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CATCHWORD

Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization

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1 Introduction

In 2023, researchers discovered that over 90% of the rainforest carbon offset credits approved by Verra did not represent actual emissions reductions. In consequence, these carbon offset credits, i.e., certificates for reduced or sequestered emissions compensating for other emissions, were deemed worthless (Greenfield 2023; West et al. 2023). While impacting not only the economic performance of renowned customers like Gucci, Shell, and easyJet, such practices also highly undermine the credibility of carbon offsetting and other sustainability measures in general (Greenfield et al. 2023).

The issuance of fraudulent credits is a telling example of insufficient Measuring, Reporting, and Verification (MRV) processes, i.e., the processes responsible for collecting emissions data, determining and reporting the environmental impact, and verifying its validity (Bellassen and Stephan 2015). Major points of criticism are the lack of transparency of the MRV processes and the resulting information asymmetries between project developers, standard providers, and the companies buying the credits (Delacote et al. 2024; Swinfield et al. 2024). Since current MRV processes involve a lot of manual work, it is prohibitively expensive and time-consuming to conduct MRV processes frequently and in a rigorous manner (Baumüller and Sopp, 2022; Bellassen et al. 2015). Beyond the example of fraudulent credits, the lack of efficient mechanisms and the resulting high costs for MRV lead to a considerable gap of valid and accountable data in sustainability assessments in general (In et al. 2019; Kotsialou et al. 2022; Leinauer et al. 2024). The growing need for transparency regarding the sustainability of business practices and the corresponding need to exchange sustainability information within and between organizations is becoming increasingly important due to regulatory initiatives and market preferences (Fassnacht et al. 2024; Pfeiffer et al. 2024). Accordingly, the focus is increasingly shifting to advancing MRV processes as they represent an important instrument to ensure reliable disclosure of sustainability measures (Körner et al. 2023b). Consequently, current MRV practices are being developed further to facilitate reliable and robust decarbonization management without overburdening administrative efforts. Since these initiatives often focus on emissions, credible *decarbonization* activities are the starting point and driver of a rapid adoption of manifold MRV processes.

Information systems and digital technologies provide essential opportunities to enhance MRV processes: This transformation of current MRV practices starts with the digitalization of individual MRV processes, with the ultimate objective of achieving end-to-end digitalized MRV,

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where all MRV-related practices are closely integrated by leveraging digital artifacts and concepts. However, the current discourse on digitalizing existing MRV processes and designing new digital MRV processes from scratch is still primarily dominated by gray literature and practical innovations from startups. Although some Business Information Systems Engineering (BISE) streams partly address current real-world problems in the context of MRV, existing literature often focuses on specific aspects of a single MRV process (e.g., related to measuring (Arsiwala et al. 2023)), without taking a more holistic perspective on the MRV system, i.e., the previous and subsequent processes. From a digitalization perspective, MRV processes should be looked at in their entirety to enhance data measuring, reporting, and verification in the context of decarbonization.

As we will outline by focusing on decarbonization, the BISE community can significantly contribute to a successful transformation from current MRV practices to end-to-end digitalized MRV processes. The BISE community may, among other things, focus on the correct representation of real-world instantiations through collected data (i.e., primary data), the environmental impact assessment of these data, as well as the transparency of pricing mechanisms and internalization of environmental costs (Püchel et al. 2024). BISE research can, in particular, address relevant challenges related to the collection and handling of emission-related primary data by digitalizing existing and designing new MRV processes through the application of suitable digital technologies and concepts. Examples include Artificial Intelligence (AI) (e.g., Schoormann et al. 2023), Distributed Ledger Technologies (DLT) (e.g., Adams et al. 2018), digital identity management (e.g., Körner et al. 2023b), and data ecosystems (e.g., Corbett et al. 2020). Resulting research insights may improve MRV, e.g., by increasing efficiency through automated emission allocations and assessments (Nishant et al. 2020).

BISE could also benefit from applying insights from digital Measuring, Reporting, and Verification (dMRV) to tackle current challenges. A dMRV perspective promises to help, for example, in dealing with multiple sources of truth and managing conflicting data requirements, such as reporting sustainability information to different stakeholders. Existing research streams in *digital sustainability*, and particularly in *Green IS*, address MRV issues through the adoption of digital artifacts and offer significant insights for this emerging field. Examples include research in *digital carbon accounting* (e.g., Körner et al. 2023b), *energy informatics* (e.g., Babel et al. 2022), and *environmental management information systems* (e.g., Corbett 2013). To drive the digitalization of MRV practices with a holistic view on the entire MRV ecosystem, we propose '*digital Measuring, Reporting, and Verification (dMRV) for decarbonization*' as an interesting research stream for BISE.

To shed light on this emerging research stream, we outline the characteristics of current MRV processes and the development toward fully digitalized systems. We then highlight the key role BISE research plays in advancing MRV. Finally, we provide directions for BISE research, encouraging our community to contribute to this field that is rapidly gaining importance for industry and research.

2 Measuring, Reporting, and Verification (MRV) Processes

MRV is a key instrument for implementing and regulating decarbonization activities. MRV processes, respectively, the MRV system, encompass 1) measuring and monitoring of data, 2) reporting it to a specific system, and 3) verifying the accuracy of the reported data. In the subsequent paragraphs, we explain these processes in more detail and provide an overview of current MRV practices (cf. Fig. 1).

First, there are *Measuring* or *Monitoring (M)* processes. While the latter notion is probably used more often in the context of MRV, the activities in this process are currently mostly focused on measuring (i.e., collecting data to assess the carbon emissions or other relevant climate impacts of a project, company, or similar). Hence, in the following, we refer to these processes as measuring. For environmental or, more specifically, emission assessments, this process may include direct physical measurement of carbon emissions or calculation thereof based on primary data and conversion factors. The underlying methodology of environmental measuring is the Life Cycle Assessment (LCA) (Finkbeiner et al. 2006). In the impact assessment of LCAs, directly measured primary data (e.g., the kilograms of biochar produced), conversion factors (e.g., the amount of carbon emissions that 1 kg of biochar can sequester), and data from other sources (i.e., secondary data) are taken into account to calculate the allocated carbon emission equivalents (Bellassen and Stephan 2015). Even though there is extensive research, especially in the field of LCA and corresponding LCA methodologies, on how to appropriately allocate emissions, many challenges remain at the data level, as illustrated in Fig. 1. In current measuring practices, companies responsible for the process predominantly collect, store, and transfer primary data for environmental assessments manually (Olczak et al. 2022; Tang et al. 2018). This includes, among other things, manually reading meter values and typing them into spreadsheets to take account of the environmental impact of business activities. In the case of a rainforest offset project, the manual data collection mostly refers to on-site inspections. Due to this high share of manual measuring processes, the

Current Practices and Exemplary Challenges of MRV

- Manual **collection, assessment, and transfer** of data and resulting (emission) information (e.g., on emissions reductions through reforestation projects)
- Error- and manipulation-prone, time-consuming **measuring** processes leading to heterogeneous, outdated, or incorrect data (e.g., double counting of emissions reductions through errors due to manual processes)
- Repeating and complex **reporting** processes given the plethora of different use cases (e.g., different standards, such as Verified Carbon Standard, Gold Standard, and more in the case of Voluntary Carbon Markets)
- Inconsistent data management processes and media disruptions impede end-to-end traceability and **verification** (e.g., from a reforestation project area to the end-consumer of offset certificates)

Fig. 1 Current practices and challenges of MRV

primary data are not only error-prone, but it is also very time- and cost-consuming to collect data on a regular, timely basis (e.g., in the sense of real-time measuring). These practices not only lead to the use of estimates or average values as a data basis (e.g., the annual energy consumption of a process) but also different degrees of data granularity in comparison to technical and economic process and product data. When considering an entire value chain, this also results in inferior data quality in databases, which in turn are used as secondary data in other LCAs.

Second, there is *Reporting (R)*, which involves aggregating the data obtained during the measuring process into inventories and other standardized formats and the communication of the resulting information to the relevant authorities (e.g., regulators) (Bellassen and Stephan 2015). Reporting aims to disclose the measurement and assessment information for subsequent verification but also to make the information publicly accessible to a wide range of users. Even though this process lays the foundation for the verification of the reported data and resulting assessments (e.g., global warming potential, carbon sequestration), the reporting itself phases challenges due to the fast development of reporting standards, such as the Verified Carbon Standard, Gold Standard, and several other existing or emerging standards in Voluntary Carbon Markets (VCMs) (cf. Fig. 1). For mandatory corporate reports like those specified in the Corporate Sustainable Reporting Directive (CSRD), the aggregation across different, internationally located sites, as well as the application of a multitude of different reporting standards depending on country and markets, leads to extensive efforts. This is mostly due to a lack of standardized business processes to manage environmental data or, respectively, conventional technical process data (Krasikov and Legner 2023; Müller et al. 2023; Püchel et al. 2024). Although, for example, current ERP systems as well as software for LCA calculation and sustainability accounting already help to capture data, concisely model and implement environmental assessments, there is often a lack of traceability (e.g., regarding the consistency of the data input or the aggregation of different data sources) and flexibility to re-use data for different regulatory and economic purposes (e.g., environmental due diligence or risk management) (Babel et al. 2024; Backer et al. 2023; Körner et al. 2023a). The reporting schemes of VCMs face similar issues with the addition of regulative uncertainty regarding the applicability of the standards for buyers as well as the risk of 'double reporting' (Kreibich and Hermwille 2021).

Verification (V) is usually conducted by a third party (i.e., a party not involved in measuring and reporting) and reviews the compliance of the reported data and their collection process with the relevant guidelines (Bellassen and Stephan 2015). It entails subjecting the reported data and assessment information to independent analysis to establish its completeness and reliability but also to discover errors and other deficiencies. Verification may, for example, include assessing evidence that emissions reductions from reforestation projects are legitimate, and is crucial to ensure the accuracy and credibility of the reported data and resulting key figures (Bellassen and Stephan 2015). However, current verification practices – either in the realm of mandatory or voluntary activities – require improvement concerning (cost-)efficiency, periodicity, and credibility. Like the data collection of the measuring process, the verification of data and its environmental assessment still rely mainly on manual approaches (e.g., the manual screening of project reports and other relevant documentation related to rainforest projects) (Kotsialou et al. 2022). These processes include, for example, manual inspection of data using the dual control principle (i.e., at least two auditors reviewing the data) to ensure a high probability of discovering errors. The efforts due to manual reviewing processes may also be the reason why the verification process itself is carried out mostly on a yearly basis with verification processes lasting up to several weeks and months (Passer et al. 2015). Hence, the verification processes conducted in large time intervals may, in combination with the media disruptions illustrated in Fig. 1 that occur within and between Measuring, Reporting, and Verification processes, significantly contribute to a lack of confidence in current MRV practices.

MRV are fundamental processes for mandatory and voluntary decarbonization instruments to ensure that emission reports, reductions, or removals are legitimate. With respect to *mandatory instruments*, MRV processes help public authorities to ensure companies' compliance, while in voluntary applications, they ensure the veracity of information and trust in the legitimacy of the respective real-world activity, supervised mostly by non-governmental organizations. The demand for companies to actively partake and conduct MRV has tremendously increased in recent years. Especially in the context of achieving a certain net-zero target (e.g., the European Union (EU) by 2050), politicians have driven forward a variety of new regulations requiring companies to report and manage the emissions from their own activities or those in their value chain (Babel et al. 2024) – e.g., the CSRD, the Corporate Sustainability Due Diligence Directive, the Carbon Border Adjustment Mechanism, the EU taxonomy, or Emissions Trading Systems (ETSs) in multiple countries. The CSRD is one of the regulations that has the most far-reaching effects on the quantity and quality of mandatory conducted MRV processes by companies. It aims at increasing transparency and accountability via a reporting obligation on corporate financial opportunities and risks stemming from environmental as well as other sustainability aspects (European Parliament and the Council 2022). Consequently, companies must detail how environmental factors impact their finances (financial materiality) and how their operations affect the environment (impact or stakeholder materiality) (Delgado-Ceballos et al. 2023). Not only the standardized way in which companies have to provide this information but also the increasing assurance requirements result in companies having to establish MRV for a large amount of new data. The CSRD also broadens the scope to small and medium-sized enterprises, which are affected directly or indirectly (as buyers or suppliers) and must manage environmental information responsibly via MRV processes.

In addition to implementing MRV processes as required by regulations and mandatory standards, companies may participate in voluntary schemes and reporting standards to reach postulated decarbonization objectives and/or disclose further environmental information on their business activities. One of the most prominent voluntary schemes that rely heavily on functioning MRV processes are Voluntary Carbon Markets (VCMs). VCMs allow emitters to voluntarily offset their emissions by purchasing carbon (offset) credits which are generated from projects designed to remove or reduce Greenhouse Gas (GHG) emissions from the atmosphere (Kreibich and Hermwille 2021). Instead of public authorities, companies like Gold Standard or Verra provide the framework and set up the MRV system for generating and trading carbon credits from these offset projects as well as ensuring their validity (Ahonen et al. 2022). However, media and researchers have criticized these frameworks and underlying MRV processes for failing to adequately reduce information asymmetries between projects and credit buyers, leading to a lack of transparency and credibility that has resulted in scandals like the previously mentioned Verra case (Delacote et al. 2024; Kreibich and Hermwille 2021; West et al. 2023). These credibility issues with VCMs, along with a growing lack of trust in voluntary carbon reduction schemes and extremely low prices for carbon credits – compared to ETS certificates –, have raised serious concerns among various stakeholders (e.g., policymakers, companies, and customers). Against this background, MRV processes need to rapidly be improved to ground decarbonization activities on valid and accountable information while also reducing the prohibitively high costs of conducting them.

We argue that the exemplary shortcomings of MRV processes in voluntary and mandatory applications outlined above call for a critical examination of current MRV practices and frameworks. Efforts to address these issues should focus on increasing transparency, ensuring rigorous verification processes, and establishing mechanisms that allow for efficient MRV processes given the increasing demand for environmental information and that restore confidence in the MRV system. As we outline in the next section, we see an incremental value and various levels for digitalization to structurally enhance MRV processes.

3 Digitalization of MRV: Introducing dMRV for Decarbonization

Against the background of challenges such as credibility issues and driven by various start-ups a few years ago, companies, politicians, and occasionally also scholars have started to analyze how digitalization may enhance the individual parts of M(easuring), R(eporting), and

V(erification) (e.g., Belenky et al. 2023; Körner et al. 2023b; Olczak et al. 2022; Tang et al. 2018; Woo et al. 2021). This strongly recognizable trend of advancing the MRV field goes hand in hand with the increasing importance of robust MRV processes in the light of decarbonization efforts. We argue that the objective of dMRV for decarbonization could be an end-to-end digitalized MRV, i.e., digital measuring, reporting, and verification processes at all stages in a value chain on the basis of interlinked information systems. These transformation processes induce significant changes and, as a consequence, raise a wide range of research questions for BISE researchers. Given the vision of an end-to-end digitalization in the MRV context, we define *dMRV for decarbonization* as a research stream that addresses *the interrelation of Information Systems with Measuring, Reporting, and Verification processes as well as the MRV concept as a whole*. In the following, we outline the specific attributes that characterize the digitalization of Measuring, Reporting, and Verification processes (cf. Fig. 2) and how the analysis of an end-to-end digitalization approach for MRV can shape a rising field of BISE research.

Digital Measuring is strongly influenced by a high demand for 'better' data and, therefore, among others, characterized by collecting, storing, and transferring primary data in an automated manner. Often motivated by reporting requirements, the data points collected increase in their granularity and accuracy (e.g., an increased number of data points measured in a specific period) (Melville et al. 2017). Drawing on the example of Verra (cf. Sect. 1), more data points on reforestation projects (e.g., the precise location of project areas, the health of the forest, and the type and amount of trees) could significantly improve data quality and, for example, reduce double counting and overestimation of emissions offsets. As illustrated in Fig. 2, a promising means to receive accurate and fine-granular data efficiently is the digital automation of capturing and processing primary data (e.g., by interconnected smart sensors to measure soil conditions or remote sensing to measure vegetation changes) (Khatua et al. 2020; Körner et al. 2023b). Regarding the disclosure of environmental information in the light of the CSRD (cf. Sect. 2), especially for Scope 2 assessments (i.e., purchased energy according to the Greenhouse Gas Protocol), energy consumption data are already digitally collected close to real-time (e.g., in units of seconds) and with increasing spatial accuracy as well (e.g., at one specific production line) (Tranberg et al. 2019). Such improved data collection processes (e.g., via IoT devices that collect data through sensors and software (Nižetić et al. 2020)) lay the foundation for effectively reporting specific product carbon footprints and identifying steering measures to reduce these carbon footprints by offering more precise and timely data in an automated manner. Hence, digital data collection can not only help fulfill CSRD requirements, but also enable carbon-adaptive decision-making (Babel et al. 2024). Combined approaches (e.g., where the automated digital data collection is connected to other BISE-based approaches like learning algorithms to increase the accuracy of the data assessment)

Characteristics and Exemplary Opportunities of End-to-End Digitalized MRV

- Automated data **collection, assessment, and transfer** of data and resulting (emission) information within and beyond organizational boundaries (e.g., verifiable end-to-end data flows from project areas to end-consumers)
- Increasing data quality through digital **measuring** processes (e.g., regarding granularity, accuracy, immutability of emissions reductions data based on IoT sensor data)
- Reduction of information asymmetries through seamless digital **reporting** processes (e.g., prevention of prohibitively high MRV costs for carbon offsets)
- Digital (bilateral) **verification** processes with seamless process interfaces and digital consistency (e.g., more credible auditing mechanisms in emissions offset projects to enhance trust in Voluntary Carbon Markets)
- Close integration of the three MRV processes at all relevant stakeholders to a **cohesive system** reducing the risks of media disruptions, errors, and manipulation while simultaneously increasing efficiency

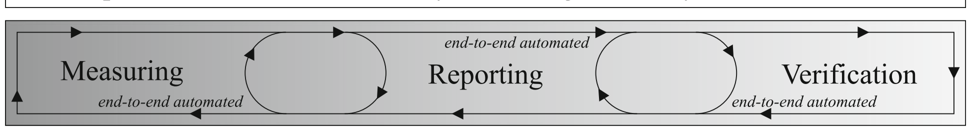

Fig. 2 Characteristics of end-to-end digitalized MRV

become a more and more relevant offer by start-ups, especially in the context of VCMs. Examples include the use of satellite images in combination with AI to monitor rainforest stock in a spatial and temporal more fine-grained manner (Albo Climate 2022; Uforest 2022). Additionally, the data models and standards developed for monitoring and measuring can be seamlessly integrated for serving multiple demands and reporting purposes in a company or value chain (e.g., the mandatory CSRD and voluntary carbon credit trading). Hence, primary data on decarbonization must be available in such a way that it may be applied flexibly for different assessments and allocations – depending on the regulations and demands for processing. The use of emissions data in different contexts and their often necessary integration with other data (e.g., financial) further requires more comprehensive data visualization and modeling. Through seamless integration and resulting end-to-end automation of data collection and processing, the efficiency of applying an entire MRV framework can be substantially elevated. In addition, this development might lay the ground for an emerging quality shift from measurement to monitoring to integrated sustainability management.

Digital Reporting can include the processing of primary and secondary data to environmental information, as well as the calculation and allocation models behind it. Accordingly, the digitalization of reporting activities entails new opportunities for creating accountability and transparency: Digital reporting – in combination with the digital verification processes illustrated subsequently – changes which data, data models, data processing, and resulting information are reported to auditors, which data are disclosed open to the public, and which data remain with the company. In light of the Verra example, this may include reporting not only whether carbon offsets have been utilized on the balance sheet but also providing comprehensive information about concrete measures, such as the issuer of credits, the project area, and the allocation methods used. This can reduce information asymmetries, as exemplified in Fig. 2. Additionally, reporting on environmental aspects, especially in the context of CSRD, is increasingly interconnected with financial reporting. This interconnection requires the integration of information systems for cross-departmental data flows. To be able to allocate financial key figures to emission key figures, relevant data collection and processing points have to be integrated into existing information systems, respectively, these information systems have to be expanded. The increasingly complex reporting task can be supported by digital tools and algorithms (e.g., for the automated creation of reports). Not only does the consideration of sustainability aspects besides finances in reports (for and after verification) lead to new approaches and opportunities for our BISE community, but also the increasing extension to considering the entire or at least large parts of a value chain. Thus, information from reports of preceding or subsequent companies and products (i.e., inter-organizational data sharing in the sense of Abraham et al. 2019) plays a vital role in the sustainability assessment of a company (e.g., in terms of Scope 3 assessment): Inter-organizational interfaces enable the utilization of reporting outputs as verifiable data inputs for other reporting purposes. In VCMs, digital reporting may solve the issue of 'double reporting' mentioned above, e.g., through algorithms to solve conflicts if different sources report conflicting data (Kotsialou et al. 2022). So far, existing information systems (e.g., ERP systems and LCA software, cf. Sect. 2) fall short of enabling a robust reporting of emissions data and BISE research (e.g., in Environmental Management Information Systems) focuses mostly on measuring energy and/or emissions data taking an intra-organizational perspective (cf. Sect. 1) (Corbett 2013; Krasikov and Legner 2023; Luo and Tang 2016; Stindt et al. 2014; Zampou et al. 2022). Against this background, our community could benefit from including an inter-organizational perspective that has not been widely considered in the context of environmental reporting so far (Ströher et al. 2025). Among other things, an inter-organizational perspective raises questions for BISE research about how reports and relevant key figures are passed down the value chain and enter and leave the individual company's information systems (Jensen et al. 2023). In this context, data ecosystems may facilitate seamless data sharing and integration between various stakeholders (e.g., land owners, carbon credit issuers, and end-consumers) by explicitly assigning and modeling distinct data-sharing rights for an enhanced reporting of environmental information (e.g., on reforestation projects).

Digital Verification is, among others, defined by ensuring that claims about the sustainability information collected and reported in the previous processes are legitimate. As mentioned before, currently, manual verification is typically carried out by third parties. This results in trust issues since the verification depends on assessing a single entity based on criteria that often lack transparency (cf. recent scandals). Digital technologies, such as DLT or digital identity management, may offer opportunities to reduce uncertainty regarding the accuracy and veracity of sustainability information and the verification process itself, thereby increasing transparency. With regard to the Verra case, for example, this can enable not only buyers of carbon credits, but also the general public, to trace the way from these credits to the project areas end-to-end based on verifiable (primary) data. Further, implementing digital end-to-end approaches can enable bilateral verifications without institutional intermediaries. Against the background of the expected dramatic increase in data that have to be verified both for reports like according to the CSRD and credits claimed in VCMs, this could lead to a reduction of complexity and, consequently, to a decrease in transaction costs associated with the verification processes. Digital identity paradigms such as Self-Sovereign Identity (SSI) aim at enabling a secure identification, authentication, and authorization of individuals, companies, and machines, thereby facilitating the verification of the origin of data and enabling chains of trust along supply chains (Preukschat and Reed 2021; Sedlmeir et al. 2021). Digital identity management may, especially in combination with privacy-enhancing technologies such as Zero Knowledge Proofs (ZKPs), increase the data sovereignty of participants in (digital) verification processes along value chains. Implemented SSI paradigms in combination with other emerging technologies such as DLT may further develop the current verification business by changing the role of the third party currently responsible for examining and validating the previously reported information (Glöckler et al. 2023; Lemieux et al. 2021). Web3 technologies, in particular, can prevent double-counting and double-spending related to sustainability information (e.g., regarding the accounting of emissions or invalidation of emissions reduction certificates). For example, DLT (e.g., blockchain) can serve as an open and decentralized registry for transactions and have already illustrated to be able to provide more transparency and address the issue of double-counting and double-spending in different use cases (Kakarott et al. 2021; Parra Moyano and Ross 2017). DLT and similar technologies also offer further characteristics that may influence how information is verified between parties: With systems that maintain an immutable record of transactions and allow for tracing each change, the validity of data within such a system can be inspected more efficient by third-party verifiers and auditors than having to inspect a multitude of different information systems and tools and the data transfer between them (cf. Fig. 2). The design and deployment of such digital verification mechanisms represent a promising area for research. However, the challenges arising from deploying DLT such as a verifiable integration of external data (i.e., oracle problem) and the appropriate trade-off with data privacy issues should be addressed by the BISE community as well to maintain and enhance trust in the system (Hawlitschek et al. 2018; Mohanta et al. 2019; Parmentola et al. 2022). This is particularly relevant in decentralized architectures, where intermediaries are absent and trust is shifted towards the edges of the system. Data ecosystems may play a central role in ensuring trust by enabling a bilateral verification between different parties and the subsequent sharing of respective proofs (e.g., via DLT).

In addition to enhancing the three processes of MRV (i.e., *Digital Measuring*, *Digital Reporting*, and *Digital Verification*) individually, we also argue for researching the digitalization of MRV as a whole that may result in a much stronger interconnection of the individual processes that allows for a more cyclic and iterative procedure within and between the Measuring, Reporting, and Verification processes (e.g., through reporting verifiable data), as illustrated in Fig. 2. This entails that new concepts such as data spaces may facilitate efficient data collection and sharing along entire value chains (Otto et al. 2022) – and, thus, even changing the established sequence of 1) measuring, 2) reporting, and 3) verification. For instance, in the electricity sector, the use of smart meters has shown promise in measuring primary data for carbon information to allocate the environmental impact of electricity consumption more precisely than current guarantees of origin and, thus, lay the foundation for direct and verifiable data sharing of Scope 2 emission assessments for the CSRD (Babel et al. 2023). In such cases, a (near) real-time measuring of verified data (M) via digital identity approaches could be directly followed by an automated and verified impact assessment (V), for example to enable more credible and efficient voluntary carbon markets through faster and more reliable end-to-end verification of carbon credits. Moreover, end-to-end digitalized MRV systems may allow for sectors and carbon emissions sources to participate in carbon credit markets (e.g., VCMs) that are currently not capable of doing so due to a lack of trustworthiness (Woo et al. 2020). Hence, the close application of insights from processes with newly developed MRV concepts may enable new business models and foster investments in verified sustainability measures. Overall, information systems and digital technologies offer tremendous potential to tackle challenges related to all areas of today's MRV practices and, thereby, change the basic principles of the current processes. By leveraging advanced technologies and paradigms, markets and companies could transition toward end-to-end digitalized MRV processes.

4 Directions for BISE Research and Conclusion

A plethora of highly relevant research questions results from addressing current real-world problems of MRV. BISE research may provide valuable contributions by designing digital artifacts and analyzing their role in advancing MRV. Figure 3 gives an overview of future research potentials that subsume many interesting future BISE research questions in the context of dMRV. For each research dimension, we provide one concrete example for further investigation. Our overview of BISE research potentials encompasses the ongoing digital transformation

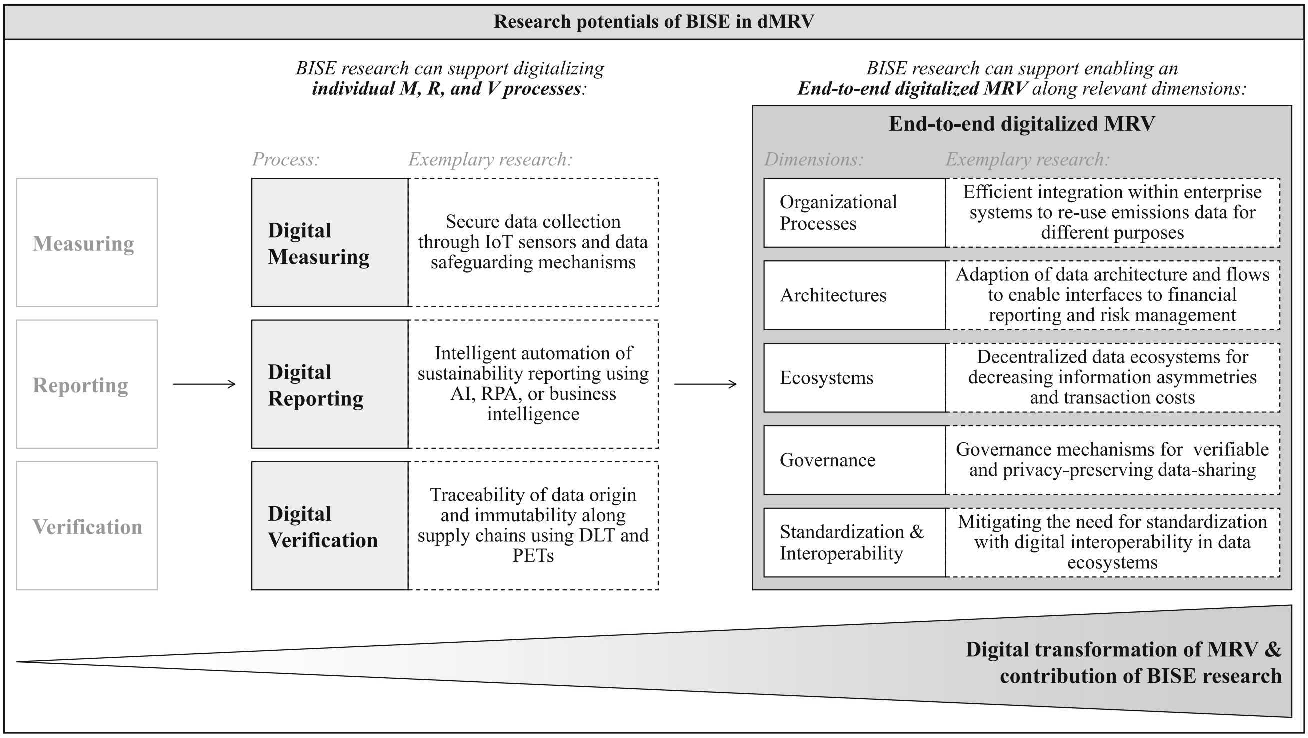

Fig. 3 Research potential of BISE in dMRV

from a more process-specific perspective (i.e., related to the single MRV processes) toward a broader systemic perspective (i.e., entire MRV systems). Especially the step from solely digitalizing individual MRV processes up to taking an integrated and systematic view on dMRV may profit substantially from existing BISE research. BISE researchers could contribute with exemplary research that mainly addresses the developments of the inner workings of organizations (e.g., their organizational processes) up the integration of an external perspective that focuses on the value chain and how organizations interact and exchange data (e.g., in ecosystems). To fully realize the potential of dMRV, these two perspectives are equally important as dMRV encompasses both. We identify five dimensions for exemplary research within and beyond organizational boundaries that contribute to an end-to-end digitalized MRV system.

For the already ongoing digitalization of individual Measuring, Reporting, and Verification (MRV) processes, BISE researchers can, first, contribute to establishing high-quality databases in the *measuring* process. BISE research may use insights from information systems engineering to securely make emissions data available, e.g., via IoT technology (cf. Sect. 3). With regard to the Verra example, BISE research could, for example, develop frameworks to collect fine-granular data on emissions reductions through reforestation projects in a scalable and secure manner. Second, especially regulations like the CSRD require the *reporting* of an increasing amount of emission and similar primary data, as well as that of the resulting environmental information with increasing demands on data quality and validity (e.g., transparency on its origin, see also Püchel et al. 2024). Against this background, BISE can, for example, support sustainability reporting by automating it (e.g., by applying AI, Robotic Process Automation (RPA), or advancing existing business intelligence). This would not only result in efficiency gains but also allow for the flexible generation of different reports (e.g., for different standards that may include or exclude the recognition of emissions offsets from VCMs). Third, since potential misappropriation of shared data may also impede data sharing, the integration of privacy-preserving mechanisms for bilateral data exchange and *verification* could be a promising research subject (Opriel et al. 2024). Thus, novel BISE research can aim to fulfill the requirements on verifiable data, e.g., based on DLT and Privacy Enhancing Technology (PET).

From an end-to-end digitalized MRV perspective, BISE researchers can address how information systems enable efficient *organizational processes*. Research questions may address how existing or new business information systems add value to organizational MRV processes and the underlying business processes. For example, BISE research ought to learn how enterprise information systems should be advanced by adding layers and interfaces that increase data quality and availability. Especially the development of design requirements and ideas for integrated enterprise systems to decrease costs from (emissions) data measuring and reporting when handling increased amounts of data may be valuable (e.g., by integrating IoT data with ERP systems, see also Sunyaev et al. 2023). Elaborated decision support systems (e.g., textual analysis tools to classify sustainability information, see also Maibaum et al. 2024) and frameworks (e.g., supporting the integration of data sources and models, see also Reefke and Sundaram 2018) may be applied to MRV processes. Focusing on such digital solutions creates the foundation for BISE researchers to further learn how complex emissions data flows can be incorporated in various business processes and what tensions and consequences from introducing digital technologies for MRV have to be managed by companies (see also Schoormann et al. 2025).

As VCMs and similar marketplaces emerge, the design of carbon markets should be further developed with appropriate digital *architectures* in mind that ensure compliance and efficiency. Among others, BISE researchers can contribute to the advancement of mandatory and voluntary MRV frameworks by providing data architectures for MRV processes to align them with state-of-the-art information systems. Since MRV processes are increasing in complexity and the number of stakeholders involved, we also encourage BISE research to identify data requirements, define standardized data models and semantics, and suggest appropriate data architectures to help the harmonization of data from different sources (see also Krasikov and Legner 2023, Püchel et al. 2024, and Wang et al. 2024). With the increasing relevance of environmental information as a risk factor (Körner et al. 2023b), research on improving data sourcing for sustainability is essential to allow for economically assessing and tracing these risks in a valid manner. In this context, researchers can also address how novel concepts of digital data verification (e.g., SSI) may be integrated into existing architectures to enhance identification and access management in MRV systems.

The processes in an MRV system rely heavily on appropriate data-sharing mechanisms between different stakeholders involved in measuring, assessing, and verifying emissions data. Thus, to address the existing problem of information asymmetries, BISE researchers ought to study the application of decentralized data *ecosystems* as a promising approach to ensure greater transparency, thereby decreasing these asymmetries (Jetzek 2017; Otto et al. 2022; Scheider et al. 2023). In this context, BISE researchers may take a closer look at the design, the governance mechanisms, and value co-creation within data ecosystems for dMRV for decarbonization and learn how to share emissions data in a transparent, verifiable, and yet privacy-preserving manner. Furthermore, organizations often do not know their specific data needs and the economic value of their data and potential data-sharing activities (Jussen et al. 2024). Consequently, BISE researchers can provide guidance to identify these data needs in the context of decarbonization and help quantify the economic incentives for participating in data-sharing activities within a data ecosystem. Moreover, investigating the effective operation of data ecosystems and the change in transaction costs (e.g., for VCMs) could constitute a crucial research focus. In particular, digital artifacts in the context of data ecosystems in combination with Web3 technologies and their properties of data immutability and traceability of transactions may be applied to MRV processes in VCMs and increase trust in VCM mechanisms. By transferring digital concepts that realize new technical trust paradigms to MRV processes (e.g., provided by start-ups), BISE research may, among others, learn how to leverage and design specific interfaces between digital technologies.

As the emergence of new digital concepts and ecosystems is progressing and upcoming reporting and market requirements (e.g., the Carbon Border Adjustment Mechanism (CBAM)) lead to an exponential growth of the amount of information to be handled by organizations and public institutions, a plethora of *governance* questions have to be answered. Given the close interlink of private and public institutions for many MRV use cases, BISE research should scrutinize how the different interests of these stakeholders can be integrated in the development of dMRV solutions and how different responsibilities are allocated and determined. This might include answering who can change the rules in multi-stakeholder ecosystems with potentially highly differing data needs and interests and who operates and maintains developed dMRV solutions. BISE researchers may give guidance on who should own and control the collected data and how public and private stakeholders can realize corresponding access mechanisms with the help of PETs. For example, when adopting and further developing digital concepts like SSI and ZKPs to increase trust and data sovereignty for active participants in the MRV system, BISE research may learn how existing prescribed regulatory governance mechanisms (i.e., from different mandatory and voluntary instruments) should be integrated or how ecosystems would benefit from adapting existing governance mechanisms. For standard providers like Verra, further developments of their standards and processes may not only include new privacy-preserving data sharing but also changes in the roles of the stakeholders and their influence on the workings of these voluntary schemes.

Closely related to governance questions is exemplary dMRV research regarding *standardization and interoperability*. Taking an internal organizational perspective, primary data and resulting environmental information are the basis for various disclosure and decision-making activities of a company. Complex data flows and corresponding information systems have to be integrated with a plethora of existing systems. Thus, BISE research can elaborate on how to ensure the interoperability of existing information systems like ERP systems and LCA software with new dMRV solutions so that a consistent and verifiable data flow – from the initial data collection to its verification and disclosure – can be realized. But not only is the interoperability with existing information systems and organizational processes an interesting research topic for BISE: Inter-organizational interoperability and standardization play a crucial role in enabling seamless data exchange across companies, regulatory bodies, and other public and private stakeholders involved in MRV processes (Ströher et al. 2025). BISE research should also explore where standardized data formats, interfaces, and communication protocols can facilitate efficient and trustworthy data sharing and where designing interoperable building blocks better fosters the development of dMRV solutions. The need for interoperable, digital solutions in the context of MRV especially arises given industry-specific data and identification standards that result in inconsistencies and redundancies in current MRV practices along complex value chains. Both developing and improving the existing standards with insights from BISE research as well as investigating the interoperability aspects can contribute to the development of scalable dMRV ecosystems.

BISE research should further incorporate exemplary research from the five presented research dimensions toward end-to-end digitalized MRV. One prominent use case integrating a plethora of research questions and perspectives for dMRV for decarbonization is the Digital Product Passport (DPP). According to the EU Ecodesign for Sustainable Products Regulation, the DPP is defined as an instrument that aims at enabling circularity by making life-cycle data related to specific products (e.g., regarding maintenance and environmental impact) related to specific products available for multiple stakeholders (e.g., suppliers, consumers, recyclers) (Jensen et al. 2023). Even if the concept of a DPP has already been introduced through this EU regulation, for many sectors the way in which product-specific data is passed on in the value chain using the so-called DPP – a digital artifact similar to a type of data container – is still being developed (Heeß et al. 2024). Consequently, BISE research could provide guidance on the design of DPPs and the underlying processes but also on related monetization and governance questions. For example, the DPP may function as a central anchor for decentralized data sharing on technical, environmental, and social due diligence information (Voulgaridis et al. 2024). As such, BISE research should explore how organizations can collect and transfer relevant data to a DPP in a rigorous and efficient manner as well as how organizations access relevant data from other organizations in the supply chain via the DPP. Exemplary research questions may include: 'How can DPPs be designed to enhance the measuring and verification of ESG and technical properties in a supply chain?' or 'How do organizational processes (need to) change between different organizations as well as within business units, such as finance, sales, and procurement, to enable and integrate DPPs?'. BISE research can also address the role, design, and financing models of the necessary digital infrastructure to facilitate DPPs, e.g., whether a digital product identification registry should be the responsibility of public or private institutions or whether such a registry should be centrally or decentrally organized. Since new data will be provided and utilized by stakeholders within a DPP ecosystem in the future, it is also a relevant research topic for BISE to examine how this data is monetized and how its provision is financed within different and complex value chains.

To sum up, this article highlights the relevant contribution of integrated, robust processes to ensure the credibility and trust of stakeholders in decarbonization efforts as well as the potential of end-to-end digitalized MRV related to sustainability data in general. The integration of new technologies and concepts from BISE research offers immense potential to improve the efficiency and effectiveness of MRV and addresses prevailing challenges, such as the handling of environmental data for organizational reporting. The research stream of dMRV for decarbonization is particularly well-suited for analyzing new opportunities and problem-solving capabilities resulting from the interaction of information systems with 'traditional' MRV processes. For BISE research, the opportunity further opens up to get 'before the wave', as start-ups, in particular, have been the drivers for dMRV for decarbonization to date and are designing a plethora of new digital concepts many of which have not yet been discussed in the BISE community. dMRV for decarbonization takes an integrated approach to developing digital artifacts for MRV processes, considering the related economic and regulatory aspects, as well as market requirements from customers. As such, dMRV research topics deal bottom-up with the availability of verifiable, fine-granular environmental data by utilizing these data for transparent environmental and economic assessments. While the development of end-to-end digitalized MRV is currently primarily focused on decarbonization and emissions data, the fundamental principles and research objectives of dMRV also extend to the entire realm of sustainability. Considering the large potential we perceive in exploring related application areas of dMRV, BISE research can make a significant contribution to future processes where organizations need to collect primary data, assess their sustainability- and business-related value as well as share and verify data for a plethora of mandatory and voluntary application areas. Hence, we urge scholars to systematically link research contributions originating from BISE (e.g., automated data collection, data governance, data sharing and processing, or digital identity management), in a targeted manner to relevant research questions surrounding MRV for boosting sustainability initiatives on a global scale. Finally, the BISE community can gain valuable insights from dMRV and contribute significant knowledge to other research streams.

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