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Research article

Unveiling the nexus of digital conversion and clean energy: An ISM-MICMAC and DEMATEL perspective

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Abstract: Our aim is to develop a hierarchical framework that assesses the interdependence of digital metrics impacting clean energy in the European energy market. The framework is evaluated to determine its applicability to clean energy and implementation. We utilize a taxonomy of digital metrics with the MICMAC ("Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement") methodology and a questionnaire-based survey using DEMATEL to validate the framework. This results in an efficient hierarchy and contextual relationship between key metrics in the European energy industry. We investigate and simulate ten key metrics of digital conversion for clean energy in the energy domain, identifying the most significant effects, including the "decision-making process" the "sustainable value chain" the "sustainable supply chain", "sustainable product life cycle", and the "interconnection of diverse equipment". The MICMAC methodology is used to classify these parameters for a better understanding of their structure, and DEMATEL is employed to examine cause-and-effect relationships and linkages. The practical implications of this framework can assist institutions, experts, and academics in forecasting essential metrics and can complement existing studies on digital conversion and clean energy. By prioritizing these key parameters, improvements in convenience, efficiency, and the reduction of product fossilization can be achieved. The value and originality of this study lie in the novel advancements in analyzing digital conversion metrics in the European energy industry using a cohesive ISM, MICMAC, and DEMATEL framework.

Keywords: digital conversion; clean energy; ISM; MICMAC; DEMATEL

Abbreviations: AI: Artificial Intelligence; DEMATEL: Decision-making trial and evaluation laboratory; DR: Driving power; DRSM: Direct relative severity matrix; FRM: Final reachability matrix; IGID: Increased grid imbalances and disparities; INC: Interconnection of various portfolio typologies; IoT: Internet of Things; IRM: Initial reachability matrix; ISO: International Organization for Standardization; ISM: Interpretive structural modelling; MICMAC: Cross-Impact Matrix Multiplication Applied to Classification; NBD: Novel business design; SDG: Sustainable development goals; SDM: Smoot decision-making process; SMIEE: System for monitoring and improving energy efficiency; SMT: Smart manufacturing technologies; SPLC: Sustainable product life cycle; SSC: Sustainable supply chain; SSIM: Structural self-interaction matrix; SVC: Sustainable value chain; TEM: Transformation of energy market; ESMT: Enhanced smart manufacturing technologies

1. Introduction

The energy industry, as a significant macroeconomic entity, is inevitably impacted by the digital era. Digital technology “offers opportunities for businesses to clarify societal concerns more effectively, adapt their strategies, and boost sustainability” [1,2]. Nevertheless, “the integration of digital conversion technologies in promoting sustainability and energy efficiency faces challenges, particularly linked to environmental issues such as climate change and global warming, which have hindered sustainable development for years” [3]. The “diverse perspectives of multiple stakeholders further complicate the achievement of sustainability goals” [4,5].

In this context, it is imperative to explore the implications of digital conversion on clean energy and bridge the existing knowledge gaps. While “digital conversion holds the potential for optimizing operations, enhancing transparency, and promoting innovation” [6–8], there are concerns regarding its implication on energy consumption and CO2 emissions. The widespread “adoption of digital inventions, such as self-driving cars, smart household systems, and 3D manufacturing, might diminish energy consumption in the generation of services and products, but rebound effects could lead to increased overall energy consumption” [9]. Consequently, understanding the interplay between digital conversion and clean energy is significant for effectively tackling environmental implications and ensuring economic development.

While “some studies have explored the potential privileges of digital transformation in terms of increased adaptability, cost reduction, and consumer satisfaction” [10,11], there is a “lack of detailed analysis on the specific Sustainable Development Goals (SDGs) within the context of digital transformation and long-term clean energy” [12]. The integration of sustainability and digitization is considered essential for achieving the SDGs, but research gaps persist, including a limited understanding of digital conversion's function, the intricate interconnections of energy systems, design limitations, leadership challenges, and underutilization of innovation" [13]. Therefore, there is a need for comprehensive exploration of the implications of digital conversion on clean energy, particularly in the European context.

We aim to fill the gaps in the literature by evaluating the points of intersection between digital conversion and clean energy. It seeks to spot the implications of digital conversion on clean energy in Europe and investigate the specific challenges and opportunities linked with this integration. By focusing on these research objectives, we aim to reveal valuable insights for decision-makers, industry practitioners, and researchers, enabling them to make informed decisions and develop strategies that effectively integrate digital conversion and promote sustainable energy solutions.

The following sections of the paper include a comprehensive review of the literature on digital conversion and clean energy, highlighting the existing gaps and challenges. Subsequently, the study methodology is presented, encompassing an integrated approach to identify key indicators, the ISM approach for capturing interrelationships, MICMAC analysis to analyze essential constructs, and the DEMATEL framework for validating cause-and-effect relationships. The paper then displays a case study and roadmap, discusses managerial implications, and concludes with limitations and recommendations for further research. Through this study, we aim to contribute to the understanding of the interplay between digital conversion and clean energy, shedding light on the opportunities and challenges for a sustainable energy future.

Nonetheless, the significance of this study lies in its potential to inform strategic decisions and guide industry practices towards sustainable energy solutions. As digital conversion continues to reshape the energy landscape, it is imperative to have a deep understanding of its implications for sustainability. By filling the existing literature gaps and investigating the specific challenges and opportunities linked to digital conversion in the European context, this study can provide valuable insights for decision-makers, industry practitioners, and researchers.

For decision-makers, the findings of this study can offer guidance on formulating effective regulations and blueprints that enable the integration of digital technologies in the energy sector while ensuring sustainable outcomes. Understanding the complexities and potential trade-offs between digital conversion and clean energy will enable experts to develop strategies that harness the privileges of digital conversion while mitigating its negative environmental influences.

Industry practitioners will harvest from the study’s insights by gaining a clearer understanding of the challenges and opportunities that arise from the intersection of digital conversion and clean energy. This knowledge can inform their decision-making processes, allowing them to form innovative solutions that enhance energy efficiency, reduce emissions, and enhance overall sustainability performance. Furthermore, industry leaders can identify potential barriers to adoption and develop strategies to overcome them, fostering the successful integration of digital technologies in their operations.

Researchers in the field will find value in this study as it identifies gaps in the existing literature and offers a comprehensive analysis of the relationship between digital conversion and clean energy. By highlighting the research needs and areas requiring further investigation, this study can inspire and guide future research endeavors, ultimately contributing to the knowledge base in the fields of sustainable energy and digital conversion.

In addition, our primary aim is to clarify the literature gaps surrounding the implications of digital conversion on clean energy. By focusing on the European context, we aim to provide a comprehensive understanding of the challenges and opportunities associated with the integration of digital technologies in the energy sector. Through its findings, we seek to inform experts, industry practitioners, and researchers, enabling them to make informed decisions, develop strategies, and contribute to a sustainable energy future.

The research objectives of this study are designed to address the identified literature gaps and contribute to the understanding of the implications of digital conversion on clean energy in Europe. These objectives guide the research process and serve as a framework for achieving the study’s goals.

The first objective is to determine the important metrics for sustainable energy resolution using digital technology. By examining the existing literature and conducting a comprehensive analysis, we aim to identify key indicators that reflect sustainable energy solutions facilitated by digital conversion. These metrics will provide a basis for assessing the impact of digital technologies on clean energy and guide future decision-making processes.

The second objective is to design a structural framework that depicts how these constructs are related to one another. Building upon the identified metrics, we develop a conceptual framework that illustrates the interrelationships between digital conversion and clean energy. This framework will provide a comprehensive overview of the factors influencing the integration of digital technologies in the energy sector and their implications for sustainability.

The third objective is to validate the developed structural model. To ensure the robustness and reliability of the conceptual framework, we employ appropriate validation methods. By testing the cause-and-effect relationships and analyzing the interdependencies between variables, the structural model will be evaluated and validated, enhancing the credibility of the study's findings.

The fourth objective is to use matrices or digraphs to evaluate the linkages and causal effects among the constituent parts of the energy system. By applying analytical tools such as ISM-MICMAC and DEMATEL, we assess the linkages and causal relationships between digital conversion and clean energy. This analysis will provide a deeper understanding of the dynamics and interdependencies within the energy system and highlight potential leverage points for promoting sustainable energy solutions.

Through these objectives, we aim to address the research gap by providing insights into the implications of digital conversion on clean energy in Europe. By exploring the challenges and opportunities associated with the integration of digital technologies in the energy sector, we seek to contribute to the development of sustainable energy regulations, inform industry practices, and inspire future research endeavors.

In conclusion, we recognize the literature gaps in understanding the implications of digital conversion on clean energy and aims to fill these gaps by conducting a comprehensive analysis in the European context. By achieving the research objectives and providing valuable insights, we seek to contribute to the knowledge base in the field of sustainable energy and digital conversion, ultimately guiding decision-makers, industry practices, and future research directions.

2. Review of literature

In this literature review, the relevant research on "digital conversion" and "clean energy" is thoroughly examined. The authors conducted an extensive investigation of the literature, identifying a total of 1462 scientific publications. Articles from the "Dimensions" database covering the years 2013 to 2022 were reviewed, extracting articles that contained the terms "digital conversion" and "clean energy" or "digital conversion" and "energy" or "digital conversion" and "sustainability" in their titles, abstracts, or keywords.

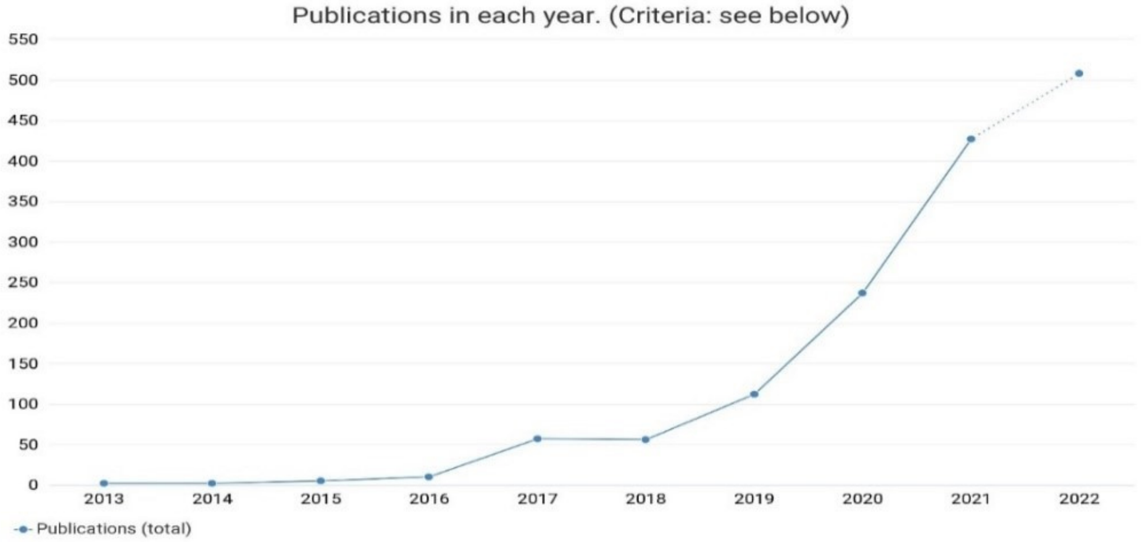

Figure 1. Number of scientific studies published in scientific journals.

In this study, a bibliometric analysis was conducted to investigate academic articles on the sustainability of digital conversion in the energy industry. The analysis aimed to identify major obstacles and patterns in the transformation process. The bibliometric approach involved searching the Dimensions database for published research.

2.1. The bibliometric overview

In order to gain deeper insights into the research landscape on the sustainable digitization of the energy sector, a comprehensive bibliometric analysis was conducted. This analysis aimed to assess the interactions between published papers based on their country of origin, assess collaborations among authors, and spot the most frequently occurring keywords in the scientific articles.

The bibliometric analysis utilized the VOSViewer program to interpret the outcomes and visualize the linkages between authors of publications based on their country of origin. Figure 2 depicts the diagram generated by the VOSViewer program, which provides a visual representation of the links among authors from different countries.

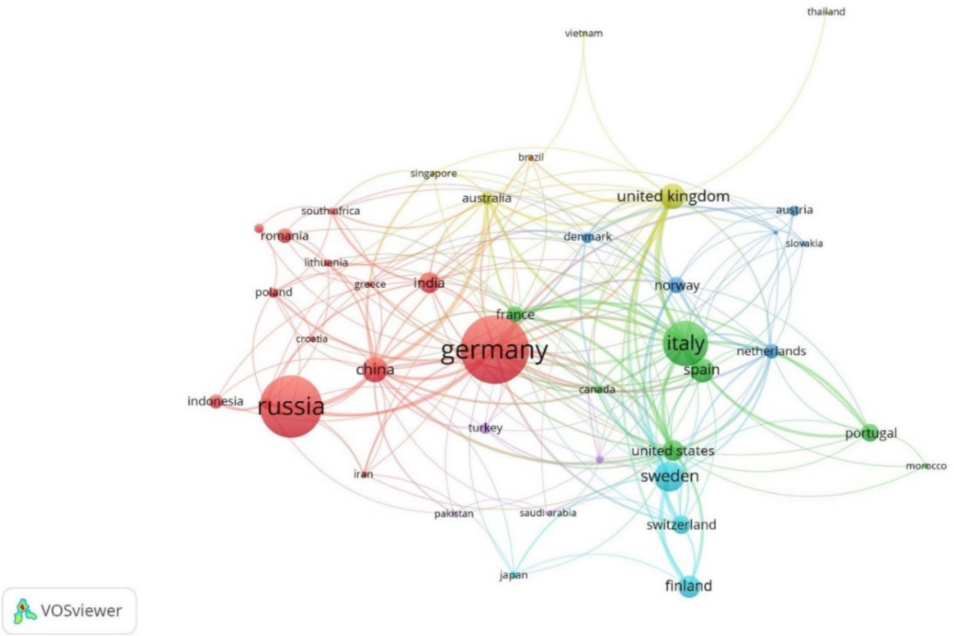

Figure 2. The visual representation of scientific study links by nations.

Furthermore, a bibliometric assessment was carried out to investigate collaborations among authors of academic articles. The analysis utilized data from the Dimensions database and focused on authors who had published at least four scientific papers on the topic under investigation. Figure 2 displays the chart generated by the VOSViewer program, highlighting significant research clusters among countries with a high level of interest in sustainable energy digitization, including Germany, Russia, Italy, China, the United Kingdom, and Sweden.

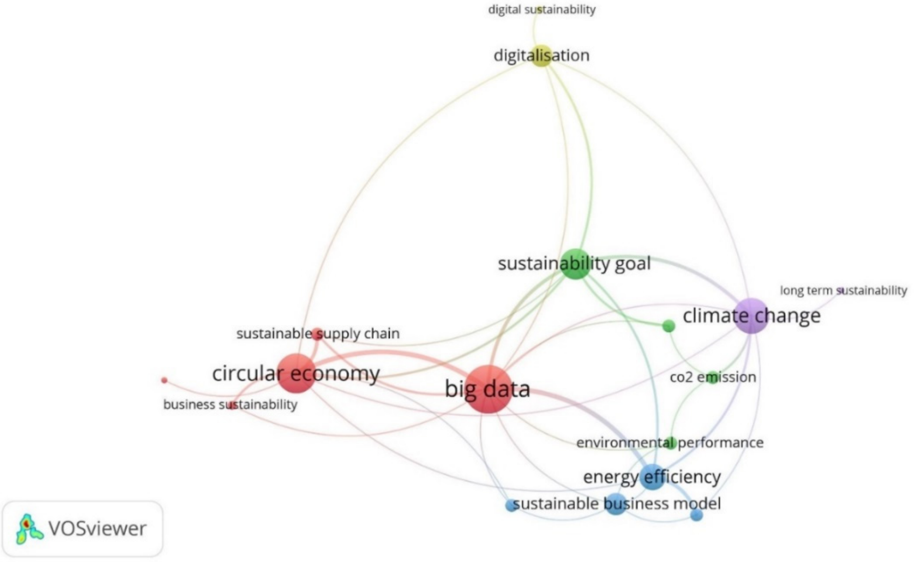

Figure 3. The visual representation of terms and their connections was generated using VOSViewer.

To gain a deeper understanding of the thematic focus in the literature, Figure 3 reveals a diagram depicting the links among the most frequently occurring keywords in the titles, abstracts, or keywords of the analyzed scientific articles. Notably, keywords such as “big data,” “sustainability,” “digital conversion,” “circular economy,” and “energy efficiency” emerged as highly relevant to the topics of digital conversion, sustainability, and energy. These keywords, as evidenced by their popularity in the assessed scientific articles (Table 1), provide valuable insights into the key areas of emphasis within the literature on sustainable digitization.

Table 1. The main clusters and topic synopsis.

Cluster	Topic	Synopsis
Big data	Circular economy	Utilization of renewable energy and decrease in Carbon Dioxide (CO_2) emissions
	Sustainable supply chain	Ecofriendly supply chain management and power storage
	Business sustainability	Company’s method for minimizing the negative environmental effects of its activities in a marketplace
	Digital conversion	Incorporation of digital technologies into business or socioeconomic processes with the goal of improving them
Sustainability goal	Carbon Dioxide (CO_2) emission	Emissions caused by the consumption of fossil fuels
	Digital conversion	Incorporation of digital technologies into business or socioeconomic processes with the goal of improving them
Clima change	Long-term sustainability	A path of organizing company or society so that it can exist in the long-term
	Sustainable business model	A model that creates value for everyone involved while not depleting the resources used to construct it
	Environmental performance	Evaluates the record of success of national governments against defined objectives of environmental quality and resource utilization effectiveness
Energy effiency	Sustainable business model	A model that creates value for everyone involved while not depleting the resources used to construct it
	Environmental performance	Evaluates the record of success of national governments against defined objectives of environmental quality and resource utilization effectiveness

The literature review examines the concepts of digital conversion and digital transformation in the context of sustainable energy production. Digital conversion highlights the interchangeable utilization of these terms and their significance in enabling organizations and society to build resilient infrastructure and achieve sustainable industrialization [14,15]. The potential advantages of digital innovations in the energy domain are emphasized, such as cost savings in the German energy sector and the role of digital conversion in pursuing the UN Sustainable Development Goals [16,13]. Nevertheless, an “obstacle to the digital conversion pathway is needed to promote knowledge transfer to the next generation of energy users, which is influenced by higher education and the diffusion of information and communication technology” [17]. Furthermore, [18] verify that leveraging AI- and IoT-based infrastructure is identified as a key future challenge to achieve green targets.

In addition, the critical review also acknowledges challenges linked with digital conversion, including increased electricity consumption and the need for a skilled workforce [19]. According to [20]. “Lack of trust in digitized multisource energy systems, particularly due to consumer data protection concerns, is another barrier to their widespread adoption”.

The literature review discloses numerous inconsistencies, gaps in knowledge, and areas requiring further research. First, there is a lack of systematic interpretation of how and why digital technologies are employed to drive inclusive innovation processes [21]. While the potential for digital technologies to facilitate the sharing economy and innovative connections among stakeholders is acknowledged, the successful installation of digital platforms and technologies, which requires novel business strategies and specific relational business models, has not been clarified [22,23].

Furthermore, the literature highlights the need for a skilled workforce to exploit and drive innovation in the context of digital conversion [19]. However, there is "limited research on developing a skilled workforce capable of leveraging digital technologies in the energy sector. Nonetheless, in this context, privacy preservation and full investment in digital conversion performance predictions are essential for future data-driven implementations" [24].

A further critical review identifies numerous gaps in the existing literature. First, there is a lack of management emphasis on the topic of digital transformation and sustainability. The literature is fragmented and spread across various journals, and there is limited attention from management journals to synthesizing and guiding companies in implementing related programs [25]. Second, there is a misalignment of terminology deployed in academic research. According to [26]. Terms like "digital sustainability" or "digital transformation" are not widely utilized in sustainability contexts, which have led to fragmented research". Third, "there is a scarcity of overarching strategic studies that can enable generalizable insights. The specificity of sectors and contexts limits the transferability of research findings. Comparative research is also limited, hindering the interpretation of the interplay between digital transformation and sustainability" [27]. Fourthly, [27] asserts that the "lack of studies conducted at the organizational level is a major limitation. The links between digital conversion, sustainability, and organizational processes need more exploration to develop research applicable to various contexts".

These gaps hinder the effective harnessing of the potential advantages of digitization. Another domain that requires attention is the influence of external factors on digital conversion efforts in the energy sector. Country policies, demographics, sociocultural preferences, taxation, and other contextual factors significantly shape the pace and extent of digital conversion. Understanding and navigating these elements is vital for successful installation and adoption of digital technologies; however, there is a lack of comprehensive research in these domains.

The terminology utilized in academic research also poses a gap. The literature review identifies a misalignment of terms such as "digital sustainability" and "digital transformation" in sustainability contexts. This misalignment hinders a unified understanding of digital conversion and sustainability as goals and phenomena, requiring researchers to converge towards a more familiar terminology for practice. Moreover, the review highlights a scarcity of comparative research and overarching strategic studies. Comparative research would provide a deeper understanding of the relationship between digital transformation and sustainability, facilitating the generalizability and transferability of findings. Similarly, more studies at the organizational level are needed to explore how organizations and stakeholders can leverage digital transformation to achieve sustainability objectives.

Lastly, there is an absence of publications that provide results applicable to different contexts, limiting the development of a universal concept of digital sustainability. The literature review calls for a focus on the management subject and the alignment of theoretical development with practical implementation.

In summation, while the literature review presents valuable insights into sustainable energy digitization, it also reveals inconsistencies, gaps, and areas requiring further research.

In addition, the literature review indicates the need for accessible digital conversion, knowledge transfer, and investment in digital technologies to achieve sustainable energy goals. However, there are gaps in management focus, terminology alignment, overarching strategic studies, organizational-level research, and comparative studies, which hinder the development of comprehensive frameworks and practical guidance. Addressing these issues will contribute to a more comprehensive understanding of the role of digital conversion in sustainable energy production and inform effective strategies for its implementation. Table 2 discloses an overview of the ten key elements examined in this study that contribute to the fostering of sustainable energy in the context of the digitization process.

Table 2. The key metrics that frame sustainable energy resolution through digitization.

No.	Key factor	Definition	Reference
1	System for monitoring and improving energy efficiency (SMIEE)	Energy consumption statistics from electrical power grids are utilized to monitor efficiency, while smart energy management systems that arrange intensive production phases during times when electricity rates are favorable are deployed to improve efficiency. Intelligent operating and savvy supply chains are facilitated by energy improvement systems.	[28,29]
2	Enhanced smart manufacturing technologies (SMT)	Flexible and smart automation, CPPS, IoT, virtualization, energy management, and other elements of digital technologies could accelerate data and improve communication for the utilization of renewable energy in the manufacturing setting. Consequently, these technologies are responsible for lower CO_2, additional energy efficiency, increased efficiency, and overall cost reduction.	[30–32]
3	Transformation of energy market (TEM)	The elements of Industry 4.0, such as smart grids, block chains, and CPPS, would significantly alter energy management in the context of how it is produced, transformed, and consumed.	[33,34]
4	Novel business design (NBD)	It emphasizes the more cooperative and knowledge-sharing aspects of openness and balance access to energy.	[35–37]
5	Increased grid imbalances and disparities (IGI)	Renewable energy intermittently generated era and real-time data tracking have allowed for much accelerated corrective and preventive actions to be become prevalent.	[38–40]
6	Interconnection of various portfolio typologies (INC)	It integrates renewable energy, power storage, and distributed energy.	[41,42]
7	Smoot decision-making process (SDM)	The communication of data processing and analysis of technological innovations such as cloud data, artificial intelligence, and data analytics would allow for the assessment of massive amounts of data generated throughout the predictive maintenance and product life cycle.	[43,44]
8	Sustainable product life cycle (SPLC)	Industry 4.0 technologies, which include sensors installed in many smart grids and machines, allow for the traceability of production performance and product data throughout the product life cycle.	[45]
9	Sustainable supply chain (SSC)	The applications of artificial intelligence, automation, and other technologically advanced across many sectors of the economy, such as the supply chain, distribution channels, and manufacturing, have a sizable influence on the natural environment, leading to less pollution, lower greenhouse gas emissions, lower energy consumption, and increased margins all at once.	[46–48]
10	Sustainable value chain (SVC)	Porter's (1998) value chain theory emphasized the essence of a company's specific trajectory of activities as a source of long-term competitive advantage, and he used the term "company activities" as a cognate for business processes that integrate supply chain processes. The emergence of novel value chains paves the way for intricate and interconnected industrial networks, altering the functions of designers, suppliers of tangible goods, and client interfaces.	[49–51]

The ISM-MICMAC-DEMATEL method is a comprehensive decision-making approach that integrates three approaches. This method has gained significant attention in the realms of research and decision-making due to its ability to analyze and interpret complex nexus among various elements.

This strategy has been deployed in various research domains, including business and management [52], mining studies [53], healthcare and public health [54], and supply chain [55], in the diamond supply chain. It enables identifying critical factors and interpreting their interactions for effective decision-making. A detailed explanation of each method and its steps would be delineated in the subsequent section.

2.2. Gap analysis

Following a review of the literature, [56,11] have noted that “numerous studies have explored the topic of digital transformation, highlighting the potential benefits of incorporating digital conversion, such as increased adaptability, rapid consumer response and satisfaction, process rejuvenation, cost reduction, and elimination of non-value-added activities”. However, [12] point out that “only a small number of these scientific publications have conducted detailed analysis on specific Sustainable Development Goals (SDGs) in the domain of digital transformation and long-term clean energy”. In a comprehensive review conducted by [13], it was found that “Sustainable Development Goals (SDGs) could be effectively achieved through the integration of sustainability and digitization. However, their findings also identified several research gaps in relation to the SDGs, including a limited understanding of digital conversion and the intricate interconnections of energy systems, design limitations, leadership challenges, and the underutilization of innovation in science and knowledge management”. Moreover, [13] assert that “there are voids in the knowledge about the function of digital conversion in dealing with SDGs, as research in this area remains largely unexplored”. [58] conducted a “systematic investigation and evaluation of digital conversion in general and found that the emergence of breakthrough digital technologies, combined with artificial intelligence and robotics, is driving a new wave of smart corporations. Furthermore, [57] argue that “additional theoretical and empirical exploration is still needed to fully comprehend the objectives of digital platforms in the domain of the open invention process”. [59] highlight that “leadership challenges related to management issues remain understudied, and this disparity becomes even more relevant as digital innovations increasingly find applicability in innovation processes”. “Advancement and knowledge management are crucial factors in addressing these challenges”, according to [59]. However, there has been a shortage of assessments conducted to validate the main established structural model in this instance. The motivation for the current study stems from these gaps and discrepancies in the literature. The authors were inspired to resume this research after identifying knowledge gaps through a thorough analysis and review of the literature.

3. Research methodology

Several research methodologies have been employed in the European energy market to analyze and model the implications of digital conversion, which significantly advances clean energy. For this study, ten key factors that frame sustainable energy were considered in the research setting. The sample sizes defined for DEMATEL analysis, as recommended by [60], fall “within the range of 10 to 30”. In the subsequent study, a sample size of 18 experts was deemed adequate for collecting data to evaluate DEMATEL and ISM methodologies. To reinforce the applicability and soundness of the data obtained, a triangulation research approach, integrating both quantitative and qualitative methods, was employed in the current study. Notwithstanding, the limitations of one framework can be tempered by the solidity of another. The qualitative study focused on substantive conversations and semi structured interview sessions with energy academics and experts, whereas the quantitative method was based on data generated through a questionnaire-based survey. To achieve the study's objectives, various methodologies were used, including ISM, MICMAC, DEMATEL, and questionnaire-based surveys throughout the European energy domain. [61] use an "ISM-based path to assess the success factors for construction projects". [62] also "deployed the ISM approach to spot the superior characteristics of agile development". However, [63] highlight that "the key drawbacks of ISM are that the link between the metrics entirely pertains to the participants' skills and their experience inside their businesses". In conclusion, it is important to acknowledge that biases in evaluating variables could potentially impact the outcome. Such biases might lead to the omission of certain parameters in the ISM model's methodology, which can significantly distort the assessment results. Therefore, combining DEMATEL with ISM is recommended to validate the interactions between obstacles and address any potential vulnerabilities. Additionally, while ISM is a capable method for assessing concerns, qualitative correlations among variables should also be considered, and the ISM dependency framework should be analyzed quantitatively to arrive at a more robust conclusion. However, the utilization of the MICMAC methodology allows for the identification and classification of variables into different types based on their driving power and dependency. This was achieved through a comprehensive literature review and expert analysis to identify key metrics of digital conversion that are relevant to sustainable energy in this research. The performance indicators displayed in Table 1 were selected by experts. A comprehensive literature evaluation of the European energy domain from 2012 to 2022 was conducted using relevant keywords such as "digital conversion," "clean energy," and "sustainable" from reputable sources such as Emerald, Scopus, and archival materials from multiple journal articles. Based on expert opinions, an extensive review of the literature was conducted to assess ten key metrics that reflect the implications of digital conversion on clean energy. Subsequently, a conceptual framework centered around "ISM" was developed, preceded by the depiction of these key metrics using MICMAC interpretation and hypothesis formulation. Ultimately, DEMATEL was employed to validate the ISM-based model and confirm the hypothesis. In brief, the ISM methodology has been utilized to determine the interactions between the identified key metrics, and the MICMAC approach has been applied to substantiate the developed interrelationships.

3.1. Procedure of ISM

"ISM is a comprehensive learning process that organizes various elements, both directly and indirectly related to each other, into a coherent and systematic model"[64]. "Researchers have utilized the pattern of value-added structure, or ISM process, to depict the interrelationships among different metrics related to the issue [65]". According to [66], the "ISM study typically involves the following eight steps":

Step 1: Conducting an extensive literature search and gathering expert opinions to identify the key metrics that influence the system under assessment in the energy industry.

Step 2: A situational link is established among the elements found in order to evaluate the pairs of metrics that ought to be examined.

Step 3: Then, a SSIM, or structural self-interaction matrix, is designed for metrics in the model that are imposing pairwise correlations between elements.

Step 4: By substituting each SSIM unit value for 1 and 0, the SSIM is utilized to construct an initial reachability matrix (IRM), and the matrix is also validated for generalizability. A crucial premise that also develops in ISM is the transitivity of the situational correlation. Variable U should be tied to variable W if variable U and variable V are related and if variable V is identified as variable W. An ultimate FRM is produced as a result.

Step 5: There are several tiers to the finalized FRM model designed in Phase 4.

Step 6: Based on the contextual links determined in the reachability matrix outlined above, a graph or digraph is constructed, and the transitive connections are eliminated from the structure.

Step 7: By substituting the relation hypotheses among the parameter nodes in the obtained digraph, an ISM model is now formed.

Step 8: The ISM model developed in Phase 7 is currently being assessed to verify certain conceptual inconsistencies, and necessary revisions are being taken into consideration based on expert assessment.

3.2. MICMAC evaluation

The MICMAC framework was utilized to classify the primary digital conversion metrics based on their "dependence and driving power." The main objective of the MICMAC, as described by [67], is to "assess the driving power and reliance power of crucial metrics that impact the system, using matrix multiplication attributes as the primary criteria for evaluation". According to [68], "records of interaction situations in the row and column were emphasized to explore the primary driver and dependency power of the key metrics identified by the MICMAC framework. Subsequently, the variables were classified into four taxonomies based on their characteristics".

Cluster I (Autonomous variables): This cluster comprises components that exhibit low interdependency. These elements will be excluded from the model as they are relatively isolated from the system. They either lack control over the system or are being utilized by it, resulting in their disorganization.

Cluster II (Dependent variables): These metrics exhibit low driving force but high reliance, and they have a negative impact on decision-makers.

Cluster III (Linkage variables): This cluster comprises a diverse range of variables with high driving power and dependability. As the name suggests, each of these variables contributes to the growth of sustainable energy. They significantly influence the direction of independent factors and assist in the development of dependent factors. They exhibit a high degree of interdependency as well as potent driving power. Any changes to these variables would impact other elements in a similar manner as they would affect them.

Cluster IV (Independent variables): These variables reflect the most determining elements, exhibiting high driving power but limited dependence. As the name suggests, these variables form a group that effectively manipulates other variables to achieve sustainable energy outcomes.

3.3. Design of the survey questionnaire

Questionnaires were utilized in academic, industrial, and government workshops and seminars to directly engage with respondents, collect data for model assessment, and test hypotheses. Pilot tests were conducted to ensure accurate and valid findings from the survey questions and discussions, and opportunities for improving the questionnaire's design were identified. This research incorporated multiple sources of evidence, such as key informant interviews, the use of validated tools, and triangulation, to mitigate bias (control and confounding factors). Additionally, Cronbach evaluation was conducted to measure consistency and ensure dependability while preventing research bias. This approach aids in establishing internal consistency and obtaining relevant data on the relationship between independent variables. The primary objective of Cronbach's alpha is to "assess the degree of interrelatedness among a group of items [69]".

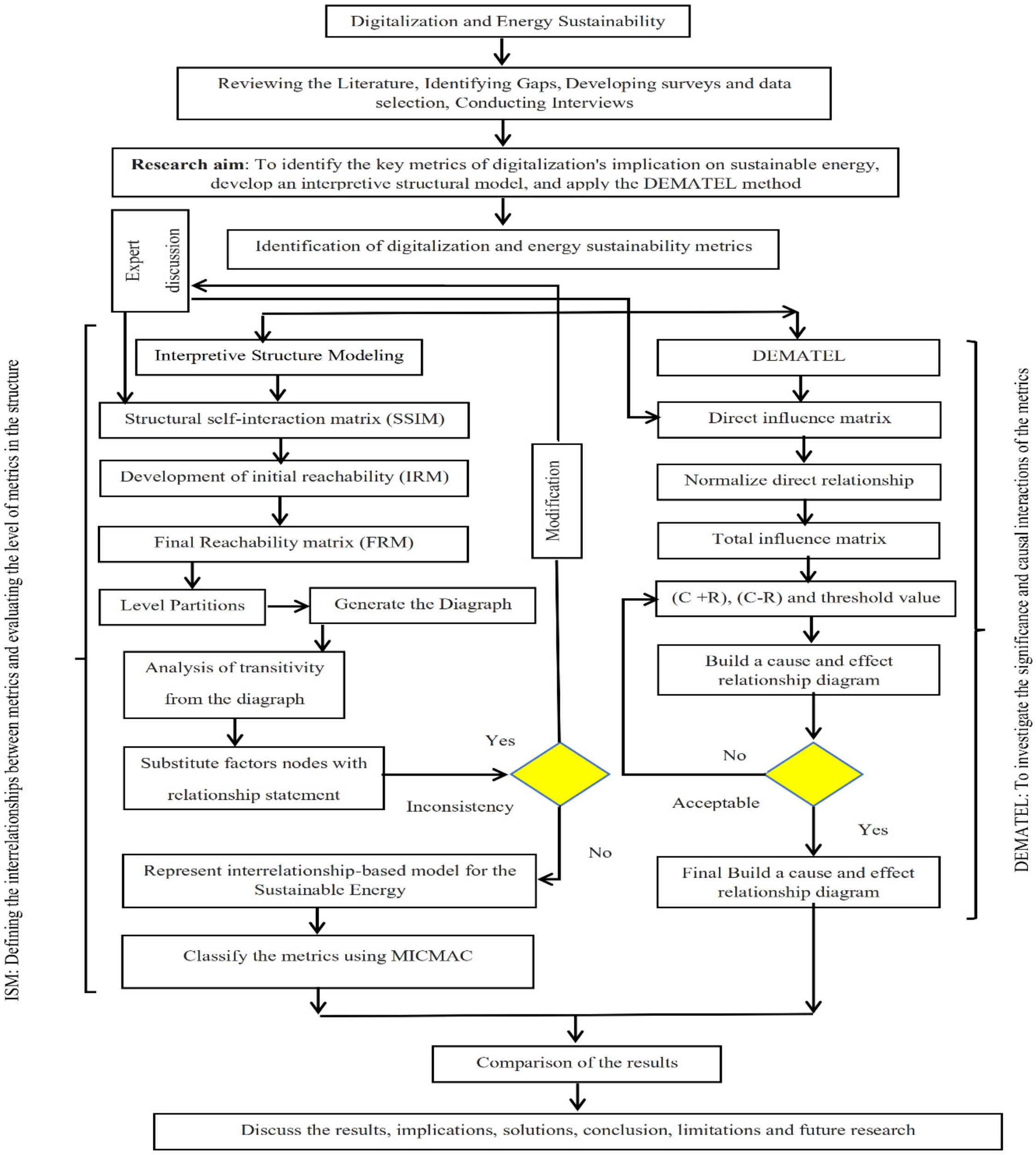

Figure 4. Research methodology flowchart.

The survey was conducted over a span of twenty months, from June 2021 to February 2023. The design of the questionnaire was informed by historical records, relevant literature on digital conversion and clean energy, and insights from industry and academic experts.

4. Case clarification and roadmap interpretation

This study was conducted at a company specializing in the development, construction, and operation of onshore wind farms that provide power to 6 million people in northern Germany. The company's vision was to create a world powered solely by renewable energy. To realize its clean energy objectives, the company adopted a digital strategy encompassing advanced analytics, digitization, and artificial intelligence (AI). This strategy would enable the company to supply data from its 1,400 onshore wind turbines to derive valuable insights for predictive maintenance, resulting in significant time and resource savings. Equipped with numerous sensors, each generator would generate vast quantities of data, which could be analyzed and optimized. Advanced cloud-based tools facilitate seamless collaboration between the company's 2000 employees, enhancing their ability to interact and work efficiently. Additionally, in the past, the computations required for the design and development of wind farms using traditional frameworks would take up to a month. However, with the application of digital conversion, we anticipate reducing this time significantly, to as little as 20 to 48 hours. Despite holding ISO 9001 and 14001 certificates, the company has experienced a prolonged phase in the construction and approval of onshore components for the past 18 years without any decline. Nevertheless, the company's management was determined to adopt certain methodological approaches to expedite the construction process, obtain environmental government approval, and streamline design verification and validation. As a result of the strong working relationship between the authors and the business coordinator, they engaged in open discussions and sought solutions to overcome obstacles. Through in-depth conversations with staff at various levels within the organization, the authors of this study were able to arrange an event that included influential elites and experts to advocate for the adoption of digital conversion in the sustainable energy framework. The executives of the energy company granted permission for the research to be conducted within their entity and supported the expansion of participant numbers. The panel of experts was comprised of three members from academia, three fellows from the same organization, and four members from other institutions, all of whom possessed vast knowledge and experience in the subject domain. Pertinent information about the panel of experts is summarized in Table 3.

Table 3. Participants in the expert panel.

Experts	Position	Qualification	Experience (in years)
Member 1	Advisor	Ph.D. in innovation	4
Member 2	Engineer	Master in digital conversion and industry	6
Member 3	Digital strategy	Master in Innovation	6
Member 4	Engineer	Master in Innovation and Digital conversion Industry	4
Member 5	Advisor	Ph.D. in Innovation	5
Member 6	Operation manager	Bachelor in electrical engineering	7
Member 7	CEO	Renewal industry	7
Member 8	Plant manager	Energy industry	3
Member 9	Engineer	Master in innovation and digital conversion	4
Member 10	Manager	Ph.D. in sustainability	3
Member 11	Advisor	Ph.D.in energy industry	4

The methodical approach for projecting digital conversion metrics and developing a structured framework for sustainable electricity consumption is outlined as follows.

5. ISM-MICMAC approach

The digital conversion metrics were identified through a systematic literature review, incorporating the example of an energy company throughout the study and expert opinions. A comprehensive review of the literature, including bibliometric assessment of scientific studies, revealed a collection of ten factors that are relevant and advancements to the performance of the sustainable energy framework in the energy domain. The list of recognized digital conversion metrics aligned with the energy sector was disclosed and finalized with the input of panel members. Subsequently, the board members identified the top ten metrics based on their relevance to the organization's context. As shown in Table 1, these finalized metrics are conceptually applicable to other energy companies as well.

5.1. Structured self-interaction matrix formation (SSIM)

SSIM, which is based on contextual linkages between the ten identified metrics for digital conversion strategies in the energy industry (as shown in Table 3), is primarily utilized. ISM has advanced to include the creation of SSIM as well. In order to establish relevant relationships between the factors, ISM suggests using multiple methodologies, such as conceptualization and the implicit aggregation system. Therefore, a relevant relationship in the "prompts" form is selected to investigate the correlation between the metrics. The implications of affiliation between two segments (I and j) and the interconnected path of their interaction are explored based on the structural patterns for each factor. The relationships "A affects B," "B influences A," "A and B affect each other," or "A and B are not connected" are indicated by annotations "V," "A," "X," and "O," respectively. These compositional interconnections are accurately captured using the SSIM approach, as displayed in Table 3. For the convenience of the experts in the analysis, a sample of each metric and their interactions is displayed as follows:

"V" indicates that variable i will either facilitate or lessen variable j.

"A" indicates that variable j will either facilitate or lessen the influence of variable i.

"X" indicates that variables i and j will assist or enhance each other.

"O" indicates that variables i and j are distinct variables.

Table 4. SSIM.

Parameter	SVC	SSC	SPLC	SDM	INC	IGI	NBD	TEM	SMT	SMIEE
SMIEE	V	V	V	A	V	V	A	X	A	
SMT	X	X	V	A	V	V	V	V		
TEM	X	X	X	A	X	A	X			
NBD	X	X	X	A	A	X				
IGI	X	X	X	A	X					
INC	X	X	X	X						
SDM	X	V	V							
SPLC	X	X								
SSC	X									
SVC										

5.2. Reachability matrix

The SSIM is converted into a paired network, known as the Initial Reachability Matrix (IRM), by replacing V, A, X, and O with '1' and '0' based on the context. The IRM for the digital conversion metrics can be found in Table 4, while Table 5 depicts the final reachability matrix obtained after incorporating the transmissivities. These tables provide insights into the driving power and dependency of each factor. The total number of variables required to achieve a specific variable's Driving Power (DP) is evident from the counts. Additionally, the overall elements that can potentially contribute to achieving the DP are considered in terms of dependability.

Table 5. Initial Reachability Matrix (IRM).

Variables	1	2	3	4	5	6	7	8	9	10	Driving power
SMIEE	1	0	1	0	1	1	0	1	1	1	7
SMT	1	1	1	1	1	1	0	1	1	1	9
TEM	1	0	1	1	0	1	0	1	1	1	7
NBD	1	0	1	1	1	0	0	1	1	1	7
IGI	0	0	1	1	1	1	0	1	1	1	7
INC	0	0	1	1	1	1	1	1	1	1	8
SDM	1	1	1	1	1	1	1	1	1	1	10
SPLC	0	0	1	1	1	1	0	1	1	1	7
SSC	0	1	1	1	1	1	0	1	1	1	8
SVC	0	1	1	1	1	1	1	1	1	1	9
Dependence power	5	4	10	9	9	9	3	10	10	10	

Table 6. Final matrix of reachability (FMR).

Variables	1	2	3	4	5	6	7	8	9	10	Driving power
SMIEE	1	1*	1	1*	1	1	1*	1	1	1	10
SMT	1	1	1	1	1	1	1*	1	1	1	10
TEM	1	1*	1	1	1*	1	1*	1	1	1	10
NBD	1	1*	1	1	1	1*	1*	1	1	1	10
IGI	1*	1*	1	1	1	1	1*	1	1	1	10
INC	1*	1*	1	1	1	1	1	1	1	1	10
SDM	1	1	1	1	1	1	1	1	1	1	10
SPLC	1*	1*	1	1	1	1	1*	1	1	1	10
SSC	1*	1	1	1	1	1	1*	1	1	1	10
SVC	1*	1	1	1	1	1	1	1	1	1	10
Dependence power	10	10	10	10	10	10	10	10	10	10	

5.3. Level partitions

The ultimate reachability grid generates the connectivity and precedence combinations for each variable. The reachability array of a variable encompasses both its attributes and the potential indicators that could aid in achieving it. The antecedent set contains the parameter itself as well as other relevant factors that could contribute to its attainment. The intersection of these pairs is calculated to determine the combined metrics. The variable that serves as the basis for comparing intersection, connectivity, and reachability arrays is identified as the dominant factor in the ISM hierarchy, as it does not depend on any other parameter to surpass its threshold. Once the leading element is characterized, it is excluded from the ranking of the remaining factors. Based on Table 6, the sustainable improvement progresses at Level I, positioning it at the top of the ISM hierarchy. This priority is reiterated as the levels of each variable are explored. The delineated levels provide a framework for designing the ISM diagram and the ultimate template. Table 6 illustrates the partition of containment levels.

Table 7. Summarized level partition.

Elements(Mi)	Reachability set R(Mi)	Antecedent set A(Ni)	Intersection set R(Mi)∩A(Ni)	Level
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
2	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
3	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
4	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
5	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
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7	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
8	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
9	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1
10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	1

5.4. The formulation of a framework based on ISM

The structural framework is constructed using Tables 4 and 5, and the corresponding diagrams are illustrated. As shown in Figure 4, the diagram is transformed into the ISM concept when transitivity is eliminated. The summarized level partitions of the parameters reveal that all elements are at level 1.

Additionally, the metrics node identified in Figure 5 is excluded when building the final ISM-based framework.

The proposed model demonstrated the significance of all parameters in initiating digital conversion and ensuring clean energy. While the ISM model establishes comprehensive interrelationships between metrics, it does not cluster the characteristics of metrics. However, the limitations of the ISM approach are overcome through the development of the "MICMAC" method, which highlights the generating and dependent forces of digital conversion metrics, enabling a more nuanced understanding of the ISM journey.

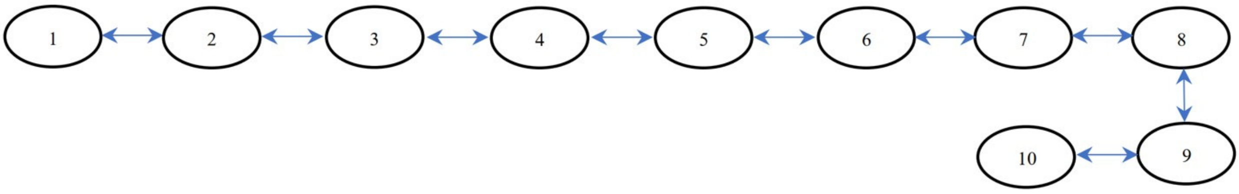

Figure 5. ISM-based model for digital conversion and sustainable energy.

5.5. Results of the ISM-based framework

The ISM-based template consists of five levels or thresholds, which are classified into three sectors: 'most extremely important', 'moderately important', and 'least important'. Based on the final interpretive structural model and hierarchical structural model, the parameters "SMIEE, SMT, TEM, NBD, IGI, INC, SDM, SPLC, SSC, and SVC" were identified as the most essential at level 1, following the calculation of level partitions for all components. This implies that all defined digital conversion metrics have the potential to contribute to clean energy.

6. Assessment of the MICMAC

The MICMAC analysis is utilized to evaluate the driving power and dependence of the components. Based on their reliance and DP, relevant concerns are grouped into four classifications: fully autonomous, dependent, linking, and independent parts (as depicted in Figure 3).

1) Autonomous elements
   The autonomous group's factors are less vital since they possess less DP and dependency.
2) Dependent elements
   Hence, the issues in this cluster are highly dependent and have limited driving possibilities, the dependent elements are the least significant factors.
3) Linkage category
   The linkage elements invoke significant power and rely heavily on one another.
4) Independent category
   These components have a driving power yet an extremely weak reliance.

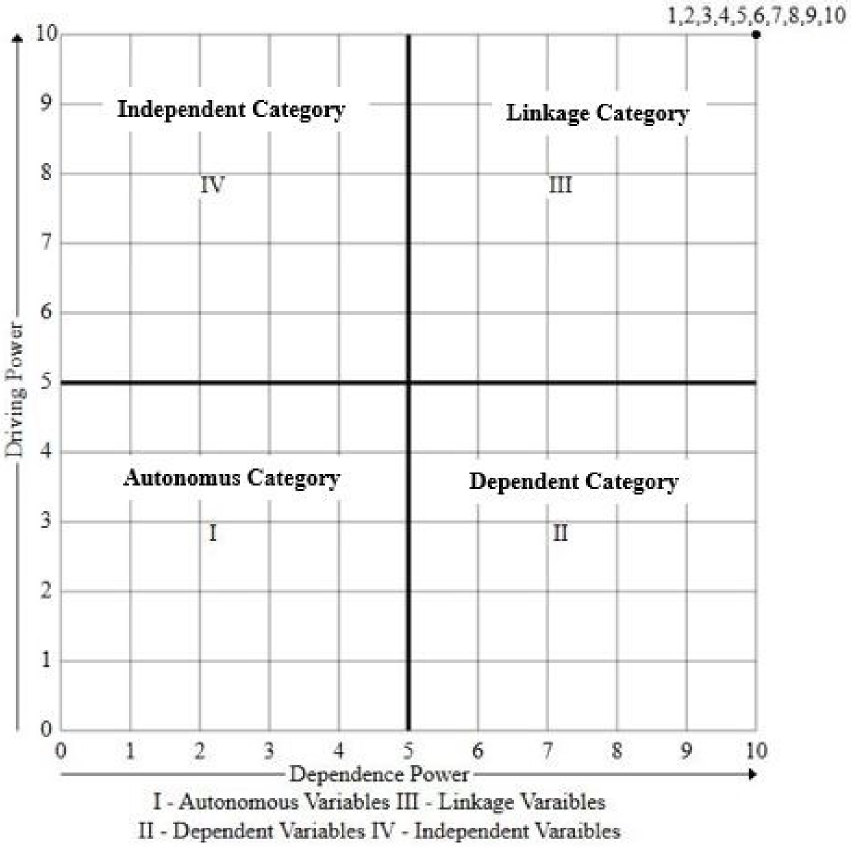

Figure 6. MICMAC analysis.

The MICMAC framework is used to classify the metrics into four distinct groups based on their "dependencies and driving forces." These classifications are vital for understanding the characteristics of the factors and assessing their significance during the deployment phase. The dependent force can be evaluated by summing the values from each metric's column, while the driving force can be projected by adding all values displayed in the FRM. The driving force indicates the parameters that drive other metrics, while the dependence force reveals the parameters that are initiated by other metrics. Figure 6 presents the findings of the MICMAC study, which groups the metrics into four dimensions, and Table 6 provides an analysis of their "driving and reliance power" (i.e., "dependent, autonomous, linkage, and independent"). In this case, metrics with high driving and dependent powers are considered under the linkage cluster, while no parameters fall under the autonomous, independent, and dependent groups.

6.1. Findings of the ISM-based approach

The TMICMAC interpretation is used to assess the influence and reliance of the constituents. By systematically evaluating the generated framework and the results of the MICMAC assessment, managers of the case organization can determine which metrics have an impact on the digitization and sustainability goals. The resulting framework provides insights into the interrelationships between the parameters, guiding managers in making decisions on the adoption process. Based on the findings of the current study, the components "SMIEE, SMT, TEM, NBD, IGI, INC, SDM, SPLC, SSC, and SVC" were all categorized under linkage category III, indicating their driving and dependent power as displayed in Figure 6. This information can help organizational managers formulate a blueprint and transform the corporate attitude in order to successfully adapt the organization to digitization and clean energy goals.

6.2. DEMATEL approach

The DEMATEL methodology, which stands for Decision-Making Trial and Evaluation Laboratory, is a Multi-Criteria Decision Making (MCDM) tool that quantifies the levels and relationships between distinct parts to determine the pattern of relationships and solve a problem [70]. The formal DEMATEL-ISM methodology involves using DEMATEL to initially assess the degree of direct relationship between factors through expert evaluation, typically on a 0–4 scale, to construct a direct relationship matrix D [71–73]. This approach addresses the issue through data visualization, and the following steps are typically involved:

Step 1: The pairwise comparison rating has four levels, with scores of 0, 1, 2, and 3.

$$D = \left\{ \begin{matrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \dots & m_{2n} \\ m_{\iota 1} & m_{\iota 2} & 0 & m_{cn} \\ m_{n1} & m_{n2} & \dots & 0 \end{matrix} \right\} \tag{1}$$

Step 2: Normalized direct correlation decision matrix as following, where all of matrix D's principal diagonal elements mij are assumed to be zero.

$$X = \frac{D}{s} \tag{2}$$

where s:

$$s = \max i\left(\sum_{j=1}^{n} m_{ij}\right) \tag{3}$$

Step 3: Calculate the cumulative relationship matrix. This phase generates a weighted normalized decision matrix.

$$T = \lim_{k \to \infty} (X + X^2 + \cdots + X^k), which\ is\ equal\ to\ X(I - X)^{-1} \tag{4}$$

Step 4: Calculate the T-matrix's prominence and relevance element, which signifies the total direct and indirect influence applied by factors. The values of R + C and R – C, whereby C is the summation of the columns and R is the total of the rows of the straight-related severity matrices, are applied to determine the rates of influence and relationship (DRSM).

$$Cj = \sum_{i=1}^{n} t_{ij}\ (j = 1, \dots, n) \tag{5}$$

$$R_i = \sum_{j=1}^{n} t_{ij}\ (i = 1, \dots, n) \tag{6}$$

(C+R) denotes prominence and indicates the element's threshold of influence and fluencies. An affiliation is summarized as (R–C). If it is, the factor is a part of the result group. The indicator is more certainly likely to be correlated when it is negative.

Step 5: Design diagram of the potential causes and relationships. Determine an appropriate threshold in this circumstance because it is vital to construct a cause-and-effect chart [74]. The decision-maker has the flexibility to choose the threshold level or seek guidance from experts in the DEMATEL methodology. However, it is important to strike a balance in selecting the threshold level, as an excessively low threshold might result in a diagram that is overly complex and fails to provide meaningful information for decision-making. On the other hand, if the threshold is set too high, many metrics might be shown as independent variables without any indication of their interactions with each other, which can limit the insights gained from the analysis. Finding the right threshold level is essential to ensure the effectiveness of the DEMATEL analysis in supporting decision-making.

6.3. Direct relation matrices' baseline and average values

The matrix is compiled based on the responses of the panel of experts, reflecting their assessment of the direct effects between each pair of metrics. The pairwise comparison is conducted on a scale ranging from 0 to 4, with scores indicating the level of influence, ranging from "no influence," "very limited influence," "limited influence," "strong influence," and "extremely high influence" (as shown in Table 8). This matrix provides a summary of the expert opinions on the direct effects between all combinations of metrics, with scores indicating the strength of the effects, ranging from "no effect," "very limited effect," "limited effect," "strong effect," and "very strong effect," using the same scale of 0 to 4 (as shown in Table 8).

Table 8. Scale level.

Linguistic variable	Assigned value
No effect	0
Very limited effect	1
Limited effect	2
Strong effect	3
Very strong effect	4

The final step involved calculating the arithmetic average of expert responses to gain further insights, as depicted in Table 9.

$$A = \left[a_{ij}\right] = \frac{1}{K}\sum_{k}^{1\le k\le K} z_{ij}^{k} \tag{7}$$

Table 9. Initial direct relationship matrix.

	SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC
SMIEE	0	4	4	2	3	3	3	3	3	3
SMT	4	0	4	3	4	3	2	4	4	3
TEM	4	4	0	4	4	3	2	3	4	3
NBD	2	3	4	0	3	4	3	3	3	2
IGI	4	4	4	3	0	4	3	2	3	2
INC	3	4	3	4	4	0	3	2	2	3
SDM	3	3	3	3	4	3	0	4	3	3
SPLC	3	4	4	3	2	3	3	0	4	4
SSC	3	3	3	3	2	2	3	4	0	4
SVC	3	3	4	3	3	2	3	4	4	0

6.4. Initial direct relationship normalization

Normalize the direct relationship matrix in Table 9 by dividing it by A to obtain the baseline correlation matrix X, as shown in Table 10.

$$D = \frac{1}{\sum_{j=1}^{n} a_{ij}} A \tag{8}$$

Table 10. Normalized direct correlation decision matrix.

	SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC
SMIEE	0.0000	0.1290	0.1290	0.0645	0.0968	0.0968	0.0968	0.0968	0.0968	0.0968
SMT	0.1290	0.0000	0.1290	0.0968	0.1290	0.0968	0.0645	0.1290	0.1290	0.0968
TEM	0.1290	0.1290	0.0000	0.1290	0.1290	0.0968	0.0645	0.0968	0.1290	0.0968
NBD	0.0645	0.0968	0.1290	0.0000	0.0968	0.1290	0.0968	0.0968	0.0968	0.0645
IGI	0.1290	0.1290	0.1290	0.0968	0.0000	0.1290	0.0968	0.0645	0.0968	0.0645
INC	0.0968	0.1290	0.0968	0.1290	0.1290	0.0000	0.0968	0.0645	0.0645	0.0968
SDM	0.0968	0.0968	0.0968	0.0968	0.1290	0.0968	0.0000	0.1290	0.0968	0.0968
SPLC	0.0968	0.1290	0.1290	0.0968	0.0645	0.0968	0.0968	0.0000	0.1290	0.1290
SSC	0.0968	0.0968	0.0968	0.0968	0.0645	0.0645	0.0968	0.1290	0.0000	0.1290
SVC	0.0968	0.0968	0.1290	0.0968	0.0968	0.0645	0.0968	0.1290	0.1290	0.0000

6.5. Analyze the matrix of all influences

By splitting the normalization baseline correlation matrix in Table 9 by the equation T, we can achieve the cumulative correlation matrix D, as shown in Table 11.

$$T = \left(t_{ij}\right) = D(I - D)^{-1} \tag{9}$$

Table 11. The total relations Matrix; Threshold (alpha) Value: 1.0966.

	SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC	Ri
SMIEE	1.0180	1.1969	1.2299	1.0207	1.0797	1.0133	0.9441	1.0789	1.1126	1.0149	10.7090
SMT	1.2245	1.1811	1.3328	1.1337	1.1933	1.0987	0.9968	1.1941	1.2318	1.0994	11.6861
TEM	1.2207	1.2918	1.2148	1.1573	1.1908	1.0968	0.9942	1.1649	1.2280	1.0950	11.6543
NBD	1.0401	1.1300	1.1873	0.9249	1.0431	1.0072	0.9127	1.0396	1.0720	0.9524	10.3092
IGI	1.1587	1.2253	1.2587	1.0724	1.0185	1.0661	0.9663	1.0760	1.1364	1.0103	10.9887
INC	1.0989	1.1899	1.1983	1.0682	1.1016	0.9229	0.9400	1.0441	1.0781	1.0054	10.6475
SDM	1.1320	1.1995	1.2343	1.0726	1.1308	1.0399	0.8806	1.1309	1.1388	1.0392	10.9986
SPLC	1.1669	1.2619	1.2989	1.1065	1.1126	1.0689	0.9974	1.0537	1.2030	1.0996	11.3692
SSC	1.0649	1.1278	1.1623	1.0098	1.0121	0.9505	0.9130	1.0702	0.9868	1.0078	10.3052
SVC	1.1315	1.1980	1.2599	1.0720	1.1024	1.0109	0.9677	1.1327	1.1670	0.9522	10.9943
Ci	10.1247	10.8040	11.1173	9.5660	9.8825	9.2644	8.5451	9.8523	10.1873	9.3241	98.6679

6.6. Analysis of prominence and influence factor

To evaluate “R plus C” and “R minus C”, refer to formulas (5) and (6) that restructure the values of R and C in the relationship matrix of the total criterion effect (direct or indirect) in Table 4 based on the order of each factor, as illustrated in Table 12.

Table 12. Summarized the causal influence level of criteria.

	Ri	Ci	Ri + Ci	Ri – Ci	Identify
SMIEE	10.7090	11.2563	21.9652	–0.5473	Effect
SMT	11.6861	12.0021	23.6882	–0.3160	Effect
TEM	11.6543	12.3772	24.0315	–0.7228	Effect
NBD	10.3092	10.6380	20.9472	–0.3287	Effect
IGI	10.9887	10.9849	21.9736	0.0038	Cause
INC	10.6475	10.2752	20.9227	0.3723	Cause
SDM	10.9986	9.5128	20.5114	1.4858	Cause
SPLC	11.3692	10.9850	22.3543	0.3842	Cause
SSC	10.3052	11.3543	21.6595	–1.0491	Effect
SVC	10.9943	10.2763	21.2706	0.7179	Cause

6.7. Data collection method and reliability assessment

The data collection source credibility, considering validity, representativeness, and consistency, which would represent the population or phenomenon under study, was conducted through a random sampling approach through evaluation for any discrepancies or outliers and expert assessment, which played a vital role in providing input, identifying relationships, and evaluating the importance of variables. In addition, the validation of the data was conducted through pilot testing and peer review, which could enable the identification of any errors or inconsistencies and improve the overall reliability of the data. Data validation (pilot testing) and Sensitivity analysis were performed by employing triangulation and pretesting.

A pre-test or pilot study was performed according to questionnaires, and observation guidelines with a small sample of participants or experts to assess the clarity of the questions, and based on the feedback and insights gained from the pretest, the necessary adjustments were executed to boost the reliability and validity of data collection. In the context of ISM-MICMAC and DEMATEL, the triangulation approach was employed by collecting data from various sources or utilizing diverse data collection approaches to ensure consistency and reliability through observations to gain a more comprehensive understanding of the underlying relationships and to verify the obtained results.

The validity of the DEMATEL approach was verified through content, face, and construct validity analysis through a review of existing literature and consultation with domain experts to validate the selection of criteria and variables. Construct validity was carried out by comparing the results of the DEMATEL assessment with other established methods or theories in the field (MCDM). Furthermore, validation of criteria was executed by comparing the outcomes or predictions generated by the DEMATEL method with external criteria or real-world observations to determine if they aligned. The reliability analysis of DEMATEL results is conducted by conducting test-retest reliability evaluations or assessing inter-rater reliability.

To perform a sensitivity analysis for the DEMATEL method, the key input parameters and the range of variation that are used in the DEMATEL method were compiled by experts, which included thresholds, influence weights, normalization factors, and scenarios. Nonetheless, the output of performance indicators was validated by centrality measures, offering insights into the decision-making process. Finally, the results were analyzed by comparing the outcomes of each scenario and observing the changes in the performance indicators.

6.8. Results from DEMATEL

Table 12 presents a synopsis of the results from the DEMATEL assessment, organizing the valid factors into cause-and-effect groups. The cause group comprises five factors: IGI, INC, SDM, SPLC, and SVC, with influence powers of 0.0038 for IGI, 0.3723 for INC, 0.3842 for SPLV, 0.7179 for SVC, and 1.4858 for SDM. On the other hand, the effect group includes five metrics: SMIEE, SMT, TEM, NBD, and SSC. Figure 7 illustrates the links between the sources and outcomes of all variables. The diagram shows that the most critical factors are those that are located further from the zero rows in the positive Y-axis direction. Metrics that are highly dependent or weakly sustainable are those that are farthest from the zero row in the opposite direction of the Y-axis. Components that are adjacent to the zero line are considered “unbiased” metrics.

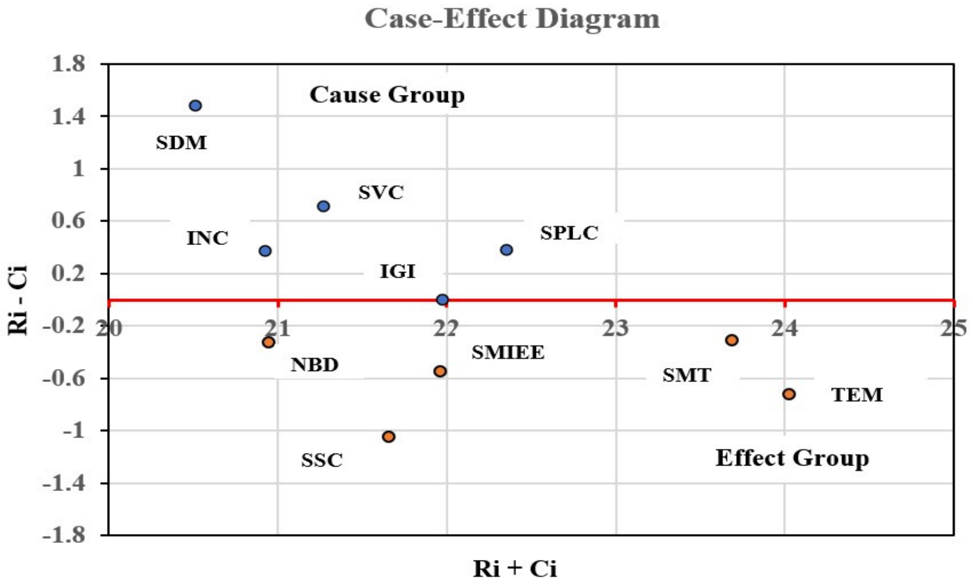

Figure 7. Cause-effect diagram.

7. Results of the research and discussion

The strengths of the internal dependency matrix (Table 13) were utilized to construct the integrated ISM-DEMATEL based on the hierarchical framework illustrated in Figure 8.

Table 13. The inner dependency matrix; threshold (alpha) value: 1.0966.

	SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC
SMIEE	1.0180	1.1969	1.2299						1.1126	
SMT	1.2245	1.1811	1.3328	1.1337	1.1933	1.0987		1.1941	1.2318	
TEM	1.2207	1.2918	1.2148	1.1573	1.1908	1.0968		1.1649	1.2280	
NBD		1.1300	1.1873							
IGI	1.1587	1.2253	1.2587						1.1364	
INC	1.0989	1.1899	1.1983		1.1016					
SDM	1.1320	1.1995	1.2343		1.1308			1.1309	1.1388	
SPLC	1.1669	1.2619	1.2989		1.1126				1.2030	1.0996
SSC		1.1278	1.1623		1.0121					
SVC	1.1315	1.1980	1.2599		1.1024			1.1327	1.1670	

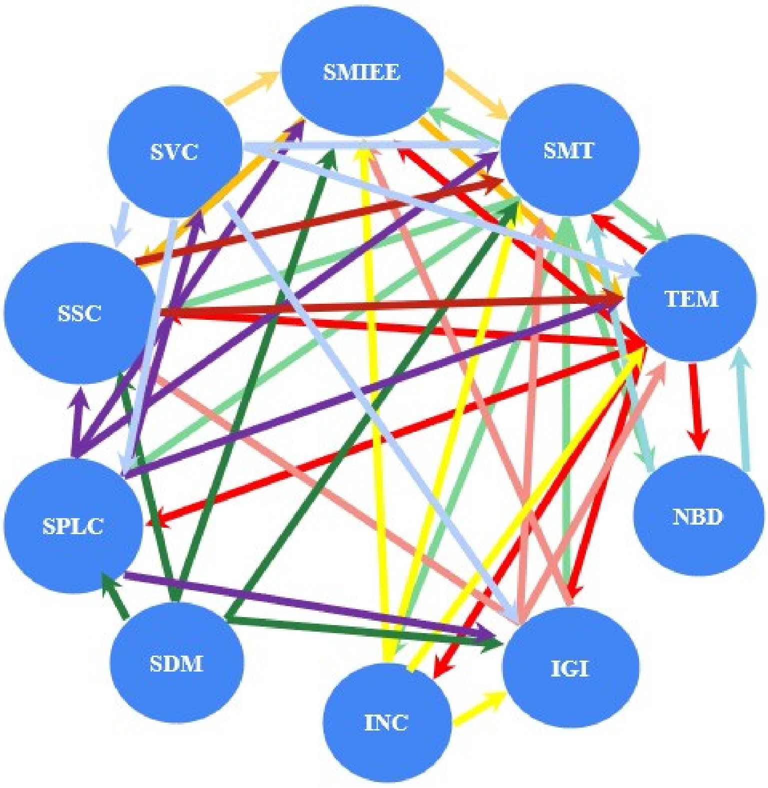

Figure 8. Diagram for digital conversion and clean energy; threshold (alpha) Value: 1.0966.

The integration of the ISM-based approach and DEMATEL analysis has enabled valuable insights into the key metrics influencing digitization and sustainability goals in the context of sustainable energy. This section presents the findings of both approaches, highlighting the interrelationships among the identified metrics and their relative importance.

The ISM-based approach, as interpreted through the MICMAC analysis, has offered a comprehensive interpretation of the influence and reliance of the identified constituents. By systematically evaluating the generated framework and the outcomes of the MICMAC assessment, managers of the case organization can discern the metrics that have a significant impact on both digitization and sustainability goals. The framework, consisting of three linkage classifications, offers insights into the interrelationships between the parameters. Based on the current study, the components "SMIEE, SMT, TEM, NBD, IGI, INC, SDM, SPLC, SSC, and SVC" were all classified under linkage type III, indicating their driving and dependent power. These metrics are deemed essential for contributing to clean energy.

The DEMATEL analysis further enriches our understanding of the interactions between the identified metrics. The assessment results, summarized in Table 12, organize the valid factors into cause-and-effect groups. The cause group comprises five factors: IGI, INC, SDM, SPLC, and SVC, with varying influence powers. On the other hand, the effect group includes five metrics: SMIEE, SMT, TEM, NBD, and SSC. Figure 7 visually reveals the links between the sources and outcomes of all variables. The diagram depicts that the most critical elements are those located further from the zero rows in the positive Y-axis direction. These metrics have a strong influence on the other elements. Conversely, metrics that are highly dependent or weakly sustainable are those farthest from the zero row but in the opposite direction of the Y-axis. Metrics adjacent to the zero line are considered "unbiased" metrics, indicating their balanced influence. The DEMATEL findings corroborate the ISM-based approach and provide additional insights into the causal relationships between the identified metrics, shedding light on their relative importance and influences on the overall digitization and sustainability goals.

The integration of the ISM-based approach and DEMATEL analysis offers a comprehensive understanding of the key metrics contributing to influential causes and the most volatile elements in the context of sustainable energy digital conversion. This integrated approach provides distinctive insights into the relationships between the identified metrics and their relevance to clean energy.

Furthermore, this study stands out from previous research by providing a comprehensive perspective from experts across European countries. The ISM-MICMAC-DEMATEL framework employed in this study, which evaluates the ramifications of digital conversion on sustainable long-term energy businesses, represents a novel contribution to the field. The integration of qualitative and quantitative analyses, as well as the comprehensive research design, initiate this study apart and enhanced its applicability across various domains.

Among the identified metrics, SDM, SVC, SPLC, and INC were found to have the highest causal effects on other elements, indicating their significance in driving digital conversion and sustainability goals. These metrics play a crucial role in improving data processing, enhancing value chains, enabling sustainable product life cycles, and integrating eco-energy assimilation, power storage, and distributed energy. The findings align with previous studies highlighting the role of digital conversion in technological advancement and the transformation of the energy sector.

The integration of the ISM-based approach and DEMATEL analysis offers a comprehensive understanding of the key metrics' interdependencies and their relevance to clean energy. This integrated approach provides valuable insights for decision-makers in formulating strategies and making informed decisions regarding the adoption of digital conversion approaches. Furthermore, the comprehensive research design employed in this study, encompassing qualitative and quantitative analyses, contributes to its significance. The inclusion of experts from various European countries enriches the perspective and enhances the applicability of the findings across different contexts.

The ISM-MICMAC-DEMATEL framework used in this study represents a novel contribution to the field as it evaluates the impact of digital conversion on sustainable, long-term energy businesses.

Although ISM-MICMAC-DEMATEL has been utilized in a variety of studies, like healthcare organizations by [54] or the study of [55] in the diamond supply chain, it has not been previously explored in the domain of digital conversion and clean energy, making this study unique and valuable. It is imperative to note that the findings and insights from this study provide a foundation for further academic research and facilitate advancements in sustainability at the intersection of power and digitization. The comprehensive assessment of digital conversion indicators and their relevance to clean energy can guide future studies and initiatives in this field.

To summarize, the findings of this study have broad implications for businesses and academia, providing guidance for the adoption of digital conversion approaches and contributing to the long-term sustainability of the energy sector. The integration of the ISM-based approach and DEMATEL analysis offers a robust framework for understanding the relationships between digital conversion metrics and their impact on clean energy goals.

7.1. Theoretical contributions

Only a limited number of studies on clean energy have examined the performance metrics of digital conversion, and none of them have integrated the framework of interpretive relationships within structural modeling and the DEMATEL concept. Such a framework enables decision-makers and strategists to systematically understand and evaluate the contextual interactions between digital conversion metrics. As pointed out by [75]. Previous studies have relied on inadequate proxies for the linkage between digital conversion and power security. In contrast, this study employs comprehensive assessment and up-to-date global data to provide a more reliable and robust response. Furthermore, while previous studies have shown that the use of the internet has implications for electricity consumption, this research highlights the importance of digital connectivity and human capital skills, as well as the causal links between the transformation of the energy sector and the advancement of innovative manufacturing technologies, which can foster sustainable energy development. However, the validation framework of previous investigations has not been validated in the literature in the domain of this study. The solution of the framework needs to be pondered in terms of its applicability and effectiveness in the realms of digital conversion and sustainable energy. Subsequently, the quantitative verification of the model contributes to mitigating the risk of failure in digital conversion efforts. Moreover, this study is the first investigation to comprehensively analyze the structural interrelationships and causal links between digital conversion and sustainable energy, utilizing a combined ISM-MICMAC and DEMATEL concept to organize key metrics in a systematic approach. Researchers, experts, and decision-makers may continue to pursue similar evaluation platforms for assessing digital conversion metrics, but the contextualization of the premises should be tailored to the specific contexts of each organization.

7.2. Research practical implications

The current study, which combined bibliometric research with an ISM approach, strengthened the identification of the most significant metrics before simulating their interdependence in a hierarchical conceptual framework. The joint utilization of ISM, MICMAC, and DEMATEL methodologies in the challenging case organization, along with bibliometric assessment of keywords related to sustainable power digitization, served multiple goals, which can be summarized as follows:

(1) The assessment revealed the interconnections between ten critical metrics from practical and business perspectives, shedding light on how these parameters can influence clean energy in the energy industry. The study’s findings are essential, as many investigations often solely focus on identifying key determinants of failure without considering the origin and implications of these metrics. Consequently, this research empowers decision-makers to understand the pervasive digital metrics necessary for the successful implementation of clean energy initiatives, as well as their interconnected nature within the energy market.

(2) One, recent evaluation conducted by a German energy company reaffirmed the claim that the connection between digital conversion, power, sustainability, and industry 4.0 is reinforced by the newly developed template. This connection is evidenced by the interrelationship among subjects such as “distribution networks, robotics, the Internet of Things (IoT), and big data”, as stated by [75].

(3) We aim to catalyze the advancement of the sustainable energy sector by hypothesizing a comprehensive hierarchy concept for the most significant digital conversion metrics. The developed structural framework reveals that all parameters play a vital role, but factors such as smooth decision-making, supply chain sustainability (SSCs), product life cycles, and interconnectedness of equipment are particularly significant. As a successful case study, the authors believe that this investigation will inspire other energy companies to adopt a digitization pathway.

(4) The findings of this analysis validate the hypothesized concept and provide a systematic approach to implementing digital conversion metrics for sustainable energy. The results of this study can also serve as a guide for decision-makers, managers, and government representatives in making informed, tactical, and strategic decisions towards achieving success in the realm of sustainable energy.

(5) Furthermore, this research can also be valuable for executives and managers in all energy-supplying industries, where similar constraints exist and the revitalized conceptual framework can be replicated. As new contexts arise, the comparative approach can be adapted to incorporate digital conversion metrics and pathways, allowing for flexibility and applicability in different settings.

8. Conclusions

The findings of this study shed light on the implications of digital conversion in the power supply industry and its interconnections with energy and sustainability. We aim to investigate the effects of digital conversion metrics on clean energy, and through a thorough analysis incorporating a literature review, panel analysis, and research conducted by the Energy Institute, ten critical parameters were identified.

The application of the ISM approach allowed for the assessment and interpretation of the links between these key metrics. The constructed model revealed that all parameters exhibited strong driving and dependent powers, emphasizing their significance in driving digital conversion and sustainability goals. These findings highlight the importance of leveraging digital conversion to achieve resource sustainability in line with the mission of a circular economy. Furthermore, the MICMAC assessment provided valuable insights by identifying the vital metrics, ascertaining their interdependencies, and classifying them into distinct taxonomies based on their strength of driving and dependency on variables. This assessment deepened our understanding of the vital elements and their roles in shaping a digitalized and sustainable framework for efficient energy utilization.

In order to embrace resource sustainability and adapt to the evolving energy landscape, it is imperative for the energy industry to adopt cutting-edge innovations, particularly digital conversion integrated with automation, robotics, and the Internet of Things. The integration of digital conversion metrics, big data analysis, and advanced technologies can greatly enhance decision-making processes and enable more efficient energy utilization. The findings of this study contribute to the existing body of knowledge by providing insights into the implications of digital conversion on clean energy. The comprehensive analysis approach, incorporating qualitative and quantitative methods, adds depth and robustness to the research findings. The involvement of experts from the Energy Institute and their contributions through panel analysis further strengthen the validity and applicability of the conclusions. It is imperative to recognize that the transition towards a digitalized and sustainable energy framework goes beyond technological advancements. It requires a holistic approach that considers the interconnectedness of digital conversion, energy, and sustainability pillars. By leveraging digital conversion metrics and embracing advanced technologies, the energy industry can pave the way for a more sustainable and efficient future, in alignment with the era of the Internet of Things and robotics.

In conclusion, we emphasize the importance of digital conversion in driving clean energy. The identified digital conversion metrics and their interrelationships offer valuable insights for decision-makers, energy industry stakeholders, and researchers. By harnessing the potential of digital conversion, the energy sector can make significant strides towards achieving resource sustainability and creating a more sustainable and resilient energy system for future generations.

8.1. Limitations and future scope

However, one limitation of this article is that not all academic article indexing sources were considered. There might be publications on the research area that are included in local or national databases of countries with smaller international audiences, that could have produced significant research findings. The ISM approach relies on comments provided by experts, and if these comments are biased, it could influence the assessment outcomes and hinder the template from achieving its overall objectives. Furthermore, this research primarily focuses on European energy entities and the key metrics that emerged from the analysis. It is possible that the presented framework might yield inconsistent outcomes for different organizational styles or industrial domains. While this research has conducted a meticulous evaluation and pilot study to highlight ten critical digital conversion metrics, it might not be a comprehensive concept. However, despite being conducted in the European energy sector, this framework can be effectively adapted and implemented in other countries with slight modifications to the parameters and a hierarchical systemic framework. The results of this investigation are based on a study conducted on onshore wind farms, and simply integrating or excluding metrics might not yield the same results. The novel model can be further adapted for other European energy providers. We believe that this research establishes a template for further investigation into the digital conversion of other institutions in the realm of clean energy. With careful evaluation and modifications, this framework can serve as a foundation for future research in other areas of clean energy beyond the European energy sector.

Use of AI tools declaration

The authors state that they did not utilize Artificial Intelligence (AI) tools in crafting this article.

Conflict of interest

The writers assert that there are no competing interests in relation to the publication of this manuscript.

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Appendix

1. Survey questionnaire (ISM)

The following table is intended to register and develop pair wise contextual relationships between digitalization and energy sustainability.

V = variable *i* will help to achieve or alleviate variable *j*
A = variable *j* will help to achieve or alleviate variable *i*
X = variable *i* and *j* will help to achieve or alleviate each other
0 = variable *i* and *j* are unrelated

2. *ISM (Interpretive structure modeling)*

Table A1. Interpretive structure modeling.

	i\j	SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC
1	SMIEE										
2	SMT										
3	TEM										
4	NBD										
5	IGI										
6	INC										
7	SDM										
8	SPLC										
9	SSC										
10	SVC										

3. *Survey questionnaire (DEMATEL)*

Table A2. Pairwise cause-effect components.

Linguistic variable	Assigned
No influence	0
Very low influence	1
Low influence	2
High influence	3
Very high influence	4

Table A3. Evaluation of direct relations among the components (Values between 0–4).

		SMIEE	SMT	TEM	NBD	IGI	INC	SDM	SPLC	SSC	SVC
1	SMIEE	0									
2	SMT		0								
3	TEM			0							
4	NBD				0						
5	IGI					0					
6	INC						0				
7	SDM							0			
8	SPLC								0		
9	SSC									0	
10	SVC										0