and more efficient management of machines and systems. For example, smart cities and communities show how the green and digital transitions can take place in a holistic and systemic manner. The combination of different technologies, such as the Internet of Things and Artificial Intelligence applied to urban systems, will foster innovative business models, new services, and better resource management. In the energy sector, 'smart' electricity grids can optimise the grid capacities by managing consumer usage (such as electric vehicle charging power walls), coordinating storage options to balance electricity generation, and shifting demand (peak shaving, valley filling). Data visualisation is enabled by geographical information systems and dashboards that improve understanding and the sense-making of data.[74] |
| **Information and communication technologies** | **Information and communication technologies enable new levels of interaction**<br>Modern information and communication technologies provide opportunities for nearly unlimited information collection and dissemination, with the potential to positively influence user behaviour. For example, labels and smart packaging can communicate the environmental footprint and 'full cost' of a product. Digital platforms can also provide matchmaking for supply and demand of specific products. Every individual could become a business actor and share and trade their excess energy, used or non-used products, and vehicles. |

Source: JRC

71 Joint Research Centre (2022b)
72 European Commission (2021h), UN Environment Assembly (2019)
73 Zhang, Zhu, and Ye (2016)
74 European Commission (2021h)

## Interplay between the digital and green transitions

**While there is a potentially large contribution by digital technologies to the green transition, their increased use can come at a cost for the environment.** This impact results from different processes involved in building and running digital systems, such as the resources required to manufacture digital and electronic technologies (including the exploitation of rare elements and critical materials), the high quantity of energy required to run them, and the resulting non-recyclable and partially toxic waste. The Information and Communication Technology industry's contribution to global greenhouse gas emissions was estimated to be between 3.0 % and 3.6 % of total emissions in 2020, with the potential to grow substantially in the future.[75] In 2018, data centres worldwide consumed around 1 % of the total global electricity use. With nearly half of the population in Asia and almost 60 % of the people on the African continent yet to go online,[76] the potential future environmental impact of digital technologies needs to be taken into account. Nevertheless, the growing data economy does not necessarily increase energy consumption, given that the 419 % increase in internet traffic between 2015 and 2021 has seen the energy demand of data centres in that timeframe remain stable at around 200 TWh.[77]

**The green transition is also affecting digital technologies because they too have to reduce their environmental impact.** Digital technologies, and the electronic components and systems value chain, could be transformed towards environmental sustainability. An adaptation of digital technologies is already considered in recent policy and legislative processes, such as the Artificial Intelligence Act[78], or regulatory framework for blockchain[79]. Towards 2050, emerging digital technologies, such as quantum computing, bio-based electronics, or self-powered devices could support a digital transition that is also climate- and environmentally-friendly.[80] At the same time, digital technologies and infrastructure will need to build up resilience to the effects of climate change, such as temperature increases and extreme weather events.

The green transition is also affecting digital technologies because they too have to reduce their environmental impact.

Digital technologies, and the electronic components and systems value chain, could be transformed towards environmental sustainability.

75 Belkhir and Elmeligi (2018)
76 Internet World Stats (2021)
77 European Union Institute for Security Studies (2021)
78 European Commission (2021i)
79 European Commission (2022e)
80 European Innovation Council (2022)

# 6. GREEN TECHNOLOGIES IN THE CONTEXT OF THE TWIN TRANSITIONS

**This chapter focuses on the green transition in the five sectors emitting most greenhouse gases in the European Union,** namely agriculture, buildings and construction, energy, energy-intensive industries, and transport and mobility. An overview of each sector is presented together with the main trends and challenges. The main sub-sectors and key green technologies are presented in order to illustrate future innovation timelines for them to become more environmentally friendly, as well as how digital technologies can support the green transition in the sectors. The future development of key technologies is shown towards 2050. Lastly, enabling factors for the roll out and uptake of green-digital solutions are presented for each sector. Case studies outline the advantages, challenges, and possible implications of two specific examples of green-digital solutions per sector, and provide a brief 'snapshot of a possible future' to sketch out what the solution might bring by 2050.

# AGRICULTURE

## Overview of the sector

**The agriculture sector plays a crucial role in food production and power generation.** The agriculture sector accounts for 10 % of the European Union's greenhouse gas emissions, of which more than 90 % are caused by methane and nitrous oxide emissions.[81] At the same time, land is also a carbon sink, absorbing more carbon from the atmosphere than it releases. This is why sustainable agriculture and food systems are key to the objectives of the European Green Deal.[82] The agriculture sector and the production, use, processing, and distribution of biological resources generates 4.7 % of the GDP in the European Union and employs approximately 8 % of its workforce.[83] The agriculture sector provides products for which there are no alternatives, such as food, feed and ecosystem services. Agriculture is also a source of biomass that is used for power generation. To contribute to the green transition, biomass resources (i.e. organic material that can be used as fuel for transport, or to produce heat or electricity) should be sourced sustainably.[84]

**The Russian war of aggression against Ukraine is impacting food prices and food security globally.** Export routes are cut by blockades in the Black Sea. Farms lack a workforce, and unexploded bombs and mines cover farmland. Russia, Belarus, and Ukraine are some of the most important agricultural commodity producers, for example for wheat, maize, and oil seeds. They are also major suppliers to the agriculture sector, for example by providing fertilizers. Their reduced ability to export these goods challenges the food security of import-dependent countries. This is particularly the case for the least developed and low-income countries that rely on supply from this region and are very price sensitive.[85] Europe is self-sufficient for most agricultural commodities, but has to adjust its feed supply.[86] The global food crisis is putting pressure on EU food production and the European Commission's regulatory proposals on biodiversity.[87] Rising energy

81 European Environment Agency (2021a), European Environment Agency (2022)
82 European Commission (2020g), Council of the European Union (2019)
83 European Commission (forthcoming), Joint Research Centre (2022c)
84 Joint Research Centre (2020b)
85 FAO (2022)
86 European Commission (2022f)
87 European Parliamentary Research Service (2022)

prices due to uncertain Russian energy imports and sanctions are also challenges for European fertilizer producers. They are leading to rising operating costs in the farming and seafood sectors.[88]

**The shift towards environmental sustainability and an increased health consciousness are reshaping the agriculture sector.** Climate change and environmental degradation are driving the emergence of new pests and diseases, water scarcity, loss of soil quality, and loss of biodiversity. For these reasons, 'resilience' is becoming an increasingly important requirement for farming. There are also shifts in food demand. Overall demand for food will increase with a global population that is expected to reach 10 billion people by 2050, and with the growing global urban middle class.[89] Consumer choices and changes in social norms can bring new trends into food consumption, such as bio-based products and lab-grown meat.[90] An increased health-consciousness and advancements in health analytics can trigger dietary changes at a wider scale. As a result, new and more diverse farming models will emerge to address environmental challenges and changing consumption patterns.[91]

**Global warming is the most influential long-term trend affecting the agriculture sector.** Climate change is putting an unprecedented pressure on natural ecosystems, affecting water availability, food production, and biomass sourcing.[92] It is also expected that global warming will increasingly affect food security by 2050.[93] Between 2000 and 2019, soil moisture deficit areas increased by 80 % in Europe[94] and the frequency of droughts is also increasing.[95] At the same time, the sector has to become more sustainable by increasing its output of organic products while decreasing nutrient losses. It also needs to decrease the use

The shift towards environmental sustainability and an increased health consciousness are reshaping the agriculture sector. Climate change and environmental degradation are driving the emergence of new pests and diseases, water scarcity, loss of soil quality, and loss of biodiversity.

of fertilizers, pesticides, and antibiotics.[96] Land use and forestry currently remove approximately 7 % of the European Union's annual greenhouse gas emissions every year.[97] However, climate change is affecting most of these carbon sinks, which are of crucial importance for achieving climate neutrality by 2050.[98] An additional challenge stems from the high average age of farmers and the continuing depopulation of rural areas. This development will

88 Scholeart (2022)
89 Howard et al. (2021)
90 Joint Research Centre (2020b), Bhat (2021)
91 Joint Research Centre (2021c)
92 IPCC (2022)
93 IPCC (2020)
94 Referring to 38 EEA member countries
95 European Environment Agency (2021b)
96 European Commission (2020c), European Commission (2021j)
97 Data refers to the so called LULUCUF (land use, land use change and forestry), emissions related to LULUCF generated by imports are excluded. See European Environment Agency (2021a) and European Commission (2020h).
98 Joint Research Centre (2021d)

affect the structure of the primary sector[99] and about 11 % of agricultural land in the European Union is at high risk of abandonment by 2030.[100]

## Technologies enabling the green transition

**Digital systems are enablers for more efficient and more sustainable production and consumption of food.**

With environmental *monitoring and tracking*, digital tools can help gather knowledge of areas such as biodiversity deficits and prioritise actions to preserve it.[101] In the circular bioeconomy, digital technologies will support tracking and characterising residues to transform them into products with information on their quality and environmental footprint.[102] Digital technologies can also contribute to efficient *systems management* and thus increased productivity through more targeted application of feed, water, energy, fertilizers, and pesticides.[103] The roll out of new *information and communication* technologies can provide opportunities for sustainable development in farming and forestry. These technologies also offer new perspectives for the growth and geographical distribution of manufacturing and services to diversify rural areas beyond food, farming, and tourism.[104]

See also Figure 1 (p. 19): Functions of digital technologies >>

**Agriculture** will have to adapt to become more resilient. Sustainable farming techniques could improve resilience and at the same time reduce chemical inputs and greenhouse gas emissions. Digital sensors and Internet of Things applications can help to monitor the condition and health of agricultural land or biodiversity in natural landscapes. Another option to improve resilience is to use gene editing and design to develop hardier and more productive crop varieties.[105] Furthermore, modern agriculture technologies enable improved crop, water, and livestock management.[106]

**Fisheries and aquaculture** need to reduce their carbon emissions, avoid emitting pollutants and diseases, and reduce their impact on biodiversity. Water recirculation systems and growing multiple species at the same time (integrated multitrophic aquaculture) could achieve that by re-using by-products and waste.[107]

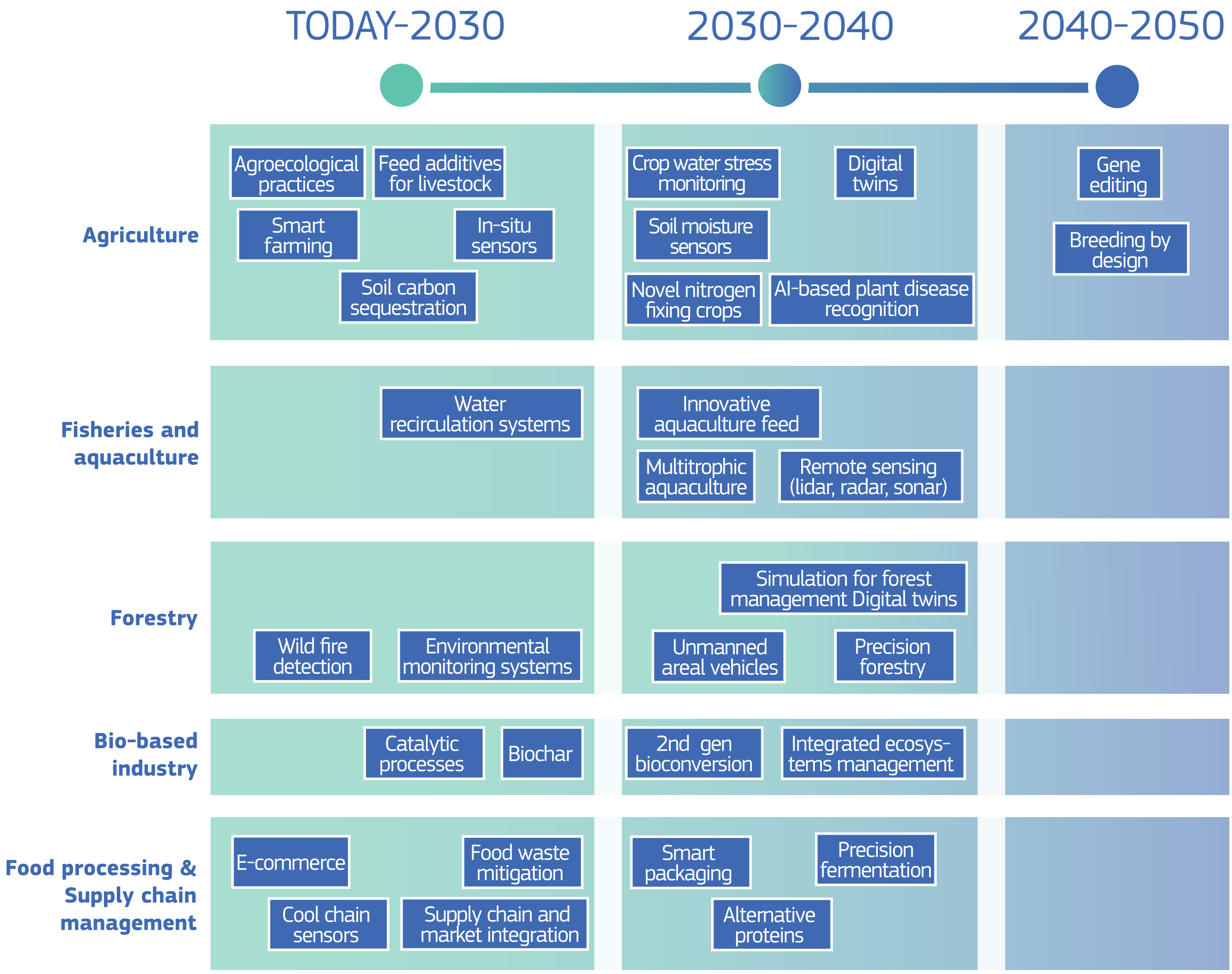
**Forests** are carbon sinks, but they also need to adapt to climate change to remain healthy. The diversification of forests and the introduction of climate resistant trees is important to ensure the long-term viability of forests.[108] Furthermore, precision forestry[109] and robotics allow for monitoring and managing the health of forests, even in remote areas.[110]

**Bio-based industry** enables the replacement of fossil resources with renewable ones, for example when producing plastics, essential oils, glues, or soaps. Second generation bioconversion processes use biomass that cannot be used for food and feed and are not in conflict with food security.[111] Lastly, 'pyrolysis' from woody residues is a process that yields biochar, which stores carbon while improving soil fertility.[112]

**Food processing and supply chain management** could make a substantial contribution to reducing greenhouse gas emissions in the sector by switching from animal to alternative proteins. Such a switch also requires a fundamental behavioural change in terms of eating habits. A potential solution for alternative protein production is precision fermentation.[113] Furthermore, avoiding food waste

99 EUROSTAT (2018)
100 Joint Research Centre (2018b)
101 AENEAS, ARTEMIS-IA, and EPoSS (2021), Hedberg and Sipka (2020)
102 Lekkas, Panagiotakis, and Dermatas (2021)
103 Flavell (2010), Franks (2014), Mahon et al. (2017) However efficiency improvements might be limited to up to 10 % $CO_2$ reduction by 2050 (Institute for European Environmental Policy (2019)) when applied in intensive agriculture (Schiefer, Lair, and Blum (2016), Paul et al. (2019))
104 European Commission (2021k)
105 Bingham et al. (2009), Messina et al. (2011), Mitchell et al. (2016), Munns et al. (2002), Nelson, Shen, and Bohnert (1998), Chinnusamy, Jagendorf, and Zhu (2005)
106 Abioye et al. (2020), Adeyemi et al. (2017), Arias, Molina, and Gualdron (2004), Bailey et al. (2018), Bwambale, Abagale, and Anornu (2022), Dukes (2020), Escriba et al. (2020), Evett et al. (2020), García et al. (2020), Gillespie (2007), Ingrand (2018), Ivanov and Novikov (2020), John et al. (2016), Kalyani, Goel, and Jaiswal (2021), Lebourgeois et al. (2008), Liang et al. (2020), Qiu et al. (2018), Ratnaparkhi et al. (2020), Ullo and Sinha (2021), Valente et al. (2011), Wolfert et al. (2017), Zeng and Li (2015)
107 Buck et al. (2018), Granada et al. (2016), Knowler et al. (2020), Ridler et al. (2007)
108 Marchi et al. (2018), Siry, Cubbage, and Ahmed (2005)
109 Precision forestry is transferring precision agriculture practices to forest management.
110 The European Commission is preparing a legislative proposal for a Forest Observation, Reporting and Data Collection to establish an EU-wide integrated forest monitoring framework. See European Commission (2021l).
111 Joint Research Centre (2021e), Ahmed et al. (2021), Kline et al. (2017), Debnath and Babu (2019)
112 Shakoor et al. (2021)
113 McKinsey & Company (2019), Duarte, Bruhn, and Krause-Jensen (2021), Nova et al. (2020), Reboleira et al. (2021), Tzachor, Richards, and Holt (2021)

Figure 2: Green technology innovation timeline in the agriculture sector




Source: JRC

**Note: These are approximate development timelines based on expert discussions and indicate when a certain technology might be available to the market.**

requires new (sustainable) solutions for packaging, storing, and distributing products.[114] Digital technologies can lead to improvements in these areas, for example by supply chain tracking via RFID[115] chips.

**Figure 2 illustrates green technology innovations** that could help the green transition in agriculture. It indicates when certain emerging technologies could become available up to 2050. Green technologies in agriculture are expected to be on the market already in the short- to mid-term, but their larger scale market roll out is a challenge due to hurdles such as cost-competitiveness. The long-term technology outlook is rather to improve and integrate these solutions. Appendix 2 provides a more detailed description of the green technology innovation timelines in this sector.

114 Knorr, Augustin, and Tiwari (2020)
115 Radio-Frequency Identification

# CASE STUDY

## DIGITAL ENVIRONMENTAL MONITORING SYSTEMS

### What is it about?

**Environmental monitoring is a key tool for achieving many European Green Deal targets.** It provides governments, civil society, and business actors with knowledge and evidence of environmental change and natural resource management strategies. It can also provide information on air pollution and water quality. Environmental monitoring systems are networks of data collection, sensing, connecting, computing, analysis, and communication devices. They gather and process information on environmental indicators that cover large areas. Data is available to different interested actors, according to standards for data production and exchange and rules of access and sharing.

### What is the role of digital technologies?

**Digitalisation boosts capacity to collect, manage, and elaborate environmental information.** It improves the accuracy and frequency of data collection and allows real-time monitoring. It provides access to data through new types of sensors, the Internet of Things, Big Data analysis, and crowd sourced data collection. Digitalisation also enables new ways of analysing and visualising data (e.g. geographical mapping). Furthermore, it makes data accessible to various audiences with different degrees of expertise. Artificial Intelligence and high-performance computing boost this capacity. Digitalisation further enables information sharing among individuals, closed groups, or the public, through internet databases and knowledge dashboards. Data availability enables the development of Digital Twins of natural resources.

### What is the advantage?

**Digitally-enabled accuracy and frequency of data collection increases the potential of environmental monitoring systems.** It allows evidence-based decision-making for managing sustainable use of natural resources, climate change mitigation, and adaptation. Predictive analytics can help to identify trends and make forecasts possible for early warning strategies. Future changes could be anticipated. Digitalisation can help to increase data quality through profiling, cleansing, matching, and enrichment. It further enables compliance control mechanisms for related regulations such as emission allowances or soil protection laws. Monitoring information can also inform decision-makers and help to improve the use of natural resources and reduce emissions. Monitoring data can be a basis for calculating the "true price" of resources, covering the environmental footprint of a product along the supply chain. Hence, it helps consumers to make informed, responsible choices.

### What are the challenges?

**High costs and the lack of available data are barriers to the implementation of environmental monitoring systems.** Environmental monitoring systems require investment and they generate operating costs.[117] Cost-effective solutions such as using multipurpose sensors in end-user devices, or re-using data collected for other purposes could be an option, but would still require calibration of the data. Ensuring interoperability of environmental data is crucial to allowing the use of the data from different locations and sources. Environmental data also needs to be safeguarded to prevent its misuse and any potential harm to citizens and companies.[118] Privacy issues and reliability of the data are key in this respect.

### Environmental sustainability

**Effective environmental monitoring systems can help to ensure a healthy environment.** Monitoring systems provide an overview of the state of the environment that in turn facilitates the identification of priorities for policy action.[119] They can help to evaluate the effectiveness of existing policy instruments and programmes and support the design of new effective policy instruments. For example, they could enable

117 MarketsandMarkets (2022)
118 World Bank (2021)
119 For example, in the review of the Marine Strategy Framework Directive, a need to better, more coordinated monitoring and reporting has been identified as one major issue (European Commission (2021m)). Other policy domains interested in environmental monitoring are forestry LULUCF (European Commission (2021n)), agriculture (European Commission (2022g)), and risk and disaster management under climate change scenarios (European Commission (2022h)).

## SNAPSHOT OF THE FUTURE

**What if digital environmental monitoring systems were rolled out successfully?**

In 2050, environmental data is available at your fingertips. When you buy food, you get an environmental score; when you look out of the window, you see the real-time air pollution data in your Augmented Reality device. Environmental monitoring systems collect data through specific monitoring networks with calibrated sensors in real-time, but also harvest information from Internet of Things devices and built-in sensors in cars, tractors, drones, and planes. Through Artificial Intelligence, this information is translated into reliable environmental monitoring data. Big Data analysis and pattern recognition are used to make sense of this data and forecasts are based on predictive analysis. Environmental data and software are open source. Automated aggregation and anonymization ensure confidentiality and privacy.[116] Context-specific data analysis and mapping makes the information and knowledge easily accessible and understandable to everyone.

116 See Shared Environmental Information System (SEIS) principles, European Commission (2008)

payments for environmentally-friendly farming practices in the context of the Common Agricultural Policy.[120] Environmental management systems that deliver frequent or real-time information can support authorities to enforce environmental regulations and provide evidence to courts when it comes to fishing quotas, bycatch prohibition, or logging regulation.

### Economic sustainability

**Environmental monitoring systems are a growing sector with a large number of specialised market players.** The global environmental monitoring market is expected to more than double in terms of market value from around EUR 18 billion in 2020 to EUR 40 billion in 2030.[121] Natural resource management, supported by environmental regulation, is the key driver for this development. Furthermore, growing concerns for public health is another supporting driver. In 2020, air pollution monitoring accounted for the largest market share, with 54 % of the environmental monitoring systems market.[122] Environmental monitoring systems can also be used as reliable and harmonised evidence for Corporate Social Responsibility reporting.[123]

### Social sustainability

**Environmental monitoring systems aim to inform and contribute to providing a safe and healthy environment to live in.** These systems play a key role in improving environmental stewardship of all kinds of stakeholders. Easily accessible and understandable environmental information empowers civil society and the private sector to raise their voices and act against harmful actions towards the environment or their well-being.[124] Individuals can also actively participate in environmental data creation. For example, citizen science initiatives involve volunteers in areas such as biodiversity conservation and waste reduction.[125] Lastly, environmental data can empower consumers to make responsible choices, for example with easily understandable information about the environmental footprint of their food and other products consumed.

120 European Commission (2022i), European Commission (2020i)
121 Allied Market Research (2021). Currency converted from USD.
122 MarketsandMarkets (2022)
123 European Commission (2021o)
124 UNECE (2021)
125 European Commission (2020j), Rubio-Iglesias et al. (2020), Balestrini et al. (2021)

# CASE STUDY

## SMART SUSTAINABLE FARMING

### What is it about?

**Smart sustainable farming means the uptake of practices already known in the context of Industry 4.0 in farm management.** It covers the potential of automation and digitalisation of farming processes and their supply and value chain relations. The goal of smart sustainable farming is to achieve enhanced sustainable development, more resilience, and increased resource efficiency. Beyond agriculture farms, the principles also apply to forestry, aquaculture, and fisheries practices.

### What is the role of digital technologies?

**Digital technologies enable optimisation in the agriculture sector.** Digitalisation has been a driver for the modernisation of the agriculture sector for many years. There are different ways digitalisation contributes to precision agriculture. These include monitoring the health of plants or livestock, data analysis to propose actions to improve farm processes, and managing autonomous devices (e.g. robotic arms, switches, valves, or sprayers). Drones can also spray pesticides, or be used to control land and livestock. Digitalisation further contributes to communication and management of the agri-food supply chain and enables traceability and transparency of products.

### What is the advantage?

**Digital agriculture has the potential to change farming practices, but also to transform the agri-food value chain.** The Internet of Things can integrate data from farms with other sources and thereby enable a shift to smart farming. Situational data of plant, livestock, and soil status, combined with weather forecasts and further environmental monitoring data, can provide decision-making support to the farmer. Such guidance can be given through data visualisation, recommendations, and user interaction. Digital technologies make it possible to deploy autonomous vehicles (e.g. tractors, robots, or drones) and other autonomous systems, such as irrigation systems. The analysis of agricultural processes and their results by Artificial Intelligence is contributing to innovation in agriculture. Such innovations include the improvement of agriculture practices, the introduction of innovative agricultural products, and less resource intensive services. Lastly, transparency of data on all interventions along the supply and production chain of food enables the communication of product characteristics and environmental footprints to market partners.

### What are the challenges?

**The transformative potential of digital technologies comes with a variety of challenges.** Digitalisation in agriculture has been developed for standardised processes in highly mechanised large-scale farms. To support more diversified farming processes and farm businesses, digital systems must advance in order to enable automation and optimisation in a rather diverse natural environment.[126] Connectivity in remote rural areas (e.g. fast mobile internet) might be challenging and requires new solutions to close digital infrastructure gaps. Digital components need to be biodegradable, or should at least not harm the environment if they get lost (e.g. sensors in soil, or on livestock). It is likely that not all farmers will be able to afford the investments in digital solutions. 'Farming-as-a-Service' could be a solution for this challenge, but it comes with issues of data ownership and reluctance to share data.[127] Lastly, there is a need to upskill farmers, which could pose a challenge, in particular for small family farms.[128]

### Environmental sustainability

**Digital technologies can help farms to become green and sell sustainable products.** Conventional farming is characterised by high specialisation, high intensity, and simplification of operations. Smart farming and precision farming can nevertheless optimise the use of energy-intensive agrochemicals such as fertilisers. Implementing smart technologies in sustainable farming

126 Ditzler and Driessen (2022)
127 Bacco et al. (2019)
128 Bacco et al. (2019), Joint Research Centre (2021c)

## SNAPSHOT OF THE FUTURE

### What if smart sustainable farming was rolled out successfully?

In 2050, farmers are supported to manage their farm through data-driven services provided by open software platforms. The platforms combine the data gathered on-farm though sensors, with public environmental information and weather forecasts. The farmers decide if they want to share their own data in an anonymised way. If data is shared, Big Data analysis helps to get a deeper understanding of how to improve farming practices and management, taking the specific context conditions and diversity of farm activities into account. Farmers receive decision-making support through an easily understandable graphical dashboard that uses augmented reality. Parts of the equipment work autonomously and are driven by Artificial Intelligence that takes local biodiversity and soil quality into account. Software deals with administrative and accounting work. The farmer holds a strong position in the food supply chain, based on a good market overview, and as a trusted provider of food with a low environmental footprint.

can increase productivity.[129] These types of farms are often more diversified, and digital technologies help farmers to deal with the resulting higher complexity. They also make it easier to experiment with innovative practices and to integrate experiences from other farms.[130] This experience speeds up the transformation of farms to more sustainable agricultural approaches and increases responsible innovation in agriculture.[131] Finally, social media communication helps to promote sustainable farm activities to consumers by opening a direct relationship and endorsing sustainable consumer habits.

### Economic sustainability

**The uptake of digital technologies in Europe's agriculture can help to manage farms better.** The intelligent agriculture market is expected to grow from EUR 1.4 billion in 2021 to EUR 2.5 billion in 2026.[132] Precision farming is the biggest market segment, followed by livestock monitoring and management. The application of digital tools is often motivated by market demand, raw material prices, or the pressure to reduce workloads. Fully digitalised farms are mostly still limited to pilot projects.[133] Digitalisation can enable farmers to increase the efficiency of their resource use, and ensure compliance with environmental and food safety regulation. It is opening up new business models via new forms of value chain relationships with suppliers and consumers.[134] With the rise of digitalisation and data-driven management of agriculture and food chains, data platforms[135] are gaining an increasing influence on the agriculture sector.[136]

### Social sustainability

**The digitalisation of agriculture and food chains provides individuals with feedback on the environmental footprint and health-related impact of their behaviour.** Hence, digitalisation enables people to understand and improve their consumption behaviour with regard to the environment and their health. Society, civil society organisations, and public administrations can more easily identify the impact of agricultural practices and food production, and choose products that are in line with sustainability goals. Digitalisation also influences the identity of farmers:[137] their role could shift from a farmer to an integrated food and bio-product provider, or to becoming a 'data labourer', which would have implications for the future of rural communities.[138]

129 Santiteerakul et al. (2020)
130 Wolfert et al. (2021)
131 Rose and Chilvers (2018)
132 Market Data Forecast (2022). Currency converted from USD.
133 Such are Horizon Europe 2020 project SmartAgriHubs (SmartAgriHubs (2022)) or solutions developed by big agrochemical players, e.g. Bayer (2022).
134 Eitzinger et al. (2019)
135 Wolfert et al. (2017)
136 Kenney, Serhan, and Trystram (2020)
137 Including concerns about farmers becoming 'data labourers' Rotz et al. (2019)
138 Bear and Holloway (2015), Hay and Pearce (2014), Klerkx, Jakku, and Labarthe (2019), Dessart, Barreiro-Hurlé, and van Bavel (2019)

# ENABLING FACTORS FOR GREEN-DIGITAL SOLUTIONS IN THE AGRICULTURE SECTOR

**Enabling factors highlight important aspects to facilitate successful transitions:**

- Trust in digital tools and the protection of private data are central factors.
- The main economic requirements include: value chain profitability; the uptake and expansion of collaborative business models; and the logistics of supply of goods and services.
- Digital skills and knowledge about the available and upcoming green-digital solutions are key requirements for farmers to be successful.
- Many aspects of agricultural activity require an adequate digital infrastructure for rolling out green-digital solutions.
- Data ownership should be ensured, together with secure platforms that can help stakeholders to use data efficiently.
- Protocols and procedures for circularity are likely to be essential requirements. Standards for data interoperability can help to increase data availability and reliability.
- Sensors and the Internet of Things will need to be energy efficient, durable, and non-hazardous.

# BUILDINGS AND CONSTRUCTION

## Overview of the sector

**Housing and office buildings make up most of the floor area in the European Union and are therefore key to the green transition.** The focus of this section is therefore on housing and office buildings, which represent 75 % of total building floor area in Europe.[139] Residential and commercial activities account for 12 % of greenhouse gas emissions in the European Union.[140] Buildings have long life times[141] and in Europe 85 to 95% of the existing buildings are expected to still be standing in 2050.[142] Circularity in the buildings and construction sector is an important aspect that includes renovation, retrofitting, and demolition of buildings.[143] A key area for the green transition is the volume and space needs for future buildings. Furthermore, the design, construction, and end-of-life phases are important. Lastly, the daily operation of buildings influences the environmental impacts via their heating, ventilation, and use of building-related appliances.[144]

**The Russian war of aggression against Ukraine has increased prices and decreased the availability of building materials in Europe.** Russia and Ukraine are the world's second and third largest steel exporters after China. Furthermore, Russia, Belarus, and Ukraine had provided about 40% of Europe's long steel products. Rising energy prices affect several construction products that come from energy-intensive industries (e.g. bricks, ceramics, cement, plastics, and steel).[145] The resulting increases in construction costs can act as a driver for energy-saving renovations. However, supply chain disruption and price volatility of core prices will further drive construction costs. Squeezed household incomes due to inflation and decreasing profitability of building projects might lead to delays or cancellation of building projects.

**The ageing population, shifting household structures, and urbanisation are changing demand patterns for living space.** The European population is ageing due to higher life expectancies and low birth rates. This is leading to an increase

139 European Academies Science Advisory Council (2021)
140 European Environment Agency (2022)
141 European Parliament (2016), Swiss Life (2017)
142 European Commission (2021p)
143 European Commission (2020d), European Academies Science Advisory Council (2021)
144 The New European Bauhaus initiative aims to push for a better alignment buildings and living spaces with the European Green Deal objectives, while addressing sustainability, aesthetics, and inclusion. See European Commission (2022j).
145 Reaper (2022)

in the total number of households (13 million households more between 2010 and 2019) with a smaller household size (2.3 people per household in 2019). Furthermore, the structure and use intensity of residential buildings varies depending on who lives in the building and where the building is located. One third of all households are single person households, with a growing number of old people living alone.[146] In rural areas, the average number of rooms per person is higher than the European average of 1.6, as relatively more people live in single family houses there.[147] Overall, the population living in European urban areas is projected to increase by almost 7 % by 2050 compared to 2015, although the picture is not uniform, as some urban areas in Europe will lose population.[148] Another driver is that more people are working remotely, which is reducing commuting numbers and will change urban social structures.

**The main challenges of the construction sector include affordable housing, energy poverty, and limited capacity to take up digital technologies.** Buildings provide a basic function for living and working. Affordable housing is needed in many countries across the globe, and social aspects such as energy poverty remain pertinent.[149] In the European Union, around three quarters of the building stock are not energy efficient, but only 0.4-1.2 % of these inefficient buildings are renovated each year.[150] Consequently, there is a window of opportunity for substantial energy savings through renovating.[151] Higher efficiency in affordable housing could also help address energy poverty by reducing energy demand. The construction ecosystem is an important sector in terms of employment with around 25 million people working in it.[152] It is a highly fragmented sector[153] where many firms are specialised in specific tasks, which makes integrated solutions more difficult. Another issue is that small and very small companies have limited capacities to implement digital technologies.[154]

Affordable housing is needed in many countries across the globe, and social aspects such as energy poverty remain pertinent.

### Technologies enabling the green transition

**Digitalisation provides several options to enable the green transition in the construction sector.**

The first and most obvious is through efficiency improvements in *systems management* such as more efficient building operations and construction processes. A second is through *monitoring and tracking* regarding the environmental impact of materials, including life cycle analysis and options for reducing environmental impacts through various actions (e.g. installing solar panels on roofs). A third is that *information and communication* technologies can support a more intense use of existing buildings (e.g. by supporting sharing of office space that would otherwise have remained empty), thus reducing the need for new constructions. A fourth is when digitalisation replaces space needs entirely through *virtualisation* (e.g. online banking and shopping make spaces for customers obsolete).

See also Figure 1 (p. 19): Functions of digital technologies >>

146 European Commission (2020k)
147 EUROSTAT (2021)
148 Joint Research Centre (2022d)
149 Housing Europe (2021)
150 European Commission (2020l)
151 European Commission (2019b)
152 European Commission (2021q)
153 European Federation of Building and Woodworkers (2022)
154 European Commission (2022k)

Building design and construction methods need to integrate resilience to possible extreme events to avoid premature decay or loss of functionality.

Digital tools can help to address this in the design phase.

**Low-carbon and resilient construction** are important drivers for greening in new buildings. Green architecture, engineering, and construction require information on the embodied grey energy in buildings (i.e. the energy associated with production). They need to consider several characteristics of the materials and components used, such as their energy efficiency performance, potential for repair, and end-of-life treatment.[155] Building design and construction methods need to integrate resilience to possible extreme events to avoid premature decay or loss of functionality.[156] Digital tools can help to address this in the design phase. For example, building information modelling can analyse long-term consequences of design choices and can help to decrease environmental impact in both the construction and use phases. One Stop Shops can support users in the complex decision-making processes and arrange related services like such as financing.[157]

**Retrofitting** will be key to makeing existing buildings greener. Keeping as many structural elements as possible means retaining the grey energy embodied in building material. Thermal and acoustic insulation and air tightness of the building envelope are crucial for deep renovations.[158] Introducing new and efficient space heating and cooling systems with smart technologies for building automation and control systems is another key element. Digital tools like digital building logbooks[159] can ease renovation, retrofitting, and recyclability of materials from old buildings.

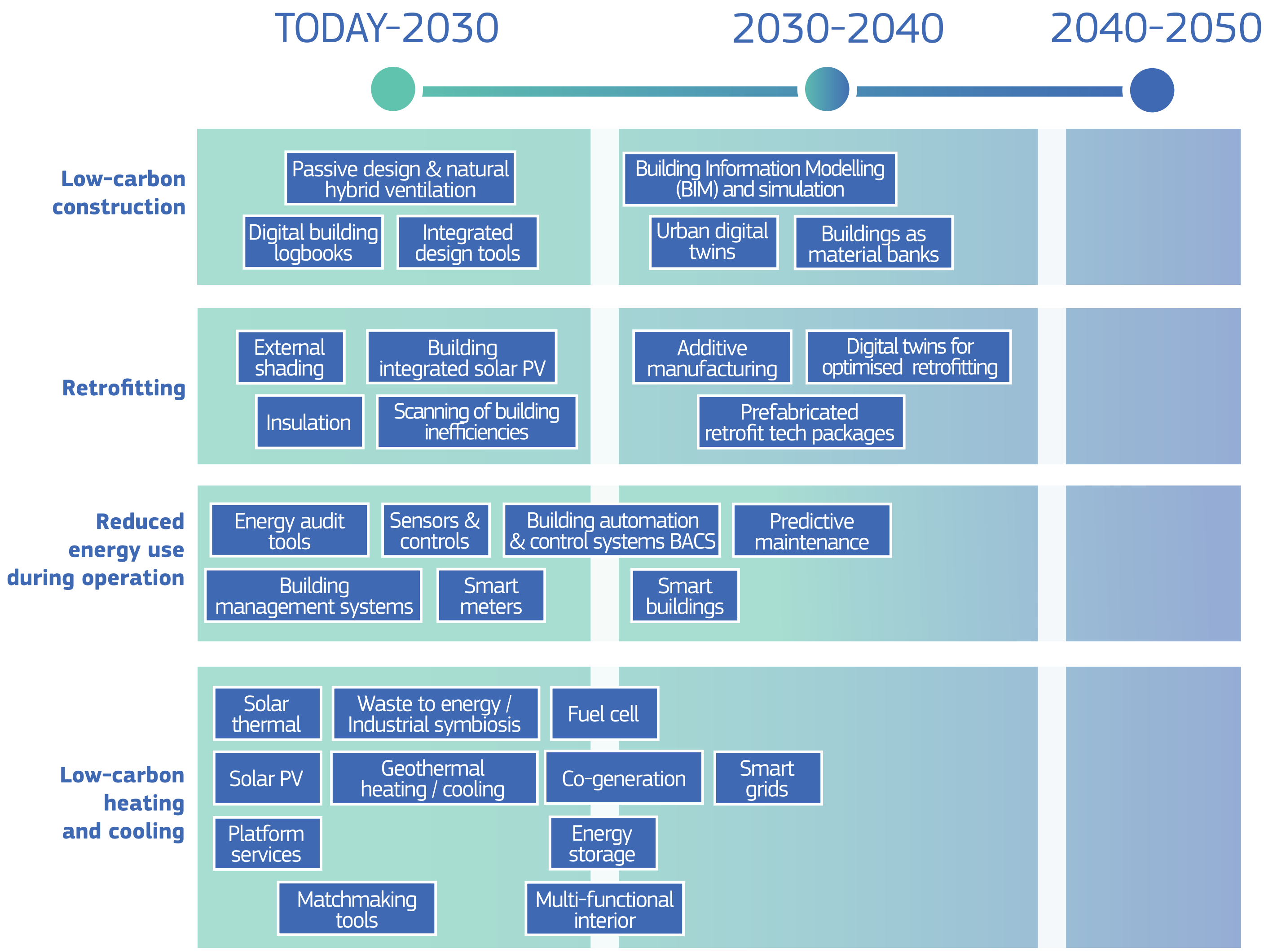
**Reduced energy use during operation** can provide a stabilising function to the overall energy system. Heating, cooling, ventilation, and lighting systems can be adaptively managed to reduce energy consumption while maintaining the same level of comfort for inhabitants. Building automation and control systems are based on sensors that recognise the building's users and their requirements, and help to actively manage energy-consuming appliances.[160]

**Low-carbon heating and cooling** reduces emissions and pollution during the use phase of a building. Electrification (e.g. using heat pumps instead of oil or gas heating) is key for sustainable heating. In addition, building-added or -integrated solar PV is a renewable electricity source with high potential for the future.[161]

**Reduced demand for building space** decreases environmental impacts from constructing and operating buildings. Options to cut building space include reducing the need for space use and increasing the usage intensity in existing buildings. Digital platforms can enable smoother sharing of space. Lastly, tiny houses and micro apartments also provide options for reduced need for space.[162]

155 CINARK (2021)
156 European Environment Agency (2021c)
157 Bertoldi (2022)
158 European Academies Science Advisory Council (2021)
159 A digital building logbook stores a building's data and information, and can be shared among building owners, inhabitants, public administrations and financial institutions.
160 European Academies Science Advisory Council (2021)
161 CE Delft, Climact, and European Climate Foundation (2020)
162 Francart et al. (2020), Falk et al. (2020), Höjer and Mjörnell (2018), Crawford and Stephan (2020)

**Figure 3: Green technology innovation timeline in the buildings and construction sector**




**Source: JRC experts workshop, GlobalABC, IEA, and UNEP (2020), European Academies Science Advisory Council (2021)**
**Note: These are approximate innovation timelines based on expert discussions and indicate when a certain technology might be available to the market.**

**Figure 3 illustrates technology innovations** for greening the construction and building sector and indicates when certain emerging technologies could become available up to 2050. Green technology innovation in the construction and building sector could reach technological maturity in the short- to mid-term. However, their market roll out is a challenge due to hurdles such as cost-competitiveness and a renovation backlog. The long-term technology outlook is rather to improve and integrate these solutions. Appendix 2 provides a more detailed description of the green technologies in this sector.

# CASE STUDY

## REDUCED DEMAND FOR SPACE

### What is it about?

**Reducing the need for indoor building space cuts down on the environmental impacts from constructing and operating buildings.** There are two strategies to reduce the demand for space: either by increasing the intensity of building use, or by reducing the need for space for a particular activity. Existing examples of the first are co-working spaces, desk sharing in offices, or renting of private holiday homes. Examples of the latter are sharing of living and working space, tiny houses, or micro apartments. Another option is the virtualisation of shop floors through online services like online banking or online retail. The predictability of the activities in a space determines how complex the organisation of sharing the space will be.

### What is the role of digital technologies?

**Digital technology can help to reduce the demand for space.** Sharing platforms and smart digital solutions such as integrated workspace management systems, place and desk booking, or digital concierge services are key enablers for the sharing of spaces. Internet of Things applications, like sensors in buildings, can provide a real-time understanding of the use of the building space. It also allows last minute flexible room or space booking alongside modelling, simulation, and forecasting of the occupancy of particular spaces. Digital technologies, like universal connectivity and wearable digital devices, also enable mobile working and make office and living space more flexible. Digitalisation of retail and service provision is currently fundamentally changing the form and function of physical stores and reducing the demand for retail space.

### What is the advantage?

**Digital tools reduce the organisational burden of sharing spaces.** They simplify booking processes, enable just-in-time booking, provide transparency of supply and demand, and offer a matchmaking service between parties to meet the mutual requirements. Artificial Intelligence and machine learning could improve predictive capacities and resource planning. If it is rolled out successfully, reducing the need for building space will also reduce the overall need for new constructions and significantly change the operation of all buildings and their related costs.

### What are the challenges?

**Reducing the amount of space we live and work in would be a radical change in many people's lifestyles and habits.** The current trend in residential buildings shows a clear increase of per-capita floor area over in recent decades in Europe.[163] Security and reliability are key concerns in both residential and office spaces when external users are sharing the building or parts of it. People's concerns about having private spaces and the security of the shared buildings need to be considered, such as the safety of valuables. The adaptability of buildings and their ability to meet different demands of users and changing demands of residents is also a special challenge. Rebound effects need to be carefully considered in this area, in order to avoid that space reduction in one place leads to expansion or increased use of other built spaces.

### Environmental sustainability

**The reduction of building space demand has a positive environmental effect.** A reduction in building space could contribute towards a large reduction of $CO_2$-emissions in Europe via two levers. Reduced use of space avoids the need for new constructions and the related environmental costs and impacts on resources. On average, avoiding the construction of a new building can save about 2 MWh per square metre.[164] The energy needed to operate buildings, such as heating, cooling, and lighting, would also be reduced at the annual amount of 250 kWh per square metre for non-residential buildings, and 180 kWh per square metre for residential buildings.[165] Further environmental benefits include reduced mobility needs due to teleworking. Shared workplace equipment and shared household appliances, which

163 Ellsworth-Krebs (2020)
164 This is a rough estimate of an average for Europe. A variety of studies provide a wide range of values (Aktas and Bilec (2012), Chastas, Theodosiou, and Bikas (2016), Ding (2004), Ramesh, Prakash, and Shukla (2010)).
165 European Commission (2022l)

## SNAPSHOT OF THE FUTURE

### What if digital technologies successfully reduced demand for space in buildings?

In 2050, many people work in companies that do not own office buildings, but rent desks and rooms by the hour. Both space and equipment are used more intensively. Most types of work can be done online, from nearly anywhere, as telecommunication and remote collaboration is now a real and regular experience. Some office buildings that are not needed anymore have been transformed into housing. Living spaces are now more flexible, and allow the use of space more efficiently. Some apartment buildings allow dwellers to book additional space, for example to accommodate visitors.

are used more intensively and need central care to guarantee their functionality, supports circular economy principles.

### Economic sustainability

**The construction business is shifting from new constructions to the management of existing buildings spaces.** Facility management needs are growing for building management and building security. Tenants might have higher, specific expectations towards extended services, while requiring adaptability of spaces.[166] The construction sector will shift from new construction business to renovation and creating modular, multi-functional spaces and to care for early wear and tear from intensive use. The furniture industry will grow in the segments of equipment for multifunctional convertible use of rooms, lockers, mobile solutions, and digital walls. Property owners can increase their revenues by renting the space to different users around the clock. New business opportunities will emerge to manage matchmaking, sharing, contracting, or providing security.

### Social sustainability

**The optimised use of building spaces could increase affordability and social contacts.** Increasing the efficiency of space use will reduce the costs for the individual users, which could drive affordability of housing and workplaces. Shared spaces also reduce the individual investment needs for shared user equipment. Spaces will become more flexible and will be tailored to the specific needs of users, even if these needs change over time. Lastly, co-working spaces and the sharing of office and living spaces and common areas could bring people closer together.

166 Royal Swedish Academy of Engineering Sciences (IVA) (2020)

# CASE STUDY

## INTEGRATED BUILDING DESIGN AND REDESIGN

### What is it about?

**The design phase of a building has a crucial impact on its environmental performance throughout its whole life cycle.** The design determines the materials used during the construction process and the circularity aspects of the materials in terms of durability (longevity), adaptability (ability for renovation) and re-use (waste reduction). In the design phase, the energy efficiency of the building is determined with respect to the building shell, the heating and cooling systems, or building-integrated power generation. Building design is key for new buildings, but in Europe even more so for the renovation of the existing building stock. Building renovation is a key initiative to drive energy efficiency, as 75 % of the existing European building stock needs to be renovated to reduce energy consumption.

### What is the role of digital technologies?

**Energy-efficient and circular building design require covering and integrating large amounts of information for which digital tools are a prerequisite.** Building-integrated modelling is a tool for a digital representation of the overall building that allows collaboration with building stakeholders and contractors. A Digital Twin could focus on the operation phase of the building to gain an understanding of the performance of the building. It can indicate when it is time for renovation or technical upgrades. A virtual model of the building generates an understanding of the building layout and its use, maps technical infrastructure, and eases planning for several trades involved in the construction phase. It is an enabler for pre-fabrication of building components, 3D printing and utilisation of robots to support the construction and renovation process. A digital building logbook could act as a common repository, including material passports, for all relevant information and support informed decision-making.
Lifecycle analysis also needs to be integrated to be able to make an informed decision about the most energy efficient and green solutions.

### What is the advantage?

**Data and knowledge about environmental implications and alternative solutions enable a redirection of existing activities towards more sustainable practices.** Integrated design that respects the full life cycle of materials is a safeguard against future lock-ins and enables the adaptation of a building according to changing needs. Integrated design can also prepare buildings better for upgrading technological infrastructure and reuse of materials. With these options, buildings are equipped for possible renovations, avoiding demolition and the waste of their embodied energy. Data repositories such as digital building logbooks and Digital Twins provide transparency about benefits for investments in renovation from a green and a financial perspective.

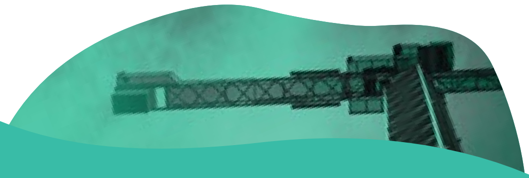
### What are the challenges?

**A lack of data is a challenge for digital tools supporting the design phase.** Data on the vast number and amount of materials used in construction is only partly available and often lacks information on the environmental footprint, particularly with respect to the complete life cycles. This lack of information makes it more challenging for building professionals to articulate the business case for green solutions and greater circularity.
Data about the existing building stock is often very marginal. This makes it extremely difficult to use building-integrated modelling or Digital Twins for existing properties. Standardisation and harmonisation of data is also a challenge with multiple actors providing and regulating the various data sets. Furthermore, the average building lifespan of 80 years[167] makes it challenging to integrate and simulate possible future use cases. Lastly, a majority of most companies in the construction sector are small and often lack IT skills, which is an additional challenge for the roll out of digital tools.[168]

**Environmental sustainability**

**Digital tools can contribute to reducing the embodied and operational energy of a building and to avoiding the use of harmful substances.**[169] Building-integrated modelling has the potential for resource and energy savings along the whole life

167 Marsh (2017)
168 RICS and United Nations Global Compact (2018)
169 Najjar et al. (2017)



## SNAPSHOT OF THE FUTURE

### What if integrated building design and redesign were rolled out successfully?

In 2050, when designing a new house or planning the renovation of an existing one, the architect and engineer can draw on fully transparent information about the environmental impact, lifetime costs, upgradability, and recyclability for all the materials and components. The energy efficiency and profitability of a design option, capital expenditures, and operating expenses are easily available. Digital planning tools offer green options and can already simulate the construction and operational phase. A virtual reality simulation makes it possible to test different layouts before construction. It shows the future gradual ageing of the building over time and already integrates renovation and upgrading options for other alternative uses of the building in the future. Through 3D scanning of the existing stock of buildings and an ever-increasing data base of millions of renovation projects, digital tools overcome data gaps by using new data sources and Big Data-based estimations.

cycle of a building, particularly in the planning and construction phase.[170] Comparing the environmental footprint and performance of construction material could boost the use of timber and low-carbon materials. Building material passports list the materials and components used in a building and provide a better knowledge base for building renovations, and enable better decision-making regarding building stability and energy efficiency. They also enable reuse, upcycling, and recycling of materials during the building demolition phase. Designing buildings in an adaptive manner reduces the risk of premature loss of usability of buildings and can avoid demolition and new construction. Integrated building design also supports resizing the building units according to changing needs. This flexibility increases space efficiency with respect to family life cycles or business developments.

### Economic sustainability

**Digital design tools, such as building logbooks and building-integrated modelling, provide platforms to overcome limitations of the fragmented construction sector.** They enable better creation of synergies of the sectoral value chain, such as data-based service plans, facilitation of material flows, property evaluation, refurbishment plans, standardised documents, and sustainability ratings. Digital tools also enable many different trades and suppliers to collaborate seamlessly in the construction phase, while integrating actors that operate buildings.[171] Transparency of sustainability-related building performance enables large building portfolio owners to develop sustainability investments strategically with respect to energy efficiency renovation activities. It also helps financial institutions to support single building owners to boost the value of their buildings by reducing energy-related costs through improving the overall building structure.[172] However, the application and use of digital tools and automated tools within the building sector is currently relatively limited.[173] There is a strong need for upskilling in the construction sector with respect to energy efficiency and digital skills.[174]

### Social sustainability

**The renovation wave and improved energy efficiency of buildings comes with several societal benefits.** Digital design tools cover people, processes, technologies, and living standards.[175] Every million euro invested in energy renovation in Europe creates about 18 new jobs.[176] Improving energy efficiency targets for buildings by 1 % could drive the deep renovation of 3 million homes in Europe and could lift 7 million people out of energy poverty.[177] Renovation can help to overcome the side effects of suboptimal living and working conditions. Poor quality housing generates medical costs,[178] while holistically renovated office buildings raise productivity by 12 %.[179]

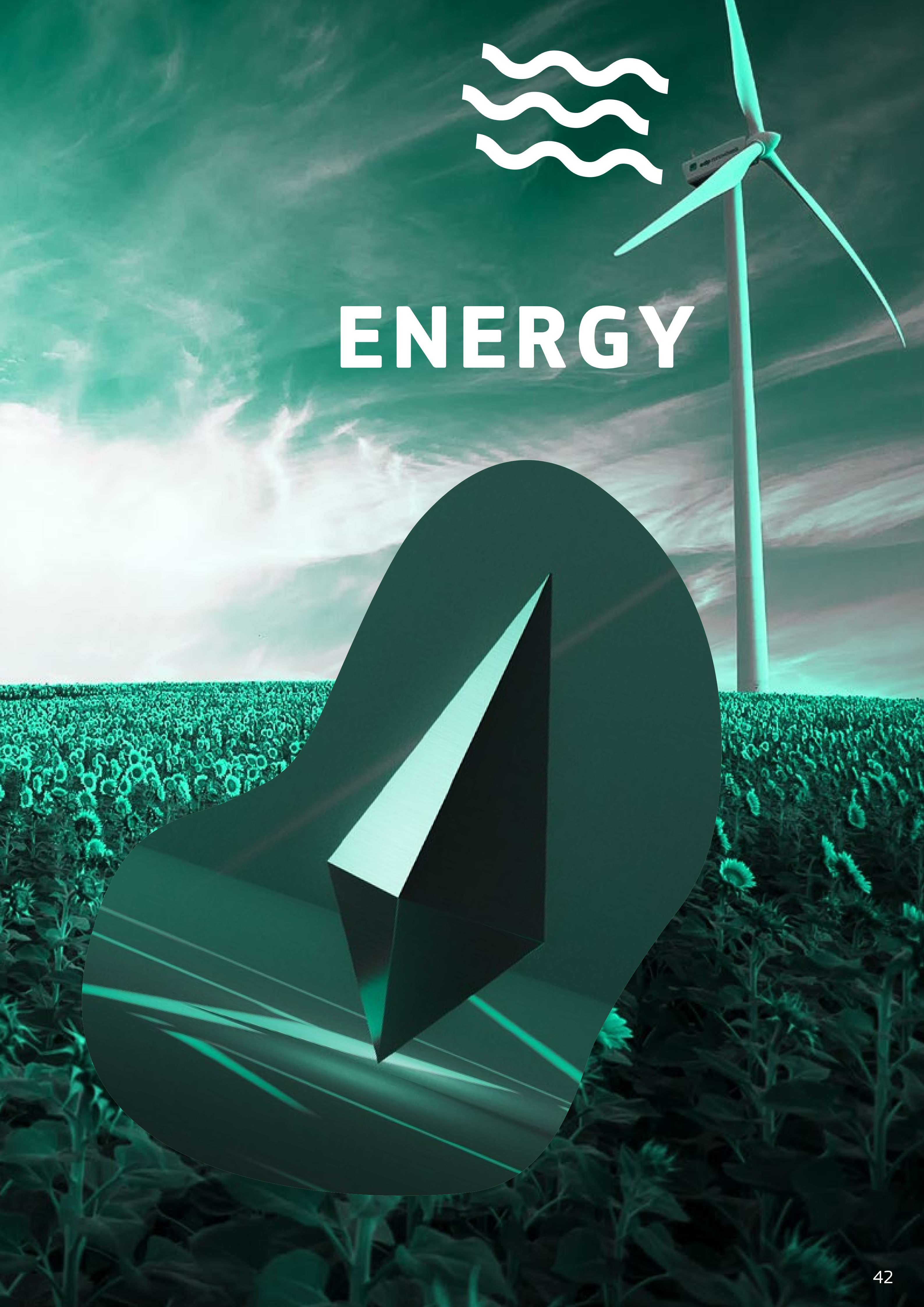
170 Beucker and Hinterholzer (2021)
171 RICS and United Nations Global Compact (2018), Hartenberger, Ostermeyer, and Lützkendorf (2021)
172 DGNB et al. (2021)
173 European Construction Sector Observatory (2021)
174 European Construction Sector Observatory (2020), European Commission (2018b)
175 DigitalEurope (2020)
176 BPIE (2020)
177 E3G (2021), Friends of the Earth Europe (2016)
178 BPIE (2020).
179 BPIE (2020)

# ENABLING FACTORS FOR GREEN-DIGITAL SOLUTIONS IN THE BUILDINGS AND CONSTRUCTION SECTOR

**Enabling factors highlight important aspects to facilitate successful transitions:**

- A key social requirement is that energy poverty and affordable housing need to be addressed to ensure fairness and public support.
- Social acceptance of technologies, for example of Internet of Things-based smart solutions and data sharing, is critical for the uptake of solutions for efficiency and space optimisation.
- Avoiding rebound effects from optimised space use, or energy efficiency gains in households, is needed to ensure these do not lead to increased consumption in other areas.
- Digital services and digital signing of contracts related to the supply of goods and services need to be mainstreamed. To enable these services, data sharing needs to be secured and trusted by all stakeholders.
- Coherent standards are needed to boost the implementation of digital building logbooks.
- Regulatory frameworks and a common set of rules for the sector could play an important role, for example for circularity, or for combining building regulations with urban planning and district-level solutions.
- Adequate financing could push the sector towards green-digital solutions, and could also ensure that there are affordable solutions available, including in rural or less-developed areas.
- Digital skills need to be strengthened in the construction sector to enable digital solutions. Skills and training are needed to realise renovation and retrofitting.

# ENERGY



## Overview of the sector

**The energy sector is the largest emitter of greenhouse gases in the European Union.** This chapter focuses on power generation (which contributes 25% of the greenhouse gas emissions in the European Union),[180] and the production of fuels. Low-cost renewable energy technologies made the energy sector a cornerstone for the transition towards a climate-neutral Europe. Research shows that early and steady emission reductions in the sector are the most cost-efficient path to climate neutrality, which means that immediate action in this sector would be highly beneficial.[181]

**The Russian military aggression against Ukraine has accelerated the changing energy security paradigm, towards energy independence and the safeguarding of critical energy infrastructures.** The war is putting an emphasis on the need for a secure energy supply and to protect an increasingly digital energy system against cyber-attacks, and possible break downs of IT systems that are of systemic relevance to the energy sector. Rising energy prices call for energy savings and energy efficiency improvements to reduce the need for fossil fuel imports. In the short term, there is the need to source gas from other suppliers and increase gas storage. Beyond short-term reactions, there is the need to speed up the energy transformation towards renewable and clean sources to decrease energy dependence.[182] Renewable energy and energy efficiency measures could reduce the European Union's dependency on Russian gas imports by two thirds by 2025 through increased efforts implementing the 'Fit for 55' package.[183]

**The transformation of the energy sector is accelerating.** For example, renewable energy-based power generation will lead to a fundamental change in how the energy system is managed. Formerly centralised power generation, where few large-scale power plants provide energy, is being replaced by more decentralised systems with a higher number of smaller-scale power generators.[184] At the same time,

180 European Environment Agency (2022)
181 Victoria et al. (2020)
182 European Commission (2022m), Delbeke (2022), Khakova (2022)
183 Bellona Europa et al. (2022)
184 Wolfe (2008)

Low-cost renewable energy technologies made the energy sector a cornerstone for the transition towards a climate-neutral Europe.

Research shows that early and steady emission reductions in the sector are the most cost-efficient path to climate neutrality.

electrification and the production of carbon-neutral fuels will increase demand for electricity. This increase can be partly mitigated through energy efficiency measures. However, it will still require a quick ramp-up of renewable power generation capacities to compensate for the phase-out of fossil-fuelled power plants.[185] Lastly, electric power systems are becoming increasingly smart with the deployment of digital technologies that help to facilitate the balancing of demand and supply. These trends are recent, but are expected to accelerate if a regulatory framework is established that fosters this energy transition.[186]

**Reaching the goal of climate neutrality by 2050 poses challenges for the energy sector.** Stakeholders have invested in centralised, inflexible fossil-based infrastructures that will have to be phased out before their end of life and could cause stranded assets of EUR 6-7 billion.[187] Furthermore, currently carbon-intensive activities, such as heating and transport, need to be electrified, which involves substantial changes in production processes and infrastructure. In addition, zero-carbon fuels such as hydrogen need to replace fossil fuels, for example where electrification is not possible.[188] The availability and costs of the critical raw materials needed for some energy technologies, such as energy storage, pose another challenge.[189] These challenges will trigger new developments that will transform the energy sector.

### Technologies enabling the green transition

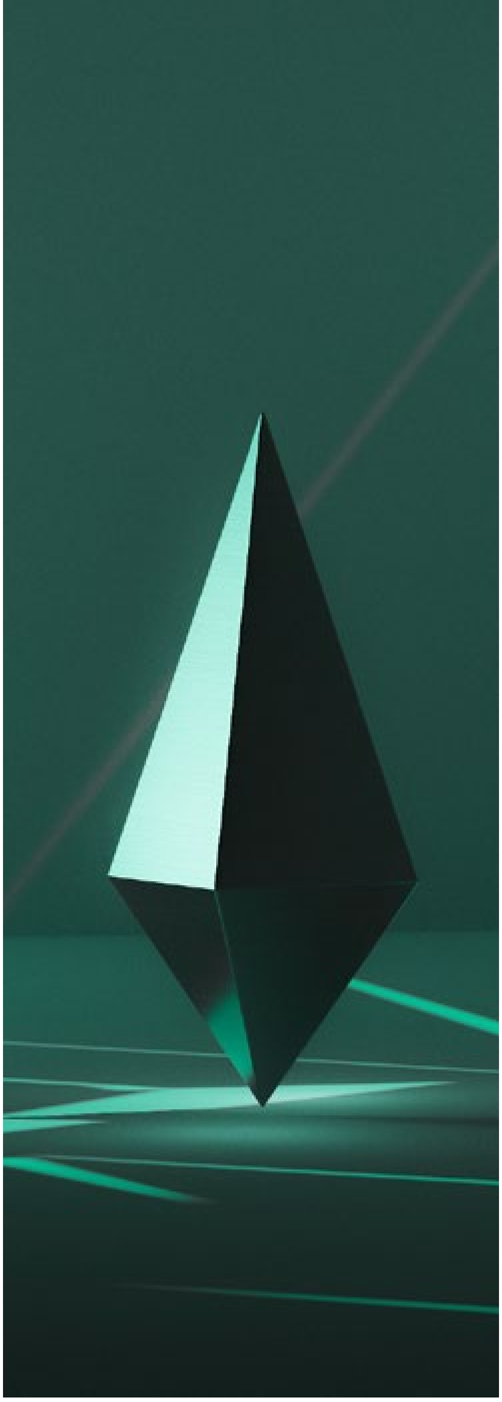
**Digital technologies can play a key role in enabling the implementation of green technologies in the energy sector.**

*Simulation and forecasting* using digital technologies can speed up research and development cycles for new materials, products, processes, or business models in areas where zero-carbon and green technologies are not yet competitive. They can also enable or improve the analysis, planning, and decision-making in the energy sector. For example, they can improve estimates of renewable power generation potential or facilitate the management of large datasets accumulated by smart meters. In addition, digital technologies can help to optimise *systems management*, in particular the operation of energy systems, power plants, electricity grids, electricity markets, or supply chains and facilities that serve such markets. Lastly, *information and communication* technologies can establish communication channels between the different stakeholders and technical elements in an energy system (e.g. to facilitate a payment between decentralised producers and consumers of electricity).

See also Figure 1 (p. 19): Functions of digital technologies >>

185 Lechtenböhmer et al. (2016), Toktarova et al. (2022)
186 MIT Energy Initiative (2016)
187 IRENA (2017), delayed policy action scenario
188 Ballentine, Connaughton, and Grossman (2019)
189 European Commission (2020m)

Several renewable power generation technologies will play a role in the energy transition but wind and solar power are the workhorses as they can be the most cost-efficient way of power generation.



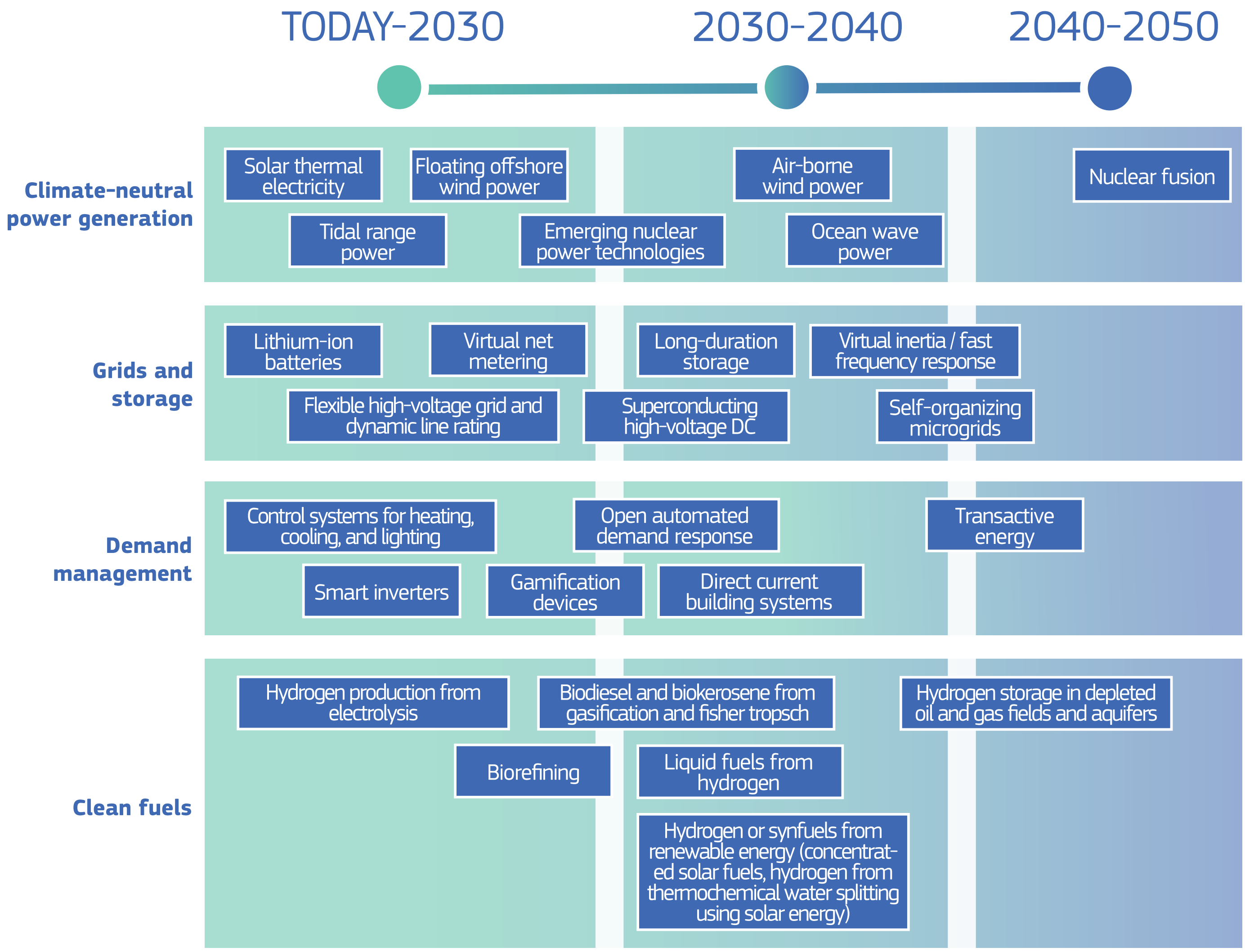
**Climate-neutral power generation** will be the backbone of the green transition. Several renewable power generation technologies will play a role in the energy transition but wind and solar power are the workhorses as they can be the most cost-efficient way of power generation.[190] Climate-neutral power generation technologies are still being improved and less mature technologies, such as ocean energy or novel nuclear technologies (e.g. Small Modular Reactors or nuclear fusion) could complement the existing technologies in the future. Digital technologies could help to track materials used in renewable energy plants and increase circularity at their end-of-life.

**Energy grids and storage** provide flexibility that will be crucial for dealing with an increasingly decentralised and variable power generation structure (i.e. where power is generated when the conditions are right, such as sufficient wind or sun).[191] This is why strengthening and modernising the energy grid and rolling out energy storage solutions will be an important enabling factor for the energy transition.[192] Digital technologies could reduce the need for grid reinforcements, for example by dynamically evaluating the capacity of the grid in real-time, which would facilitate an increase in the usable capacity of the grid.

**Demand side management** could enable the uptake of high shares of renewable energy. By

190 Joint Research Centre (2020c), International Energy Agency (2021a), Broom (2019), Lazard (2021)
191 Al-Shetwi et al. (2020)
192 Joint Research Centre (2020d), World Energy Council (2019)

**Figure 4: Green technology innovation timeline in the energy sector**




**Source: JRC expert workshops, International Energy Agency (2021b)**
**Note: These are approximate innovation timelines based on expert discussions and indicate when a certain technology might be available to the market.**

shifting energy consumption to periods of abundant renewable power generation, less renewable power generation capacity would be required, which would make the energy transition more cost-efficient.[193] Digital tools could help to simulate the demand and thus improve demand management. In addition, gamification devices and metaverses could animate end users to change their behaviour and shift their energy use.

**Clean fuels** will have to replace fossil fuels to achieve the green transition. For example, in transport, alternatives to fossil fuels will play an important role in a successful energy transition where electrification is not possible, or too expensive. Hydrogen is a promising fuel; in particular if it is produced with excess renewable energy (green hydrogen). It can be used in many applications, including aviation, long-distance road transport, residential heating, and industry.[194]

**Figure 4 illustrates green technology innovations** that can help the green transition in the energy sector and indicates when certain emerging technologies could become available up to 2050. Appendix 2 provides a more detailed description of the green technology innovation timelines in this sector.

193 Moura and de Almeida (2010)
194 Fuel Cells and Hydrogen Joint Undertaking (2019)

# CASE STUDY

## MESHED MICROGRIDS AND SELF-ORGANIZED GRIDS

### What is it about?

**Meshed microgrids and self-organised grids are closely linked concepts that could become a bottom-up way of managing the energy system.** Microgrids are small-scale energy systems that manage power generation, storage, and consumption locally. They can be 'meshed' (i.e. connected to) neighbouring microgrids to support each other if needed. Self-organised grids provide transparent signals to all users to indicate the status of the energy system (such as if there is an energy shortage risk), without the need for a central intermediary. Making the limitations of an energy grid visible to all users (e.g. by price signals) incentivises them to act in the interest of the energy system, and thereby to ensure that the security of the energy supply is guaranteed. Meshed microgrids and self-organised grids are compatible and interoperable with the current energy system, which makes a gradual phase-in possible.

### What is the role of digital technologies?

**Only full digitalisation makes the implementation of self-organised grids possible.** Digital technologies have the potential to disrupt the way the energy sector is organised. While microgrids are already implemented today, meshing them is an emerging concept. Self-organised grids still need to demonstrate the feasibility of some essential functions, such as flawless communication between all market participants, reliable peer-to-peer trading, or the real-time optimisation of power generation assets. To enable these functions, advanced information and communication technologies (e.g. sensors and fast mobile internet) are necessary. Distributed Ledger technologies such as blockchain could enable direct and fast interaction between market participants. Lastly, a self-organised grid can only function if it is fully digitalised so that real-time data on power generation, forecasts, and other analytics can be combined to optimise the management of the grid.

### What is the advantage?

**Meshed microgrids and self-organised grids are well suited to take on the energy challenges of the future.** Electricity grids in particular will experience an increase in loads by a factor of 2 by 2050 (e.g. through electrical vehicle charging). Microgrids aim to use local power generation sources, which reduces the transport distance of energy and the need to strengthen the electricity grid (by installing new lines) too. Microgrids also increase the resilience of energy supply by isolating single-point failures. In the traditional electricity grid, one failure can lead to a cascade of outages, while in a system of meshed microgrids, such a failure is contained locally, and the remaining part of the grid continues to function. This characteristic becomes increasingly important considering the increasing risks of extreme weather phenomena and cyber-attacks. Self-organised grids will increase transparency regarding issues with security of supply, and at which capacity they currently run.

### What are the challenges?

**While the openness of microgrids provides advantages, it could also lead to an unequal distribution of benefits amongst the different stakeholders, and to lower levels of grid reliability.** To date, microgrids have only been implemented where no other options existed, as their increased resilience comes at the price of higher costs. This competitive disadvantage is the biggest challenge for the large-scale introduction of microgrids and self-organised grids. Wealthy and well-educated individuals might be able to become active prosumers, but this might be less the case for the vulnerable groups of society. The openness of microgrids also means that private, less professional stakeholders will be part of the energy system with implications for the grid's stability.

# SNAPSHOT OF THE FUTURE

## What if meshed microgrids and self-organised grids were rolled out successfully?

In 2050, the energy market is not dominated by big players anymore but has become much more local. Private households have become prosumers that are selling their overflow electricity to their neighbours, or to local storage facilities, and in doing do, are ensuring the security of electricity supply. Electricity grids are now open to everyone that wants to engage and no central operators are necessary. Extreme climate change-related weather events are causing damage to the infrastructure of electricity grids. Such events would have led to wide electricity outages the 2020s, but now thanks to 'meshed microgrids', outages are contained locally and the cost to society is substantially lower.

## Environmental sustainability

**Microgrids and self-organised grids can increase the feed-in of renewable electricity without the need for grid extensions.** They can facilitate the integration of higher shares of renewable energy than the conventional transmission and distribution grids. They are also more flexible in adjusting to changes in the supply of variable electricity feed-in (e.g. from wind turbines).[195] Microgrids and self-organised grids are also well-suited to integrate small-scale power generation units such as rooftop solar PV, which would not be able to compete in a centralised energy grid. The increase in local consumption would require less new constructions of long-distance transmission lines that have an environmental impact through resource consumption and land use.[196] Lastly, the direct feedback of grid congestion to users via pricing signals could both reduce the need for back-up generation and build-up of renewable power generation capacity, which also has an environmental footprint.

## Economic sustainability

**Microgrids are a growing market that could lead to an increase in the number of small and local players in the energy sector.** The global microgrid market is expected to amount to EUR 55-190 billion in 2030.[197] Generally, grid investments create economic activity, with one study concluding that the benefit for society is four times higher than the investment.[198] A crucial advantage of microgrids is their increased reliability, as the annual cost of outages for society are substantial.[199] Furthermore, the roll out of such solutions could accelerate a shift in the energy sector from a domination of big players to a more diverse market, where many smaller local players are able to compete.

## Social sustainability

**Microgrids and self-organised grids open possibilities for a wider active participation in the energy market.** Microgrids can be a catalyst for their own social acceptance by creating an ecosystem that is much better suited for local energy communities and co-operatives. Such energy communities can provide opportunities for private individuals to benefit from the green transition and be an active part of the energy system. An easier participation in the energy market and direct transactions between local individuals or small local businesses (e.g. through smart contracts enabled by digital ledger technologies) also enable new grassroots movements. These movements could strengthen the social connections of local communities.

195 Modi and Figueroa (2015)
196 Dynge et al. (2021)
197 Allied Market Research (2022a), Transparency Market Research (2021)
198 National Energy Technology Laboratory (2007)
199 A study claims that the cost of such outages in Northeastern U.S. go into billions. See Hirsch, Parag, and Guerrero (2018).

# CASE STUDY

## ENERGY-AS-A-SERVICE

### What is it about?

**Energy-as-a-Service (EaaS) is an innovative business model that changes the way energy suppliers and consumers interact.** Currently, energy providers offer electricity, fuels, and heat to end users. EaaS is a different approach where an energy service provider would offer energy solutions in other ways to end-users: Energy service providers do not simply offer a form of energy, but rather a 'turn-key energy product' such as keeping the temperature in a building in a certain temperature range. The offer of such energy service providers includes a wide range of solutions, including energy efficiency, renewable energy provision, and solutions to stabilise electricity grids.

### What is the role of digital technologies?

**Digital technologies enable an optimised operation of energy services.** The digital transition is a catalyst for more systemic thinking. In the case of EaaS, it can help to shift from thinking in energy silos (e.g. electricity provision as separate from energy efficiency) to thinking in interconnected solution chains that can then be optimised. A variety of digital technologies enable this optimisation process. Smart meters and sensors can provide a data basis that allows for the optimisation of a certain energy service. The Internet of Things and Artificial Intelligence provide means to deal with the increased quantity of data that can be collected and enable new solutions, such as the automation of energy services.

### What is the advantage?

**Energy-as-a-Service offers a range of advantages to end-users that have to cope with an increasingly complex energy system.** A main advantage of EaaS for end users is that it reduces the need for upfront investments and simplifies the supply of energy. Covering energy-related needs has become increasingly complex, as it involves a wide range of different technologies that have to work together (e.g. power generation, power storage, or energy efficiency optimisation). This increasing complexity calls for an integrated approach to deal with energy installations. EaaS offers a chance to maximise the efficiency of the end use of energy, as energy service companies can accumulate experience, allowing them to implement better performing solutions compared to individual efforts. For example, a specialist in lighting can offer a cost-efficient and ergonomically optimised solution to illuminate a building.

### What are the challenges?

**Most challenges for the roll out of Energy-as-a-Service are linked to societal and institutional issues.** The shift from focusing on cost efficiency to a more holistic approach that also considers the environment is a challenge. End users could be reluctant to give up the ownership of the hardware that is installed on their premises,[200] or to accept new pricing models. Furthermore, as EaaS relies on real-time data collection and analysis, the energy-efficiency gains could be negated by the energy consumption of the digital technologies required for the energy service. There are also some institutional challenges, such as the risk of big players dominating the market, as they have the capacity to get expertise in the wide range of technologies that are needed to provide an energy service.

### Environmental sustainability

**Energy-as-a-Service could improve energy efficiency and enable the integration of renewable energy technologies.** Higher levels of energy efficiency could be realised, if the energy service provider is responsible for rolling out the optimal technologies to and maximising performance at the facilities of a client. EaaS could also lead to new, more democratic forms of energy sourcing,[201] for example by creating energy communities that do not maximise profits but environmental performance.[202] In addition, energy service providers could help with the integration of higher shares of variable renewable

200 Sorrell (2007)
201 Heldeweg and Séverine Saintier (2020)
202 Cleary and Palmer (2019)

## SNAPSHOT OF THE FUTURE

### What if Energy-as-a-Service was rolled out successfully?

In 2050, households no longer have to think about how to heat their homes efficiently. They will have a contract, similar to a mobile phone contract, with an energy service provider who takes care of the installation and maintenance of all the technical installations needed. Those end users who are not fortunate enough to be able to invest in state-of-the art technology can still benefit from it, as the energy service provider will cover the investment costs and charge a monthly fee to the end user. The emergence of Energy-as-a-Service has helped to achieve the European Union's energy efficiency targets by overcoming the barrier of private households' unwillingness to invest in energy efficiency measures (e.g. in rented accommodation).

energy. They can combine different types of renewable power generation technologies and manage them in a way that is in line with ensuring the stability of energy grids.[203]

### Economic sustainability

**Energy-as-a-Service is a growing market that could lead to job creation and increased innovation rates.** EaaS has already been established between businesses and is increasingly entering the business-to-customer segment. It is a market segment experiencing fast growth, with an expected compound annual growth rate of 7.6 % between 2021 and 2030, reaching a market size of EUR 113 billion.[204] EaaS could catalyse energy efficiency measures, which would have a positive impact on employment, as they lead to domestic job creation.[205] With EaaS, products become more transparent and comparable, which increases the pressure on energy service providers to offer competitive prices. This last characteristic is becoming even more important in the current geopolitical environment, with rising energy prices and increasing uncertainty about the security of energy imports.

### Social sustainability

**Energy-as-a-Service could reduce the risk of energy poverty but will also lead to fundamental changes in how energy-related infrastructure is owned.** EaaS could mitigate energy poverty because it is expected to reduce energy costs and contractually fix prices for energy services. It changes a market where utilities benefit from higher energy consumption, into one that rewards the most energy- and cost-efficient provider.[206] However, the introduction of EaaS will lead to new pricing models and ownership structures to which users will have to adapt. There will also be a shift from having full control over local physical installations, to sharing this control with a central operator. Lastly, customers will become more transparent as they share the consumption data that is necessary to optimise energy services with the energy service providers. Trust and data protection are therefore relevant factors for successful implementation.

203 IRENA (2019a)
204 Allied Market Research (2022b)
205 International Energy Agency (2017)
206 Moorhead (2022)

# ENABLING FACTORS FOR GREEN-DIGITAL SOLUTIONS IN THE ENERGY SECTOR

**Enabling factors highlight important aspects to facilitate successful transitions:**

- Coherent policies will help to establish a consensus between decision-makers in the energy sector. Such a consensus is necessary to raise the investments needed to roll out infrastructure or develop the backbone for accounting and payment systems of Energy-as-a-Service.

- The complexity of the underlying technology and processes could be a barrier for some stakeholders. Securing coherent and connected technological solutions are therefore critical, also to avoid the development of a patchwork of isolated solutions.

- Strong resistance towards the entry of new actorswould hamper the transition to more service orientation, and coherent standards could lower market entry barriers.

- Supportive regulations will be key enabling factors for the energy transition, such as carbon pricing or fewer zoning restrictions for renewable energy systems.

- The social challenges for the energy sector include overcoming opposition at national and local level, for example 'Not In My Backyard'[207] sentiments. Participation schemes for local inhabitants might increase social acceptance, for example through co-operatives.

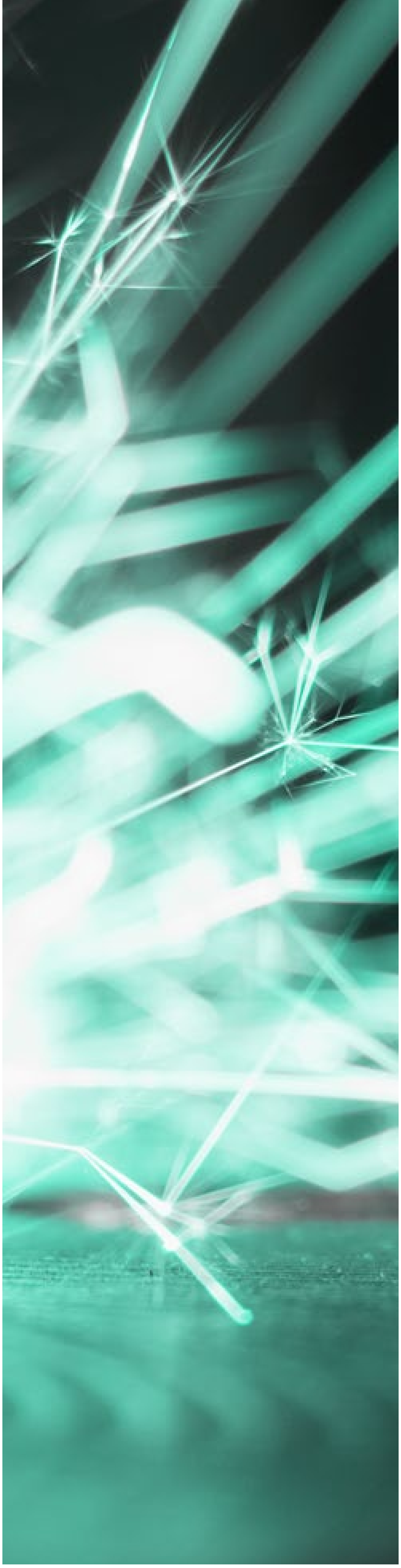
- Some of the solutions require a rethinking of current lifestyles and values, for example overcoming the idea of private ownership.

- Sustainability benefits brought by digital technologies may be negated by rebound and adverse secondary effects - unless the energy system is (re-)oriented towards inclusive practices, democratic governance, and environmental regulation.

- Regulations and institutions could be enablers for the green-digital solutions by establishing standards for interoperability in smart grids.

207 Not In My Backyard, or NIMBY, is a common term to describe the arguments and emotions of people opposing a development or activity in their vicinity while not being against a similar or equivalent action elsewhere.

# ENERGY-INTENSIVE INDUSTRIES



## Overview of the sector

**The industrial sector has a large environmental footprint, but it is crucial for the European economy and society.** Overall, the industrial sector accounts for more than 20 % of the European Union's economy and employs around 35 million people.[208] The industrial sector comprises *process industries* - that are devoted to the production of basic materials such as cement, steel, chemicals, plastics, and paper. This sector also includes *manufacturing industries* - that are devoted to the production of goods using machinery, such as components, or final products. Process industries are particularly energy-intensive and depend heavily on fossil fuels, leading to significant greenhouse gas emissions. Industry (overall) accounts for about 20 % of the greenhouse gas emissions in the European Union[209]. This chapter focuses on four selected energy-intensive industries, because approximately 70 % of the global carbon dioxide emissions from industry are caused by these four sub-sectors:[210] 1) steel production, 2) cement production, 3) chemicals production, and 4) pulp and paper production.

**The Russian military aggression against Ukraine is threatening energy-intensive industries, because they rely on gas as an essential raw material.** Gas supply is at risk due to the sanctions against Russia and due to Russia stopping exports as a geopolitical lever. Rising energy prices are already increasing the production costs of energy-intensive industries, at times even making production unprofitable. Under a severe gas shortage, governments can implement emergency measures to decide on the priority distribution of gas. These measures could force energy-intensive industries in countries that are mainly dependent on Russian gas to shut down their production.[211] Rising energy prices and the reassessment of supply dependence could push green hydrogen production as a long-term option to decarbonise energy-intensive industries.[212] The tripling of natural gas prices between March 2021 and 2022 has made

208 European Commission (2020c), European Environment Agency (2022)
209 European Environment Agency (2022)
210 International Energy Agency (2020a)
211 Sterner and Kotzur (2022), BMWK (2022)
212 Grinschgl and Pepe (2022)

renewable energy-based hydrogen production competitive already.[213] A wide supply of green hydrogen would require a substantial ramp up of production capacities and significant additions of dedicated renewable power generation capacity.[214]

**Servitisation of formerly pure manufacturing businesses and reductions in material consumption are two main trends in energy-intensive industries.** European industry is already experiencing a strong shift from manufacturing to providing services in product-service bundles, blurring the line between the secondary and tertiary sectors. Aggravating resource scarcity is perceived as a trend likely to put pressure on energy-intensive industries, because of their strong dependence on energy (so far fossil fuels) and raw materials. There is therefore already a clear trend towards less demand for raw materials. This development is supported by the emergence of technologies like 3D printing[215] and accompanied by a shift towards the purchase of services instead of products.[216]

**Greening energy-intensive industries will require rethinking on how basic materials are produced.** Industry will have a key role in reaching the European Union's climate targets. However, to date most of the 15-30 % greenhouse gas emission reductions in energy-intensive industries over the last 30 years have been achieved through energy efficiency improvements. Therefore, the effect of further efficiency measures will be small and the sector will require breakthrough technologies. Circularity is only one part of a wider transformation of industry towards climate neutrality and long-term competitiveness.[217] While new raw materials may still be needed, achieving more circularity could lead to competitive advantage by optimising waste and resources flows.[218] A variety of stakeholders will need to be involved and it will require transforming linear value chains into closed loops. In addition, enough secondary materials need to be available in adequate quality to rely on closed loop cycles. However, secondary steel production is currently not able to cover the complete demand.

## Technologies enabling the green transition

**Digital technologies can play a significant role to make energy-intensive industries greener.**

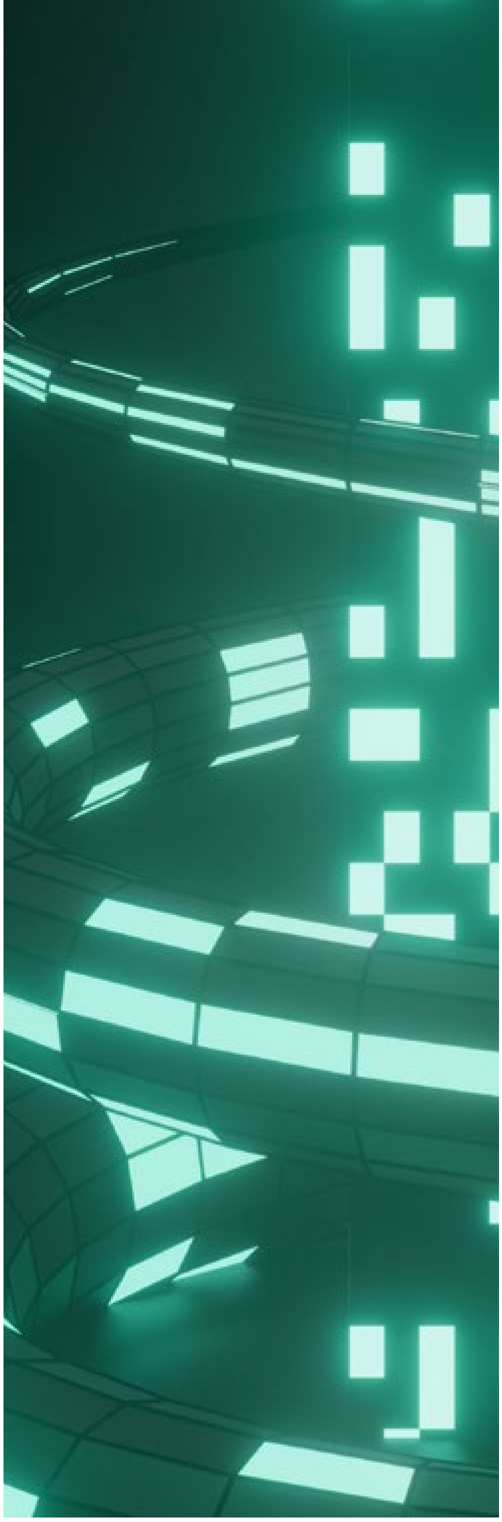
Concepts such as Industry 4.0[219] and Cyber Physical Systems[220] have led to policies that stimulate the integration of manufacturing, information technology, and other advanced technologies.[221] For example, *information and communication* solutions such as the Internet of Things (e.g. with smart meters and sensors) can play a major role in optimising energy use[222] by providing real-time awareness of energy consumption.[223] Additionally, digital technologies already play a significant role in optimising *system management* in the industry sector, for example manufacturing and process equipment are optimised using big data analytics.[224] Digital Twins can help to select green materials optimally through *simulation and forecasting*. Lastly, *monitoring and tracking* provides information about the kind of materials and parts that are used in products to intensify circularity in the economy through better maintenance and recycling.

See also Figure 1 (p. 19): Functions of digital technologies >>

In **steel** production, using scrap instead of virgin steel is already done today. However, as the amount of scrap steel is limited, primary steel production has to be transformed to become green. Digital technologies can help to optimise the production process of secondary steel while ensuring a high

213 Campbell (2022)
214 IRENA (2021)
215 European Commission (2020n)
216 Hedberg and Šipka (2020)
217 The new Circular Economy Action Plan puts forward a series of measures to allow the European Union's industry to become cleaner and more competitive. See European Commission (2020e).
218 Marchi, Zanoni, and Zavanella (2017)
219 Schmidt et al. (2015)
220 Lee, Bagheri, and Kao (2015)
221 Yin and Kaynak (2015)
222 Haller, Karnouskos, and Schroth (2009)
223 Shrouf and Miragliotta (2015)
224 Compare, Baraldi, and Zio (2020)

In chemicals production, a variety of technologies are available to reduce the environmental footprint. These include the electrification of heat, using hydrogen or biomass instead of fossil feedstock, applying carbon capture and storage, and chemicals recycling.



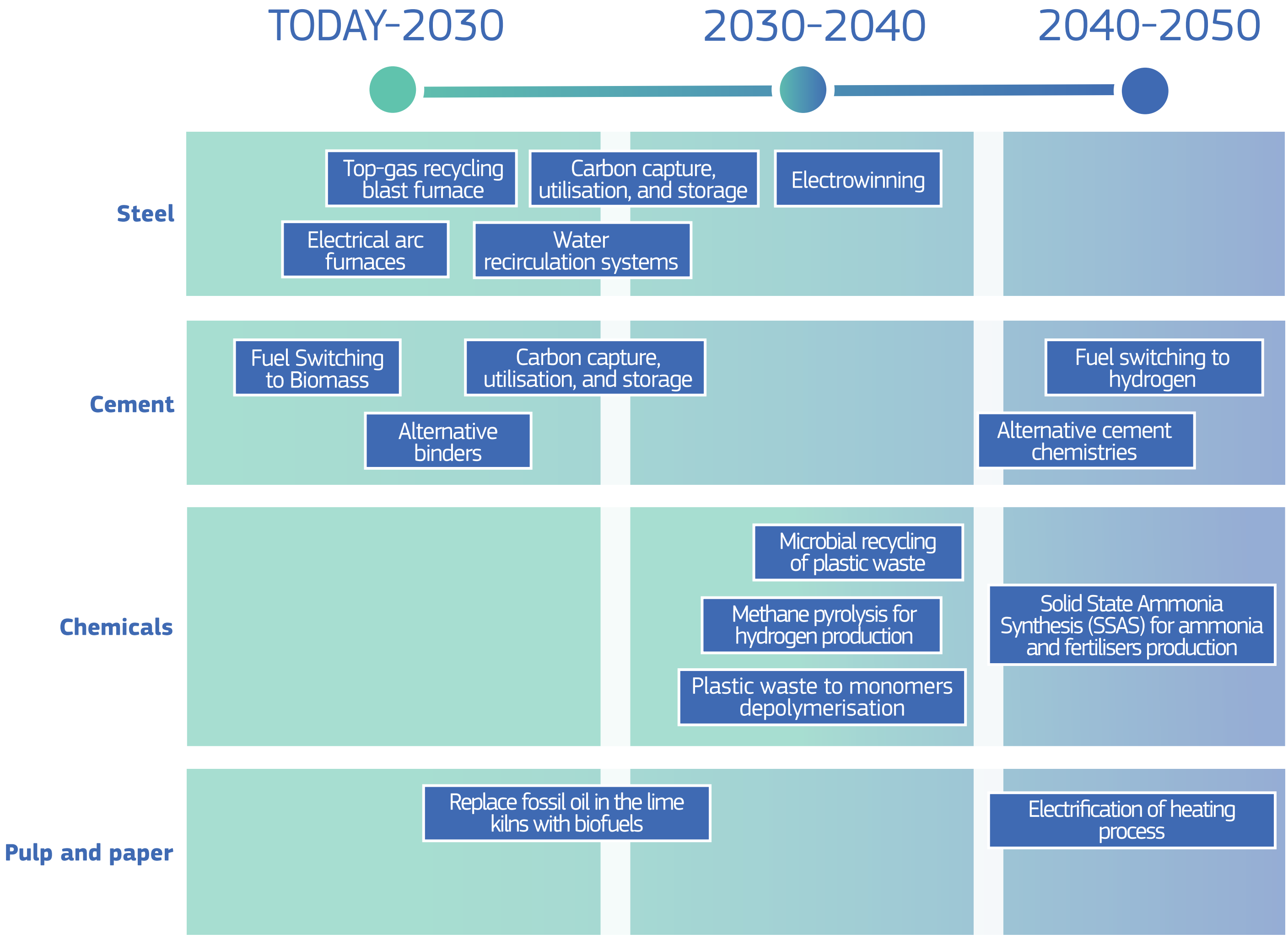
quality. Hydrogen-based steel production technologies are most promising for primary steel production and could help to decarbonise the steel sector.[225]

In the production of **cement**, clinker is an essential input material but also the main cause for emissions. Ways to reduce greenhouse gas emissions from clinker production include to replace clinker with less carbon-intensive additives,[226] or to capture the $CO_2$ emissions that cannot be avoided when producing clinker.[227] Data-driven materials optimisation for substitute materials of clinker is an example of how digital technologies can speed up research and innovation in this area.

In **chemicals** production, a variety of technologies are available to reduce the environmental footprint. These include the electrification of heat, using hydrogen or biomass instead of fossil feedstock, applying carbon capture and storage, and chemicals recycling. However, the technological readiness of these solutions in the chemicals sector is low and

225 Öhman, Karakaya, and Urban (2022)
226 UNEP (2017)
227 Voldsund et al. (2019)

**Figure 5: Green technology innovation timeline in energy-intensive industries**




Source: JRC expert workshops

Note: These are approximate innovation timelines based on expert discussions and indicate when a certain technology might be available to the market.

new research and innovation is necessary to bring these green solutions to the market.

The **pulp and paper** sector will need to deploy new production processes to become greener. New processes offer ways to develop new products and applications. Furthermore, new technologies to reduce the heat used in paper production through reduced water consumption, and the electrification of heat generation are needed to make this sector greener. Digital Twins could help to simulate how different solutions to electrify heat production could reduce the environmental footprint of the sector.

**Figure 5 illustrates green technology innovations** that can help the green transition in energy-intensive industries and indicates when certain emerging technologies could become available up to 2050. Appendix 2 provides a more detailed description of the green technology innovation timelines in this sector.

# CASE STUDY

## DATA-DRIVEN MATERIALS OPTIMIZATION

### What is it about?

**Data-driven materials optimisation helps to improve existing materials and processes and to develop new generations of materials.** Materials optimisation refers to finding the optimal characteristics of a certain material, for example to increase performance and lifetime, or to improve rates of recirculation. It also plays a role in the development of low-carbon substitute materials and feedstock. Opportunities for optimised materials can be found in each life cycle stage of a product. Data analytics-based optimisation of materials is a way to systematically reveal relations between processing, structure, property, and performance of materials, which are fundamental cornerstones in materials science. It also helps to develop new materials and production processes and to improve existing ones.

### What is the role of digital technologies?

**Artificial Intelligence and Digital Twins can help deal with the complexity of material science.** Two digital technology groups play a major role in materials optimisation. Artificial Intelligence, and more specifically machine learning, can help reduce the time needed to discover material design solutions. Artificial Intelligence can help allocate resources and preselect promising solutions, particularly if the amount of potential solutions is large and hence difficult to manage. Furthermore, Digital Twins build high-fidelity virtual models that can be used to mimic material characteristics, explore new material variants, and evaluate performance throughout the whole life cycle of a material.

### What is the advantage?

**Material optimisation can speed up innovation and analyse the complete life cycle of a product.** The use of digital technologies in material optimisation processes has several advantages. It takes between 10-30 years to develop advanced materials with conventional methods. Digital technologies can help to substantially reduce the time it requires to develop new materials and help to manage the complexity of optimisation processes. Digital technologies can also optimise materials and components throughout the life cycle of a product to increase its lifetime and re-usability.

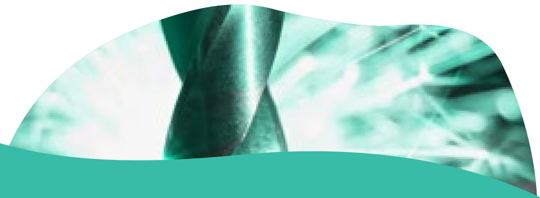
### What are the challenges?

**Technology readiness, cybersecurity, and potential societal implications are issues that might hamper digitally-assisted materials optimisation.** A main challenge is the amount of time required to fully develop some of the applications of digital technologies for material optimisation processes. Cybersecurity is also a critical issue because Artificial Intelligence and Digital Twins could do harm if they were misused. Furthermore, Artificial Intelligence requires a substantial amount of energy, which lessens the overall benefit to the green transition. There are also fears that Artificial Intelligence will endanger jobs by executing tasks that are now done by humans. There is certainly a need for highly skilled specialists to develop the digital technologies needed for materials optimisation, but these specialists might be in short supply.

### Environmental sustainability

**Materials optimisation can reduce the environmental footprint of materials production.** Materials play an essential role when it comes to the green transition, because demand for currently carbon-intensive materials is expected to grow substantially (e.g. steel +30 % and cement +10 % by 2060, compared to 2017).[228] Material innovation could reduce the need for producing carbon-intensive materials by providing greener alternatives and prolonging the lifetime of materials. In addition, shorter innovation cycles could accelerate the green transition by reducing the costs and the quantity of materials required for green technologies, such as solar panels.[229] Lastly, material design to optimise recyclability could help make the economy more circular, particularly for

228 International Energy Agency (2019)
229 Tabor et al. (2018), International Energy Agency (2019)



## SNAPSHOT OF THE FUTURE

**What if data-driven materials optimisation was rolled out successfully?**

In 2050, materials science has become a truly interdisciplinary research field. A wide range of different disciplines work together to make the best use of digital technologies in this research area, including engineers and computer specialists. Philosophers are involved to address ethical issues arising from the use of Artificial Intelligence. New materials development now happens much faster, which has helped to reduce the environmental footprint of materials production. Materials development now focuses not only on performance characteristics, but on its complete life cycle, which has helped to make the economy much more sustainable.

products and materials that are currently difficult to recycle, such as alloys.

### Economic sustainability

**Digital technologies can increase the innovation rates in material science.** Data-driven materials optimisation is a market with substantial growth potential. The global market size was EUR 88 million in 2021 and is expected to grow to EUR 749 million by 2030.[230] However, this growth prospect depends on the availability of well-educated specialists and the transferability of successful use cases (e.g. from biotech or aerospace[231]) to other sectors. Should this prove possible, an increase in innovation rates is possible, which could lead to rapid developments in materials science.

### Social sustainability

**The misuse of digital technologies and increasing competition with human intelligence might create societal tensions.** The reduction in time needed to develop new materials could also have implications for society at large. Using advanced computational resources such as Artificial Intelligence may create ethical issues. For example, while materials can be optimised to last longer, at the same time digital technologies could also be misused to develop harmful materials, or even biological weapons.[232] There might also be increasing tensions due to the competition between digital and human intelligence, which might lead to fear among workers of all skill levels.[233]

230 Globe Newswire (2022). Currency converted from USD.
231 See for instance Karthikeyan and Priyakumar (2022)
232 Urbina et al. (2022)
233 Frank et al. (2019), Webb (2019)

# CASE STUDY

## MATERIALS TRACING FOR CIRCULARITY

### What is it about?

**Materials tracing is an essential element of implementing a more circular economy.** The concept of circularity or circular economy refers to closing loops in material flows, by re-using materials at the end of a product life cycle. It also comprises other options to reduce resource consumption, such as the re-design of products to make it easier to repair them and to extend their lifetime. In a more circular economy, manufacturers would have to take on the responsibility of their product and its materials throughout the whole life cycle. Tracing will be crucial to enable the monitoring of materials and products in a circular economy. This refers to having real-time information about where materials are at a given moment, and where they have been in the past.

### What is the role of digital technologies?

**Digital technologies are essential to enable accurate, transparent, and secure tracing of materials.** Distributed Ledger Technology (the underlying technology of Blockchain) is one of the enabling digital technologies in the area of materials tracing. If needed, Distributed Ledger Technology can create an information trail that is accessible, transparent, secure, and can ensure high data standards. Another enabling digital technology is the Internet of Things, which can combine material and information flows. In this way, the Internet of Things can facilitate data collection to increase the accuracy and visibility of material and product flows. Lastly, digital product passports provide information about a product's complete value chain and thus increase transparency, which helps consumers to make greener choices and facilitates recycling. Digital product passports can also be used by authorities to verify compliance with green standards.

### What is the advantage?

**Digital technologies could increase the accuracy, availability, and trust in the information necessary to optimise materials tracing.** A combination of Distributed Ledger Technology and the Internet of Things will result in a powerful tool enabling tracing of materials throughout complex supply chains. Digital technologies could connect different stakeholders in a value chain and allow much closer collaboration between them than is possible now. Another advantage is the transparency provided by Distributed Ledger Technology, which could increase trust and foster the sharing of information with other stakeholders. Such transparency could also translate into a stronger global push for circularity. In addition, accurate data about material flows facilitates optimisation and the detection of inefficiencies.

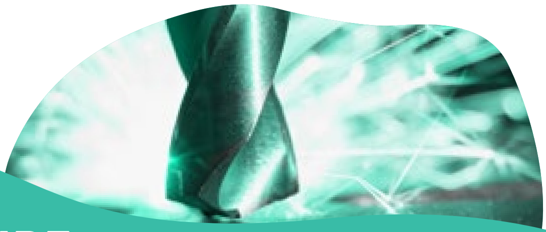
### What are the challenges?

**While digitally enabled materials tracing has a lot of potential, there are challenges to overcome.** Some of the digital technologies have a large environmental footprint. For example, Distributed Ledger Technology uses a substantial amount of energy and will have to be optimised in the future to not negate the positive environmental effect of materials tracing. Another example is the resource consumption of RFID chips, which are hard to recycle. Furthermore, the risk of misuse for surveillance and ethical issues increases with the amount of data generated through tracing. Another issue could be circular economy rebound effects,[234] which relate to an increase in resource consumption due to lower per-unit-production impacts, or price decreases for primary materials due to a reduction in demand (which would render secondary materials less competitive).

### Environmental sustainability

**A more circular economy could decrease resource consumption and greenhouse gas emissions.** Today's global throwaway society requires over 100 billion tonnes of raw materials per year.[235] Between 2010 and 2030, the consumption of materials is expected to double in the European Union without changes in consumer behaviour.[236] Digitally-enabled materials tracing could create substantial advantages, such as prolonged lifetimes of products,

234 Zink and Geyer (2017)
235 World Resources Institute (2020)
236 European Parliament (2022)



## SNAPSHOT OF THE FUTURE

### What if materials tracing was rolled out successfully?

In 2050, the European Union has implemented far-reaching measures to maximise the circularity of its economy. Digital technologies enable the tracing of materials and components of most of the products we use. This transparency has led to the emergence of organisations that provide guidance on the most sustainable products, and society is much more aware about the resource use of different products and activities. Local communities share equipment that is not frequently used (e.g. drilling machines), and repair studios for household equipment are now a common part of shopping streets.

improved waste handling, increased collection rates of end-of-life scrap, and better segregation of material streams for recycling. These impacts could reduce the consumption of primary raw materials substantially and mitigate the increase in resource consumption. Research has shown that a circular economy could decrease greenhouse gas emissions by up to 70 %.[237]

### Economic sustainability

**Circularity could have a positive economic effect and will trigger a rethinking of economic logic.** Making the economy more circular is expected to have a positive impact and would lead to job growth of approximately 4 %.[238] Furthermore, this job growth would strengthen local economies because it is expected to be rather local than centralised.[239] Another positive aspect is the reduction in dependence on material imports. The circular economy would also lead to prolonged product lifetimes and thus reduce overall material consumption. This reduction is particularly relevant for scarce materials such as rare earths.[240] A circular economy would also entail a more fundamental change in how the economy functions, as it would shift the focus away from production towards sufficiency.[241]

### Social sustainability

**A circular economy could profoundly change the way society works.** Moving from a linear to a circular economy would also impact society. With more transparent material flows, consumers could become aware of their own environmental footprint and could make better-informed decisions when buying goods and products. Longer lifetimes of products would slow down the pace of consumption, which would be a change from today's throwaway society. Households, and particularly families, would benefit from such a development, which research has shown could result in an increase of disposable income of 11 %.[242]

237 Stahel (2016)
238 Stahel (2016)
239 Joint Research Centre (2021b)
240 Joint Research Centre (2021a)
241 Stahel (2016)
242 Circular Economy for SMEs (2022)

# ENABLING FACTORS FOR GREEN-DIGITAL SOLUTIONS IN THE ENERGY-INTENSIVE INDUSTRIES SECTOR

**Enabling factors highlight relevant areas of action to facilitate successful transitions:**

- Circularity is a main component of the twin transitions and it requires a coherent technology ecosystem.
- Another key requirement is cybersecurity to protect the data of industrial processes and the integrity of their functioning, together with protection against threats to digital infrastructure that support supply-chains and logistics.
- Political factors are relevant for end-of-life and waste regulations. They could also boost the demand for cooperative business models and extend the responsibility of producers.
- Local governments play a major role in the transitions, because the collaboration with local communities and municipalities is crucial, for example to ensure high recycling rates.
- The environmental footprint of digital technologies will need to be kept in check to maintain a positive net impact on the climate and environment.
- Major societal requirements include overcoming the lack of corporate culture for sustainability and the general poor knowledge about materials.
- There is a need for improved insights into consumption patterns, lifestyles, and social acceptance, which could come from increased social science and humanities research.
- Competition for highly skilled specialists will likely play a role in the near future. Developing such talent in the EU, together with effective and adequate upskilling efforts, are key requirements for the materials sector.
- Necessary mentality changes in the sector may be to shift focus from single production units to clusters of firms. This development links to holistically addressing the structure of value chains and benefit sharing across different actors of the value chains

# TRANSPORT AND MOBILITY

## Overview of the sector

**While not the largest emitter of greenhouse gases in the European Union, the transport sector is a polluter, and its greenhouse gas emissions are increasing.** Transport covers different modes of mobility: air, waterborne, rail, and road. One development in this sector is the shift to multimodality, by combining different modes of transport in a single journey.[243] Domestic transport contributed to approximately 22 % of the European Union's greenhouse gas emissions in 2020.[244] A particular characteristic of the transport sector is that despite policy measures aiming to reduce emissions, they increased by 10 % between 2011 and 2019.[245] Other relevant environmental impacts of this sector in addition to greenhouse gases are fine particles, nitrogen oxide, and noise. E-mobility has the potential to reduce emissions and reduce oil dependency of transport. Electricity is already being used for cars and trains, while waterborne and airborne transport have been limited by the long lifetimes of the existing fleet and the technical limitations of the possible distance range.

**The Russian war of aggression against Ukraine is posing supply chain risks to vehicle manufacturing because it has put production sites in Ukraine and Russia at risk.** The automotive sector has been affected by short-term supply shortages due to production shutdowns in Ukraine, for example with regards to wiring and cables. Sanctions against Russia are also affecting the ability to operate at Russian production sites of automotive suppliers and manufacturers. Raw material shortages of steel products from Russia, Ukraine, and Belarus are further challenging the global mobility and transport industry.[246] Finally, rising energy prices are driving up supply costs for products from energy-intensive production, such as steel, aluminium, and glass. Therefore, the costs of production processes for vehicles is increasing. Record-high fuel costs could be a driver for a change in mobility patterns and a reduction in travelling.[247]

243 Joint Research Centre (2020e)
244 European Environment Agency (2022)
245 European Commission (2020o)
246 CLEPA News (2022)
247 International Energy Agency (2022)

For the green transition to be a success, a systemic reduction of overall environmental impacts is needed as well as adequate transport and digital infrastructures to keep the quality of the service high.

**Trends in the transport sector may be pointing to fundamental changes in technologies and user behaviour.** While urban and rural areas face different challenges,[248] there are some overarching trends in the transport sector. Growing consumer awareness of the environmental impact of transport could lead to a shift from owning a means of transport to using it as a service.[249] For the green transition to be a success, a systemic reduction of overall environmental impacts is needed as well as adequate transport and digital infrastructures to keep the quality of the service high. Transport is becoming more personalised and a larger share of micro-mobility solutions is making the personalisation of transport possible (for example bicycles and scooters for rent).[250] Furthermore, the focus on circularity is forcing stakeholders in the transport sector to change their business models to adapt product life cycles, reconfigure value chains, and rethink the end-of-product use.[251]

**The transport sector faces distinct challenges in the context of the green transition.** It is crucial to both guarantee sufficient access to clean electricity and strengthen electricity grids to transport this electricity. Renewable energy availability is also key to reducing the carbon footprint of battery manufacturing. Solutions are needed to store enough energy for heavy duty forms of transport over long distances. An appropriately dense charging and refuelling network is also necessary. Furthermore, over 70 % of passenger journeys are made by car, and 75 % of all the goods transported across Europe are delivered by road freight transport currently. It is estimated that passenger transport will increase by 42 %, and freight transport by 60 % by 2050.[252] Lastly, the creation of a value proposition and incentives are crucial for users to change their habits. To successfully do that, there is a need for a deeper understanding of user needs, and how to give the right incentives for both users and service providers to change. Purposeful approaches to urban policy and planning are central in this context. In the same vein, the main challenge is to make transport systems cleaner and fairer by improving both the technologies and governance needed for the green transition and involving citizens in the rollout of innovative mobility solutions.[253]

### Technologies enabling the green transition

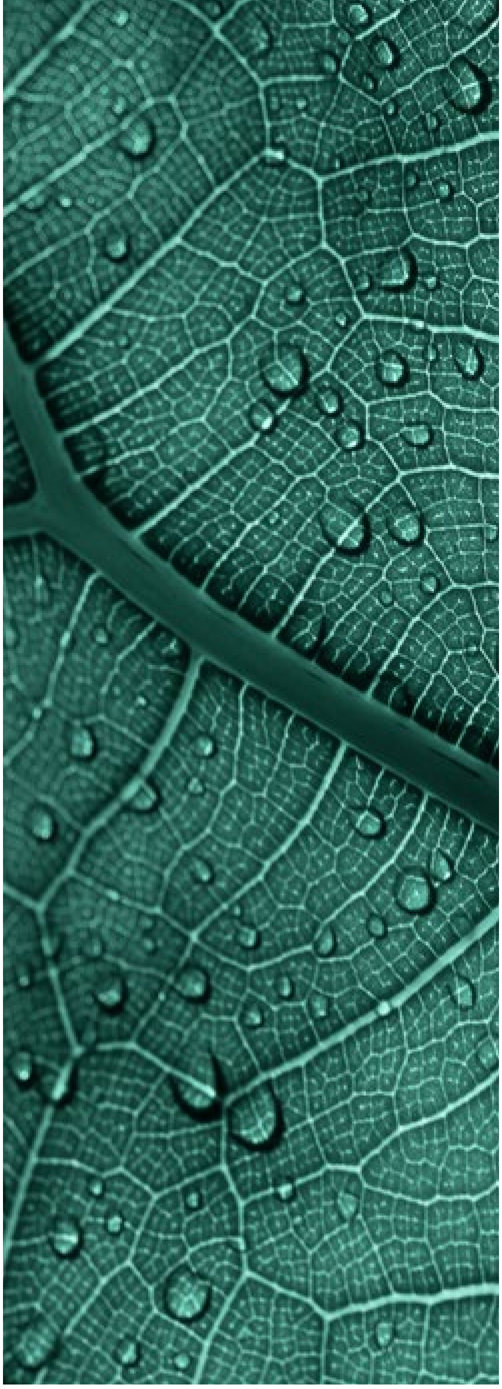
**Digital technologies could help to optimise the lifetime of vehicles.**

*Monitoring and tracking* via digital technologies could extend the lifetime of the mobility means. *Simulation and forecasting as well as virtualisation tools* can also support and boost the design of mobility assets for a maximised lifetime, taking into account circularity issues and the environmental footprint. These tools are being used at the initial stages of designing new transport means, which could be rolled out in the coming decades.

See also Figure 1 (p. 19): Functions of digital technologies >>

248 United Nations Economist Network (2020)
249 Deloitte (2017)
250 Abduljabbar, Liyanage, and Dia (2021)
251 Lacy, Long, and Spindler (2020)
252 2Zero Partnership (2021)
253 Joint Research Centre (2019)

New mobility solutions could reduce the environmental burden of travelling. Service-oriented mobility models, such as Mobility-as-a-Service could increase the willingness of and convenience for end users to switch to low-carbon transport means.



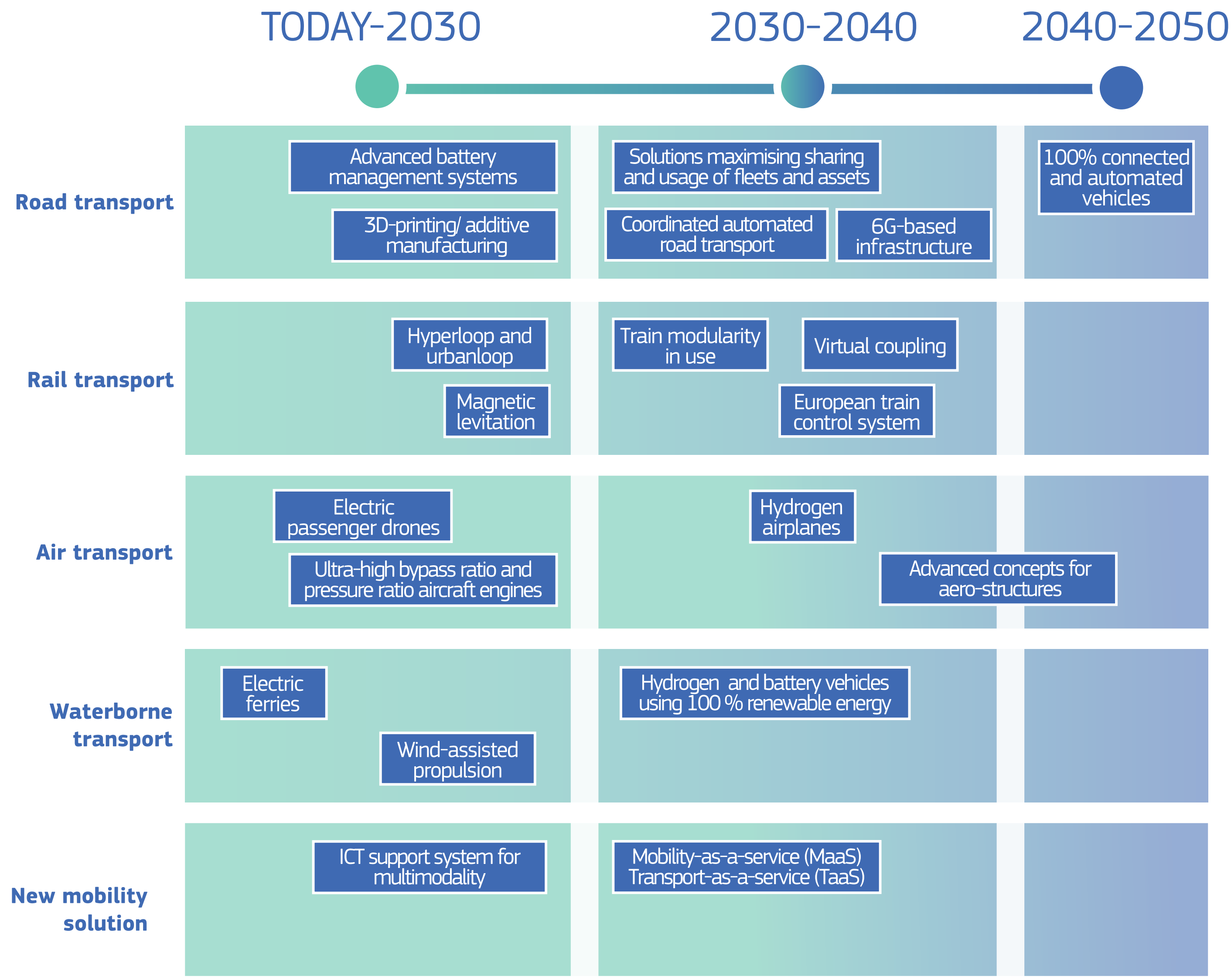
In **road transport**, developing technologies that are user friendly will be critical. Options to decarbonise road transport include electrification, for example by using batteries or hydrogen instead of fossil fuels.[254] The optimisation of energy use in road vehicles will be important to increase their range.[255] Fast mobile internet and universal connectivity in combination with improved traffic management systems will be key to optimising traffic circulation.

In **rail transport**, new concepts and the optimisation of infrastructures are being pursued. An example of such new concepts is the so called 'hyperloop' (or train in a tube), which would substantially increase the speed of trains.[256] In addition, further development of existing technologies could lead to environmental improvements and an increased attractiveness of trains as a means of transport.[257]

In **aviation**, changing the propulsion to zero-carbon technologies could be a game changer. New propulsion systems include hybrid electric planes for shorter ranges and hydrogen-powered planes for longer ranges.[258] These new developments would likely require a re-

254 Joint Research Centre (2020f)
255 Padilla P. (2020)
256 Joint Research Centre (2020f)
257 Joint Research Centre (2021f), Shift2Rail (2022)
258 Fuel Cells and Hydrogen Joint Undertaking (2020)

**Figure 6: Green technology innovation timeline in the mobility and transport sector**




Source: JRC expert workshops

Note: These are approximate innovation timelines based on expert discussions and indicate when a certain technology might be available to the market.

design of aeroplanes. Digital technologies such as quantum computing could play a role in speeding up the development of such novel architectures. Drones might also play an important role in future urban transport.[259]

In **waterborne transport**, electric engines and zero-carbon fuels could enable the green transition. Switching from fossil fuels to batteries, hydrogen, or ammonia are promising options to decarbonise waterborne transport. Furthermore, digitalisation has a high potential to optimise operations and traffic management in waterborne transport.

**New mobility solutions** could reduce the environmental burden of travelling. Service-oriented mobility models, such as Mobility-as-a-Service[260] could increase the willingness of and convenience for end users to switch to low-carbon transport means. There are also new forms of micro-mobility that might render the use of cars unnecessary for shorter distance transport.[261] The need to reduce environmental impacts at systemic level remains crucial when rolling out new mobility solutions.

**Figure 6 illustrates green technology innovations** that can help the green transition in the transport and mobility sector and indicates when certain emerging technologies could become available up to 2050. Appendix 2 provides a more detailed description of the green technology innovation timelines in this sector.

259 Aurambout, Gkoumas, and Ciuffo (2019)
260 Joint Research Centre (2020f)
261 ORCHESTRA (2020)

# CASE STUDY

## MOBILITY-AS-A-SERVICE

### What is it about?

**Mobility-as-a-Service (MaaS) is a solution whereby a digital platform provides integrated travel options using a variety of means in real-time.** The solution covers both passenger and goods transport. Users would be able to make their decisions based on accurate, real-time information on the travel time, cost, and environmental footprint. MaaS should enable users to get the best value proposition and pay for the whole journey through a single payment system. MaaS is a promising way to organise passenger mobility, and already today there are multiple initiatives in Europe. However, there is a need to scale up MaaS solutions, and to include many mobility options such as micro mobility, public transport, taxis, and shared vehicles. It is important that public transport, including the rail sector, provides the reliable backbone of MaaS solutions. In the short term, MaaS needs to become mainstream and move beyond local trials to demonstrate its viability at a broader level. MaaS is likely grow gradually, initially mostly in cities but eventually also to inter-urban connections.

### What is the role of digital technologies?

**Digital platforms and the Internet of Things underpin Mobility-as-a-Service.** MaaS is largely driven by the digital and intelligent transport systems industries, and many public authorities are beginning to embrace this concept. MaaS relies on several digital technologies to link real-time data, a user platform, and a single payment system, all of which are accessible on mobile devices. Secure data sharing is a main enabler of MaaS. In addition, data can be used to optimise the mobility system by enhancing traffic management. Digitalising mobility providers and secure data-sharing is important to include all mobility means in MaaS, including public and micro mobility. Reliable and fast connectivity is needed to unlock the full benefits of MaaS for both the user and provider. Digital tools will also be instrumental when striving for system optimisation. Artificial Intelligence provides clear advantages in dealing with complex optimisations, for example to find optimal routes, or to dynamically assign prices to rides corresponding to demand. Digital technologies also enable autonomous vehicles, which are expected to form a part of the mobility ecosystem by 2050 and could increase the convenience of MaaS solutions.

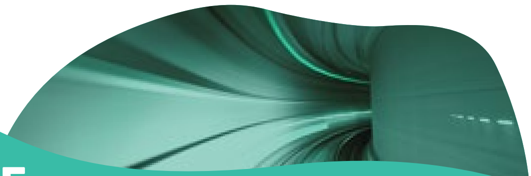
### What is the advantage?

**Mobility-as-a-Service could help to provide a more efficient, reliable, and climate-friendly transport ecosystem.** Private cars have been the default option in most European societies, with significant detrimental effects on the environment, climate, and human health. In the context of the twin transitions, MaaS has the potential to make mobility more accessible, inclusive, and sustainable if it is implemented with a fleet of clean and low-carbon vehicles and favours public transport solutions. Creating interconnectivity across the transport modes and working towards a more systemic approach for the mobility sector could lead to large efficiency gains as well as to a better organised system overall. MaaS could lead to the optimisation of mobility, including resource efficiency of transport assets (infrastructure and transport means), transport system efficiency, overall reduced waiting times and congestion, and reduced emissions and pollution if appropriate technologies are used and implemented successfully.

### What are the challenges?

**Securing cooperation between all mobility service providers and reliable, integrated mobility options in rural areas are main challenges for rolling out Mobility-as-a-Service.** Currently, the potential of MaaS exists mainly in urban areas. To make a real difference, a variety of integrated mobility options must also be available in rural and less-developed areas, which is not the case today.[262] Furthermore, MaaS has to build on low-carbon transport means to ensure an overall reduction of environmental impacts of transport. It is essential that the overall transport system becomes better integrated. This is a significant challenge given the complexity of the sector. A whole range of aspects will need to be addressed together, including road infrastructure management and the availability and financing of public transport. Improving the governance of the transport system, and ensuring that public transport plays a central role, are also necessary to make sure MaaS contributes to the green transition. The public and private sectors must be aligned, and an environment of efficient and trusting collaboration needs to be created. Finally, MaaS must be developed and deployed with the needs of the end-user in mind. This is also critical for a positive environmental impact, because MaaS needs to be convenient and affordable

262 Labee, Rasouli, and Liao (2022)



# SNAPSHOT OF THE FUTURE

**What if Mobility-as-a-Service was rolled out successfully?**

In 2050, integrated mobility and transport solutions are available in cities, towns, and rural areas. Everyone can find the travel options best suited to their needs through easily accessible digital platforms on their mobile devices. Mobility-as-a-Service is convenient and affordable, combining various low-carbon transport means, real-time data, and a single payment system. Digital platforms and apps vary across Europe but are similar and interoperable, and users can intuitively operate new platforms. Public transport is favoured and the private car is less dominant now. In cities, many roads and parking lots have been turned into liveable spaces. Transportation is optimised and efficient in both cities and rural areas, and there is little traffic and congestion. New transportation modes, like autonomous vehicles, have been designed to easily integrate into the Mobility-as-a-Service solution. Appropriate governance systems support this integration.

enough to surpass the private car. Changing travelling behaviour from individual motorised transport to MaaS is challenging for many people who are used to the routine of using their own car.

## Environmental sustainability

**An effective roll out of Mobility-as-a-Service could reduce the use of private cars.** Passenger and freight transport are estimated to increase significantly by 2050, making it more difficult to achieve Europe's climate and environmental targets.[263] MaaS could have a high impact on the green transition by reducing the use of cars and shifting transport to more environmentally-friendly means, if it is appropriately integrated in the transport system. If MaaS would totally replace individual private car usage, there could be a reduction in $CO_2$ emissions of over 50 % according to one simulation study.[264] In addition, MaaS could lead to a more efficient use of a range mobility options and an overall reduction of congestion and traffic. The environmental impact of ticketing systems could also be reduced by switching to online platforms. User awareness could be raised by promoting the most environmentally-friendly means of transport.

## Economic sustainability

**Mobility-as-a-Service draws on a systemic approach of mobility and the sharing economy.** Providers of MaaS may be public, private, or public-private partnerships. MaaS can also enable new business models with actors that are new to the transport and mobility sector. New actors, such as SMEs for ticketing, micro mobility means, or data handling could enter the market and boost the economy. The market size of MaaS is expected to grow significantly to EUR 210 billion worldwide by 2025.[265] Global revenues generated by the use of MaaS platforms have been estimated to exceed EUR 48 billion by 2027.[266] Lastly, MaaS can increase the convenience of multimodal transport and thereby be a means to gain more customers for public transport providers.

## Social sustainability

**Mobility-as-a-Service can make travel more convenient and inclusive.** MaaS can have a positive impact on well-being by optimising mobility (less traffic, pollution, and noise) and by promoting healthier mobility options. As MaaS enables a large ecosystem of mobility options, it can be affordable and inclusive, with many alternatives including many public transport options. Ultimately, a successful MaaS solution would be more convenient, cheaper, and healthier for the user.

263 2Zero Partnership (2021)
264 ITS4Climate (2019)
265 Statista (2020). Currency converted from USD.
266 Lebas, A. and Crutzen, N. (2021)

# CASE STUDY

## DIGITAL TWINS IN TRANSPORT

### What is it about?

**A Digital Twin is a virtual counterpart to a real-world system, asset, or process**. A Digital Twin is a digital space that shows what is happening in the real world. It is a mapping technology of the virtual and physical world, based on real-time data. This rich virtual environment can use Artificial Intelligence to optimise and predict real-world situations, and it can help to overcome the barriers to data analysis that arise from lacking interoperability and heterogeneous data. For the mobility and transport sector, Digital Twins could use data from sensors and Internet of Things-enabled vehicles to control vehicles safely from the cloud. They also help to facilitate the matching of vehicles with appropriate services and lead to significant reductions in development periods and costs. Digital Twins are highly relevant in the context of smart cities, for example to optimise traffic flow.

### What is the role of digital technologies?

**Digital Twins rely on many emerging digital technologies, such as the Internet of Things and Artificial Intelligence.** Digital Twins require a fast network infrastructure in order to send real-time information from physical objects to their digital counterparts and vice versa. Fast mobile internet is also needed to accommodate the growing number of devices sharing the frequency spectrum. Digital Twins are at a very early stage and face several challenges that still need to be overcome. Digitalisation of the real world requires dynamic infrastructural information that creates large amounts of data. Managing this exponential growth of data requires strong computational power. Nevertheless, digital Twins are continuously improving and delivering increasingly better insights into how products and processes can be optimised.[267]

### What is the advantage?

**The main advantage of Digital Twins is enabling better decision-making, optimisation, and efficiency.** Digital Twins can be used to optimise the mobility sector in a number of ways, but their usage in the sector is still at an early stage. Digital Twins of single assets or components can be used to test and develop products, track functions (e.g. vehicle health), and predict maintenance needs. Digital Twins of larger ecosystems can be used to monitor transport and infrastructure, traffic and logistics management, or intelligent driver assistance. Digital twin technology can also be used in battery management, smart charging, and battery life cycle management. Digital Twins of urban environments can optimise the real-time urban mobility conditions by predicting future states. On this basis, they can support advanced decision-making to align resources more efficiently for passenger and freight transport. For example, urban Digital Twins could simulate and evaluate the effect of new city structures on urban mobility and transport to improve city planning.

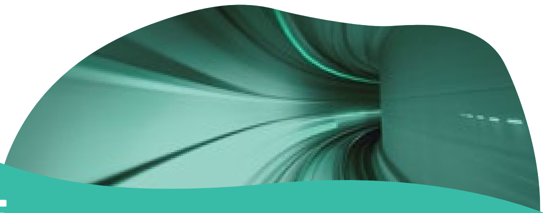
### What are the challenges?

**The main challenge for Digital Twins is the complexity of real-life situations, lack of standardisation and data governance, and digital infrastructure requirements.** Whole ecosystems, such as cities, include complex real-life situations with many stakeholders and behaviours. This is a challenge for Digital Twins that often draw on linear logic, based on more stable cause and effect relationships. Another challenge is that data between very heterogeneous players must be standardised. The benefit of Digital Twins is based on a network effect. This means that the value creation increases with the number of participants. In order to achieve this, standardisation and interoperability is needed.[268] Furthermore, Digital Twins rely on having a vast number of data sources, making privacy and data security essential components for success. Safe, protective, and transparent data governance is necessary to build the foundation for user acceptance.

### Environmental sustainability

**Digital Twins can help us to make better decisions for sustainability.** Digital Twins can optimise mobility by analysing a range of information, such as user behaviour and local traffic flow patterns.

267 IBM (2022)
268 ERTRAC (2022)



## SNAPSHOT OF THE FUTURE

**What if Digital Twins were rolled out successfully in the transport and mobility sector?**

In 2050, Digital Twins are a standard part of decision-making in the transport sector. They are used in product development for businesses, academia, and by local and regional governments. This way, they are able to identify and test solutions to find the most suitable and sustainable option. This testing ability allows them to react and adapt more quickly to changes. Digital Twins are integrated into the management of many processes, from cities and towns to production lines. Digital Twin technology in mobility has made travel safer and more efficient.

By identifying inefficiencies, Digital Twins can be used to find more energy-efficient approaches. They can also lower the carbon footprint of different transport systems by optimising the overall mobility process. Within transport manufacturing, Digital Twins enable resource-friendly product development and testing because it can be done digitally. Based on user feedback and improved data collection of requirements, product usage, and user preferences, the Digital Twin technology can enable a better alignment of products to user needs. This is particularly relevant in the context of an expected increase in demand for customised products and services.[269]

### Economic sustainability

**Digital Twins could help to speed up innovation cycles and identify areas for optimisation.** Digital Twins can help companies to monitor assets and projects, accelerate product development and testing, optimise the operation process, improve service quality, and improve the accuracy of risk assessments.[270] Digital Twins could provide businesses with insights on where to cut costs and boost profits. Research and development could also be improved with Digital Twins by predicting performance outcomes of innovations. Digital Twins would provide actionable information to stakeholders and service providers to analyse data and control vehicles safely from the cloud. This information could facilitate the matching of vehicles with appropriate services and lead to significant reductions in development periods and costs. Digital Twins could also be used in vehicle manufacturing, to improve efficiency of complex machinery and engines. Urban Digital Twins could help to roll out new mobility solutions, such as Mobility-as-a-Service.

### Social sustainability

**Digital Twins could provide a basis for informed decision-making by visualising potential options.** Digital Twins can visualise higher degrees of complexity by creating links between diverse sources of information and integrating predictive and scenario elements. This function can bridge the gap between data and its use in advanced decision-making. A city will be able to simulate different scenarios of urban development and their impacts on various outcomes, such as noise, the environment, and citizens' well-being.[271] Digital tools such as metaverses and extended reality could provide an experimental playground to try out alternative organisations of cities and societies.[272]

269 A. Rasheed, O. San, and T. Kvamsdal (2020)
270 Tao, F., Zhang, M., and Nee, A.Y.C. (2019)
271 The project DUET (Digital Urban European Twins) is an early example of this. See DUET Digital Twins (2022).
272 Helbing, D. and Sánchez-Vaquerizo, J. A. (2022)

# ENABLING FACTORS FOR GREEN-DIGITAL SOLUTIONS IN THE TRANSPORT & MOBILITY SECTOR

**Enabling factors highlight important aspects to facilitate successful transitions:**

- Citizen involvement, social acceptance and trust are key for the roll out of many of the targeted new technologies, such as E-mobility, car-sharing, Mobility-as-a-Service, or automated vehicles.

- Consumers and citizens will need to adapt to these new technologies and business models, which is why convenience and ease-of-use are essential.

- A shift from owning towards sharing will help, if it is based on clean and low-carbon transport means and if it reduces overall environmental impacts from a life-cycle perspective.

- Possible rebound effects will need to be considered when designing solutions and policies, for example to avoid the situation that a higher efficiency and service level of mobility leads users to travel more than they do now, or emptying roads encourages private car use.

- Upskilling, especially at public transport providers, could help to make such systems open and more amenable to more advanced green-digital solutions, with the engagement of more mobility stakeholders (including city authorities).

- A large variety of stakeholders need to collaborate in an open ecosystem, and an improved governance of the mobility sector is needed.

- There are clear digital and physical infrastructure requirements for the transport and mobility sector. These include fast and reliable connectivity, seamless integration of all the physical connections between different mobility options, schedule integration, and a broad service coverage.
- An important political factor is the implementation of an adequate regulatory framework, for example an effective pollution regulation, an autonomous driving regulation, and technology certification.
- Political factors will play a role in ensuring integration and interoperability, and in securing fair data processing and exchange.
- As in other sectors, financial and other incentives play an important role in motivating people and businesses to change.
- Public financing to boost market dissemination will be needed for quite some time, until prices are able to compete to unlock green benefits.

# 7. KEY REQUIREMENTS FOR THE GREEN AND DIGITAL TRANSITIONS

**The green and digital transitions face several challenges.** Chapter 6 illustrates the benefits and future potential of digital technologies for the green transition, but also highlights some challenges of green-digital solutions. In fact, the successful implementation of these solutions faces several social, technological, environmental, economic, and political barriers. Table 1 provides an overview of such potential hurdles for the twin transitions, identified through an analysis of ten case studies.

**Meeting certain key requirements would increase the chances of successful green and digital transitions.** The goal of this chapter is to raise the awareness of stakeholders and policymakers of potential enablers to overcome these identified challenges for the twin transitions. There are often several policy instruments to achieve a certain goal, and a successful green and digital transition will be no exception. For example, the goal of overcoming energy poverty can be addressed by different measures, including financial aid to households at risk, support to increase the energy efficiency of buildings, setting caps for energy prices, or increasing the share of cheap renewable energy generation. This study does not focus on the optimal policy options, but rather on key requirements that have to be met to increase the chance of successful twin transitions. Building on this scientific evidence, the European Commission has adopted the Communication '2022 Strategic Foresight Report: Twinning the green and digital transitions in the new geopolitical context', which identifies key areas where political action is needed to reinforce the synergies between the twin transitions.

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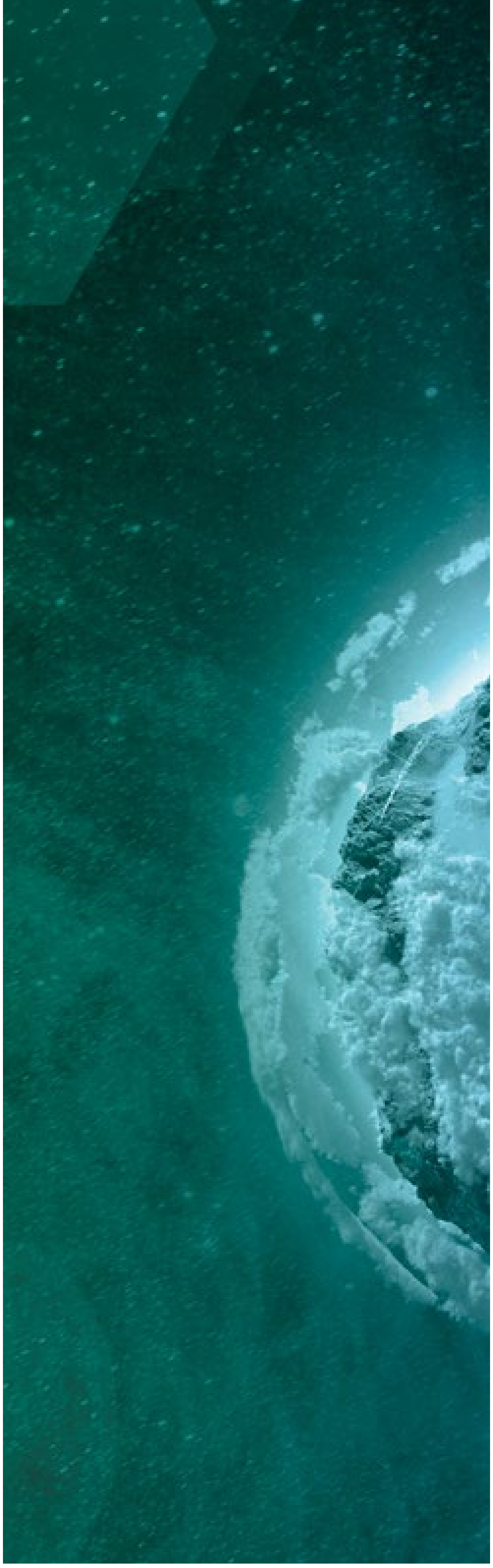
This study does not focus on the optimal policy options, but rather on key requirements that have to be met to increase the chance of successful twin transitions.



**Key requirements are presented according to different relevant areas: social, technological, environmental, economic, and political.** Most of the key requirements depicted in Table 1 affect several of these areas but have been allocated to the one for which they are most relevant. For example, *ensuring privacy* of end users is a relevant topic for politics, as regulations can guarantee high levels of privacy.[273] However, privacy is a crucial factor that may decide whether society will support the green and digital transitions. It has therefore been listed as a social issue. Another example is to *create enabling markets*, which would likely be a catalyst for innovation, acceptance, and market uptake of green-digital solutions. Nevertheless, a functioning *innovation infrastructure* is still necessary to fill the pipeline of emerging technologies and enable markets to turn research into innovation. Therefore, both are listed as separate key requirements. These examples also show that the key requirements are often interlinked, and underline that solutions and interventions need to be considered holistically.

273 European Commission (2020p)

**Table 1: Challenges and key requirements for the green and digital transitions**

| | Challenges | Key requirements | |
|---|---|---|---|
| **Social** | • Risk of energy poverty<br>• Unequal access to green subsidies<br>• Unequal opportunities created by the twin transitions<br>• Digital divide (between social groups and regions) | **Ensure just transitions** | ✓ |
| | • Green efforts focus on marginal improvements instead of step changes<br>• No sense of urgency to implement the green transition<br>• Focus only on economic instead of also on environmental aspects<br>• Reluctance to change habits<br>• Green lifestyle questions status symbols<br>• Established values are questioned | **Increase societal commitment to the need to change** | ✓ |
| | • Privacy issues related to digital technologies<br>• Ethical and surveillance-linked threats<br>• Lack of trust in new technologies | **Ensure privacy and ethical use of technology** | ✓ |
| **Technological** | • Some technologies not yet mature enough<br>• Insufficient capacity for digital innovation (in rural areas or SMEs)<br>• No business case for green-digital research and innovation<br>• New technologies and standards become quickly outdated<br>• Missing enabling infrastructure | **Implement innovation infrastructure** | ✓ |
| | • Increase in technological complexity<br>• Patchwork of technological solutions<br>• Isolated solutions that are not in line with overall system<br>• Lack of interoperability<br>• Lack of technological reliability of equipment | **Build coherent and reliable technology ecosystem** | ✓ |
| | • Reluctance to share data<br>• Unclear data ownership<br>• Lack of access to relevant data<br>• Cybersecurity threats<br>• Lack of interoperability and reliability of data<br>• Data difficult to interpret | **Ensure data availability and security** | ✓ |

| | | | |
|---|---|---|---|
| **Environmental** | • Demand shift to green products lowers price for polluting products<br>• Greener and more efficient products tempt higher rates of consumption | **Avoid rebound effects** | ✓ |
| | • Substantial resource footprint of digital technologies<br>• Difficult recyclability of digital devices<br>• High energy requirements of digital technologies | **Reduce environmental footprint of green-digital technologies** | ✓ |
| **Economic** | • No business case for emerging green-digital solutions<br>• High operating costs of green-digital solutions<br>• Business shifts away from declining sectors<br>• Risk of stranded assets and sunk costs | **Create enabling markets** | ✓ |
| | • Advantage of legacy technologies (lock-in)<br>• Market entry barriers<br>• Dominance of large companies<br>• Small players lack capacity to adapt to new technologies<br>• Increasing technological capacity difficult to manage for small players | **Ensure diversity of market players** | ✓ |
| | • Reliance on digital technologies decreases knowledge<br>• Lack of knowledge of digital technology options<br>• Skills gaps | **Equip labour with relevant skills** | ✓ |
| **Political** | • Missing standards for new technological solutions<br>• Outdated standards<br>• International standard setting by first movers outside the European Union | **Implement adequate standards** | ✓ |
| | • Lack of political consensus across government levels and Member States<br>• Too much red tape<br>• Regulations that do not foster innovation and change | **Ensure policy coherence** | ✓ |
| | • High investment needs for green-digital technologies<br>• Competition over public resources | **Channel investments into green-digital solutions** | ✓ |

Source: JRC

# SOCIAL

## ENSURE JUST TRANSITIONS

**To ensure widespread acceptance of the green and digital transitions, they have to be fair and inclusive.** The twin transitions offer new opportunities such as the more active participation of households in self-organised energy grids. However, not everybody will be able to benefit from these opportunities. One-sided subsidies could actually have the opposite effect. For example, subsidies to buy electric cars or rooftop solar panels would benefit only those who can afford expensive cars or own a property. However, such subsidies are also financed by the taxes of those who are not in such a privileged position. Regulations will have to ensure that lower-income or vulnerable groups of society will see a benefit from the two transitions, too. Another aspect is the digital divide, because not everyone has access to the digital technologies that are needed to benefit from the green and digital transition solutions. This issue can be of spatial nature (e.g. rural areas without access to fast internet) or concerning social groups (e.g. elderly without knowledge on how to use digital technologies). Lastly, the green and digital transitions will lead to the emergence of new sectors and industries and to changes in existing work flows. Therefore, education and training will be crucial to equip labour with the skills to thrive in this changing environment. To move from openness to action, individual and societal routines will have to change. Low hurdles to changing habits and adopting new solutions will be crucial for the change of routines. Therefore, digital tools need to be user-centric to support this change process and the regulatory burden needs to be minimised.

## INCREASE SOCIETAL COMMITMENT TO THE NEED TO CHANGE

**A high level of societal support can fuel behavioural change in favour of the twin transitions.** Society will play a decisive role when it comes to successfully implementing the green and digital transitions. For example, reducing meat production and consumption is a cost-efficient way to reduce greenhouse gas emissions and land use in the agriculture sector. However, these kind of changes are difficult to implement top-down. Societies need to stimulate increased awareness and broad agreement that such changes are necessary for successful twin transitions. Reaching societal commitment to the twin transitions will make many of the green-digital solutions much easier to implement. The willingness to feed products and materials back into the system will foster the implementation of a circular economy. Reducing the living space per capita and reshaping or moving out of family homes once children have grown up will help to save energy. Inclusive societal debates could raise awareness and commitment, and in turn help overcome the barrier of losing status symbols (e.g. SUVs or quickly outdated technological equipment), or to re-think ownership structures (Energy-as-a-Service might involve giving up ownership of one's heating system).

## ENSURE PRIVACY AND ETHICAL USE OF TECHNOLOGY

**Ensuring privacy and the ethical use of technology will be key to enable the twin transitions.** Many of the green-digital solutions presented in this study require the collection of data from end users to improve or optimise current operations. This means that end users could potentially become much more exposed and transparent than today. It is essential to ensure that data and technology is used ethically. Strict requirements to anonymise and protect data need to be implemented and monitored. This will help to make sure that the social acceptance of data sharing will not decrease. These requirements should also enforce 'data minimisation' by limiting the collection of personal data to that which is absolutely necessary for the specific purpose. This should go hand in hand with efforts to inform end users, including businesses, of the need and added value of sharing certain data to make the twin transitions happen. Efforts should aim to empower people to share their data and to personally reap the benefits of the insights that can be drawn from it. The end user should be aware of such direct benefits of green-digital solutions, only then will there be willingness to share the data needed to enable such technologies. Informing end users about how their privacy is secured would help to counteract reluctance around data sharing.

# TECHNOLOGICAL

## IMPLEMENT INNOVATION INFRASTRUCTURE

**The creation of an enabling innovation infrastructure will determine whether research breakthroughs are taken up at scale.** While a large part of the technologies required for the twin transitions are already developed, there are still some that are not yet mature enough to be rolled out widely. In addition, there will be continuous improvements to green and digital technologies to make them more environmentally-friendly and more cost-efficient. Continued innovation is also needed to ensure the ease-of-use of green-digital solutions, which is a critical aspect for a successful roll out. To foster these research and innovation efforts, there has to be a clear business case, for example through development roadmaps that are linked to public funding. Technology transfer from research institutions to innovative business is required, as well as support to scale up market diffusion and production capacities. Furthermore, many of the digital technologies will require enabling infrastructure (e.g. fast mobile data), which still needs to be rolled out in many regions, particularly in rural areas. It will also be crucial to make sure that new developments are ‘backward compatible’, so that technologies will not become obsolete before their end-of-life. Policymakers should establish favourable framework conditions to make sure that domestic innovation in technology areas of systemic importance will be strong.[274] Green-digital solutions need to avoid critical dependencies for intellectual property, data storage, critical raw materials, and primary products. Lastly, the twin transitions can only be successful when implemented across the whole European Union. This means that particularly economically disadvantaged areas and rural areas will require support to roll out state-of-the art green-digital solutions.

## BUILD COHERENT AND RELIABLE TECHNOLOGY ECOSYSTEM

**A coherent approach will be necessary to make sure that an increasingly complex technological system will remain manageable and reliable.** The twin transitions require the implementation of a complex technological ecosystem, where the various solutions are interlinked. It is crucial to address the twin transitions holistically to make sure that the green-digital solutions are interoperable. To ensure interoperability, technology developers, service providers, and regulators must work together. For example, the cooperation and integration between different stakeholders needed to deliver Energy-as-a-Service will be hindered if solutions are developed in isolation. Digitalisation could create substantial cross-cutting information flows that will be challenging to manage. Technologies such as Artificial Intelligence or next generation computing technologies will be important to deal with this increased complexity. Another important aspect in an interdependent ecosystem is reliability. Particularly small-scale installations used in SMEs or households are prone to being less reliable, as maintenance might be conducted less rigorously. Therefore, strict maintenance standards and sufficient back-ups should ensure the functioning of green-digital solutions of systemic importance.

## ENSURE DATA AVAILABILITY AND SECURITY

**The twin transitions will depend on the mutual benefits of data sharing, standardised high-quality data, and adequate security systems.** Data is the backbone of a digitalised society and a building block for many green-digital solutions. This is why the willingness of all relevant stakeholders to share data is crucial. Data governance and regulations have to create clarity and trust with regard to who owns data, how data is used, and who has access to it. In doing so, regulations must ensure that there are no one-sided benefits between providers (often small stakeholders such as farmers) and accumulators of data (often powerful corporates such as providers of farming equipment). Data necessary for realising the goals of the European Green Deal will have to be accessible to the relevant stakeholders to be useful. To ensure the security of shared data, cybersecurity will have to be a cross-cutting technology priority.[275] Lastly, using data from different sources is challenging because it might not always be of sufficient quality, or might not be interoperable with other data sources. Data standards will play an important role in ensuring that data from different origins can be used efficiently and reliably.

274 Strengthening innovation in the European Union is one of the topics discussed in last Strategic Foresight report. See European Commission (2021a).
275 Joint Research Centre (2020g)

# ENVIRONMENTAL

## AVOID REBOUND EFFECTS

**Rebound effects call for their own measures to reach the goals of the green and digital transition.** The green-digital solutions presented in this study contribute to achieving the goals of the twin transitions. However, they can also create rebound effects, which are unintended side effects. For example, teleworking might lead to increased housing space requirements, with an additional separate office room. Another possible rebound effect is that a greener alternative such as low-carbon transportation or green electricity might lead to an increase in demand, because they are perceived to be more environmentally-friendly than fossil fuel-based solutions. An increasing demand for green substitute products might lead to a lower demand for carbon-intensive products which would make them cheaper and in turn more competitive vis-a-vis their greener counterparts. Rebound effects could be avoided by implementing a variety of different measures. For example, education and awareness raising could address rebound effects that are caused by changes in consumer behaviour. In addition, there are also solutions to address rebound effects caused by market failures (that focus on short-term cost optimisation instead of long-term societal benefit), for example the introduction of standards and regulation to ensure that a minimum percentage of secondary materials is used in new products.

## REDUCE ENVIRONMENTAL FOOTPRINT OF GREEN-DIGITAL TECHNOLOGIES

**Green and digital technologies still have to be further developed to reduce their environmental impacts.** Technologies required for the green and digital transitions have their own environmental footprints. Wind turbines require steel and copper, Distributed Ledger technologies and Artificial Intelligence use substantial amounts of electricity, and RFID chips require resources and are difficult to recycle. There is also the issue of hazardous waste from some of the green-digital technologies. To ensure that these solutions are not negating their positive environmental effect, research and innovation has to keep the whole life cycle of these technologies in mind to optimise these life cycles for environmental performance. Regulatory policies could also support the uptake of technologies with a lower environmental footprint.

# ECONOMIC

## CREATE ENABLING MARKETS

**Enabling markets could guide green innovation in the long term.** New green-digital technologies often compete with already established ones, which are more mature and therefore have a competitive advantage. Support to emerging technologies is necessary to bridge the gap from research to applied innovation, also known as the 'innovation valley of death'. Enabling markets provide supportive market and regulatory conditions for the successful commercialisation of green-digital technologies. They have to be created to facilitate business cases for green innovation, instead of only focusing on short-term profits. Markets have to be designed in a way that reflect the green goals of the European Union, for example by internalising environmental and societal costs of pollution or emissions, or by introducing green standards. Internalising costs would mean that all actors have an incentive to think long-term for investments and planning. Such long-term signals help to avoid investments in technologies that do not have a future in a green Europe and risk being written off before their planned end-of-life (stranded assets). Long-term market signals also incentivise companies to change their production processes to become greener, or to diversify if necessary.

## ENSURE DIVERSITY OF MARKET PLAYERS

**The green and digital transitions benefit from market structures that include big and small players.** The increasing technological complexity triggered by the twin transitions and potentially dominating market power of digital platforms might make it difficult for smaller players to compete. However, a diversity of players is crucial for high levels of competition and innovation, and would ensure local value creation. Therefore, support to SMEs (e.g. local farmers and craftsmen) should be given to ensure that they have the capacity to develop, implement, and manage sophisticated green-digital solutions. Data ownership rules would also have to make sure that no data monopolies are created, as such monopolies could lead to only a few players dominating the market.

### EQUIP LABOUR WITH RELEVANT SKILLS

**Solutions in the green and digital transitions will require specific skills and knowledge that need to be fostered in all sectors.** Upskilling, reskilling, and awareness-raising is needed in most sectors to implement green-digital solutions. Knowledge and understanding of the benefits of new technologies needs to be accessible. For example, many farmers in the agriculture sector lack the knowledge about new technologies and are unaware of the benefits they could bring. Education and training programmes (e.g. vocational education and upskilling) could ensure the availability of skills that are required for the green transition. An additional necessity is the availability of skilled specialists, for example in the field of Artificial Intelligence. In the area of research and development of green-digital solutions, digital specialists are needed that understand the key intervention logic of green technologies to drive innovation. This points to the advantage of adapting and shaping education and steering research towards the skills and knowledge needed for the twin transitions in the long term.

## POLITICAL

### IMPLEMENT ADEQUATE STANDARDS

**Standards could ensure high interoperability and avoid the misuse of market power.** A complex digital technology system like the one needed for the green and digital transitions will require the highest level of interoperability of soft- and hardware. Therefore, standards have to create a common basis for the development of new technologies. Standards also help to avoid situations where big players create market entry barriers. For example, big players could develop proprietary platforms but discriminate against other market players using them, which would not be in the interest of implementing the twin transitions. Establishing robust standards will help to avoid circumstances where new technologies quickly become obsolete because they will not be able to interoperate with new generations of technology. Lastly, establishing European standards early would put the European Union in the position of 'first mover', which might be beneficial to the establishment of leading players in new growing economic sectors and segments.

### ENSURE POLICY COHERENCE

**A political consensus is crucial to implement a policy framework and a common set of rules that guides stakeholders towards reaching the goals of the twin transitions.** Policy plays a vital role in triggering and guiding transitions. Therefore, a firm political consensus on the goals of the green and digital transitions and how to reach them is important. Considering the magnitude of change that will happen due to the twin transitions up to 2050, policymakers must formulate long-term goals to guide all the relevant stakeholders. Consistency is also important across the different government levels and across different regions. Realising the green-digital solutions will require cooperation and co-creation between a wide range of stakeholders across sectors, disciplines, and policy areas. A common set of rules is needed to facilitate their cooperation. Consistency in regulations is key to avoiding unnecessary burden, particularly for smaller players. Regulations should also trigger innovation in support of the twin transitions and not in areas that are going against them, such as fossil fuel-based power generation. This applies to research and innovation programmes and to regional support programmes.

### CHANNEL INVESTMENTS INTO GREEN-DIGITAL SOLUTIONS

**Unlocking necessary public and private investment will be crucial for the green and digital transitions.** The twin transitions will require substantial public and private investments in infrastructure and technologies. Public investments in research and innovation will be helpful when it comes to developing the technologies needed. They can help to build prototypes and proofs of concepts before any large-scale rollout. However, an economy-wide implementation of green-digital technologies cannot be realised only with public investments. Governments and institutions could help to unlock the private investments that will be crucial for successful twin transitions. One solution is to indicate which economic activities are sustainable with respect to the goals of the European Union Green Deal. To support green-digital solutions, policymakers could also indicate which technologies are not contributing to an environmental objective themselves but could enable other green technologies. This is the case for many of the digital technologies that are part of green-digital solutions presented in this study.

# 8. CONCLUSIONS

**Several studies that look at the twin transitions exist, but policy implications in the long-term have so far not been thoroughly analysed.**

There is a substantial amount of research on how digital technologies can help to reduce greenhouse gas emissions,[276] how digital technologies change lifestyles,[277] and which technological innovation pathways would make sure that Europe's industry will be competitive in the long-term.[278] Most of this research focuses on the technical aspects of parts of the economy, or on certain aspects of either the green or digital transition. Only more recently has research been undertaken to look into policy needs for the cross-cutting topics of the green and digital transitions.[279]

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276 Rolnick et al. (2022), Lange and Santarius (2020), Hedberg and Sipka (2021), Sipka (2021), Hedberg and Sipka (2020), Pietrón, Staab, and Hofmann (2022), techUK and Deloitte (2020), The Royal Society (2020)
277 WBGU (2019), IIASA (2019), Santarius, Pohl, and Lange (2020), Frick et al. (2021)
278 E.g. AENEAS, ARTEMIS-IA, and EPoSS (2021), EFFRA (2021), ASPIRE (2021), Brewster et al. (2019)
279 E.g. Hedberg and Šipka (2020), Iddri et al. (2018)

**This study contributes to the existing research with a forward-looking analysis to derive key requirements for successful twin transitions.** The study analyses the drivers shaping the agriculture sector, building and construction sector, energy sector, energy-intensive industries, and the transport and mobility sector; and what is needed for their green transitions. It also analyses how current and emerging digital technologies can enable the green transition or cause environmental burdens. Furthermore, it considers the impact of contextual factors on the twin transitions. On this basis, the study has derived key social, technological, environmental, economic, and political requirements for successful twin transitions.

**Linking the green and digital transitions requires balancing the advantages and disadvantages of green-digital solutions.** For example, decentralised bottom-up digital solutions for location-specific green issues might deliver unique solutions but could reduce their interoperability. Over-engineering digital processes, products, and services could reduce their reliability and lead to the loss of knowledge about analogue work procedures. This loss of knowledge could lead to dramatic results in the case of a failure of a digital solution. A fully digitalised green transition will enable new solutions but could be more vulnerable to the forging of environmental performance data.

**Along with cutting-edge technology development, there is a call for frugal innovation.** The climate crisis and geopolitical pressure on the supply of resources are calling for more green solutions, processes, and habits. Frugal innovation research is needed, for example to critically reflect on the extent to which digitalisation is actually needed to enable green innovation. Technology development needs to consider the reliability and resilience of solutions. It also needs to ensure forward compatibility to later upgrades that the digital age might bring in the future.

**The twin transitions need transdisciplinary research to enable transformational change.** This study has brought together different perspectives from academia, industry, non-governmental organisations, and public services. It has shown how important it is to work across disciplines in order to analyse a topic as complex as the twin transitions. Future research also needs to make sure that these different perspectives are incorporated. A solid knowledge base is needed to interlink the digital and green transitions with the social dimension of the just transition and to ensure that 'no one is left behind'. It will also be an important political task to steer the ground-breaking shifts in the right direction.

> Future research also needs to make sure that different perspectives are incorporated. A solid knowledge base is needed to interlink the digital and green transitions with the social dimension of the just transition and to ensure that 'no one is left behind'.

**While this study analyses key aspects of the twin transitions, it also has its limitations.** This study gives an overview of the current research on green and digital technology innovation timelines and how contextual factors could influence them. It aims to provide political decision-makers with an overview of this topic, but is also addressed to researchers in the respective fields by providing a holistic and forward-looking perspective. Trends and megatrends have been analysed to identify their influence on future developments in the five sectors covered in this study. To further grasp the potential impact of future uncertainties, a foresight scenario analysis could shed light on how unexpected developments might evolve and challenge common assumptions and biases. Such a scenario analysis was not in the scope of this study, but would be a valuable addition in the future.

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# 10. APPENDICES

## Appendix 1: Digital technology scope

The categories below formed the basis for examining the role of digital technologies in supporting the green transition of various sectors, and in identifying key functions that digital technologies enable for the green transition. While the categories provide an overview, they are not comprehensive and significant interlinkages exists between and across categories.

| Focus area | Description | Included technologies (non–exhaustive) |
|---|---|---|
| **Artificial intelligence and smart robotics** | Artificial Intelligence and smart robotics refer to a family of technologies that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals. | Image, video, and audio processing<br>Virtual assistants and recommendation systems<br>Robotic process automation and automated vehicles<br>Artificial Intelligence-optimised hardware<br>Natural language processing<br>Artificial Intelligence-empowered management systems<br>Machine and deep learning |
| **Data-driven technologies** | Data-driven technologies refer to applications that use vast amounts of data to provide insights, make predictions, produce recommendations, and take actions. | Descriptive analytics and data visualisation<br>Predictive analytics and simulation<br>Prescriptive analytics and algorithmic decision-making<br>Security analytics and threat intelligence |
| **Internet of Things** | The Internet of Things can be defined as a set of physical objects embedded with sensors or actuators and connected to a network. | Mobile and wearable devices<br>Smart sensors and devices<br>Internet of Things platforms<br>Geolocation technologies |
| **Computing infrastructure** | Computing infrastructure is an umbrella term that stands for a collection of hardware and software elements enabling an organisation to perform IT operations such as data storage and processing, networking, simulation, and visualisation. Quantum computing is an emerging computing paradigm, proposing new computing infrastructure and algorithms that are significantly different from classical computers and supercomputers. | High-performance computing<br>Cloud computing<br>Edge computing<br>Quantum computing<br>Optical computing<br>DNA digital data storage<br>Graphene-based transistors<br>Fog computing<br>Distributed computing<br>Data centres |
| **Communication technologies** | Communication technologies is an umbrella term that refers to a collection of hardware and software elements enabling an organisation to send and receive information over long distances. | 5G networks and handheld devices<br>Software-defined networks<br>6G networks<br>Internet Protocol version 6<br>Wi-Fi (wireless networking technology)<br>WiMAX - Worldwide Interoperability for Microwave Access<br>LoRa (short for Long Range) Low-Power Wide-Area Network protocol<br>Bluetooth<br>Satellite-based communication<br>Drones |

| Focus area | Description | Included technologies (non–exhaustive) |
|---|---|---|
| **Software and service technologies** | Software and service technologies is an umbrella term that refers to the activities of a specific industry concerned with the development, maintenance, and publication of software products. The term also includes the provision of business support services, technical assistance and training, engineering, consulting, and documentation. | Application programming interfaces, web services, and micro services (e.g. registries and marketplaces, focused on software and system integration)<br>Enterprise service bus technologies and service utilities (e.g. open and linked data collection, processing, and diffusion, next generation service delivery models)<br>Industrial process and machine programming and embedded systems<br>Additive manufacturing (3D/4D printing)<br>Nanotechnology (e.g. microprocessors and software components)<br>Identification technologies (e.g. RFID, QR-codes, bar codes) |
| **Distributed Ledger technologies** | A Distributed Ledger technology is a decentralised way of recording asset transactions. The recording happens in several places at the same time. | Cryptocurrencies<br>Smart contracts<br>Decentralised autonomous organisations<br>Decentralised finance<br>Tokenised economy (e.g. initial coin offerings, security token offerings, non-fungible tokens |
| **Bio-inspired and neuromorphic computing** | The 'bio-inspired and neuromorphic computing' cluster encompasses a large array of research endeavours and developments, which shares the commonality of: 1) a concern for the body and brain connections, and 2) the determination to explore the way to understand, visualize, and stimulate this connection through digital means, in the large sense. | Mind2machine2mind<br>Sensorial repair<br>Electro-stimulation<br>Neuromorphic paradigms |
| **Extended reality and metaverses** | Extended reality and metaverses comprise a cluster of technologies that aim to: 1) augment the information available and its sourcing in a given perceptive and informative frame of action, 2) simulate options or even entirely imagined ecosystems, 3) visualise and interact with these augmented or virtual realities, and 4) construct them as fully interactive, enriched and immersive environments. | Social computing<br>Augmented reality<br>Mixed reality<br>Virtual reality<br>Interactive holograms<br>Augmented environments<br>Immersive environments<br>Avatarisation<br>Metaverses |
| **Other** | Digital technologies not classifiable in the previous categories or new technologies. | Digital technologies not classifiable in the previous categories or new technologies |

## Appendix 2: Green technologies

### Agriculture

**The transformation of the agriculture sector is enabled by a variety of technological innovations.** With respect to genetic resources, biotechnologies advance breeding options to grow enhanced species. The resilience of plant and animal species is gaining higher priority, such as their tolerance against pest and antibiotic stress.[280] In addition, novel perennial grains[281] and nitrogen-fixing cereals[282] are promising lines of research in the green transition. Crop management uses agro-ecosystem engineering approaches to avoid chemical inputs into the soil by closing natural loops. Digital sensing on-site and remotely is allowing treatments to be adapted to specific conditions.[283] Improving irrigation practices requires monitoring and prediction tools as well as intelligent control systems for water management.[284] In livestock management, digital tools will enable monitoring of the health of animals. This information helps to reduce veterinary drug use, and the identification of genetic profiles for breeding.[285] Digital Twins improve the prediction capacity of farmers.[286] Farm management uses data input from information systems to monitor operations and provide decision support.[287] An agricultural knowledge and innovation system will enable land managers to increase carbon removal in land management.[288]

**Fisheries and aquaculture methods need to advance to reduce their carbon emissions and negative impacts on biodiversity.** Recirculation systems in aquaculture allow working in isolation from natural aquatic systems to avoid emitting pollutants and diseases. Integrated multi-trophic aquaculture is a circular system that re-uses by-products and waste as feed and nutrients inputs for other species.[289] In fisheries, new approaches to avoid by-catching and catching of undersize individuals is an important but underdeveloped area.[290] Monitoring fish stocks has become a key tool for enhancing catching productivity, which unintendedly leads to unsustainable pressure on biological stock.[291] However, these tools also allow the monitoring of vessel trajectories and fishing operations to control and govern fishing at sustainable levels.[292]

**Forests are seen as carbon sinks but they need care in order to provide sustainable ecosystem services.** In forestry, similar principles for technologies apply as in agriculture. Diversification and climate resistant trees are an issue at the level of genetic resources.[293] Monitoring is needed to get information on the state of forests and their contribution to ecosystem services, such as carbon sequestration, biodiversity, and protection against landslides.[294] Unmanned aerial vehicles and Big Data-based image analysis can improve wildfire protection.[295] Precision forestry allows detailed control of operations, selective intervention from planting seedlings, specific nutrient provision, and the automation of operations to optimised decision-making.[296]

**Bio-based industry enables the replacement of parts of fossil resources with bio-based ones.** Biorefinery technology is a key growth area[297] that yields resources for bio-materials like plastics, essential oils, glues, soaps, and detergents.[298] To avoid conflicts between biomass production and food security, sustainable approaches are needed that do not compete for land.[299] Catalytic processes using enzymes are promising technologies for the conversion of lignocellulosic biomass, plants, or plant-based material that are not used for food and feed.[300] Biochar is a charcoal-like substance produced by pyrolysis that can improve soil

280 Bingham et al. (2009), Messina et al. (2011), Mitchell et al. (2016), Munns et al. (2002), Nelson, Shen, and Bohnert (1998), Chinnusamy, Jagendorf, and Zhu (2005)
281 Grain crops that are productive over more than one year, allowing several harvests. Crews (2005), Crews and Brookes (2014), Crews, Carton, and Olsson (2018), Crews and Cattani (2018), Crews and DeHaan (2015), Duchene et al. (2019), Glover et al. (2010), Ryan et al. (2018)
282 Aasfar et al. (2021), Bennett, Pankievicz, and Ané (2020), Dent and Cocking (2017), Fujita, Ofosu-Budu, and Ogata (1992), Goyal, Schmidt, and Hynes (2021), Pankievicz et al. (2019), Rosenblueth et al. (2018)
283 Escriba et al. (2020), García et al. (2020), Kalyani, Goel, and Jaiswal (2021), Lebourgeois et al. (2008), Qiu et al. (2018), Ratnaparkhi et al. (2020), Ullo and Sinha (2021), Valente et al. (2011), Zeng and Li (2015)
284 Bwambale, Abagale, and Anornu (2022), Abioye et al. (2020), Adeyemi et al. (2017), Bwambale, Abagale, and Anornu (2022), Dukes (2020), Evett et al. (2020), Liang et al. (2020)
285 Arias, Molina, and Gualdron (2004), Bailey et al. (2018), Gillespie (2007), John et al. (2016), Ingrand (2018), Ivanov and Novikov (2020)
286 Jo et al. (2018), Norton et al. (2019)
287 Wolfert et al. (2017)
288 European Commission (2021r)
289 Buck et al. (2018), Granada et al. (2016), Knowler et al. (2020), Ridler et al. (2007)
290 Poisson et al. (2021), Provost et al. (2020), Suuronen and Gilman (2020), Watson et al. (1999)
291 Toonen and Bush (2020)
292 Pauly et al. (2002)
293 Marchi et al. (2018), Siry, Cubbage, and Ahmed (2005)
294 The European Commission is preparing a legislative proposal for a Forest Observation, Reporting and Data Collection to establish an EU-wide integrated foresight monitoring framework. See European Commission (2021l).
295 Athanasis et al. (2019)
296 Nitoslawski et al. (2021), Dassot, Constant, and Fournier (2011)
297 Joint Research Centre (2021e)
298 Ubando, Felix, and Chen (2020)
299 Ahmed et al. (2021), Kline et al. (2017), Debnath and Babu (2019)
300 Lignocellulosic biomass include agricultural redicues, energy corps, forestry residues, and yard trimmings. Cardona Alzate, Solarte Toro, and Peña (2018), Toda et al. (2005)

fertility and carbon storage.[301] The use of waste streams to produce edible insects[302] or for microbial protein[303] are other emerging bio-based areas. The exchange of residue biomass as part of an industrial symbiosis[304] is also part of the circular economy.

**Food processing and supply chain management have to switch to more sustainable sources of proteins and reduce food waste.** Pathways to climate neutrality point to the need to reduce the consumption of calories and meat nutrition.[305] Precision fermentation is a possible solution to the key challenge of the food industry to produce non-livestock based alternative proteins.[306] Furthermore, food processing and supply chain-related innovations aim to increase the food quality and durability of processed food.[307] Wearable devices that monitor health status and body activities can recommend nutrition plans,[308] which lead to healthier and more sustainable diets.

## Buildings and construction

**Low-carbon and resilient construction are important drivers for greening in new buildings.** Innovation in materials and production processes is key to improve the grey energy of the material. Green architecture needs to consider the characteristics of the materials used. These characteristics include grey energy, lifetime, energy efficiency performance, potential for repair, and recyclability.[309] Furthermore, the building design needs to integrate resilience to seismic conditions and adapt to climate change to avoid premature decay or loss of functionality.[310] Urban planning is key to define local requirements for new buildings. Nature-based solutions can help to avoid heat islands, or absorb and filter water to reduce flooding.[311]

**High retrofitting rates will be key to make existing buildings greener.** Over 85 % of Europe's current building stock is expected to still be in use by 2050.[312] Renovation is the key lever to reduce greenhouse gas emissions from these buildings. The current renovation rate of about 1 % of the stock needs to be at least doubled to achieve the decarbonisation targets.[313] From the perspective of the embodied grey energy in building materials, as many structural elements as possible should be retained. Thermal and acoustic insulation, air tightness of the building envelope, new space heating and cooling systems, and building automation and control systems are key elements for deep renovations.[314] Renovations should not impair the integrity of buildings and are an opportunity to improve health and safety.[315]

**Optimising energy use during operation can provide a stabilising function to the overall energy system.** Electric appliances can be adaptively managed to reduce energy consumption while maintaining the same level of comfort to inhabitants. Building automation and control systems build on sensors to recognise users and their requirements and actively manage energy-consuming appliances.[316] Building automation and control systems can learn the routines of particular users and can predict their consumption. If this prediction is combined with weather forecasts, it can inform users of energy inefficiencies and system issues. Building automation and control systems can further support peak shaving of electricity demand and valley filling by providing demand response management of electric appliances where and when they are not time critical (e.g. by charging electric vehicles when abundant renewable energy is available).[317]

**Low-carbon heating and cooling reduces emissions and pollution during the use phase of a building.** Phasing out fossil fuels for heating fuel has the highest contribution to possible emission reduction in the building sector.[318] Heat pumps or geothermal heat provision are low-carbon alternatives if powered by renewable energy.[319] District heating systems can be powered by geothermal sources, biomass residues, or waste heating. Semi-decentral combined heat and power plants can work at higher efficiency than single generation units. They can use a

301 Shakoor et al. (2021)
302 Govorushko (2019), Huis (2020), Carvalho, Madureira, and Pintado (2020), Liceaga (2021)
303 Alternative sources of high-quality protein to replace animal-based protein like fishmeal in livestock nutrition and aquaculture. See Tubb and Seba (2021).
304 Neves et al. (2020)
305 Institute for European Environmental Policy (2019)
306 McKinsey & Company (2019), Duarte, Bruhn, and Krause-Jensen (2021), Nova et al. (2020), Reboleira et al. (2021), Tzachor, Richards, and Holt (2021)
307 Knorr, Augustin, and Tiwari (2020)
308 Galimberti et al. (2019)
309 CINARK (2021)
310 European Environment Agency (2021c)
311 European Environment Agency (2021c), European Academies Science Advisory Council (2021)
312 European Commission (2020l)
313 European Academies Science Advisory Council (2021), Filippidou and Jimenez Navarro (2019)
314 European Academies Science Advisory Council (2021)
315 European Academies Science Advisory Council (2021)
316 European Academies Science Advisory Council (2021)
317 Beucker and Hinterholzer (2021)
318 CE Delft, Climact, and European Climate Foundation (2020)
319 European Academies Science Advisory Council (2021)

variety of low-carbon fuels such as biogas, solid biomass, or hydrogen. District cooling systems can circulate cold water from nearby rivers. Cooling systems can profit from nature-based solutions, such as green roofs and walls.

**A reduction of space requirements will decrease environmental impacts from constructing and operating buildings.** The global floor area of building space is expected to increase at a rate of 2.3 % per year, while current annual energy efficiency improvements are at a level of 1.5 %.[320] A reduction in space use means fewer buildings are necessary that cause environmental impacts from construction and operation. Options to cut building space include reducing the need for space use in general, and increasing the intensity of space use in existing buildings. Co-housing and other forms of sharing large apartments and houses for living and working reduce the space use per person.[321] Tiny houses and micro apartments also provide options for reduced need for space.[322] In office buildings, using workplaces in more shifts during the day or hot-desking can reduce space requirements. Platform providers offer services with the potential to support more efficient use of space from co-working services, and support companies to adjust the size of their offices.[323] As with all major changes, care needs to be taken to not create new problems (e.g. overcrowdedness or bad working environments) when trying to solve an existing problem.

## Energy

**Climate-neutral power generation will be the backbone of the green transition.** Renewable energy can be divided into renewable energy sources that are variable (the power generation varies according to external factors) or dispatchable (the power generation can be planned). Variable renewable energy sources include solar, wind, and ocean energy. Solar systems convert sunlight into heat or electricity with photovoltaics being the prevalent technology for the production of electricity.[324] Wind systems have grown in scale in the last decade, allowing substantial cost reductions. Affordable off-shore wind turbines that do not require land space have led to an increased penetration of wind energy.[325] The cost for photovoltaics and wind has dropped by 90 % and 70 % respectively between 2009 and 2021,[326] making them now the cheapest source of electricity in the right conditions (sufficient sun or wind).[327] Due to the high energy density of water, ocean energy is also a potential source for renewable energy. However, the harsh environment of oceans has so far hampered the roll out of ocean energy such as tidal stream.[328] Dispatchable renewable energy sources include hydropower, geothermal, and bioenergy. While they tend to be more expensive than solar and wind, they have the advantage of providing energy on demand.[329] Hydropower is a mature technology but has only limited additional capacity potential in Europe, as it is difficult to build new hydropower storage and run-of river capacity is already mostly used.[330] Geothermal power generation has so far also remained a niche despite mature technologies and a good availability of resources, because there has been a lack of public acceptance.[331] Bioenergy has the disadvantage that it has to compete with other sectors for scarce sustainable biomass. However, advanced biofuels could play an important role in the green transition.[332]

**Energy grids and storage technologies are crucial to guarantee the security of energy supply.** Energy systems are experiencing substantial changes in the context of the energy transition. An increasing amount of variable power generation puts pressure on energy grids, and grid management has to ensure that the energy provision and demand are balanced at all times.[333] Furthermore, the number of energy producers is increasing substantially with the roll out of small-scale renewable power generation.[334] One possible solution is the strengthening of electricity grids through grid extension and modernization. Geographically enlarging energy grids with long-distance transmission lines would allow transporting electricity over long distances from where it is abundant to where it is needed.[335] Modernising the energy grids, particularly the distribution grids, would enable the integration of high amounts of variable renewable energy and the electrification of carbon-intensive activities such as transport or heating.[336] Another

320 Falk et al. (2020)
321 Francart et al. (2020), Falk et al. (2020), Höjer and Mjörnell (2018)
322 Crawford and Stephan (2020)
323 Vaddadi et al. (2020)
324 Joint Research Centre (2020c)
325 Broom (2019)
326 Lazard (2021)
327 International Energy Agency (2021a)
328 Husseini (2018), Layton (2008), Joint Research Centre (2020h)
329 Harack (2010)
330 Joint Research Centre (2020i)
331 International Energy Agency (2011), Joint Research Centre (2020j)
332 Joint Research Centre (2020k)
333 Al-Shetwi et al. (2020)
334 Muench, Thuss, and Guenther (2014)
335 Joint Research Centre (2020d)
336 Deloitte (2015)

possible solution is energy storage, which can help making energy grids more resilient and reducing the curtailment of renewable energy by increasing the flexibility of grids.[337] Energy storage technologies can be divided into mechanical systems (e.g. pumped hydro), thermal systems (e.g. using a liquid or solid medium to store heat), chemical systems (e.g. hydrogen), electrochemical systems (e.g. batteries), and electrical systems (e.g. supercapacitors). There are already several technology options available for short-term storage, but longer-term storage solutions such as flow batteries are still under development.[338]

**Demand side management could enable the uptake of high shares of renewable energy.** Energy users play an important role in an energy system that relies exclusively on renewable energy. They could use energy more efficiently to reduce the overall amount of energy consumption, which would reduce the overall cost of energy. Furthermore, they could shift their energy consumption from times when variable renewable power generation is scarce (e.g. in periods without sun and wind) to times with abundant variable power generation.[339] Digital technologies such as real-time energy price monitors could provide incentives to consumers to shift their electricity and heat consumption. Opportunities for demand side flexibility exist both in industrial facilities and in residential or commercial buildings. Technical solutions to provide demand side flexibility include power-to-heat (e.g. heat pumps), power-to-gas, (e.g. hydrogen production), smart charging of electric vehicles, smart usage of electrical appliances, and industrial demand response.[340] The first three options are also referred to as sector coupling, as they connect electricity and heat or gas consumption and production. The central management of demand response (e.g. using big data analysis and state-of-the-art information and communication equipment) is crucial for stable electricity grids. Digitalisation allows to keep the level of service (e.g. hot water or heating) while increasing flexibility.

**Clean fuels will have to replace fossil fuels to achieve the green transition.** Promising options for clean fuels are green hydrogen, synthetic fuels, and biofuels. Hydrogen is a versatile energy carrier that can, to a certain extent, use the existing gas transport infrastructure.[341] It could be critical for the green transition, as it can replace fossil fuels and feedstock in residential and industrial heat production (e.g. in the production of steel and chemicals), and in long-distance transport.[342] Currently, the leading technology for the production of green hydrogen is electrolysis. Widespread use is hindered by the higher production costs compared to conventional (fossil-fuel based) hydrogen production and infrastructure investments. However, substantial cost improvements are expected before 2050.[343] Disadvantages of hydrogen are its low energy density, high volatility, flammability, and the infrastructure needs.[344] These limitations can be addressed by further processing hydrogen to produce liquid fuels, such as methane or ammonia. A particular advantage of ammonia is the option to use existing technologies and infrastructures, for example in conventional engines in maritime transport. However, ammonia causes local toxic pollution, should it leak into water.[345] If produced sustainably, biofuels can be another building block for the green transition. Their advantage in the short term is that they require only minimal retrofits of existing infrastructure and end-user equipment (e.g. airplane engines). However, the scarcity of sustainable feedstock limits their widespread use in the future.[346]

## Energy-intensive industries

**Using scrap instead of virgin steel is already done today, with hydrogen-based primary steel production being another option for the long-term.** Steel is an essential material that is used across the whole economy. Over 40 % of demand is served by secondary production (using scrap steel) in the European Union. Secondary steel production uses electric arc furnaces which can substantially reduce emissions compared to primary steel production.[347] However, the use of secondary steel production is limited by the availability and quality of scrap steel.[348] To ensure high levels of quality of secondary steel, impurities (e.g. copper) have to be avoided by improved sorting of scrap steel.[349] Green hydrogen could help to reduce greenhouse gas emissions from the production of primary steel. However, this solution still requires substantial research and innovation efforts.[350]

337 World Energy Council (2019)
338 Denholm et al. (2021), Deloitte (2015)
339 Moura and de Almeida (2010)
340 IRENA (2019b)
341 A.T. Kearney Energy Transition Institute (2014)
342 Fuel Cells and Hydrogen Joint Undertaking (2019)
343 Wang et al. (2019a), International Energy Agency (2021b), Edwardes-Evans (2020)
344 Eljack and Kazi (2021)
345 A.T. Kearney Energy Transition Institute (2014)
346 International Energy Agency (2020b), Wei et al. (2020)
347 ESTEP (2019)
348 Joint Research Centre (2022e)
349 Joint Research Centre (2022e)
350 Öhman, Karakaya, and Urban (2022)

**Clinker is the main cause for emissions in the production of cement.** Cement production is primarily local due to high availability of raw materials and high cost of transportation. It is the most produced basic material in Europe (179.8 million tons in 2018).[351] Most of the emissions from cement kilns come from the production of clinker, the main component of cement. These process emissions are an unavoidable reaction in the production of clinker. In addition to the process emissions, heat production in the kiln to produce clinker is energy-intensive. Two main areas for emission reductions are to increase the use of additives to replace clinker, and the more efficient use of clinker.[352] Furthermore, several technological solutions are being developed to capture emissions during the production process of cement, leading to emission reductions of up to 90 % when carbon dioxide is permanently stored.[353]

**A variety of technologies are available to green the production of chemicals.** The chemical industry uses a very wide range of processes and products but most of its emissions are caused by processing fossil hydrocarbons. About 60 % of its direct and indirect emissions are linked to steam cracking and distillation of ethane and naphtha into its derivatives (ethylene, propylene, and other aromatics), the precursor chemicals to make plastics.[354] A wide range of options could reduce emissions in the chemicals sector. These include electrification of heat, using hydrogen or biomass instead of fossil feedstock, applying carbon capture and storage, and chemicals recycling. Particularly the use of green hydrogen as a feedstock is an upcoming solution, for example for the production of ammonia.[355] However, it still leads to higher production costs in comparison to conventional chemicals production and cost reductions in hydrogen production are necessary for a large-scale roll out.[356]

**The pulp and paper sector will need to deploy new production processes to become greener.** The pulp and paper industry in Europe is mostly located in Finland, Sweden, and Germany and accounts for about a quarter of the global production (over 90 million tons of paper and board and over 36 million tons of pulp annually). It is a large user of renewable energy and had achieved a recycling rate of 74 % in 2020.[357] New processes offer ways to develop new products and applications based on cellulose fibre that generate more added value. Breakthrough technologies, such as those reducing heat use in paper production through reduced water consumption are needed to achieve the sector's objectives for 2050. Furthermore, combined heat and power (CHP) can significantly enhance the energy efficiency of the pulp and paper industry.[358]

## Transport and mobility

**In road transport, developing consumer-friendly technologies will be critical.** Fuel and energy are essential for road transport. A main option for greening of transport is the electrification of transport means, for example by using batteries or hydrogen.359 The roll out of battery-powered electric vehicles will depend on a continuing fall in production costs and on their ease of use. Possible ways to improve the user experience include charging while riding (wireless) and fast charging batteries.360 There is already some charging station infrastructure in Europe. However, 3 million charging station are required by 2030 while currently only 185,000 exist.361 Experiments with fast charging busses at bus stops to increase their range are already undertaken362. Similarly, vehicles with auxiliary photovoltaic power have been developed for passenger transport.363 Fuel cell electric vehicles for heavy-duty trucks exist but their use is hindered by the limited availability of infrastructure, refuelling times, drive range, and costs.364 Lastly, the energy use of road vehicles can be optimized, which can lead to range extensions of 7.5 %.365

**In rail transport, new concepts and the optimisation of infrastructures are being pursued.** One technology option is hyperloop that combines the convenience of a train and the speed of an airplane.[366] Another high-speed option is provided by magnetic levitation (magnetic shoes sliding on magnetic tracks). More personalised options can be provided by automated buses or shuttles operating on

351 CEMBUREAU (2020)
352 UNEP (2017)
353 Voldsund et al. (2019)
354 Verband der Chemischen Industrie (2019)
355 McKinsey & Company (2018)
356 Wyns and Khandekar (2019)
357 CEPI (2020), Costa et al. (2017)
358 Joint Research Centre (2018c)
359 Joint Research Centre (2020f)
360 Joint Research Centre (2019), Vallera, Nunes, and Brito (2021)
361 Joint Research Centre (2020f)
362 Joint Research Centre (2019)
363 Yamaguchi et al. (2021)
364 Böckin and Tillman (2019)
365 Padilla P. (2020)
366 Joint Research Centre (2020f)

designated rails.[367] Conventional trains can also decrease their environmental impact by capacity optimisation (e.g. with modular concepts for train interiors) and efficiency improvements.[368] Novel braking systems increase brake rates and reduce noise.[369] Furthermore, a more efficient use and better trans-European Union interoperability of rail infrastructure will increase the capacity of rail transport. The European Rail Control System aims to increase the safety of train transport and hence contributes to the European high-speed rail network by 2050.[370]

**In aviation, changing the propulsion to zero-carbon technologies seems to be a game changer.** New engine designs[371] aim to reduce engine noise, increase fuel efficiency (expected up to 50 % fuel burn reduction), and reduce landing and take-off NOx emissions by 75 %.[372] Other possibilities are hybrid electric regional aircraft, as there is the need for new solutions for short-range air transport (500-1,000km). Hydrogen-powered engines can reduce climate impacts of air transport by 50 - 75 %, and fuel-cell propulsion by 75 – 90 %. Hydrogen could be used by 2035 to power commercial passenger aircrafts on flights of up to 3,000 kilometres.[373] Fuel consumption and carbon emissions can be reduced by up to 10%, by optimising the flow of air around an aircraft using hybrid laminar flow control.[374] Another area is urban air mobility, including drones. Small scale deployment of package deliveries has recently begun and electric passenger drones (development of air taxis) are underway.[375]

**In waterborne transport, electric engines and zero-carbon fuels could enable the green transition.** The relatively long lifetime of vessels stresses the need for retrofit solutions to be developed and deployed as soon as possible. For inland navigation, the average lifetime of inland vessels is typically 40 to 60 years.[376] New sources of climate-neutral energy include electricity from batteries and hydrogen. E-ferries can travel about 10 nautical miles and are expected to substantially reduce greenhouse gas emissions and air pollution.[377] Research on ammonia-powered fuel cells on vessels shows that they can sail solely on the clean fuel for up to 3,000 hours annually. Hybrid fuel-cells using pre-combustion carbon capture on-board could yield greenhouse gas emission reductions of 97 % compared to conventional fuels, and almost eliminate sulphur oxides ($SO_x$) and particulate matter emissions.[378] Furthermore, developing zero-emission and automated vessels will enable a sustainable shift from road to waterway freight.

**New mobility solutions could reduce the environmental burden of travelling.** Mobility-as-a-Service is an open platform concept for mobility services. Such a platform provides multimodal travel options in real-time.[379] Co-modal ticketing systems improve the interoperability between different booking and ticketing systems at regional or even national level and are an enabler for Mobility-as-a-Service.[380] Another personal transport technology is micro mobility, comprising small, lightweight, and low-speed (below 25 km/h) mobility options. They are typically used for short-distance trips and include e-bikes, e-scooters, and other similar vehicles.[381] A key challenge is to integrate these technologies into existing urban mobility systems.

367 Tromaras et al. (2019)
368 Shift2Rail (2022)
369 Joint Research Centre (2021f)
370 Joint Research Centre (2020f), Joint Research Centre (2021f)
371 E.g. ultra-high bypass ratio or pressure ratio aircraft engines
372 Joint Research Centre (2020f)
373 Fuel Cells and Hydrogen Joint Undertaking (2020)
374 Joint Research Centre (2020f)
375 Aurambout, Gkoumas, and Ciuffo (2019)
376 Waterborne (2021)
377 Joint Research Centre (2020f) Joint Research Centre (2021h)
378 Joint Research Centre (2021f)
379 Joint Research Centre (2020f)
380 Joint Research Centre (2021f)
381 ORCHESTRA (2020)

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