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Closing the Loop in Photovoltaic Solar and Wind Power Supply Chains: An investigation in Turkey through Neutrosphopic-DELPHI-based Force Field Analysis and Neutrosphopic-DEMATEL

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ABSTRACT

Since solar panels and wind turbines have limited lifespans, solar photovoltaic energy supply chain (SPvESC) and wind energy supply chain (WESC) in Turkey needs a paradigm shift to improve the efficiency and recyclability of solar panel and wind turbine components. The circular economy (CE) is a viable strategy for reducing the negative effects of linear supply chains in the SPvESC and WESC. However, despite the several drivers of implementing CE in the SPvESC and WESC, there are also barriers to CE initiatives. It is argued that further studies are needed to explore the drivers and challenges for CE adoption in different industries of developing and developed countries. Hence, the goal of this research is to explore the driving and restraining forces for CE adoption in Turkey's SPvESC and WESC through a decision framework that includes *Neutrosphopic DELPHI-based Force Field Analysis*, *Neutrosphopic-DEMATEL*, and *Nominal Group Technique*. The findings of this research suggested that because the total score of restraining forces is higher than that of driving forces in force field analysis, it is critical to investigate the relationships among the restraining forces. Our findings also suggested that nonexistence of effective incentives and regulations proved to be the most prominent restraining force.

Introduction

Renewable energy resources are those that may be regenerated in a human lifetime in contrast to finite fossil fuels including coal, crude oil, and natural gas [1]. Hydro, solar, wind, biomass, waste, wave, tidal, and ocean energy, as well as geothermal energy, are the most prevalent means of renewable energy generation with the goal of reducing worldwide dependency on fossil fuels, which may eventually lower the global level of greenhouse gas emissions [2]. According to the International Energy Agency [3], renewable energy capacity is expected to grow at a faster rate in the subsequent years, accounting for about 95 percent of the increase in worldwide power capacity by 2026. More specifically, between 2020 and 2026, global renewable electricity capacity is projected to grow by more than 60 percent, reaching over 4800 GW. In 2021, about 290 giga-watts (GW) of new renewable energy were installed, a 3 percent increase over 2020′s already impressive growth [3].

Out of these renewable resources of power generation, solar photovoltaic (Pv) and wind has been by far the most dynamic ones due to the dramatic cost reductions in solar and wind installations in previous years. In 2021, solar Pv accounted for more than half of the global renewable energy expansion, followed by wind and hydropower [3]. However, since the first quarter of 2021, prices for various industrial materials, as well as freight costs, have been rising, driving up the cost of solar panels and wind turbines. Despite rising costs and contract pricing, solar Pv and wind remain competitive compared to the fossil fuel alternatives, especially due to the current high prices of natural gas and coal. More precisely, while solar will contribute 203 GW, 225 GW, 239 GW, and 266 GW in 2022, 2023, 2024 and 2025, respectively [4], approximately 469 GW of new onshore and offshore wind power will be added in the next five years, or nearly 94 GW each year until 2025 [5].

Nonetheless, despite their exponential growth, solar panels and wind turbines will not remain in use forever. According to industry standards, while the productive lifespan of a solar panel is typically about 25–30

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years, a wind turbine will usually last 20–25 years, suggesting that some of the solar and wind power plants built during the present boom are nearing the end of their useful lives [6]. With each passing year, more will be withdrawn from service, implying that we will soon have to take action to manage tens of millions of metric tons of end-of-life materials. For example, solar panels are expected to generate between 60 and 78 million tons of material by 2050, according to The International Renewable Energy Agency (IRENA) [6], requiring one of three end-of-life options: recycling, reuse, or disposal.

Several parts of Pv panels and turbines are currently stacking up in landfills across the globe. Hence, addressing end-of-life materials effectively entails a novel approach that differs from linear supply chains built on the paradigm of "take, make, dispose" trilogy. The circular economy (CE), with a strong emphasis on closing the loop in a supply chain, is defined as "an industrial system that is restorative or regenerative by intention and design" [16]. In another definition, Kirchherr et al. [7] describes CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes". According to the CE model, waste should not only be avoided, but also reversed back into production processes [8]. CE aims to eliminate waste through superior design of materials [9,10] products, information systems and technologies [11–15], and business models [16–23]. Using the foundation of CE, note that many individual components, such as solar panel aluminum and glass, and turbine steel towers can be recycled. Furthermore, as technology progresses, companies in Solar Photovoltaic Energy Supply Chain (SPvESC) and Wind Energy Supply Chain (WESC) are looking for ways to improve the component efficiency, durability, and recyclability. As awareness for CE grows, more research is being conducted on new approaches such as high-value recycling technologies that recover ecologically sensitive materials to recycle and reuse solar Pv and wind turbine elements.

Due to her rapid industrialization and urbanization over the last three decades, Turkey has also faced resource management difficulties as well as the need to transform its industrial structure to be more resource-efficient and ecologically friendly [24]. This transformation outlines the country's long-term development goals, focusing on environmental sustainability, sustainable resource management, and CE in various industries. However, note that there are several challenges to applying CE in the SPvESC and WESC just as there are in other industries, notwithstanding the driving forces that include technical, economic, organizational, regulatory, infrastructural, and cultural [25,26]. Hence, Hina et al. [26], Zhang et al. [27], Farooque et al. [28], and Rizos and Bryhn [115] argued that it's vital to develop a comprehensive decision framework to address the primary drivers and barriers for CE in different industries of developing and developed countries. In another study, Kirchherr and van Santen [118] argued that existing research lack in empirical work on CE. They also argued that practitioners need further analyses discussing how CE can be implemented in real life cases. de Jesus and Mendonça [93] suggested that it's critical to gain a comprehensive grasp of the elements that help or hinder the shift to the CE through new research. Moreover, Kirchherr [119] argued that new empirical studies are needed, at least, to pave the way for addressing the social impact of CE in emerging economies through the concept of circular injustice. However, although several studies emphasized the importance of conducting sector specific studies in emerging economies, no study has been done, to our knowledge, to thoroughly explore the driving and restraining forces for CE adoption in SPvESC and WESC, which is also consistent with the opinions of Gautam et al. [29] and Beauson et al. [30] indicating that current research should pay attention to empirical studies specifically on end-of-life solar Pv and wind turbines management challenges especially in emerging countries. Hence, the goal of this research is three-fold: (1) to ascertain the driving and restraining forces for CE adoption in the Turkey's SPvESC and WESC through *neutrosophic DELPHI-based force field analysis*, (2) to reveal the associations between the forces by employing *neutrosophic-DEMATEL* and (3) to suggest policies towards effective CE implementations in the SPvESC and WESC.

Hence, the research questions (RQs) of this study are as follows: RQ_1: What are the driving and restraining forces for CE adoption in Turkey's SPvESC and WESC through Force Field Analysis? RQ_2: Out of the driving and restraining forces for CE adoption in the SPvESC and WESC, which one work against the other? RQ_3: What are the associations among the restraining forces? RQ_4: How may the findings of this study aid decision makers implement CE more effectively in Turkey's SPvESC and WESC?

Note that the proposed decision framework used in this study is grounded on the integration of force field analysis and multi-criteria decision-making. Force Field Analysis considers the change as a dynamic balance of forces working in opposite directions [31]. When the sum of the forces supporting change (Drive Forces) is stronger than the sum of the forces against change (Restraining Forces), the status quo or equilibrium will shift. Simply put, any social situation, according to a Force Field Analysis, is a balance of these factors.

The findings of this research with its integrated approach make several contributions to the existing literature. First, hitherto, although a few studies have been done to investigate the barriers to implementing CE in some industries of various countries, no quantitative study has been performed to discover the driving and restraining forces for CE adoption in SPvESC and WESC through Force Field Analysis. In this study, the traditional Force Field Analysis was empowered using *Neutrosphopic-DELPHI* to address the ambiguity of the expert opinions. Second, using the results of *Neutrosphopic -DELPHI-based Force Field Analysis*, *Neutrosphopic-DEMATEL* was also employed to reveal the associations between the forces, which is crucial since addressing all the forces concomitantly is realistically infeasible. Third, based on the findings of this study, the policy implications of Turkey's possible CE activities in the SPvESC and WESC were discussed in detail.

The structure of this study is as follows: in the following section, background information on SPvESC and WESC in Turkey, and driving and restraining forces through Force Field Analysis is addressed. Then, the proposed methodology is introduced followed by the application and results. Next, Discussion and Implications are provided. Finally, Conclusions are demonstrated.

Background

SPvESC and WESC towards circular economy in Turkey

Turkey was one of the first countries to seek closer ties with the new European Economic Community. This collaboration took place under the auspices of an "association agreement," known as the Ankara Agreement, signed on September 12, 1963. On April 14, 1987, Turkey submitted her application for full membership, and from that time on, the Turkish Governments have adopted the National Programme for the Adoption of the Acquis, reflecting the accession partnership. More specifically, Turkey has enacted administrative and technical laws that are in line with European Union directives. One of the laws that have been passed was the incentive mechanism that has been put into effect to expand the use of renewable energy resources. There has been a significant increase in both solar photovoltaic and wind turbine installations in Turkey since the "feed-in-tariff" based incentive mechanism, known as YEKDEM was enacted. While Turkey focused on investing in solar panels and wind turbines with the help of YEKDEM, the EU started to implement CE in SPvESC and WESC. Put another way, Turkey faced an additional challenge of how to deal with end-of-life materials of solar panels and wind turbines.

According to Republic of Turkey Ministry of Energy and Natural Resources [32], in Turkey while solar Pv installations are forecasted to create 558,420 tons of waste by 2046, end-of-life towers and blades are expected to generate 534,800 and 35,858 tons of materials, respectively by 2041. Turkey will also be ranked fifth in Europe for increasing renewable energy capacity, with 22.2 gigawats expected to be added by

2025, bringing total capacity to 66.8 gigawats. Given the expected volume of solar and wind waste, note that both sources require a large amount of material to be recycled. However, Turkey had not yet implemented a regulation in line with European Union legislation at the time this research was conducted. More explicitly, no decree regulating the solar panel and wind turbine waste has been included in Turkey's Waste Electrical and Electronic Equipment Directive (WEEE) yet.

DFs and RFs for building CE in the SPvESC and WESC through Force Field Analysis

Force Field Analysis is founded on Kurt Lewin's paradigm [31] for thinking about change, which viewed institutional behavior as a dynamic balance of forces working in opposite directions rather than a static pattern. Change materializes when there is an imbalance between the sum of the forces against change (Restraining Forces) and the sum of the forces for change (Drive Forces), according to this perspective on behavior (Driving Forces). Any social situation, according to Force Field Analysis, is a balance of these factors. An imbalance can arise due to a change in size or direction in any of the forces, or due to an addition of a new force. Force field analysis is investigative and analytical. After identifying the forces working for and against change, priorities are identified, and goals are set.

Force Field Analysis has been used in several decision-making problems including effective information system implementations, automotive supply chain strategy selection, tourism supply chain resilience, and municipality management [33–36]. In this study, *Neutrosphopic DELPHI-based Force Field Analysis* is used. The details of the proposed approach are provided in the following Section.

Methodology

This study is based on the integration of qualitative and quantitative research methodology to answer the research questions provided in Section 1. A step-by-step procedure for gathering, examining, and processing data is used as displayed in Fig. 1. In this research, first, the driving and restraining forces for CE adoption in Turkey's SPvESC and WESC are ascertained and evaluated through *neutrosophic DELPHI-based Force Field Analysis*. Then, the associations between the forces are investigated by employing *neutrosophic-DMATEL*, which enables decision makers to suggest policies towards effective CE implementations in the SPvESC and WESC. Finally, the results of the study are validated by using Nominal Group Technique.

Neutrosphopic-DELPHI-based Force Field Analysis

Force Field Analysis was developed by Kurt Lewin [31] as a systematic technique and is widely used in planning and implementing changes in organizations as a part of decision-making process [31]. According to Lewin, behavior within organizations is dynamic, not static [31]. Therefore, if a change is to be executed successfully, it is necessary to ascertain both the driving forces that will support the change and the restraining forces that will prevent it [34]. Fig. 2 depicts the Force Field Analysis framework, which aids organizations in identifying the forces that favor change and those that oppose it.

The following steps may be used to conduct Force Field Analysis [34,37]:

1- Ascertain all forces for the change *(Driving Forces-DFs)* on one side and all forces against the change *(Restraining Forces-RFs)* on the other side.
2- Evaluate the impact of each force on an appropriate scale.
3- Calculate the total scores on each side. If the score of DFs is greater than the score of RFs, then the company should most likely to implement the change.
4- Otherwise, precautions should be taken to shift the imbalance. In this study, *Neutrosphopic-DELPHI* was used to obtain the total scores of DFs and RFs.

Delphi Technique was developed in 1950 by RAND Corporation to investigate the impact of technology on a war. Defined as a systematic iterative process, Delphi is a prospective expert-based method that is aimed to obtain the opinions and, if possible, consensus of a group of experts who have a close relationship on the issue [38]. There are a few variants of Delphi method rather than the classical one. Selecting a Delphi method variant depends on the objective of a study. This selection depends on the algorithm's characteristics, the number of rounds, anonymity, feedback, sampling, and analysis [38].

This study utilizes *Neutrosphopic-DELPHI* based on [39] to obtain the total scores in FFA. Subjective judgments of expert opinions can cause a major ambiguity in decision-making process [40]. Hence, the fuzzy set (FS) theory was developed by Zadeh to tide over the vagueness and uncertainty associated with information in decision-making process [41]. "As fuzzy set theory takes into account only the degree of truth-

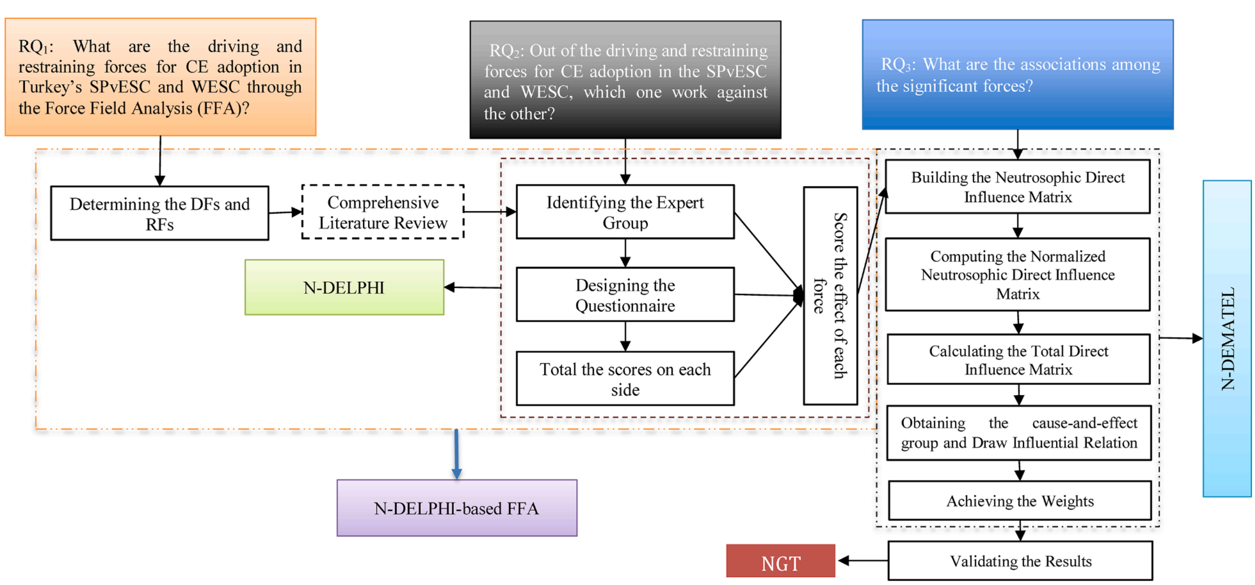

Fig. 1. The Proposed Methodology.

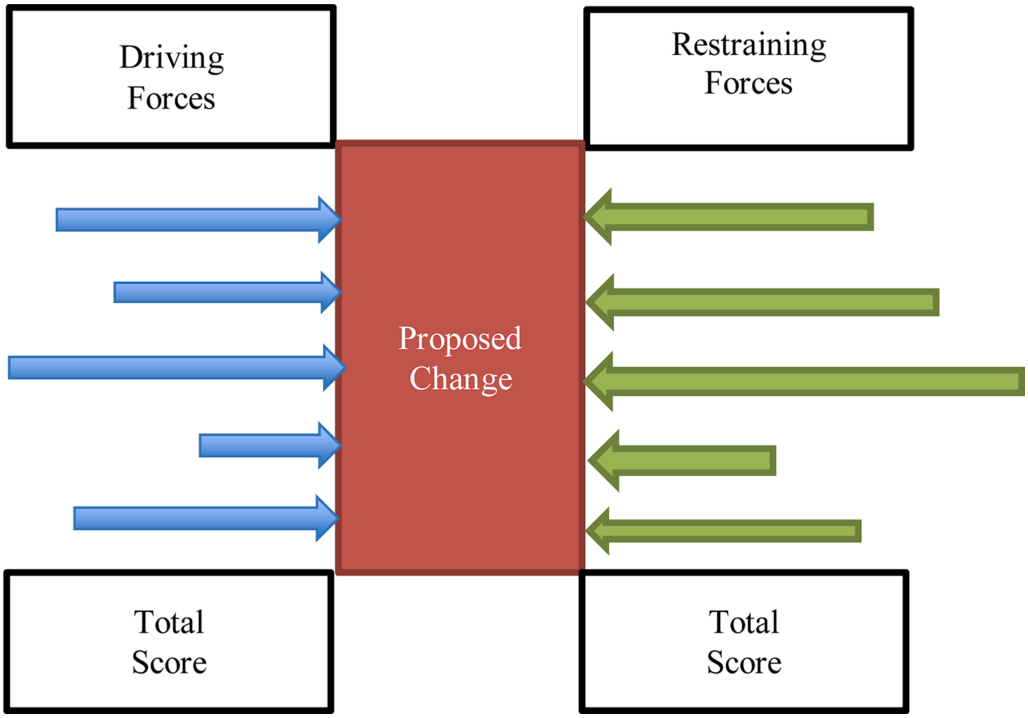

Fig. 2. The Framework of FFA.

membership, it cannot present the truth and cannot efficiently display ambiguous and inconsistent information" [42]. To address the fuzziness more effectively, the notation of the intuitionistic fuzzy sets (IFS) was put forwarded by Atanassov [43] as a continuation of the fuzzy set theory [44]. However, while IFS can only tackle minus information, they are not sufficient to address imprecise and contradictory information commonly found in real systems [45]. To tackle this problem, Smarandache offered neutrosophic set in 1995, which is the generalization of IFS and FS. Neutrosophic set theory is utilized in this research to express decision maker's preferences [46]. Neutrosophic sets (NSs) are strengthening the IFS by exhibiting the judgments and clarifying the vagueness more accurately [47]. NS has the following benefits [48,42,47]:

- It shows the degree of indeterminacy, which helps decision-makers express their ideas more correctly.
- It exemplifies the degree of decision makers' disagreements. The proposed model also combines different interests of decision makers' in one opinion in order to eliminate inconsistencies or to address the inconsistencies of expert decisions and improve consistency.
- "NSs, especially, single valued NSs, are identified by three independent membership functions: falsity (rejection), truth (acceptance), and indeterminacy (uncertainty)".
- "NSs demonstrate the positive, negative and indeterminate information more effectively than FSs and IFS".
- Because indeterminacy in NSs is precisely quantified, it can deal with indeterminate and inconsistent data.

The *Neutrosphopic-DELPHI* technique employed in this study is based on a series of questions. The questions asked to an expert group are answered using the scale in [48,42,47] that summarizes the scale of evaluations associated with the single-valued triangular neutrosophic numbers (SVTNN).

There are several ways of applying *Neutrosphopic-DELPHI* technique with one or two iterations depending on the degree of agreement between the members of an expert group. To this end, after every round, the responses of expert group are analyzed by using medians and confidence intervals, which enables us to achieve the consensus among the expert group as much as possible. In this study, consensus is measured by using the variance of the expert group's responses. Variance values, described as the difference between the first and third quartiles, are basically the main indicators of consensus and should be less than 1.5 [49].

Neutrosophic-DEMATEL

DEMATEL is a method for developing a structural model that contains causal links between several variables [50]. This method can convert the interactions between variables into a system-wide structural model that can be divided into two categories: cause and effect. As a result, investigating interwoven linkages between several factors in a complex system and sorting them for long-term strategic decision-making and identifying improvement areas is a realistic and beneficial strategy [51]. This methodology can validate the associations among the factors and provides a visual diagram of the relationships between them, which is referred to as the direct relationship map. In this study, *neutrosophic DEMATEL* is used to obtain the associations among the forces. Neutrosophic sets are capable to address indeterminacy and imprecision in the decision-making process as discussed in Section 3.1 [52].

The steps of *neutrosophic DEMATEL* used in this study is presented as follows [42,53]:

1. Build the problem by identifying the forces.
2. Construct the *Neutrosophic Direct-Influence Matrix* which is represented by A^G by using the evaluation scale shown in [42,53].

Table 3 shows the collection of each expert's evaluation about the influence of one factor over the other. A^G is constructed as displayed in Eq. (1).

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

3. Calculate the *normalized neutrosophic Direct-Influence matrix (B)* by Eqs. ((2)–(3)).

$$B = k.A^G \tag{2}$$

$$k = Min\left(\frac{1}{\max\sum_{j=1}^{n}|X_{zij}|}, \frac{1}{\max\sum_{i=1}^{n}|z_{X,j}|}\right) i \text{ and } j = 1, 2, 3 \tag{3}$$

Hence, note that that while conducting the normalization, k value is calculated using the truth-membership values of the aggregated direct influence matrix. Next, the multiplication is conducted to obtain the normalized matrix.

4. Compute *the total neutrosophic Direct-Influence matrix (S)* by using Eq. (4). *I* represents the identity Matrix.

$$S = B + B2 + B3 + B4 + \ldots + Bm = B.(I - B) - 1(\rightarrow\infty) \tag{4}$$

However, in neutrosophic set, "similar operations are performed separately for each element including the truth-membership (T), indeterminacy-membership (I), and the falsity-membership (F) functions" by utilizing Eqs. (5) – (7).

$$[Tij] = B_T.(\mathrm{I} - B_T)^{-1} \tag{5}$$

$$[Iij] = B_I.(\mathrm{I} - B_I)^{-1} \tag{6}$$

$$[Fij] = B_F.(\mathrm{I} - B_F)^{-1} \tag{7}$$

5. Obtain the vector *D and R* by the Eqs. ((8)–(9)).

$$D = [di]\mathrm{nx1} = \left[\sum_{\mathrm{j=1}}^{\mathrm{n}} S_{ij}\right]_{\mathrm{nx1}} \tag{8}$$

$$R = [rj]\mathrm{nx1} = \sum_{\mathrm{i=1}}^{\mathrm{n}} S_{ij} \tag{9}$$

The sum of the $\mathrm{i_{th}}$ row shows the total impact of the $\mathrm{i_{th}}$ force on other forces and is symbolized as d_i. The sum of the $\mathrm{j_{th}}$ column shows the total impact of the forces by other forces and is symbolized as $\mathrm{r_j}$. The highest $(D + R)$ values mean that they have high relationships with other forces and have important impacts. If a force's (*D-R*) value is positive, it has a large impact on other forces and is referred to be the cause group. The effect group is made up of the negative (*D-R*) values and is influenced by the others. Deffuzified *T*, *I*, and *F* values are obtained by using the transformation formula given in Eq. (10).

$$X = T_{ij} - I_{ij} + (2\alpha - 1)F_{ij} \tag{10}$$

6. Apply Eqs. ((11)–(12)) to normalize the forces and obtain the final significance weights of the forces.

$$w_i = [(D_i + R_i)^2 + (D_i - R_i)^2]^{0,5} \tag{11}$$

$$W_i = \frac{w_i}{\sum w_i} \tag{12}$$

7. "Set a threshold value to draw *Influential Relation Map (IRM):* To simplify the *S* and avoid the complexity of minor effects, it is necessary to assign a threshold value (α) by the experts. Specifying an appropriate threshold (α) is extremely critical. If the threshold (α) is detected too high, the impact will not appear on the IRM". However, if it is discovered to be too low, the number of forces in the IRM increases, making the map excessively complicated. Based on Eq. (13), threshold (α) is calculated by finding the average of the S-matrix where *N* represents the sum of the elements in the *S-matrix*.

$$\alpha = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}}\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{t_{ij}}}{\mathrm{N}} \tag{13}$$

Validating the results using Nominal Group Technique

Once all the calculations of *Neutrosophic DEMATEL* were finalized, the *Nominal Group Technique* was used to validate the results. The *Nominal Group Technique* is a qualitative method for eliciting stakeholder judgment that is based on a combination of individual and group reflection. *Nominal Group Technique* eventually comes up with a prioritized list of activities and/or recommendations [54]. NGT has been applied in a variety of fields including healthcare services [55], consumer preference research [56], health promotion [57] and criminology [58]. Ascertaining problems, finding solutions, and determining priorities are just a few of the most common *Nominal Group Technique* applications [59].

Application and the results

In this research, the proposed methodology displayed in Fig. 1 is applied. The details of the procedure are as follows:

Determining the driving and restraining forces

First, in this study, we conducted a thorough review of the literature to identify existing studies on potential DFs and RFs for CE adoption in SPvESC and WESC specifically, as well as other industries in general. Our search in major databases was grounded on the following keywords: "drivers for CE", "restraining forces for CE", "barriers for CE", and "challenges for CE". The literature review comprised the studies until April 2022 and concentrated exclusively on peer-reviewed research papers and theses. Given the results of the review, we identified a comprehensive list of DFs and RFs that will be used to investigate the potential of CE in Turkey's SPvESC and WESC. The final list provides the descriptions and references for DFs and RFs as displayed in Tables 1 and 2.

Neutrosphopic-DELPHI-based Force Field Analysis

In this stage, first, the score of each driving and restraining force was obtained by using *Neutrosphopic-DELPHI*. To this end, first we listed the driving and restraining forces for CE adoption in the SPvESC and WESC through a literature review. Detailed information about the forces is presented in Tables 1 and 2. Then, a group of experts were built as displayed in Table 3 since it is more beneficial to construct a robust Force Field Analysis through expert opinions [37]. Individual preferences and information gaps may make it difficult for a single person to effectively grasp the dynamics that influence a strategy. A group discussion of forces, however, can help the expert group comprehend how the forces will affect a strategy they're considering [105].

Furthermore, it is suggested that there is no hard and fast rule for determining the appropriate number of experts to consult. To put differently, in such research, the number of experts is frequently unknown [106].

After the preliminary list of the *DFs* and *RFs* demonstrated in Table 1 and 2 was provided to the expert group, the two sessions of virtual meetings were held. Each meeting lasted about 30 min. During these meetings, the expert group examined the list of the forces in terms of their comprehensiveness and concluded that no change is necessary.

Once the *DFs* and *RFs* were finalized, questionnaires were created and disseminated to the Expert Group via an online platform to prevent group members from interfering with one another. The Expert Group was asked to score the importance levels of *DFs* and *RFs* based on the 1–7 point Likert scale indicated in [48,42,47].

Once the answers of the expert group were received, the 1st round of

Table 1
DFs, their descriptions and references.

Driving Forces	*Description*	*Reference*
The necessity of ensuring resource efficiency (*DF_1*)	SPvESC and WESC should use unique waste reduction strategies to achieve better levels of resource efficiency, allowing them to keep a leaner structure and gain a competitive advantage over their competitors. CE is mostly based on a series of techniques to achieve resource efficiencies in various supply chains.	[60,61,8]
The necessity of lowering supply chain costs using CE-based novel techniques (*DF_2*)	CE enables SPvESC and WESC to implement alternative strategies to contribute to cost reductions. Cost savings result from the reductions in virgin material usage and the increasing share of recovered products in resource consumption.	[62,63,25]
Global laws and regulations towards CE (*DF_3*)	Regulations have been the main driver to improve CE in various supply chains, "contributing to the development of pollution prevention approaches and eco-efficiency strategies by changing the relative costs of pollution and cleaner production". To date, various laws have been enacted internationally, which have an impact on the circularity of SPvESC and WESC.	[64,65,66,67]
The need for reducing green house gas emissions (*DF_4*)	There has been a high increase in greenhouse gas emissions for decades due to various supply chain activities. This rising level of greenhouse gas emissions lead to a global climate change. CE initiatives in SPvESC and WESC may address the global climate problem through its novel closed-loop-based strategies.	[63,68,61,25,69,70,60]
The necessity of adopting CE related strategies (*DF_5*)	Business models that result in resource inefficiencies in SPvESC and WESC are no longer adequate. In today's business world, the employment of eco-innovative solutions to migrate to CE is the norm. Hence, SPvESC and WESC must adopt CE-based strategies to gain better bottom-line and market value.	[26,71,72,73,74,75,69,76,77]
The need for more collaboration and trust among organizations (*DF_6*)	SPvESC and WESC need to enhance collaboration with other organizations, which ultimately ensure synergy between them. Effective CE strategies may help build trust between entities. Note that once built, enhanced trust may become customary, which improve collaboration in a circular supply chain.	[73,78]
Retaining a better corporate reputation (*DF_7*)	Higher CE performance in SPvESC and WESC improves the organization's green corporate image, resulting in increased credibility among existing customers and the potential to secure new ones. CE's global recognition allows the organization to get visibility in an international setting, allowing it to develop into new geographical areas.	[25,79]
Increasing stakeholder awareness for CE (*DF_8*)	Stakeholders have been placing great importance on the potential cost savings, resource efficiency, and the other economic incentives resulting from CE. Increasing stakeholder awareness leads to an incentive for top managers to adopt CE related strategies.	[80,81,67]
Accessibility to new technologies (*DF_9*)	Recently, several technological advancements have been made, which lead to better visibility. These innovations ultimately ensure improved trust, integration, and collaboration in supply chains. Adopting novel technologies enable supply chains to implement more effective CE initiatives.	[25,65,82,69,72]
The need for improved CE performance (*DF_{10}*)	Supply chains should improve their CE performances in response to several internal and external incentives. SPvESC and WESC need new strategies to improve their CE performances. Simply put, supply chains should come up with better ways for	[68,74]

(*continued on next page*)

Table 1 (*continued*)

Driving Forces	*Description*	*Reference*
	the transition towards successful CE.	
Changing competitive emphasis (*DF_{11}*)	There is a need for organizations to shift their organizational culture from competition to cooperation. CE has a potential to ensure that SPvESC and WESC build a sustainable business environment through trust and integration.	[83,26,84]
The need for providing more employment opportunities (*DF_{12}*)	Job creation is essential because, the more people are employed the more the economy becomes stable. New CE-based strategies have potential to create more employment opportunities that help to increase the welfare of societies. Hence, social sustainability is improved eventually in SPvESC and WESC.	[85,86]
Availability of novel business models towards CE (*DF_{13}*)	New business models based on CE principles in SPvESC and WESC are available for companies recently. They assist to change their mindsets concerning their EOL streams. New mindsets require companies to consider EOL products as potential resources. In other words, they provide opportunities that lead to potential synergies and technological innovations.	[26,71,72,73,74,75,69,76,77,22]
Growing importance of the EOL material recycling (*DF_{14}*)	Solar and wind have become the most affordable renewable energy alternatives recently. Therefore, they are being implemented all over the world. Due to their high amount of usage, EOL solar panels and the components of wind turbines should be addressed through effective circular supply chain strategies.	[25,81,76,87]
Increasing the percentage of solar photovoltaic panels and wind Turbine installations (*DF_{15}*)	Falling costs have been the biggest factor in the explosion of solar and wind energy in the world. Turkey is also experiencing the same pace of growth. With this exponential spread of solar panels and wind turbines, Turkey will face a serious problem of EOL material recycling and have to address accordingly.	[25,88,89]
Availability of design for CE (*DF_{16}*)	New technologies are available for companies to design solar panels and wind turbine components considering the economic recovery of EOL materials. One strategy for companies to address EOF products effectively is called design for CE. Due to the robustness of the strategy, recycling EOL solar panels and wind turbine components has never been easy.	[61,76,90,71,70]

N *Neutrosphopic-DELPHI* was completed. The answers of the expert group were combined and then clarified. The first round's answers were used to calculate "the median", "first quartile", "third quartile", and "range statistics". In the 2nd round, a new questionnaire was created, which was customized for each expert. Expert group was told about the overall inclination of the opinion and given the option to re-assess their responses. In the 2nd round, none of the experts appeared to have modified their decisions. Next, it was concluded that the variance values were below 1.5 for all *DFs* and *RFs*, and the consensus was achieved. Finally, the total scores for *DFs* and *RFs* were calculated as *75.00* and *77.50*, respectively. Our findings indicate that *DF_3* (Global laws and regulations towards CE) turned out to be the most significant driving force, while *RF_6* (Nonexistence of effective incentives and regulations) is the most crucial restraining force. Finally, overall, since the total score of *RFs* is greater than that of *DFs*, it is crucial that *RFs* should be explored systematically through identifying the associations between them, enabling decision makers to shift the imbalance.

Neutrosphopic-DEMATEL

In this section, *Neutrosphopic-DEMATEL* was used to identify the associations between *RFs*. The *RFs* used in *Neutrosphopic-DEMATEL* analysis were demonstrated in the previous stage, and the detailed information on them is presented in Table 2. The *Neutrosphopic-DEMATEL* questionnaire, which was created to test the level of influence of *RFs* on each other, was presented to the expert group specified in Table 3. Experts answered the questionnaire using the scale in [48,42,47]. After the answers of the expert group were taken and combined, the process steps of the *Neutrosphopic-DEMATEL* method stated in Section 3.2 were applied sequentially.

First, *neutrosophic direct influence matrix (A^G)* was constructed by totaling the evaluations taken from the experts. Second, *the normalized neutrosophic direct-influence matrix (B)* was built using the Eqs. (2)–(3). Third, *the total direct-influence matrix (S)* was designed using the Eqs. (4)–(7). Finally, Eqs. (8) and (9) were used to calculate ($D + R$) and (D-R) values of the *RFs*, as shown in Table 4. ($D + R$) and (D-R) values also indicate the cause-and-effect groups of the *RFs*. The relationships between *RFs* based on Influential Relation Map are shown in Fig. 3.

Validating the results through Nominal Group Technique

In this study, *Nominal Group Technique* based on virtual meetings used by Rankin et al. [54] and Huge et al. [107] were adopted to validate the results obtained in *Neutrosphopic-DEMATEL*. To this end, first, the findings demonstrated in Table 4 were provided to the expert group.

Table 2
RFs, their descriptions and references.

Restraining Forces	*Description*	*Reference*
Absence of CE policies (*RF_1*)	Managers are motivated by organizational policies, goals, and performance measurements to develop and engage in synergy projects that contribute to the company's CE performance. Otherwise, absence of policies and commitment towards CE-based business bottom-lines would be a recipe for ineffective operations.	[26,25,78,82,73,8]
Absence of top management commitment to CE (*RF_2*)	Top management commitment is vital for achieving a strategy. However, some managers do not provide adequate support to accomplish CE strategies. Hence, top management commitment is essential to effectively implement CE in SPvESC and WESC.	[26,62,91,63,92,76,22]
Undesirable impact of the existing culture (*RF_3*)	Companies must undergo a significant culture transformation to go from an individualistic perspective to an integrated CE system. Companies are urged to transition from a competitive culture to one based on cooperation and collaboration. However, note that there may be cultural barriers that challenge the further adoption of a collaboration-based CE approach in SPvESC and WESC.	[26,81,63,93,92]
Lack of knowledge and proper training (*RF_4*)	The focus of the stakeholders is mainly on their core businesses, which is the main constraint on the full development and implementation of CE-based strategies in SPvESC and WESC. This usually refers to the insufficient understanding of CE-based strategies and concepts due to the lack of mechanisms to educate potential stakeholders	[80,68,70,117]
Ineffective information systems (*RF_5*)	CE is based on a learning environment, where collection and exchange of information, and integration are fostered by cross-company cooperation. Absence of an effective information system has a negative impact on ensuring effective communication and exchange of relevant information with other entities in SPvESC and WESC.	[71,69,22]

Table 2 (*continued*)

Restraining Forces	*Description*	*Reference*
Nonexistence of effective incentives and regulations (*RF_6*)	Regulations and incentives have been the main driver to improve CE in various supply chains Lack of incentives and regulations often create disincentives to CE initiatives and exchange of knowledge through eco-innovation. Effective CE initiatives in the SPvESC and WESC are also mainly dependent on the existence of successful regulatory management.	[82,60,89,72,73,94,67,117]
Absence of economic benefits in short-run (*RF_7*)	Economic barriers may prevent short-term benefits due to the cost of the CE projects. Implementing CE effectively may require a long and complex process.	[95,61,78,96,81,67,23]
The necessity of making high investment (*RF_8*)	CE often involves building new facilities and purchasing new equipment, which altogether establish reverse supply chain network. However, there is usually a lack of financial resources to promote CE.	[96,71]
Lack of effective recycling technologies (*RF_9*)	When it comes to recycling, effectiveness is everything. Companies are investing more and more into the technologies that can help them in waste removal and product recovery management. Absence of necessary technologies may result in ineffective CE applications in the SPvESC and WESC.	[85,92,80,66,22]
Lack of reverse logistics network (*RF_{10}*)	Effective CE initiatives may pose some infrastructural challenges. Lack of facilities including recycling centers, collection centers, RandD labs, and technical resources hinder the potential avenues for effective CE implementations in the SPvESC and WESC.	[63,76,22]
Reluctance to share information (*RF_{11}*)	Different stakeholder objectives can create conflicts between entities, which result in limited sharing of information. In addition, entities may sometimes be reluctant to share information due to the privacy issues, Reluctance to share information is one of the most crucial reason for ineffective CE	[71,70,25,88,22]

(*continued on next page*)

Table 2 (*continued*)

Restraining Forces	*Description*	*Reference*
	implementations in the SPvESC and WESC.	
High level of inflexibility in organizational systems and processes (*RF_{12}*)	Companies may lack the flexibility to shift their operations to adapt to the requirements of CE. Absence of this kind of flexibility may cause ineffective CE implementations.	[71,84]
Insufficient level of trust and collaboration among organizations (*RF_{13}*)	Trust lies at the core of any network and stands as a major collaboration mechanism in circular supply chains. Therefore, lack of trust is one of the major challenges to building an effective CE. The absence of trust ultimately inhibits communication between actors and willingness to collaborate in the SPvESC and WESC.	[80,79,78,73],
End-of-Life product uncertainty (*RF_{14}*)	Risk and uncertainty are significant obstacles to the diffusion of CE. CE involves a new way of doing business and therefore may lead to some uncertainty regarding the operations. More specifically, cooperation between companies implies higher levels of inter-dependency, and the CE adds more uncertainty to collecting, processing, and recovering EOL materials in the SPvESC and WESC.	[22,25,97,81]
Emissions and pollution generated during recycling (*RF_{15}*)	Some critics of recycling note that the costs outweigh the benefits and/or exceed community resources because recycling processes require high amount of energy, and may cause CO_2 emissions that pollute the atmosphere.	[25,98,99]
Lack of in-depth EOL projections and LCA (*RF_{16}*)	Turkey lack in current and projected EOL and LCA assessments on solar panels and the components of wind turbines in the SPvESC and WESC. Therefore, building effective plans regarding circular initiatives is highly challenging in the SPvESC and WESC due to the nonexistence of the future EOL projections.	[100,25,101,102,103,104,67]

Then, one session of virtual meeting was held with the expert group, which lasted about 40 min. During the meeting, the expert group examined the results, analyzed the cause and effect relationships among *RFs* and a consensus was achieved on the validation of the results. Hence, they concluded that no change is necessary.

Table 3
Members of the expert group.

Group	***Number***	***Characteristics***
Academicians	10	They are faculty members at various departments in Turkey, who published scientific papers on renewable energy and also did research on CE.
Governmental decision makers	4	They are employed in the Ministry of Energy and Natural Resources and are involved in renewable energy projects towards CE and sustainability.
Renewable energy company managers	7	They have roughly 10 years of hands-on experience both in several renewable energy sources and sustainability.
Energy experts	4	They are consultants who have conducted renewable energy projects towards sustainability.

Table 4
D + *R* and *D-R* values of the RFs.

Codes	*RFs*	*D* + *R*	*D-R*	*Cause (C) /Effect (E)*
RF_1	Absence of CE policies to CE	8.357	−2.333	E
RF_2	Absence of top management commitment to CE	8.909	−4.814	E
RF_3	Undesirable impact of the existing culture	8.023	−3.737	E
RF_4	Lack of knowledge and proper training	8.623	−0.031	E
RF_5	Ineffective information systems	7.390	−0.080	E
RF_6	Nonexistence of effective incentives and regulations	9.319	0.948	C
RF_7	Absence of economic benefits in short-run	9.295	1.160	C
RF_8	The necessity of making high investment	8.416	1.493	C
RF_9	Lack of effective recycling technologies	4.852	−0.088	E
RF_{10}	Lack of reverse logistics network	6.122	−0.085	E
RF_{11}	Reluctance to share information	8.115	1.656	C
RF_{12}	High level of inflexibility in organizational systems and processes	7.345	0.340	C
RF_{13}	Insufficient level of trust and collaboration among organizations	8.085	0.861	C
RF_{14}	EOL product uncertainty	7.797	3.496	C
RF_{15}	Emissions and pollution generated during recycling	4.817	1.349	C
RF_{16}	Lack of in-depth EOL projections and LCA	9.507	−0.133	E

Discussion and implications

In this section, the findings of this research are discussed by making reference to the limited amount of quantitative studies on CE adoption mostly in Electric and Electronic Equipment industries. First, in the Force Field Analysis, our results indicated that *DF_3* (Global laws and regulations towards CE) was the most crucial driver to CE adoption, which supports Farrell et al. [108] and Wrålsen et al. [89] arguing that the most important driver for circular lithium-ion battery and photovoltaic modules turned out to be "national and international regulation and policies". However, Sica et al. [109] and Bressanelli et al. [110] stated that the main motivation for CE implementations in the electrical and electronic equipment supply chains including photovoltaic solar is the environmental, social, and economic benefits. However, despite the expected benefits of CE addressed in the existing research as the main drivers of CE implementations, Kirchherr [119] coined the term circular justice and urged researchers to further investigate the social impact of CE on the electronics industry especially in emerging economies. Second, based on the Force Field Analysis, the total score of *RFs* is greater than that of *DFs*, which implies that *RFs* should be examined for the

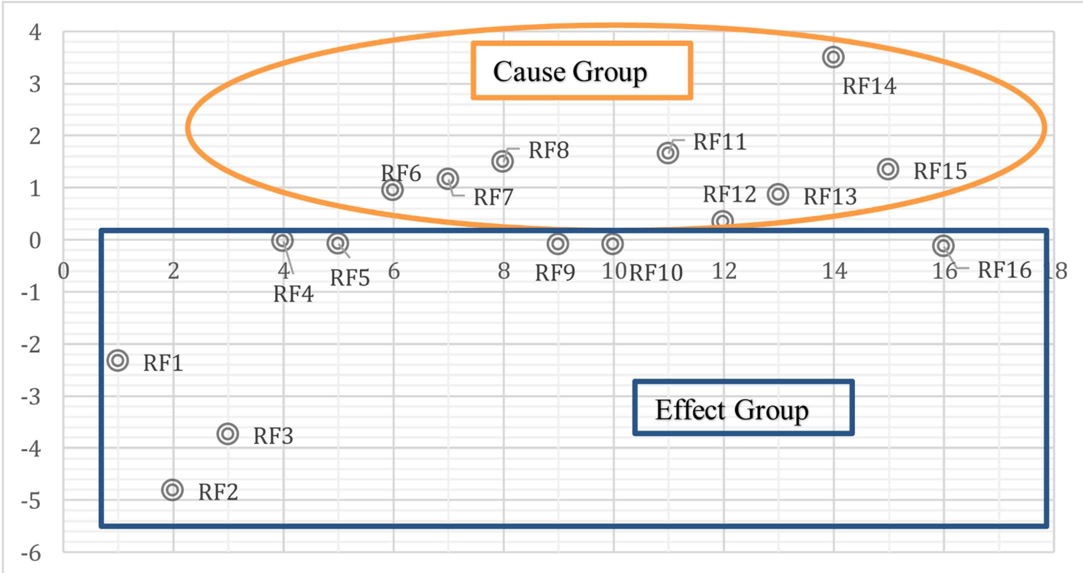

Fig. 3. Influential Relation Map.

SPvESC and WESC to implement CE effectively in Turkey. Comparing 16 *RFs*, RF_6 (Nonexistence of effective incentives and regulations) discovered to be the most critical restraining force. Govindan et al. [66] indicated that governments could stimulate the effectiveness of CE implementations through enacting legislation, building effective principles, providing technical support, and developing an effective price mechanism. Financial incentives are also an effective instrument to encourage managers in the SPvESC and WESC towards CE [111,108,89]. Hence, we argue that effective incentive programs and legislation can aid in constructing new business models, which supports the results of [112].

Second, the results of this research indicated the associations among the *RFs* of SPvESC and WESC using "the $D + R$ and D-R values" as displayed in Table 4 and Fig. 3. Note that examining the *RFs* is essential for forming CE effectively in the SPvESC and WESC. Based on the results of Table 4, the *RFs* are classified into three classes including "prominent", "influencing", and "resulting" ones. They are demonstrated in Table 5.

Note that since no empirical study has been conducted to evaluate the associations among the *RFs* to CE adoption specifically in SPvESC and WESC, we'll compare our findings with those of limited number of quantitative research performed on circular economy adoption in various countries of manufacturing industries. With that in mind, based on the results in Table 5, the most prominent factors were RF_{16} (Lack of in-depth EOL projections and LCA), RF_6 (Nonexistence of effective incentives and regulations), RF_7 (Absence of economic benefits in short-run), RF_2 (Absence of top management commitment to CE), RF_4 (Lack of knowledge and proper training), RF_8 (The necessity of making high investment), and RF_1 (Absence of CE policies to CE). However, the most insignificant RFs were discovered to be RF_{15} (Emissions and pollution generated during recycling) and RF_9 (Lack of effective recycling technologies). These findings are mostly in agreement with those of Mangla et al. [85], Liu et al. [60], Kumar et al. [82], Kumar and Dixit [113], Wrålsen et al. [89], Lahane and Kant [114], Milios et al. [117], Rizos and Bryhn [115], Manoharan et al. [62], and Hartley et al. [8]. To elaborate further on the main findings of the existing research, for example, based on their ISM-MICMAC analysis, Mangla et al. [85] suggested that in a developing country such as India, insufficiency in legal framework and incentive mechanism is the most important barriers to CE adoption, followed by top management commitment. In another study, Liu et al. [60] employed fuzzy DEMATEL framework and concluded that legal framework and infrastructure should be built to achieve effective implementations of CE in Chinese food manufacturing industry. In their research conducted in India, Kumar et al. [82] used a multi-criteria decision framework and suggested that governmental support and national policies must be enhanced for effective CE implementations. Kumar and Dixit [113] conducted another study in India. Their research was based on DEMATEL framework that concluded the regulatory and socio economic barriers including environmental awareness are the most significant ones. Wrålsen et al. [89] performed a DELPHI-based research in lithium-ion battery industry, which suggested that lack of short-term economic benefits and insufficiency in regulatory framework turned out to be the most crucial barriers. Lahane and Kant [114] developed another multi-criteria decision framework based on DEMATEL and argued that top management commitment was discovered to be the main barrier to effective CE adoptions in India. Milios et al. [117] conducted a series of interviews in the maritime industry to identify the most crucial barriers to CE implementations. They suggested that high costs and lack of policy framework were the most important barriers. Using a case study approach based on interviews, Rizos and Bryhn [115] investigated the most important barriers to CE adoption. They concluded that weak enforcement of WEEE requirements, lack of international CE standards and lack of incentives for collecting unused devices turned out to be the most important ones. In another multi-criteria decision making-based study, Manoharan et al. [62] argued that the need for high investments and lack of information on economic benefits were the most crucial barriers. Lastly, Hartley et al. [8] utilized semi-structured interviews and suggested that lack of supply chain wide policies are eminent. Given the main findings of the current research on CE adoption barriers, despite the several similarities with the results of this study, note that none of the present papers have addressed lack of end-of-life projections and life cycle assessments among the most important barriers to CE adoption. In our in-depth Nominal Group Technique interviews, however, the members of the expert panel suggested that effective CE implementations are only achievable through

Table 5
Ranking of the RFs.

Aspects	*Rankings*
Prominent	$RF_{16} > RF_6 > RF_7 > RF_2 > RF_4 > RF_8 > RF_1 > RF_{11} > RF_{13} > RF_3 > RF_{14} > RF_5 > RF_{12} > RF_{10} > RF_9 > RF_{15}$
Influencing (Cause)	$RF_6 > RF_7 > RF_8 > RF_{11} > RF_{13} > RF_{14} > RF_{12} > RF_{15}$
Resulting (Effect)	$RF_2 > RF_3 > RF_1 > RF_{16} > RF_9 > RF_{10} > RF_5 > RF_4$

comprehensive End-of-Life projections and life cycle assessments in Turkey's SPvESC and WESC.

In addition to the prominent *RFs*, the ones having the highest net causal-effect (*D-R*) values have the greatest long-term impact on other *RFs*, denoting that the effectiveness of CE implementations is mostly dependent on casual *RFs*. Hence, note that casual *RFs* should be addressed to achieve effective CE applications in Turkey's SPvESC and WESC. Table 5 reveals that RF_6 (Nonexistence of effective incentives and regulations), RF_7 (Absence of economic benefits in short-run), RF_8 (The necessity of making high investment), RF_{11} (Reluctance to share information), and RF_{13} (Insufficient level of trust and collaboration among organizations) were found out to be the most important casual *RFs*. These findings further support the ideas of Mangla et al. [85], Liu et al. [60], Wrålsen et al. [89], Lahane and Kant [114], and Kumar et al. [82], suggesting that regulations and incentives should be enacted, economic benefits should be ensured, and trust should be built among organizations before everything else to achieve effective circular economy implementations in electric and electronic industries. Furthermore, de Jesus and Mendonça [93] stated that even if they have not systematically prioritized the barriers to CE adoption, having established regulations and fiscal policies are one of the most important factors for effective CE implementations. They also stated that the CE should be boosted by an optimal combination of taxes, standards, infrastructures, and educational setups, which is mostly consistent with our findings.

Lastly, note that the resulting (the effect group) *RFs* have negative *D-R* values, denoting they are influenced by the other *RFs*. This is not to say that they are unimportant or that they should be overlooked; rather, they should be carefully analyzed in the later stages of a strategy to improve the effectiveness of CE implementations in the SPvESC and WESC. Fig. 3 and Table 5 indicate that RF_2 (Absence of top management commitment to CE), RF_3 (Undesirable impact of the existing culture), RF_1 (Absence of CE policies to CE), and RF_{16} (Lack of in-depth EOL projections and LCA) turned out to be the most crucial resulting *RFs*. However, the findings of this study do not support those of the previous quantitative research [85,82,114], which indicated that Absence of top management commitment to CE, Absence of CE policies to CE, and Undesirable impact of the existing culture are influencing factors in electric and electronics industries. In our in-depth Nominal Group Technique interviews, the members of the expert group concluded that RF_6 (Nonexistence of effective incentives and regulations), RF_7 (Absence of economic benefits in short-run), and RF_8 (The necessity of making high investment) should be addressed before dealing with the challenges about lack of top management commitment, lack of supportive organizational culture, and lack of CE-based policies. In other words, RF_6, RF_7, and RF_8 are the ones that should be primarily emphasized at the outset to encourage managers to build top management commitment, effective policies, and supportive culture towards CE.

Implications of the study

Droege et al. [120] argued that since the transition to CE is extremely slow, a more drastic way that paves the way for circular disruption is needed. Bauwens et al. [121] defines circular disruption 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". The concept of circular disruption is based on the idea that advancing the circular economy requires a network of stakeholders, including companies, policymakers, non - governmental organizations, and communities [122]. Given Turkey's rising population and industrial growth, note that waste minimization and pollution prevention towards CE are critical development issues. Specifically, SPvESC and WESC will be major contributors to ecological problems since the usage of renewable energy sources including solar and wind are exponentially increasing in Turkey. Due to the limited lifespans of solar panels and wind turbines, Turkey is expected to face serious ecological problems soon given the existing linearity of the SPvESC and WESC. Hence, in Turkey, a new paradigm based on circular disruption should be devised and implemented as quickly as possible.

The goal of this research is twofold. It first aims to identify the *DFs* and *RFs* for CE adoption in Turkey's SPvESC and WESC through Force Field Analysis. Second, it intends to investigate the association between the forces resulting from Force Field Analysis. More specifically, this research categorized these forces into prominent, influencing, and resulting ones. Our findings overall suggested that the total score of *RFs* is greater than that of *DFs*. Thus, note that it is important to explore *RFs* through ascertaining the associations between them, enabling decision makers to shift the imbalance. The findings of this study also suggested through *Neutrosphopic-DEMATEL* that RF_{16} (Lack of in-depth end-of-life projections and life cycle assessments), RF_6 (Nonexistence of effective incentives and regulations), RF_7 (Absence of economic benefits in short-run), RF_2 (Absence of top management commitment to CE), RF_4 (Lack of knowledge and proper training), RF_8 (The necessity of making high investment), and RF_1 (Absence of CE policies to CE) are prominent barriers. However, we concluded that the effectiveness of CE in the SPvESC and WESC entails taking several actions: building new incentive mechanism to trigger the willingness of CE adoption, enacting effective regulations towards CE, exploring the short-term economic benefits of implementing CE, and considering the lifespans of solar and wind energy investments. During the time when this paper was being written, Turkey had not enacted a regulation in line with the European Union legislation yet. More specifically, waste electrical and electronic equipment directive (WEEE) in Turkey does not contain any decree associated with solar panel and wind turbine waste. Moreover, the government in Turkey has not established a new incentive mechanism to boost circularity in the SPvESC and WESC. Thus, a strategic regulatory framework and an effective incentive mechanism towards CE should be developed. Several guidelines for various stakeholders to enable circular disruption in Turkey's SPvESC and WESC are summarized in Table 6.

This research also revealed a number of theoretical implications. In this paper, the potential of CE in Turkey's SPvESC and WESC was investigated using a combination of *Neutrosphopic DELPHI-based Force Field Analysis*, *Neutrosphopic-DEMATEL*, and *Nominal Group Technique*. Structured qualitative/quantitative decision frameworks can help decision makers organize the problem and provide a tool for combining multiple factors. The main focus is on developing a decision-making

Table 6
Guidelines for the stakeholders.

Stakeholders	Guidelines
Government	• Building a strategic regulatory framework towards CE [67] • Forming an effective incentive mechanism [89] • Establishing national CE policies [8] based on circular disruption [121,122] • Setting specific targets for re-use and CE [67]
Non Governmental Organizations	• Investigating the lifespans of solar and wind energy investments [67]. • Evaluating the short and long-term economic benefits of implementing CE [23] by considering circular injustice [119]
Companies	• Ensuring top management commitment [85,82]. • Providing proper training towards CE for white collar and blue-collar employees [117]. • Assessing the feasibility of CE investments [23]. • Adopting CE strategies consistent with the national and supply chain-wide policies [85,82].
Supply Chains	• Building proper supply chain policies and strategies suited with the national and international policies and regulations [8]. • Developing an effective reverse supply chain network [22].

framework that allows for the formation of a structure to make reliable decisions. Simply put, structured decision frameworks assist decision makers in better fathoming the problem by considering the goals of all parties. They never try to replace intuition or experience; rather, they help to strengthen them. In conclusion, the primary purpose of formalized decision frameworks is not to arrive at a single best solution.

Conclusions

Renewable energy is currently the world's fastest-growing energy resource. As opposed to the fossil fuels, the optimal use of these resources results in the least amount of environmental impact and produces the smallest volume of secondary waste. Out of these renewable resources, wind and solar have had an exponential growth globally. Keep in mind, however, that solar Pv panels and wind turbines will not be in use forever. Rather, they will be withdrawn from service, indicating that we will soon have to take action to manage tens of millions of metric tons of EOL materials resulting from the wind turbines and solar panels currently in use. To address this challenge, the CE has been developed, which ultimately ease the negative impact of linear supply chains.

Turkey, as a developing country, has also been installing solar panels and wind turbines for some time to achieve her transition to renewable energy effectively. However, SPvESC and WESC in Turkey need a paradigm shift to improve the efficiency, durability, and recyclability of the components of wind turbines and solar panels. Despite the several drivers of implementing CE in the SPvESC and WESC to achieve that shift, there are also barriers to CE initiatives. To the best of our knowledge, no study has been conducted to explore the drivers and challenges for CE adoption in SPvESC and WESC's of any country. To this end, the goal of this research is to explore the driving and restraining forces for CE adoption in the Turkey's SPvESC and WESC through *Neutrosphopic DELPHI-based Force Field Analysis*, *Neutrosphopic-DEMATEL*, and *Nominal Group Technique*.

The findings of this research suggested that because the total score of RFs is higher than that of DFs, it is critical to investigate RFs by discovering the relationships between them, allowing decision-makers to correct the imbalance. Our findings also suggested that out of 16 RF_{16} (Lack of in-depth EOL projections and LCA), RF_6 (Nonexistence of effective incentives and regulations), RF_7 (Absence of economic benefits in short-run), RF_2 (Absence of top management commitment to CE), RF_4 (Lack of knowledge and proper training), RF_8 (The necessity of making high investment), and RF_1 (Absence of CE policies to CE) proved to be the most prominent restraining forces. Finally, we argued that that the effectiveness of CE in Turkey's SPvESC and WESC requires building new incentive mechanism as well as passing effective regulations towards CE to boost the eagerness of CE adoption.

Based on the limitations of this study, there are also various research prospects. For example, since our research relied on information from a small number of experts, new studies may be conducted using more experts. According to Campagne et al. [116], having more experts may be beneficial, although expert groups with a smaller number of experts can still produce consistent results. However, the most crucial thing is to select the correct experts with sufficient insight and knowledge on a given topic, which is especially true in a complex study like this one that aims to discover the CE adoption opportunities in Turkey's SPvESC and WESC. To address the ambiguity of expert data more effectively, integrated multi-criteria decision-making approaches combining innovative fuzzy and rough sets can be used. Furthermore, more case studies on CE adoption in SPvESC and WESC should be conducted to verify the results of quantitative research. Lastly, since the goal of our research is not solely and directly to address the social impact of CE, new empirical research is needed to investigate the societal aspect of CE adoption in SPvESC and WESC of emerging economies specifically through the concept of circular justice.

Finally, both practitioners and researchers can benefit from the results of this study. The methodological development, findings, discussion, and implications of this study may be of interest to practitioners. Thus, they can better grasp the opportunities for CE adoption in SPvESC and WESC of Turkey. Note that the findings of this study are based on a quantitative analysis conducted in Turkey, which has a unique set of socioeconomic characteristics. As a result, it cannot be suggested that the overall findings would be equally relevant or beneficial in all socioeconomic and geographic contexts. Note also that generalization, the degree to which the results of an empirical study can be applied to other contexts, may only be possible, provided various peculiarities are considered. Only then, the results of this study may be applicable to SPvESC and WESC of other developed and developing countries. Finally, researchers will also be interested in this study since it includes a decision aid that blends a qualitative method (*Nominal Group Technique*) into quantitative methods (*Neutrosphopic-DELPHI-based force field analysis* and *Neutrosphopic-DEMATEL*).

CRediT authorship contribution statement

Ismail Erol: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Validation, Supervision. **Iskender Peker:** Methodology, Formal analysis, Validation, Data curation, Writing – original draft. **İsmet Turan:** Writing – review & editing, Investigation, Validation. **Tolga Benli:** Writing – review & editing, Investigation.

Declaration of Competing Interest

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

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