



Exploring the enablers for building resilience in solar photovoltaic Energy supply chains

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Abstract

A solar photovoltaic energy supply chain (SPvESC) is a global network with several linkages, including mineral and metal mining, material processing, and module and panel manufacturing. Due to the wide range of uncertainties and the unfavorable environmental effects associated with current linear business models, this global network is vulnerable to disruptions. Strengthening the resilience of SPvESCs is crucial for addressing any disturbances. This requires identifying the key enablers of resilience in SPvESCs, an area that has been understudied in the existing literature. An enabler is an aspect that facilitates the achievement of a goal by another aspect. This research contributes to the existing literature by systematically investigating the enablers for SPvESCs to achieve resilience. Thus, the objective of this analysis is to identify enablers that have the potential to enhance the resilience of SPvESCs in Türkiye. This was done by applying the Nominal Group Technique (NGT) in conjunction with a review of the current literature. Neutrosophic (N)-DEMATEL was then utilized to determine the relationships between the identified enablers. Finally, the results were validated using N-DELPHI. The results revealed that sensing and seizing new business models, adaptability to changes in novel energy generation and information technologies, and business contingency plans for natural and man-made disasters were the most influential enablers. The findings provide implications for practitioners, policymakers, and researchers to help ensure improved resilience in SPvESCs.

Keywords Supply chain resilience · Enablers · Solar photovoltaic supply chain · N-DEMATEL · Nominal group technique · N-DELPHI

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1 Introduction

Supply chains are complex, interconnected networks that operate in uncertain contexts, exposing them to a variety of disturbances and disruptions (Pettit et al. 2010). Uncertainty depicts how knowledge of a system and its conditions is inadequate, leading to deviations from an expected outcome (Ivanov 2018). Supply chains are susceptible to disruptions resulting from uncertainties both at the planning and the execution stages, which ultimately call for building effective measures to achieve targeted performance (Hohenstein et al. 2015). Supply chain resilience has become an essential complement to the traditional risk management paradigm, which was unable to deal with unanticipated supply chain interruptions. This had serious effects on the bottom line of supply chains and cast doubt on business continuity. Supply chain resilience theory focuses on how complicated systems can ensure integration, survival, and improvement during and after disruptions and severe crises (Wieland and Durach 2021). The recent disruptions resulting from the COVID-19

pandemic, war in Ukraine, and earthquakes in Türkiye revealed that a lack of strong supply chain resilience has contributed to adverse impacts on the day-to-day operations of businesses and daily lives of individuals around the world. When supply chain resilience is either very poor or nonexistent, the complexity of supply chains makes them even more prone to failure. Supply chains are a backbone of economic systems, and providing markets and societies with goods and services in an uninterrupted manner is directly associated with supply chain resilience (Ivanov 2021). Furthermore, supply chain resilience leads to higher performance (Todo et al. 2022).

A solar photovoltaic energy supply chain (SPvESC) comprises material processors, panel suppliers, assemblers, and energy generators. Ineffectiveness in any part of a SPvESC and (or) disturbances in its external environment may have an unfavorable influence on system resilience (Foster et al. 2010). The PV equipment manufacturing industry has undergone significant changes in the last 10 years, with China now holding the top spot, replacing the US, Japan, and Europe in terms of both size and geographic distribution (IEA 2023). The International Energy Agency (IEA) (IEA 2023) argues that solar photovoltaic (SPv) technology is an essential building block of the clean energy transition, helping to pave the way for achieving global energy and climate goals. Various countries are planning to expand their SPv-based electricity generation capacity to address its climate targets, electrification, and decarbonization (McKinsey 2022). However, existing government measures are insufficient to increase solar PV demand to a sufficient degree, based on IEA estimates (IEA 2023). The solar PV supply chain, which includes mineral supplies and polysilicon, wafer, cell, and module manufacture, would need to grow to enable greater resilience should governments set policies in line with their net zero goals. In addition, governments provide significant financial support and incentives to build more resilient solar manufacturing supply chains (AA Energy 2022).

IRENA (2019) and Chowdhury et al. (2020) argue that SPv energy is among the most attractive renewable energy technologies, and that it has the potential to soon become a major energy source. To keep pace with the IEA's Roadmap to Net Zero Emissions by 2050, annual SPv capacity additions must more than quadruple to 630 gigawatts by 2030. Moreover, the manufacturing capacity for polysilicon ingots, wafers, cells, and modules must more than double from current levels by 2030 (IEA 2023). IEA (2023) argues that maintaining the high growth rates anticipated for SPv requires resilient SPvESCs. The need to significantly expand manufacturing capacity in order to meet future demand raises concerns about the world's ability to produce sufficient solar photovoltaic panels in the near-term. Where possible, Erol et al. (2021) argued that SPvESCs should

be streamlined to improve resiliency, with particular attention devoted to the outdated and unsustainable linear business models that are widely used in the industry. Erol et al. (2022), Gautam et al. (2022), Granata et al. (2022), Nain and Kumar (2022), Aşkın et al. (2023), Maqbool et al. (2023), and Sinha and Ghosh (2024) contended that SPvESCs must focus on improving the efficiency and recyclability of solar panel components. As Kirchherr et al. (2022) argued, this means that circular disruption is needed to build more resilience in SPvESCs. Circular disruption is defined as “an interference occurring in the elements of a socio-technical system and how they relate to each other which causes the systemic, widespread, and rapid change from take-make-use-dispose systems to socially and environmentally desirable and sustainable systems that address structural waste - e.g., seen and unseen types of waste - through the strategic deployment of circular strategies” (Kirchherr et al. 2022). Erol et al. (2021), Gawusu et al. (2022), Sahebi et al. (2022), and Sinha and Ghosh (2024) further suggested that more innovation is required for SPvESCs to achieve greater resilience. For example, cutting-edge information technologies, such as blockchain, could strengthen the data infrastructure required to support resilience through a circular economy, especially during the introduction of disruptive digital platforms.

Erol et al. (2022), Gawusu et al. (2022), and Sahebi et al. (2022) argue that building SPvESCs has never been more challenging given the requirements to control uncertainty and increase resilience in such environments. As more businesses have outsourced manufacturing, supply chains have been stretched, the number of nodes has been expanded, and the intricacy and interdependency of supply chain networks have escalated exponentially (Handfield and McCormack 2008). Effectively addressing disruptions in ever-extended supply chains has become a critical priority in recent years, underscored by natural and human-made disasters, epidemics, logistics problems, and unreliable suppliers. This has raised the prominence of supply chain resilience, which Novak et al. (2021:332) explain as follows: “A supply chain is resilient to the extent that the system can maintain core functionality by continually adapting, evolving, and transforming in response to the dynamic multi-scale feedback that occurs between the multitude of interconnected organizations, institutions, and social and ecological systems that are all parts of the larger supply chain”.

Resilience is crucial for supply chain executives as they prepare for an increasingly uncertain future. Recent interruptions and shortages have compromised just-in-time production, leading to delivery delays, price hikes, and a reduction in the range of sourcing options. As supply networks break down, supply-chain executives also have to deal with the long-term shift of global integration. Simply put, future success depends on resilience; however, developing

it may be expensive, and many companies and supply chains are making cutbacks (Novoszel and Wakolbinger 2022). Boosting business and supply chains' capacity to respond to unforeseen catastrophic events is essential. This is an all-encompassing strategy that addresses every function within a firm as well as its supply chain partners, rather than a focused emphasis on a specific function (Wakolbinger et al. 2022). Corporate executives have been seeking various ways to strengthen the resilience of their supply chains. Ali et al. (2017a, b) suggest that identifying enablers is essential for developing resilience initiatives that can help supply chains prepare for disruptions. In this study, enablers are elements that facilitate a firm's adoption of a supply chain strategy (Sancha et al. 2015). According to Grzybowska (2012), an enabler is a factor that makes it possible for another factor to accomplish a goal. For small, medium, and large-sized companies, enablers may bring about transformation. Ponomarov and Holcomb (2009) claim that enablers, building on the dynamic capability, assist policymakers in making efficient use of the limited resources in the case of a disruption in order to achieve better performance and a competitive advantage. Enabler enforcement is affected by managerial perspectives, the structure of the company, the availability of resources, public interactions or perception, experience, and data availability, among other possibilities.

Several studies, most of which are conceptual, have been published on the enablers (critical factors) of supply chain resilience in many industries. For example, Reeves and Whitaker (2020) explained why resilience is essential for supply chain sustainability. Then, they conceptually addressed "the challenge of measuring and managing resilience" considering enablers. Furthermore, Falagara Sigala and Maghsoudi (2022) identify and analyze the enablers of resilient humanitarian supply chains. To this end, they conducted a comprehensive literature review. They finally suggested that further quantitative studies are needed to better grasp supply chain resilience. Novak et al. (2021) argued that conceptions of supply chain resilience focused on equilibrium may not be compatible with the idea of a supply chain as a complex adaptive system (CAS). They provide recommendations on how scholars and practitioners might use a complexity-based approach, or CAS, to enhance supply chain resilience theory and practice. In another study, Riglietti (2022) presented a conceptual examination of business continuity management (BCM) as a crucial enabler of supply chain resilience. The author demonstrated how the current BCM may significantly improve response times and recovery capabilities as well as agility, flexibility, velocity, visibility, and teamwork. Parast (2022) emphasized that business, industry, country, and global demand for more effective supply chain risk initiatives is increasing. Parast also emphasized that further basic research is needed to properly quantify supply chain disruption at the macro and micro levels, as well as

to accurately estimate the risk factors of supply chain interruption. Parast further emphasized that increasing supply chain resilience requires widespread coordinated effort. In another study, Rahman et al. (2022a, b) conducted a systematic literature review of 151 papers to address supply chain resilience strategies. They provided a basis for various research questions and future research directions including on the enablers of supply chain resilience. Yang et al. (2023) argued that business, industry, country, and global demand for more effective supply chain resilience initiatives is increasing. In addition, they maintained that further fundamental research is required in order to precisely measure supply chain disruption at the small and large scales. The researchers also conducted various studies on quantitatively analyzing the enablers of supply chain resilience in diverse industries. For example, Zamiela et al. (2022) proposed a multi-criteria decision framework to identify the enablers for resilient healthcare supply chains. They concluded that "redundancy", "collaboration", and "robustness" are key indicators of a resilient healthcare supply chain. In another study, Liu et al. (2023) analyzed the enablers for enhancing maritime supply chain resilience. To achieve that, they propose a methodological framework that involves a series of multi-criteria decision approaches. The study's findings indicate that the redundancy plan is the most important enabler, with freight rate stability and freight service continuity.

Enablers help drive effective implementation. Hence, investigating enablers for boosting a supply chain is crucial. As indicated earlier, few attempts have been made to systematically analyze the enablers for resilient supply chains in various industries (Piprani et al. 2020; Zamiela et al. 2022; Liu et al. 2023). In addition, Anderluh and Herburger (2022) concluded that there are still important gaps in the supply chain resilience literature that must be addressed in the coming years by other studies. Many authors have also pointed out that customized frameworks for exploring supply chain resilience and (or) sustainability are needed to account for specific industry characteristics using empirical data (Ali et al. 2017a, b; Singh et al. 2019; Pettit et al. 2019; Agarwal et al. 2020; Mohammed et al. 2021; Rahman et al. 2022a, b; Aşkın et al. 2023; Maqbool et al. 2023; and Sinha and Ghosh 2024).

Since SPv is expected to become an increasingly common energy technology and source, building a resilient SPvESC is important (Erol et al. 2021; Erol et al. 2022; Dashtpeyma and Ghodsi 2022). However, other than Oteng et al. (2022) and Aşkın et al. (2023), who limited their focus to the enablers of implementing recycling in SPvESCs, no study has yet investigated the enablers for SPvESCs to achieve resilience by quantitatively considering their cause-and-effect relationships. This study, therefore, is unique in systematically investigating the enablers that help decision-makers improve the resilience of SPvESCs in Türkiye. The enablers

for SPvESCs were identified by reviewing the existing literature and using the Nominal Group Technique (NGT). The enablers address factors throughout the SPv network, including “material processors”, “SPv panel suppliers”, “photovoltaic assemblers”, and “solar energy producers”. Since addressing all enablers simultaneously is infeasible, Neutrosophic (N)-DEMATEL was utilized to ascertain the links among the enablers. Lastly, Neutrosophic (N)-DELPHI was applied to verify the results.

This research addresses the following research questions:

RQ1: What are the enablers for achieving greater resilience in SPvESCs?

RQ2: What are the associations between the enablers of SPvESC resilience?

RQ3: How do the results assist decision-makers in strengthening resilience in SPvESCs?

This study makes three key research contributions. First, although there have been some conceptual studies associated with the enablers of resilience in general, no study has yet scrutinized the enablers of SPvESCs in the context of achieving greater resilience. Second, there has been limited qualitative research on the associations among the enablers of supply chain resilience. Nevertheless, no quantitative study has used expert opinions to investigate the interactions between the enablers to improve resilience in SPvESCs. Third, the findings provide insight into policy directions towards greater resilience in SPvESCs of emerging countries.

The rest of the paper is structured as follows: Literature review involving the enablers of supply chain resilience and the research gap is addressed in Section 2. The research methodology is presented in Section 3, and the application is discussed in Section 4. The results, discussion, and implications are provided in Section 5. Lastly, the conclusions are provided in Section 6.

2 Literature review

The transition to a sustainable, low-carbon future has been radically impacted by the rise of renewable energy on a global scale (Rahman et al. 2022a, b). This transition journey has been defined by many advances such as the sharing of vast amounts of information, financial assistance, legislative frameworks, technology transfer, and capacity building, all of which are firmly rooted in cooperative partnerships (Hassan et al. 2024). Technological innovation has had a positive influence on renewable energy production in various countries, particularly those with robust innovation bases and substantial R&D expenditures, such as the USA, Germany,

the Netherlands, Sweden, and the United Kingdom (Khan and Su 2023). However, while it can help facilitate green economic development, renewable energy consumption may not necessarily promote it due to technical constraints. Wen et al. (2022) argue that advancing renewable energy technologies also fosters gross domestic product growth in countries. In another study, Luo et al. (2024) maintain that China’s capacity to continue economic growth and attain environmental sustainability will depend on the adoption of renewable energy technologies and systems. Along the same line, Yadav and Mahalik (2024) suggest that for emerging countries, encouraging the development of alternative renewable energy sources will have major long-term benefits in terms of enhancing the balance of payments and ensuring ecosystem sustainability. To this end, Gök (2023) argues that it may be necessary to create special financial products tailored to the needs of the renewable energy industry, such as green bonds or certificates with a focus on renewable energy, in order to create a favorable financial environment that encourages investment in renewable energy projects.

Hassan et al. (2024) suggest that integrating more solar energy into the energy network would potentially encourage greater distributed energy generation, while adding a greater proportion of clean energy sources to the electricity mix. Moreover, relying on solar energy allows countries such as Türkiye to decrease their reliance on imported energy sources, including coal and natural gas, thus improving the financial stability of their energy systems. This serves to lower overall CO₂ emissions by displacing less environmentally friendly energy sources (Lee et al. 2023). Ongoing technical innovations in solar energy have increased the efficiency of the panels, which serve to further enhance their environmental attractiveness. However, building resilient SPvESCs is challenging and requires a thorough understanding of the enablers of supply chain resilience.

In this study, a comprehensive literature review on the enablers of resilience was conducted. Given the lack of research in this area on SPvESCs, all industries were considered. The following keywords served as the basis for the search in scholarly databases: “enablers of supply chain resilience”, “critical factors of supply chain resilience”, “indicators of supply chain resilience”, and “metrics of supply chain resilience”. The literature review focused on peer-reviewed research articles published in journals in English.

2.1 The enablers of supply chain resilience

The results of the literature review are discussed from the perspective of two main aspects. The first aspect focuses on defining a set of factors for supply chain resilience. This initial view showed that several conceptual papers have considered the enablers (critical factors) of supply chain resili-

ience. For example, based on their own literature review, Ponomarov and Holcomb (2009) identified the following factors: agility, responsiveness, visibility, flexibility, collaboration, and integration. Pettit et al. (2010) developed a conceptual framework for evaluating and improving supply chain resilience through an analysis of supply chain disruptions. Their framework included supply chain vulnerabilities and capabilities (enablers), which they defined as characteristics that allow a company to predict and deal with interruptions. Drawing on focus groups, they identified a list of capabilities, including flexibility, capacity, efficiency, adaptability, recovery, collaboration, security, and financial strength. In another study, Vugrin et al. (2011) proposed a framework for assessing the resilience of infrastructure and economic systems. Their approach contained a new definition of resilience, a resilience cost assessment, and a qualitative method to measure the system aspects that disturb resilience.

Tukamuhabwa et al. (2015) completed a comprehensive literature review on supply chain resilience. They discussed supply chain resilience in terms of complex adaptive systems theory and identified the following supply chain resilience strategies and factors: logistics capabilities, security, cooptation, collaboration, innovation, visibility, sustainability compliance, inventory management, contingency planning, demand management, and agility. Similarly, Elleuch et al. (2016) reviewed 40 studies on supply chain vulnerability and resiliency, concluding that there is a lack of research in building policies for concurrently alleviating vulnerability and improving supply chain resilience capabilities. Kamalahmadi and Parast (2016) also reviewed the literature on enterprise and supply chain resilience. Based on an analysis of 100 papers, they identified the principles of supply chain resilience including supply chain reengineering, collaboration, trust, information sharing, agility, visibility, velocity, innovation, risk management. This was used to suggest supply chain resilience strategies for companies. Ali et al. (2017a, b) conducted another review, this time of 103 papers. They classified the definitions and strategies of supply chain resilience, and categorized supply chain capabilities as “ability to anticipate”, “ability to adapt”, “ability to respond”, “ability to recover”, and “ability to learn”. In addition, they proposed a supply chain resilience concept map linking capabilities and elements of resilience. Following up on their studies conducted in 2010 and 2013, Pettit et al. (2019) reviewed the current state of supply chain resilience research, discussed life cycle resilience, and suggested further research opportunities. For example, they suggested that new frameworks for supply chain resilience should be developed to indicate industry-specific features, as well as recommending studies on event management systems, behavioral aspects of resilience, disruptive technologies for building resilience, and system interdependencies. Singh et al. (2019) reviewed the literature on supply chain

resilience indicators. After reviewing 55 papers, they classified resilience into three stages: anticipation, resistance and, recovery and response. Anticipation includes capabilities such as visibility, awareness and sustainability, while resistance contains enablers such as flexibility, collaboration, and robustness. Recovery and response are built on velocity, adaptability, and agility. As in many earlier studies, the authors also recommended further research to empirically investigate supply chain resilience.

Lam and Bai (2016) proposed a quality function deployment approach to improve maritime supply chain resilience through customer requirements and maritime risks. They carried out an analysis via in-depth interviews of three major shipping lines and their respective major shippers, concluding the most important resilience factors are contingency plans, monitoring and maintenance, and supply chain relationship management. Building on the theoretical foundations of Pettit et al. (2010), Pettit et al. (2013) developed an assessment tool to assist decision-makers in applying the proposed supply chain resilience framework. To validate the tool, they conducted a numerical example comparing the resilience of seven companies. Rajesh (2019) proposed a fuzzy multi-criteria methodology to measure the resilience of a company in the electronics industry. Based on a literature review, the author identified the attributes (enablers) of supply chain resilience as supply chain risk, collaboration, agility, responsiveness, visibility, velocity, and supply chain efficiency. Agarwal et al. (2020) addressed the enablers to achieve resilient supply chains in the automotive industry. They identified the following list of enablers: flexibility, collaboration, risk management, information sharing, top management support, visibility, agility, use of information technologies, and interoperability. The authors then used The Automated Layout Design Program to explore the relationships among the enablers for a resilient supply chain. In another 2020 study, Piprani et al. employed a two-stage methodology. In the first stage, they reviewed the literature and identified resilient capability factors (enablers) based on experts’ reviews. In the second stage, they used the Analytical Hierarchy Process (AHP) methodology to rank the resilient capability factors in Pakistan’s textile industry. The authors classified the resiliency factors into different dimensions such as readiness (visibility), responsiveness (flexibility and collaboration), and recovery (contingency, social capital and knowledge management) capabilities. They finally calculated the importance weights of each factor for each dimension separately using the AHP. Behzadi et al. (2020) reviewed the existing metrics (enablers) for supply chain resilience and proposed a new metric. The existing metrics included time to recovery, recovery level, and the recovery period, while the new metric focused on the net present value of the loss of profit. Finally, Zamiela et al. (2022) proposed a decision framework to investigate

resilience enablers during the Covid-19 pandemic using a multi-criteria approach in the healthcare supply chain. Their findings indicated that redundancy, collaboration, and robustness are the most important enablers of a resilient supply chain in healthcare supply chains.

In addition to the studies conducted on the enablers of industrial supply chain resilience, research on resilience in energy supply systems was reviewed as the second aspect of the literature review. There are only a few studies on enablers, critical success factors, and barriers for resilience in renewable energy supply chains. For example, Dashtpeyma and Ghodsi (2022) proposed a methodology for energy system efficiency in Iran. They started by identifying the following resilience enablers: integration, risk management, political practices, financial practices, system capacity, vulnerability, sustainable practices, safety performance, logistics capabilities, adaptability, flexibility, visibility, and information sharing. Then, they used data envelopment analysis to measure the effectiveness of alternative strategies in terms of resilience. In another study, Siskos and Burgherr (2021) proposed a multi-criteria decision support tool based on three main energy supply chain resilience dimensions, namely “resist”, “restabilise” and “recover” to measure energy supply resilience. To this end, the authors identified the (evaluation criteria) sub-enablers: “reliability of electricity supply”, “severe accident risks”, “loss of load expectation”, “political stability”, “natural gas importation risk”, “price volatility”, “electricity import dependence”, “average outage times”, “annual gross domestic product growth”, and “government effectiveness”. Then, they evaluated and ranked 35 European countries according to their energy supply resilience on 17 interacting evaluation criteria using the Choquet Integral and the Simos Method.

Mujjuni et al. (2021) reviewed the literature as a basis for proposing a conceptual framework for resilience indicators in Uganda’s electricity supply industry. Some of the indicators of resilience were reliability, redundancy, robustness, flexibility, efficiency, and integration. The proposed framework was then used in a case study evaluating the influence of COVID-19 on Uganda’s electricity supply industry in general. Erol et al. (2021) investigated the critical success factors for enhancing the performance of a blockchain-based SPvESC for a better circular economy in Türkiye using Intuitionistic Fuzzy-DEMATEL. They concluded that effective government incentive programs and regulations are important in implementing effective blockchain-based SPvESCs towards a resilient circular economy in Türkiye. In another study, Erol et al. (2022) investigated the driving and hindering factors for CE adoption in Türkiye’s SPvESC and wind energy supply chain using a decision framework that incorporates Neutrosophic-DEMATEL, Neutrosophic-DELPHI-based Force Field Analysis, and the NGT. The lack of effective incentives and regulations were found to

be the most vital restraining force. Lastly, Dashtpeyma and Ghodsi (2022) explored the resilience of a wind power system using a multi-criteria decision framework. First, they identified eleven enablers. Then, they investigated the link among these enablers using a decision framework based on fuzzy DEMATEL and Analytic Network Process. They concluded that performance is the most important enabler for system resilience.

In addition to the studies focusing on supply chain resilience, note that resilience and sustainability have massive, complicated, significant systemic concerns, and combined implementation efforts should be carefully considered to lower the risk of inadequate performance resulting from a lack of knowledge about their differences and commonalities (Marchese et al. 2018). Note also that the ideas of resilience and sustainability are quite similar. One of the commonalities between sustainability and resilience is that they both discuss the status of a system or feature across time, emphasizing the system’s capacity to persevere both in the face of disruptions and under typical operating settings (Fiksel et al. 2014). According to Bocchini et al. (2014), sustainability and resilience also share research approaches such as life-cycle analysis, structural analysis, and socioeconomic analysis because of their common emphasis on system survival. In order to discover the ways that resilience and sustainability are used together, in this study we embrace one of widely held viewpoints considering resilience as the system’s ultimate goal, with sustainability serving as a catalyst for resilience. In other words, when social, environmental, and economic well-being improve, that vital functioning becomes more resilient to adverse conditions (Bansal and DesJardine 2014). This literature review focuses on several existing quantitative studies regarding the enablers and obstacles for adopting circular economy towards achieving environmental sustainability. Note that improving environmental sustainability ensures more resilience. There are just a few quantitative studies on identifying enablers and barriers for circular economy adoption in solar photovoltaic supply chains. For example, Erol et al. (2022) scrutinized the restraining and driving forces for implementing circular economy in solar photovoltaic supply chains. To achieve that, the authors built an expert group and gathered data on the association among the restraining forces. They also proposed a MCDM framework to finalize the analysis. Finally, they concluded that nonexistence of effective incentives and regulations were the most crucial influencing restraining force. In another study, Aşkın et al. (2023) investigated the enablers that help achieve enhanced recycling performance in solar photovoltaic supply chain. To this end, the authors surveyed a group of experts with 57 people and used a statistical analysis to obtain the most crucial enablers. The authors concluded that “innovative business models for collection, reuse and recycling” turned out to be the most significant enabler.

Based on our review of the literature, we identified the comprehensive list of SPvESC enablers displayed in Table 1. It provides the descriptions and references for each enabler. The list was developed using enablers in renewable energy, as well as other supply chains, discussed throughout this section. As explained later, the list in Table 1 was finalized through expert opinions in the further stages of this study.

2.2 Research gap

The literature review shows that several studies, most of which are conceptual, have been published on the enablers (critical factors) of supply chain resilience in many industries. However, as Ali et al. (2017a, b), Singh et al. (2019), Pettit et al. (2019), Agarwal et al. (2020), Mohammed et al. (2021), and Rahman et al. (2022a, b), Zamiela et al. (2022), have pointed out, customized frameworks for exploring supply chain resilience are needed to account for specific industry characteristics using empirical data. Since SPv is expected to become an increasingly common energy technology and source, building a resilient SPvESC is crucial (Erol et al. 2021; Erol et al. 2022; Dashtpeyma and Ghodsi 2022). Nevertheless, to the best of our knowledge, no study has investigated the enablers for SPvESCs to achieve resilience, including considering their cause-and-effect relationships. Hence, the aim of this study is two-fold: (1) to analytically investigate the enablers of resilience for SPvESCs using expert data, and (2) to develop policy guidelines for SPvESC decision-makers to achieve greater resilience.

3 Methodology

The integrated methodology used in this study is illustrated in Fig. 1. In the first step, the aim of the study was established. In the second step, the comprehensive list of enablers for SPvESC resilience was specified via a literature review. Then, the NGT was applied to finalize the set of enablers. N-DEMATEL was used to analyze and to create an influential relation map of the enablers. In the last step, the results were validated using N-DELPHI.

3.1 Nominal group technique (NGT)

NGT is a qualitative method based on stakeholder judgment. It combines individual and collective knowledge among participants and facilitates reaching quick consensus on the relative importance of the matters under consideration (Hugé and Mukherjee 2018). NGT is an effective tool for balancing participant viewpoints in the decision-making process. The most significant benefit of

this method is that it encourages people to think and make decisions on their own (Bhandari and Hallowell 2021). It generates a list of prioritized actions and/or recommendations (Rankin et al. 2016) and has been employed in a wide range of fields, including healthcare services (Harvey and Holmes 2012), consumer preference research (Coker et al. 2013), health promotion (Hutchings et al. 2013), and criminology (Van der Laenen 2015). The most common applications of NGT are used to clarify the problem for experts, to find out what experts think about the problem, to collect expert opinions, and to make the final decision (Delbecq and Van de Ven 1971). This study employs NGT to develop agreement on the enablers of SPvESCs. The approach is adopted from Rankin et al. (2016) and Hugé and Mukherjee (2018).

3.2 Neutrosophic-DEMATEL (N-DEMATEL)

A structural model with complex causal relationships may be created using the DEMATEL approach. Govindan et al. (2015) and Si et al. (2018) explain that DEMATEL enables decision-makers to divide factors into two major domains: cause and effect. They also argue that examining the inter-linked associations among a network's factors is a robust and effective strategy. When a traditional DEMATEL is used, a decision-maker's subjective opinions may lead to vagueness in the decision-making process (Dutta and Guha 2015). To address information vagueness, Zadeh created the fuzzy set (FS) theory (Zadeh 1965). However, as Abdel-Basset et al. (2018) explained, only the degree of truth membership is considered by fuzzy set theory (i.e., it is unable to initiate the truth or effectively exhibit vague and erratic data). To deal with fuzziness more effectively, Atanassov (1986) introduced intuitionistic fuzzy sets (IFS) as an extension to the fuzzy set theory (Abdullah and Najib 2016). However, because IFS can only handle missing information, they are insufficient to deal with unclear and inconsistent data that is ubiquitous in real-world systems (Akram and Luqman 2017). To this end, Smarandache presented neutrosophic sets (NSs) in 1995, which is the generalization of IFS and FS. NSs are an extension of the IFS. They present and interpret opinions and ambiguity more accurately, where the membership of a value or an element is defined as a number between 0 and 1. More specifically, IFSs use hesitation degree, while NSs are based on indeterminacy degree (Sodenkamp et al. 2018). In other words, "NS moves one step further by examining the membership of truth, the membership of indeterminacy and the non-membership of a member of a given set" (Abdel-Basset et al. 2018). Moreover, NS requires obtaining experts' opinions to assess influences. NS has the following benefits (Deli 2017; Abdel-Basset et al. 2018; Sodenkamp et al. 2018):

Table 1 Initial List of the Enablers for SPvESC Resilience

Enabler	Description	Reference
Business contingency plans (E_1)	A business contingency plan lays out what an organization will do in the event of an unforeseen incident or circumstance, such as natural (weather, earthquake, etc.) and human-made disasters (terror, war, cyber-attacks, etc.). A contingency plan, frequently denoted as “Plan B”, prepares an organization for whatever may occur, whereas a crisis management plan prepares an organization to deal with the aftermath of a disaster. Effective business contingency plans, based on potential supply chain vulnerabilities and bottlenecks, should be devised for building resilience in SPvESCs.	Pettit et al. (2010), Chopra and Sodhi (2004), Rajesh (2019).
Legislation & incentive programs (E_2)	Governments should enact effective legislation and incentive programs to spur further development of SPvESCs. New regulatory frameworks and incentive mechanisms should enable companies to implement new business models towards improved resilience through disruptive technologies.	Leisen et al. (2019), Siskos and Burgherr (2021).
Occupational health and safety systems (OHSAS) (E_3)	Implementing effective OHSAS helps supply chains become more resilient. Effective OHSAS can help in detecting and minimizing hazards, reducing staff absences due to less illness and injury, and improving employee morale and relations. Implementing an effective OHSAS reduces the likelihood of accidents or injuries, potentially increases efficiency and productivity, and contributes to a safer and a less stressful workplace.	Seixas de Siqueira et al. (2015), Peciilo (2016), Siskos and Burgherr (2021).
Cost effectiveness and resource efficiency (E_4)	Cost effectiveness is a form of economic analysis that compares the relative costs and outcomes (effects) of different courses of action. Resource efficiency supports cost effectiveness through, for example, less waste of materials, components, and products. Hence, enhanced resource efficiency and more cost-effective operations can free funds to pursue further improvements towards more resilience.	Pettit et al. (2010), Vugrin et al. (2011), Sinha and Ghosh (2024).
Economic robustness at local and global levels (E_5)	Businesses must examine and respond to changes in economic conditions. Economic growth is defined as an increase in the value of an economy's goods and services through time. It can provide opportunities for increased profits, improved business confidence, enhanced technological innovation and increased capital investment. Hence, better economic growth ensures more resilient supply chains.	Vugrin et al. (2011).

Table 1 (continued)

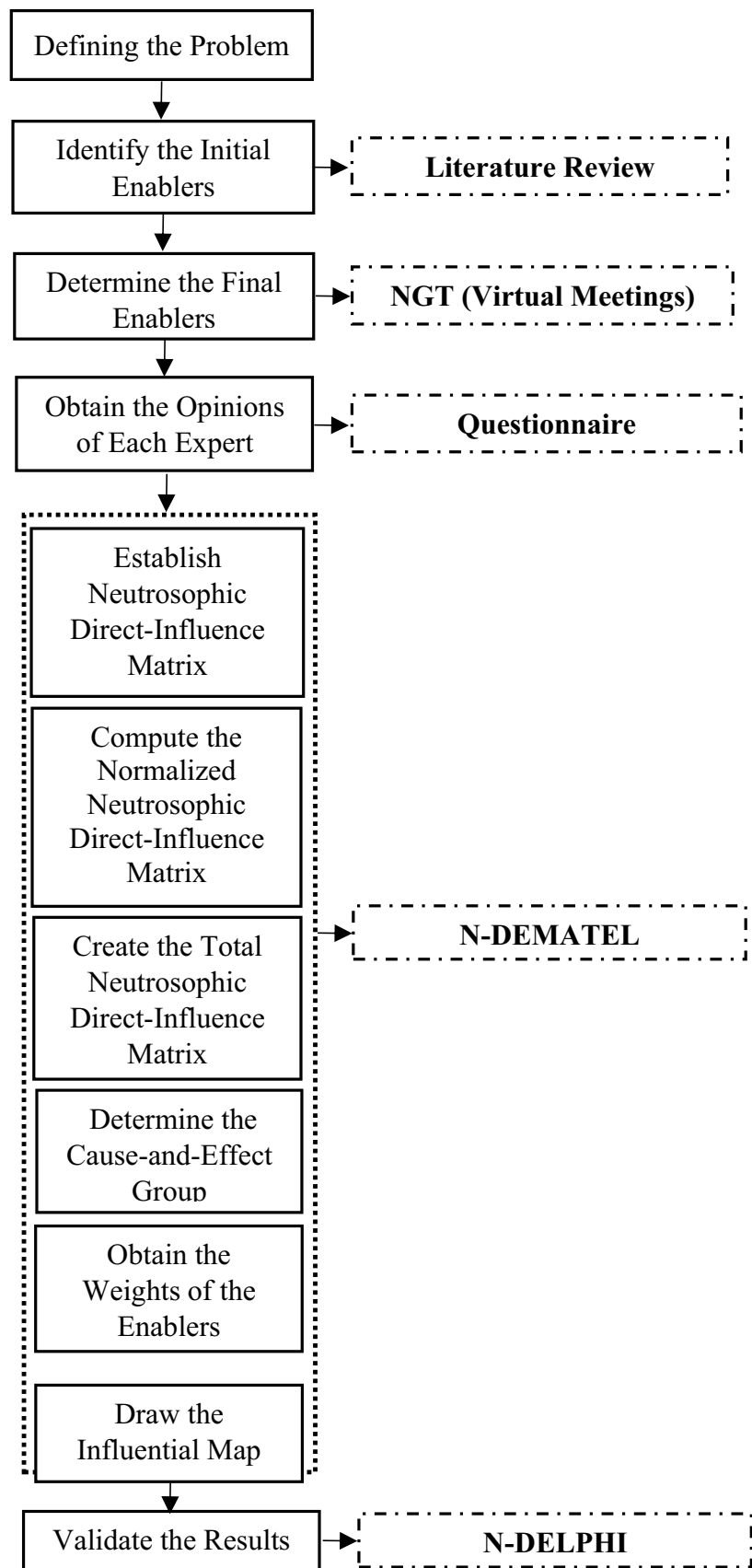
Enabler	Description	Reference
Human capital management (E_6)	People are viewed as capital in human capital management, which means that firms can develop their capital by investing in employees. Human capital management assists companies in hiring the best employees. Human capital management practices have a critical role in employee performance, including knowledge and skill development through training and development, compatibility and competency through recruiting and selection, and confidence and morale through performance appraisal. Effective human capital management can have an important impact on improving the resiliency of a supply chain.	Chuang et al. (2015), Zeb et al. (2018), Djunaidi et al. (2021).
Preventive maintenance management (E_7)	Preventive maintenance seeks to foresee and prevent catastrophic equipment breakdowns before they happen. An increase in equipment efficiency is a key outcome of a preventative maintenance strategy. Routine maintenance, such as basic inspections, oil and fluid changes, and part replacements, can increase the likelihood that equipment runs smoothly. Managing preventive maintenance effectively helps improve the overall resiliency of a supply chain.	Ma et al. (2007), Lazim et al. (2016), Badiea et al. (2020).
Adaptability to the changes in novel energy generation and information technologies (E_8)	Adaptability here refers to the ability to adjust swiftly to shifting trends, innovation, destabilization, and the solar industry developments, among other things. This ability to change or shift makes an overall SPvESC nimble, which is vital in today's world where industries can be unstable. Technical innovations include product, process, information technologies innovations, and adaptability to these new technologies help managers in building a resilient SPvESC.	Szabo (2017), Melane-Lavado et al. (2018).
Transmission line capacity (E_9)	The importance of electric power transmission line systems in SPvESCs cannot be overstated. Electricity is transported from power plants to end users via transmission lines. Power outages can occur as a result of infrastructure failures, with significant implications for citizens and industry. Understanding these systems' structural behavior under diverse stresses is essential. Supply chains require adequate transmission line capacity to improve the resilience of SPvESCs.	Bryant (2016).

Table 1 (continued)

Enabler	Description	Reference
Generation-integrated energy storage systems (GIES) (E_{10})	Energy storage will play a vital role in future electricity systems as they decarbonize. Energy is stored in generation-integrated energy storage systems at some point during the conversion from a primary energy type to electricity. In terms of performance and total cost, GIES systems outperform comparable non-integrated systems including both generation and storage. Affordable and secure low-carbon generation systems with effective storage structures, such as GIES, are critical in building sustainable and resilient SPvESCs.	Garvey et al. (2015), Erol et al. (2022).
Sensing and seizing new business models (E_{11})	The way a company integrates, grows, and reorganizes internal and external capabilities to respond to changing business conditions is determined by its dynamic capabilities. Dynamic capabilities characterize a company's ability to innovate, adapt to change, and produce change that benefits customers while staying ahead of competitors. Sensing, seizing, and transforming the supply chain in response to changing conditions is essential if it is to build greater resilience.	Teece et al. (1997), Teece (2007).
Circular economy practices (E_{12})	By decreasing waste, the circular economy allows supply chains to optimize linear networks and build creative business models that improve environmental, societal, and economic performance. The circular economy's business models have three basic functions: "circular design", "circular use", and "circular recovery". To achieve resilient SPvESCs, decision-makers must address circular design, use, and recovery simultaneously.	Teufel et al. (2019), Gentilini and Salt (2019), Erol et al. (2021).
Supply chain visibility and traceability (E_{13})	Supply chain visibility and traceability refers to the capability to track components, final products, and services as they move from supplier to manufacturer to customer. Companies can use this data to minimize inventory shortages, alleviate bottlenecks, meet regulatory requirements, and follow items from start to finish. Enhanced visibility and traceability is critical for building resilient SPvESCs.	Lam and Bai (2016), Ahl et al. (2019), Casion et al. (2019), Erol et al. (2021).
Trust and collaboration (E_{14})	When it comes to preserving the integrity of any supply chain, customers need to know that their suppliers will deliver their goods on time and at the agreed-upon price. Buyers must also treat their suppliers with respect by doing everything possible to make payments according to agreed-upon terms. Trust in the supply chain increases supply chain collaboration, which has a favorable impact on SPvESC resilience. Supply chain collaboration occurs when supply chain partners work together to achieve a common goal.	Mentzer et al. (2011), Chen et al. (2017), Erol et al. (2021).

Table 1 (continued)

Enabler	Description	Reference
Policy making and top management commitment towards resilience (E_{15})	Management commitment refers to top management's direct involvement and support for crucial components or programs in an organization, such as safety, quality, environment, and security. Building a resilient supply chain through sustainability requires commitment from top management towards the financial, ecological, and societal goals of SPvESCs.	Neutzling et al. (2018), Lim and Sonko (2019).
System performance monitoring (E_{16})	Monitoring the operation of a Grid-Connected Utility-Scale PV power plant in real time to ensure a reliable and uninterrupted power supply plays an important role in SPvESCs' resilience. This technology not only allows for improved control of all PV plant components' performance by identifying any failures or deviations in production, but it also checks the power quality of the injected signal and its impact on the distribution grid. Among other things, it also provides data on energy generation and consumption, energy efficiency, and solar system damage.	Moreno-Garcia et al. (2016), Erol et al. (2022).
Energy pricing policy (E_{17})	End-users become more motivated to conserve energy if energy prices represent the true cost of energy, and the energy supply chain should be working to allocate energy to activities offering the most value. When developing a pricing framework, consider that there are many factors that influence market pricing. For example, due to seasonal cycles and occasional moments of volatility, the system is complicated and constantly changing. Decision-makers can choose the proper approach towards enhanced resilience for their supply chain if they understand the existing and predicted market conditions that affect energy pricing.	Tsao et al. (2021), Kuznetsova and Anjos (2021), Siskos and Burgherr (2021).

Fig. 1 The proposed methodology

- It presents the indeterminacy degree, which aids experts in expressing their viewpoints.
- It depicts the degree to which decision-makers disagree, as well as combining the distinct interests of decision-makers into one opinion in order to reduce inconsistencies or resolve inconsistencies in expert judgments.
- Three distinct membership functions, namely refusal, approval, and vagueness, distinguish single-valued NSs.
- Since they effectively display positive, negative, and uncertain information, NSs are more adaptable than IFSs.
- Since vagueness is clearly measured, it can address uncertain and variable information.

In the decision-making process, NSs have a significant ability to tackle indeterminacy and ambiguity (Liu et al. 2018; Kilic and Yalcin 2021). This study therefore utilizes N-DEMATEL to ascertain the associations amongst enablers. The stages of the N-DEMATEL method are presented as follows (Abdel-Basset et al. 2018; Awang et al. 2019):

1. Specify the problem structure by defining the criteria and alternatives.
2. Build the *matrix* A^G based on the scale exhibited in Table 2. Table 2 shows the collection of each expert's evaluation about the influence of one factor over the other factor.

$$A^G = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}$$

In A^G matrix, a_{ij} is a 1×3 vector and represents the level of impact that factor i has on factor j in the form of T_{ij} , I_{ij} , and F_{ij} . T_{ij} , I_{ij} , and F_{ij} were designated as “truth-membership”, “indeterminacy-membership”, and “falsity-membership” values, respectively.

3. Obtain the normalized Neutrosophic direct-influence matrix (B) by Eqs. (1) and (2)

$$B = k.A^G \quad (1)$$

$$k = \text{Min} \left(\frac{1}{\max \sum_{j=1}^n |X_{z_{ij}}|}, \frac{1}{\max \sum_{i=1}^n |z_{x_{ij}}|} \right) \quad i \text{ and } j = 1, 2, 3, \dots, n \quad (2)$$

Therefore, when the normalization is conducted, the truth-membership values of the combined direct influence matrix are used to determine the k value. The normalized matrix is then obtained by doing the multiplication (Kilic and Yalcin 2021).

4. Create the Total Neutrosophic direct-influence matrix (S) by using Eq. (3)

$$S = B + B^2 + B^3 + B^4 + \cdots + B^m = B.(I-B)^{-1} \quad (m \rightarrow \infty) \quad (3)$$

where I denotes the identity matrix.

S is developed as follows: $S = \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nn} \end{bmatrix}$. In S matrix, s_{ij} is a 1×3 vector and a SVNN in the form of T_{ij} , I_{ij} , and F_{ij} .

Related operations are performed independently for each element in a neutrosophic set using Eqs. (4)–(6) (Kilic and Yalcin 2021).

$$[T_{ij}] = B_T.(I-B_T)^{-1} \quad (4)$$

$$[I_{ij}] = B_I.(I-B_I)^{-1} \quad (5)$$

$$[F_{ij}] = B_F.(I-B_F)^{-1} \quad (6)$$

Before the deneutrosophication step, the values of truth-membership, indeterminacy membership, and falsity-membership are merged to produce the entire direct-influence matrix, S .

5. Obtain the vector D and R using the Eqs. (7)–(8)

Table 2 Linguistic Terms and Their Corresponding Single-Valued Neutrosophic Numbers (SVNN) (Awang et al. 2019)

Classical DEMATEL	Definition of Linguistic Terms	SVNN		
		Truth-membership (T)	Intermediacy-membership (I)	Falsity-membership (F)
4	Very high influence (VHI)	0.90	0.10	0.10
3	High influence (HI)	0.80	0.20	0.15
2	Medium influence (MI)	0.50	0.40	0.45
1	Low influence (LI)	0.35	0.60	0.70
0	No influence (NI)	0.10	0.80	0.90

$$D = [d_i]_{n \times 1} = \left[\sum_{j=1}^n S_{ij} \right]_{n \times 1} \quad (7)$$

$$R = [r_j]_{n \times 1} = \left[\sum_{i=1}^n S_{ij} \right]_{1 \times n} \quad (8)$$

The aggregate impact of the i_{th} factor on the rest of the factors is signified by the total of the i_{th} row, which is denoted by d_i . The entire influence of the criteria by other criteria is characterized by r_j , which is the sum of the j_{th} column. The greatest $(D + R)$ number indicates that it is highly related to other factors/criteria and plays a significant role. The cause group is formed when the value of the criteria $(D - R)$ is positive and has a considerable impact on other criteria. The effect group is defined by negative values of $(D - R)$ for specific criteria, implying that they are influenced by others (Erol et al. 2021).

The deneutrosophication values of T , F , and I are calculated by using the transformation formula given in Eq. (9).

$$X = T_{ij} - I_{ij} + (2\alpha - 1)F_{ij} \quad (9)$$

6. Perform normalization by using the Eqs. (10) and (11) and compute the weights of the enablers (criteria)

$$w_i = \left[(D_i + R_i)^2 + (D_i - R_i)^2 \right]^{0.5} \quad (10)$$

$$W_i = \frac{w_i}{\sum w_i} \quad (11)$$

7. Establish a limit to draw an *Influential Relation Map (IRM)*: Decision-makers must come up with a threshold value (α) to simplify the entire relation matrix (S) and avoid the complexity of insignificant impacts. Ascertaining a proper threshold (α) is important. There will be no influence on the IRM if the threshold (α) is discovered to be too high. Yet, if it is too small, the number of factors in the IRM escalates, and the map will become extremely sophisticated. Based on Eq. (12), the average of the S -matrix where N is the total number of the elements in the S -matrix, is computed threshold (α) (Erol et al. 2021).

$$\alpha = \frac{\sum_{i=1}^n \sum_{j=1}^n T_{ij}}{N} \quad (12)$$

3.3 Neutrosophic-DELPHI (N-DELPHI)

The Delphi technique is utilized to facilitate structured group dialogue to attain expert agreement in complicated decision-making environments containing unclear contexts (Erol et al. 2021). In this study, N-DELPHI based on Smarandache et al. (2020) is utilized to validate the results of N-DEMATEL. N-DELPHI is an add-on that helps “with group

decision-making” and “data ambiguity”. In N-DELPHI, the results from N-DEMATEL are introduced to experts. Then, each expert examines the outcomes and determines if they are in harmony with their understanding of the enabler-to-enabler relationships. This assessment includes surveys that ask experts how much they agree with the associative linkages discovered by N-DEMATEL.

4 Application and the results

This section provides details on the results of applying the methodology shown in Fig. 1. The main goal of this study is to investigate the enablers of resilience for SPvESCs, including addressing their cause-and-effect relationships. Then, based on the findings, the implications of the study are explored.

4.1 Enablers

In this stage, the enablers for SPvESCs to achieve greater resilience were identified. This was done through a review of existing studies, followed by employing the NGT informed by expert data. In this study, experts were defined as a group of respondents possessing satisfactory knowledge, research, and hands-on experience with respect to SPvESCs. The selected experts included researchers, decision-makers, and practitioners. The experts were identified through purposive sampling supplemented with snowball recruitment. To this end, we carried out an extensive search and investigation process, finishing with the experts identified in Table 3. Note that the experts included academics and company managers employed in various universities, and solar energy and software companies, respectively. This ensured a strong cross-section of views on the emerging issues studied in this paper.

There is no specific rule for deciding how many experts to contact (Bulut and Duru 2018), however, the wide range of experts included in our study allowed us to address our research questions. Campagne et al. (2017) indicated that an increased number of experts may be favorable, but expert groups with a limited number of experts can still provide consistent evaluations. In other words, finding the right experts who have satisfactory understanding and knowledge on a specific topic is the most important consideration.

Table 1 displays the initial list of enablers and their detailed explanations. The NGT analysis was conducted with the expert group through an online meeting. This meeting took approximately an hour. The experts discussed the list of enablers shown in Table 1 during the meeting to see how thorough they were and concluded that no revision was required. Table 4 summarizes the ultimate set of the enablers.

Table 3 The Expert Group

Group	Number	Characteristics
Academics	7	They are professors at several universities in Türkiye, who have written academic articles on supply chains for renewable energy sources.
Company managers employed by software companies	5	They have been conducting projects in improving renewable energy supply chains for almost 15 years. They also have an average of 7 years of experience in digital transformation in renewable energy supply chains.
Senior managers employed by SPvESC companies	8	Their years of experience in SPvESCs range from 10 to 15.

4.2 Analysis

In this stage, the N-DEMATEL steps shown in Fig. 1 were applied sequentially. Their details are presented below as follows: Data for this study were collected from the expert group via a questionnaire, which was based on the enablers displayed in Table 4. The questionnaire asked the experts to assess the impact of the enablers on each other by considering the scale in Table 2. The neutrosophic direct influence matrix A^G was established by combining the assessments of the expert group obtained by utilizing Table 2. Table 5 shows an example of a decision-maker's direct influence matrix.

The normalized neutrosophic direct-influence matrix (B) exhibited in Table 6 was calculated using Eqs. (1) and (2). After this matrix has been built, the total neutrosophic

Table 4 Final List of the Enablers for SPvESC Resilience

Code	Enablers
E_1	Business contingency plans
E_2	Legislation & incentive program
E_3	Occupational Health and Safety Systems (OHSAS)
E_4	Cost effectiveness and resource efficiency
E_5	Economic robustness at local and global levels
E_6	Human capital management
E_7	Preventive maintenance management
E_8	Adaptability to the changes in novel energy generation and information technologies
E_9	Transmission line capacity
E_{10}	Generation-integrated energy storage systems (GIES)
E_{11}	Sensing and seizing new business models
E_{12}	Circular economy practices
E_{13}	Supply chain visibility and traceability
E_{14}	Trust and collaboration
E_{15}	Policymaking and top management commitment towards resilience
E_{16}	System performance monitoring
E_{17}	Energy pricing policy
E_{18}	Supply chain financial risk management

direct-influence matrix (S) in Table 7 was calculated using Eqs. (3)–(6).

$D + R$ and $D - R$ values summarized in Table 8 were calculated by using Eqs. (7) and (8). Table 8 signifies the associations among the enablers by using the $D + R$ and $D - R$ values.

The importance weights of the enablers were obtained by using Eqs. (9)–(11) as shown in Fig. 2. Figure 2 shows that “*Adaptability to changes in novel energy generation and information technologies*” (E_8) was ranked first.

Based on the results of Table 8 and Fig. 2, the enablers are categorized into three classes including “prominent”, “influencing (cause)”, and “resulting (effect) enablers”. High prominence enablers receive a higher $D + R$ value, indicating a closer relationship with the other enablers. Supply chain executives should pay particular attention to these enablers since they have a significant influence on the other enablers, resulting in increased SPvESC resilience. Influencing (cause) enablers continue to have the highest positive $D - R$ value, indicating that they have stronger relationships with the other enablers. Additionally, they have a substantial impact on the other enablers due to having the largest positive $D - R$ values. The resulting (effect) ones, on the other hand, are considered as the most influenced enablers. Simply put, SPvESC decision makers should only address them after responding to the influencing enablers. This classification was demonstrated in Table 9.

Lastly, the relationships among the enablers were established according to their $D - R$ values as demonstrated in Fig. 3. In Fig. 3, x and y coordinates represent $D - R$ values. Accordingly, the cause group is formed when the $D - R$ value of the criteria is positive and has a considerable impact on other criteria. The effect group is defined by the negative $D - R$ values for specific criteria, implying that they are influenced by the others.

4.3 Validating the results

Once the associations between the enablers were identified, the results were validated. In this study, N-DELPHI was used as shown in Fig. 1. To avoid group members interacting with one another, survey forms were developed and directed

Table 5 Neutrosophic Direct Influence Matrix A^G

Enablers	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}
E_1	NI	NI	MI	MI	NI	MI	LI	MI	MI	LI	HI	NI	HI	LI	MI	LI	LI	LI
E_2	MI	NI	LI	MI	NI	LI	LI	MI	MI	MI	MI	MI	MI	LI	LI	LI	MI	LI
E_3	MI	MI	NI	MI	LI	MI	LI	LI	NI	NI	MI	NI	LI	LI	MI	NI	LI	NI
E_4	LI	MI	LI	NI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	MI	LI	LI	LI
E_5	MI	MI	NI	LI	NI	MI	LI	MI	HI	MI	MI	MI	HI	MI	MI	LI	MI	HI
E_6	LI	LI	MI	LI	MI	NI	MI	HI	LI	LI	VHI	MI	MI	MI	MI	LI	LI	LI
E_7	LI	MI	LI	NI	MI	LI	NI	LI	NI	NI	LI	LI	MI	LI	MI	LI	MI	MI
E_8	MI	MI	MI	LI	HI	LI	MI	NI	HI	HI	HI	MI	VHI	MI	MI	HI	MI	LI
E_9	MI	MI	LI	LI	HI	LI	LI	HI	NI	HI	LI	NI	MI	LI	MI	NI	LI	MI
E_{10}	LI	MI	LI	LI	HI	LI	LI	HI	LI	NI	LI	LI	LI	NI	MI	MI	MI	LI
E_{11}	MI	LI	MI	LI	HI	LI	MI	HI	MI	HI	NI	HI	LI	LI	MI	LI	MI	LI
E_{12}	MI	MI	HI	LI	HI	LI	MI	HI	LI	LI	HI	NI	NI	LI	MI	NI	LI	LI
E_{13}	MI	MI	HI	LI	HI	MI	MI	HI	LI	NI	VHI	HI	NI	MI	MI	LI	MI	HI
E_{14}	MI	MI	MI	MI	HI	LI	LI	HI	LI	LI	VHI	LI	HI	NI	MI	MI	HI	H
E_{15}	LI	LI	MI	LI	NI	MI	MI	VHI	MI	MI	HI	MI	HI	MI	NI	LI	MI	LI
E_{16}	MI	MI	LI	NI	HI	LI	LI	HI	HI	NI	HI	LI	MI	LI	LI	NI	MI	LI
E_{17}	MI	MI	MI	MI	HI	HI	LI	HI	MI	MI	HI	LI	HI	MI	MI	MI	NI	LI
E_{18}	LI	MI	LI	LI	HI	MI	NI	HI	LI	LI	HI	LI	LI	LI	MI	LI	MI	NI

to the Expert Panel provided in Table 3. On a 1–7-point Likert scale, the experts were asked to rate their level of agreement with the N-DEMATEL results (1: strongly disagree, ..., 7: absolutely agree). The answers in the first round were employed to compute “the median”, “first quartile”, “third quartile”, and “range statistics”. In the second phase, each expert’s responses were considered when a revised questionnaire was built. The results from the first round

were communicated to the experts, and they were given the chance to revise their comments. In the second round, however, none of the experts changed their assessments. These findings are displayed in Table 10.

Two-round N-DELPHI involves range values, which are designated as the difference between the first and third quartiles. They serve as the primary indicators of consensus when their values are lower than 1.5 (Ab Latif et al.

Table 6 Normalized Neutrosophic Direct-Influence Matrix (B)

Enablers	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}
E_1	0.000	0.000	0.040	0.048	0.008	0.040	0.024	0.048	0.040	0.032	0.073	0.008	0.073	0.016	0.048	0.032	0.024	0.032
E_2	0.048	0.000	0.032	0.048	0.008	0.032	0.032	0.048	0.048	0.048	0.040	0.040	0.048	0.024	0.024	0.024	0.048	0.032
E_3	0.040	0.040	0.000	0.048	0.016	0.048	0.032	0.032	0.000	0.000	0.056	0.000	0.024	0.032	0.048	0.000	0.016	0.000
E_4	0.032	0.040	0.016	0.000	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.048	0.032	0.032	0.032
E_5	0.048	0.048	0.008	0.008	0.000	0.056	0.032	0.056	0.073	0.056	0.056	0.040	0.073	0.040	0.048	0.016	0.048	0.065
E_6	0.024	0.016	0.040	0.016	0.040	0.000	0.056	0.073	0.024	0.024	0.089	0.048	0.056	0.048	0.040	0.032	0.008	0.024
E_7	0.024	0.040	0.032	0.008	0.056	0.024	0.000	0.032	0.000	0.000	0.032	0.024	0.056	0.032	0.048	0.024	0.056	0.040
E_8	0.048	0.040	0.056	0.016	0.065	0.032	0.056	0.000	0.073	0.081	0.065	0.040	0.089	0.056	0.048	0.081	0.040	0.032
E_9	0.040	0.040	0.032	0.016	0.065	0.032	0.024	0.065	0.000	0.065	0.032	0.008	0.048	0.016	0.048	0.000	0.024	0.048
E_{10}	0.024	0.032	0.024	0.016	0.065	0.032	0.032	0.065	0.016	0.000	0.032	0.032	0.032	0.000	0.048	0.056	0.040	0.032
E_{11}	0.048	0.056	0.048	0.016	0.065	0.032	0.056	0.065	0.040	0.073	0.000	0.081	0.024	0.016	0.048	0.032	0.056	0.032
E_{12}	0.040	0.040	0.073	0.016	0.065	0.032	0.040	0.065	0.032	0.016	0.065	0.000	0.000	0.024	0.048	0.008	0.032	0.032
E_{13}	0.048	0.040	0.081	0.040	0.065	0.056	0.040	0.065	0.016	0.000	0.089	0.081	0.000	0.056	0.048	0.032	0.040	0.065
E_{14}	0.040	0.040	0.048	0.032	0.065	0.032	0.016	0.065	0.016	0.024	0.089	0.032	0.065	0.000	0.048	0.048	0.073	0.081
E_{15}	0.032	0.024	0.040	0.008	0.008	0.040	0.040	0.097	0.040	0.040	0.073	0.056	0.073	0.056	0.000	0.032	0.040	0.032
E_{16}	0.040	0.040	0.016	0.016	0.065	0.032	0.024	0.065	0.065	0.000	0.065	0.032	0.056	0.016	0.024	0.000	0.048	0.032
E_{17}	0.048	0.048	0.048	0.040	0.065	0.065	0.032	0.065	0.056	0.048	0.065	0.032	0.065	0.056	0.048	0.056	0.000	0.032
E_{18}	0.024	0.040	0.032	0.016	0.065	0.056	0.008	0.065	0.032	0.024	0.065	0.032	0.032	0.032	0.048	0.024	0.056	0.000

Table 7 Total Neutrosophic Direct-Influence Matrix (S)

Enablers	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}
E_1	1.392	0.378	0.488	0.333	0.499	0.477	0.408	0.674	0.441	0.417	0.728	0.412	0.631	0.374	0.542	0.388	0.448	0.439
E_2	0.500	1.391	0.490	0.347	0.521	0.481	0.436	0.697	0.474	0.464	0.694	0.479	0.610	0.401	0.518	0.388	0.510	0.456
E_3	0.368	0.352	1.304	0.274	0.378	0.387	0.332	0.492	0.274	0.270	0.548	0.296	0.422	0.318	0.425	0.246	0.332	0.283
E_4	0.430	0.428	0.415	1.227	0.511	0.438	0.397	0.611	0.410	0.397	0.620	0.426	0.533	0.381	0.512	0.367	0.442	0.420
E_5	0.607	0.583	0.561	0.335	1.637	0.635	0.533	0.878	0.620	0.581	0.889	0.591	0.793	0.524	0.684	0.462	0.622	0.624
E_6	0.492	0.460	0.543	0.302	0.623	1.451	0.515	0.791	0.461	0.451	0.835	0.536	0.668	0.476	0.586	0.429	0.479	0.478
E_7	0.416	0.428	0.446	0.246	0.550	0.428	1.334	0.607	0.351	0.334	0.623	0.414	0.576	0.387	0.510	0.350	0.486	0.434
E_8	0.686	0.646	0.722	0.399	0.851	0.670	0.645	1.885	0.691	0.683	1.018	0.664	0.919	0.615	0.771	0.638	0.690	0.643
E_9	0.480	0.461	0.480	0.280	0.611	0.478	0.416	0.720	1.382	0.494	0.672	0.419	0.611	0.384	0.555	0.342	0.462	0.483
E_{10}	0.439	0.436	0.450	0.269	0.597	0.463	0.420	0.701	0.410	1.358	0.653	0.450	0.565	0.345	0.536	0.432	0.478	0.438
E_{11}	0.599	0.591	0.619	0.345	0.740	0.582	0.570	0.873	0.557	0.599	1.765	0.645	0.695	0.471	0.674	0.482	0.627	0.550
E_{12}	0.488	0.469	0.559	0.285	0.613	0.482	0.453	0.725	0.450	0.414	0.737	1.401	0.530	0.404	0.562	0.354	0.483	0.454
E_{13}	0.653	0.615	0.736	0.424	0.801	0.681	0.591	0.950	0.560	0.513	1.016	0.704	1.710	0.595	0.735	0.521	0.654	0.660
E_{14}	0.626	0.603	0.661	0.401	0.790	0.628	0.531	0.933	0.555	0.549	0.994	0.609	0.816	1.478	0.718	0.547	0.701	0.678
E_{15}	0.559	0.522	0.603	0.323	0.633	0.581	0.532	0.912	0.539	0.528	0.887	0.599	0.764	0.537	1.569	0.478	0.587	0.542
E_{16}	0.514	0.493	0.486	0.299	0.653	0.508	0.445	0.764	0.538	0.408	0.776	0.493	0.662	0.411	0.544	1.357	0.537	0.486
E_{17}	0.662	0.636	0.683	0.429	0.816	0.703	0.583	0.967	0.644	0.611	0.984	0.627	0.849	0.600	0.743	0.578	1.586	0.617
E_{18}	0.494	0.503	0.525	0.305	0.663	0.562	0.427	0.783	0.488	0.462	0.795	0.506	0.632	0.451	0.600	0.418	0.562	1.431

2017). Hence, since the range values displayed in Table 10 are less than 1.5, the associations between the enablers based on N-DEMATEL were validated. In other words, given the findings of Table 10, it can be concluded that the cause-and-effect group distributions of the enablers are verified.

5 Discussion and implications

Prominent enablers have high prominence D + R values, suggesting a greater association with the other enablers. Since prominent enablers considerably impact the other

Table 8 D + R and D-R Values of the Enablers

Code	Enablers	D + R	D-R	Cause (C) / Effect (E)
E_1	Business contingency plans	19.872	0.935	C
E_2	Legislation & incentive program	19.850	0.138	C
E_3	Occupational Health and Safety Systems (OHSAS)	18.071	0.771	C
E_4	Cost effectiveness and resource efficiency	15.789	-2.141	E
E_5	Economic robustness at local and global levels	24.646	0.329	C
E_6	Human capital management	21.206	0.057	C
E_7	Preventive maintenance management	18.490	0.648	C
E_8	Adaptability to the changes in novel energy generation and information technologies	28.797	1.126	C
E_9	The capacity of transmission lines	19.573	0.111	C
E_{10}	Generation-integrated energy storage systems (GIES)	18.971	0.092	C
E_{11}	Sensing and seizing new business models	27.219	3.250	C
E_{12}	Circular economy practices	20.132	0.408	C
E_{13}	Supply chain visibility and traceability	26.104	-0.132	E
E_{14}	Trust and collaboration	21.971	-3.666	E
E_{15}	Policymaking and top management commitment towards resilience	23.477	0.091	C
E_{16}	System performance monitoring	19.151	-1.595	E
E_{17}	Energy pricing policy	24.002	-2.634	E
E_{18}	Supply chain financial risk management	20.724	-0.490	E

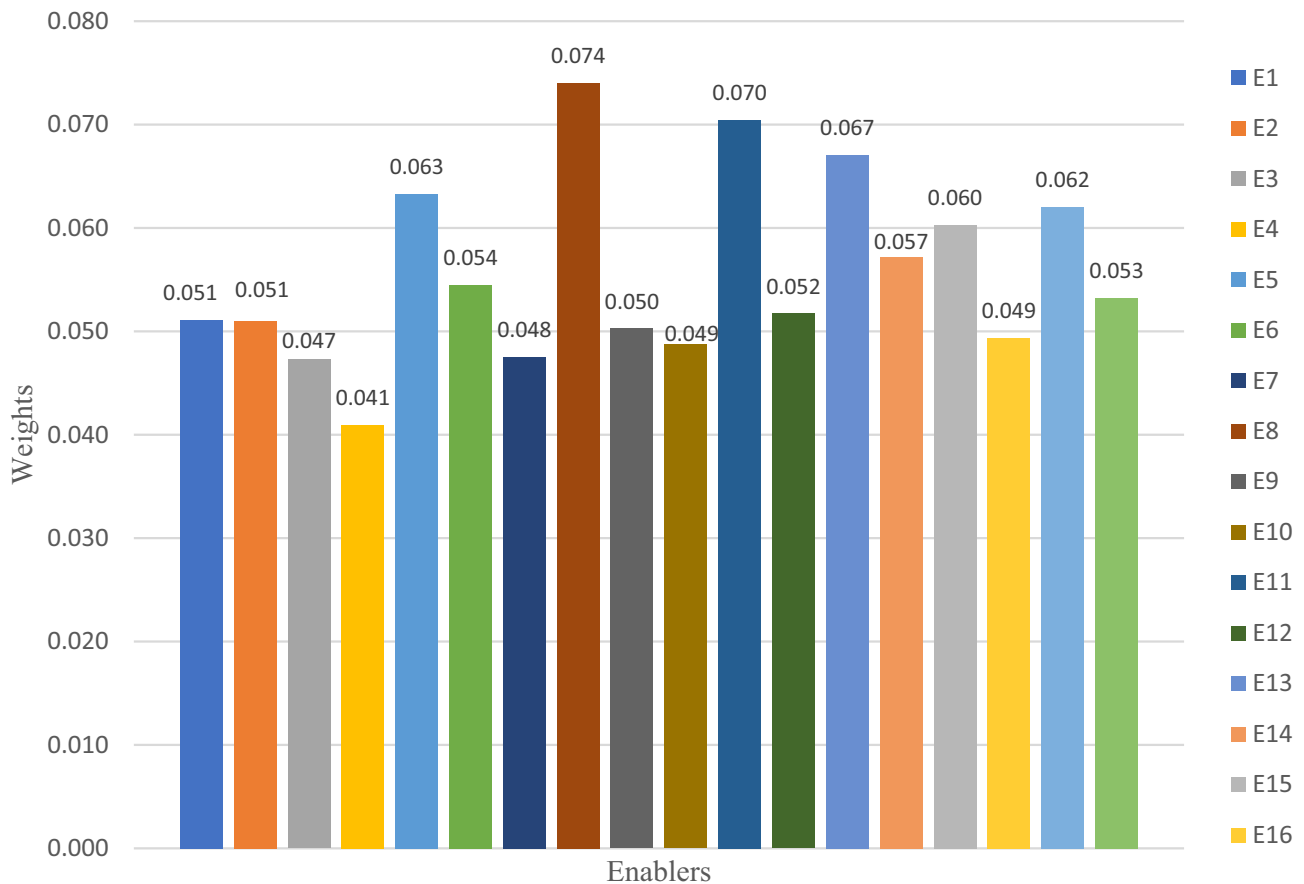


Fig. 2 The Weights of the Enablers

enablers, supply chain executives should pay close attention to them to ensure improved resilience in SPvESC. Thus, it is sufficient to consider the $D+R$ values to find the answer to the first research question (RQ1). Tables 8 and 10 indicated that Adaptability to the changes in novel energy generation and information technologies (E8), Sensing and seizing new business models (E11), and Supply chain visibility and traceability (E13) were the most prominent enablers. These findings reflect earlier literature (Dashtpeyma and Ghodsi 2019) that adaptability to innovative technologies and building new business models suited with them are crucial to improving resilience through greater visibility and traceability, though it extends that literature by focusing in particular on

SPvESC. The results also imply that capability to visualize and share information across SPvESCs should be improved to develop more resilient operations, which is in line with findings in another context from Perrons and Cosby (2020).

Tables 8 and 10 also revealed the following influencing factors: Sensing and seizing new business models (E_{11}), Adaptability to the changes in novel energy generation and information technologies (E_8), Business contingency plans (E_1), Occupational Health and Safety Systems (OHSAS) (E_3), Preventive maintenance management (E_7), Circular economy practices (E_{12}), Economic growth rate at local and global levels (E_5), Legislation & incentive program (E_2), Transmission line capacity (E_9),

Table 9 Classification of the Enablers

Type	Ranks
Prominent	$E_8 > E_{11} > E_{13} > E_5 > E_{17} > E_{15} > E_{14} > E_6 > E_{18} > E_{12} > E_1 > E_2 > E_9 > E_{16} > E_{10} > E_7 > E_3 > E_4$
Influencing (Cause)	$E_{11} > E_8 > E_1 > E_3 > E_7 > E_{12} > E_5 > E_2 > E_9 > E_{10} > E_{15} > E_6$
Resulting (Effect)	$E_{14} > E_{17} > E_4 > E_{16} > E_{13} > E_{18}$

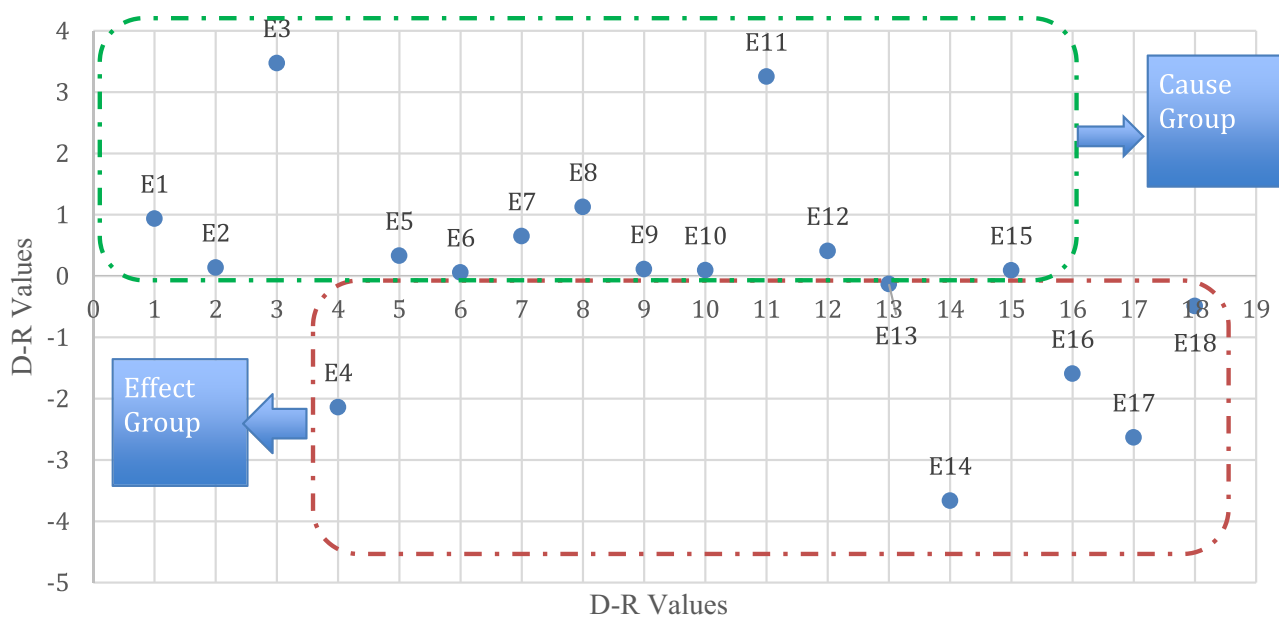


Fig. 3 The Relationship Map of the Enablers

Generation-integrated energy storage systems (GIES) (E_{10}), Policymaking and top management commitment towards supply chain resilience (E_{15}), and Human capital management (E_6). These enablers retain higher $D + R$

values, implying that they exhibit greater associations with the rest of the enablers. Furthermore, due to their $D-R$ being positive values, it is clear that these enablers significantly influence the other enablers. Therefore, they

Table 10 N-DELPHI Results

Code	Enablers	N-DEMATEL		IF-DELPHI ANALYSIS			
		Cause/Effect	Weight	First Quartile	Third Quartile	Range	Median
E_1	Business contingency plans	C	0.051	5.7	7	1.3	6.25
E_2	Legislation & incentive program	C	0.051	5.7	7	1.3	6.28
E_3	Occupational Health and Safety Systems (OHSAS)	C	0.047	5.6	7	1.4	6.15
E_4	Cost effectiveness and resource efficiency	E	0.041	5.9	7	1.1	6.43
E_5	Economic robustness at local and global levels	C	0.063	7	7	0	7
E_6	Human capital management	C	0.054	6	7	1	6.53
E_7	Preventive maintenance management	C	0.048	5.7	7	1.3	6.24
E_8	Adaptability to the changes in novel energy generation and information technologies	C	0.074	7	7	0	7
E_9	Transmission line capacity	C	0.050	6.1	7	0.9	6.41
E_{10}	Generation-integrated energy storage systems (GIES)	C	0.049	6.3	7	0.7	6.38
E_{11}	Sensing and seizing new business models	C	0.070	7	7	0	7
E_{12}	Circular economy practices	C	0.052	5.8	7	1.2	6.12
E_{13}	Supply chain visibility and traceability	E	0.067	7	7	0	7
E_{14}	Trust and collaboration	E	0.057	5.9	7	1.1	6.31
E_{15}	Policymaking and top management commitment towards resilience	C	0.060	6.3	7	0.7	6.51
E_{16}	System performance monitoring	E	0.049	5.6	7	1.4	6.13
E_{17}	Energy pricing policy	E	0.062	7	7	0	7
E_{18}	Supply chain financial risk management	E	0.053	5.8	7	1.2	6.33

are classified as the influencing (cause) group, and they are critical for accomplishing SPvESC resilience. For example, the findings show that Sensing and seizing new business models (E_{11}) is by far the most important influencing enabler for improving SPvESC resilience. Teece explained in two articles (1997 and 2007) that, “A firm’s dynamic capabilities govern how it integrates, builds, and reconfigures internal and external competences to address changing business environments”. Dynamic capabilities, in a sense, illustrate enablers to innovate, adapt to change, and implement change that benefits customers while building and maintaining competitive advantage. Capabilities enabling decision-makers to sense changing business environments and deploy resources to address new opportunities are vital. Extending the work of Teece et al. (2016), sensing and seizing new business models are essential if a supply chain is to build greater resilience in its operations. Hence, the answer to the second research question (RQ_2) about the associations between the enablers of SPvESC resilience was provided.

Adaptability to the changes in novel energy generation and information technologies (E_8) is also critical in terms of SPvESC resilience. Dashtpeyma and Ghodsi (2019), Erol et al. (2021), and Erol et al. (2022) also argued that implementing novel information technologies helps SPvESC improve its resilience through building enhanced integration and increased velocity. Furthermore, while not specifically in a SPvESC context, Pettit et al. (2010), Pettit et al. (2013), Rajesh (2017), Agarwal et al. (2020), and Dashtpeyma and Ghodsi (2019) argued that adopting and implementing novel operation and information technologies is important in ensuring visibility, traceability, trust and collaboration, and resource efficiency in supply chains.

The positive D-R values of the other cause (influencing) enablers are similar. Based on the results, Business contingency plans (E_1) is noteworthy, and the organization should prepare for natural and human-made disasters (e.g., terror, war, cyber-attacks, etc.) (Pettit et al. 2010; Chopra and Sodhi 2004). Effective business contingency plans based on supply chain vulnerability and bottlenecks are one of the most important building blocks of improving resilience in supply chains, regardless of the industry (Pettit et al. 2013; Rajesh 2019). Legislation & incentive program (E_2) is another important influencing enabler for SPvESCs. Erol et al. (2021), Govindan and Hasanagic (2018), Erol et al. (2022), Oteng et al. (2022), Aşkın et al. (2023), Maqbool et al. (2023), and Sinha and Ghosh (2024) indicated that governments could stimulate resilience in SPvESCs through enacting legislation, building effective principles, providing technical support, and developing an effective price mechanism. Financial incentives are also an effective instrument to increase the resilience in SPvESCs (Tsao and Thanh 2021). Hence,

we argue that effective incentive programs and legislation can aid in constructing new business models, which supports the results of Inês et al. (2020), Aşkın et al. (2023), Maqbool et al. (2023), and Sinha and Ghosh (2024).

Our findings also suggested that Transmission line capacity (E_9) and Generation-integrated energy storage systems (GIES) (E_{10}) are key influencing enablers in building more resilient SPvESCs. Bryant (2016) argued the resilience of SPvESCs is contingent on adequate electricity transmission line capacity. However, as Garvey et al. (2015) argue, building affordable and secure low-carbon generation and transmission systems are important, but insufficient conditions for resilience. Effective storage infrastructure, such Generation-integrated energy storage systems (GIES), is also needed. The findings also revealed that enhanced resilience in SPvESCs depends on the success of Occupational Health and Safety Systems (OHSAS) (E_3) and Preventive maintenance management (E_7). Effective OHSAS and preventive maintenance programs help improve the overall resource efficiency of a supply chain through providing a more reliable and resilient environment (Badiea et al. 2020; Siskos and Burgherr 2021).

Policymaking and top management commitment towards resilience (E_{15}) is another influencing enabler for increasing resilience in SPvESCs. Previous research has argued that ineffective policymaking and weak top management commitment towards resilience results in lower-than-expected supply chain performance (Govindan and Hasanagic 2018). This eventually causes ineffective resource allocations and decisions (Fawcett et al. 2006). Hence, effective policymaking and a sufficient level of top management commitment are a foundation of SPvESC resilience.

Our findings also revealed the most-influenced enablers. SPvESCs can focus on these factors after taking care of the others. This does not imply that they are unimportant and may be disregarded; they should be considered in the later stages of a plan to increase SPvESC resilience. Tables 8 and 10 show that they are as follows: Trust and collaboration (E_{14}), Energy pricing policy (E_{17}), Cost effectiveness and resource efficiency (E_4), Supply chain visibility and traceability (E_{13}), and Supply chain financial risk management (E_{18}). The resulting (the effect group) factors have D-R with negative values, implying that they are affected by the rest of the enablers. For example, Trust and collaboration (E_{14}), Cost effectiveness and resource efficiency (E_4), and Supply chain visibility and traceability (E_{13}) in SPvESCs heavily depend on the performance of influencing enablers such as Sensing and seizing new business models (E_{11}), Adaptability to the changes in novel energy generation and information technologies (E_8), and Business contingency plans (E_1), which supports the findings of Chen et al. (2017), Pettit et al. (2010), and Casion et al. (2019).

5.1 Implications for practitioners

This research offers several implications for practitioners working in SPvESCs, as well as government employees working in related areas. This research identified and classified the enablers for SPvESC resilience into prominent, influencing, and resulting enablers. We conclude that, even if a SPvESC is commercially successful, improving resilience depends on the key enablers identified in this study. Of particular note are the capabilities to sense and seize new business models, to adapt disruptive technologies, and to develop effective business contingency plans. The findings also indicate that “building effective incentive programs” and “legislating new regulations” to address new business models are plausible ways to facilitate building greater resilience in SPvESCs. Moreover, making business plans for several contingencies and taking steps to build and maintain top management commitment are also important for SPvESC resilience. Companies must also develop a comprehensive business contingency plan to deal with uncertainties. The findings further indicated that differentiating cause enablers from resulting enablers is crucial. For example, SPvESCs must ensure trust and collaboration, resource efficiency, and visibility and traceability to improve resilience. These, however, are mainly the resulting factors. Therefore, identifying the influencing enablers to emphasize in order to achieve progress in them is vital.

The findings also have implications for sustainability. Circular economy practices (E_{12}) is one of the most significant influencing enablers in this study. The circular economy and its practices reduce waste in supply chains, enabling them to optimize linear networks and develop innovative business models that enhance economic, social, and environmental sustainability performance. “Circular design,” “circular use,” and “circular recovery” are three fundamental business model roles in the circular economy, which contribute to sustainability. Decision-makers must simultaneously consider circular design, usage, and recovery in order to achieve resilient SPvESCs. Moving towards a circular economy will enable SPvESCs to achieve Cost effectiveness and resource efficiency (E_4). In addition, improving Supply chain visibility and traceability (E_{13}) is essential to developing environmentally sustainable and resilient SPvESCs. Being capable of tracking components, finished goods, and services as they travel from supplier to manufacturer to final customer is known as supply chain visibility and traceability. Solar panels and their components should also be tracked throughout its useful life so that product and component recovery decisions can be made rationally. Businesses may utilize this data to monitor things through to completion, reduce inventory shortages, improve resource efficiency, relieve bottlenecks, and comply with regulations towards environmental sustainability.

5.2 Implications for policymakers

The findings can provide important starting points for policymakers looking to increase the resilience in SPvESCs. Table 11 presents some policy directions for SPvESC stakeholders based on our findings. It also provides an answer to the third research question (RQ_3) which examines how the results assist the decision-makers in strengthening resilience in SPvESC through policy building.

5.3 Theoretical implications for researchers

This study also has several theoretical implications for researchers. It proposes a methodology that combines NGT, N-DEMATEL, and N-DELPHI to identify the associations between the enablers of SPvESC. The proposed methodology therefore integrates quantitative and qualitative methods. Structured qualitative/quantitative decision frameworks can assist in organizing the problem and building an instrument to combine several aspects. The main emphasis is on building an integrated decision-making framework, which provides a structure to make well-grounded decisions. The proposed framework and similar ones used in other studies do not seek to substitute intuitive judgment or experience; rather, they are intended to bolster them. In other words, the main goal of using formalized decision frameworks is not to come up with a final optimum solution, but one that is appropriate to the context in which it is applied. The proposed framework is intended as a decision support tool that supports managerial experience and judgement.

6 Conclusion and future works

Solar energy will be an increasingly important energy source in the future. A SPvESC is a global network with multiple linkages, including mineral and metal mining, material processing, module and panel production, and transportation between each step of the chain. This global network, however, is subject to an array of uncertainties and the undesirable ecological impacts associated with linear business models applying the take-make-use-dispose paradigm. Given the significance of solar energy generation, the resilience of SPvESCs is critical in addressing potential disruptions. To develop resilient supply chains, it is necessary to identify the enablers of resilience in support of the supply chain's goals.

This is the first study focused on investigating the enablers to enhance the resilience of a SPvESC. In this research, the enablers for SPvESC were specified by reviewing the literature and applying the NGT based on expert data. The enablers for SPvESC resilience address the factors throughout the supply chain network, including “SPv panel suppliers”, “photovoltaic assemblers”, and “solar energy producers”.

Table 11 Building Policies for Strengthening Resilience in SPvESCs

Stakeholders	Illustrative Options
Local and National Government Agencies	• Establishing an effective legal and incentive framework to support sustainability and resilience in SPvESCs. • Providing more research funding through national research institutions for SPvESC strategies to uphold resilience.
Non-governmental Organizations and Business Associations	• Developing innovative SPvESC-based business models towards greater resilience and circular economy. • Building policies and strategies to address vulnerabilities, such as resource efficiency, trust, visibility and traceability towards greater resilience.
Companies and Supply Chains	• Enhancing top management commitment towards building more resilience. • Constructing a performance measurement system specifically for evaluating resilience and progress towards a circular economy in SPvESCs. • Ensuring that white and blue-collar employees have sufficient training on how to improve resilience and circular economy in SPvESC. • Building effective organizational strategies towards resilience and circular economy in SPvESCs. • Stimulating the development of new technologies that enhance recycling practices and SPv panel design for recycling, reusability, and increased durability.
Research and Educational Institutions	• Focusing research and development on enhancing solar cell conversion efficiency and lowering the cost and consumption of raw materials to enhance circular economy and environmental sustainability performance. • Conducting research on how to use disruptive technologies, such as the Internet of Things and blockchain for improving resilience and circular economy in SPvESCs. • Creating guidelines for improving resilience in SPvESC. • Performing qualitative and quantitative research on how to build greater resilience and environmental sustainability in SPvESC.

Since addressing all enablers concurrently is realistically infeasible, N-DEMATEL was used to draw an influential relation map of the enablers. Finally, N-DELPHI was used to validate the study's findings.

Our results indicated that *Adaptability to the changes in novel energy generation and information technologies* (E_8), *Sensing and seizing new business models* (E_{11}), and *Supply chain visibility and traceability* (E_{13}) were the most prominent factors. Moreover, *Sensing and seizing new business models* (E_{11}), *Adaptability to the changes in novel energy generation and information technologies* (E_8), and *Business contingency plans* (E_1) were the most significant influencing factors. Our results also indicated that *Trust and collaboration* (E_{14}), *Energy pricing policy* (E_{17}), *Cost effectiveness and resource efficiency* (E_4), and *Supply chain visibility and traceability* (E_{13}) were the most important influenced resiliency factors.

Despite some unique characteristics specific to Türkiye, our findings are also helpful for other countries and can serve as a reference point. We contend that the idiosyncrasies of developing countries in creating resilient SPVEE are generally fairly similar to one another, with the absence of norms, laws, and general technology possibly being the most significant factor. That absence can deter both local and international business owners from funding resilient and sustainable SPvESC. Türkiye has unique characteristics as a developing nation. Most notably, Türkiye became a member of the Customs Union of the European Union in 1995

and was recognized as a candidate for full membership in 1999. As a result, the EU directly imposes some regulatory adjustments on Türkiye. This broader context should be considered when applying the process and results to other countries.

This research contributes to the existing literature as follows: (1) To date, there have been limited empirical studies on the enablers for supply chain resiliency. However, no study has investigated the enablers for SPvESCs to achieve resilience. In this study, the enablers for SPvESCs to achieve resilience were identified via the literature and NGT using expert opinions. (2) There have been few studies examining the associations between the enablers of supply chain resilience. Nevertheless, no study has investigated the interactions between the enablers to achieve resilience in SPvESCs using expert opinions. In this research, N-DEMATEL was employed to identify the associations between the enablers. (3) The results were validated using N-DELPHI, and policy and managerial implications regarding the results were developed.

There are several future research opportunities arising from the limitations of this study. For example, integrated multi-criteria decision-making methods using novel extensions such as rough sets and other improved fuzzy extensions can be employed to address the ambiguity of expert data more effectively. In addition, MCDM methods other than DEMATEL can be used to better investigate the associations among the enablers. Hence, the findings obtained

from various methods can be compared to increase the robustness of the methods. The method employed here could also be applied to other contexts. Practitioners can also use the findings to better understand the prominent, influencing, and resulting enablers for resilience of other supply chains. This improved understanding could lead to additional questions over time including the differences between the most important enablers in various supply chains. Lastly, the number of experts can be enlarged to improve the integrity of the results.

Author contributions Ismail Erol: Conceptualization, Investigation, Methodology, Writing - Original Draft, Writing - Review & Editing, Validation. Iskender Peker: Methodology, Formal analysis, Validation, Writing, Data Curation. Tolga Benli: Writing - Review & Editing, Investigation, and Validation. İlker Murat Ar: Writing - Review & Editing, Investigation, and Validation. Cory Searcy: Writing - Review & Editing, Investigation.

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Data availability Data and codes are available upon request.

Declarations

Ethics approval and consent to participate All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Baskent University, and the protocol was approved by the Ethics Committee of Baskent University.

Competing interests The authors declare they have neither financial nor non-financial interests.

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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