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ADVANCEMENTS IN CLEAN ENERGY FOR SUSTAINABLE DEVELOPMENT

Blockchain Technology Application Challenges in Renewable Energy Supply Chain Management

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Abstract

With the advent of new technologies and globalization of business, supply chains have turned into indispensable tools for gaining competitive advantage. The application of new technologies like blockchain can benefit sustainable energy supply chains by improving chain and logistics operations in the areas of trust, transparency and accountability, cooperation, information sharing, financial exchanges, and supply chain integration. However, the efforts to adopt such technologies in supply chains tend to face many challenges and challenges, which can seriously threaten their success. Therefore, it is crucial to carefully examine the challenges to blockchain technology application. This research focuses on identifying the criteria and challenges to the application of blockchain in renewable energy supply chains and also ranks the identified challenges in terms of their capacity to disrupt the process. The applicability of the suggested structure is examined in a case study of the renewable energy supply chain of Iran. In this study, the challenges are evaluated and ranked by the hybrid developed methods by the integration of the concept of gray numbers into the gray stepwise weight assessment ratio analysis (SWARA-Gray) and the gray evaluation based on distance from average solution (EDAS-Gray). Another group of hybrid methods including the gray weighted sum method (WSM-Gray), the gray complex proportional assessment (COPRAS-Gray), and the gray technique for order of preference by similarity to ideal solution (TOPSIS-Gray) is used to validate the results. The rankings obtained from all of these techniques show high degree of correlation. Among the identified challenges, "high investment cost" is found to be the most important challenge to the application of blockchain in sustainable energy supply chains.

Keywords Blockchain · Challenges · Ranking · Supply chain management · Renewable energy

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Introduction

In today's ever-changing world, supply chain networks tend to have diverse needs in terms of information assessment and risk management, which could be difficult to address (Ivanov et al., 2018). Indeed, the evolution of information and communications technologies (ICT) is constantly changing the requirements and capabilities of logistics and supply chain management (Goldsby & Zinn 2016). In recent years, blockchain has been hailed as a ground-breaking technology capable of transforming the form and size of businesses and how they conduct transactions (Behnke & Janssen 2020). Blockchain and Bitcoin were introduced by the person (or persons) using the pseudonym Nakamoto in 2008 (Nakamoto, 2008). Since its advent, this decentralized currency and transaction technology has been a major driver of change in business and is expected to play an even larger role in both the industry and service sectors (Iansiti 2017). The impetus behind the invention of blockchain was the lack of a transparent and sustainable independent decentralized financial system (Christidis & Devetsikiotis 2016). Blockchain prevents forgery and fake transactions by building encrypted blocks of all transaction records and storing them across the web such that they are constantly validated. Furthermore, the use of intelligent agreements in blockchain to control operations improves transaction transparency and increases trust among users (Constantinides et al. 2018). It has been argued that blockchain technology can modify numerous sectors of the economy, including supply chain management (Hofmann & Rüsch 2017), and may have far-reaching economic, social, and environmental impacts (Mathivathanan et al. 2021). Blockchain technology can benefit the supply chains by exampling facilitating real-time connection, ensuring the partners' trust, establishing trusting relationships, accelerating payment processes and making them cheaper, reducing product costs, decreasing delivery times, improving demand forecasts, reducing resource consumption, and even affecting environmental aspects of business such as recycling (Casado-Vara et al. 2018). Figure 1 shows the features and areas of utilization of blockchain in the supply chain.

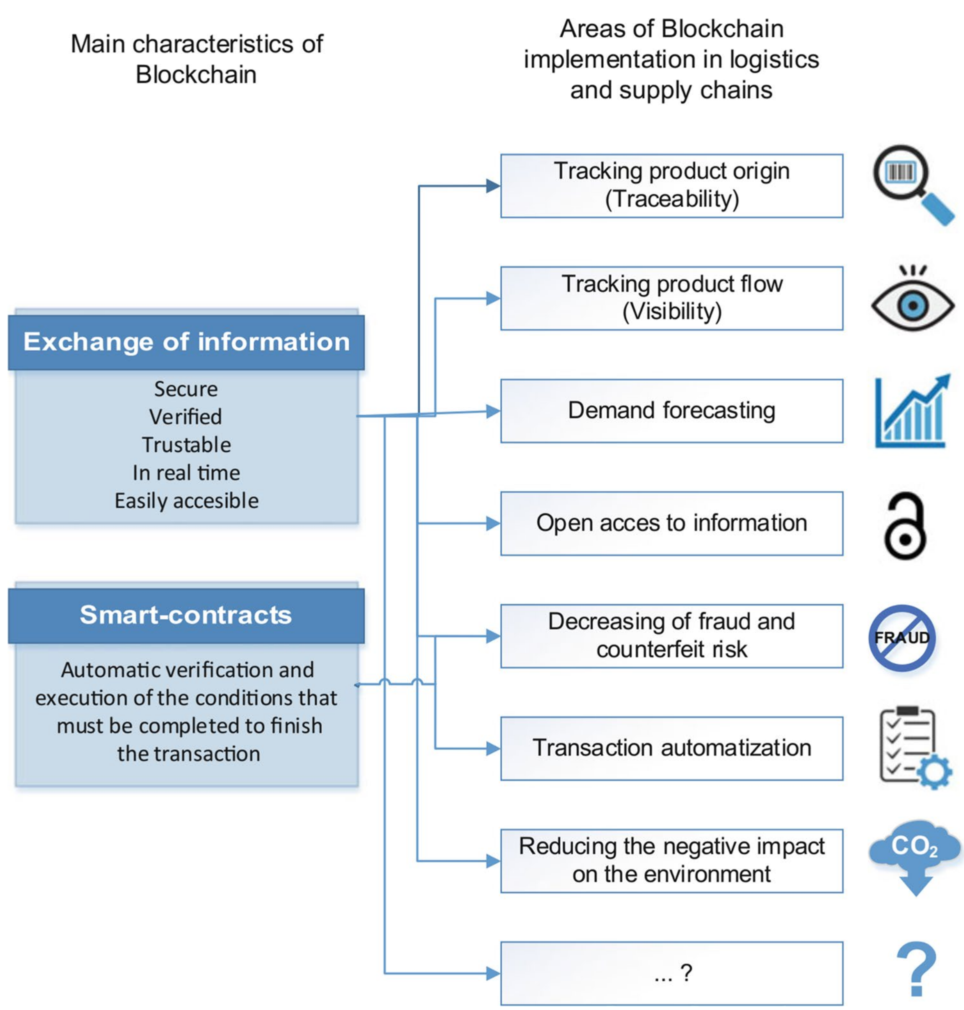

Fig. 1 The features and areas of utilization of blockchain in the supply chain (Dujak & Sajter 2019)

Whether blockchain can be successfully utilized in supply chain management somewhat depends on how well it is accepted by the supply chain participants (Yadav & Singh 2020). As with all innovations, early adopters of this technology tend to face some challenges in this regard. In fact, blockchain has several qualities that can act as challenges to its acceptance (Queiroz et al. 2019). Thus, it is currently difficult to use blockchain technology to build sustainable supply chain systems (Janssen et al. 2020). There is however a growing understanding of the challenges of combining this technology into older supply chain operations (Mougayar 2016; Saberi et al. 2018). There have been numerous research studies regarding the use of renewable energies which could help to reduce carbon emission in many countries (Zarezade and Mostafaeipour 2016). Some corporations and organizations have conducted research into the potential applications of blockchain in business and whether its potential benefits justify the problems arising from its application (Janssen et al. 2020). Certainly, for the successful integration of blockchain technology into a supply chain, it is crucial to identify and assess the challenges to this integration. However, very few studies in the literature have tried to identify the challenges to the application of blockchain technology. There is also a gap in the research regarding the priority of challenges to the application of blockchain technology.

One field that may be able to benefit from blockchain technology is the energy supply chain. Energy is an essential input for all economic activities in both the industry and commerce sectors and can have a great impact on the GDP of a country (Lorde et al. 2010). Given the importance of the energy industry worldwide, extensive studies have been conducted to identify the challenges of this industry and how they can be tackled. It has been argued that high energy prices can have substantial negative impacts on the economic performance and growth of a country (Lorde et al. 2010). Proponents of blockchain claim that this technology can reduce transaction costs and risks, eliminate human error, and save time in transactions (Korpela et al. 2017). The use of blockchain in energy supply chains may lead to not only cost reduction but also improved cooperation, coordination, trust, security, and improved transactions and exchanges between different levels of the supply chain. Therefore, it is necessary to identify the challenges and determinants that can inhibit the application of blockchain in energy supply chains.

Real-world problems are often highly complex and involve decisions that are too complex to be made based only on a single criterion (Hosseini Dehshiri 2019). Therefore, decision problems often involve comparing a set of options about a set of criteria that are weighted based on their importance for the desired outcome (Heidary Dahooie and Hosseini Dehshiri 2019). The process of evaluating in this paper can also be considered as a multi-criteria decision-making (MCDM) issue. In many MCDM problems, the presence of incomplete or ambiguous information complicates the assessments that should be made by decision makers (Almutairi et al. 2021a). In such cases, the classical MCDM techniques use definite values and do not provide accurate decision making (Mostafaeipour et al. 2020a). In such cases, one should somehow ensure that decisions are made with these uncertainties taken into account. Gray numbers are widely believed to be an effective method for solving problems in which a part of the information is unknown, ambiguous, or unreliable (Heidary Dahooie and Hosseini Dehshiri 2019).

This research tried to know the determinants of and challenges to the application of blockchain technology in energy supply chains and also rank the identified challenges in terms of their importance. The study used the combinations of this method with SWARA and EDAS, which are called SWARA-G and EDAS-G, respectively. Also, the hybrids of this method with WSM-G, COPRAS-G, and TOPSIS-G were used to validate the results.

The introduction of a new utilization of blockchain technology in the area of energy is one of the novelties of this study work. In addition, the study provided and analyzed the requirements and obstacles to blockchain deployment in the energy supply chain. In this study, uncertainty in the real world was also considered. Gray numbers have been used in hybrid MCDM methods and the results were validated by other methods. The use of several MCDM methods leads to increased accuracy and stability of results. The use of the proposed method in the energy supply chain due to its importance and lack of applied studies in this field is another novelty of this research.

The remaining of this research is structured as follows: In Section 2, the research literature is examined. Section 3 describes the theory of gray numbers and the processes of hybrid MCDM approaches. Section 4 describes the data analysis process and presents the results obtained from a case study of the Iranian renewable energy supply chain. At the end, Section 5 concludes the paper, provides some practical recommendations, and offers some suggestions for future works.

Literature review

Blockchain can be described as an encrypted database providing the infrastructure for the secure transaction of cryptocurrencies (Beck 2018). Blockchain is a shared and decentralized technology that keeps a report of all digital commerce in sequential order using cryptographic techniques (Li & Wang 2017). Once a transaction is registered in a blockchain, it can only be updated with the consensus of participants in the network, a requirement that makes transactions more transparent and controllable (Dorri et al. 2017). One of the most promising potentials of blockchain is its capacity to eliminate economic inefficiencies by replacing bureaucratic processes with simpler and safer alternatives (5). Blockchain safeguards the truth in environments where there is no trust among participants, thus allowing people to make transactions with higher confidence (Beck et al. 2018). Given the features of blockchain technology in terms of automating transactions and contracts and cutting off intermediaries, multi-level supply chain networks and logistics operations can benefit from this technology (Du et al. 2019). Blockchain technology can be turned into an effective means for supply chain connection, administration, and information governance, and monitoring of the entire product life cycle (Underwood 2016). In the area of sustainable supply chains, blockchain can be used to combine demand, delivery, and pay management, communications and information sharing, and environmental and social management (Korpela et al. 2017). Blockchain technology can improve the transparency of some supply chain networks. This technology also offers new opportunities for tracing and controlling products at different stages of their life cycle, which can provide a more realistic view of the sustainability of a supply chain (Saberi et al. 2019). Thus, the application of this technology can contribute to the sustainable development of a supply chain.

This section examines the renewable energy supply chain and the application of blockchain technology in the supply chain.

Renewable energy supply chain

The conversion of crude energy into usable energy is characterized as the renewable energy supply chain, which encompasses an effective set of management principles from the point of access to energy resources to the point of useable energy consumption (Luthra et al. 2015). The renewable energy supply chain includes supply, production, transmission, distribution, consumers at five levels, and all processes along the renewable energy supply chain, from primary input to energy production (Engelken et al. 2016). According to Fig. 2, the renewable energy supply chain is separated into three procedures: upstream, production, and downstream (Luthra et al. 2015). Its main purpose is to ensure a consistent and reliable supply of energy while also expanding the usage of renewable energy (Jraisat & Hattar 2017).

The renewable energy supply chain includes wind, solar, hydropower, and geothermal energies (Luthra et al. 2015).

The wind energy supply chain consists of three processes (Choukri et al. 2017; Sovacool 2017; Jelti et al. 2021): Wind energy sources are considered by the generation of power by wind turbines in the upstream procedure. The site of the wind turbine's installation is critical during the production process. The key problem in the downstream phase is

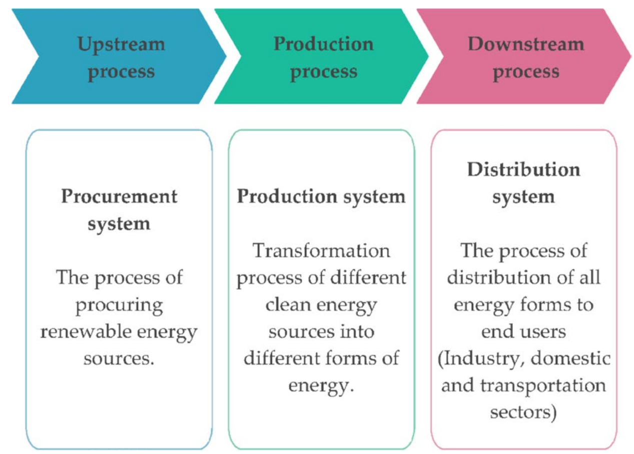

Fig. 2 Renewable energy supply chain processes (Luthra et al. 2015)

network integration and load balancing. Project development and planning, turbine installation, and finally energy generation and distribution in the network are the three steps of wind turbine project implementation (Li et al. 2017).

Solar energy has seen a surge in technology investment and a slew of new initiatives in recent years (El-Karmi & Abu-Shikhah 2013). Solar photovoltaics and solar heat are two types of techniques to manage solar energy. The implementation of solar photovoltaic or solar thermal power generation systems is the upstream procedure (Jelti et al. 2021). PV modules or thermodynamic cycles of concentrated solar collectors are used to generate power. Finally, the downstream step in the supply chain entails ensuring that end-users have access to electricity (Jelti et al. 2021).

Dams and seas are used to generate electricity by the hydropower supply chain. Water is released through a turbine, which is coupled to generators to produce alternating currents, and electricity is generated (Jelti et al. 2021). The downstream process involves distributing power to end-users according to their energy requirements. The hydropower supply chain confronts a number of obstacles that must be overcome in order to build novel methods that decrease or eliminate environmental impacts (Yaqoot et al. 2016).

The supply chain of geothermal energy consists of three main processes (Jelti et al. 2021): The extraction of heat sources from the earth as input is part of the upstream process. Water is heated during the manufacturing process for it to evaporate. The steam powers the turbine, which produces energy that is ultimately transformed into electricity by a generator. This energy must be adjusted to the mains' needed voltage. The downstream process culminates in the distribution of electricity to end-users. Project planning, exploration, excavation and building above and below ground, and finally operation and maintenance operations are typically separated into stages in the execution of a geothermal project (Li et al. 2017).

Application of blockchain in supply chain

The main applications of blockchain in supply chain management include product tracing (Kshetri 2017), aware shipping planning (Lei et al. 2017), fighting counterfeit/inappropriate goods (Montecchi et al. 2019), surety enhancement (Dorri et al. 2017), knowledgeable purchasing and contracts (Sikorski et al. 2017), complex governance (Shermin 2017), business development (Khaqqi et al. 2018), sharing of knowledge (van Engelenburg et al. 2019), supply chain flexibility improvement (Min 2019), sustainable productivity improvement (Kshetri 2018), and carbon emission reduction (Liu et al. 2019).

Given the potential benefits of blockchain for supply chains, various investigations have been conveyed in this field in recent years.

Hackius and Petersen (2017) examined the applications, challenges, and outlook of the application of blockchain technology in supply chains. These researchers reported that most participants emphasized the benefits of blockchain for supply chains and the need to integrate this technology into business. Kshetri (2018) described the impact of blockchain on different objectives of supply chain management and provided successful industry examples for each case. In a study by Prasad et al. (2018), these researchers identified 19 success factors for improving the performance of blockchain-based cloud services by reviewing the literature and taking the opinions of experts in this field. Perboli et al. (2018) tried to implement blockchain technology in food production and identified the important factors of this application. Saberi et al. (2019) examined the main challenges to the use of blockchain, especially smart contracts, to reach the objectives of a sustainable supply chain. In a study by Min (2019) on the effect of blockchain on supply chain resilience, the findings showed that this technology can indeed increase supply chain resilience. In a study by Rožman et al. (2019), they provided a framework for implementing blockchain and the Internet of Things (IoT) in supply chain operations. Tang et al. (2019) assessed different types of blockchain using entropy and TOPSIS methods. In this study, 30 blockchains were evaluated in terms of three measures: technology, recognition, and activity. Helo & Hao (2019) presented a model for using blockchain in supply chain operations. These researchers evaluated numerous utilizations of blockchain in supply chains and presented and implemented a logistics system based on the Ethereum platform. In a study by Kamble et al. (2020), they identified the enablers of blockchain and used DEMATEL to examine how they are linked and their importance. Mistry et al. (2020) developed a model for IoT industrial automation based on blockchain and 5G and evaluated this model in terms of various criteria. Venkatesh et al. (2020) introduced an architecture based on blockchain technology for improving the social sustainability of supply chains. These researchers reported that blockchain facilitates the process of maintaining social sustainability and retaining good personnel in the production chain. In a study by Choi et al. (2020a, 2020b) on the impact of blockchain technology in enhancing group media analytics for the management of supply chain procedures, it was reported that blockchain is indeed effective in this respect. Yoon et al. (2020) examined the analytical models of implementing blockchain technology in international transactions. In this study, blockchain was implemented to measure the risk of demand fluctuations. The finding of numerical investigation and simulation explained that the application of blockchain technology would result in reduced transport costs and shorter delivery times. In a study by Yang et al. (2021) on the requirements of knowledge-based dialogue systems, they presented a decision model for identifying the most suitable blockchain platform for such systems. In the proposed method, the FAHP and FTOPSIS were used to analyze data and create consistent results. The results were then used to select the best blockchain platform for improving the efficiency of the decision process. Wu et al. (2021) examined different procedures for using blockchain technology in a fresh produce supply chain. These researchers reported that the application of blockchain technology does not necessarily lead to better decisions for a fresh supply chain. Tagde et al. (2021) evaluated and implemented blockchain technologies and new artificial intelligence novelties in the healthcare sector. This research led to the introducing of artificial intelligence models in the e-health sector. It was also possible to share health information using the blockchain. Moosavi et al. (2021) studied the use of blockchain in the supply chain in a study. The blockchain's most important applications in the supply chain were recognized. The findings revealed a paucity of operational studies on the use of blockchain in the supply chain. In addition, the use of blockchain in the supply chain was a major area of research.

As can be seen, most studies in this field only provide case examples for implementing blockchain technology. Also, there is a gap in the literature about the systematic identification and assessment of factors and challenges to the application of blockchain in supply chains. Therefore, the present study first identified the factors of and challenges to the application of blockchain in energy supply chains and then ranked the identified challenges in terms of their importance by the combined use of gray numbers and SWARA and EDAS. Also, WSM-G, COPRAS-G, and TOPSIS-G techniques were used to validate the results.

Methodology

Gray numbers

Introduced by Deng in 1982, the gray systems theory tries to combine the ideas of system theory, space system, and control system (Pan et al. 2019). This method is especially effective in cases where:

- Information is incomplete;
- It is crucial to avoid certain statistical weaknesses;
- Data is expected to be discrete and imperfect (Wu 2006).

A gray number is represented by $\left[\underline{x_1}, \overline{x_1}\right]$. The primary mathematics operations $(+, -, \times, \div$ for addition, subtraction, multiplication, and division, respectively) between two gray numbers like $\otimes x_1$ and $\otimes x_2$ are determined as regards (Dahooie et al. 2020):

$$\otimes x_1 + \otimes x_2 = \left(\underline{x_1} + \underline{x_2}, \overline{x_1} + \overline{x_2}\right) \tag{1}$$

$$\otimes x_1 - \otimes x_2 = \left(\underline{x_1} - \overline{x_2}, \overline{x_1} - \underline{x_2}\right) \tag{2}$$

$$\otimes x_1 \times \otimes x_2 = \left(\underline{x_1} \times \underline{x_2}, \overline{x_1} \times \overline{x_2}\right) \quad \underline{x_1}, \underline{x_2}, \overline{x_1}, \overline{x_2} > 0 \tag{3}$$

$$\otimes x_1 \div \otimes x_2 = \left(\frac{\underline{x_1}}{\overline{x_2}}, \frac{\overline{x_1}}{\underline{x_2}}\right) \quad \underline{x_1}, \underline{x_2}, \overline{x_1}, \overline{x_2} > 0 \tag{4}$$

$$k \times \left(\otimes x_1\right) = k \times \left[\underline{x_1}, \overline{x_1}\right] = \left[k\underline{x_1}, k\overline{x_1}\right] \quad k > 0 \tag{5}$$

SWARA-Gray

For many MCDM problems, criteria weighting is one of the critically important phases of the solution process (Mostafaeipour et al. 2020b; Kalbasi et al. 2021; Almutairi et al. 2021b). Typically, experts play an indispensable role in this process by determining which criteria should be considered and how they should be weighted (Almutairi et al. 2021c; Mostafaeipour et al. 2021c). SWARA is a method developed by Keršulienė et al. (2010) to assist decision makers in selecting, evaluating, and weighting criteria (Keršuliene et al. 2010; Mostafaeipour et al. 2020d). In addition to user-friendliness, the convenience of use, and reduced application time (Zolfani et al. 2018), it also allows experts to confer with one another while receiving feedback, and it tends to yield more precise findings than other MCDM methods (Mostafaeipour et al. 2020e). The SWARA approach requires far fewer comparisons than other weighting methods, such as the AHP method, therefore it is easier to utilize when collecting responses from decision makers (Stanujkic et al. 2015).

The main stages of criteria weighting in the gray version of SWARA are as follows (Mavi et al. 2018):

Stage 1: Sorting the criteria

First, the criteria must be selected and sorted in terms of their importance.

Stage 2: Calculating the relevant significance of criteria (S_j)

This step involves calculating the relevant significance of each criterion with respect to the criterion that is one rank higher in the importance ranking, which is denoted by S_j.

Stage 3: Computing K_j

In this step, the coefficient K_j should be obtained from Eq. 6.

$$K_j = \begin{cases} [1,1] j = 1 \\ S_j + [1,1] j > 1 \end{cases} \tag{6}$$

Stage 4: Computing the weights of criteria with Eq. 7.

$$q_j = \begin{cases} [1,1] j = 1 \\ \frac{q_{j-1}}{K_j} j > 1 \end{cases} \tag{7}$$

Stage 5: Computing the ultimate normalized weights with Eq. 8.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{8}$$

EDAS-Gray

The core logic of EDAS is very innovative but takes inspiration from some famous MCDM approaches such as WSM, TOPSIS, and VIKOR (Keshavarz Ghorabaee et al. 2015). It has been predicted that EDAS can become the preferred solution method for many MCDM problems (Stanujkic et al. 2017). This approach is particularly beneficial when the model parameters are conflicting (Dahooie et al. 2020).

The main steps of the gray version of EDAS with m alternatives and n criteria are as develops (Stanujkic et al. 2017):

Stage 1: Forming the evolution model using Eq. 9

$$\otimes X = \begin{bmatrix} [\underline{x}_{11},\overline{x}_{11}] & [\underline{x}_{12},\overline{x}_{12}] & \cdots & [\underline{x}_{1n},\overline{x}_{1n}] \\ [\underline{x}_{21},\overline{x}_{21}] & [\underline{x}_{22},\overline{x}_{22}] & \cdots & [\underline{x}_{2n},\overline{x}_{2n}] \\ \vdots & \vdots & \vdots & \vdots \\ [\underline{x}_{m1},\overline{x}_{m1}] & [\underline{x}_{m2},\overline{x}_{m2}] & \cdots & [\underline{x}_{mn},\overline{x}_{mn}] \end{bmatrix} \tag{9}$$

Stage 2: Computing the medium gray solution for all criteria using Eqs. 10, 11, and 12.

$$\otimes x_j^* = ([\underline{x}_1^*,\overline{x_1^*}],[\underline{x}_2^*,\overline{x_2^*}],\ldots,[\underline{x}_n^*,\overline{x_n^*}]) \tag{10}$$

$$\underline{x}_j^* = \frac{\sum_{i=1}^{m} \underline{x}_{ij}}{m} \tag{11}$$

$$\overline{x_j^*} = \frac{\sum_{i=1}^{m} \overline{x_{ij}}}{m} \tag{12}$$

Stage 3: Computing the gray versions of PDA and NDA depending on whether the criterion is of the profit type or the cost type using Eqs. 13, 14, 15, and 16.

$$\underline{d}_{ij}^+ = \begin{cases} \dfrac{max\left(0,\left(\underline{x}_{ij}-\overline{x_j^*}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{max} \\ \dfrac{max\left(0,\left(\underline{x}_j^*-\overline{x_{ij}}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{min} \end{cases} \tag{13}$$

$$\overline{d_{ij}^+} = \begin{cases} \dfrac{max\left(0,\left(\overline{x_{ij}}-\underline{x}_j^*\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{max} \\ \dfrac{max\left(0,\left(\overline{x_j^*}-\underline{x}_{ij}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{min} \end{cases} \tag{14}$$

$$\underline{d}_{ij}^- = \begin{cases} \dfrac{max\left(0,\left(\underline{x}_j^*-\overline{x_{ij}}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{max} \\ \dfrac{max\left(0,\left(\underline{x}_{ij}-\overline{x_j^*}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{min} \end{cases} \tag{15}$$

$$\overline{d_{ij}^-} = \begin{cases} \dfrac{max\left(0,\left(\overline{x_j^*}-\underline{x}_{ij}\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{max} \\ \dfrac{max\left(0,\left(\overline{x_{ij}}-\underline{x}_j^*\right)\right)}{0.5(\underline{x}_j^*+\overline{x_j^*})}; j\epsilon\Omega_{min} \end{cases} \tag{16}$$

Stage 4: Computing the weighted aggregate of gray PDA and NDA for each choice utilizing Eqs. 17, 18, 19, and 20.

$$\underline{Q}_i^+ = \sum_{j=1}^{n} w_j \underline{d}_{ij}^+, \tag{17}$$

$$\overline{Q_i^+} = \sum_{j=1}^{n} w_j \overline{d_{ij}^+}, \tag{18}$$

$$\underline{Q}_i^- = \sum_{j=1}^{n} w_j \underline{d}_{ij}^-, \text{ and} \tag{19}$$

$$\overline{Q_i^-} = \sum_{j=1}^{n} w_j \overline{d_{ij}^-} \tag{20}$$

Stage 5: Normalizing the weighted aggregate of gray PDA and NDA for each choice utilizing Eqs. 21, 22, 23, and 24.

$$\underline{S}_i^+ = \frac{\underline{Q}_i^+}{\max_k \overline{Q_k^+}}, \tag{21}$$

$$\overline{S_i^+} = \frac{\overline{Q_i^+}}{max_k \overline{Q_k^+}}, \tag{22}$$

$$\underline{S}_i^- = 1 - \frac{\overline{Q_i^-}}{max_k \overline{Q_k^+}}, \text{ and} \tag{23}$$

$$\overline{\mathrm{S}_\mathrm{i}^-} = 1 - \frac{\underline{Q}_i^-}{\mathrm{max_k}\overline{\mathrm{Q_k^+}}}. \tag{24}$$

Stage 6: Computing the S_i score of the alternatives using Eq. 25 or 26.

$$S_i = \frac{1}{4}(\underline{S}_i^+ + \overline{S_i^+} + \underline{S}_i^- + \overline{\mathrm{S}_\mathrm{i}^-}), \text{ or} \tag{25}$$

$$S_i = \frac{1}{2}\left[(1-\alpha)\left(\underline{S_i^-} + \underline{S_i^+}\right) + \alpha\left(\overline{S_i^-} + \overline{S_i^+}\right)\right] \tag{26}$$

Stage 7: Sorting the choices in decreasing order of their Si scores.

To evaluate the performance of EDAS-G, the correlation of its results with the findings of other approaches is measured using Spearman's rank correlation coefficient as given by Eq. 27 (Dahooie et al. 2020).

$$r_s = 1 - \frac{6\sum_i d_i^2}{n^3 - n}. \tag{27}$$

Given this description of the analysis process, the stages of this study can be summarized as shown in Fig. 3.

Data analysis

Case study

This study was carried out on the renewable power supply chain of Iran. This supply chain consists of wind and solar power plants that generate electricity in an integrated manner. Sustainable electricity generation from renewable sources can play an essential role in keeping up with the rising demand of both residential and industrial consumers. One of the measures available to pursue this goal is to implement blockchain technology in the supply chain to integrate this chain in the sense of coordinating the flow of materials, information, and financial resources. Using blockchain technology in this supply chain may also improve its performance and stability in meeting the demand. However, given the practical challenges to the application of blockchain technology, many projects that follow this approach end up in failure. So, this is essential to carefully recognize

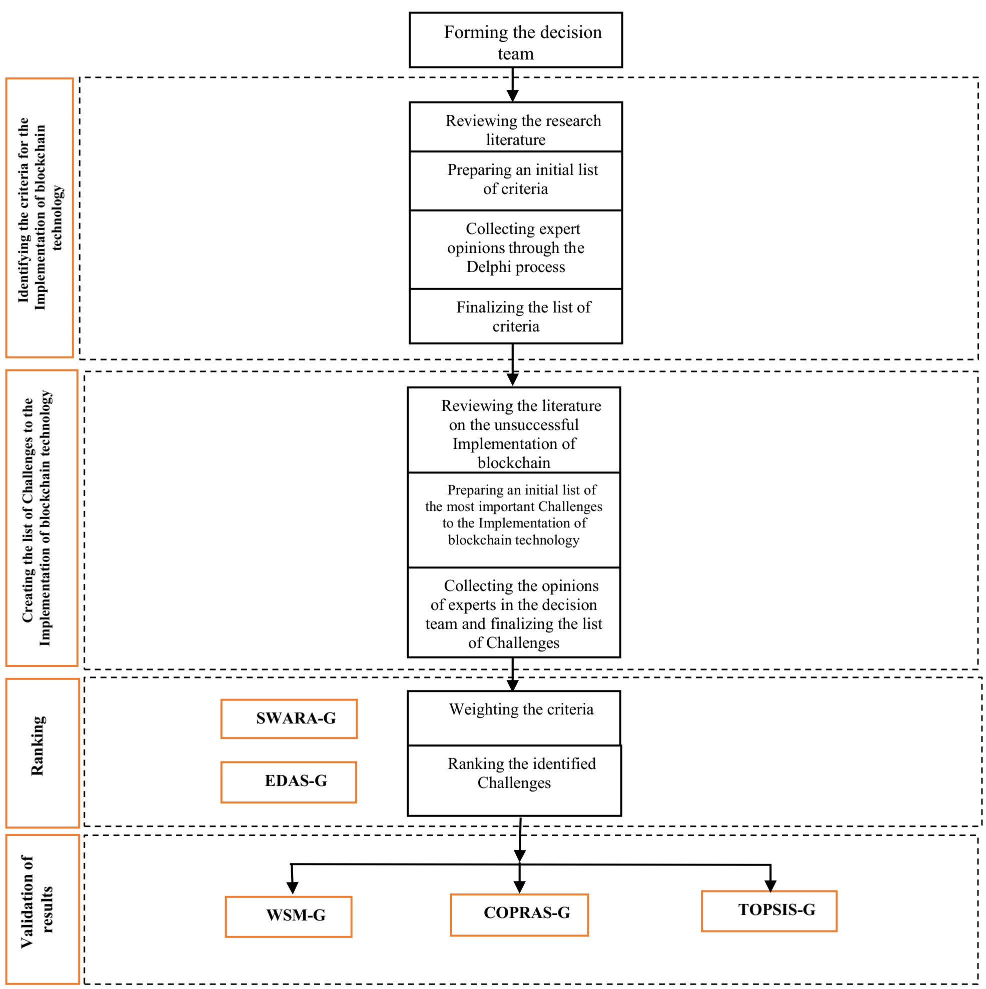

Fig. 3 Stages of the present study

and evaluate the challenges to the application of blockchain in the renewable power supply chain.

In this study, these challenges were identified and assessed through a field study followed by a survey of experts in the energy sector by a questionnaire to weigh the criteria and rank the challenges. Experts were selected by purposive judgmental sampling because their judgments would directly affect the results. The decision team consisted of four individuals with excellent records in the renewable energy industry (at least 10 years), at least a master's degree, fairly good knowledge of IT and blockchain technology, and interest in collaborating on this research. During the research, other researchers and academics with expertise in this field were also consulted when needed. The consulted academics were three university professors with expertise in the area of supply chain operations and IT in Iran. Also, several presentations were given to the decision team about the features, benefits, limitations, and capacity of utilizing blockchain in the supply chain. The summary of the characteristics of the decision-making team is given in Table 1.

Table 1 The summary of the characteristics of the decision-making team

Decision makers	Role
D_1	Policymaker in the field of IT
D_2	Supervisory manager of electricity projects
D_3	Administrator in the field of renewable energy
D_4	Executive manager in the field of environment
D_5	Academic expert in the field of IT and blockchain technology
D_6	Academic expert in the field of supply chain
D_7	Academic expert in the field of operations research

Identification of criteria of and challenges to the application of blockchain in renewable energy supply chains

Most studies in the area of adopting blockchain technology only provide case examples of this process. Also, very few studies have tried to systematically identify and assess the factors of and challenges to the application of blockchain in supply chains. In this study, we first identified the criteria of and practical challenges to the application of blockchain in a renewable energy supply chain and then ranked the identified challenges. For this purpose, the authors first reviewed the literature to create a listing of criteria that influence the application of blockchain technology. These factors are presented in Table 2.

Then, we reviewed the studies on challenges to the application of blockchain in supply chains to create a list of potential challenges. These potential challenges are presented in Table 3.

Weighting of criteria and sub-criteria with SWARA-G

Based on the first step of the SWARA-G method, experts were asked to sort the criteria in descending order of importance. Experts then assessed the relative importance of each criterion relative to the previous more important criterion based on the gray numbers provided by Turskis & Zavadskas (2010). The corresponding language variables are then converted to gray numbers. Next, the average of gray numbers was calculated, and the relative importance of each

Table 2 Criteria of application of blockchain technology

Criteria	Sub-criteria	Studies
Efficiency feature (A)	Cost payment (A_1)	Bai and Sarkis (2013), Kshetri (2018)
	Short application time (A_2)	Bai and Sarkis (2013), Kshetri (2018)
Security feature (B)	Privacy (B_1)	Yuan (2018), Casion et al. (2019a, 2019b), Kamble et al. (2020)
	Security (B_2)	Oh and Shong (2017), Yuan (2018), Reyna et al. (2018a, 2018b), Prasad et al. (2018), Saberi et al. (2019)
Operational feature (C)	Trust (C_1)	Kshetri (2018), Lu (2018), Makhdoom et al. (2019), Queiroz et al. (2019), Choi, Feng, et al. (2020), Choi, Guo, et al. (2020)
	Reliability (C_2)	Bai and Sarkis (2013), Kshetri (2018), Ar et al. (2020)
Technological feature (D)	Scalability (D_1)	Lu (2018), Yuan (2018), Ramkumar (2018), Reyna et al., 2018a, 2018b), Casion et al. (2019a, 2019b), Makhdoom et al. (2019)
	Adaptability and Scalability (D_2)	Makhdoom et al. (2019), Ar et al. (2020)
	Low complexity (D_3)	Bai and Sarkis (2017), Niranjanamurthy et al. (2019)
Cooperation and coordination feature (E)	Visibility (E_1)	Casion et al. (2019a, 2019b), Makhdoom et al. (2019), Saberi et al. (2019), Kamble et al. (2020), Hastig and Sodhi (2020)
	Interoperability (E_2)	Lu (2018), Casion et al. (2019a, 2019b)
	Partner support (E_3)	Robinson (2016), Kshetri (2018)

Table 3 Potential challenges to the application of blockchain in supply chains

Code	Challenges to the application of blockchain	References
S_1	Lack of trust or a shared vision among participants	Yadav et al. (2020)
S_2	System design complexity	Iansiti and Lakhani (2017); Yadav et al. (2020)
S_3	Inadequate technological development	Swan (2015)
S_4	Lack of IT workforce	Britchenko et al. (2018)
S_5	High investment cost	Baud-Lavigne et al. (2014)
S_6	Lack of R&D unit	Öztürk & Yildizbaşi (2020)
S_7	Payment problems	Swan (2015)
S_8	Insufficient funds for expanding technology infrastructure	Bohme et al. (2015)
S_9	Resistance to change (difficulty of changing people's mind)	Öztürk & Yildizbaşi (2020)
S_{10}	No information sharing on environmental and social affairs	Swan (2015)
S_{11}	Waste of environmental and social resources	Zohar (2015), Yli-Huumo et al. (2016)
S_{12}	Lack of proper government support and laws	Saberi et al. (2018); Kamilaris et al. (2019); Zhao et al. (2019); Thakur et al. (2020); Biswas and Gupta (2019)

criterion was calculated. Then, the third to fourth steps of the SWARA-G method were calculated. Finally, by taking the final step of the SWARA-G method and normalizing the weights, the final weight of each criterion was obtained, which is shown in Table 4.

Similar steps were taken to calculate the weight of sub-criteria of each main criterion. The outcomes of this process are presented in Table 5.

Ranking of challenges with EDAS-G

Experts were asked to evaluate each challenge regarding the use of blockchain using the oral parameters mentioned in the study of Turskis & Zavadskas (2010), based on the following criteria. Group members discussed the score of each challenge on each condition for this reason and then concluded on the decision. The results of the evaluation of the identified challenges are given in Table 6.

Following the steps of EDAS-G, the matrices of gray PDA and NDA were determined about to the kind of criteria. The results of this process are presented in Tables 7 and 8.

Then, the weighted and normalized values of gray PDA and NDA were calculated as explained in Section 3.3. The outcomes of the measuring are presented in Table 9.

The Si values of all challenges were then calculated as instructed in the next step of EDAS-G. The challenges ranking obtained with EDAS-G is presented in Table 10.

Validation of results

To investigate the robustness of the approach, the findings of EDAS-G were matched with WSM-G, TOPSIS-G, and COPRAS-G, which are commonly used MCDM methods for ranking alternatives. The results of the comparison between the rankings produced by EDAS-G, WSM-G, COPRAS-G, and TOPSIS-G are presented in Table 11.

Challenges rankings obtained from these methods are also compared in Fig. 4.

In this equation, di is the distinction within the rankings of alternative i in EDAS and different approaches, and n is the number of rankings being compared. The obtained Spearman's correlation coefficient values are proposed in Table 12.

The findings of EDAS-G are deeply correlated with the results of WSM-G, TOPSIS-G, and COPRAS-G. The rankings obtained with EDAS-G, WSM-G, COPRAS-G, and TOPSIS-G all show that the fifth challenge, i.e., high investment cost, is the most important challenge to the application of blockchain in the supply chain.

Table 4 Weight calculations for the criteria

Code	Computing (S_j)		Computing k_j		Computing q_j		Computing w_j	
A	--	--	1.00	1.00	1.00	1.00	0.35	0.46
D	0.33	1.00	1.33	2.00	0.50	0.75	0.17	0.35
B	0.23	0.32	1.23	1.32	0.38	0.61	0.13	0.28
C	0.18	0.24	1.18	1.24	0.31	0.52	0.11	0.24
E	0.14	0.19	1.14	1.19	0.26	0.46	0.09	0.21

Table 5 Weight calculations for the sub-criteria

Code	Computing (S_j)		Computing k_j		Computing q_j		Computing local w_j		Final weight	
Main Criteria: Performance (A)										
A_1	--	--	1.00	1.00	1.00	1.00	0.64	0.65	0.22	0.30
A_2	0.76	0.87	1.76	1.87	0.54	0.57	0.34	0.37	0.12	0.17
Main Criteria: Feasibility (B)										
B_1	--	--	1.00	1.00	1.00	1.00	0.57	0.61	0.08	0.17
B_2	0.32	0.54	1.32	1.54	0.65	0.76	0.37	0.46	0.05	0.13
Main Criteria: Applicability (C)										
C_1	--	--	1.00	1.00	1.00	1.00	0.59	0.61	0.06	0.15
C_2	0.46	0.58	1.46	1.58	0.63	0.69	0.38	0.42	0.04	0.10
Main Criteria: Effectiveness (D)										
D_1	--	--	1.00	1.00	1.00	1.00	0.46	0.48	0.08	0.17
D_2	0.46	0.58	1.46	1.58	0.63	0.69	0.29	0.33	0.05	0.11
D_3	0.35	0.44	1.35	1.44	0.44	0.51	0.20	0.25	0.04	0.09
Main Criteria: Compliance with environmental requirements (E)										
E_1	--	--	1.00	1.00	1.00	1.00	0.50	0.52	0.05	0.11
E_2	0.66	0.77	1.66	1.77	0.57	0.60	0.28	0.32	0.03	0.07
E_3	0.56	0.63	1.56	1.63	0.35	0.39	0.17	0.20	0.02	0.04

Table 6 Final decision matrix obtained from the evaluation of challenges based on the linguistic variables corresponding to gray numbers

Challenges	A_1	A_2	B_1	B_2	C_1	C_2	D_1	D_2	D_3	E_1	E_2	E_3
S_1	VH	H	MH	VH	H	ML	VH	VH	VH	MH	MH	M
S_2	VH	VH	VH	H	H	H	H	VH	H	H	M	L
S_3	H	VH	VH	H	VH	ML	H	VH	VH	M	M	M
S_4	VH	VH	H	VH	H	ML	VH	VH	VH	H	ML	L
S_5	H	VH	VH	VH	H	H	VH	VH	VH	MH	MH	MH
S_6	VH	VH	VH	VH	VH	ML	VH	VH	VH	M	MH	ML
S_7	VH	VH	VH	VH	VH	ML	VH	VH	VH	H	ML	L
S_8	H	H	VH	VH	VH	L	VH	VH	VH	M	M	ML
S_9	VH	H	VH	VH	VH	ML	H	VH	VH	MH	ML	ML
S_{10}	H	H	H	H	H	ML	H	VH	VH	M	M	M
S_{11}	H	H	H	H	MH	ML	H	VH	VH	H	M	L
S_{12}	VH	VH	VH	VH	VH	ML	VH	ML	VH	H	ML	L

Implications for practice

This study provided a framework for blockchain implementation in the energy supply chain for Iran. Implementation of blockchain technology in the energy supply chain leads to improved communication and information sharing, increasing trust between partners, building secure relationships, fast processing, lower transaction costs, lower costs, improving forecasting, matching supply and demand for energy, and reducing resource consumption at different levels of the chain. In this regard, for the successful implementation of blockchain technology, the existing obstacles must be removed. Therefore, in this study, the existing barriers to blockchain implementation were identified and these barriers were evaluated using the SWARA-G technique. Then, barriers of blockchain implementation in the energy supply chain were presented and these solutions were evaluated using EDAS-G, WSM-G, COPRAS-G, and TOPSIS-G techniques. The results showed that for implementing blockchain in the energy supply chain in Iran, it is necessary to attract the necessary capital to develop the main blockchain infrastructure by providing incentives and facilities. Then, the cost must be reduced at each stage of the blockchain implementation and a system with low complexity consisting of different levels of the energy supply chain must be designed. On the other hand, the implementation of blockchain technology has required continuous research and development activities. The novelty of information technology at various levels of the supply chain is essential to the implementation of this system.

Table 7 Gary matrix of PDA

Challenges	A_1		A_2		B_1		B_2		C_1		C_2		D_1		D_2		D_3		E_1		E_2		E_3	
S_1	0	0.184	0	0.165	0	0.049	0	0.269	0	0.188	0	0.333	0	0.358	0	0.905	0	1.232	0	0.358	0	0.905	0	1.232
S_2	0	0.184	0	0.282	0	0.282	0	0.154	0	0.188	0.6	1.667	0	0.506	0	0.595	0	0.207	0	0.506	0	0.595	0	0.207
S_3	0	0.301	0	0.282	0	0.282	0	0.154	0	0.307	0	0.333	0	0.136	0	0.595	0	1.232	0	0.136	0	0.595	0	1.232
S_4	0	0.184	0	0.282	0	0.165	0	0.269	0	0.188	0	0.333	0	0.506	0	0.078	0	0.207	0	0.506	0	0.078	0	0.207
S_5	0	0.301	0	0.282	0	0.282	0	0.269	0	0.188	0.6	1.667	0	0.358	0	0.905	0.427	1.671	0	0.358	0	0.905	0.427	1.671
S_6	0	0.184	0	0.282	0	0.282	0	0.269	0	0.307	0	0.333	0	0.136	0	0.905	0	0.5	0	0.136	0	0.905	0	0.5
S_7	0	0.184	0	0.282	0	0.282	0	0.269	0	0.307	0	0.333	0	0.506	0	0.078	0	0.207	0	0.506	0	0.078	0	0.207
S_8	0	0.301	0	0.165	0	0.282	0	0.269	0	0.307	0	0.067	0	0.136	0	0.595	0	0.5	0	0.136	0	0.595	0	0.5
S_9	0	0.184	0	0.165	0	0.282	0	0.269	0	0.307	0	0.333	0	0.358	0	0.078	0	0.5	0	0.358	0	0.078	0	0.5
S_{10}	0	0.301	0	0.165	0	0.165	0	0.154	0	0.188	0	0.333	0	0.136	0	0.595	0	1.232	0	0.136	0	0.595	0	1.232
S_{11}	0	0.301	0	0.165	0	0.165	0	0.154	0	0.069	0	0.333	0	0.506	0	0.595	0	0.207	0	0.506	0	0.595	0	0.207
S_{12}	0	0.184	0	0.282	0	0.282	0	0.269	0	0.307	0	0.333	0	0.506	0	0.078	0	0.207	0	0.506	0	0.078	0	0.207

Table 8 Gary matrix of NDA

Challenges	A_1		A_2		B_1		B_2		C_1		C_2		D_1		D_2		D_3		E_1		E_2		E_3	
S_1	0	0.282	0	0.301	0	0.417	0	0.192	0	0.287	0	0.733	0	0.184	0	0.176	0	0.215	0	0.284	0	0.009	0	0.305
S_2	0	0.282	0	0.184	0	0.184	0	0.308	0	0.287	0	0	0	0.301	0	0.176	0	0.327	0	0.136	0	0.526	0	1.037
S_3	0	0.165	0	0.184	0	0.184	0	0.308	0	0.168	0	0.733	0	0.301	0	0.176	0	0.215	0	0.654	0	0.526	0	0.305
S_4	0	0.282	0	0.184	0	0.301	0	0.192	0	0.287	0	0.733	0	0.184	0	0.176	0	0.215	0	0.136	0	0.836	0	1.037
S_5	0	0.165	0	0.184	0	0.184	0	0.192	0	0.287	0	0	0	0.184	0	0.176	0	0.215	0	0.284	0	0.009	0	0
S_6	0	0.282	0	0.184	0	0.184	0	0.192	0	0.168	0	0.733	0	0.184	0	0.176	0	0.215	0	0.654	0	0.009	0	0.744
S_7	0	0.282	0	0.184	0	0.184	0	0.192	0	0.168	0	0.733	0	0.184	0	0.176	0	0.215	0	0.136	0	0.836	0	1.037
S_8	0	0.165	0	0.301	0	0.184	0	0.192	0	0.168	0	1	0	0.184	0	0.176	0	0.215	0	0.654	0	0.526	0	0.744
S_9	0	0.282	0	0.301	0	0.184	0	0.192	0	0.168	0	0.733	0	0.301	0	0.176	0	0.215	0	0.284	0	0.836	0	0.744
S_{10}	0	0.165	0	0.301	0	0.301	0	0.308	0	0.287	0	0.733	0	0.301	0	0.176	0	0.215	0	0.654	0	0.526	0	0.305
S_{11}	0	0.165	0	0.301	0	0.301	0	0.308	0	0.406	0	0.733	0	0.301	0	0.176	0	0.215	0	0.136	0	0.526	0	1.037
S_{12}	0	0.282	0	0.184	0	0.184	0	0.192	0	0.168	0	0.733	0	0.184	0.412	0.882	0	0.215	0	0.136	0	0.836	0	1.037

Table 9 Weighted and normalized values of gray PDA and NDA

Challenges	$\otimes Q_i^+$		$\otimes Q_i^-$		$\otimes S_i^+$		$\otimes S_i^-$	
	$\underline{Q}_i^+$	$\overline{Q}_i^+$	$\underline{Q}_i^-$	$\mathbf{B_1}$	$\underline{S}_i^+$	$\overline{S}_i^+$	$\underline{S}_i^-$	$\overline{S}_i^-$
S_1	0.000	0.438	0.000	0.459	0.000	0.640	0.328	1.000
S_2	0.024	0.539	0.000	0.419	0.035	0.789	0.387	1.000
S_3	0.000	0.470	0.000	0.457	0.000	0.687	0.331	1.000
S_4	0.000	0.396	0.000	0.489	0.000	0.579	0.285	1.000
S_5	0.031	0.683	0.000	0.279	0.045	1.000	0.591	1.000
S_6	0.000	0.459	0.000	0.442	0.000	0.672	0.353	1.000
S_7	0.000	0.433	0.000	0.452	0.000	0.633	0.339	1.000
S_8	0.000	0.427	0.000	0.488	0.000	0.625	0.286	1.000
S_9	0.000	0.390	0.000	0.495	0.000	0.571	0.276	1.000
S_{10}	0.000	0.413	0.000	0.514	0.000	0.604	0.248	1.000
S_{11}	0.000	0.393	0.000	0.505	0.000	0.576	0.261	1.000
S_{12}	0.000	0.399	0.021	0.532	0.000	0.584	0.221	0.970

Conclusions and recommendations

The advent of new technologies in recent decades has transformed how people do business across the world. This also applies to supply chains, and especially energy generation chains, which have undergone significant changes in the past decades. The application of new technologies like blockchain can benefit sustainable energy supply chains by improving chain and logistics operations in the areas of trust, transparency and accountability, cooperation, information sharing, financial exchanges, and supply chain integration. Blockchain technology can indeed have extensive economic, social and environmental impacts and hinder or accelerate sustainable development. Therefore, it is important to carefully consider adopting this technology in sustainable energy supply chains. However, as with all innovations, early adopters of this technology tend to face some resistance as well as unforeseen challenges. Blockchain has several features that can create challenges to its practical application. A survey of the research literature showed that the greatest studies on the application of blockchain have only provided case examples for this process in different contexts. Also, only a few studies have tried to systematically identify and evaluate the criteria and challenges to the application of blockchain in supply chains. To discuss this space in the literature, this research first identified the criteria of and practical challenges to the application of blockchain in a renewable energy supply chain and then ranked the identified challenges. The ranking was conducted by the combined use of gray numbers and SWARA and EDAS. Also, WSM-G, COPRAS-G, and TOPSIS-G techniques were used to validate the findings.

The contributions of this paper to the literature include the identification and evaluation of factors of and challenges

Table 10 Estimated scores (S_i)

Challenges	$\mathbf{S_i}$	**Rank**
S_1	0.492	6
S_2	0.553	2
S_3	0.505	4
S_4	0.466	8
S_5	0.659	1
S_6	0.506	3
S_7	0.493	5
S_8	0.478	7
S_9	0.462	10
S_{10}	0.463	9
S_{11}	0.459	11
S_{12}	0.444	12

Table 11 The findings of the MCDM methods

Challenges	WSM-G	TOPSIS-G	COPRAS-G	EDAS-G
S_1	8	7	5	6
S_2	2	2	2	2
S_3	3	4	3	4
S_4	7	10	10	8
S_5	1	1	1	1
S_6	4	9	4	3
S_7	5	11	6	5
S_8	6	12	7	7
S_9	10	8	11	10
S_{10}	11	3	8	9
S_{11}	9	6	9	11
S_{12}	12	5	12	12

Table 12 Spearman's correlation coefficient for the correlation between the MCDM approaches

Methods	WSM-G	TOPSIS-G	COPRAS-G
CC	0.94	0.25	0.95

to the application of blockchain, the use of the concept of gray numbers to incorporate uncertainty into two MCDM approaches, and validation of the results with several other decision-making methods. Another innovation of this paper is the use of the method in the field of energy supply chain, where applied studies with such methods are scarce. A summary of the most significant results of this study is presented below:

- The criteria for the application of blockchain in the supply chain were extracted from the literature. A list of practical challenges to the application of blockchain was also created by reviewing the relevant literature and reports of unsuccessful projects.
- The criteria and sub-criteria were weighted by SWARA-G, leading to the results presented in Table 5.
- The challenges to the application of blockchain in renewable energy supply chains were ranked using the EDAS-G. Using this method, "high investment cost" (5th challenge), "system design complexity" (2nd challenge), and lack of R&D unit (6th (challenge) were identified as the most important practical obstacles to the application of blockchain in supply chains.
- The results of EDAS-G were validated with WSM-G, COPRAS-G, and TOPSIS-G. The validation results are compared in Table 11 and Fig. 4. These results showed a high correlation between the rankings of all methods.
- All MCDM methods identified the "high investment cost" (5th challenge) as the most important challenge.
- The results suggest that before adopting blockchain technology in renewable energy supply chains, it is necessary to carefully consider the initial investment that must be made in the infrastructure and weigh it against the cost reduction that can be achieved at each stage of the blockchain application process, design a system with low complexity so that it can be used at all levels of the supply chain, and shift focus to the R&D activities that lay the foundation for utilizing Blockchain features in the chain.

Suggestions for future research

Those interested in this subject are recommended to consider the following avenues for future research:

- Using other MCDM approaches and other theories such as the rough set approach or the type 2 fuzzy set approach to rank the challenges.
- Implementing the model proposed in this study in other supply chains.
- Expanding this study and the proposed method to the field of oil and gas energy, and renewable energy in other countries.
- Developing a framework to improve performance of energy supply chains under uncertain conditions.

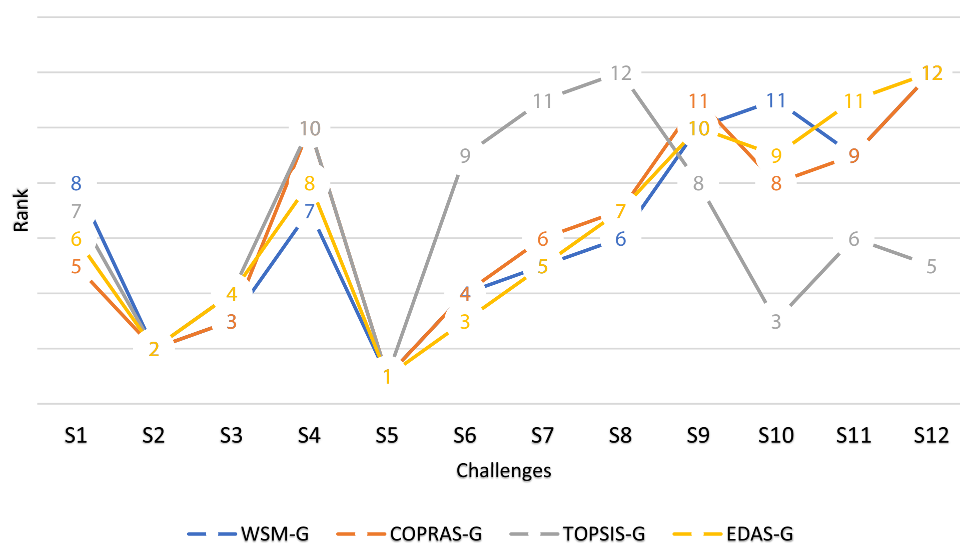

Fig. 4 Rank of each solution in all used MCDM methods

Authors Contributions **Ali Mostafaeipour** contributed to supervision, writing, conceptualization, software data curation, and software. **Seyyed Jalaladdin Hosseini Dehshiri and Ao Xuan Hoa** contributed to conceptualization, writing, methodology, software, and software data curation. **Seyyed Shahabaddin Hosseini Dehshiri and Joshuva Arockia Dhanraj** contributed to reviewing and editing, original draft preparation, visualization, and investigation. **Kuaanan Techato** contributed to methodology, writing, editing, and software. **Khalid Almutairi** contributed to conceptualization, writing, software, and editing. **Alibek Issakhov** contributed to writing, conceptualization, and methodology.

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Declarations

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References

Almutairi K, Hosseini Dehshiri SS, Hosseini Dehshiri SJ, Mostafaeipour A, Issakhov A, Techato K (2021a) A thorough investigation for development of hydrogen projects from wind energy: A case study. Int J Hydrogen Energy 46(36):18795–18815. https://doi.org/10.1016/j.ijhydene.2021.03.061

Almutairi K, Hosseini Dehshiri SS, Hosseini Dehshiri SJ, Mostafaeipour A, Jahangiri M, Techato K (2021b) Technical, economic, carbon footprint assessment, and prioritizing stations for hydrogen production using wind energy: A case study. Energ Strat Rev 36:100684. https://doi.org/10.1016/j.esr.2021.100684

Almutairi K, Hosseini Dehshiri SS, Hosseini Dehshiri SJ, Mostafaeipour A, Issakhov A, Techato K (2021c) Use of a Hybrid Wind—Solar—Diesel—Battery Energy System to Power Buildings in Remote Areas: A Case Study. Sustainability 13(16):8764

Ar IM, Erol I, Peker I, Ozdemir AI, Medeni TD, Medeni IT (2020) Evaluating the feasibility of blockchain in logistics operations: A decision framework. Expert Systems with Applications 158:113543

Bai C, Sarkis J (2013) Green Information Technology Strategic Justification and Evaluation. Inf Syst Front 15(5):831–847

Bai C, Sarkis J (2017) Improving Green Flexibility Through Advanced Manufacturing Technology Investment: Modeling the Decision Process. Int J Prod Econ 188:86–104

Baud-Lavigne, B., Agard, B., & Penz, B. (2014). Environmental constraints in joint product and supply chain design optimization. Comput Ind Eng. 76:16–22.

Beck R (2018) Beyond bitcoin: the rise of blockchain world. Computer 51(2):54–58

Beck R, Müller-Bloch C, King JL (2018) Governance in the Blockchain Economy: A Framework and Research Agenda. J Assoc Inf Syst 19(10):1020–1034

Behnke K, Janssen MFWHA (2020) Boundary conditions for traceability in food supply chains using blockchain technology. International Journal of Information Management 52:101969

Biswas B, Gupta R (2019) Analysis of barriers to implement blockchain in industry and service sectors. Comput Ind Eng 136:225–241

Böhme R, Christin N, Edelman B, Moore T (2015) Bitcoin: Economics, technology, and governance. Journal of Economic Perspectives 29(2):213–238

Britchenko I, Cherniavska T, Cherniavskyi B (2018) Blockchain technology into the logistics supply chain implementation effectiveness. In Yevheniia Polishchuk & Igor Britchenko (eds.), *Development of small and medium enterprises: the EU and East-partnership countries experience: monograph*. pp. 307–318.

Casado-Vara R, Prieto J, De la Prieta F, Corchado JM (2018) How Blockchain Improves the Supply Chain: Case Study Alimentary Supply Chain. Procedia Computer Science 134:393–398

Casion F, Dasaklis TK, Patsakis C (2019) A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics and Informatics 36:55–81

Casion F, Dasaklis TK, Patsakis C (2019b) A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics Inform 36:55–81

Choi TM, Guo S, Luo S (2020) When blockchain meets social-media: Will the result benefit social media analytics for supply chain operations management? Transportation Research Part E: Logistics and Transportation Review 135:101860

Choi T-M, Feng L, Li R (2020) Information disclosure structure in supply chains with rental service platforms in the blockchain technology era. International Journal of Production Economics 221:107473

Choukri K, Naddami A, Hayani S (2017) Renewable energy in emergent countries: lessons from energy transition in Morocco. Energy, Sustainability and Society 7(1):1–11

Christidis K, Devetsikiotis M (2016) Blockchains and smart contracts for the internet of things. IEEE Access 4:2292–2303. https://doi.org/10.1109/ACCESS.2016.2566339

Constantinides P, Henfridsson O, Parker GG (2018) Introduction – Platforms and Infrastructures in the Digital Age. Inf Syst Res 29(2):381–400. https://doi.org/10.1287/isre.2018.0794

Dahooie JH, Dehshiri SJH, Banaitis A, Binkytė-Vėlienė A (2020) Identifying and prioritizing cost reduction solutions in the supply chain by integrating value engineering and gray multi-criteria decision-making. Technol Econ Dev Econ 26(6):1311–1338

Deng JL (1982) Control problems of grey systems. Syst Control Lett 1(5):288–294. https://doi.org/10.1016/S0167-6911(82)80025-X

Dorri A, Steger M, Kanhere SS, Jurdak R (2017) Blockchain: A Distributed Solution to Automotive Security and Privacy. IEEE Commun Mag 55(12):119–125

Du WD, Pan SL, Leidner DE, Ying W (2019) Affordances, experimentation and actualization of FinTech: A blockchain implementation study. J Strateg Inf Syst 28(1):50–65

Dujak D., Sajter D. (2019) Blockchain Applications in Supply Chain. In: Kawa A., Maryniak A. (eds) SMART Supply Network. EcoProduction (Environmental Issues in Logistics and Manufacturing). Springer, Cham. https://doi.org/10.1007/978-3-319-91668-2_2

El-Karmi FZ, Abu-Shikhah NM (2013) The role of financial incentives in promoting renewable energy in Jordan. Renewable Energy 57:620–625

Engelken M, Römer B, Drescher M, Welpe IM, Picot A (2016) Comparing drivers, barriers, and opportunities of business models for renewable energies: A review. Renew Sustain Energy Rev 60:795–809

Goldsby TJ, Zinn W (2016) Technology innovation and new business models: can logistics and supply chain research accelerate the evolution? J Bus Logist 37(2):80–81

Hackius, N., & Petersen, M. (2017). Blockchain in logistics and supply chain: trick or treat?. In *Digitalization in Supply Chain Management and Logistics: Smart and Digital Solutions for an Industry 4.0 Environment. Proceedings of the Hamburg International Conference of Logistics (HICL), Vol. 23* (pp. 3–18). Berlin: epubli GmbH.

Hastig GM, Sodhi MS (2020) Blockchain for supply chain traceability: Business requirements and critical success factors. Prod Oper Manag 29(4):935–954

Heidary Dahooie J, Hosseini Dehshiri SJ (2019) Identify and prioritize Strategies to Reduce Plant Power Equipments Supply Chain Costs Through Value Engineering. Industrial Management Studies 17(52):125–152. https://doi.org/10.22054/jims.2017.17702.1634

Helo P, Hao Y (2019) Blockchains in operations and supply chains: A model and reference implementation. Comput Ind Eng 136:242–251

Hofmann E, Rüsch M (2017) Industry 4.0 and the Current Status as Well as Future Prospects on Logistics. Comput Ind 89:23–34

Hosseini Dehshiri SJ (2019) Using Gray Numbers Theory in Multi-Attribute Decision Making Methods for the Evaluation the Risk of Outsourcing of Information Technology Projects. IT Management Studies 7(28):167–198

Iansiti M (2017) The Truth About Blockchain. Harv Bus Rev 95(1):118

Iansiti M, Lakhani KR (2017) The truth about blockchain. Harvard Business Review 95:118–127

Jahanshahloo GR, Lotfi FH, Izadikhah M (2006) An algorithmic method to extend TOPSIS for decision-making problems with interval data. Appl Math Comput 175(2):1375–1384. https://doi.org/10.1016/j.amc.2005.08.048

Janssen M, Weerakkody V, Ismagilova E, Sivarajah U, Irani Z (2020) A framework for analysing blockchain technology adoption: Integrating institutional, market and technical factors. Int J Inf Manage 50:302–309

Jelti F, Allouhi A, Büker MS, Saadani R, Jamil A (2021) Renewable power generation: A supply chain perspective. Sustainability 13(3):1271

Jraisat L, Hattar C (2017) The Awareness of Renewable Energy efficiency for Supply Chain Management. Energies 10:1618

Kalbasi, R., Jahangiri, M., Mosavi, A., Dehshiri, S. J. H., Dehshiri, S. S. H., Ebrahimi, S., ... & Karimipour, A. (2021). Finding the best station in Belgium to use residential-scale solar heating, One-year dynamic simulation with considering all system losses: Economic analysis of using ETSW. *Sustainable Energy Technologies and Assessments*, *45*, 101097.

Kaliszewski I, Podkopaev D (2016) Simple additive weighting—A metamodel for multiple criteria decision analysis methods. Expert Syst Appl 54:155–161

Kamble SS, Gunasekaran A, Sharma R (2020) Modeling the blockchain enabled traceability in agriculture supply chain. International Journal of Information Management 52:101967

Kamilaris A, Fonts A, Prenafeta-Boldύ FX (2019) The rise of blockchain technology in agriculture and food supply chains. Trends Food Sci Technol 91:640–652

Keršuliene V, Zavadskas EK, Turskis Z (2010) Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA). J Bus Econ Manag 11(2):243–258

Keshavarz Ghorabaee M, Zavadskas EK, Olfat L, Turskis Z (2015) Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). Informatica 26(3):435–451

Khaqqi KN, Sikorski JJ, Hadinoto K, Kraft M (2018) Incorporating Seller/Buyer Reputation-Based System in Blockchain-Enabled Emission Trading Application. Appl Energy 209:8–19

Kildienė S, Kaklauskas A, Zavadskas EK (2011) COPRAS based comparative analysis of the European country management capabilities within the construction sector in the time of crisis. J Bus Econ Manag 12(2):417–434. https://doi.org/10.3846/16111699.2011.575190

Korpela, K., J. Hallikas, and T. Dahlberg. 2017. "Digital Supply Chain Transformation Toward Blockchain Integration." In *Hawaii International Conference on System Sciences*, 4182–4191. Waikoloa Beach, HI. https://doi.org/10.24251/HICSS.2017.506

Kshetri N (2017) Blockchain's Roles in Strengthening Cybersecurity and Protecting Privacy. Telecommunications Policy 41(10):1027–1038

Kshetri N (2018) Blockchain's Roles in Meeting Key Supply Chain Management Objectives. Int J Inf Manage 39:80–89. https://doi.org/10.1016/j.ijinfomgt.2017.12.005

Lei A, Cruickshank H, Cao Y, Asuquo P, Ogah CPA, Sun Z (2017) Blockchain-Based Dynamic Key Management for Heterogeneous Intelligent Transportation Systems. IEEE Internet Things J 4(6):1832–1843

Li H, Bao Q, Ren X, Xie Y, Ren J, Yang Y (2017) Reducing rebound effect through fossil subsidies reform: a comprehensive evaluation in China. J Clean Prod 141:305–314

Li X, Wang CA (2017) The Technology and Economic Determinants of Cryptocurrency Exchange Rates: The Case of Bitcoin. Decis Support Syst 95:49–60

Liu KH, Chang SF, Huang WH, Lu IC (2019) The Framework of the Integration of Carbon Footprint and Blockchain: Using Blockchain as a Carbon Emission Management Tool. In: Hu AH, Matsumoto M, Kuo TC, Smith S (eds) Technologies and Eco-Innovation Towards Sustainability I. Springer, Singapore, pp 15–22

Lorde T, Waithe K, Francis B (2010) The importance of electrical energy for economic growth in Barbados. Energy Economics 32(6):1411–1420

Lu Y (2018) Blockchain and the related issues: a review of current research topics. Journal of Management Analytics 5(4):231–255

Luthra S, Kumar S, Garg D, Haleem A (2015) Barriers to renewable/sustainable energy technologies adoption: Indian perspective. Renew Sustain Energy Rev 41:762–776

Mac Crimmon, K. R. (1968). *Decision making among multiple-attribute alternatives: a survey and consolidated approach* (No. RM-4823-ARPA). RAND CORP SANTA MONICA CA. https://www.rand.org/pubs/research_memoranda/RM4823.html. Also available in print form https://apps.dtic.mil/sti/citations/AD0681005

Makhdoom I, Abolhasan M, Abbass H, Ni W (2019) Blockchain's adoption in IoT: The challenges, and a way forward. Journal of Network and Computer Applications 125:251–279

Mathivathanan D, Mathiyazhagan K, Rana NP, Khorana S, Dwivedi YK (2021) Barriers to the adoption of blockchain technology in business supply chains: a total interpretive structural modelling (TISM) approach. Int J Prod Res 59(11):3338–187. https://doi.org/10.1080/00207543.2020.1868597

Mavi RK, Zarbakhshnia N, Khazraei A (2018) Bus rapid transit (BRT): A simulation and multi criteria decision making (MCDM) approach. Transp Policy 72:187–197

Min H (2019) Blockchain Technology for Enhancing Supply Chain Resilience. Bus Horiz 62(1):35–45

Mistry I, Tanwar S, Tyagi S, Kumar N (2020) Blockchain for 5G-enabled IoT for industrial automation: A systematic review, solutions, and challenges. Mechanical Systems and Signal Processing 135:106382

Montecchi M, Plangger K, Etter M (2019) It's Real, Trust me! Establishing Supply Chain Provenance Using Blockchain. Bus Horiz 62(3):283–293

Moosavi J, Naeni LM, Fathollahi-Fard AM, Fiore U (2021) Blockchain in supply chain management: a review, bibliometric, and network analysis. Environ Sci Pollut Res, 1–15. https://doi.org/10.1007/s11356-021-13094-3

Mostafaeipour A, Dehshiri SJH, Dehshiri SSH (2020a) Ranking locations for producing hydrogen using geothermal energy in Afghanistan. Int J Hydrogen Energy 45(32):15924–15940

Mostafaeipour A, Dehshiri SJH, Dehshiri SSH, Jahangiri M (2020b) Prioritization of potential locations for harnessing wind energy to produce hydrogen in Afghanistan. Int J Hydrogen Energy 45(58):33169–33184

Mostafaeipour A, Dehshiri SSH, Dehshiri SJH, Almutairi K, Taher R, Issakhov A, Techato K (2021) A thorough analysis of renewable hydrogen projects development in Uzbekistan using MCDM methods. Int J Hydrogen Energy 46(61):31174–31190

Mostafaeipour A, Hosseini Dehshiri SJ, Hosseini Dehshiri SS, Jahangiri M, Techato K (2020c) A Thorough Analysis of Potential Geothermal Project Locations in Afghanistan. Sustainability 12(20):8397

Mostafaeipour A, Jahangiri M, Haghani A, Dehshiri SJH, Dehshiri SSH, Issakhov A, Sedaghat A, Saghaei H, Akinlabi ET, Sichilalu SM, Chowdhury S, Techato K (2020d) Statistical evaluation of using the new generation of wind turbines in South Africa. Energy Rep 6:2816–2827

Mougayar, W. 2016. *The Business Blockchain: Promise, Practice, and Application of the Next Internet Technology*. Hoboken, NJ: John Wiley & Sons. https://knigavpodarok.com.ua/wa-data/public/site/folder5/blokchein_dlia_biznesa.pdf

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. Decentralized Business Review, 21260.

Niranjanamurthy M, Nithya BN, Jagannatha S (2019) Analysis of blockchain technology: pros, cons and SWOT. Clust Comput 22(6):14743–14757

Oh JS, Shong I (2017) A case study on business model innovations using blockchain: Focusing on financial institutions. Asia Pacific Journal of Innovation and Entrepreneurship 11(3):335–344

Opricovic S (1998) Multicriteria optimization of civil engineering systems. Faculty of Civil Engineering, Belgrade 2(1):5–21

Öztürk C, Yildizbaşi A (2020) Barriers to implementation of blockchain into supply chain management using an integrated multicriteria decision-making method: a numerical example. Soft Comput 24(19):14771–14789

Pan W, Jian L, Liu T (2019) Grey system theory trends from 1991 to 2018: a bibliometric analysis and visualization. Scientometrics 121(3):1407–1434. https://doi.org/10.1007/s11192-019-03256-z

Perboli G, Musso S, Rosano M (2018) Blockchain in logistics and supply chain: A lean approach for designing real-world use cases. IEEE Access 6:62018–62028

Prasad S, Shankar R, Gupta R, Roy S (2018) A TISM modeling of critical success factors of blockchain based cloud services. Journal of Advances in Management Research 15(4):434–456. https://doi.org/10.1108/JAMR-03-2018-0027

Queiroz MM, Telles R, Bonilla SH (2019) Blockchain and Supply Chain Management Integration: A Systematic Review of the Literature. Supply Chain Manag 25(2):241–254. https://doi.org/10.1108/SCM-03-2018-0143

Ramkumar M (2018) Executing large-scale processes in a blockchain. Journal of Capital Markets Studies 2(2):106–120

Reyna A, Martin C, Chen J, Soler E, Diaz M (2018) On blockchain and its integration with IoT. Challenges and opportunities. Future Generation Computer Systems 88:173–190

Reyna A, Martin C, Chen J, Soler E, Diaz M (2018b) On blockchain and its integration with IoT. Challenges and opportunities. Futur Gener Comput Syst 88:173–190

Robinson, A. (2016) "What is Blockchain Technology, and What is Its Potential Impact on the Supply Chain." https://cerasis.com/2016/06/29/blockchain-technology/. Accessed 2 Apr 2017

Rožman N, Corn M, Požrl T, Diaci J (2019) Distributed logistics platform based on Blockchain and IoT. Procedia CIRP 81:826–831

Saberi S, Kouhizadeh M, Sarkis J, Shen L (2019) Blockchain technology and its relationships to sustainable supply chain management. Int J Prod Res 57(7):2117–2135

Saberi S, Kouhizadeh M, Sarkis J (2018) Blockchain Technology: A Panacea or Pariah for Resources Conservation and Recycling? Resour Conserv Recycl 130:80–81

Shermin V (2017) Disrupting Governance with Blockchains and Smart Contracts. Strateg Chang 26(5):499–509

Sikorski JJ, Haughton J, Kraft M (2017) Blockchain Technology in the Chemical Industry: Machine-to-Machine Electricity Market. Appl Energy 195:234–246

Sovacool BK (2017) Reviewing, reforming, and rethinking global energy subsidies: towards a political economy research agenda. Ecol Econ 135:150–163

Stanujkic D, Karabasevic D, Zavadskas EK (2015) A framework for the selection of a packaging design based on the SWARA method. Engineering Economics 26(2):181–187. https://doi.org/10.5755/j01.ee.26.2.8820

Stanujkic D, Zavadskas EK, Liu S, Karabasevic D, Popovic G (2017) Improved OCRA method based on the use of interval grey numbers. Journal of Grey System 29(4):49–60

Swan, M. (2015). *Blockchain: Blueprint for a new economy*. " O'Reilly Media, Inc.". https://isidore.co/calibre/legacy/get/PDF/5503/CalibreLibrary/Blockchain_%20Blueprint%20for%20a%20Ne%20-%20Swan%2C%20Melanie_5503.pdf

Tagde, P., Tagde, S., Bhattacharya, T., Tagde, P., Chopra, H., Akter, R., ... & Rahman, M. (2021). Blockchain and artificial intelligence technology in e-Health. *Environmental Science and Pollution Research*, 1–22.

Tang H, Shi Y, Dong P (2019) Public blockchain evaluation using entropy and TOPSIS. Expert Syst Appl 117:204–210

Thakur V, Doja MN, Dwivedi YK, Ahmad T, Khadanga G (2020) Land records on blockchain for implementation of land titling in India. International Journal of Information Management 52:101940

Turskis Z, Zavadskas EK (2010) A novel method for multiple criteria analysis: grey additive ratio assessment (ARAS-G) method. Informatica 21(4):597–610

Underwood S (2016) Blockchain Beyond Bitcoin. Commun ACM 59(11):15–17

van Engelenburg S, Janssen M, Klievink B (2019) Design of a Software Architecture Supporting Business-to-Government Information Sharing to Improve Public Safety and Security. Journal of Intelligent Information Systems 52(3):595–628

Venkatesh VG, Kang K, Wang B, Zhong RY, Zhang A (2020) System architecture for blockchain based transparency of supply chain social sustainability. Robotics and Computer-Integrated Manufacturing 63:101896

Wu HH (2006) Applying grey model to prioritise technical measures in quality function deployment. The International Journal of Advanced Manufacturing Technology 29(11–12):1278–1283. https://doi.org/10.1007/s00170-005-0016-y

Wu XY, Fan ZP, Cao BB (2021) An analysis of strategies for adopting blockchain technology in the fresh product supply chain. *International Journal of Production Research*, 1-18. https://doi.org/10.1080/00207543.2021.1894497

Yadav S, Singh SP (2020) Blockchain Critical Success Factors for Sustainable Supply Chain. Resour Conserv Recycl 152:104505. https://doi.org/10.1016/j.resconrec.2019.104505

Yadav VS, Singh AR, Raut RD, Govindarajan UH (2020) Blockchain technology adoption barriers in the Indian agricultural supply chain: an integrated approach. Resources, Conservation and Recycling 161:104877

Yang W, Garg S, Huang Z, Kang B (2021) A decision model for blockchain applicability into knowledge-based conversation system. Knowledge-Based Systems 220:106791

Yaqoot M, Diwan P, Kandpal TC (2016) Review of barriers to the dissemination of decentralized renewable energy systems. Renew Sustain Energy Rev 58:477–490

Yli-Huumo J, Ko D, Choi S, Park S, Smolander K (2016) Where is current research on blockchain technology?—a systematic review. PloS one 11(10):e0163477

Yoon J, Talluri S, Yildiz H, Sheu C (2020) The value of Blockchain technology implementation in international trades under demand volatility risk. Int J Prod Res 58(7):2163–2183

Yoon K P, Hwang CL (1995) *Multiple attribute decision making: an introduction* (Vol. 104). Sage publications

Yuan Y (2018) Blockchain and cryptocurrencies: Model, techniques, and applications. IEEE Transactions on Systems, Man, and Cybernetics: Systems 48(9):1421–1428

Zarezade M, Mostafaeipour A (2016) Identifying the effective factors on implementing the solar dryers for Yazd province. Iran Renewable and Sustainable Energy Reviews 57:765–775

Zavadskas EK, Vilutiene T, Turskis Z, Tamosaitiene J (2010) Contractor selection for construction works by applying SAW-G and TOPSIS grey techniques. J Bus Econ Manag 11(1):34–55. https://doi.org/10.3846/jbem.2010.03

Zhao G, Liu S, Lopez C, Lu H, Elgueta S, Chen H, Boshkoska BM (2019) Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions. Comput Ind 109:83–99

Zohar A (2015) Bitcoin: under the hood. Commun ACM 58(9):104–113

Zolfani SH, Yazdani M, Zavadskas EK (2018) An extended stepwise weight assessment ratio analysis (SWARA) method for improving criteria prioritization process. Soft Comput 22(22):7399–7405. https://doi.org/10.1007/s00500-018-3092-2