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Linking sustainability and the Fourth Industrial Revolution: a monitoring framework accounting for technological development

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Abstract

Background In this article, the concept of the Fourth Industrial Revolution and related implications for the measurement of sustainable development are analyzed. Technological innovations can play an important role in countering errant developments of the past and can support the transformation process towards a green economy in pursuit of the Sustainable Development Goals. On the other hand, they pose challenges to the social control of technology and represent a methodical quandary known as the Collingridge dilemma. The core statement of the dilemma is that the implications of new technologies will only be fully visible once they are embedded in socio-economic-ecological systems when the possibilities to control diminish. The main objective of this study is thus to develop a monitoring framework enabling the ex ante assessment of related technological shifts and their implications for sustainable development.

Results To approach the resulting difficulties for sustainability monitoring, digitization indicators should be accounted for in the German Sustainable Development Strategy. An enhanced strategy complemented by related Global Competitiveness Index 4.0 indicators, for which the Word Economic Forum assumes a modest link between competitiveness and inequality, illustrates the feasibility of linking research regarding the Fourth Industrial Revolution and sustainable development to measure its social and environmental consequences. The newly developed Sustainable Digital Socio-Economic-Ecological Indicator System categorizes the sustainability indicators into one index covering all Sustainable Development Goals along with four sub-indices emphasizing crucial aspects relevant to navigating a successful transformation. This novel and innovative approach is illustrated using the examples of Germany.

Conclusions The Fourth Industrial Revolution is fundamentally driven by introducing renewable energy resources as a new energy regime. However, the effects extend beyond energy and necessitate comprehensive measurement frameworks for assessing sustainable development implications. This work contributes by analyzing the related impact on sustainable development and providing decision-makers with new insights for early recognition. Preliminary results for Germany expose a discrepancy between the status quo and the desired pathway, indicating emerging effects of the Fourth Industrial Revolution on inequality, employment, and education. While none of the sectors are sustainable, the sub-index analysis highlights distinct disparities among economic, social, and ecological sectors.

Keywords Fourth Industrial Revolution, Sustainable Development Goals, Global Competitiveness Index 4.0, Sustainability indicators, Collingridge dilemma, Digitization

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Background

Since the beginning of the First Industrial Revolution in England during the second half of the eighteenth century, rapid technological developments and scientific breakthroughs have changed the lives of millions of people worldwide. Especially in the northern hemisphere, people now experience increased life expectancy and have access to foodstuffs and goods in abundance [1]. At the same time, however, a large part of the earth's current environmental problems—such as climate change, the loss of biodiversity, air pollution or large quantities of waste in the oceans—is closely linked to the previous industrialization in the form of unintended consequences [2, 3]. Moreover, the benefits of technological innovations are increasingly unequally distributed, globally and nationally, leading to a greater concentration of wealth in the hands of fewer people [4, 5].

In the midst of these environmental, social, and economic challenges, the world will face another fundamental shift in the upcoming years, namely the technological developments coined as the Fourth Industrial Revolution (4IR). While earlier industrial revolutions relied mainly on fossil resources as a primary energy resource, the upcoming one will likely be based on renewable energy sources (RES) [6–10]. Associated trends of the 4IR, such as decarbonization, digitalization and decentralization, will profoundly change the underlying power and data infrastructures and substantially influence business models and industries within and beyond the energy market [11]. It is essential to consider not only the positive implications for the standard of living, but also the related social and environmental consequences [3, 12, 13]. Shaping these complex developments involves considerable uncertainty and risk, requiring long-term strategic decisions under quickly changing circumstances [14]. Previous research has shown that technical advancement under such circumstances benefits from a comprehensive goal and a guiding point to orientate to ensure stability [15]. However, it has also been found that, in practice, such conditions tend to evoke tentative rather than assertive governance [16]. Addressing this challenge, Klaus Schwab (founder of the World Economic Forum (WEF)) suggested that it is necessary to "address what human needs are in relation to technology" [17], which is not a simple task since values differ significantly among individuals and societal groups [e.g., 18, 19], and technologies have a comparably wide scope beyond political and geographical boundaries [e.g., 3, 5, 20].

An attempt to formulate and define a set of universal values and goals can be recognized in the international process related to sustainability. During the last decades, the United Nations (UN) and several member states have made a significant effort to establish sustainability as a common global goal [21, 22]. Thus, the term can serve as "a compass which provides orientation for a journey towards a more sustainable future" and therefore assists in the future direction of political decisions [3, 23]. Implementing sustainability as a guiding compass effectively requires the strategies and concepts of sustainable development to be up-to-date and able to grasp current technological developments. Therefore, comprehensive approaches to sustainability assessment require the use of prospective assessment methods [24]. This entails the necessity to utilize appropriate indicator systems and indices that can monitor the transition of the energy system and consider the interplay between the different aspects of sustainability in the process [25–27]. If a systemic approach and political support and collaboration across stakeholders are not in place, the deployment of new technologies will pose a threat to existing political and economic systems rather than enhance performance and improve overall well-being [17, 28]. For instance, introducing new technologies can disrupt established power structures, leading to opposition and potential conflicts among stakeholders who may feel threatened by the changes. This resistance can affect progress and impede the integration of technologies into existing systems. Moreover, deploying new technologies can exacerbate economic inequalities. If access to and benefits from these technologies are not distributed equitably, it can widen the gap between those who have access and those who do not, further marginalizing certain parts of society.

The 4IR and associated developments understood as industry 4.0 have recently gained considerable attention in academic debates [29]. Governments worldwide have begun to acknowledge the scope of the changes ahead, and several countries have adopted public policies related to the 4IR, specifically in Europe, North America and East Asia. These policies differ significantly in scope, timeframe, financial budget and primary objectives [30]. Consistent with the term's widespread use, the academic debate regarding related policies is predominately focused on possibilities to foster manufacturing industries, raise productivity and economic development in general [29]. In contrast, publications about the regulatory framework, for instance, are remarkably underrepresented [29]. It is apparent that non-linear transformations in socio-economic systems also constitute demanding sustainability and environmental management tasks, for which governments are yet to find adaptive governance and regulatory mechanisms as well as suitable indicator and analytical frameworks as the systematic basis for empirical analyses [3, 5, 31, 32]. Since a change of manufacturing techniques on the scale currently assumed will inevitably have significant effects on societies and the environment, the limited research in that context indicates the need for further scientific effort in these fields. Especially because political systems historically had a strong influence and play an increasingly important role in the energy transition [33].

Following the multilateral effort by the UN, several countries have adopted national sustainability strategies and translated the UN's Sustainable Development Goals (SDGs) set out in the Agenda 2030 into national objectives using indicators to measure their progress. In the case of Germany, the most recent has been the German Sustainable Development Strategy (GSDS) 2021. In previous versions of the strategy, the technological upheavals coined as 4IR and challenges linked to digitization were not considered in the Agenda 2030 and the GSDS [34]. Therefore, a peer-review of the strategy in 2018 recommended including education in systems thinking and increasing the focus on digitization, which has not been a major focus of the strategy and its indicators [35]. Despite updates to the strategy in several areas, the issue of lacking appropriate indicators remains. This poses the risk of reverting to outdated measurement standards for these new developments, which need to be equipped to capture the unique characteristics. Moreover, it highlights the need for a comprehensive approach before widespread implementation, as adjustments may become difficult and costly later.

The Global Competitiveness Index 4.0 (GCI 4.0) addressed this gap and was developed by the WEF to include the 4IR in the overall assessment concerning competitiveness. At present, there has been no comparable effort to integrate the 4IR into the sustainable development strategy. The gap in the scientific literature that thoroughly combines digitization and sustainable development has been repeatedly emphasized, including by the German Advisory Council on Global Change [34]. In this paper, we thus propose to embed indicators gathered from the GCI 4.0 in the existing monitoring system of the GSDS in order to better capture and account for the upheavals caused by the technological transformation.

The remainder of this paper is structured as follows: subsequent to this introductory chapter, the next section introduces essential concepts that illustrate the necessity for updated measurement frameworks under consideration of the 4IR. Building upon these insights, new indices will be created in the proceeding sections and initial empirical results for an application in Germany will be presented and discussed. The last section concludes by summarizing this paper's main results and contributions.

Methods

This chapter is subdivided into four main sections, designed to comprehensively address the research objectives. First, a literature review of the 4IR is conducted. This review incorporates scholarly articles, books, reports, policy documents, conference papers, and other reputable sources to ensure a comprehensive understanding of the subject matter. By synthesizing and critically analyzing existing research, we identify the key themes, trends, and challenges associated with the 4IR.

Building upon the insights gained from the literature review, the next section delves into the Collingridge dilemma and its implications for the governance of innovation within the 4IR context. The literature review, together with the analysis of the Collingridge dilemma, establishes a strong foundation and guidance for capturing the key dimensions and interconnections between technological shifts, sustainable development goals, and socio-economic-ecological systems. In the subsequent sections, we leverage these insights to propose and develop new indices that account for the multidimensional aspects of the 4IR.

Through an evaluation of the fundamental principles and attributes of the GSDS and the GCI 4.0, specific indicators are identified that correspond to the tenets of sustainable development and effectively encompass the essential aspects of technological progress in the 4IR.

The Sustainable Digital Socio-Economic-Ecological Indicator System (SDSEEIS) is subsequently constructed by categorizing the selected sustainability indicators into a comprehensive index covering all SDGs, along with four sub-indices. Germany is chosen as an illustrative example to apply the developed indices. Data gathered from the GSDS, specific to Germany's context, are utilized to assess the country's progress towards sustainable development and to identify emerging effects of the 4IR.

The results obtained from the developed indices are then analyzed for patterns, trends, and discrepancies within and between sectors, provide insights for decision-makers, and enable early recognition of unintended developments. By following this research methodology, the study integrates digitization indicators into the GSDS, develops a novel monitoring framework, and generates valuable insights into the implications of the 4IR on sustainable development.

Literature review

The concept of the Fourth Industrial Revolution

To understand the WEF's reason for developing an entirely new indicator framework in response to the changes triggered by the 4IR in the context of competitiveness and comprehend why the 4IR has severe implications for sustainability strategies, it is essential to elucidate what the 4IR encompasses. This section provides the 4IR's conceptual background, differentiating between different concepts and counting schemes. Moreover, the main technological and scientific advancements of the 4IR are illustrated.

There has yet to be a universal agreement in the international debate on what constitutes the 4IR.Describing similar technological and scientific developments, Rifkin refers to a "Third Industrial Revolution" [36], while McAfee and Brynjolfsson name it the "Second Machine Age" [37]. In the German language area, however, the terms Industry 4.0 and Fourth Industrial Revolution have become widespread in academia and politics and are often used as synonyms [38]. This can be misleading since Industry 4.0 mainly refers to new manufacturing and production technologies, as illustrated by the application of the German Ministry of Research and Education [39]. Schwab differentiates his understanding of the 4IR explicitly from an insulated change in manufacturing and production technology by enlarging its sphere of influence far beyond [40]. Industry 4.0 is consequently only a part of the 4IR.

The term revolution implies a radical and abrupt change. Throughout history, various revolutions occurred, often accompanied by the adoption of new technologies, leading to remarkable social and economic changes [3, 5, 41] (Fig. 1).

According to Schwab, the Third Industrial Revolution (or Digital Revolution) was triggered by the development of semiconductors, employed in particular in mainframe computing (1960s), personal computing (1970s and 1980s) and thereafter the internet [40]. This is the key element on which Schwab and Rifkin disagree. In contrast to Schwab, Rifkin argues that "the IT sector and the Internet did not in and of themselves constitute a new industrial revolution" since this would require a new energy regime [36]. By deploying renewable energy and innovative technologies, this missing energy regime is now completing the declared matrix (Fig. 2).

Thus, even though Rifkin and Schwab disagree on whether or not commonly available personal computers and the internet constituted an industrial revolution, they both agree on the hypothesis that another major transition is now happening. Rifkin justifies his assumption based on the role of renewables in filling the gap in his proclaimed energy–communication–transportation matrix. Schwab acknowledges that, historically, these general-purpose technologies have had a major impact and laid out the groundwork for other innovations. For the 4IR, those could be artificial intelligence (AI), distributed ledger technologies (such as blockchain) and new computing technologies, but Schwab stresses this is too early to predict [17]. Thus, renewable energy is considered a fundamental aspect of the 4IR.

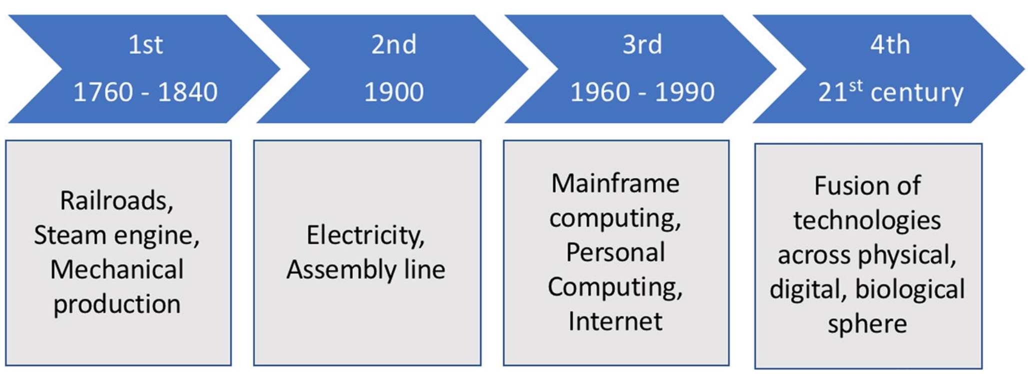

Fig. 1 Approximate timeline industrial revolutions, *Source*: Authors, based on Schwab 2017

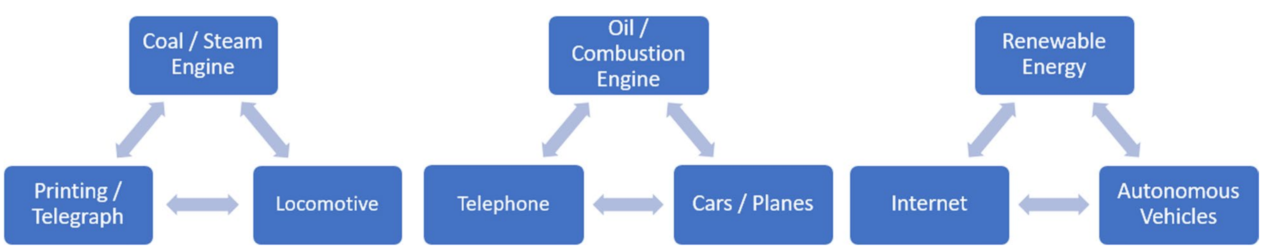

Fig. 2 Technology platform industrial revolutions, *Source*: Authors, based on Rifkin 2015

Schwab expects that the most surprising and impactful advancements will come from the combination of various new technologies. These advancements might require new organizational structures, potentially making the vertical structures described by Rifkin for the First and Second Industrial Revolution outdated [17]. Furthermore, Schwab emphasizes the importance of enhanced cognitive power, which augments human production, making the upcoming transition even more impactful than the previous industrial revolutions [40]. This coincides with the observation of Brynjolfsson and McAfee [37], who stated that the world is at an inflection point with three main characteristics: "exponential, digital and combinatorial". Observers agree that the world is on the brink of a new era, regardless of whether the recognition of the internet and advancements in the IT sector as a separate industrial revolution is considered. They believe that Information and Communications Technology (ICT) will play a crucial role as enabling technologies, while they consider different aspects most vital.

The narrow definition of *Industrial Revolution* (capitalized) usually refers to the events which have been described as the First Industrial Revolution. The broader definition of *industrial revolution*—written in lower case—can refer to "any rapid significant technological change" [42]. It is thereby impracticable as a distinguishing working definition. Therefore, this paper follows the definition coined by Schwab [40], consisting of two parts. He emphasizes that it is not just about specific inventions—such as the steam engine, for instance—but instead, he states:

> *It is the fusion of these technologies and their interaction across the physical, digital and biological domains that make the fourth industrial revolution fundamentally different from previous revolutions.*

An example of these interactions—often termed cyber-physical systems—can be observed in autonomous vehicles, or, for instance, in the implementation of better AI on more powerful computers possibly leading to breakthroughs in material science, which enable the production of even more powerful computers.

> *Digital technologies that have computer hardware, software and networks at their core are not new, but in a break with the third industrial revolution, they are becoming more sophisticated and integrated and are, as a result, transforming societies and the global economy. [40]*

The second part stresses that these technological changes do not occur in isolation but have notable effects on societies and the global economy. Overall, the 4IR is characterized by a blend of technological advancements and scientific innovations across various fields, transforming production methods and significantly impacting society and the global economy (Fig. 3).

Many scientific themes that have attracted considerable attention and have been implemented in various sectors in the context of the 4IR, such as e.g., AI, were initially developed several decades ago (see e.g., [43]). Due to insufficient computing power, they could only be fully applied recently. The decisive difference is the exponential growth of processing power combined with falling prices—referred to as Moore's Law. It is important to note that this is not a law of physics but an observation made by Gordon Moore, a co-founder of Intel. In an article firstly published in 1965, he noted that computing power is doubling approximately every 18–24 months [44]. Although his prediction has been remarkably accurate, it should be viewed cautiously since it is less a law than a historic observation extended to the future [45]. Most of the 4IR technologies rely on a continuation of *Moore's Law* and it is commonly assumed that this development will maintain [37, 40, 46]. This is congruent with the German AI strategy, which also identifies the exponential improvement in the ICT sector as fundamental for the progress in several key technologies [47].

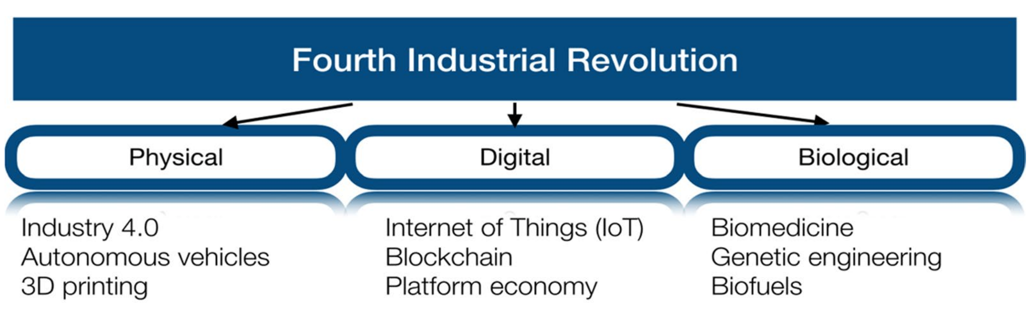

Fig. 3 Terminology, *Source*: Authors, based on Schwab 2017

Even faster-decreasing costs than Moore noted in regard to semiconductors and storage can be observed for the decoding of the human genome. While the costs for the first sequencing were estimated between 500 million and 1 billion US-Dollar by the National Human Genome Research Institute, the costs for sequencing human gene material between 2006 and 2016 dropped from 14 million to less than one thousand [48]. Biological innovation has already opened new frontiers and is constantly raising new questions, especially of ethical nature. It is questionable whether the proclaimed possibilities of the 4IR can be considered a chance to leverage the transformation process towards a more sustainable civilization or should be perceived as a part of an ideology that regards technology as the solution for every problem humanity is facing.

While digital developments do not exclusively determine the 4IR, it crucially relies on the infrastructure provided by the ICT sector and the developments associated with Moore's law. Traditional IT infrastructure, however, is currently challenged by the phenomenal growth and speed requirements demanded by smart grids, data storage capacity, data governance and several other related obstacles [49, 50]. Key enabling technologies, such as blockchain and RES, have an increasingly essential role in the energy system transformation worldwide [51–55]. Beyond that, several other 4IR technologies cannot unfold their full potential without a matching digital and energy infrastructure [56]. However, currently, there are several research gaps concerning the development of essential aspects of this infrastructure, such as smart grids, within the social sciences [57]. Despite this immediate link between digital and especially the energy infrastructure, indicators aimed at assessing the current state of digitization still need to be included in the entire measurement framework of the GSDS in its current form [34]. Thus, a crucial lack of knowledge needed to make informed decisions exists for measuring sustainable development [20]. The challenge to anticipate and control potential impacts of new technologies has influenced the discourse on the governance of science and technology for decades [58, 59]. Coined as the Collingridge dilemma, it is therefore also crucial for the developed monitoring framework concerning sustainability and will be illustrated in the following section.

The Collingridge dilemma and the Fourth Industrial Revolution

Given the growing complexity and increasing societal, political and environmental uncertainties, it is now more important than ever to reflect upon present decisions and act with foresight. Measuring the 4IR at an early stage and linking it to sustainability implies methodological challenges comparable to those dealt with in technology assessment (TA). Methods used in TA have been established as approaches to investigate technological developments at an early stage and explore intended and unintended consequences [60].

The current methods in TA, which primarily focus on assessing individual technologies (e.g., nanotechnology [61]), cannot fully evaluate the impact of the 4IR in a sustainability context.

This is because the 4IR involves multiple interrelated innovations happening simultaneously rather than just one technology [40].

The Collingridge dilemma, as a central methodological quandary in TA, is still relevant for every attempt to control, influence and explore the impacts of new technologies. Trying to assess the social consequences of technology early faces a lack of reliable information [62]. By the time enough reliable information becomes available, it is often too late to shape and manage related outcomes effectively [62]. Even though this difficulty should be taken into account, it relies on two overstatements [60]. Firstly, epistemologically, it assumes that there is a strict dichotomy between pure speculation and certain knowledge, which is generally not the case. It is evident that the predictive validity of information on technological consequences varies over time. Some conclusions can be drawn even at an early development stage since there is already knowledge about the goals and intended purposes for which a technology is meant to be developed in the first place. Secondly, in practical terms, the dilemma assumes a dichotomy between the existence of possibilities to shape technology and the full absence of control [59, 60]. Undoubtedly, the prospects of leading technologies in a specific direction change over time and narrow towards the end of the development process. But the question of whether technology and its effects are controllable cannot be answered with *yes* or *no* [63]. Even when technologies have reached a mature status of development, the way they are embedded into society remains open, and with it the social consequences they might cause, which can vary significantly [59]. Technological (as well as social) inventions are therefore prerequisites of a transformation process, but to become a real innovation, they usually need to reach a degree of diffusion—possibly through market success or wide adoption by society [64].

The Collingridge dilemma's implications for the control of technology and innovation are still widely discussed in the academic literature [59, 65–67]. And while its determinism relies on the two overstatements mentioned above, the value of assessing effects of innovative technologies as early as possible should not be underestimated. Reliable information on technological developments can support decision-makers in taking informed actions to guide future transformation processes. Bearing in mind the limitations stated above, it facilitates constructive dealing with the dilemma. At the same time, it illustrates the need to measure the 4IR's impact at the earliest opportunity to recognize its social and environmental consequences. The sustainability measurement framework developed in this paper should thus be regarded as an approach to deal with the effects on sustainability measurement frameworks in the context of the 4IR's rapid technological development and the implications drawn from the Collingridge dilemma.

To measure the impact of the 4IR on sustainable development, the 4IR-related indicators of the CGI 4.0 of the WEF were integrated into the systematics of the German SDGs. In line with the scientific call for more knowledge-based tools to guide policy-making [e.g., 32], the WEF [68] introduced several new concepts and approaches to provide an economic "compass for policymakers and other stakeholders" to navigate the 4IR. In particular, these can be utilized in the context of sustainability to complement the existing compass for sustainable development, which, in the case of Germany, can be recognized in the current GSDS. This can be done by identifying overlaps and content-related conformity with regard to the broader objectives of the UN SDGs and the sustainability postulates set out in the GSDS. An enhanced GSDS complemented by related GCI 4.0 indicators thus illustrates a feasibility of linking research regarding the 4IR and sustainable development and enables measuring its social and environmental consequences. Thereby, it is intended to enhance the scope of the GSDS and enable it to capture developments affected by the 4IR, leading to an overall improved strategy offering decision-makers the possibility to respond with foresight. While Germany's sustainable development strategy is used as an exemplary case study, the approach and indicators presented in this paper are not limited to Germany and can be utilized in other sustainable development strategies likewise. The next section looks at the GSDS and the GCI 4.0 of the WEF in detail.

The German Sustainable Development Strategy

The current GSDS rests upon the goals and philosophy of the Agenda 2030 [69]. In the aftermath of the UN's declaration, the German federal government translated those into an agenda specifically for Germany while adding indicators to measure progress concerning the stated goals. Based on the UN's SDGs, the German SDGs serve as a basis for a long-term strategy, which assures planning security for all stakeholders involved. Especially the implementation of the strategy as a long-term and cross-party plan can be regarded as a significant achievement since occurring changes in government did not result in abandonment. This long-term planning reliability is of particular importance. Its lack tends to lead to the misallocation of capital and resources towards undesired technology paths since government support is often one of the key drivers of central technologies, especially in the energy sector [70].

The GSDS is grounded on the Brundtland report's understanding of sustainability [69, 71]. Further, it recognizes relative and absolute limits as boundaries, where the earth's natural capacities represent the absolute limits and sustainability as a guiding principle the relative one [69]. The strategy has been continuously updated, is monitored by the Federal Statistical Office every two years, and will be further developed and renewed every four years [69]. Furthermore, the strategy is regularly peer-reviewed by an independent team of professionals of various disciplines to identify improvement possibilities [35, 69]. Generally, the strategy formulates objectives and measures across almost the entire political spectrum [69]. It is based on a holistic and integrative approach, stating that it aims to achieve a development which balances the interrelationship of the three dimensions economically capable of high performance, socially balanced and ecologically compatible [69]. The primary goal of GSDS is to drive change in the economy and society by encouraging changes in lifestyles, work, and consumption and shifting technologies, institutions, and practices [69, 72]. This aligns with the transformations expected from the 4IR [40]. Additionally, the GSDS is grounded on certain main principles, including emphasizing international cooperation and ensuring the overall goals are consistent and continuously improved upon [72]. Concurrently, it is aimed to maintain the overall communicability and controllability of the strategy by focusing on several key indicators without overextending its scope [69, 72]. The GSDS considers enhancing technological efficiency and scientific progress as possibilities for decoupling economic growth from resource consumption [69, 72].

The widely accepted definition provided in the Brundtland report lacks concrete and actionable principles and goals, highlighting the need for operationalization. Moreover, the concept of sustainability is subjective and has normative elements, making it challenging to deduce specific sub-targets, indicators, and measurement systems logically. This leads to a dynamic and constantly evolving meaning for sustainability. The GSDS can thus be seen as the outcome of an ongoing political negotiation process to define these sub-targets and measurement systems for Germany. The priorities for advancing the latest versions of the GSDS are to involve all relevant stakeholders in promoting sustainable development and ensuring that all sustainability-related policies are consistent and aligned with each other [69, 72].

Due to the sheer scope of the subject, it is neither theoretically nor practically doable to cover every affected aspect of the 4IR.Hence, it is not possible for the proposed indicators or any sustainable development strategy assessing the 4IR to be exhaustive.However, any improvement in the strategy increases its effectiveness and helps to understand current developments better. Therefore, it is necessary to apply criteria of relevance and decide normatively which parts will be covered, which naturally inheres to the risk of ignoring specific sectors that could be important in hindsight [60]. The following section lays out how the GCI 4.0 addresses these challenges.

The Global Competitiveness Index 4.0

The GCI 4.0 was released in October 2018, following a multi-stakeholder process that began in 2014 and involved various events and expert consultations [73].

The WEF identified the lasting impacts of the 2008 Great Recession and the accelerated pace of innovation brought about by the 4IR as the leading causes behind the overhaul of the previous Global Competitiveness Index [68].

The GCI 4.0 is thus conceptualized as a tool to anticipate nascent tendencies concerning economic and social developments [68]. Moreover, the WEF recognized the matter of effectively addressing and managing the social and economic effects of these technological advancements and disruptive trends. It established four guidelines for thriving economies [68]. Following the WEF, successful economies in the 4IR must be agile, resilient, innovative, and human-centric [68]. Resilience means being prepared for external shocks and crises, such as financial instability or mass unemployment. Agility implies being able to adapt to altering circumstances effectively and quickly. Innovation is about constructing an ecosystem that encourages new ideas and promotes technological advancements. Finally, a human-centric approach prioritizes human well-being and acknowledges the importance of human capital for prosperity.

Compared to previous versions, the GCI 4.0 places greater emphasis on the quality of institutions and policies, recognizing their crucial role in promoting long-term growth and prosperity [68]. The WEF encloses 20 indicators linked to this aspect to measure the quality of an economy's institutions [68]. In this connection, the WEF understands institutions as "including formal, legally binding constrains—rules, laws, constitutions and associated enforcement mechanisms—and informal constraints, such as norms of behavior, conventions and self-imposed codes of conduct" [68]. Particular attention has been paid to the public sector's ability to react to technological change and adopt long-term strategies [68]. These characteristics play a vital role in accomplishing future sustainable development. Globally, the median score under the pillar *Institutions* is the second-lowest out of the overall 12 pillars [68]. This suggests that significant effort is necessary for governments to prepare for the impending disruptions.

The GCI 4.0 further emphasizes the crucial role of innovation, recognizing that having a well-functioning innovation ecosystem will become increasingly important in the future [68]. Unlike in previous decades, competitiveness and growth cannot be achieved simply by improving efficiency and reducing costs but requires adopting new concepts and practices [68]. Thus, the index measures countries' innovation capabilities and emphasizes the importance of being open to new concepts and procedures. This is particularly essential in light of the environmental and social challenges brought about by the 4IR that will require new solutions and increased adaptability.

The WEF claims the GCI 4.0 "holds some predictive power" as it evaluates a country's ability to sustain economic growth over an extended period [68]. Although the accuracy of this claim is uncertain, the GCI 4.0 is designed as a forward-looking approach to allow policymakers to act proactively. In the context of the rapid technological development of the 4IR and the GSDS's long-term approach, using forward-looking indicators represents a meaningful enhancement and complementation. The WEF recognizes that balancing economic, social, or environmental goals can be challenging. However, they believe that productivity is a crucial factor in improving the standard of living and is a requirement for greater human development [68]. The GCI 4.0 provides a perspective on these conflicting goals and the next section will elaborate on it.

Deduced from connecting the Gini coefficient as the measurement of inequality and the GCI 4.0 for competitiveness, the WEF assumes a relationship between *competitiveness and inequality*, although not very pronounced [68]. It further rejects the hypothesis that more competitiveness will soundly lead to neither more nor less inequality [68]. Azerbaijan (GCI 4.0 60.0/Gini 16.6) and South Africa (GCI 4.0 60.8/Gini 63.0), for instance, obtain an almost similar score in terms of competitiveness while differing significantly with respect to inequality [68]. Moreover, the WEF assumes that inequality is not caused by growth and that growth and inequality can coexist in balance if appropriately managed by the government [68]. This is congruent with the assumption underlying the GSDS (GSDS SDG 8.4).

The WEF recognizes the complex relationship between the *environment and competitiveness* and emphasizes that economic activity must be conducted within the boundaries set by the natural limitations of the earth [68].

According to the GCI 4.0 score and the ecological footprint per unit of output, the WEF finds that more competitive countries tend to use resources more efficiently [68]. However, they generally have a larger overall ecological footprint [68]. The WEF realizes the importance of countries committing to green growth, as environmental issues like biodiversity loss, climate change, and resource scarcity will affect growth and even threaten humanity's very existence. [68].

Thus, the GCI 4.0 and the GSDS regard green growth as a means to decouple economic growth from resource consumption through the implementation of innovative technologies [68, 69]. Furthermore, both assume that growth can be aligned with addressing inequality and preserving the planet's boundaries.

Competitiveness is an important policy objective, but it cannot be the only goal of sustainability strategies. On the other hand, sustainability is a clear political objective that provides guidance for future policies. The WEF identified indicators within the GCI 4.0 framework as highly relevant for assessing the 4IR in terms of competitiveness. These indicators, either directly or indirectly related to its digital foundation, have a complementary use within a sustainability measurement framework. They present a promising option for integration into sustainability indices and can serve as the basis for sustainability monitoring.

Overall, the GCI 4.0 is a measurement framework based on insights from multiple disciplines developed through a comprehensive process involving many stakeholders. Its indicators align well with the philosophy and approach of the GSDS, as both recognize the significance of technology and green growth for sustainability and share-related core assumptions. This distinguishes them from other measurement frameworks focusing only on digitalization or competitiveness. The subsequent section explores how the GCI 4.0 indicators can be incorporated into a novel measurement framework.

Results

Historical observations highlight the importance of measuring and monitoring what societies consider essential, as it impacts policy design and decision-making [74]. This chapter thus provides a Sustainable Digital Socio-Economic-Ecological Indicator System (SDSEEIS) that gives policymakers vital information to address the consequences of the Collingridge dilemma.

The Sustainable Digital Socio-Economic-Ecological Indicator System

The new indicator system was developed by linking selected indicators from the GCI 4.0 framework to the German SDGs while maintaining the structure of overall goals and sustainability postulates. To address the impacts of the 4IR, 14 new digital indicators were added to the existing indicators framework. This resulted in a comprehensive list of indicators, shown in Table 1, designed to provide policymakers with meaningful information within a sustainability context.

Table 2 summarizes the goals and indicators of the GSDS strategy. The number of indicators used to measure each SDG varies, with some having fewer indicators and others having more. For example, SDG 1 is measured by two indicators, while SDGs 2, 5 and 6 are each described by three indicators. Meanwhile, SDG 7 is measured by four indicators and SDGs 3 and 4 are measured by eight and six indicators, respectively.

Furthermore, Table 2 shows that the largest number of indicators describes SDG 8 "Decent work and economic growth". The German government selected nine indicators to capture economic development and to describe their idea of decent work.

Currently, SDG 9 "Industry, Innovation and Infrastructure" is only measured by one indicator addressing private and public spending on research and development. The absence of other indicators highlights the need to integrate additional sources of information. Hence, this goal is supplemented with the proposed indicator 9-1b, which encompasses 14 sub-indicators to evaluate the disruptions caused by the 4IR. The German government uses two indicators to describe SDG 10, seven indicators to describe their concept of sustainable cities

Table 1 List of derived SDG 9-related indicators for the German SDGs

Number of sub-indicators	Measuring indicator 9-1-b
1	E-Participation
2	Intellectual property
3	Mobile-cell telephone subscriptions
4	Mobile-broadband
5	Fixed-broadband
6	Fiber internet
7	Internet users
8	Digital skills
9	Venture capital availability
10	Growth of innovative companies
11	Companies embracing disruptive ideas
12	Governments' responsiveness to change
13	Legal frameworks' adaptability to digital business models
14	Governments' long-term vision

Detailed descriptions concerning the measuring approach of the individual indicators can be found in WEF [75] as well as in publications of the related institutions. Further information regarding the indicator field is set out in German Federal Government [69]

Table 2 German Sustainable Development Goals complemented by digital indicators

SDG no.	Indicator field	SDG measuring indicator	
1	Poverty	Materially deprived persons	1-1-a
		Severely materially deprived persons	1-1-b
2	Farming	Nitrogen surplus	2-1-a
		Organic farming	2-1-b
		Payments to developing and emerging countries to support good governance for food security	2-2-a
3	Health and nutrition	Premature mortality—female	3-1-a
		Premature mortality—male	3-1-b
		Smokers, adults	3-1-c
		Smokers, youth	3-1-d
		Obesity, youth	3-1-e
		Obesity adults	3-1-f
		Emissions air pollutants	3-2-a
		Fine dust	3-2-b
4	Education and training	Early school leavers	4-1-a
		Early school leavers, female	
		Early school leavers, male	
		30 to 34-year-olds with tertiary or post-secondary non-tertiary education	4-1-b
		Full day care, 0–2-year-olds	4-2-a
		Full day care, 3–5-year-olds	4-2-b
5	Equal opportunities	Earnings gap between women and men	5-1-a
		Women in management positions in the economy	5-1-b
		Professional qualification of girls and women through German development cooperation	5-1-c
6	Water quality	Phosphorus in running waters	6-1-a
		Nitrate in groundwater	6-1-b
		Development cooperation for drinking water and sanitation	6-2-a
7	Resource conservation	Final energy productivity	7-1-a
		Primary energy consumption	7-1-b
		Share of renewable energies in gross final energy consumption	7-2-a
		Share of electricity from renewable energy sources in gross electricity consumption	7-2-b
8	Employment	Total raw material productivity	8-1-a
		Government deficit	8-2-a
		Structural deficit	8-2-b
		Debt level	8-2-c
		Ratio of gross fixed capital formation to GDP	8-3-a
		Gross domestic product per inhabitant	8-4-a
		Employment rate, 20–64 years	8-5-a
		Employment rate, 60–64 years	8-5-b
		Number of members of the Textile Alliance	8-6-a
9	Innovation	Private and public expenditure on R&D	9-1-a
		Digitalization	9-1-b
10	Equal educational opportunities	Foreign school leavers	10-1-a
		Gini coefficient for income distribution	10-2-a
11	Housing	Increase in settlement and transport area	11-1-a
		Loss of free space	11-1-b
		Population density	11-1-c
		Final energy consumption in freight transport	11-2-a
		Final energy consumption in passenger transport	11-2-b
		Accessibility of central and regional centers by public transport	11-2-c
		Share of persons in households spending more than 40% of disposable income on housing	11-3-a

Table 2 (continued)

SDG no.	Indicator field	SDG measuring indicator	
12	Sustainable consumption	Market share of products with government eco-labels	12-1-a
		Direct CO_2 emissions and CO_2 content of consumer goods	12-1- b
		Use of the environmental management system EMAS in Germany	12-2-a
		Share of recycled paper with the Blue Angel in the total paper consumption of the immediate federal administration	12-3-a
		CO_2 emissions per mileage of public-sector vehicles	12-3-b
13	Climate protection	Greenhouse gas emissions in CO_2 equivalents	13-1-a
		German payments primarily to developing and emerging countries for climate financing	13-1-b
14	Protecting the oceans	Total nitrogen concentration in North Sea	14-1-a
		Total nitrogen concentration in Baltic Sea	
		Proportion of sustainably exploited fish stocks in the North Sea and Baltic Sea	14-1-b
15	Ecosystems	Biodiversity and landscape quality	15-1-a
		Ecosystems with exceedance of load limits for eutrophication due to nitrogen inputs	15-2-a
		Payments to developing and newly industrializing countries for the proven preservation or reconstruction of forests under the REDD + scheme	15-3-a
16	Good governance	Crimes	16-1-a
		Number of projects implemented by Germany in affected regions of the world to secure, register and destroy small arms and light weapons	16-2-a
		Corruption Perception Index in Germany	16-3-a
		Corruption Perception Index in the partner countries of German Development Cooperation	16-3-b
17	Knowledge transfer, especially in technical areas	Share of public development expenditure in gross national income	17-1-a
		Students and researchers from developing and transition countries in Germany	17-2-a
		Imports from least developed countries (LDCs)	17-3-a

The Digitalization category contains WEF-derived indicators and complements SDG 9 [75, 76]. This table illustrates how they integrate into the overall measurement approach of the GSDS

and communities (SDG 11), five indicators to describe responsible consumption and production (SDG 12), and two indicators to describe climate action (SDG 13). SDGs 14, 15, and 17 are described by three indicators, while SDG 16 is described by four.

The integration of the proposed indicators thus leads to a total of 55 indicators that describe the challenges of sustainable development while taking into account the impact of the 4IR in Germany, thus forming a SDSEEIS.

Measuring digital sustainability—SDG indices

The following indices were developed to describe the SDSEEIS. The respective measuring indicators are defined for two cases.

The first case measures the decrease required to reach the sustainability target. Here, if an indicator's value decreases, the sustainability target is being met. For instance, decreasing CO2 emissions indicate that the country is moving towards a more sustainable energy mix.

The second case measures the increase required to reach the sustainability target. If the value of an indicator increases, it implies that the sustainability target is being met. For example, an increase in RES utilization indicates that the country is moving towards a more sustainable energy mix:

$$\mathrm{SD} - \mathrm{I}^{1}_{\text{decrease}} = \frac{\mathrm{SDI}_{\text{target value}_y}}{\mathrm{SDI}_{\text{current value}_z}}, \tag{1}$$

y = individual target year for the specific indicator of the goal, z = latest available empirical value for the specific indicator of the goal, SD - I^1 is defined between 0 and 1.

$$\mathrm{SD} - \mathrm{I}^{2}_{\text{increase}} = \frac{\mathrm{SDI}_{\text{current value}_z}}{\mathrm{SDI}_{\text{target value}_y}}, \tag{2}$$

y = individual target year for the specific indicator of the goal, z = latest available empirical value, SD - I^2 is defined between 0 and 1.

If SD-I is 1, then a development is sustainable, if SD-I < 0, the development is unsustainable. It is assumed that if the target of a sustainability goal is over-fulfilled, the indicator is also defined as 1 in order to avoid that unsustainable development measured by one indicator can be compensated by sustainable development as measured by other indicators [77].

In the next step, the value for the single SDG is defined:

$$\mathrm{SDG{-}I}_g = \frac{1}{J}\sum_{j=1}^{J} SD - I_j,\ \mathrm{j = 1..J}, j = \text{number of measuring indicators of the specific SDG}, g = \text{SDG number.} \tag{3}$$

The overall sustainability indices are defined as:

$$\mathrm{SD}_{\mathrm{index}}^{\mathrm{FEW}} = \frac{1}{K}\sum_{k=1}^{K}\left(\mathrm{SDG} - \mathrm{I}_g\right)_k, k = 1..K,\ \text{number of SDGs per sub-index}, K = 6, \tag{4}$$

$$\mathrm{SD}_{\mathrm{index}}^{\mathrm{Social}} = \frac{1}{K}\sum_{k=1}^{K}\left(\mathrm{SDG} - \mathrm{I}_g\right)_k, k = 1..K,\ \text{number of SDGs per sub-index}, K = 7, \tag{5}$$

$$\mathrm{SD}_{\mathrm{index}}^{\mathrm{Economics}} = \frac{1}{K}\sum_{k=1}^{K}\left(\mathrm{SDG} - \mathrm{I}_g\right)_k, k = 1..K,\ \text{number of SDGs per sub-index}, K = 4, \tag{6}$$

$$\mathrm{SD}_{\mathrm{index}}^{\mathrm{Digital}} = \frac{1}{D}\sum_{d=1}^{D}\mathrm{SD} - \mathrm{I}_d, d = 1..D, D = 14, \tag{7}$$

$$\mathrm{SD}_{\mathrm{index}}^{\mathrm{All}} = \frac{1}{k}\sum_{k=1}^{K}\left(\mathrm{SDG} - \mathrm{I}_g\right)_k, k = 1..K,\ \text{number of SDGs per index}, K = 17. \tag{8}$$

Subsequently, the digital index is included in the All SDG Index:

$$\mathrm{SDG}_{\mathrm{incl.digital}}^{\mathrm{All}} = \frac{\sum_{i=1}^{N} X_i \mathrm{SDG} - \mathrm{Pillars}}{N};\ i = \text{SDG{-}Pilars (FEW - Nexus, social, economics, digital).} \tag{9}$$

This measuring procedure leads to a renormalization with the advantage that every SDG is represented by one value in the overall index and the respective sub-indices. Accordingly, the SDGs are treated equally.

Application for the case of Germany

The first results of the enlarged sustainable development model show that Germany is currently not on a sustainable pathway. The four sub-indices further show that none of the analyzed sectors are currently sustainable. However, the analysis highlights a clear difference between the economic, social and ecological sectors.

The SDG index, based on 55 measuring indicators, shows that Germany has covered over 75% of its journey towards sustainable development according to the standards set by the federal government. This is indicated by the corresponding index value of 0.760. The food–energy–water (FEW) nexus index, which is based on 17 indicators related to food, energy, and water sectors and is frequently regarded as central to sustainable development, reveals that the level of sustainable development in these key sectors is only around 65% at present. The respective index value is 0.651. The social index, with a value of 0.837, emphasizes that the social aspects of sustainable development are nearest to achieving a sustainable level. However, there is still space for improvement in the economic sector, which

Table 3 Results of the authors' SDG index and sub-indices for Assessing Sustainable Development in Germany

Index	Value	Indicators
All SDGs	0.760	55
All SDGs incl. Digital	0.734	69
FEW nexus	0.651	17
Social	0.837	26
Economics	0.788	12
Digital	0.660	14

The column indicator illustrates the number of indicator considered

retains an index value of 0.788, primarily due to a lack of digitalization. The digital sector has an index value of 0.66 and currently stands at a similar level of sustainable development as the FEW nexus sectors. The impact of integrating digital indicators into the All-SDGs Index slightly reduces the sustainability achievement level from 0.760 to 0.734. The results are summarized in Table 3 and visualized in Fig. 4.

Discussion

The idea of measuring sustainable development is based on the tradition of measuring the welfare development of society, and the SDGs are the latest indicator set for measuring sustainable development and progress. In this connection, these indices and their underlying concept will enable policymakers to develop measures to foster sustainability in the various sectors. The sub-indicators of the SDGs further allow monitoring the development of single objectives more closely. The SDG-based measuring concept enables monitoring not only of what is produced, such as indicators like the GDP (gross domestic product), but also how it is distributed and the effects a particular way of production has on society and the environment.

The application for the case of Germany indicates that the effects of the 4IR on inequality, employment and education already emerge. Hence, this work opens avenues for further research and debates addressing technological shifts within the context of sustainability. Since many countries already use sustainability strategies to help

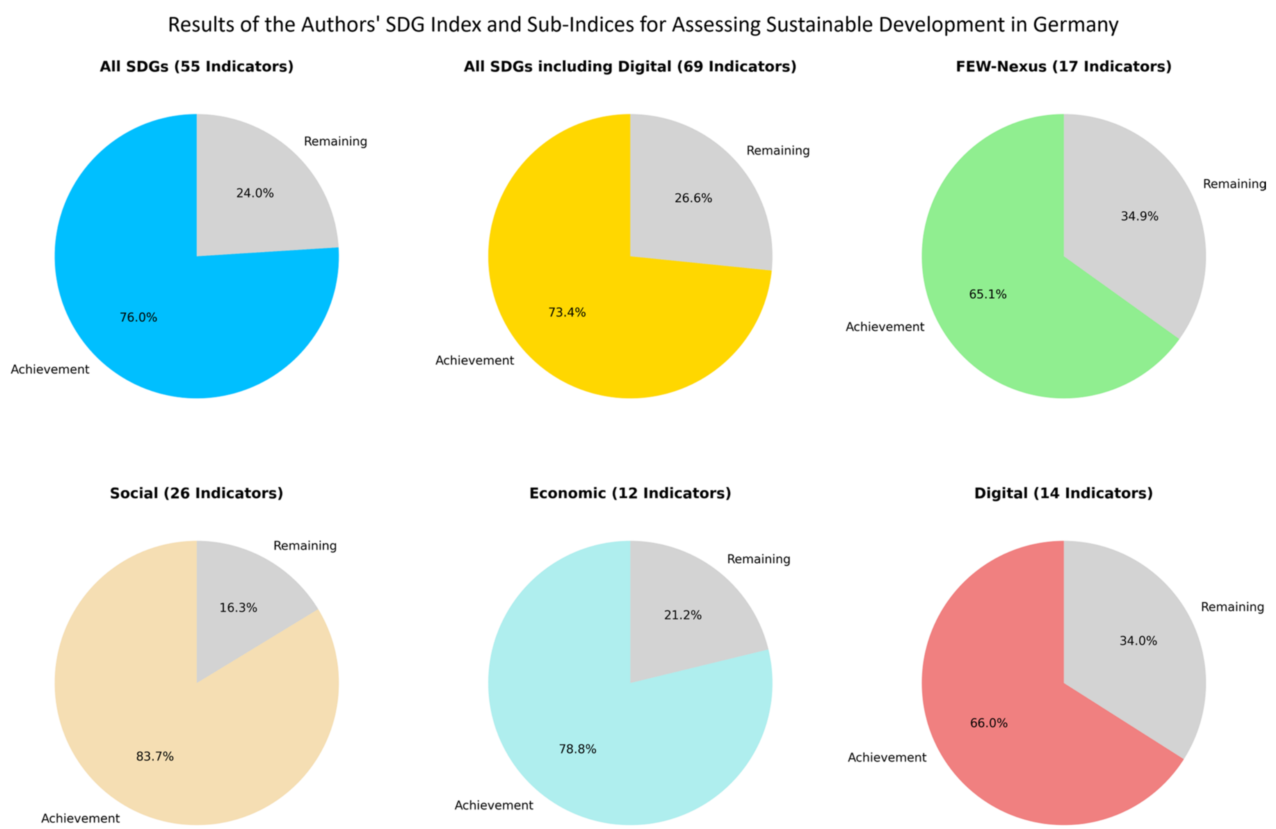

Fig. 4 Results of the SDG index and sub-indices for assessing sustainable development in Germany, *Source*: Authors

influence policy direction, this can also be applied and further developed with reference to other countries, as shown in the example of Germany. Comparative studies could identify how different countries approach shifts in related sectors and identify best practices.

In this context, the outcome that Germany, as the largest economy in Europe and a country actively emphasizing the significance of transitioning towards greater sustainability, falls short of the desired targets stated in the sustainability strategy, raises concerns. The sustainability challenges faced by countries with fewer financial resources and industrial capacities can be even more substantial than the difficulties encountered by industrialized nations like Germany.

In particular, in the context of innovation capabilities, significant disparities arise between developing and affluent nations. The measurement framework assesses various factors that contribute to innovation, such as research and development investments, technological infrastructure, intellectual property rights protection, and access to financing.

These factors are often more abundant in economically advanced countries, granting them a competitive advantage in innovation-driven endeavors. Consequently, developing countries may face challenges in attaining higher scores on the index due to resource constraints, limited access to cutting-edge technologies, and inadequate investment in research and development.

Indices used to measure these capabilities underscore the significance of embracing novel concepts and approaches. Thus, they tend to be less favorable towards developing countries. For applying the developed approach in a different context or comparing respective results, it is thus vital to pay attention to existing disparities between countries and reflect the need for targeted efforts to promote innovation capacity and foster inclusive development globally.

At the same time, sustainability efforts are not solely reliant on innovation capabilities, financial resources or a countries industrial basis. While the absence of such elements can certainly pose further hurdles, it can also stimulate the development of creative and context-specific solutions, considering the differences in notions of sustainability and the various pathways to its realization. In such cases, international cooperation, knowledge sharing, and capacity development can play crucial roles. Collaborative initiatives, partnerships, and support from international organizations can help countries with fewer financial resources overcome challenges and implement sustainable practices. Additionally, leveraging local expertise, traditional knowledge, and community participation can lead to sustainable solutions that are cost-effective and tailored to the specific needs and capacities of each respective countries. Addressing sustainability challenges requires a comprehensive approach that considers social, environmental, and economic dimensions, taking into account the unique circumstances of each country. When applied, the developed indices can serve as a valuable blueprint that needs to be carefully considered and potentially adjusted to align with the specific context.

In this regard, indicators play a vital role as quantifiable benchmarks for monitoring progress towards goals, necessitating a correlation between activities and indicators to ensure an accurate evaluation of progress. It is crucial to prioritize establishing clearly defined measures and activities that align with appropriate indicators and are grounded in a comprehensive understanding of societal requirements. Such an approach can enhance the effectiveness of strategies and policies, ensuring their genuine contribution towards attaining defined strategic goals. Policymakers must prioritize substance over superficiality, emphasizing the importance of a comprehensive grasp of societal challenges and needs. Strategic decisions to arrive at a more sustainable pathway should be guided by this understanding, aligning policies with the genuine requirements of the society being served. By prioritizing the essence and ensuring alignment, policymakers can design decisions with greater impact and effectiveness. It is precisely in this context that the indices can crucially contribute by providing valuable information and empowering decision-makers.

Another important aspect is addressing the number and type of indicators employed in Germany's existing monitoring framework. It is crucial to pay attention to manageability and relevance. While adhering to the monitoring guidelines established within the GSDS, there is value in reassessing the existing indicators frequently to ensure their continued effectiveness. Additionally, exploring the possibility of removing obsolete or less relevant indicators, if feasible, can enhance the efficiency of the monitoring process.

However, this can be a challenging task as it involves analyzing the potential impact of removing an indicator on the overall assessment of progress. There is a need to carefully assess the potential consequences and implications of removing an indicator to ensure that the monitoring system remains robust and provides a comprehensive understanding of the progress towards the goals set out in the GSDS. Since the GSDS covers a wide range of aspects, removing indicators may also face challenges related to stakeholder engagement and acceptance. Different stakeholders may have vested interests in specific indicators or rely on them for their own reporting and decision-making processes. Therefore, careful consultation and collaboration with relevant stakeholders are essential to ensure that the removal of indicators is transparent, inclusive, and widely accepted.

Evaluating the existing indicator framework beyond the identified gap with respect to the 4IR is not within the scope of this work. However, it is recognized that the number of indicators should not increase indefinitely. Acknowledging this concern, the present study introduced the developed sub-indices. These sub-indices enable a comprehensive overview of sustainable development but also facilitate a more focused assessment of specific sectors. By incorporating these sub-indices, a more nuanced and sector-specific evaluation can be achieved, offering valuable insights for policymakers and researchers alike while keeping the overall monitoring system manageable.

Overall, the developed indices cannot be regarded as the final result. The ongoing technological development will constantly introduce new challenges for every concept concerning sustainable development. Thus, sustainability as a normative concept requires continuous reflection and further development. The UN SDGs are a normative directive to organize a sustainable society and to measure its transformation based on sustainable development indicators. The current transformations induced by the 4IR underline the need for an up-to-date measurement approach to accurately assess our progress and align with the aspirations outlined in the SDGs.

Conclusions

The fusion of new technologies and their interplay across the digital, physical and biological spheres, along with an accelerated pace of innovation, characterize the 4IR. These developments are enabled and fundamentally driven by introducing RES as a new energy regime. However, the effects entail implications far beyond the energy sector.

The resulting challenges for the social control of technology, known as Collingridge dilemma, illustrate the need for appropriate measurement frameworks to comprehensively assess related implications concerning sustainable development as early as possible and act with foresight. This implies that decision-makers must be enabled to recognize undesirable effects in a timely manner.

The scientific contribution of this work lies in its comprehensive analysis of the concept of the 4IR and related implications for measuring sustainable development. While the potential of technological innovations in supporting the transformation towards a green economy and achieving the SDGs is recognized, this paper highlights the challenges posed by technological advancements, particularly linked to the Collingridge dilemma. In this connection, we propose to insert digitization indicators into the GSDS as a solution.

The developed SDSDEEIS, incorporating an overall index and four sub-indices, provides valuable insights into vital aspects of successful transformation. Through the case of Germany, the article illustrates the practical application of the framework, offering new insights for decision-makers. The work highlights the need for appropriate measurement frameworks to comprehensively assess the social and environmental consequences of the 4IR. Additionally, it identifies a gap between the current status quo and the desired pathway for sustainable development in Germany, with notable differences among economic, social, and ecological sectors.

Based on the developed indices, Germany currently has achieved roughly 75% of the path towards sustainable development according to the SDG index, with an index value of 0.760. It performs best with respect to social aspects. It achieves promising results concerning the economic sector, while the digital and FEW nexus sectors perform notably worse and are at a similar, lower level of sustainable development.

Overall, this work contributes to the understanding of the 4IR by developing a measurement framework to assess its impacts on sustainable development. Based on this, directions for future studies can be derived.

As pointed out, sustainability challenges faced by countries can differ notably and need to be considered in respective capacities to address these. Especially the differences concerning innovation capabilities between developing and affluent nations need to be considered. Thus, further exploration of the specific implications of the 4IR on sustainable development in different countries and regions is required. This could involve analyzing the unique challenges and opportunities presented by 4IR-related technological advancements in various socio-economic contexts.

Moreover, future studies could examine policy interventions and governance mechanisms that can effectively guide and regulate the 4IR towards sustainable development goals. Related research could focus on identifying policy approaches, regulatory frameworks, and institutional arrangements that promote responsible innovation and ensure the equitable distribution of benefits generated during the 4IR.

In addition, insights generated by longitudinal studies that track and evaluate the progress of countries and regions in achieving sustainable development targets in the context of the 4IR are promising. Such studies could include monitoring the changes in sustainability indicators over time, assessing the effectiveness of policy interventions, and identifying best practices and lessons learned for successful transformations, not least in view of how these differ depending on the region.

These potential research directions aim to further deepen our understanding of the 4IR's impact on sustainable development and contribute to the development of suitable policies and strategies for a sustainable future.

Abbreviations

4IR	Fourth Industrial Revolution
AI	Artificial intelligence
FEW	Food–energy–water
GCI 4.0	Global Competitiveness Index 4.0
GDP	Gross Domestic Product
GSDS	German Sustainable Development Strategy
ICT	Information and Communications Technology
RES	Renewable energy sources
SDSEEIS	Sustainable Digital Socio-Economic-Ecological Indicator System
TA	Technology assessment
UN	United Nations
WEF	World Economic Forum

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Availability of data
Not applicable, there is no further data used in this study.

Declarations

Ethics approval and consent to participate
The authors declare that they have adhered to the ethical standards of research.

Consent for publication
The authors declare their consent for publication.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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