acatech STUDY

Digitainability

Digital Technologies for Environmentally Sustainable Economic Activity: Market Potential and Strategic Implications

Christoph M. Schmidt (Ed.)

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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Foreword

We are living in an era of transformation on two fronts which will take us into a digital and sustainable future. One striking demonstration of these trends is to be found in the German federal government's current coalition agreement – the very first two chapters deal with digital awakening and the transformation to environmental sustainability. This is a development which is being taken up at the European level too. For instance, the EU's largest economic stimulus package to date, amounting to 1.8 trillion euro, which was established in response to the coronavirus pandemic, has the principal aim of moving decisively towards a Europe that is both greener and more digital. However, while digitalisation and the transformation to sustainability are the megatrends of our time, there is an inherent degree of inconsistency between them.

Digitalisation inevitably involves a certain level of artificiality. The all-encompassing technologisation of many facets of our lives simultaneously results in increasing virtualisation, with humans becoming part of a digital world with increasingly immersive experiences, in both the professional and the private spheres. Digital twins and artificial intelligence make it possible to replicate and optimise reality in digital space and often decouple the digital world from external real circumstances. In this way, digitalisation also brings about definite environmental externalities, for example in the form of rising energy demand for the creation and use of digital applications or through the raw material requirements and increasing waste generation due to the necessary hardware.

In contrast, the focus of the transformation to environmental sustainability is on preserving the natural world. In particular, it is about making use of renewable resources without harming and indeed while actively conserving nature. The intention is to mitigate or ideally even remedy the consequences of anthropogenic climate change. Ideally, the external costs of environmental impact would be reflected in market prices. The signal provided by market prices having been corrected by the pricing of externalities would lead to sustainable resource use while simultaneously encouraging more widespread use of digital technologies for sustainability. At present, however, there is a lack of political support, especially at the global level, for implementing this strategically promising policy.

From a national perspective, this entails a risk of manufacturing and thus value creation being relocated abroad in order to benefit from environmental standards which are in some cases far less stringent than in Germany. This is also detrimental in terms of global sustainability because environmental measures and impact can no longer be considered locally, but instead require a supraregional, ideally global, perspective: the primary concern is to stay within planetary boundaries. This makes it all the more important to provide a local demonstration of the benefits of market-based mechanisms in the pursuit of sustainable solutions and so advocate for their implementation on a larger scale.

If we are to preserve the ability to secure material prosperity in a modern affluent society, we need to harmonise our thinking about the two defining aspects of our era: sustainability is the prerequisite for permanently preserving the foundations of life, while digitalisation is capable of enabling participation and prosperity for all even in a complex, growing society. There is a need for greater "digitainability", i.e. an intertwining of digitalisation with sustainability to maximise the benefits of both. This image of mutual empowerment is reflected in many small details in both the digital and natural realms: AI can for example identify the companion flora in agriculture necessary for maintaining biodiversity, while the nervous system serves as the structural model for artificial neural networks in modern AI applications.

Digitainability is capable of creating market opportunities for Germany as a place to do business, but only if we gain an understanding of this symbiotic relationship and continuously improve how these two transformations interact. If this is to be the case, key questions need to be answered: how can the effect of digitalisation on sustainability be measured? Which digital solutions that strengthen environmental sustainability are currently already commercially available? How can digitalisation be put to sustainable use? To what extent can market mechanisms and the prevalence of digital technologies in the markets help digitalisation unleash its sustainability potential? What regulatory framework will be required?

This is where the present publication comes in. It creates an evidence basis for the intertwining of digitalisation and environmental sustainability in the German economy. To this end, a market study will analyse available digital/sustainable solutions in leading German sectors, describe both their prevalence and their positive environmental impact in the respective sector and finally quantify their economic value creation potential. This analysis is not limited to the current situation but also identifies development potential for the future and defines promising options for unlocking this potential.

Being limited to environmental sustainability and to specific sectors, this study is intended to provide an initial impetus. Future consideration of digitainability should bring a holistic sustainability perspective, which integrates the economic, environmental and social dimensions, into sharper focus. A symbiotic relationship will then be able to emerge in which digitalisation will provide the tools necessary to implement sustainability, while the three dimensions of sustainability will together define the guidelines for the development of digital technologies. This is a market opportunity for Germany as a place to do business and we should seize it.

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Executive summary

On its current course, Germany will not achieve the climate targets it has set itself – a 65 per cent reduction in emissions by 2030 in comparison with 1990 and complete greenhouse gas neutrality by 2045. There is an urgent need for additional measures. Digitalisation can be a key starting point here by helping to decouple economic growth from the resultant negative environmental impact. A harmonised approach to digitalisation and environmental sustainability is required and has given rise to the concept of digitainability. However, several problems stand in the way: inadequate digital infrastructure and availability of digital technologies, a lack of awareness of digital, environmentally sustainable solutions on the part of business, especially among small and medium-sized enterprises (SMEs), and the inconsistency which often still subsists between economic incentives and environmental sustainability. In addition, environmental sustainability is rarely considered in public funding initiatives for digitalisation.

This acatech STUDY provides an overview of currently available digital solutions with a positive impact on environmental sustainability, focusing on a total of eight leading sectors of the German economy with a major environmental impact:

- Agriculture
- Water management
- Manufacturing
- Electrical and mechanical engineering
- Primary materials, chemicals and pharmaceuticals
- Transport and logistics
- Construction and real estate industry
- Information and communication technology

An economic and environmental market analysis is used to investigate which solutions (products and services) based on digital technologies are available for promoting environmental sustainability.

Cross-sectorally, over half of companies are already using digital solutions to create environmentally sustainable value, in particular those solutions based on digital technologies which are becoming more widespread under the Industrie 4.0 paradigm (internet of things, cyber-physical systems, modern communication technologies). However, these solutions primarily serve to increase efficiency and a positive impact on resource and energy consumption is for the most part just a side effect. As a result, the deployment of digital technologies is currently motivated primarily by economic rather than environmental considerations. Given appropriate incentives, more than 75 per cent of companies could potentially be using digital solutions for environmentally sustainable value creation by 2030, which would also generate significant savings in environmental costs and energy inputs.

Drawing on expert interviews, this study comprises an analysis of the current use of digital solutions for sustainability, an evaluation of the economic and environmental potential for their extended application as well as the development of options for the expansion of digitainability in the German economy. A main recommendation is to boost environmental sustainability by applying digital solutions to increasing not only efficiency, but also effectiveness. To this end, digital technologies themselves must be made more environmentally friendly, for example by energy efficiency being measured and taken into account in software development or by hardware being improved in terms of repairability and service life. At the same time, the use and prevalence of digital technologies must be actively encouraged without bringing about rebound effects in the pursuit of environmental added value through digitalisation.

The expansion of platform solutions and of economic incentives for implementing a Circular Economy is key to the use of digital applications for generating environmental added value which goes beyond simply boosting efficiency and to making users and customers an integral part of sustainable business models. This will require not only more accurate and comprehensive metrics for holistic sustainability assessment but also better traceability of products along the value chain, for example by means of a digital product passport. In addition to adjusted carbon pricing, this extended data set could be used as the basis for using further environmental indicators to strengthen economic incentives for environmental sustainability. At the same time, there is a need for greater regulatory freedom in order to trial new concepts in this area, for example regulatory sandboxes or real-world laboratories. On the basis of this symbiotic intertwining of digitalisation and environmental sustainability, the impact of digitalisation on social sustainability should also be considered in the future to promote sustainability holistically through digitalisation.

1 Introduction

In its 2022 biennial report on past developments in greenhouse gas (GHG) emissions, trends in annual emissions and the effectiveness of measures, the German Council of Experts on Climate Change drew a clear conclusion: on its current course, Germany will not achieve the climate targets it has set itself – a 65 per cent reduction in emissions by 2030 compared with 1990 and complete greenhouse gas neutrality by 2045[1]. At the same time, climate disasters on both a global and national level are highlighting the need to use all possible levers to ensure sustainable compliance with environmental planetary boundaries. All this has to be achieved without undermining economic prosperity along the path to transformation.

Digitalisation can be a key lever here. Not only does it offer opportunities to reduce greenhouse gas emissions in all relevant industrial sectors, it can also have a positive impact on energy and raw material consumption while enabling new value creation potential. Digitalisation is a tool for decoupling economic growth from negative environmental impacts by increasing production and resource efficiency through the deployment of digital technologies and by digitally replacing business models or even creating new models (digital sustainability).[2,3] This will entail mitigating digital technologies' negative impact on environmental sustainability (sustainable digitalisation), in particular in terms of possible rebound effects due to more attractive usage options, software solutions' high energy demand and the resource requirements for digital hardware.[4]

This means that digitalisation and environmental sustainability must be strategically harmonised. Only in this way will it be possible to fully exploit the potential of digital technologies for environmental sustainability. It is therefore important to support the German economy in understanding digitainability[5] as the guiding principle for environmental sustainability and digitalisation and so use it as a driver of value creation.

The cornerstones for such success are the extensive use of digital technologies and the availability of products and (smart) services which are based on digital technologies and have a positive impact on environmental sustainability. However, German companies have some catching up to do here, as revealed by the European Commission's Digital Economy and Society Index (DESI), in which Germany ranks 16th out of 27 when it comes to integration of digital technology by companies.[6] The federal government's digital and sustainability strategy and further initiatives (e.g. the federal government's AI strategy, the Federal Ministry of Education and Research's (BMBF) Natural.Digital.Sustainable action plan, the Federal Ministry for Economic Affairs and Climate Action's (BMWK) DE.DIGITAL initiative and the joint BMWK and BMBF GreenTech funding framework) are promoting digital initiatives which take some account of environmental sustainability. However, these initiatives have not so far been following a common strategic line. In addition, there is a lack of specific (funding) instruments which provide incentives for using sustainability-enhancing digital technologies.[7] And, although some companies have recognised the need to act in line with environmental, social and governance (ESG) criteria, digitalisation and sustainability are not usually thought of together.

In addition to the inadequate prevalence of digital technologies, however, German companies sometimes also lack the ability or willingness to use them for the purposes of environmental sustainability. For example, only one in two companies in Germany has the necessary skills to conduct business sustainably.[8] A 2020 study by the Federal Ministry for Economic Affairs and Energy showed that the economic aspects which are crucial to the competitive success of companies continue to determine economic activity, while environmental requirements do so only to a limited extent. In some cases, these requirements even conflict with economic success, for example due to an increased administrative overhead as a result of expanded data acquisition and processing. Problems accordingly arise in integrating IT systems along the value chain and in virtualising assets.[9] SMEs in particular rarely speak of digitalisation and

1 | See ERK 2022.
2 | See Santarius 2020.
3 | See Ramesohl 2021.
4 | See TU Berlin 2022.
5 | The term "digitainability" was coined in 2017 and is a portmanteau of digitalisation and sustainability intended to encourage joined-up thinking about these two concepts (see Gupta 2022).
6 | See DESI 2022.
7 | See Öko-Institut e. V. 2021.
8 | See TCS 2021.
9 | See BMWi 2020.

sustainability in the same breath and digital projects also sometimes fail due to a lack of financial resources.[10] The economic value and opportunities for businesses of using digital technologies to increase their environmental sustainability are too rarely made clear.[11]

This shows that digitainability is not yet a strategic paradigm in German business, even though awareness of it is growing. If companies are to take notice of digital solutions and put them to strategic use as a vehicle for strengthening their environmental sustainability, this field of interaction will first have to be practically structured and ordered. The following aspects are relevant here:

- Overview of currently available digital solutions which strengthen environmental sustainability and identification of well-defined environmental indicators which might be able to capture the extent of this effect.
- Assessment of the actual level of use of digital sustainability-enhancing solutions in the German economy.
- Quantification of the economic value creation potential associated with the deployment of digital solutions to increase environmental sustainability.
- Well-defined options for decision makers in politics and business as to how increased use of digital solutions for environmental sustainability can be implemented.

The present acatech STUDY aims to structure the field of interaction in the light of these aspects. An **environmental market analysis** is therefore used to evaluate a selected set of digital technologies, environmental indicators and sectors to identify those environmental sustainability-enhancing solutions (products and services) based on digital technologies which are available in the German economy. In addition, an **economic market analysis** (analysis of value creation potential, opportunities for environmental cost savings and market potential) of digital/sustainable economic activity is also carried out. On this basis, companies will be able to take strategic decisions as to the sectors in which there are opportunities for (further) developing environmentally sustainable areas of business and which solutions and environmental indicators can be used for this purpose.

Drawing on these market analyses and on interviews with experts, **options** will be developed for policy makers and business as to how the corresponding solutions can be made more widely available, along which sustainability and value creation levers the development of further digital solutions can be focused, and how digitalisation and sustainability can come to interact in a practically-oriented, symbiotic manner.

10 | See acatech 2022.
11 | See Gupta 2022.

2 Methodology

The study consists of environmental and economic market analyses and the identification of options (see figure 1). The environmental market analysis was carried out by the Wuppertal Institute and acatech, and the economic market analysis by the RWI – Leibniz Institute for Economic Research. Both parts of the study are based on a uniform, jointly developed conceptualisation which also allows options to be identified.

Environmental market analysis	Economic market analysis	Identification of options
▪ Identify digital solutions with good environmental impact ▪ Evaluate sectoral availability of these solutions ▪ Identify transfer potential & barriers to other sectors	▪ Quantify environmental impact of digital solutions ▪ Determine value contribution of these solutions (in 2020) ▪ Estimate value creation potential in best, likely & worst case scenarios (in 2030)	▪ Evaluate & condense market analysis insights ▪ Conduct interviews with experts ▪ Define options for in-depth use of digital solutions with good environmental impact

Figure 1: Overview of the individual aspects of the study including the issues addressed and methodology used in each case (source: own presentation)

2.1 Conceptualisation

The digitainability field of interaction was structured by selecting sectors, environmental indicators, digital technologies and sustainability levers for consideration (see figure 2). This selection framework defines the study and allows meaningful conclusions to be drawn.

The understanding of this study is that the objective of environmental sustainability is to remain within planetary boundaries and thus also guarantee a safe operating space for future generations. This acatech STUDY used the UN's Sustainable Development Goals (SDGs) as the frame of reference for selecting the environmental indicators for measuring the influence exerted on environmental sustainability by the leading sectors under consideration. SDGs 8 (Decent Work and Economic Growth), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production) and 13 (Climate Action) are of particular relevance to environmental sustainability and are used as the basis for deriving eight indicators, following the model of Germany's Sustainability Strategy, which allow the fulfilment of sustainability goals to be measured.

The study focuses on eight sectors which include, on the one hand, industries with a particularly severe negative impact on environmental sustainability and, on the other, industries which are central to the creation or application of solutions based on key digital technologies, such as the information and communication technology (ICT) industries.[12] The industries were defined and assigned to the sectors on the basis of the 2008 Classification of Economic Activities (WZ).[13] Some industry groups were combined into one sector due to their structural similarity in a sustainability context.[14]

The digital technologies considered in this study were identified from the BMWK's technology and trend radar[15], either because they promise to have a positive impact on environmental sustainability or because they are of great relevance to the German economy due to their prevalence.

- Cloud and edge computing
- Internet of things (IoT)
- Cyber-physical systems (CPS)

12 | The energy industry was not considered in this study.

13 | See Statistisches Bundesamt 2008.

14 | The assignment of individual industries is available on the project website at https://www.acatech.de/projekt/digitainability-marktpotenziale-und-strategische-implikationen-digitaler-technologien-fuer-oekologisch-nachhaltiges-wirtschaften/.

15 | See BMWi 2021.

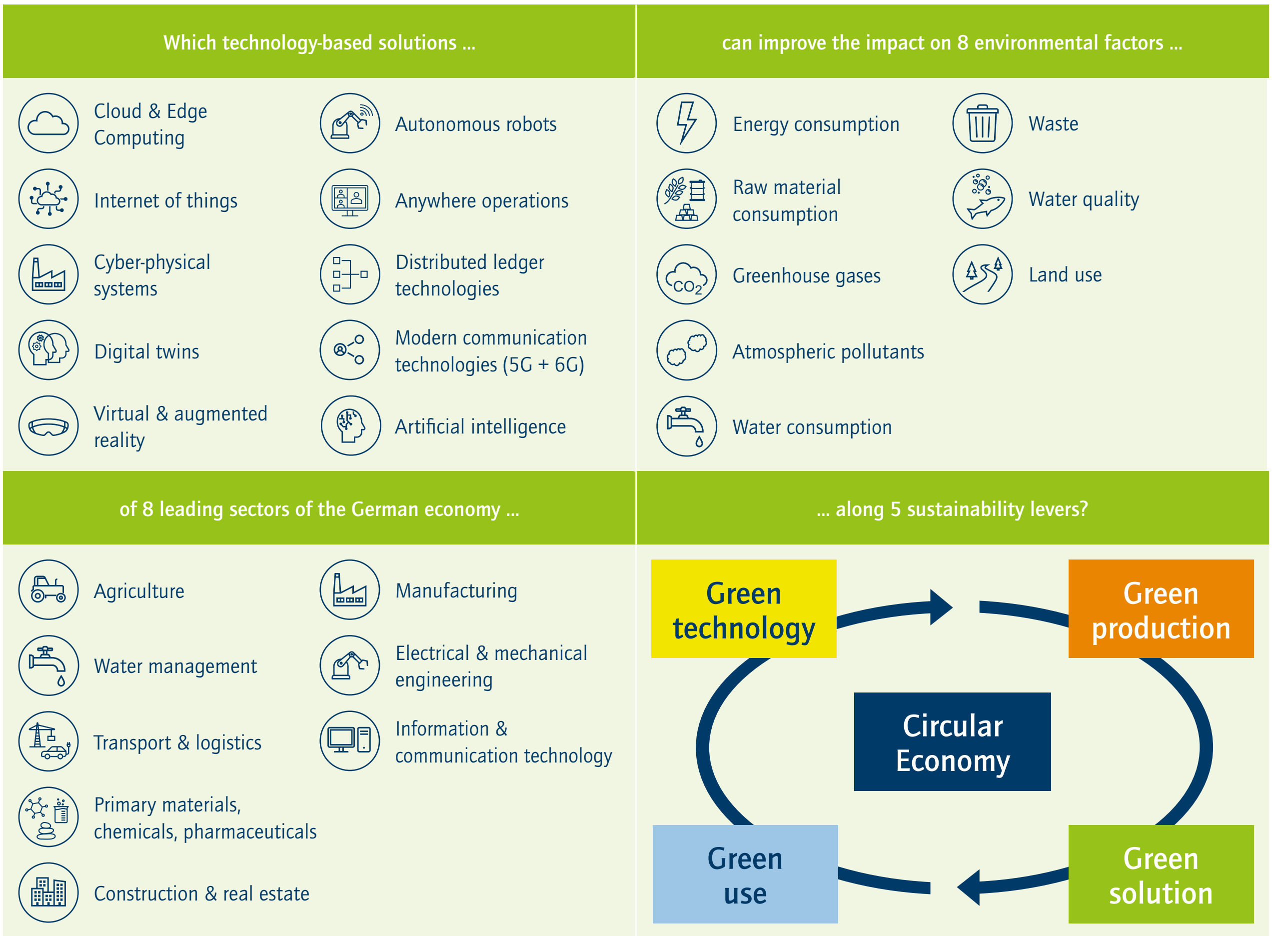

Figure 2: Fundamental question underlying the present study and overview of the technologies, environmental factors, economic sectors and sustainability levers considered (source: own presentation)

- Digital twins
- Virtual and augmented reality (VR and AR)
- Autonomous robots
- Anywhere operations
- Distributed ledger technologies (DLT)
- 5G + 6G (advanced communication technologies)
- Artificial intelligence (AI)

These digital technologies serve as "search grids" for the digital solutions identified with this study. In other words, each of the digital solutions listed in this study is based on at least one of the stated digital technologies and often on a combination of several technologies.

Five sustainability levers along the value chain were identified to clarify the points at which digital solutions act in order to strengthen a sector's environmental sustainability:

1. **Green technology** – the development of a solution based on a digital technology or a mix of digital technologies: this involves evaluating processes which are required to produce deployable digital technologies. Any reductions in environmental impact and increases in value creation potential, achieved by process improvements, of information and communication technology (ICT) products (e.g. a more energy-efficient AI algorithm) are generally attributed to the ICT sector.

2. **Green manufacturing** – the application of a solution based on a digital technology or a mix of digital technologies in processes for producing other solutions: this involves evaluating the processes required for taking products/services to marketable completion. Any reductions in environmental impact generated by deployment of a technology-based solution are generally attributed to the industry in which these products/services are deployed (e.g. AI-based process improvement in automotive manufacturing is attributed to the automotive manufacturing industry in the manufacturing sector).
3. **Green solution** – the use of a solution based on a digital technology or a mix of digital technologies in a final product: this involves evaluating final products/services whose environmental impact is reduced by integrating technology-based solutions (e.g. digital engine management in efficient cars). Such a reduction in environmental impact is usually attributed to the industry in which the technology-based solutions are deployed as part of the final product/service (in this case the automotive manufacturing industry in the manufacturing sector).
4. **Green use** – the use of digital solutions to reduce environmental consumption by users in both private and commercial applications: this involves evaluating solutions which are not themselves environmentally sustainable, but which nudge consumer behaviour towards a reduction in environmental impact (such as mobility as a service solutions for reducing private motor vehicle use). Such a reduction in environmental impact is usually attributed to the sector in which the prompted change in consumer behaviour leads to reduced environmental impact (in this case, the passenger transport industry in the transport and logistics sector).
5. **Circular Economy** – the deployment of digital solutions to enhance raw material recirculation in product manufacture and use in order to reduce environmental impact and decouple economic growth from resource consumption (see Digital solutions for the Circular Economy information box for examples): this involves evaluating digital solutions which enhance the reusability and longevity of products and services for the purposes of a Circular Economy. Such a reduction in environmental impact is usually attributed to the sector in which the greater circularity brought about by the digital solution leads to reduced environmental impact (as in remanufacturing in the mechanical engineering industry).

Digital solutions for the Circular Economy

Digital solutions ensure the proper functioning of circularity throughout the product cycle.

Product Design: The Circular Economy must be considered right from the product design stage (design for circularity). For instance, products can have sensors incorporated into them which transmit real-time information about the products during their service life and so enable preventive maintenance or repair.

Transparancy: Digital solutions enable transparent and collaborative sharing of relevant information and data along the entire supply chain, for example by digital product passports or other solutions based on distributed ledger technologies (DLT) and so enable sustainable purchasing decisions along the entire value chain.

Operationalisation of circular business models: Digital solutions make new business models in a Circular Economy possible. By providing and efficiently transferring data and information, solutions based on technologies such as the internet of things (IoT), digital twins or distributed ledger technologies (DLT) create value which can be used for new products or services in a circular economy.

Product service life: Digital solutions which document product data and evaluate them in real time during the product's service life can be used to extend product service life, maintain maximum quality during use, optimise the development of new products and close material and energy cycles.

Recycling: Good documentation and access to data from the design and life cycle of the product enable a more efficient recycling process. Digital solutions can additionally be used to simplify and optimise material identification and sorting in the recycling process.

The tight focus on the five sustainability levers is intended to create evidence on (1) how sustainability potential is distributed sector by sector between increasing efficiency ("doing things right") and increasing effectiveness ("doing the right things") in value creation and (2) which levers in the value creation process might promise a significant reduction in the sector's environmental impact.

During preparation for the market analyses, i.e. identification of digital solutions and quantification of value creation potential, each sector was characterised in terms of its environmental impact, sustainability levers and technology potential. These sector profiles were developed on the basis of expert interviews and secondary data analysis and include various interdependent aspects:

- Environmental impact: assessment of the sector's negative impact on the environmental indicators considered (see figure 2 top right) in order to identify the most important environmental indicators for this sector.
- Sustainability levers: identification of the most important sustainability levers per sector according to their environmental impact (e.g. circularity in manufacturing instead of purely linear product creation, avoidance of mobility in transport and logistics).
- Technological enablers: identification of the most important technologies from the study's technology set (see figure 2 top left) which, used in digital solutions per sector, might have significant promise in reducing the respective environmental impact.

These sector profiles were used to organise the field of interaction between sector-specific environmental impact and sector-specific leverage effects of the digital technologies under consideration. They accordingly form the basis for the in-depth analysis of the potential of digital solutions in terms of both their environmental sustainability and their economic value creation.

2.2 Environmental market analysis

Along the sector profiles and the environmental indicators, digital technologies, sustainability levers and points for consideration which were identified here as being of particular relevance, solutions based on a digital technology or on a mix of digital technologies which contribute to enhancing environmental sustainability were identified in each sector. This forms the basis for the qualitative evaluation of sectoral environmental sustainability potential through the sustainable use of digital solutions.

The qualitative evaluation of the environmental sustainability potential of specific digital solutions was based on four steps per sector: exploratory research, recording and structuring of the digital solutions, specific extension of the research and summary assessment of its environmental potential.

On the basis of internal expertise and preliminary work, relevant generic digital technologies were selected and digital solutions based on them were derived for the sectoral use cases. Two search directions (technologies and sectors) were mapped by exploratory internet research and an overview of technology combinations which are already in use or under discussion in research projects was obtained. In the next step, these were validated by internal expert evaluation and combined and structured into prototype digital solutions. On the basis of this list, the internet research could be extended by practical use cases, research projects and isolated quantitative analyses of environmental potential and specifically further researched.

Finally, each digital solution was qualitatively evaluated for its environmental potential on the basis of the research findings. In addition to describing and ranking the sustainability levers defined in the project along the value chain, the environmental effect of the solution is classified into four categories on the basis of sustainability indicators. Given the stated objective of making a qualitative assessment and in the light of the significant scatter of the quantitative data in the secondary literature, consistent quantification was not possible, so an internal expert estimate of indicative mean values was made as a point of reference. Depending on the particular indicator, the environmental potential of the digital solution is categorised and assigned to a low (0 to 10 per cent), medium (11 to 30 per cent) or high (> 30 per cent) impact. A digital solution can furthermore also act as a higher-level enabler and thus be a necessary and supportive prerequisite for the deployment of digital solutions across a wide range of sectors and use cases.

Since the evaluation is based on secondary literature, the limitation of this methodological approach is the availability of findings on the quantified sustainability potential of digital solutions. It should be emphasised that the quantified sustainability potential only reflects the figures for a specific practical use case and thus indicate a case-specific potential which may develop differently on scaling (linear, exponential etc.).

Separately from the specific digital solutions, environmental costs which can be reduced by the deployment of digital technologies were calculated for the sectors as part of a scenario analysis (see also section 2.3). These are the internalised costs for the respective sector which are caused by the prevention, elimination, recycling and monitoring of environmental nuisances and impact. They are thus a quantitative measure of the extent to which increasing environmental sustainability can also have direct positive effects on the cost structure in the economy.

2.3 Economic market analysis

The starting point for the economic market analysis was a calculation of the information and communication technology (ICT) inputs per sector as a quantitative measure of the use of digital technologies; these inputs are taken to mean the operating resources directly expended in the manufacturing process for each sector. These figures include domestically produced and imported goods volumes and so provide a complete picture of the use of technologies in the current situation.

Starting from these figures, the sector-specific economic value creation potential of more environmentally sustainable economic activity due to the use of digital technologies was quantified on both a value creation and a cost basis. The focus was on three dimensions of the impact of information and communication technologies (ICT) (figure 3): (1) quantitative consideration of the prevalence of ICT with the aim of achieving a sustainable economy (ICT penetration), (2) quantification of the potential operational cost savings and savings of macroeconomic environmental costs (environmental cost savings) and, where this was possible, (3) estimation of the market potential of ICT-based environmental products (market assessment). An inventory of the current situation was drawn up for each of the three building blocks of the investigation. On this basis, questions were asked about possible developments up to 2030, a probable case in the event of an unchanged regulatory framework (likely case) being compared with a situation with a favourable regulatory framework (best case) and a development under unfavourable conditions (worst case).

In estimating the penetration of information and communication technology (ICT) in sustainable solutions (investigation building block 1), price-adjusted gross value added in 2020 was first determined for each sector in an analysis of the current situation. Taking this as a starting point, existing studies were used to quantify the extent to which already deployed digital technologies strengthen environmental sustainability. In manufacturing sectors, the focus was on ICT in the form of the deployment of Industrie 4.0, i.e. the networked application of digital technologies (such as additive manufacturing, augmented reality or internet of things (IoT) platforms) in a manufacturing context. In contrast, a broader definition of digital technologies was used for the investigations in agriculture and water management where Industrie 4.0, being a manufacturing concept, naturally plays a lesser role. Anticipated price-adjusted gross value added in 2030 was calculated for a scenario analysis. On the basis of different future assumptions regarding the prevalence of digital technologies, a likely case, a worst case and a best case were developed and used to estimate the prevalence of digital technologies which strengthen environmental sustainability in gross value added terms.

On the cost side, energy input costs for the status quo in 2019[16] were considered and the associated savings potential of using digital technologies was economically quantified in a scenario analysis up to 2030 (investigation building block 2). The investigation of the input side focused on an analysis of industry linkages on the basis of an input-output analysis. This analysis revealed the extent to which information and communication technology are entering into the various industries and consequently what significance digital technologies have for these industries measured in terms of industry-specific output value. Based on the input-output considerations, the potential economic savings for the sustainable use of digital technologies was determined for each of the different scenarios.

In addition to this market-related approach, questions were also asked from another perspective about potential savings in the use of resources through the application of digital technologies (environmental costs). The expected development of environmental costs in 2030 was based on energy consumption for light heating oil, gases, lignite and hard coal as well as electricity, disregarding feedstock (non-energy) use of these resources in

16 | This year was selected because data from the current Federal Statistical Office input-output table for 2019 were used for this evaluation.

the chemical industry. These energy sources are primarily used in industrial combustion processes and, in the case of electricity, for drive and control purposes. These are processes where the deployment of digital technologies could increase sustainability.

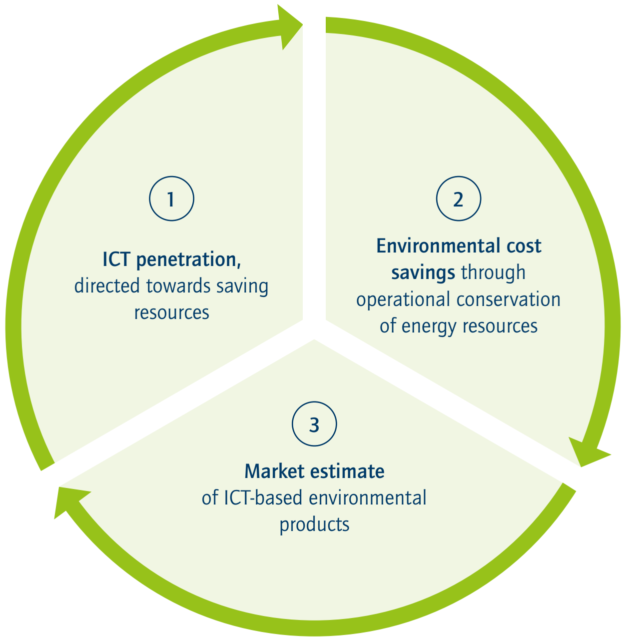

Figure 3: Investigation building blocks of the economic market analysis (source: own presentation)

Sector-specific market potential (investigation building block 3) was quantified by identifying sector-specific opportunity profiles. It was investigated which of the products and services offered for sale in an industry involve environmentally sustainable solutions based on the use of information and technology. These offerings were identified for the industries under consideration on the basis of (a) current value creation in these industries, (b) assessments from existing studies on the use of digital technologies for sustainability and (c) evaluations from expert interviews. Time-series analytical econometric methods were furthermore used to develop a baseline scenario.

With regard to information and communication technology (ICT) use, the methodology was extended on the basis of the previously described calculations for the various scenarios (likely case, worst case, best case). Accordingly, energy savings and the environmental potential in connection with green IT were estimated for the various scenarios by forecasting the power consumed by the use of ICT hardware and the associated environmental costs. One application of ICT which will continue to be a particular focus in future is increased homeworking, which would be inconceivable without intensive use of ICT. The potential of a further expansion of homeworking is expressed in direct cost savings for reduced commuting, in time savings (measured by opportunity costs), and in falling environmental costs.

One cross-industry effect of digitalisation relates to the Circular Economy becoming more deeply rooted. To this end, the development of sales revenue and value creation of the Circular Economy in 2030 was firstly forecast for the various scenarios. With the assistance of an estimate of the sales revenue shares of the Circular Economy for which digitalisation is likely to be of particular importance in the future, it was possible to determine the anticipated market potential which is particularly suitable for digital applications and the resulting potential with regard to greater sustainability.

The investigation is associated with some limitations. Firstly, while studies by Bitkom in particular have already painted an up-to-date picture of the prevalence of digital technologies and their relationship to sustainability, there is still a considerable need for research in terms of a more accurate reflection of what is happening across the breadth of the economy with regard to this key aspect in relation to technology use. In relation to potential savings through the deployment of digital technologies, only energy resources were considered, there being some limitations with regard to data availability at certain points.[17] The latter also concern the combination of environmental and economic market analysis, which is limited due to the difficulty of quantifying the economic value creation potential of digital solutions. The economic market analysis therefore focuses more on the impact of digital technologies on sectoral sustainable value creation, while the environmental market analysis ventures a more specific look at individual solutions. Taken together, however, this provides a complementary picture of the status and potential of digitainability in the German economy.

17 | The raw data for the economic and environmental market analysis are available on the project website at https://www.acatech.de/projekt/digitainability-marktpotenziale-und-strategische-implikationen-digitaler-technologien-fuer-oekologisch-nachhaltiges-wirtschaften/.

2.4 Identification of options

Options for deepening the strategic joint consideration of environmental sustainability and digitalisation were identified by firstly combining the variety of evidence from the market analyses. The evidence was structured by identifying three areas of action:

- **Efficiency gains:** the deployment of digital solutions to make existing processes, technologies and products more environmentally sustainable.
- **Effectiveness gains:** the supportive deployment of digital solutions to initiate fundamental adjustments in usage behaviour and business practices (e.g. Circular Economy) to strengthen environmental sustainability.
- **Regulatory framework:** necessary adjustments to extensively enable a strategic joint consideration of environmental sustainability and digitalisation.

Semi-structured interviews along these areas of action were then conducted with experts from the technical and environmental sciences as well as users from the sectors under consideration. In the course of these interviews, options were evaluated to determine how the intersectoral transfer of existing digital solutions can be strengthened and barriers to exploiting the potential for value creation and sustainability can be overcome. In addition, the manner in which the attention paid to environmental sustainability and the use of digital technologies can be brought together for the development of new business models was also discussed, as was the role the various stakeholders in the economic system should take onboard to ensure a successful, digitally assisted transformation to sustainability.

Arising from these discussions, options were derived and formulated in the three areas of action. These options are thus based both on the empirical evidence from the economic and environmental market analysis and on the experts' qualitative assessment. The options were worded in an addressee-specific manner (see table 1) and structured along the stated areas of action (see section 4).

3 Current situation and potential of digital solutions for environmental sustainability in the German economy

On the basis of the outlined methodology, the findings of the economic and environmental study are presented below. In addition to presenting the most important digital solutions available in each sector, this includes a summary of the current economic situation and an analysis of potential for 2030, as well as a summary of the opportunities and challenges of more in-depth application of digital solutions. Each sector is firstly presented before a cross-sectoral comparison is drawn in terms of the digital technologies considered and the digital solutions based on them.

3.1 Most important solution groups

Due to the sheer mass of available digital solutions which strengthen environmental sustainability, the explanations are limited to an overview. The environmental market analysis has shown that, with the exception of a few sector-specific applications and despite their sometimes great technological diversity, digital solutions can be classified into ten solution groups, each with different effects on the environmental indicators:

- **Data ecosystem:** a system of various stakeholders, services and applications (software) in which data are put to use in order to be utilised economically or societally.
- **Data analysis and tools for system modelling and strategic planning:** the use of statistical methods for analysing corporate data as a basis for digitally mapping processes in a model, on which basis technical and business systems can be designed.
- **"Green" enterprise resource planning systems:** a management system for providing necessary corporate management functions (finance, human resources, manufacturing, logistics, services, procurement, etc.) which internally optimises a company in terms of sustainability, for example by reduced material consumption, optimised machinery utilisation or paperless document transfer.
- **Digital twin:** a concept with which, for example, products and machines, components and infrastructure are modelled in virtualised form using digital tools, including all geometry, kinematics and logic data. A digital twin is a representation of a physical asset which allows it to be simulated, controlled and improved.
- **Digital product passport:** a data record which summarises a product's components, materials and chemical substances or indeed information on repairability, spare parts or proper disposal.
- **Integrated and interconnected machinery and plant control:** an interlinked system of information and software components using sensors to acquire data, evaluate them by means of embedded systems and exchange them with other machines or data sources.
- **Virtual product design and development and virtual training and maintenance:** product design based on simulations, for example, with regard to physical processes, vibration, materials etc. or performance of maintenance or training measures based on 3D simulations, for example of manufacturing machinery or vehicles.
- **Data-based optimisation for example of inventory management and logistics:** the use of process measurement data for the design and analysis of control systems without using an explicit process model and a priori assumptions for direct online implementability in processes.
- **Sustainable procurement:** the sustainable procurement of goods, evaluating requirements, specifications and criteria across the entire associated value chain which are compatible with environmental protection and social progress and promote economic development, in particular resource efficiency, product quality improvement and cost optimisation.
- **Smart energy supply and management:** the use of smart technologies in power generation, storage, transmission and consumption control.

Figure 4: Schematic overview of the relationship between digital technologies, digital solutions and digital solution groups (source: own presentation)

In this study, the solution groups act as the basis for the following overview presentation of the sector-specific analysis findings, so simplifying interpretation, enabling comparability between sectors and allowing the identification of technologies and applications with expansion potential. The technologies used in the solution groups can in fact be identified once again via the digital solutions combined in solution groups (see figure 4 for the relationship between solution groups, solutions and technologies).

Granular information on environmental sustainability impact and availability of digital solutions per sector can be found in the supplementary digitainability slide deck published with this study and in the open-access raw data for the environmental market analysis.[18]

3.2 Findings of the environmental and economic market analyses

The focal sectors influence the environmental indicators under consideration in different ways (see figure 5). This is accompanied by different levels of urgency per sector when it comes to reducing negative impact on environmental sustainability.

An inherent factor here is that, both hitherto and in future, digital solutions which strengthen environmental sustainability are differently distributed depending on the sector simply due to demand. In addition, there are further sector-specific hurdles or conditions for success for the prevalence of digital solutions, such that, depending on the sector, a different picture emerges with regard to the availability of corresponding solutions and their economic value creation and savings potential.

Sector	Energy consumption	Raw material consumption	Greenhouse gases	Atmospheric pollutants	Water consumption	Waste	Water quality	Land use
Agriculture	low	medium	high	high	medium	low	high	high
Water management	medium	low	low	low	high	low	low	low
Transport & logistics	high	medium	high	high	low	medium	medium	high
Primary mtrls., chems., pharms.	high	high	medium	low	high	low	high	medium
Construction & real estate	high	medium	low	low	medium	high	medium	high
Manufacturing	high	high	high	medium	low	medium	medium	medium
Electrical & mech. engeneering	high	high	medium	medium	low	medium	medium	medium
Information & communication tech.	high	high	low	low	low	low	low	low

Negative environmental impact per leading sector: high, medium, low

Figure 5: Overview of tendency of negative impact on considered environmental indicators per sector (source: own presentation)

18 | The raw data for the economic and environmental market analysis and the digitainability slide deck are available on the project website at https://www.acatech.de/projekt/digitainability-marktpotenziale-und-strategische-implikationen-digitaler-technologien-fuer-oekologisch-nachhaltiges-wirtschaften/.

3.2.1 Agriculture

While agriculture is the smallest sector considered in this study in terms of generated value added, at 26.3 billion euro, it has a major negative impact on the economy's environmental footprint due to its high greenhouse gas emissions and energy intensity (2020: 6.4 terajoules per million euro gross value added, 2030 forecast: 8.8 TJ/million euro GVA) and its impact on water quality (including through fertilisers). At the same time, in this area, unlike most other sectors, many digital solutions are already aimed at increasing environmental sustainability and resource conservation, as these factors have a direct impact on profitability. In particular, they have an influence on reducing energy consumption, greenhouse gas emissions and resource use, as well as on reducing water consumption and land take.

From a technological standpoint, modern communication technologies, cloud and edge computing, and big data approaches to collecting and processing the resulting volumes of data are of particular relevance in agriculture, especially via the distributed systems used in the field. In some cases, AI is already being used to analyse data, and sensors and machines are working together using the internet of things (IoT) and cyber-physical systems. Distributed ledger technologies, augmented reality), virtual reality and anywhere operations, on the other hand, are at present hardly used at all in agriculture.

Deployed digital solutions

There are specific solutions with major sustainability potential in terms of the considered environmental indicators in the solution groups digital twin, tools for (eco-)system modelling and strategic planning, ecosystem monitoring and aquaculture/insect culture in the context of data-based optimisation and smart energy supply and management systems. In addition, the data analysis and integrated and interconnected plant control system solution groups already include solutions whose effect is primarily apparent in energy and raw material consumption, in greenhouse gas emissions and in improvements in water quality.

Use case: smart field robotics for sustainable agriculture

The AI-assisted field robot from the NOcsPS project enables autonomous mechanical weed removal without chemical plant protection products. The robot is equipped with camera and laser sensors and is capable of distinguishing crops from weeds using AI methods. The image data are evaluated in real time in the robot.

Weed removal without chemical plant protection products maintains biodiversity and soil fertility and avoids chemical residues in foodstuffs. The robot is powered entirely electrically using renewable power which means that no climate-damaging emissions occur during operation.[19]

Solutions are already being deployed to provide assistance in many areas of agriculture but focus primarily on arable farming rather than animal husbandry, which is very harmful in terms of greenhouse gas emissions and water quality. In arable farming, the automation of small machines (see use case information box), route optimisation for tractors and the monitoring of cultivated areas in terms of soil quality as well as the creation of digital field twins stand out in particular. These solutions, which target improved plant control systems and machine use, have great promise in terms of energy efficiency while data spaces for regional agricultural networking also integrate producers beyond the field. Such ecosystem services offer great potential for releasing new value creation potential. Regarding animal husbandry, applications already exist for data-based optimisation of feed use and for monitoring animal health and wellbeing. Animal husbandry could be replaced by data-optimised, in vitro cultured meat. Building-integrated agriculture, which is already in more widespread use in other countries (e.g. Singapore), has disruptive potential, especially for reducing land take. In terms of more circularly oriented agriculture, initiatives for organic raw

19 | See NOcsPS 2023.

material production through traceable supply chains and regional digital distribution platforms (e.g. distribution of vegetable boxes) or networking platforms for joint composting should be mentioned.

Agriculture therefore primarily involves industry-specific solutions which, with a few exceptions in the area of nutrition, can be attributed above all to **green manufacturing** (see section 2.1) and are thus primarily aimed at achieving efficiency gains in terms of environmental sustainability and less at increasing effectiveness through adapted use or circularity. It should be emphasised that these solutions are specifically designed to meet industry needs and that resource conservation is a key objective of using digital solutions since such use promises both economic efficiency gains and environmental improvements.

Economic potential

In the best case, digitainability value added in agriculture may be increased by almost 50 per cent by 2030 compared with 2020. In line with the wide range of applications for digital technologies in agriculture, the increase in information and communication technology inputs used in agriculture of 8.0 per cent annually from 2008 to 2019 is distinctly higher than the average annual growth of 6.7 per cent in other sectors. Given the wide range of applications of different digital solutions, the best-case potential in agriculture is for 96 per cent of companies to be using digital solutions by 2030 (+22% vs. 2020). This could generate environmental value added, i.e. the deployment of digital technologies for environmentally friendly production, of 24 billion euro in agriculture (see figure 6). In the best case, consistent deployment of digital technologies will enable potential savings on environmental costs due to energy consumption of some 204 million euro in agriculture by 2030. Even in the best case, energy input costs will increase by 3.0 per cent compared with 2019 to 2.3 billion euro. The deployment of digital solutions to boost energy efficiency will therefore continue to be crucial to the success of economic and environmental sustainability in agriculture.

Status quo at a glance	
17.6 % Dom. raw material equivalents (share of total, 2020)	**8 %** Fine particulate emissions (share of total, 2020)
6.4 TJ/€ million GVA Energy intensity	**€51 million** ICT inputs

Energy & environmental costs	
€2.6 billion Energy input costs (likely case 2030)	**€2.3 billion** Energy input costs (best case 2030)
+ €30 million Environmental costs vs. 2019 (likely case 2030)	**- €204 million** Environmental costs (best case 2030)

Scenario-based value creation analysis

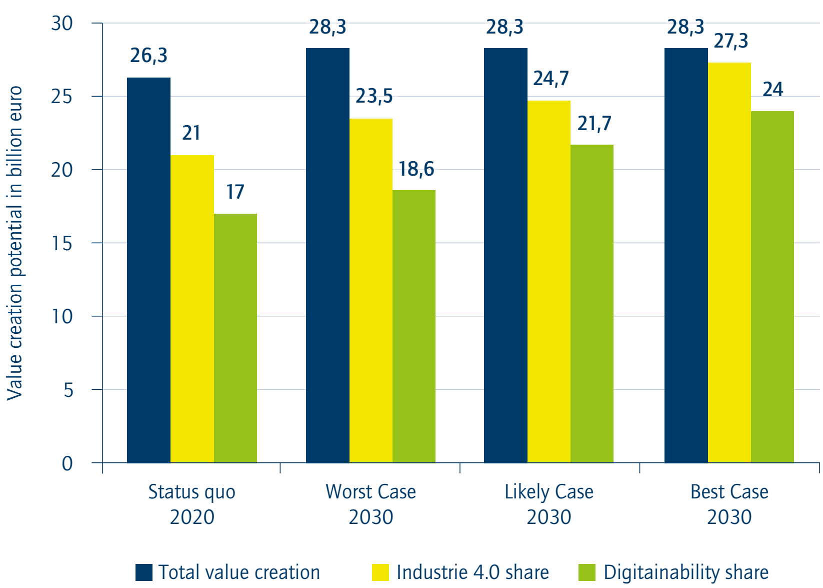

Figure 6: Key findings of the economic market analysis in the agriculture sector. Dom. = domestic; TJ/ € million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

When it comes to the use of interconnected systems, in particular over extensive cultivated areas, there is still a lack of digital infrastructure in some cases. At the same time, the possibilities of digital technologies in terms of environmental sustainability are not yet embedded in the minds of users throughout the industry. There is great potential here, especially in the area of animal husbandry, but currently there are still few digital solutions. Digitalisation could also make a major contribution to promoting the direct marketing of local agricultural products (plant products, meat and milk) to final consumers in terms of marketing and customer management through the expansion of digital distribution channels to greater transparency and traceability of agricultural products.[20,21] At present, there is still a lack of incentive structures for environmental economic activity and of digital solutions which are based across the board on standards, reference architectures and open data ecosystems.

3.2.2 Water management

In 2020, water management generated value added of 35.1 billion euro. This sector is characterised by its interface function, as it interacts with all other fields. The main negative environmental impacts of water management are its consumption of both water and energy. In comparison with other sectors, there are currently still few digital solutions explicitly designed for this sector which strengthen environmental sustainability. These are primarily methods for data collection and analysis and for optimising water cycles on the basis of these data (e.g. in the form of autonomous measuring instruments for water quality and subsequent evaluation by means of an internet of things platform), as well as agriculture-related digital solutions.

Deployed digital solutions

The deployed technologies have clear overlaps with agriculture since here too the emphasis is on communication technologies, AI, big data approaches and cloud and edge computing. Solutions based on the internet of things, cyber-physical systems and autonomous robots are also in use.

The digital solutions applied in this sector have so far mainly been directed towards efficiency gains in water treatment. Monitoring systems in conjunction with gamification approaches can, however, also be used to encourage water consumers – both private individuals and companies – to reduce their water use. There are already initial solutions in this direction, for example in the form of consumption apps. Digital solutions are already being applied to effectiveness levers in the water industry to a greater extent than in agriculture (qualitative prevalence via sustainability levers), although the quantitative concentration of digital solutions is lower than in agriculture.

Due to the expected deeper prevalence of corresponding digital solutions, there is future potential for increasing water quality, for reducing water consumption and for reducing energy usage (2020 219.8 petajoules, 2030 forecast 160.6 petajoules). The latter could be achieved primarily on the basis of significantly increased energy efficiency by expanding the stated digital technologies. Data-based optimisation of irrigation or autonomous measurement of pesticide contamination in wastewater to improve fertiliser strategy are initial promising examples. Modern data management systems will play an important role in water management in the future.

Economic potential

Inadequate data availability means that sales revenue and value creation potential cannot be directly captured in water management. However, the clear increase in the use of information and communication technology inputs of 7.7 per cent annually between 2008 and 2019 suggests that water management also has the potential to achieve high digitainability value creation. In the best case, environmental costs (see section 2.2) in this sector would fall by up to 506 million euro by 2030 (see figure 7).[22] Energy input costs, on the other hand, will increase in the likely case by 18 per cent from 1.5 billion euro in 2019 to 1.8 billion euro in 2030. Only if energy efficiency can be distinctly increased would a best-case reduction in the corresponding costs of 29 per cent compared with 2019 to 1.2 billion euro in 2030 be achievable.

20 | See TU Berlin 2022.

21 | See Bitkom 2022.

22 | Due to inadequate data availability, environmental value creation cannot be estimated for water management so forecasts up to 2030 also cannot be made.

Status quo at a glance	
219.8 PJ Energy consumption (2020)	**9.0 billion m³** Annual wastewater volume (2020)
9.8 TJ/€ million GVA Energy intensity	**€1.1 billion** ICT inputs

Prerequisites for best case

- Adjustment of incentive system to take advantage of leverageable sustainability potential
- Doubling of energy efficiency growth rate to 10.0 %
- Realisation of cost saving potential for electricity & gas/oil/coal

Energy & environmental costs (billion euro)

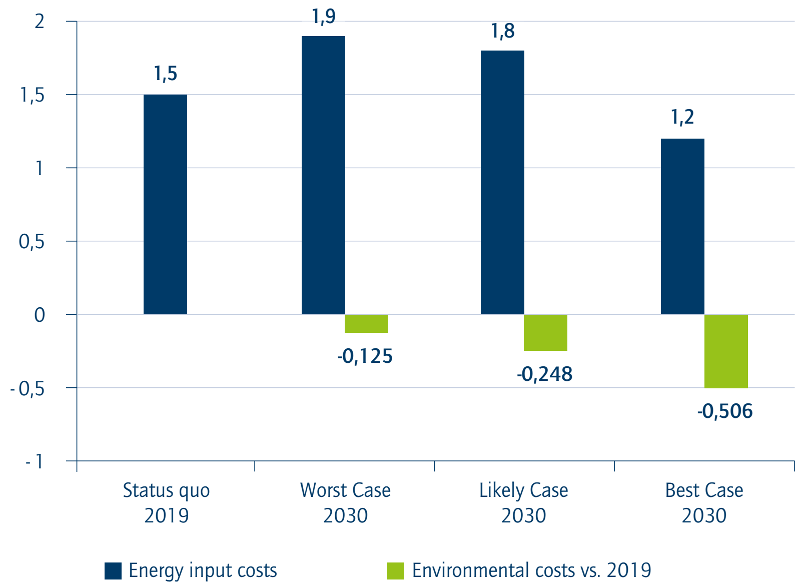

Figure 7: Key findings of the economic market analysis in the water management sector. PJ = petajoules; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

The importance of having an interconnected, smart water supply is becoming apparent in view not only of ever more frequent water scarcity in certain regions and the resulting distribution conflicts but also of increasingly frequent droughts. Accordingly, there is great potential in digitalising water management, especially in the form of improved, ideally real-time capable data acquisition. This would enable improved drinking water balancing in a supply area as well as predictive infrastructure maintenance. Added value is here primarily generated by the evaluation of shared data. This is, however, at variance with the regulatory challenges for data provision due to federal data collection and data protection guidelines. At the same time, improved digitalisation in water management permits closer interconnection with building information modelling, which is used in the construction and real estate industries, so as to achieve additional savings and a more sustainable link with existing water management. There are at present only few concrete use cases which illustrate that sustainability-enhancing capital spending in water management (e.g. for the necessary measurement infrastructure) also pays off economically in the long term.[23,24,25]

3.2.3 Transport and logistics

The transport and logistics sector generated value added of 120.7 billion euro in 2020. With an energy intensity of 10.7 terajoules per million euro gross value added, it is one of the most energy-intensive sectors. Significant negative features are the sector's high greenhouse gas and atmospheric pollutant emissions and its land use, for example for roads and railways. In the context of this sustainability assessment, transport and logistics are of particular significance due to their interface function between several sectors. There are already some digital solutions for strengthening environmental sustainability which act not only on efficiency but also on effectiveness levers of use (e.g. shared mobility).

From a technological standpoint, digital solutions based on communication technologies, AI, big data approaches and cloud and edge computing are the main ones deployed in the transport and logistics sector. At present, the focus is on interlinking and route optimisation for heterogeneous mobility users. Internet of things-based solutions are used in logistics in

23 | See DWA 2020.
24 | See DVGW 2023.
25 | See UBA 2022.

particular, but also in relation to autonomous driving. Distributed ledger technologies, cyber-physical systems, augmented and virtual reality have so far found limited applications. In particular during the COVID 19 pandemic, solutions based on anywhere operations have enabled massive reductions in mobility, and thus in associated emissions. Autonomous robots are likewise currently in somewhat limited use, but are increasingly coming to the fore, in particular in the automation of logistics processes.

Deployed digital solutions

In terms of solution groups, it is above all digital twins which have the potential to cut the sector's energy and raw material consumption and its greenhouse gas emissions. Applications relating to data ecosystems as well as to data analysis and decision support primarily impact raw material consumption and thus greenhouse gas emissions. Integrated machinery and plant control systems lead to a reduction in energy and raw material consumption, while data-based optimisation and electrification of vehicles and logistics enable a reduction in energy and raw material consumption. Digital product passports primarily influence raw material consumption by increasing transparency in purchasing processes and enabling more efficient recycling, while the use of virtual product design or virtualisation of training can reduce greenhouse gas emissions.

Specific solutions are directed towards linking mobility users and offers on digital platforms for sustainable route optimisation and the integration of smart systems in transport and logistics networks. This can be achieved, for example, by using traffic computers as a basis for driving suggestions or route optimisation. From a strategic planning perspective, environmental impact can be included via AI-assisted predictive urban planning using digital twins by design; the same also applies to logistics planning within a holodeck. Virtualised applications, such as virtual training of flight attendants or helicopter pilots, additionally contribute both directly and indirectly to reducing this sector's environmental impact. Particularly in the logistics sector, process automation similar to that in manufacturing can already be found in the form of automated parts picking. From a circularity perspective, digital deposit systems for products can also be the basis for traceability of the resultant waste. From a use-oriented standpoint, mobility platforms which connect different road users for optimised mobility use are a step towards promoting green use through digital technologies.

Economic potential

In comparison with other sectors, digitalisation in transport and logistics is already above average. This is also reflected in ICT inputs, which were 4.0 billion euro in 2020 and are set to rise 7.3 per cent annually until 2030. The economic added value of Industrie 4.0 (in particular efficiency gains through optimisation) means that it is already in use in 95 per cent of companies, with 64 per cent of them also using it in an environmentally sustainable way. Accordingly, sustainable value added in transport and logistics currently already amounts to 77 billion euro. Starting from this level, sustainable value added of 135.2 billion euro might be possible in 2030 if ICT inputs were to increase by 4.5 per cent annually (see figure 8).

The sustainable use of digitalisation in transport and logistics thus offers great potential, with the positive environmental effects scaling with the degree of interconnection in both transport and logistics. In the transport sector, not only should private transport vehicles be interconnected, but ideally also different transport solutions, for example via data spaces such as the mobility data space. For private transport in particular, electrification additionally plays a key role, with battery capacity and smart charging processes tailored to capacity being crucial. In the logistics sector, above and beyond interconnected intralogistics, logistics centres can be clustered and at the same time more distributed solutions can be integrated to achieve further efficiency gains.

Status quo at a glance	
14.5 % GHG emissions (share of total, 2020)	**55.4 %** Fine particulate emissions (share of total, 2020)
10.7 TJ/€ million GVA Energy intensity	**€4.0 billion** ICT inputs

Energy & environmental costs	
€16.9 billion Energy input costs (likely case 2030)	**€14.3 billion** Energy input costs (best case 2030)
+ €2.135 billion Environmental costs vs. 2019 (likely case 2030)	**- €0.592 billion** Environmental costs vs. 2019 (best case 2030)

Scenario-based value creation analysis

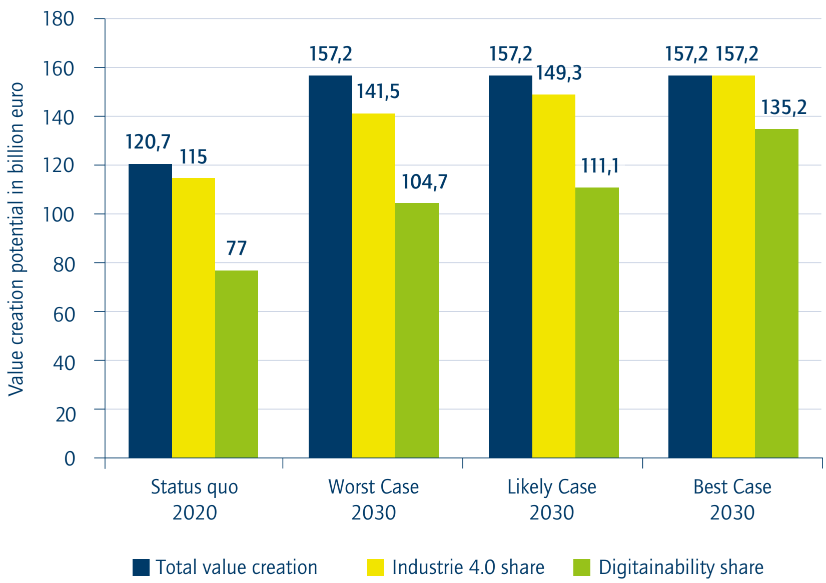

Figure 8: Key findings of the economic market analysis in the transport and logistics sector. GHG = greenhouse gas; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

3.2.4 Primary materials, chemicals and pharmaceuticals

The chemical and pharmaceutical industries generated value added of 78.3 billion euro in 2020. This sector has by far the highest energy intensity (25 terajoules per million euro gross value added) of the sectors considered. In addition, there is very high use of resources, particularly by the primary materials industry, high water consumption, a negative impact on water quality and a not inconsiderable impact on greenhouse gas emissions. There is thus a considerable need to deploy digital solutions to strengthen environmental sustainability, but Industrie 4.0 applications, which were in use in 58 per cent of chemical and pharmaceutical companies in 2020[26], are used to a significantly lesser extent than in manufacturing, for example. Major solution groups which are in use are primarily directed towards increasing efficiency rather than towards effectively increasing environmental sustainability.

In terms of technological foundations, communication technologies, AI, big data approaches, cloud and edge computing and cyber-physical systems play a central role because, like manufacturing, this sector primarily focuses on enhanced data acquisition and evaluation to enable a reduction in environmental impact by optimising efficiency. Digital solutions based on the internet of things approach play a subordinate but nevertheless important role. Autonomous robots, distributed ledger technologies, virtual and augmented reality are in only very sporadic use.

Deployed digital solutions

In solution group terms, it is in particular data ecosystem, data analysis and system modelling, digital product passport, sustainable procurement and recycling information loop applications which can help reduce the sector's negative environmental impact. In addition, the deployment of digital twins and a virtual development approach significantly reduce energy and raw

26 | Due to inadequate data availability for the primary materials industry, economic value creation potential could only be analysed for the chemical and pharmaceutical industries, but the environmental market analysis does include the primary materials industry.

material consumption as well as greenhouse gas emissions but their prevalence in this sector is still low. Integrated machinery and plant control and data-based optimisation of inventory management and logistics primarily influence energy consumption and greenhouse gas emissions, while the effects of smart energy supply and management systems are primarily seen in the sector's energy consumption.

The digital solutions which are available can above all contribute to reducing energy consumption, greenhouse gas emissions and the use of resources. Digital solutions already in use focus on manufacturing optimisation and monitoring including with regard to sustainability (e.g. in the context of integrating a carbon footprint for products, digital product development by modelling product lines or general digital molecule development). The sector's high energy demand is countered, for example, with smart energy supply systems for predicting peak loads and, as a result, the timely deployment of battery storage. In terms of enhancing circularity, solutions are available for improving recycling efficiency through product tracing and the use of alternative raw materials and return programmes, as well as solvent recovery methods in the chemical industry. Overall, however, a concentration of solutions on green manufacturing can also be observed in the primary materials, chemical and pharmaceutical industries, while available digital solutions have so far hardly addressed any effectiveness levers.

Economic potential

In the best case, digitainability value creation in the chemical and pharmaceutical industries may rise by more than two thirds by 2030 in comparison with 2020. Despite the comparatively average prevalence of Industrie 4.0 applications in the chemical and pharmaceutical industries, information and communication technology inputs at 0.8 per cent of output value are distinctly below the average of 1.9 per cent for the sectors considered here. At the same time, however, there is also the potential to establish Industrie 4.0 technologies in up to 86 per cent of companies by 2030 and so potentially generate sustainable value added of 62 billion euro. In terms of energy and environmental costs, only in the best-case scenario is there significant savings potential compared with 2019. Compared with 2019, a 60 per cent boost in energy efficiency can cut energy input costs by 26 per cent. Environmental costs will only decrease in the best case and even in the likely case they are expected to rise by almost 2 billion euro compared with 2019 (see figure 9). This highlights the urgent need to significantly boost the prevalence of digital technologies to strengthen environmental sustainability in these industries.

It is clear that very good use is already being made of efficiency levers in the pharmaceutical and chemical industries, energy-intensive mass processes already having been optimised. Obstacles to more in-depth use and the transfer of solutions lie, in particular, in the extremely heterogeneous structure and highly specific manufacturing requirements of the speciality chemicals and pharmaceuticals industries. This results in great demand for customised digital solutions. The Circular Economy is therefore key to success in strengthening environmental sustainability in the primary materials, chemical and pharmaceutical industries. In this way, the sector's high energy and resource requirements can be significantly reduced. Improved traceability along the value chain and transparency are crucial for this purpose, especially for enabling separation and recycling of individual product components after use. In terms of an ecosystem approach, objections can be raised against the lack of standardisation and the failure to use reference architectures which are necessary enablers for the emergence of a digital/sustainable data ecosystem and for collaborative data use.

Status quo at a glance	
4.14 % GHG emissions (share of total, 2020)	**15.5 %** Water usage (share of total, 2020)
25 TJ/€ million GVA Energy intensity	**€1.5 billion** ICT inputs

Energy & environmental costs	
€10.2 billion Energy input costs (likely case 2030)	**€8.0 billion** Energy input costs (best case 2030)
+ €2.010 billion Environmental costs vs. 2019 (likely case 2030)	**- €2.979 billion** Environmental costs vs. 2019 (best case 2030)

Scenario-based value creation analysis

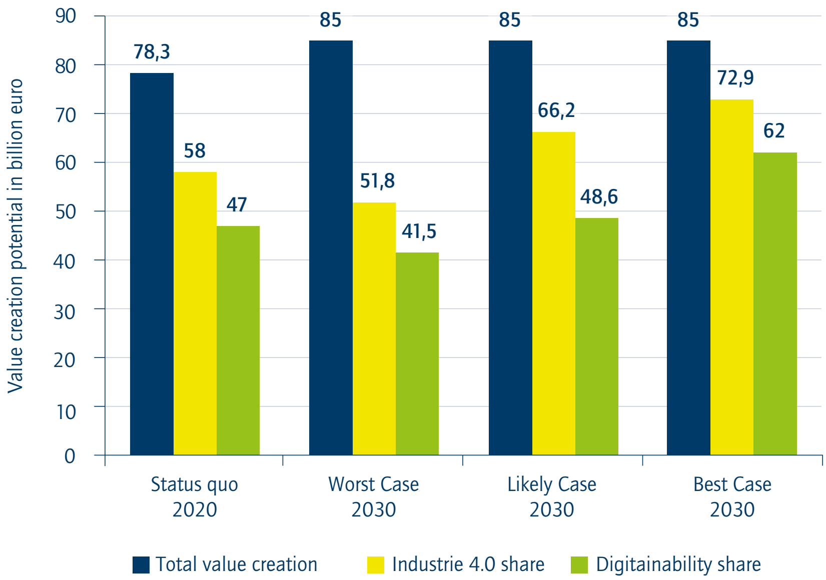

Figure 9: Key findings of the economic market analysis in the chemical and pharmaceutical sector.[27] GHG = greenhouse gas; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

3.2.5 Construction and real estate industry

With value added of 468.2 billion euro in 2020, the construction and real estate industry is the sector with the highest sales revenue in the evaluation considered here. In addition to high energy consumption during the construction phase, building use and possible renovation, the high raw material and water consumption as well as land take by buildings generate significant negative impacts on the environmental indicators considered here. Further negative impacts on the environment (e.g. the urban heat island effect) have not even been taken into account. The sector therefore plays a substantial role in compliance with planetary boundaries, with digital technologies being capable of making a contribution here too. The penetration of digital solutions for strengthening environmental sustainability has so far lagged behind the levels in other sectors, but some digital solutions, such as building information modelling (digital twin-based) hold significant promise for the future. At present, there is a focus on efficiency gains and less on effectiveness gains in the deployment of digital solutions.

The most important technologies for increasing sustainability in the construction and real estate sector are cloud and edge computing, big data approaches and AI, since the primary requirement is for the analysis of large volumes of data from existing real estate which are subsequently used for smart optimisation. Internet of things and communication technologies also play an essential role in interconnecting and integrating the wide range of sensors used to analyse real estate data. Augmented and virtual reality are furthermore used in digital building design. Distributed ledger technologies, anywhere operations and autonomous robots, on the other hand, play only a minor role.

Deployed digital solutions

In comparison with other sectors, digital solutions which are already available are concentrated in distinctly fewer solution groups. It is primarily data analysis and decision support together with data-based optimisation in design which here offer opportunities for reducing energy and raw material consumption as well as greenhouse gas emissions. Digital twins

27 | Due to inadequate data availability for the primary materials industry, the analysis of economic value creation potential could only be considered for the chemical and pharmaceutical industries.

primarily have an impact on raw material consumption and greenhouse gas emissions, while smart energy supply and management systems optimise energy consumption, as does the digitalisation of building management, for example through the electronic maintenance and modernisation of electrical, water and heating systems. Building information models (BIM) are outstanding digital solutions with major sustainability levers which can be used on both existing and newly constructed buildings. On the one hand, digital building models can be used, for example, to carry out carbon analyses in relation to heating, so reducing operating costs, while at the same time these digital models also enable energy optimisation right from the planning stage.

The considerable time lag between data acquisition for BIM during the construction phase and the value which these data often only acquire in the renovation or demolition phase must be borne in mind. There is a risk here that the information collected in the BIM will be forgotten or become obsolete and no longer be taken into account when its true sustainability value comes to the fore. This would potentially reduce the economic incentive for data collection and retention. This risk can be countered by also making active use of BIM for optimisation in the use phase. In the construction process, product passports for increasing recycling efficiency and as a basis for urban mining are already in existence for some of the building materials used. In addition, robots under smart control are already taking over construction tasks, for example on construction sites that are difficult to access or dangerous.

Economic potential
Digitainability value creation in the construction and real estate industry cannot be estimated due to inadequate data availability. However, it is clear that the sector is still lagging considerably behind in relation to digitalisation; ICT inputs were 1.7 billion euro in 2020 and thus amounted to just 0.3 per cent relative to the sector's output value, which is distinctly below the average of 1.9 per cent for the overall economy. Given the size of the sector, there is huge potential for reducing costs and increasing value creation by digitalisation. In terms of usage costs in the real estate and housing sector, which account for 80 per cent of the approx. 140 billion euro sales revenue in this sector, digital building management could reduce costs by up to 17 billion euro by 2030. At the same time, energy efficiency could in the best case be increased by 70 per cent compared with 2019 and 316 million euro of environmental costs could be saved (see figure 10). In the worst and likely case, however, an increase in environmental costs in the triple-digit millions compared with 2019 is to be anticipated. The picture is similar with regard to energy input costs: only in the best case will these be reduced compared with 2019, from 5.1 billion euro to 4.2 billion euro, a reduction of 19 per cent. There is thus a need to considerably increase the use of digital solutions to raise the sector's energy efficiency.

Sustainability potential in the construction and real estate sector will primarily be unlocked through changes in consumption patterns. Existing digital solutions are catalysts here, but not a panacea. For example, because energy prices have long been low and the carbon balance of residential properties has been attributed to the landlord, residents have had little incentive to reduce their energy consumption. Rising energy costs due to the current energy crisis are now creating intense pressure on residents to take action. This is where smart metering for example has a great opportunity to act as a technological enabler on real-time consumption monitoring and discipline. Gamification approaches embedded in digital solutions could incentivise further changes in consumption patterns. In particular, it is essential to focus on the high negative environmental impact of using existing real estate, where digital solutions based on extended data acquisition, such as single-room control or weather-based regulation for energy optimisation can be implemented more quickly than structural measures. However, current regulatory hurdles are hindering the implementation of digitalisation projects in the construction industry, for example in the prequalification process for feeding locally generated solar power into the grid. With regard to the effectiveness lever, there is potential to increase recyclability and integrate the construction and real estate sector into a Circular Economy in the long term by means of material or product passports and the modularisation of construction elements. This will entail strengthening the ecosystem approach in this sector.

Status quo at a glance	
38.6 % Dom. raw material equivalents (share of total, 2020)	**56.9 %** Waste generation (share of total, 2020)
0.8 TJ/€ million GVA Energy intensity	**€1.7 billion** ICT inputs

Prerequisites for best case

- Adjustment of incentive system to take advantage of leverageable sustainability potential
- Doubling of energy efficiency growth rate to 5.0 %
- Realisation of cost saving potential for electricity & gas/oil/coal

Energy & environmental costs (billion euro)

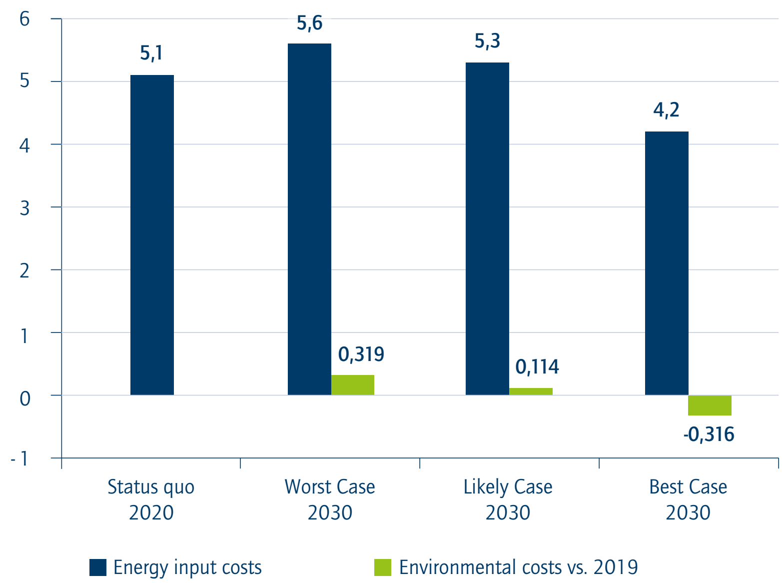

Figure 10: Key findings of the economic market analysis in the Construction and real estate sector.[28] Dom. = domestic; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

3.2.6 Manufacturing

The manufacturing sector generated value added of 373.6 billion euro in 2020 and, with an energy consumption of 3,431.4 petajoules, is the sector with the highest energy demand in this study. Further significant negative environmental impacts include high raw material consumption, significant greenhouse gas emissions and not inconsiderable land take for manufacturing plants. With regard to the described solution groups, the deployment of digital solutions from the data ecosystem, data analysis and tools for system modelling, digital product passport, sustainable procurement or recycling information loop solution groups offer the possibility of having an overall positive influence on the environmental indicators under consideration in this sector. The penetration of digital solutions in manufacturing is comparatively advanced, due among other things to successful Industrie 4.0 initiatives and good support for the digital transformation of manufacturing companies (see acatech Industrie 4.0 Maturity Index[29]).

From a technological standpoint, use is primarily made of modern communication technologies as well as cloud and edge computing, as these are crucial for data processing and interconnecting manufacturing plants to optimise processes. Starting from this point, some use is also made of internet of things, anywhere operations, cyber-physical systems, AI and big data-based solutions for improving data evaluation and autonomising manufacturing. Augmented and virtual reality are currently still used very selectively in virtual product design and virtual maintenance. Distributed ledger technologies have as yet found little application in industry. Similarly, digital technologies with the potential for greater transparency and automation are still little used for tapping into new X-as-a-service business models, such as manufacturing-as-a-service.

28 | Due to inadequate data availability, no analysis of economic value creation potential can be carried out for construction and real estate.
29 | See acatech 2020.

Use Case: Catena-X

Catena-X is the first collaborative open data ecosystem for the automotive industry and aims to establish globally standardised data exchange based on European values. One of Catena-X's central goals is to increase sustainability in vehicle manufacturing and along the entire supply chain. In particular, this is to be achieved by reducing greenhouse gas emissions.

Catena-X can add value here because pooling all the data along the entire manufacturing chain enables standardisation and thus comparability of carbon data measurement. Transparent comparability enables all participants in the process not only to classify their own carbon emissions but also to make informed purchasing decisions. Information about sustainable manufacturing becomes transparent and reliable and can thus also become a competitive advantage.[30]

Deployed digital solutions
Manufacturing already makes use of various Industrie 4.0 applications, which primarily increase efficiency but also contribute to environmental sustainability by saving energy and resources. Only in a few exceptional cases, such as digital twins or product passports, do digital solutions address actual starting points, despite the greatest sustainability potential in manufacturing residing in optimising the upstream supply chain and circularising business models. In aircraft, printed circuit board or vehicle body fabrication, there are some noteworthy instances of (partial) automation using smart motors with integrated load detection. In the same way, digitalisation and thus the virtualisation of manufacturing is advancing under the Industrie 4.0 paradigm, from digital factory planning and virtual commissioning to the digital twin in manufacturing and virtual prototype design. Digital solutions of the "green" ERP system, digital twin, integrated machinery and plant control, additive manufacture, virtual product design and data-based optimisation of inventory management and logistics types enable a highly application-dependent, limited reduction in energy and raw material consumption and greenhouse gas emissions of between 10 and 30 per cent. Smart energy supply and management solutions permit an up to 50 per cent improvement in energy consumption. Within manufacturing, data platforms are helping to optimise machinery utilisation, for example. Digital product passports, for example for batteries, potentially allow the materials used in them to be traced and thus also recovered. This principle could be transferred to all branches of manufacturing for the purposes of a truly Circular Economy.

Economic potential
In the best case, digitainability value creation in manufacturing may be increased by almost 90 per cent by 2030 in comparison with 2020. Already in 2020, the manufacturing sector invested 10.1 billion euro in ICT inputs and this investment is set to continue growing by 5.2 per cent annually until 2030. In line with the currently already high ICT inputs in manufacturing, Industrie 4.0 solutions were already in use in 58 per cent of companies in 2020, 47 per cent of which had already been able to reduce their negative environmental impact as a result. In the best case, given annual growth in value added of 4 per cent for Industrie 4.0 and of 4.5 per cent for sustainable solutions, the proportion of companies using Industrie 4.0 applications may rise to 86 per cent by 2030, which would enable sustainable value added of 327 billion euro (see figure 11). At the same time, energy efficiency might be increased by 76 per cent by 2030 compared with 2019, so allowing sectoral environmental costs of 13.1 billion euro to be avoided.

A central challenge for strengthening the environmental sustainability of the manufacturing sector is to reduce resource requirements through improved raw material recovery. While existing digital solutions, among other things for cost reduction reasons, primarily focus on linear resource optimisation, a properly functioning Circular Economy is the more effective lever for increasing the manufacturing sector's environmental sustainability. In addition to digital solutions, this requires further, potentially also digitally assisted, preparatory work, namely, on the one hand, comprehensive measurability of sustainability along the value chain and, on the other, traceability of raw materials within the value chain. The product passports which are gradually coming into use have considerable potential here.

Obstacles to strengthening digitainability include poor data availability and interface heterogeneity between individual processes and participants in the manufacturing value chain. While some initiatives have been launched to encourage more in-depth use of standards and reference architectures (RAMI 4.0, OPC UA etc.), these must become more prevalent in the sector. With regard to incentive systems for strengthening environmental sustainability, it should be noted that the environmental assessment of products is currently primarily based on

30 | See Catena-X 2022.

CO_2 equivalents from the manufacturing process, while the sector's environmental impact is distinctly more complex and longer term (see resource requirements etc.) but has so far not been possible to fully capture. This inadequate modelling of environmental impact has meant that environmental sustainability has so far played only a subordinate role in product design, for example, despite there being great potential here, for instance through modular design or easily separable components. Assessing environmental impact in way which goes beyond CO_2 equivalents and ensuring product traceability are thus prerequisites for exploiting the potential of digitainability in manufacturing.

Status quo at a glance

22.5% GHG emissions (share of total, 2020)	**6.8%** Water usage (share of total, 2020)
10.2 TJ/€ million GVA Energy intensity	**€10.1 billion** ICT inputs

Energy & environmental costs

€47.1 billion Energy input costs (likely case 2030)	**€32.4 billion** Energy input costs (best case 2030)
-€4.045 billion Environmental costs vs. 2019 (likely case 2030)	**-€13.102 billion** Environmental costs vs. 2019 (best case 2030)

Scenario-based value creation analysis

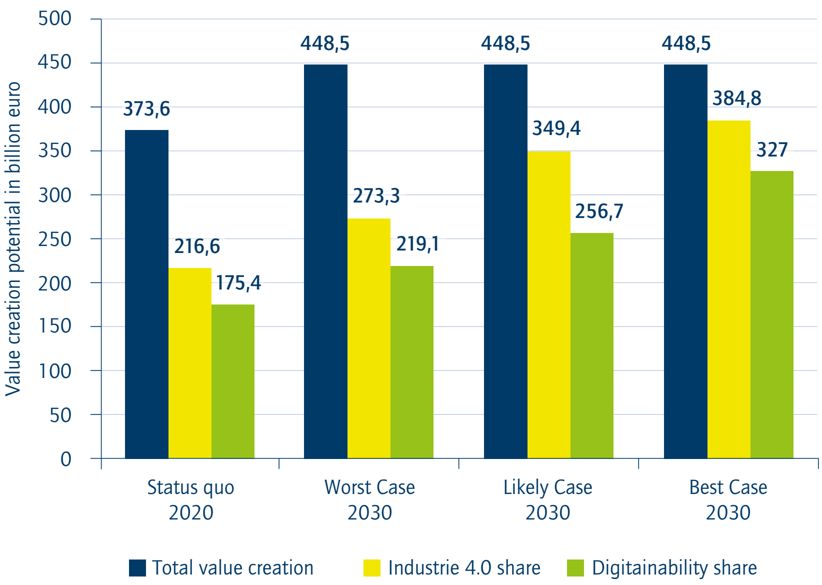

Figure 11: Key findings of the economic market analysis in the manufacturing sector. GHG = greenhouse gas; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technologies (source: own presentation)

3.2.7 Electrical and mechanical engineering

The electrical and mechanical engineering sector generated value added of 134.2 billion euro in 2020 and, like manufacturing, is one of the most advanced sectors in terms of digitalisation, again thanks to the Industrie 4.0 paradigm being followed. Similarly to manufacturing, this sector is also characterised by particularly high energy and raw material consumption; greenhouse gas emissions and land take are also not insignificant. The digital solutions already in use for increasing environmental sustainability overlap considerably with the manufacturing sector in terms of the relevant solution groups and technologies, since here too the focus is on digitalisation and interconnection of the machines used, with virtualisation or smart data evaluation providing assistance with the planning and optimisation of manufacturing.

Accordingly, in terms of the technologies used, the focus is on modern communication technologies and cloud and edge computing which provide the basis for interconnection and systems integration of the plant and equipment used. In this context, applications based on internet of things, anywhere operations, cyber-physical systems, AI and big data are also already being used to extend the database to manufacturing processes and to systematically evaluate these data. Augmented and virtual reality are already being put to some use for virtual maintenance support and virtual product design. Due to applications being mainly in-house, distributed ledger technologies are hardly used since data storage is handled by systems which are already available.

Deployed digital solutions

With regard to the solution groups used, the focus here too, as in manufacturing, is on increasing the efficiency of existing processes. In addition to applications for data-based optimisation of intralogistics, for example, virtualisation is a central component here. This involves virtually planning machines and components and then modelling them as a digital twin which is used as the basis not only for the described process optimisation but also for establishing predictive maintenance (see Use case). This primarily results in energy and resource savings and thus also indirectly influences the sector's environmental sustainability

Despite the already widespread use of digital technologies, there is still further potential for efficiency gains here, prevalence already being encouraged by the underlying economic added value. However, this sector still makes little use of solutions with a leverage effect for environmental sustainability. Similarly to manufacturing, the focus here has so far not been on repair and adaptability and technological obsolescence is accepted due to a lack of economic incentives for environmental sustainability. Virtualisation, which is already in use, can offer great potential here, for example for more detailed and simultaneously more resource-efficient prototyping which prioritises component longevity and recyclability. Virtualisation and the integration of product passports into the value chain could effectively integrate the sector into a Circular Economy.

Use Case: asset administration shell (AAS)

The asset administration shell (AAS) is an implementation of a digital twin for Industrie 4.0 and provides a digital representation of the information, features and behaviour of an asset. The entire life cycle of products, equipment, machines and plant can be modelled in this way. This digital solution enables cross-manufacturer interoperability and creates the basis for end-to-end value chains.

Using AAS, a product's operating parameters can be recorded throughout its service life. The resultant information can be exchanged between all partners in the value chain. Not only does this ensure a longer asset service life due to timely maintenance and repair but it also supports the development of new models using the information collected during use. This can boost resource efficiency.[31]

Economic potential

In the best case, digitainability value creation in electrical and mechanical engineering may thus more than double by 2030 in comparison with 2020, a growth rate which is the highest among the sectors considered. In 2020, information and communication technology inputs already amounted to 2.5 per cent of the sector's output value and 64 per cent of companies were using Industrie 4.0 solutions. Already in 2020, the comparatively advanced level of digitalisation in this sector was reflected in digital/sustainable value creation of 69.3 billion euro. Nevertheless, there is still clear growth potential in the electrical and mechanical engineering sector, in particular via synergistic effects due to standardisation and interoperability (see Use case). In the best case, the proportion of companies using Industrie 4.0 may be increased to 94 per cent by 2030. This could generate sustainable value added of 140.3 billion euro in this sector, and environmental costs of 584 million euro would be avoided if energy efficiency can be increased by 5.9 per cent annually until 2030 (see figure 12). In any event, this will be accompanied by a reduction in energy input costs, which amounted to 3.3 billion euro in 2019. In the best case, these costs may be reduced by 42 per cent by 2030.

Due to the high consumption of resources and energy, the transition to circularity is similarly important in electrical and mechanical engineering as it is in the manufacturing sector. Accordingly, the focus here too is on traceability and increasing transparency along the value chain, which can be strengthened via digital twins and product passports. However, in electrical and mechanical engineering too, there is a lack of incentives to develop circular business models or business models which promote an environmentally sustainable usage and value proposition. Similarly to manufacturing, the heterogeneity of interfaces is another problem for exploiting digitainability potential despite increasing standardisation efforts being made.

31 | See Plattform Industrie 4.0 2019.

Status quo at a glance	
56.1 % PFC emissions (share of total, 2020)	**6.3 %** Dom. raw material equivalents (share of total, 2020)
1.8 TJ/€ million GVA Energy intensity	**€9.1 billion** ICT inputs

Energy & environmental costs	
€2.7 billion Energy input costs (likely case 2030)	**€1.9 billion** Energy input costs (best case 2030)
+ €0.030 billion Environmental costs vs. 2019 (likely case 2030)	**- €0.584 billion** Environmental costs vs. 2019(best case 2030)

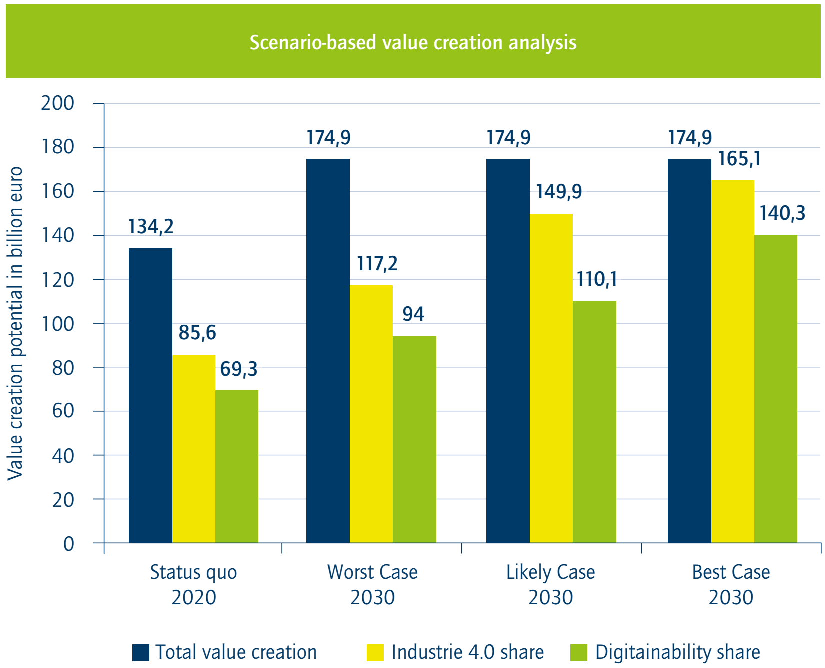

Figure 12: Key findings of the economic market analysis in the electrical and mechanical engineering sector. PFCs = per- and polyfluorinated chemicals; Dom. = domestic; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

3.2.8 Information and communication technology

The information and communication technology (ICT) sector generated value added of 169.7 billion euro in 2020 at a comparatively low energy intensity of 1.8 terajoules per million euro gross value added. This sector has a special role in the analysis because, on the one hand, digitalisation is evaluated within it and, on the other hand, technological developments in the ICT sector simultaneously have an enabling function for digitalisation in all the other sectors. Accordingly, this sector is the basis for an expansion of digital technologies and thus also for digitainability in the German economy. The ICT sector's negative environmental impact in particular relates to the energy consumption of data centres and software (development) and to the use of raw materials and, in particular, resource requirements (e.g. rare earths). Many available digital solutions are therefore directed at efficiency gains, for example through more energy-efficient algorithms and optimised product design.

The digital solutions used to increase the environmental sustainability of the ICT sector are based primarily on cloud and edge computing, modern communication technologies such as 5G and 6G, and big data. AI and internet of things applications are playing an increasingly important role, for example in determining hardware energy requirements.

Deployed digital solutions

In terms of solution groups, it is above all data ecosystems and virtual product design which are capable of strengthening the environmental sustainability of the information and communication technology (ICT) sector. Applications for data analysis, data-based optimisation or smart energy supply act selectively on greenhouse gas emissions or energy consumption for the purposes of green IT. Specific applications here relate for example to AI-based cooling of data centres or the development of cloud applications and open-source frameworks for edge computing, these applications also being usable beyond the sector.

Rebound effect

Rebound effects in the event of efficiency gains are said to occur when the efficiency gain brings about an increase in demand or use and so, contrary to the original objective, weakens rather than strengthens environmental sustainability. This can happen in various ways – the resources freed up by efficiency gains may be allocated to using the more efficient solution more frequently than the previous one (direct rebound effect) or to using other goods or services (indirect rebound effect). Finally, there are also more global rebound effects. If, for example, energy prices drop and intermediate and end products become cheaper, entire manufacturing or consumption patterns may change.[32]

Many existing sustainability-enhancing solutions in the ICT sector are directed towards efficiency gains. However, more efficient ICT applications run the risk of bringing about rebound effects and thus having an indirect negative environmental impact which significantly exceeds the direct positive environmental impact of a more efficient ICT application. The focus is on green IT as a holistic sustainability-enhancing approach for the future, namely making environmentally friendly and resource-efficient use of ICT over the entire life cycle (manufacture, use, disposal) in conjunction with increasing energy efficiency and a reduction in costs for the economy as a whole. There has so far been hardly any focus on effective digital solutions which enable a change in the way ICT is used, but the focus has instead primarily been on the development of green technologies or the deployment of digital solutions for greener production of ICT solutions.

Economic potential

In the best case, digitainability value creation in the information and communication technology (ICT) sector may rise by almost 80 per cent by 2030 in comparison with 2020. Not unexpectedly, ICT inputs already accounted for 9.7 per cent of the sector's output value in 2020, well above the average for the sectors considered in this study. 67 per cent of companies in the ICT sector already use Industrie 4.0 applications, with this figure potentially increasing to 98 per cent by 2030. This could generate digitainability value added of 163.2 billion euro (see figure 13). At the same time, the sector's energy efficiency could in the best case be improved by 96 per cent by 2030. Energy input costs can thus be reduced in all the scenarios considered. In the best case, compared with costs of 7.8 billion euro in 2019, energy input costs can be reduced by 45 per cent to just 4.3 billion euro by 2030. Environmental costs could also be reduced in this best case by 1.9 billion in comparison with 2019. However, even in the worst case, environmental cost savings of over 1.4 billion euro can be expected in 2030 in comparison with 2019.

It is also apparent that in particular green IT technologies have major savings potential. In the best case, a 0.5 per cent annual decrease in power demand from 2019 to 2030 could reduce electricity costs by 7.5 billion euro and environmental costs by 2.3 billion euro in 2030 in comparison with 2019. However, the fact that there are hardly any verifiable criteria for measuring the contribution of green IT to environmental sustainability is currently an obstacle to achieving these goals. For example, there are as yet no suitable indicators for providing guidance in the programming process as to how energy efficient a particular algorithm will be. Moreover, it is unclear to what extent green IT by design could mitigate or prevent rebound effects. The potential savings show that, despite possible rebound effects, efficiency gains in the production and development of digital solutions explicitly for increasing environmental sustainability in the area of ICT use are indispensable for greater digitainability in the German economy. However, it remains unclear how software can be produced and used more energy efficiently and hardware can be produced and used in a more resource-efficient way.

32 | See Bitkom 2021.

Status quo at a glance	
0.25 % GHG emissions (share of total, 2020)	**1.7 %** Primary energy consumption (share of total, 2020)
1.8 TJ/€ million GVA Energy intensity	**€46.8 billion** ICT inputs

Energy & environmental costs	
€5.9 billion Energy input costs (likely case 2030)	**€4.3 billion** Energy input costs (best case 2030)
- €1.662 billion Environmental costs vs. 2019 (likely case 2030)	**- €1.941 billion** Environmental costs vs. 2019 (best case 2030)

Scenario-based value creation analysis

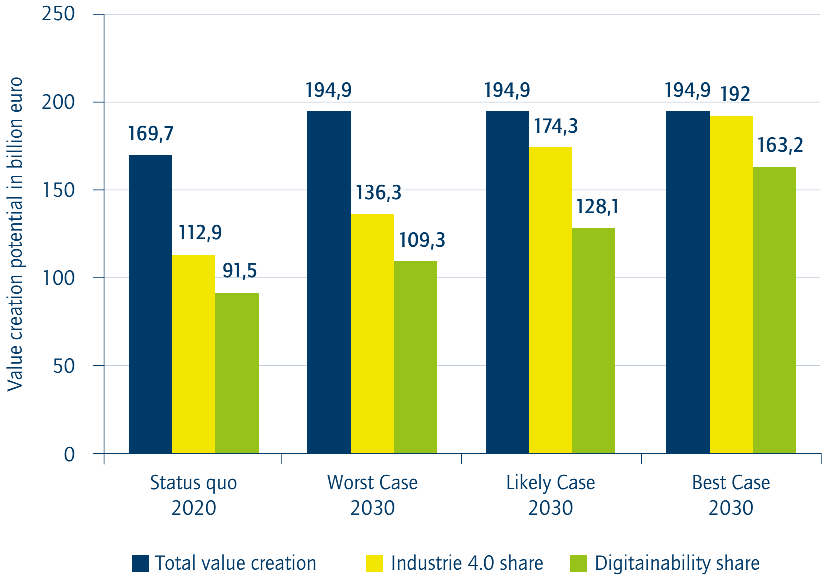

Figure 13: Key findings of the economic market analysis in the ICT sector. GHG = greenhouse gas; TJ/€ million GVA = terajoules per million euro gross value added; ICT = information and communication technology (source: own presentation)

3.3 Environmental sustainability comparison of solution groups and technologies

The sector-specific analysis of digital solutions which strengthen environmental sustainability illustrates the different levels of penetration of digital solutions depending on the technology, the considered influence on environmental indicators or the sustainability lever on which the technology acts. If possible, potential for and obstacles to transfer, general trends and sector specifics are to be identified, there is a need for an overarching evaluation of the findings of the analysis.

3.3.1 Technologies

A comparison of technologies across sectors (see figure 14) reveals a repeating trend: the technologies considered differ in their range of applications and can be roughly divided into three groups.

Figure 14: Overview of the use of selected technologies in the various sectors. IoT = internet of things; CPS = cyber-physical systems, Auton. = autonomous; Ops. = operations; DLT = distributed ledger technologies; AI = artificial intelligence (source: own presentation)

The first group consists of communication technologies, AI, big data approaches and cloud and edge computing which are already widely used regardless of the sector, as it is very straightforward to derive use cases with clearly identifiable economic added value. At the same time, the investment hurdle is comparatively lower, as the necessary data are often already available, and it is mainly the in-house IT infrastructure which needs to be improved.

Similarly well-defined and economically viable applications can often be found for the second group (internet of things and cyber-physical systems) but the initial investment is higher here. Research into the Industrie 4.0 transformation has shown that SMEs in particular are often unable and unwilling to make this initial investment; the added value generated by environmental sustainability is often not economically attractive enough for such companies to incorporate into their proprietary business practices.[33]

The third group includes distributed ledger technologies, anywhere operations, autonomous robots, augmented reality (AR) and virtual reality (VR). These technologies, in particular autonomous robots, AR and VR, require greater initial investment and moreover their technological maturity has only recently reached a level comparable to that of the first group. Sustainability potential, in particular for predictive maintenance, promises increasing penetration of these technologies and their implementation in attractive solutions in various sectors. Accordingly, investment support measures here could lead to more effective use, even if technological specifics have to be taken into consideration:

- Distributed ledger technologies (DLT): companies have so far only been able to tap the environmental and economic added value of DLT to a limited extent, not least because there are often much more cost-effective replacements for DLT-based solutions. It therefore simply makes no sense for many companies to opt for DLT-based solutions. In addition, this technology is not yet sufficiently sustainably digitalised for its deployment to be attractive in a corporate setting. However, if, as is repeatedly hypothesised, DLT's energy requirements are distinctly reduced in the future, its trust and storage characteristics by design may make the technology of particular interest for circular business models (e.g. for the data storage of digital product passports).
- Anywhere operations: Measuring the extent to which anywhere operations contribute to environmental sustainability was difficult for many of the sectors considered, as the savings are often located outside the sectors, particularly in the changed (mobility) behaviour of employees. Anywhere operations are in particular a catalyst for homeworking. If homeworking were introduced for an average of two days per week, potential savings of up to 312 million euro in commuting costs, time (opportunity costs) and environmental costs could be generated by 2030. Homeworking is thus an outstanding example of a change in usage behaviour which strengthens environmental sustainability. It is now in widespread use, and the technological potential of anywhere operations is accordingly already being utilised in some cases, even if this is not directly reflected in the sector-oriented market study.

It may be concluded from the above that digital solutions based on AR, VR or autonomous robots in particular should receive particular attention in development and application funding to allow further environmental sustainability potential to be unlocked.

3.3.2 Solution groups

A cross-sectoral consideration of the effects of solution groups on environmental indicators reveals a dichotomy between digital solutions with limited impact (10 to 30 per cent improvement) on selected environmental factors and those with a universal leverage effect on all the considered environmental factors. In principle, there is potential for distinctly improved environmental sustainability in the German economy by way of the solutions considered.

The category of technologies with an effect on selected environmental factors includes "green" ERP systems, virtualised applications for product design, maintenance or training, integrated machinery and plant control, data-based optimisation and electrification of vehicles and logistics, and smart energy supply and management. In comparison, data ecosystems, tools for data analysis and decision support, digital product passports, digital twins and sustainable procurement have the potential to positively impact all the environmental indicators considered and to a greater extent (see figure 15).

At the same time, there are still major differences in prevalence of the solution groups and, consequently, in the value added generated by each. While digital twins and data-based optimisation are already widely used across sectors, little use is yet being made in particular of technologies with a leverage effect on environmental sustainability, such as sustainable procurement and digital product passports.

33 | See acatech 2022.

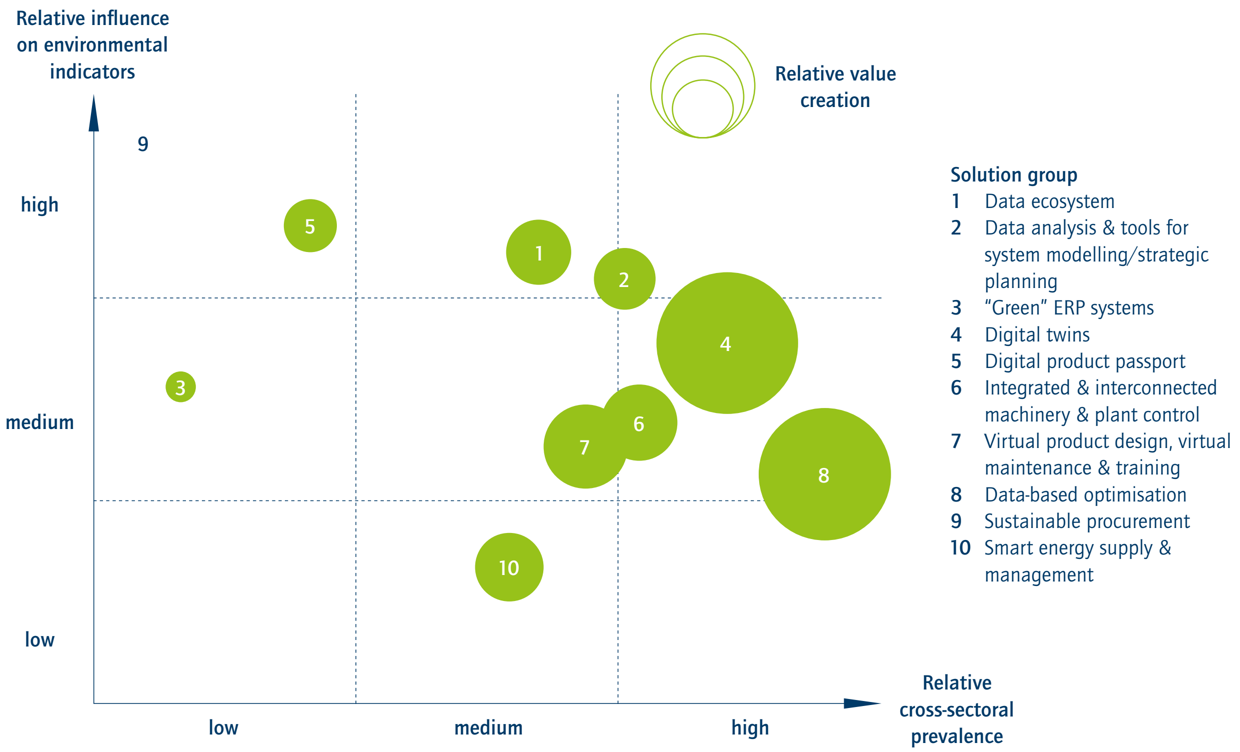

Figure 15: Schematic overview of the cross-sectorally considered solution groups in terms of prevalence, environmental impact and value added[34] (source: own presentation)

The latter are important for strengthening the Circular Economy. Digital technologies could help to close material cycles and so enable more resource-efficient and sustainable production, consumption and recovery (recycling). Digitalisation could additionally contribute to urgently needed improvements in product recyclability (circular product design) and recycling technologies. Higher material efficiency and substitution have an important role to play, most particularly for climate-neutral energy, and digital technologies, including AI methods which are used in materials research, could be important in unlocking possible potential. At present, however, very little of this potential is utilised due to the somewhat inadequate availability of appropriate digital solutions.

Value creation potential of the Circular Economy

Measured by sales revenue, the Circular Economy will have a market potential of up to some 150 billion euro in 2030, just under half of which is likely to be accounted for by waste treatment and recycling, just over a quarter by collection, and the remainder by trade in end-of-life materials and technology (development). In 2030, just under one fifth of the market potential of the Circular Economy will offer starting points for digitalisation (a share roughly twice that in 2020), which amounts to up to 26 billion euro.

34 | No specific digital solutions could be identified for sustainable procurement (solution group 9), which is why it was not possible to make a qualitative estimate of value added here, as such an estimate is based on the prevalence of the solution group in conjunction with the particular sector's value added.

The study makes it clear that companies are primarily aiming to use digital solutions to increase the efficiency of their products since this creates both environmental and economic value. Since the focus is primarily on making internal processes and solutions more economically and environmentally sustainable, many companies give no consideration to modifying usage behaviour or circularising the way they do business. This inward-looking perspective has meant that it has also not yet been possible to strategically unlock the cross-sector transfer potential of digital solutions.

Consequently, one of the key observations of this study is that the majority of the digital solutions considered are acting on the sustainability lever of either **green manufacturing** or **green solutions.** To date, there are only very isolated examples of digital solutions which strengthen the sustainability of digital tools themselves (sustainable digital solutions), i.e. **green technologies**, but they are the focus of green IT and clean IT initiatives. There are as yet hardly any digital solutions which explicitly focus on green use. Digital product passports and digital twins are enabling the shift to circularity **(Circular Economy)**, but otherwise there is a lack of digital solutions in this area as well.

The following picture emerges: the digital solutions available in the German economy are primarily acting on efficiency levers (technology, manufacturing, solution) and reducing the negative environmental impact of the sector in which they are deployed under the existing linear economy paradigm. However, with a few exceptions, there is a lack of available digital solutions which effectively enable the strengthening of environmental sustainability via modified sustainable usage behaviour and circular business practices. This underlines the importance of stepping up the pace of implementation of a circularity strategy as a complementary framework. There is thus a need for wide-ranging incentives and a transformation of corporate self-image so that the environmental sustainability potential and associated economic value creation potential of using digital solutions can be more fully unlocked.

4 Options for maximising digital/sustainable potential

The market analyses have clearly revealed that, in principle, digital technologies have the potential to strengthen environmental sustainability in leading sectors of the German economy. Currently available digital solutions primarily focus on increasing efficiency in existing processes and thus reducing energy and resource consumption as well as greenhouse gas emissions. These incremental savings strengthen environmental sustainability and should continue to be developed in the future.

However, the effective levers which must be focused on if Germany is to achieve its climate targets involve fundamental adjustments to usage behaviour and business practices with the assistance of digital solutions – new, sustainable business models must be established, and value creation systems transformed. The market analyses have shown that these levers are not yet being widely used, not least because they entail the development of new business models or the adjustment of processes, i.e. they go hand in hand with business challenges when it comes to taking a holistic view of digitalisation and sustainability.

Digital technologies are "general purpose technologies" which can be applied in business with different objectives. This means that it is the regulatory framework and thus ultimately also the costs for companies' use of the environment which decide on the practical deployment of the technologies for reducing environmental impact. If a commitment to conserving resources becomes more economically attractive, either because the price of resource use increases or government subsidies make it more affordable, digital solutions will also increasingly be used for resource conservation. At the same time, it must be borne in mind that, if costs rise for companies, there is a risk that manufacturing will be relocated from Germany to other regions where lower environmental standards prevail, so resulting in environmental harm.

Real digitainability, which opens up new market opportunities above and beyond efficiency gains, will therefore require vigorous efforts on the part of all political and economic stakeholders. The options set out here along the considered sustainability levers (digital green technology, digital green manufacturing, digital green solution, digital green use and Circular Economy) are directed towards efficiency and effectiveness. These are supplemented by options in the regulatory framework area of action which should be addressed to ensure more intensive use of digital solutions for the purposes of environmental sustainability.

4.1 Efficiency

On the one hand, the market analyses have shown that digital solutions are being used in all the sectors considered in order to increase the efficiency of existing processes and so achieve positive effects both economically and environmentally. On the other hand, it has also become clear that no sector has yet fully utilised this potential and that greater penetration by digital solutions is capable of replacing or optimising existing solutions with more resource-efficient alternatives.

Making digital technologies more environmentally friendly: If digitalisation is to be environmentally sustainable, irrespective of whether or not its direct aim is to strengthen environmental sustainability, the environmental footprint for the creation of digital solutions must be reduced. This relates in particular to AI (outstanding digital sustainability lever) and distributed ledger technologies (limited digital sustainability lever). There is a need for targeted basic research into resource-efficient programming for software products, as this has previously been very difficult to measure in software development and is therefore not very widespread. Furthermore, a taxonomy should be developed which, depending on the application, identifies the best possible technology for the particular company to use for the development of a digital/sustainable solution. It should be in line with the principle "as resource-intensive as necessary, as environmentally friendly as possible". In the context of the stated green IT approach, sustainability indicators (e.g. energy efficiency, resource efficiency) should be embedded as quality indicators (KPIs) in the development of software and the manufacture of hardware, in addition to efficiency indicators such as computing time and costs, so that digital solutions themselves can be produced more environmentally sustainably. Standardisation and certification regimes (e.g. DIN, ISO) are appropriate lines of approach here. Public and private funding programmes should create incentives for the development of environmentally sustainable solutions based on various digital technologies – this is a market opportunity for Germany as a place to do business. In terms of public funding, interdepartmental initiatives are desirable, such as the current GreenTech funding framework of the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry of Education and Research (BMBF).

Communicating the availability of digital/sustainable solutions: If digital and sustainable solutions are to be used more widely, user companies across all sectors need to be better informed about their availability and, in particular, their potential for adding value in both environmental sustainability and economic terms. The present acatech STUDY is a first step in this direction and is intended to provide an initial impetus for the development of a continuously updated system which gives potential users an easily accessible "shop window" providing a market overview of available digital solutions and their impact on the environment and value creation ("digitainability directory"). This market overview could be reproduced on an open technology platform ("digitainability platform"). Digital solution developers could apply for inclusion in the "digitainability directory" which would enable indirect incentivisation and provide users with a quick overview of how they could strengthen their own environmental sustainability.

Encouraging adoption of digital/sustainable solutions: In relation to the lever technologies and digital solutions identified in this study, follow-up projects should clarify why these have so far been applied only to a limited extent and, taking this as a starting point, what incentives are required to increase their prevalence. SMEs in particular often shy away from deploying digital/sustainable solutions in the manufacture and development of their products and/or services due to high purchase costs or lack of digital expertise. Communicating best practice (e.g. the Lernende Systeme platform's AI map[35]) could make the long-term sustainability and value creation benefits of digital and sustainable solutions clear to them. Incentives for adoption could also be provided through funding support for the transition to more environmentally sustainable, digital solutions. At the same time, the study has shown that an expansion of digital infrastructure is vital for greater use of digital technologies.

Strengthening use of digital solutions "as a service": Demand optimisation by individual users and utilisation of the digital solution as a whole are essential if the deployment of digital solutions is to be inexpensive and simultaneously environmentally sustainable. By using digital solutions "as a service", developing providers can broaden their customer base and optimise revenue, while users can deploy the solution only when required and thus inexpensively and environmentally responsibly. "As a service" models require open interfaces, and this is where standardisation and open-source approaches are of assistance.

Countering rebound effects of digital technologies: Rebound effects are a central barrier to fully utilising the potential for environmental sustainability through efficiency gains, as the freed-up resources (frequently time or money) are used for further investment or increased use. These effects are inherent in the process of increasing efficiency but must be reduced or avoided in order to utilise the sustainability potential of digital solutions as fully as possible. Sustainable use of the freed-up resources might be, for example, investing these resources in (even) greener alternatives. In this way, efficiency gains could create a virtuous cycle. However, in most contexts, this scenario is only to be expected if there are sufficient incentives for these green alternatives to be taken up.

4.2 Effectiveness

The options which have so far been addressed are directed towards efficiency gains by the deployment of digital solutions (doing things right) which pay off for companies in the short to medium term from both a sustainability and a cost perspective (e.g. by reduced energy consumption in manufacturing). However, efficiency gains within the framework of traditional value creation paradigms (e.g. product use in ownership, cradle-to-grave) are not sufficient in order to achieve climate targets and remain within planetary boundaries because they ignore rebound effects of use and provide little incentive to take a circular approach to product use. There is a need for effective approaches (doing the right things) and these require a willingness to develop new digital/sustainable business models if the sustainability potential of deployed digital technologies is to be fully realised. This inevitably entails abandoning short-term but environmentally harmful profitability in favour of long-term but environmentally and economically more sustainable value creation in order to give circularity primacy over product- and output-oriented business practices.

Strengthening technical platforms: To date, only limited use has been made of intra- and cross-industry synergies for environmental sustainability. By allowing pooling of sector-specific data and by providing access to and enabling evaluation and

35 | See https://www.plattform-lernende-systeme.de/map-on-ai-map.html.

utilisation of existing data for different stakeholders, digital platforms can create environmental sustainability and value creation potential. These need to be strengthened, not least also to drive the development of new digital/sustainable B2B and B2C business models **(green use)**. Some sectors have particular potential in this respect:

- Transport and logistics: In the transport sector, interconnecting existing mobility providers and integrating their services on a single digital platform can remove the barriers to users being able to optimise the environmental sustainability of their mobility behaviour by providing incentives for greater use of local public transport or sharing services and so reducing private transport use. However, for providers, such platforms entail the risk of losing customer loyalty. One starting point might be to bring all mobility services together on a digital platform that can be used by all providers (IT backbone), but offer them the option of using their own user interface. In order to promote such applications, the public sector should lead by example and make available the traffic data it has access to. Another appropriate approach is to promote platforms which explicitly favour sustainable mobility solutions. Initial steps in this direction are already being taken by the Federal Ministry for Digital and Transport (BMDV).[36]

- Real estate industry: In this industry, digital solutions such as smart electricity meters or smart thermal energy meters generate data on resource consumption in buildings. The resultant information is of relevance to all parties concerned in the construction and real estate industry value network. At present, however, these data are often not available in a timely manner, and many stakeholders currently have no incentive to use resources sparingly. Real-time capable consumption monitoring would make it possible to create more transparency for the actual users of the resources; at the same time, suitable economic incentives could be set. Access to the data would also enable multiple alternatives through comparability with other users. In this way, potential savings could be identified, or resource-efficient routines shared. With a more open data culture and faster access to consumption data, building management could take early action through structural measures or modernisation work in the buildings with the highest consumption in relative terms. Digital solutions could significantly reduce building heat consumption by means of single-room control, weather-based regulation and other tools.

- Construction: In the construction industry, platform solutions can, on the one hand, help increase efficiency and, on the other, promote new concepts such as modularisation during the planning stage of new buildings. "Building information modelling" (BIM) which can be used to implement end-to-end digitalisation of the information relevant to the planning and realisation of construction projects is key here. All the parties involved in the construction project can access this model. This enables greater transparency and improved planning and coordination opportunities which can ultimately lead to resource savings and thus positive environmental effects. A high degree of digitalisation in the early planning stage also makes it possible, for example by improved interconnection with water management, to identify new opportunities for savings with economic and environmental added value, such as the modularisation of components which allows the advantages of mass production to be exploited without having to give up on the building's individuality. Algorithms can then be used to assist in digital planning in order to identify possible applications for the modularised components. This would require the creation of a digital platform for harmonising the data and standardising the modularisation. In addition, the deployment of BIM as standard in public construction projects could have a pull effect on private sector construction projects. Virtualising planning permission processes via BIM would also reduce significant bureaucratic hurdles and should also be considered.

Promoting the deployment of digital solutions for the Circular Economy: As an alternative to the linear economy which currently prevails, Circular Economy is an integrated system solution for remaining within planetary boundaries and also enabling future generations to live well on earth.[37] Digital solutions cannot alone set a change towards a Circular Economy in motion but they do have the potential to play a crucial role in implementing circular business models, in particular for resource optimisation. In particular, digital twins, product passports (e.g. Battery Pass project[38]) and data spaces (e.g. Mobility Data Space[39]), which are already being used or are under development in some sectors, are suitable starting points if

36 | See https://bmdv.bund.de/DE/Themen/Digitales/Mobilithek/mobilithek.html.
37 | See acatech 2021.
38 | See https://www.acatech.de/projekt/batteriepass-made-with-germany-umsetzung-einer-neuen-generation-digitaler-produkthandhabung/.
39 | See https://www.mobility-data-space.de/.

they are put to comprehensive use. The development of circular business models based on these solutions could be addressed more comprehensively with a separate funding framework. There is also a need for research into sustainable procurement, i.e. into which products or raw materials can, on the one hand, be replaced by sustainable alternatives and, on the other hand, what regulatory conditions are required. At the same time, digital virtualisation solutions enable more sustainable product design in terms of repairability, modularisability and separability of components at the end of the life cycle. These factors accordingly improve circularity, for example in manufacturing or in the chemical and pharmaceutical industry, and should consequently be incentivised.

Strengthening win-win business models for green use: The development of green solutions which modify usage behaviour is a critical effective lever for strengthening environmental sustainability. Developers, however, often fear that such solutions will cannibalise their sales revenue (e.g. that shared mobility might depress car sales). There is a need for more intensive work here to highlight the benefits of green solutions and for specific use cases which catalyse greener use and so demonstrate the economic added value of digital/sustainable solutions to companies. Agriculture can be one application sector for the development of pilot projects in this context since projects relating to green use are already ongoing here (e.g. smart services for agricultural machinery which diversify sales and strengthen sustainability, or regional distribution platforms for the direct marketing of local products). Their analysis and the further development of business models illustrate mutual consumer-producer incentives, i.e. win-win business models for green use, and there is a need to transfer such models to other sectors, with idea competitions, hackathons or business model contests possibly being usable for this purpose.

rengthening interdisciplinary research on environmental impact and effectiveness levers: Given the lack of available digital solutions described above, there is a fundamental need to effectively strengthen environmental sustainability and accelerate an awakening in application-oriented research and development. Initial steps in this direction have been taken, for example, with the GreenTech innovation competition promoted by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and Federal Ministry of Education and Research (BMBF). Any further expansion should, however, be targeted towards practical, strategic and, above all, interdisciplinary research and development on digital solutions which drive toward environmentally sustainable usage adjustments or circular business models. Research initiatives should be explicitly directed towards designing digital solutions in such a way that they effectively reduce a respective industry's environmental impact by transforming usage behaviour and/or strengthening circularity. A dedicated public call for proposals in this direction could be helpful. Interdisciplinarity should be a core requirement in the composition of research and/or development teams, especially where they are directed towards sustainability-enhancing changes in usage behaviour. Psychological and sociological expertise is particularly helpful for incentivizing effective, environmentally sustainable changes in usage behaviour through digital solutions.

4.3 Regulatory framework

Since many digital solutions which have positive effects on environmental sustainability are often accompanied by economic drawbacks due to purchase costs and the complexity of integrating them into business processes, companies use them only sporadically and not strategically. If the federal government's sustainability targets are to be achieved by 2030, the regulatory framework must be designed in such a way that it is also economically attractive to make the digital transformation to sustainability more quickly and comprehensively.

Extending carbon pricing: Pricing carbon emissions remains a key regulatory tool for accelerating the transformation to sustainability. Higher pricing, as called for by many stakeholders, would create strong incentives for greater sustainability and thereby indirectly reduce the use of digital tools and technologies which are associated with very high energy consumption (e.g. bitcoin mining). In this way, a higher carbon price encourages both environmentally sustainable digitalisation and digital/environmental sustainability. Digital solutions would again act as enablers to make such regulation implementable and transparent. Pricing negative environmental impacts is a tool that could also be applied to other environmental indicators (e.g. consumption of resources) and which has, for example, already been identified as an instrument for avoiding rebound effects; it has not, however, been implemented as yet.[40] Once the effectiveness of carbon pricing has been thoroughly evaluated, legislators should therefore consider extending it to further environmental indicators.

Strengthening sandboxing: The development of digital solutions requires innovation spaces in which the limits of technical

40 | See UBA 2016.

feasibility, implementability and practical usability can be tested. The concept of a "regulatory sandbox" or "real-world laboratory", which involves relaxing regulations for a limited period of time and for a small number of participants in a model project, should also be trialled for digitainability projects, in particular in relation to regulations which prevent the use of valuable data sets. In this way, new digital solutions, such as smart meters, could be tested on a small scale in the real world without all theoretical concerns having to be fully resolved in advance. The data and experience from such practical testing could then be used to inform the regulatory process. At the same time, developers could use the sandboxing data to create new solutions. A similar situation applies to the simplified provision of data. For example, federal data management puts limits on more sustainable water management and should be standardised accordingly. This would mean that the innovation process could start much earlier, allowing market opportunities to be seized. The regulatory freedom of action to establish regulatory sandboxes should expediently be opened up down to regional level.

Establishing monitoring systems for measuring the environmental impact of industries and digital solutions: In many, but not all, sectors there is a lack of reliable data for assessing digital solutions' environmental impact and potential for environmental value creation (specifically in the water management sector and in transport and logistics). At present, there is no uniform yardstick for assessing environmental impact. The focus is often solely on sub-aspects of environmental sustainability, as in the case of CO_2 equivalents. The Sustainable Development Goal indicators are a starting point, but there is a need for dialogue between academia and business to investigate which data are necessary for a general sustainability assessment, to what extent these are already recorded or can even be recorded, and how a standardised assessment for classifying digitalisation measures can be derived. On this basis, it would be helpful to develop a sound and continuously updated set of indicators which measure the negative environmental impact attributable to individual industries while also taking account of rebound effects. This could then be used to develop an urgency matrix which is capable of directing the prioritisation and direction of research and development initiatives relating to digital/sustainable solutions in an evidence-based manner both within and across sectors. At the same time, there is a need for a system for monitoring the environmental impacts of digital solutions so that companies, both developers and users, can take a strategic and holistic view of digitalisation and environmental sustainability. This monitoring system could be included in a digitainability platform which could also be the home for tools based on a maturity model for environmentally sustainable digitalisation which is yet to be developed.

Aligning incentive systems with a digitainability monitoring system: If digitainability is to be embedded as a competitive factor in the German economy, it would be advisable to incentivise the development and deployment of digital/sustainable solutions in line with clear indicators borrowed from the digitainability monitoring system. Funding programmes could, for example, target the use of specific technologies or a positive environmental impact on specific environmental indicators and their success would be clearly measurable on the basis of these indicators. The same applies to any digital solutions which are developed. Making their environmental impact transparent would provide a welcome commercial opportunity to exploit their contribution to environmental sustainability as a promotional tool. In addition, incentivisation in line with the monitoring system would be a useful instrument for enabling a dynamic response to changing environmental impacts, a new regulatory framework or adjusted targets.

Establishing interdisciplinary stakeholder exchange on digitainability: All stakeholders must become more aware of the relevant interdependencies. This is why there is a need to create links between stakeholders from business, academia, society and policy making in order to (1) sound out possibilities for economically meaningful digitalisation, (2) forecast their environmental effect and (3) build on this to create a regulatory framework which prevents digitalisation purely for economic optimisation, avoids possible rebound effects and includes important aspects of digitalisation (increasing significance of data protection and cybersecurity). Well-defined, sector-specific use cases could be developed in order to derive guidelines.

Taking a holistic view of digitainability including environmental, social and economic aspects: In addition to the focus set on environmental sustainability in this acatech STUDY, the term sustainability always also includes social and economic aspects, in particular with regard to the use of digital technologies. The economic and social sustainability dimensions require more attention in the future. It is therefore essential to continue bringing the concept of digitainability into line with this holistic standpoint and to understand the resultant initiatives and digital solutions accordingly. Only in this way can digitalisation be put to use for the sustainable good of society.

Overview of Options

Dimensions/ Stakeholders	Policy makers	Society	Companies	Academia
Efficiency				
Increasing the availability and adoption of digital/sustainable solutions	Launching of interdepartmental funding initiatives for the transition to environmentally sustainable digital solutions	Nurturing of user skills for the sustainable use of digitalisation Creation of a digitainability directory of environmentally sustainable digital applications	Further development of process efficiency while simultaneously investigating the necessary extent of digitalisation	Development of methods for minimising resource consumption by software applications
Avoidance of rebound effects	Incentivisation of durability and recyclability and of green alternatives in relation to the respective business models	Active communication of the environmental consequences of excessive technology use	Development of alternative business models by digitalisation or substitution Focusing the additional resources generated by efficiency gains on green alternatives	Development of methods for avoiding psychological rebound effects among users
Effectiveness				
Platform solutions	Expanding digital infrastructure and ensuring data security Promoting the use of crowd data	Nurturing of user skills for the sustainable use of digitalisation Definition of security requirements for shared use of data	Development of uniform data interfaces to establish regional, application-specific platforms	Development of uniform data standards and concepts for secure data sharing
Circular Economy	Introduction of a regulatory framework for digital product passports Creation of economic incentives for implementing a Circular Economy	Promotion of intersectoral links to open up points of contact in previously separate value chains	Focusing sustainable product design in terms of repairability, modularisability and recyclability	Exploration of sustainable natural resources and products as the basis for sustainable procurement Development of metrics for assessing sustainability along the value chain
New business models	Creation of funding frameworks explicitly for circular or digital business models	Communication of the advantages of green solutions on the basis of specific use cases	Development of pilot projects for promoting green use	Analysis of existing applications involving green use Interdisciplinary exploration of incentive mechanisms for green use

Dimensions/ Stakeholders	Policy makers	Society	Companies	Academia
Regulatory Framework				
Carbon pricing	Setting a carbon price to promote an environmentally sustainable economy	Development of carbon pricing corridors to link economic and environmental interests	Implementation of a carbon assessment relating to the entire value chain	Development of metrics for the carbon assessment of digital business models
Sandboxing	Enabling test scenarios with simplified regulations Expanding freedom of action at regional level, for example for the establishment of regulatory sandboxes	Development of model scenarios for trialling new regulations	Implementation of test scenarios including a sustainability-related evaluation of findings Promoting the exchange of sandboxing data	
Monitoring and incentivisation of digitainability	Launching of funding programmes for increasing the use of technologies with leverage effect with regard to environmental sustainability	Development of sector-specific use cases as the basis for a maturity model for environmentally sustainable digitalisation	Expansion of data acquisition in the value chain as the basis for sustainability assessment	Development of models for predicting the effect of digitalisation measures on environmental sustainability Development of evidence-based maturity models for digitainability transformation

Table 1: Synopsis of options broken down by areas of action and stakeholder (source: own presentation)

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Digitalisation and sustainability are the two great transformations of our era. A combination of these two trends offers an opportunity to secure material prosperity while simultaneously achieving Germany's climate targets. Digitainability can be a key first step towards decoupling economic growth from the resultant negative environmental impact. Achieving this demands further development of digital technologies and environmentally sustainable digital solutions within businesses to create a productive relationship between economic incentives and environmental sustainability.

This acatech STUDY evaluates the current situation of digitainability in the German economy and shows ways forward for shaping and strengthening it. An environmental market analysis focusing on eight leading sectors of the German economy identifies currently available digital solutions with a positive impact on environmental sustainability, while an economic market analysis provides data on current digitainability value creation and shows its potential for 2030. Building on these analyses, the study proposes options for using digital technologies to further improve environmental sustainability.