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Resilient and Sustainable Energy Supply Chains: Insights on Sourcing and Pricing Strategies in a Non-collaborative and Collaborative Environment

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Energy supply chain resilience and sustainability are essential for dependable, ecologically responsible energy availability, reducing interruptions, and creating a sustainable future. In this regard, this study explores the resilience and sustainability of a single energy supply chain through two distinct scenarios. The focus is on a manufacturer capable of sourcing products from renewable and non-renewable power plants. Although the renewable power plant is the preferred clean option, disruptions may occur. On the other hand, the fossil fuel power plant offers reliability at the cost of environmental impact. The manufacturer employs two sourcing strategies based on disruption probabilities: single sourcing from just the renewable power plant and dual sourcing from fossil and renewable power plants. In the second scenario, a collaboration between the power plants is introduced. If a disruption occurs at the renewable power plant, it orders the fossil fuel power plant to generate electricity on its behalf. Using a game-theoretic approach, the research examines the effects of dual-sourcing techniques, and the efficacy of cooperation in minimizing disruptions. It also examines the trade-offs between energy supply chain resilience and environmental sustainability. The results shed light on sourcing strategy decision-making and add to the literature on sustainable and resilient energy supply chains.

Keywords: energy supply chain; resilience; environmental sustainability; collaboration; game theory

1. Introduction

The energy supply chain is essential to satisfying global energy demand. With growing environmental concerns, renewable energy sources have become a cleaner, more sustainable alternative to fossil fuels (Tian et al. 2022). Figure 1 represents Germany's gross electricity generation from renewable energy trends from 1992 to 2022 (BDEW 2022).

[Figure 1 here]

Renewable energy like solar, wind, hydro, and biomass is widely adopted for reducing greenhouse gas emissions and lessening reliance on finite fossil fuels (Gonela et al. 2019).

Several causes drive the switch from fossil fuels to renewable energy. Burning fossil fuels emits greenhouse gases and air pollutants, making cleaner options essential. Renewable energy uses plentiful, readily accessible natural resources for a more sustainable approach (Rajabzadeh and Babazadeh 2022; Usman et al. 2022).

However, the energy supply system has its issues. As with any supply chain, energy supply chain disruptions may hurt businesses, consumers, and the economy (Wang, Li, and Cui 2023). Factors such as extreme weather events, equipment failures, and supply chain disruptions can all contribute to interruptions in the energy supply (Ivanov, Tsipoulanidis, and Schönberger 2021). These disruptions can lead to production delays, increased costs, and negative environmental impacts.

Multi-sourcing as a mitigation strategy is essential to address energy supply chain risks. Manufacturers may provide a more dependable and steady energy supply by diversifying energy sources and including both renewable and fossil fuel power plants (Suryadi and Rau 2023). Renewable power plants offer clean energy and align with sustainability goals, while fossil fuel power plants provide a backup option with greater reliability.

Resilience in any supply chain involves designing systems and strategies to withstand and recover from disruptions efficiently (Ivanov 2017). For the energy supply chain, it includes energy redundancy, sturdy infrastructure, adaptive tactics, and risk management. Manufacturers may reduce interruptions, sustain output, and ensure a stable energy supply by incorporating resilience into the energy supply chain (Lotfi et al. 2021).

In addition to resilience, sustainability is a fundamental aspect of the energy supply chain. Sustainability encompasses environmental, economic, and social considerations (Bai, Sarkis, and Ibrahim 2023). It entails reducing environmental impact, optimizing resource use, boosting renewable energy, and assuring long-term sustainability. Manufacturers may reduce climate change and carbon emissions and build a sustainable future by adopting sustainability throughout the energy supply chain (Fontes and Freires 2018).

In this study, we examine a model that explores the resilience and sustainable energy supply chain in two scenarios.

The first scenario considers a manufacturer who can source energy from renewable and fossil fuel power plants. While the renewable power plant is the preferred choice due to its clean nature, it is susceptible to disruptions. In contrast, the fossil fuel power plant offers reliability but comes with environmental concerns. The manufacturer employs two sourcing strategies based on the disruption probability. At low probabilities, energy is sourced solely from the renewable plant. When disruption probability exceeds a critical point, the manufacturer uses both power plants.

The second scenario builds upon the first, incorporating collaboration between the power plants. This collaboration involves the renewable power plant ordering the fossil fuel power plant to produce power on its behalf during disruptions. The renewable plant buys energy from the fossil fuel plant and sells it to the manufacturer, ensuring a continuous energy supply.

Our analysis focuses on assessing the resilience and sustainability of these two scenarios. We examine the decision variables, including wholesale energy prices from the power plants and the retail price of the manufacturer's products. Additionally, we analyze the split of orders between renewable and fossil fuel power plants. By exploring these factors, we seek insights into optimal strategies for enhancing resilience and sustainability amid potential disruptions in renewable energy supply.

The remainder of the paper is arranged in the following way. In Section 2, the definitional, practical, and theoretical foundations set the stage for this study. Notation and model description are detailed in Section 3. Section 4 encompasses scenarios' descriptions and profit functions. Section 5 evaluates the game-theoretic results of various sourcing strategies and outcomes. Numerical and sensitivity analyses together with additional managerial insights are provided in section 6. In Section 7, we present conclusions, model applications, and guidance for future studies.

2. Literature review

This section delves into the research background of the investigation, including resilient and environmentally sustainable energy supply chains, along with a game-theoretical approach.

2.1 The resilient energy supply chain

The energy supply chain is vulnerable to various disruptions, including extreme weather events, equipment failures, and supply chain disruptions (Huang et al. 2023). These disruptions can severely affect manufacturers, consumers, and the overall economy (Gupta and Ivanov 2020). Therefore, it is essential to study and enhance the resilience of the energy supply chain.

Recently, researchers have shown a keen interest in the significance of resilience in the supply chain especially energy supply chain. For instance, Han et al. (2017) explored the impact of remanufacturing cost disruptions in closed-loop supply chains, highlighting the strategic importance of collection channel selection for enhancing supply chain resilience. Ivanov (2022a) investigated the severe effects of blackouts on supply chains, underscoring the critical need for resilience through simulation analysis. This study highlights the disruptive ripple effects of blackouts on operational continuity and the effectiveness of digital twins in crafting adaptive recovery strategies. Ivanov's work stresses the importance of integrating energy resilience into supply chain management. In terms of energy, Chrisandina et al. (2022) introduced a framework to enhance energy supply chain resilience across four operation levels: molecular, unit, process, and supply chain. Jamali, Rasti-Barzoki, and Altmann (2023) devised the Energy Resilience Index. They have examined its significance in the rivalry between a conventional and a renewable energy manufacturer within an energy distribution network. They have utilized a game-theoretic methodology.

Resilience and disruption management in the supply chain now includes single- and multi-sourcing techniques (Gupta and Ivanov 2020). Single sourcing was seen to be a good management strategy for efficiency and cost savings. Recent threats and disruptions have challenged the single focus on these objectives. Diversifying sourcing may reduce currency rate volatility, supply interruptions, labor strikes, and political instability (Li et al. 2023). In this regard, Li et al. (2023) analyzed hoarding and contingent sourcing in supply chains facing disruptions, offering strategies that underscore decision-making complexity due to uncertain events and information asymmetry, enhancing resilience understanding. Babaei, Zhao, and Liu (2017) considered the risks faced by wind power providers in terms of potential energy shortfall in the energy market. To mitigate these risks and enhance resilience, the authors evaluated the feasibility of a backup power capacity from conventional suppliers as a secondary source. Namdar et al. (2018) explored solutions to enhance supply chain resilience, including backup supplier contracts, single/multiple sourcing, spot buying, cooperation, and visibility design. Rajabzadeh and Babazadeh (2022)examined power pricing decisions in a resilient supply chain, including the main biomass supplier, a biorefinery, hybrid power plant. They have considered fossil fuel supplier as a backup supplier. The study centered on a renewable primary power source, with a fossil fuel backup used during power shortages.

Another strategy to enhance resilience is through collaboration between suppliers. This collaborative approach, horizontal or vertical, further strengthens the resilience of the supply chain (Duong and Chong 2020). In this field, Chen, Sohal, and Prajogo (2013) analyzed three risk categories: supply risk, demand risk, and process risk. They explored three forms of collaboration: supplier, customer, and internal collaboration, aiming to mitigate these risks.

The paper authored by (Xiang 2020), presents a sophisticated model for enhancing collaboration in energy emergency supply chains. The study effectively reconciles the optimization of emergency supply chain collaboration with group consensus and reinforcement learning.

2.2 The environmentally sustainable energy supply chain

In addition to resilience, sustainability is a fundamental aspect of the supply chain (Warmbier, Kinra, and Ivanov 2022). Sustainability in the energy supply chain involves minimizing the environmental footprint, optimizing resource utilization, and promoting renewable energy sources (Mohammadi and Harjunkoski 2020). Several academics have examined supply chain especially energy supply chain sustainability recently, owing to its relevance. Related studies are briefly discussed below.

Emphasizing the significance of innovative approaches in enhancing both resilience and sustainability, Ivanov's (2022) investigated into sustainable recovery strategies using digital twins underscores the potential of advanced technologies, like additive manufacturing and electric trucks, to mitigate environmental impacts within supply chains. Potrč et al. (2021) presented the EU-27 synthesis of sustainable renewable energy supply networks. They recommended a phased energy transition in the transport and power sectors to achieve a carbon-neutral objective by 2050. Noorollahi, Pourarshad, and Veisi (2021), diversified energy resources in their research. They aimed to increase energy security and reduce environmental concerns in energy networks by transitioning to renewable power production. In another research, Kabeyi and Olanrewaju (2022) analyzed energy transition techniques. They proposed a plan for sustainable energy transition to ensure power production and supply align with Paris Agreement obligations.

2.3 The game-theoretical approach in the energy supply chain

Game-theoretical techniques assist academics, regulators, and industry stakeholders. They aid in understanding strategic behavior, optimizing decision-making, fostering cooperation, and improving the efficiency, resilience, and sustainability of the energy supply chain (Agi, Faramarzi-Oghani, and Hazır 2021). Within this context, a range of studies conducted within this particular industry are presented.

Maddouri, Elkhorchani, and Grayaa (2020) introduced a resilient optimization framework. It utilizes prospective game theory and a hybrid genetic algorithm to tackle challenges in real-time pricing and energy management. Utilizing a game-theoretic approach, Jamali and Rasti-Barzoki (2022) studied government support strategies and licensing contracts. They explored how these factors foster technological innovations in the energy supply chain, especially in the context of market failure. Yang, Tang, and Nehorai (2012) presented a game-theoretic method for optimizing the time-of-use pricing schemes in an energy supply chain. This technique aimed to maximize profits. Jamali, Rasti-Barzoki, and Altmann (2023) established the Energy Resilience Index. They employed a game-theoretic technique to analyze its role in the competition between a conventional energy producer and a renewable energy producer.

Table 1 summarizes the research backgrounds investigated in the energy supply chain field ,and the research conducted to fill the study gap.

[Table 1 here]

From the literature review part and Table 1 it can be seen that several studies are relevant to ours, but still, there are some gaps they could not cover.

Our study broadens the discussion on supply chain resilience by integrating sustainability with a game-theoretical approach, contrasting with Li et al. (2023) focus on hoarding and contingent sourcing strategies. Offering a comprehensive analysis of resilience mechanisms, including dual sourcing and environmental sustainability, our research provides actionable insights not only for mitigating disruptions but also for advancing green energy initiatives. This dual focus on resilience and sustainability, coupled with innovative methodological applications, positions your study as a significant contribution to the field, addressing both immediate and long-term supply chain challenges.

Compared to Ivanov (2023a), our study leverages game theory for a comprehensive take on supply chain resilience and sustainability, offering a broader framework than Ivanov's specific focus on digital twins for recovery strategies. This approach not only enriches the theoretical discourse but also provides versatile, actionable insights for the energy sector.

Namdar et al. (2018), explored resilience through single and multiple sourcing, emphasizing collaboration. However, the study did not address sustainability and the trade-off between resilience and sustainability. Besides, the collaboration they studied was between buyer and supplier. This is different from ours that is between suppliers, which not only includes collaboration but also encompasses the non-collaboration mode for better comparison. While they have used mixed integer linear programming as a solving approach, we have studied the sourcing and pricing decisions using game theoretic approaches.

In another similar study Jamali and Rasti-Barzoki (2022) on the electricity supply chain, the authors employed game theory to examine pricing issues. They considered dual sourcing strategies and collaboration between suppliers.

The aspects that they did not consider and well studied in our models are as follows:

1- Although they have studied dual sourcing, they never considered various sourcing strategies (dual versus single) based on disruption probability.
2- As a result of the previous gap, they did not study resilience in their model either.
3- In this study, just like the previous one, the sustainability issues are not considered.

4- Although supplier collaboration is well studied, there is no non-collaboration scenario as a benchmark.

5- This study employed a single Stackelberg game approach. In contrast, our study utilized three game models (two Stackelberg games with different leaderships and one Nash game) across two scenarios (collaboration and non-collaboration) to derive comprehensive results.

Through a game-theoretical framework, our model explores strategic interactions and solutions for various disruptions, positioning your work as a versatile contribution to supply chain management and sustainability practices contrasting with Ivanov (2022a) simulation-based examination of blackout impacts.

The most relevant study could be considered Rajabzadeh and Babazadeh (2022) since they have studied resilience and pricing issues in an energy supply chain using a dual-sourcing approach. Their paper also benefits from different game-theoretic approaches. However, also here there are some important aspects the authors did not consider, like differing sourcing strategies based on disruption probability or studying collaboration between energy suppliers. Besides, they have not examined the effect of resilience on sustainability.

Based on the mentioned gaps, this study evaluates a single energy supply chain under two scenarios. A manufacturer that may use renewable and non-renewable energy sources is at the center of the study. While the manufacturer prefers and views renewable power plants as a clean choice, there are still potential disruption issues. By contrast, the fossil fuel power plant is reliable but dirty. The manufacturer uses two sourcing methods regarding the power plants. Energy comes completely from the renewable power plant when a disruption is extremely unlikely. When the chance of disruption surpasses a certain level, electricity is supplied from both the renewable power plant and an alternate source. Except for collaboration across power plants, the second scenario is similar to the first. A fossil fuel power station will produce energy for a renewable power plant in the case of an interruption. The renewable power plant will buy energy from the fossil fuel power plant and sell it to the manufacturer.

The main objectives of our model revolve around optimizing sourcing strategies, enhancing resilience, and promoting sustainability within the energy supply chain. First and foremost, the model aims to determine optimal sourcing decisions, considering varying disruption probabilities, to ensure a stable energy supply. The model aims to balance environmental sustainability and reliability. It strives to minimize the risk of production stoppages, ensuring customer satisfaction and promoting the use of renewable energy sources.

Additionally, the model investigates the resilience of the energy supply chain, identifying vulnerabilities and developing contingency plans to withstand unexpected events. It highlights the potential benefits of collaboration between power sources, enabling mutual support during disruptions and maintaining a reliable energy flow. Furthermore, the model delves into pricing and sourcing strategies, utilizing a game-theoretic approach to incentivize renewable energy adoption while ensuring economic viability. Ultimately, our model aims to offer valuable insights for energy supply chain management. It facilitates informed decision-making aligned with short-term operational resilience and long-term sustainability objectives.

Our main contributions can be summarized as follows:

- **Sourcing strategies:** By considering different disruption probabilities, the study provides insights into optimal sourcing decisions and the trade-offs between environmental sustainability and reliability in energy supply. The benefit lies in ensuring a consistent energy supply even during disruptions. This approach reduces the risk of production stoppages and maintains customer satisfaction while still promoting the use of renewable energy sources.

- **Resilience analysis:** The findings contribute to the understanding of resilience in the context of renewable and non-renewable energy sources. The benefit is the ability to identify vulnerabilities, develop contingency plans, and enhance the resilience of the energy supply chain against unexpected events.
- **Collaboration between power sources:** This study highlights the potential benefits of collaborative strategies in enhancing the resilience and reliability of the energy supply chain. The benefit is the increased ability to handle disruptions smoothly through mutual support. This collaboration mitigates supply shortages and maintains a reliable energy flow to the manufacturer.
- **Pricing and sourcing decisions:** The study explores the pricing and sourcing strategies using a game-theoretic approach that can be employed to incentivize renewable energy utilization while maintaining economic viability.
- **Resilience and sustainability trade-offs:** The findings contribute to the ongoing discussions on balancing environmental sustainability and operational resilience in energy supply chain management. The benefit is the ability to strike a balance between environmental goals and reliability. This insight helps in making informed decisions aligned with long-term sustainability objectives.

3. Notation, problem statement, and assumptions

3.1 Notation

The notations used in this paper are listed in Table 2.

[Table 2 here]

3.2 Problem statement

The energy supply chain elements in this study consist of a manufacturer, a renewable power plant (RPP), and a fossil fuel power plant (FPP). The manufacturer supplies energy for its production purposes from these two power plants (PPs) and sells the produced products to the customers at a price of $p^j_{l,i}$. The renewable energy power plant is the primary power plant of the manufacturer, with a wholesale price of $w^j_{l,r}$. However, the renewable power supply is unreliable in the sense that it may come across disruption due to many factors like being seasonal, location-dependent resource availability, intermittency, variability, or Grid Integration Challenges (Verzijlbergh et al. 2017; Engeland et al. 2017). In contrast, the fossil fuel power plant with a wholesale price of $w_{l,f}$ is reliable but it is not the manufacturer's first preference due to the environmental issues and fossil fuel crises. The model examines how cooperation between energy providers affects supply chain resilience and sustainability under two scenarios: non-collaborative (Figure 2 (a)) and collaborative (Figure 2 (b)), which are explained in detail in the following sections. It is worth mentioning that the sustainability term in this paper refers to environmental aspects only, just like in Pal and Sana (2022), and Rajabzadeh, Altmann, and Rasti-Barzoki (2022).

[Figure 2 here]

At the beginning of the planning horizon, the manufacturer places an order with its main supplier, RPP. Afterward, the plant learns whether it is affected by a disruption: It faces a disruption with probability q, which materializes during order lead time. A disruption results in no energy supply by the renewable power plant. The fossil fuel power plant is not affected by disruption risk. The general timeline of the events is shown in Figure 3.

[Figure 3 here]

The manufacturer decides on its sourcing strategy, considering the disruption probability of the renewable power plant based on gathered data. Two sourcing strategies can be chosen by the manufacturer based on the disruption probability.

1) **Dual sourcing (DS):** This is the baseline (status quo) and main strategy. It occurs when $\delta < q < 1$ where δ represents a threshold parameter. In this situation, the manufacturer splits its order between the renewable power plant (α_l) and the fossil fuel power plant ($1 - \alpha_l$) based on the disruption risk (Figure 4 (a and c)).
2) **Single sourcing from the renewable power plant (RS):** This strategy will be chosen for $q \leq \delta$. Although there is still a marginal probability of disruption, the manufacturer prefers to supply from the renewable power plant only, as depicted in Figure 4 (b and d).

[Figure 4 here]

When the disruption probability is lower than 1, there is a critical disruption probability δ, at which the manufacturer decides to switch from single sourcing from the renewable power plant to dual sourcing or vice versa. Hence, for $q \leq \delta$, the manufacturer supplies only from the renewable power plant, and for $\delta < q < 1$, the manufacturer will choose a dual sourcing strategy. This threshold is important in understanding the dynamics of sourcing decisions and resilience strategies in an environmentally sustainable supply chain. The properties of δ are explored in detail in the subsequent sections. How the optimal sourcing strategy changes with q is illustrated in Figure 5.

Our analysis primarily targets the frequent occurrence of partial disruptions in real-world supply chains, with a particular emphasis on renewable energy sources as the primary and preferred option. This focus enhances the practical applicability of our findings for practitioners. Additionally, the aim to reduce model complexity, we concentrated on how supply chains, especially those implementing resilience and redundancy measures like dual sourcing strategies, navigate through various levels of disruption, opting not to delve into scenarios of complete shutdowns ($q = 1$). This approach allows us to present a more manageable and relevant analysis to supply chain management challenges.

In this model, the price-dependent linear demand function is used for customers. This type of function is widely used by researchers (Allameh and Saidi-Mehrabad 2021) as the standard in Industrial Economics and beyond (Tirole 1988). Where demand declines as product prices rise.

$$D_{l,i}^{j} = \alpha - bp_{l,i}^{j} \tag{1}$$

α and b are the market-based demand and self-price elasticity of demand for the produced power, respectively. As usual (Kumar, Basu, and Avittathur 2018; Rajabzadeh wt al. 2022), it is assumed that $b > 1$.

4. The scenarios and profit functions

In this section, we investigate our model under two scenarios: 1- Non-collaboration and 2- Collaboration. In the case of collaboration, both plants enter into an agreement requiring FPP to step in and provide energy to the cooperation partner in the case of a disruption.

The scenarios as well as the supply chain members’ profit functions in each sourcing strategy are provided below.

4.1 Non-collaboration scenario

In this scenario, there is no collaboration between the two power plants. It means that when the renewable power plant comes across disruption, the manufacturer does not receive any energy from this supplier. In DS strategy when disruption happens, it just receives those ordered from the fossil fuel power plant. As a result, there are two types of retail prices for the manufacturer:

- The retail price in disruption mode ($p_{1,d}^{j}$) when it only receives the ordered amount from the fossil fuel power plant
- The retail price in non-disruption mode ($p_{1,n}^{j}$) when it receives orders in full from both energy suppliers.

The profit functions and the optimal values of decision variables in each sourcing strategy – dual sourcing (DS), and single sourcing from the renewable power plant (RS) - are now developed and presented below.

4.1.1 Dual sourcing (DS)

Considering all assumptions and the model definition, in this sourcing strategy, the profit functions of the manufacturer ($\pi_{1,m}^{DS}$), the renewable power plant ($\pi_{1,r}^{DS}$) and the fossil fuel power plant ($\pi_{1,f}^{DS}$) are shown in Equations (2), (3), and (4), respectively.

$$\pi_{1,m}^{DS} = (1-q)\big(p_{1,n}^{DS} - \alpha_1 w_{1,r}^{DS} - (1-\alpha_1) w_{1,f}^{DS}\big)\big(a - b p_{1,n}^{DS}\big) + q\big(\, p_{1,d}^{DS} - w_{1,f}^{DS}\,\big)\big(a - b p_{1,d}^{DS}\big)$$

s.t., (2)

$$(1-\alpha_1)\big(a - b p_{1,n}^{DS}\big) \geq \big(a - b p_{1,d}^{DS}\big)$$

$$\pi_{1,r}^{DS} = (1-q)\alpha_1\big(w_{1,r}^{DS} - c_r\big)\big(a - b p_{1,n}^{DS}\big) \qquad (3)$$

$$\pi_{1,f}^{DS} = (1-q)(1-\alpha_1)\big(w_{1,f}^{DS} - c_f\big)\big(a - b p_{1,n}^{DS}\big) + q(w_{1,f}^{DS} - c_f)\big(a - b p_{1,d}^{DS}\big) \qquad (4)$$

The manufacturer's profit function consists of two parts. Part one displays the manufacturer's income from selling new items in a non-disruption mode. it includes the retail price, energy ordered to the renewable power plant, fossil fuel power plant, and demand function. The second half shows the retail price, fossil fuel power plant energy cost, and the disruption mode demand function, respectively. The second part shows that in the disruption mode, the manufacturer receives the split of the order from the fossil fuel power plant only. The constraint demonstrates that order from the fossil fuel power plant in non-disruption could be received in disruption. This scenario has two retail prices: non-disruption ($p_{1,n}^{DS}$) and disruption ($p_{1,d}^{DS}$).

The renewable power plant's profit function in Equation (3) represents its revenue from selling power to the manufacturer in non-disruption mode. It contains the wholesale price, power generation cost, and the demand function.

Equation (4) depicts the profit function of the fossil fuel power plant. It represents revenue from selling power to the manufacturer in non-disruption (part one) and disruption (part two) modes. Both parts contain the wholesale price, power generation cost, and demand function.

4.1.2 Single sourcing from the renewable power plant (RS)

Considering all assumptions and the model definition, in this sourcing strategy, the profit functions of the manufacturer ($\pi_{1,m}^{RS}$), and the renewable power plant ($\pi_{1,r}^{RS}$) are shown in Equations (5) and (6), respectively.

$$\pi_{1,m}^{RS} = (1-q)(p_{1,n}^{RS} - w_{1,r}^{RS})\left(a - bp_{1,n}^{RS}\right) \tag{5}$$

$$\pi_{1,r}^{RS} = (1-q)\left(w_{1,r}^{RS} - c_r\right)\left(a - bp_{1,n}^{RS}\right) \tag{6}$$

The manufacturer's profit function includes the retail price in non-disruption mode, the renewable power plant wholesale price, and the demand function. The renewable power plant's profit function includes its wholesale price, power production cost, and demand. Although $q \leq \delta$ under this sourcing strategy, there is still a chance of disruption. Thus, the manufacturer chooses to receive the whole amount of energy from the renewable power plant.

4.2 Collaboration scenario

In this scenario, two power plants collaborate. When the renewable power plant experiences disruption, it orders the fossil fuel power plant to provide the manufacturer's electricity. The renewable power plant profits by buying energy from the fossil fuel power plant at a price of b_f lower than $w_{l,r}^{j}$ .Then, it sells the bought electricity to the manufacturer to satisfy the order at $w_{l,r}^{j}$ in the event of a disruption. However, the fossil fuel power plant wins since it not only fulfills the manufacturer's order and profits but also fulfills the renewable power plant's order and profits. In this scenario, there is just one retail price (p_2^j) since the manufacturer always gets its orders.

The profit functions and the optimal values of decision variables in each sourcing strategy - dual sourcing (DS), and sourcing from the renewable power plant (RS) - are now developed and presented in the sub-sections below.

4.2.1 Dual sourcing (DS)

Considering all assumptions and the model definition, in this sourcing strategy, the profit functions of the manufacturer ($\pi_{2,m}^{DS}$), the renewable power plant ($\pi_{2,r}^{DS}$) and the fossil fuel power plant ($\pi_{2,f}^{DS}$) are shown in Equations (7), (8), and (9), respectively.

$$\pi_{2,m}^{DS} = (p_2^{DS} - \alpha_2 w_{2,r}^{DS} - (1-\alpha_2) w_{2,f}^{DS})(a - bp_2^{DS})$$

s.t., (7)

$$q(\alpha_2)(a - bp_2^{DS}) \geq \beta$$

$$\pi_{2,r}^{DS} = (1-q)\alpha_2 \left(w_{2,r}^{DS} - c_r\right)(a - bp_2^{DS}) + q(\alpha_2 \left(w_{2,r}^{DS} - b_f - v\right)(a - bp_2^{DS})\right) + c) \quad (8)$$

$$\pi_{2,f}^{DS} = (1-\alpha_2)\left(w_{2,f}^{DS} - c_f\right)(a - bp_2^{DS}) + q(\alpha_2 \left(b_f - c_f\right)(a - bp_2^{DS})\right) \quad (9)$$

The manufacturer's profit function ($\pi_{2,m}^{DS}$) consists of one part. It is showing its revenue from selling new products to the customers considering the retail price, orders received from both the renewable and the fossil fuel power plants, and the demand function. There's a constraint ensuring the renewable power plant, as the primary source, must supply at least the minimum required power (β). This is vital for critical parts of the manufacturer, such as the data center, safety systems, or refrigeration and cooling systems that constantly need power. In the non-collaborative scenario, the constraint was omitted. In this context, the manufacturer understands that during disruptions, power cannot be supplied by the renewable power plant. Consequently, the critical power needed is consistently provided by the fossil fuel power plant.

Equation (8) shows the renewable power plant's earnings from selling electricity to the manufacturer in non-disruption and disruption modes as parts 1 and 2. The first section displays the wholesale price, power generating cost, and demand function, while the second shows the renewable power plant's earnings from selling fossil fuel power to the manufacturer. This part includes:

- The wholesale price of power,
- The price of power generated by the fossil fuel power plant,
- The variable costs of that power sold to the renewable power plant (transfer cost, storing cost, etc.),
- The demand function,
- and the constant costs (infrastructure and interconnection costs).

Equation (9) shows the fossil fuel power plant's income from selling electricity to the manufacturer in a non-disruption mode. It is including the wholesale price, power generating cost, and demand function. In disruption mode, fossil fuels provide electricity without direct manufacturer orders. The fossil fuel power plant sells electricity to the renewable power plant to handle the disturbance. Then, the income which fossil fuel power plant gains and the demand function are presented in a second part.

4.2.2 Sourcing from the renewable power plant (RS)

Considering all assumptions and the model definition, in this sourcing strategy, the profit functions of the manufacturer ($\pi_{2,m}^{RS}$), the renewable power plant ($\pi_{2,r}^{RS}$), and the fossil fuel power plant ($\pi_{2,f}^{RS}$) are shown in Equations (10-12), respectively.

$$\pi_{2,m}^{RS} = (p_2^{RS} - w_{2,n}^{RS})(a - bp_2^{RS}) \tag{10}$$

$$\pi_{2,r}^{RS} = (1-q)\left(w_{2,r}^{RS} - c_r\right)(a - bp_2^{RS}) + q(w_{2,r}^{RS} - b_f - v)(a - bp_2^{RS}) + c) \tag{11}$$

$$\pi_{2,f}^{RS} = \left(w_{2,f}^{RS} - c_f\right)(a - bp_2^{RS}) + q(b_f - c_f)(a - bp_2^{RS}) \tag{12}$$

The manufacturer's profit function includes the retail price, the renewable power plant's wholesale price, and demand. Since the manufacturer receives everything from the renewable power plant, renewable and fossil fuel profit functions are the same as the DS approach considering $\alpha_2 = 1$. Therefore, the fossil fuel power plant's non-disruption part is removed. In this sourcing approach, there is still a possibility of disruption ($q \leq \delta$). However, the manufacturer would not be harmed as the collaboration between renewable and fossil fuel power plants still remains during the disruption period.

5. The solving approach and optimal values

To determine the optimal values of the decision variables, a game-theoretic approach is used. In all studied games, the manufacturer is considered the overall leader, and the power plants are followers. The leadership of the manufacturer is widely studied in academic literature (Ranjbar et al. 2020), and companies like Xerox (Savaskan, Bhattacharya, and Van Wassenhove 2004) and Apple (Sahebi, Nickel, and Ashayeri 2015) achieved great success with this strategy.

The game models studied in each scenario, and each sourcing strategies are as follows:

- ***Scenario 1***

  Dual sourcing: In scenario 1 in DS, with the manufacturer as the overall leader, three sub-games analyze optimal wholesale prices. These sub-games involve the renewable power plant as the Stackelberg leader, the fossil fuel power plant as the Stackelberg leader, and Nash games.

  Renewable power plant sourcing: In scenario 1, in SR strategy, one game model is studied. In this game, the manufacturer is considered as the Stackelbeg leader and the renewable power plant as the follower.

- ***Scenario 2***

  Dual sourcing: The game models in DS strategy in scenario 2 are the same as scenario 1, with one difference. The difference is that in the dual sourcing strategy in scenario 2, after conducting sub-games between power plants to gain optimal wholesale prices, in each sub-game, another Stackelberg game with fossil fuel power plant leadership is taken into account. This is to gain the optimal value of the price of the power which fossil fuel power plant produces and sells to the renewable one.

  Renewable power plant sourcing: The game model in RS strategy in scenario 2 is the same as scenario 1 with one difference again. The difference is that in SR in scenario 2 a Stackelberg game between the fossil fuel and renewable power plant with a leadership of fossil fuel power plant is studied. This is to gain the optimal value of the power price which fossil fuel power plant produces and sells to the renewable power producer.

Since the leader has higher decision power, it will reach a higher profit. Therefore, the leader accepts to be a part of the business if the proportion of his profit to every one of his followers is more than or equal to a constant value as below.

$\frac{\pi_{l,m}^{j}}{\pi_{l,r}^{j}} \geq \tau_1$ and $\frac{\pi_{l,m}^{j}}{\pi_{l,f}^{j}} \geq \tau_1$ where $\tau_1 \geq 1$.

The conditions for the other member's profit margins (τ_2 and τ_3) with values lower than τ_1 are similar (Jafari, Hejazi, and Rasti-Barzoki 2017). The games in this study are solved backward based on game theory principles (Aumann 2019).

5.1 The optimal values

The optimal values of decision variables in each scenario for each sourcing strategy are provided in Table 3.

Proofs of all lemmas, propositions, and solving process for each optimal value is provided in Appendix A.

[Table 3 here]

It is clear that $\alpha_l^* = 1$ implies that the manufacturer supplies only from the renewable power plant (RS). Therefore, by solving for $\alpha_l^* = 1$ with respect to q in all game models of the DS strategy, we get the specific point of q, which we called critical disruption probability earlier (δ_l). As a result, in situations where $q \leq \delta_l$, the manufacturer prefers the RS strategy while in the range of $\delta_l < q < 1$ the dual sourcing strategy is its choice.

6. Analysis and Managerial insights

We initially introduce an exemplary set of parametric values. The set of values appears in Table 4. Then, based on the initial data set from Table 4, a sensitivity analysis is conducted to investigate outcomes and derive insights from various managerial and organizational parameters and their relationships to decision variables and functions. In the end, some managerial insights are provided.

[Table 4 here]

6.1 Sensitivity analysis

6.1.1 Resilience

How resilient is the manufacturing at different disruption probabilities? This section investigates this question. As a resilience element, this section examines fulfilled demand in both disruption and non-disruption modes at varying disruption probabilities. While Figure 6 shows the demand satisfaction in different values of disruption probability in both scenarios, Table 5 indicates the resilience of each scenario based on expected and satisfied demand in disruption and non-disruption modes.

[Figure 6 here]

[Table 5 here]

In Figure 6, and as presented in Table 5, the manufacturer wants to use the RPP to meet the whole demand. If a disruption occurs owing to a shortage of alternative power plants, the RPP would satisfy 0% of demand. The RPP's required supply decreases as q rises in the RS strategy in the second scenario. Due to the FPP backup, the ultimate demand is fully supplied in disruption and non-disruption conditions despite this decline in demand. RS strategy has no unfulfilled demand in this scenario.

In scenario 1, the manufacturer distributes the order between RPP and FPP in DS. Without disruption, the entire demand would be satisfied. The graphic indicates that the FPP can satisfy the tiny amount of demand when disruption is minimal. However, q enhances resilience, reducing unfulfilled demand from around 300 at $q = 0.4$ to around 150 at $q = 0.8$. Disruption causes the manufacturer to get only FPP orders, which are low at lower q and high at higher q. This result is in line with those gained by the model presented by (Kumar, Basu, and Avittathur 2018). In their study, the retailer who supplies from both reliable and unreliable suppliers increases its supply from the reliable but expensive one when the disruption probability increases.

Even if q increases satisfied demand, the demand of a non-disrupted situation can never be satisfied. Thus, no q value will provide us with 100% resilience. Just like the model presented by (Kumar, Basu, and Avittathur 2018), this is because the price in disruption mode is higher than in non-disruption one, reducing the demand.

DS's approach to demand fulfillment in scenario 2 is different. In scenario 2, where power plants collaborate to meet demand, we delve into collaborative emergency adaptation, a concept essential for managing ripple effects in intertwined supply networks.

In this scenario, a constant demand is supplied at any value of q. This is despite the decrease in demand compared to the RS approach (indicated by the orange arrow). The decline is attributed to the participation of the fossil fuel power plant and the non-disruption mode of scenario 1.This is because both power plants will meet demand regardless of interruption owing to their collaboration. The collaboration between power plants mitigates disruptions' ripple effects and maintains a reliable energy flow. In this way, we have enhanced the model of (Kumar, Basu, and Avittathur 2018). Similar to our first scenario, the absence of collaboration and varying retail prices in their model made achieving full resilience impossible.

There remains still one question. Why doesn't the firm switch to DS if the RS strategy decreases demand due to q? The answer is that the RS approach always has more fulfilled demand than the DS strategy, even if the disruption is significant.

In the end, the ultimate resilience of two scenarios in each disruption probability is presented in Table 5 based on the expected demand for each scenario. In the RS strategy, the ultimate resilience for scenario 1 is zero since in disruption, there is no satisfied demand. On the other hand, in scenario 2, although the rise in q reduces the demand, the remaining demand is satisfied in both disruption and non-disruption mode. This is true for DS sourcing for scenario 2 as well, since no matter whether disruption occurs or not, the whole demand will be satisfied. On the other hand, in the DS strategy in scenario 1 at the beginning, when q is around 0.3 if disruption happens, the manufacturer can only satisfy 8 demand units out of 388. However, with the rise in q, the supply from FPP also increases. It increases the resilience of the manufacturer in a way that at q values of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9, the satisfied demand values are 104, 163, 200, 228, 247, and 263, respectively out of 388, and they never reach 388.

6.1.2 Sustainability

In supply chain management, resilience and sustainability are key. For varying disruption probability (q), we now assess our supply chain's sustainability. For this purpose, we examined FPP demand as an unsustainability factor since CO2 emissions increase with FPP demand. In other words, RPP demand or not having any is a sustainability factor.

Figure 7 indicates 0% FPP demand in scenario 1 for the RS approach. Since the manufacturer ordered everything from RPP and the FPP produces no electricity, this makes sense. Thus, this scenario has the highest sustainability. Scenario 2 may encounter two distinct conditions as Figure 7 shows that the non-disruption situation, like SC1, has no FPP demand and is the most sustainable. In a disruption event, scenario 2 has the lowest sustainability since the FPP would supply the RPP's needs for the manufacturer.

Figure 7's blue line shows that rising q increases FPP demand, which lowers the first scenario's sustainability. In non-disruption mode, scenario 2 in the DS strategy loses sustainability as q rises since the FPP simply meets manufacturer demand, which rises with q.

Scenario 2 has the lowest sustainability when the RPP is disrupted. In this case, as illustrated in a red line in Figure 7, the FPP meets both the manufacturer's and the RPP's needs. Thus, the FPP meets the whole manufacturer demand directly and indirectly. Since the manufacturer's FPP demand grows with q, the demand from FPP in non-disruption mode becomes closer to that in disruption mode.

In the non-disruption mode of scenario 2 in the DS strategy, the demand from the fossil fuel power plant (FPP) is lower than in scenario 1. This difference arises because in scenario 1, the overall demand from the manufacturer is higher.

It could be concluded that in both scenarios, the RS strategy has the highest environmental sustainability while the DS has a lower one. This result aligns with several studies in the field of resilience and environmental sustainability. Including (Ivanov 2018; Kim and Chai 2017), showing that multiple sourcing reduces environmental sustainability. In our model, a fossil fuel-based power plant experiences greater strain as disruption probability increases. This contributes to making the dual sourcing (DS) strategy less environmentally sustainable.

6.1.3 Resilience vs. Sustainability

In the previous analyses, the sustainability and resilience of two scenarios in various sourcing strategies were investigated.

In this regard, first of all, we have defined the *Resilience Index (RI)* and *Sustainability Index (SI)* according to the equations below, which give the results as shown in Figure 8.

$$RI = \frac{The\ satisfied\ demand\ in\ disruption\ mode}{Overall\ demand} \tag{13}$$

$$SI = \frac{The\ overall\ demand - The\ satisfied\ demand\ throug\ the\ FPP}{Overall\ demand} \quad (14)$$

[Figure 8 here]

Figure 8 demonstrates that in scenario 1 of the RS approach, there is no FPP in disruption mode; hence, the RI is 0, and the SI is 1. RS strategy scenario 2 is the opposite. This scenario has the highest disruption resilience but the lowest level of sustainability. This tendency extends beyond scenario 2's RS approach. The scenario 2 DS approach shows the same pattern since resilience relies on the FPP. Thus, resilience and sustainability are inversely proportional in this constellation.

Due to the changes in DS techniques, scenario 1's resilience increases and sustainability decreases, but not linearly. There is a difference between resilience/sustainability in the DS strategy of scenarios 1 and 2. The difference is that in scenario 2, the FPP satisfies not only the ordered portion of power but also the shortage due to collaboration. Hence, the manufacturer receives the full amount of power from two PPs. When an interruption occurs in scenario 1, the FPP merely provides the manufacturer's demand. If an interruption occurs at $q = 0.5$, Figure 8 (c) shows that the manufacturing facility can only supply 40% of demand. This is lowering SI from 100% to 60%. It could be concluded that in the DS strategy of both scenarios, there is an inverse correlation between the RI and SI, which is consistent with (Ivanov 2018) . Ivanov (2018) showing that multiple sourcing increases resilience while the environmental sustainability deteriorates.

The balance point in which RI equals SI is at $q = \sim 0.6$. Before this disruption probability at any value of q, scenario 1 could be considered more sustainable than resilient, while after q =~0.6, this is vice-versa.

In scenario 1, RI rises, and SI falls, but RI and SI never reach their highest and worst values (1 and 0, respectively). Rising q lowers demand, which is the key cause. Thus, demand is lower in disruption mode than in non-disruption mode.

6.1.4 The Manufacturer's Profit

In this section, we will investigate the expected profit earned by the manufacturer in different sourcing strategies in both scenarios.

[Figure 9 here]

Figure 9 (a) demonstrates that scenario 1's manufacturer's profit is maximum in the non-disruption mode but zero if a disruption occurs. In scenario 2, the manufacturer's profit maximizes at a low level of q since rising q decreases demand and profits.

At first appearance, all DS strategy game modes show identical profit patterns for the manufacturer in all scenarios. In scenarios 1 and 2, the manufacturer's profit decreases as q rises in non-disruption mode. This is because with increasing q, the supply from the FPP increases in the price, leading to lower demand and profit loss. This is consistent with the study of (Gupta, Ivanov, and Choi 2021).Their study is showing that the non-disrupted supplier is always able to charge the highest wholesale price if a disruption occurs.

In scenario 1's disruption mode, the manufacturer's profit rises with q. The intersection points of the manufacturer's profit in disruption and non-disruption mode in RL, FL, and Nash games are (0.46,15100), (0.49,16000), and (0.46,148000), respectively, in scenario 1's DS strategy. In the area to the left of these intersection points, the manufacturer makes a greater profit from non-disruption than disruption, and after these points, the opposite is true. Then, the manufacturer may prefer to switch from the DS to the FPP for higher profits. The intersection point in the FL game has the greatest q value of 0.49 and the highest profit value of 16000. This is proving that the DS approach is better in FL game modes than others. The FL game mode also profits more at the start of the DS strategy when q is about 0.3. In scenario 1's non-disruption mode, the Nash game could be considered the most unattractive game variant. This is because the profit level in this game is always lower compared to other game models. The gained results is consistent with the results gained by (Gupta, Ivanov, and Choi 2021; Kumar, Basu, and Avittathur 2018). In our study, we explored beyond scenario 1, known as the non-collaboration scenario. Scenario 2 was investigated differently, taking collaboration into account.

In scenario 2, the Nash game may be the worst game type since its profit decline is greater. In other words, the manufacturer loses more profit in a Nash game as q increases. This also becomes evident by looking at the manufacturer's profit at the start and end of the DS diagram in Figure 9 (d).

Comparing the manufacturer's earnings in all scenarios shows that in all game modes at the start of the DS strategy, scenario 2's profit is similar to scenario 1's non-disruption mode. However, RL, FL, and Nash have positions (0.64, 25000), (0.65, 25000), and (0.61, 24000) where the manufacturer's profit in scenario 2 and scenario 1 (disruption mode) cross. This shows that PP cooperation boosts manufacturer profitability. This happens practically from the start of the DS approach until q reaches 0.61 (Nash). After the crossing point, the manufacturer benefits from non-collaboration. Based on intersection locations, the FL game covers a larger range of q. The manufacturer prefers non-collaboration at high disruption probabilities.

6.1.5 Power Plants' Profit

In this section, the changes in the profit level of the PPs in different sourcing strategies of both scenarios are analyzed. The different game models in the DS strategy are taken into account.

[Figure 10 here]

Figure 10 (a) shows that in the RS strategy of scenario 2, both profits of the RPP and FPP decrease by increasing q. The main reason why the RPP profit drops is that based on $p_{2,n}^{RS*}$ the retail price of the manufacturer increases by increasing q. This reduces the demand and profit of RPP based on Equation (1). Another reason is that the rise in q increases the RPP's demand from FPP. Since the price at which the FPP sells power to RPP (${b_f}^*$), has a higher value than the power generation cost of RPP (c_r), its profit shrinks as well.

The reason why the profit of the FPP goes down is that the rise in q increases the demand from the FPP. Thus, the increase in demand from FPP drops the FPP sells power to the RPP (${b_f}^*$), but a drop in overall demand reduces the profit of FPP. On the other hand, In the RS strategy of scenario 1, without collaboration between power plants, the profit of the fossil fuel power plant (FPP) is zero. Meanwhile, the profit of the renewable power plant (RPP) decreases with the increase in q. The reason is that an increasing q leads to a drop in the wholesale price of the RPP ($w_{1,r}^{RS*}$) based on its optimal value to maintain the market. Since the overall demand is constant due to the constant retail price ($p_{1,n}^{RS*}$) the profit of the RPP goes down.

In every scenario, rising q lowers FPP and RPP profits. The reason is that the increase in q diminishes the manufacturer's order split from RPP in both scenarios for RPP. However, switching demand from RPP to FPP does not boost FPP's profit in any scenario. This is because As fossil fuel power plant (FPP) demand rises, its wholesale price falls. The constant retail price exacerbates the negative impact of the decline in the FPP's wholesale price on its profitability.

As predicted, in DS strategy games between PPs, the leader always has the greater profit, whereas, in Nash games, they have equal profit. In all game models, the collaborative situation is not profitable for RPP and FPP. In all game models, scenario 1 is beneficial for both FPP and RPP after q approximately 0.7, when the RPP and FPP profits cross. At $q = 0.7$, both PPs may elect to stop collaborating.

The validity of the obtained results could be proved by comparing the results with those gained in a paper by (Gupta, Ivanov, and Choi 2021). In their paper, they have shown that at lower disruption probability, when the disrupted supplier is a leader (RPP here), the non-disrupted supplier (FPP here) charges a higher equilibrium wholesale price than the corresponding price charged in the Nash game. On the other hand, at higher disruption levels, the disrupted supplier's (RPP here) equilibrium order's wholesale price is lower compared to the price in the Nash game. By comparing these results with the profits of power plants in Figures 10 (b) and (d), we see the same results. Although the mentioned studies lacked collaboration, we introduced it as an additional option. Based on our analyses, we conducted the same analysis, considering horizontal collaboration between the power plants.

6.1.6 Viability

Considering the previous analyses, In this part, by taking one step ahead, we are trying to analyze our model in terms of viability. Viability may be regarded as the system's adaptation and evolution through a dynamic equilibrium between disruptions and responsive actions within an open system framework (Ivanov 2023b). As an alternative definition, viability is the supply chain's capacity to endure and thrive in a dynamic environment. It involves reconfiguring structures and reevaluating performance strategies with lasting consequences (Ivanov et al. 2023). In our analyses, just like (Ivanov 2022b), viability is considered as an underlying SC property spanning three perspectives, i.e., adaptability, resilience, and environmental sustainability. In research related to Ivanov, agility was considered instead of adaptability. In our approach, adaptability is defined as comprising both agility and supply chain changeability (Ivanov 2022b).

Firstly, we have defined agility as the reaction of the manufacturer to various disruption levels by a change in order split to reliable supplier (FPP) and formulated as below:

$$Agility = \frac{Split\ of\ the\ order\ to\ FPP\ (1-\alpha_l)}{disruption\ level} \tag{15}$$

[Figure 11 here]

The agility concept as defined in our paper shows the same behavior in both scenarios under different game models, as in Figure 11. As can be understood from Figure 11, the agility is zero in the RS strategy. This is because the manufacturer prefers to supply the whole energy from RPP and split the order from RPP (α_l) equal to zero. On the other hand, for disruption probabilities higher than the critical level (δ) ,DS strategy, agility starts to rise with increasing q . This happens till $q = 0.58$, which after that the agility gradually drops. This shows that at the beginning ($q = 0.29$), the value of the q compared to the split of the order to FPP, $(1-\alpha_l)$, is much higher based on the arrow´s slope. But as can be seen from the figure, with a rise in q, the slopes´ of the arrows are decreasing. This shows a reduction in the difference between the values of q and $(1-\alpha_l)$. In other words, it shows the agility of the manufacturer in response to the disruption by increasing supply from the reliable supplier (FPP). But it never reaches 1 and starts to drop, showing the increase between the values of q and $(1-\alpha_l)$. This is because the rise in supply from the FPP decreases the demand, as explained in previous analyses. Besides, it decreases the supply from the primary supplier (RPP). This makes the manufacturer lower the amount of supply from the FPP after a specific value of q, ($q = 0.58$). The reason is to leverage the demand and keep the primary supplier (RPP) still motivated.

Based on our model structure, we have defined supply chain changeability as the ability to switch between sourcing strategies. In our model could be defined as the ability to switch from RS to DS or vice-versa. The best indicator which could be considered to measure this factor could be critical disruption probability δ_l, which is defined as follows:

"In a situation where the disruption probability is lower than 1, there is a critical disruption probability δ_l. In this point, the manufacturer decides to switch from single sourcing from the renewable power plant to dual sourcing, or vice versa. Hence, for $q \leq \delta_l$, the manufacturer supplies only from the renewable power plant. Consequently, for $\delta_l < q < 1$, the manufacturer will choose a dual sourcing strategy."

We have considered δ_l as the factor to measure the changeability of the supply chain. It is based on the disruption probability, and it could show how the manufacturer is adaptable to disruptions and changing conditions.

$$\delta_1 = \frac{(c_f - c_r)b}{(a - bc_r)} \tag{16}$$

$$\delta_2 = \frac{2\beta}{(a - bc_f)} \tag{17}$$

From the values of δ_l in scenarios 1 and 2 (Equations 16 and 17, respectively), it could be understood that the value of δ_l is independent of q. In other words, according to the concept of supply chain changeability of our model, q is not important. the δ_l is the constant value depending on FPP and RPP costs of production, market potential, and the price elasticity in scenario 1. In scenario 2, instead of RPP cost of production, there is minimum critical power needed. This is aligned with the study conducted by (Kumar, Basu, and Avittathur 2018). The independence of δ_l from q is plausible for extreme situations like COVID- 19 pandemic. Since, the level of disruption is not so important when the society needs some other critical production which the manufacturer is capable of producing by changing the supply chain. Just like the BMW company which dedicated some producing lines to produce face mask (Ivanov 2022b))

Based on the definition of a viable supply chain, we compared both scenarios in case of disruption:

1. **Resilience**: Scenario 2 demonstrates higher resilience compared to Scenario 1. In Scenario 2, collaboration between the renewable and fossil fuel power plant ensures a constant energy supply despite disruptions. This collaborative approach allows for uninterrupted demand fulfillment, as both power plants together can meet demand regardless of interruptions.

2. **Environmental sustainability**: In Scenario 2, environmental sustainability decreases during disruptions. This is because the fossil fuel power plant (FPP) is needed to supply the renewable power plant's needs, which are larger compared to Scenario 1. In this case, it could be concluded that the SC1 performs better in a balance between environmental sustainability and resilience.

3. **Profitability**: Profitability is an essential aspect of long-term environmental sustainability. Scenario 2 exhibits a more favorable profit trend for the manufacturer, especially when the disruption probability (q) is low. The collaboration between power plants in Scenario 2 allows for higher profits under certain conditions, contributing to the long-term viability of the supply chain.

4. **Collaboration**: Collaboration between the power plants in Scenario 2 is a key feature that enhances the overall viability of the supply chain. This collaboration ensures a constant energy supply and improves adaptation to disruptions. This aligns with the concept of a viable supply chain capable of adapting to changing environments and sustaining itself in the long term.

5. **Adaptability**: It's challenging to determine which scenario is better in terms of adaptability. In terms of agility, both scenarios yield the same outcome, leaving supply chain changeability independent of disruption probability.

In summary, Scenario 2, the collaboration between power plants, appears to be more viable than Scenario 1 based on its higher resilience, favorable profit trends, and the collaborative approach that enhances adaptation and long-term survival.

6.2 Managerial insights

Due to global supply chain disruptions, natural disasters, and the Ukraine war, the global economy is more affected by supply shortages than at any time since the oil crisis in the 1970s. Against a backdrop of increased uncertainty, profit slumps in most industrial sectors, and inflation, it is crucial for companies to make their supply chain resilient. This, in turn, stands and falls with a reliable energy supply.

As the game-theoretic analysis has shown, both diversification and cooperation are two crucial levers that, in combination, reduce the risk of production failures and prevent anticipated production failures from causing sharp price increases. Thus, the advantage of cooperation here is based on the same principle as in the well-known phenomenon of double marginalization, with the difference that in the presented model, cooperation enables efficient risk hedging.

In the presented model, FPP plays an important role, which might, at first glance, lead to the conclusion that resilience and efficiency can only be realized at the expense of sustainability (in the sense of low decarbonization). However, the message from these analyses is different: Conventional technologies that society may wish to abandon for reasons of inefficiency or unsustainability still serve an important support function for the transition, which can be used to hedge the transition risks. These risks result from the system change itself (conversion costs) as well as from the fact that the new system elements have not yet been tried and tested, and the new technologies are only at the beginning of their maturity cycle.

This point is highly relevant not only at the political level, as Germany experienced at the beginning of the Ukraine crisis, when the country, amid the ongoing and complicated energy transition process, had to make the immediate and expensive switch to liquefied natural gas. It is at least as important for companies to recognize that the decarbonization path is a process in which conventional energy sources can also continue to make a substantial contribution to system stability for some time. In the medium and long term, the companies that succeed in managing the challenging trade-offs, especially in the triangle of efficiency, resilience, and sustainability, along the risky path of energy system transformation will be successful.

The model results suggest that this process will take place in three stages: In the phase in which renewables are not yet mature enough and carry too much volatility into the system (high q), fossil fuels should be scheduled as stable backup suppliers. As renewables mature, they become more reliable (decreasing q to a low level), making horizontal cooperation among energy companies lucrative. Last but not least, this cooperation can support the fossil plants in a regulated phase-out. In the last step, the renewable technologies should be so functional that there is no need for additional risk hedging by fossil energy sources.

7. Conclusion and model applications

7.1 Conclusion

This research considers energy supply, including renewable and fossil fuel power plants and a manufacturer. The manufacturer's main power source is renewable. However, disruptions may occur. Thus, at lower disruption probability, it directs power exclusively to the renewable power plant, but at greater disruption probabilities, it adopts a dual-sourcing technique that includes the fossil fuel power plant. This model is examined under two scenarios. In the first scenario, there is no collaboration between the two power plants, so when the renewable power plant is disrupted, the manufacturer receives only the portion ordered for the fossil fuel power plant. In the second scenario, power plants collaborate such that the renewable power plant may order fossil fuel electricity when disruptions occur.

As a consequence, the manufacturer never runs out of supply. The manufacturer's order split and each supply chain member's product prices are the decision variables. Game theory is used to find optimum values for different forms of strategic interaction (game variants). Finally, the resilience and sustainability of the two scenarios and the profitability of supply chain participants in different game models are analyzed in the analysis section.

Our model's primary objectives are to optimize sourcing, enhance resilience, and promote environmental sustainability in the energy supply chain. It determines the best sourcing decisions considering disruptions, ensuring a stable energy supply while balancing environmental sustainability and reliability. It assesses resilience, identifies weaknesses, and can help to develop contingency plans. The model highlights power source collaboration benefits during disruptions. It also explores pricing and sourcing strategies, using game theory to encourage renewable energy adoption while staying economically viable. Overall, our model offers insights for energy supply chain management, aiding decisions that align with short-term resilience and long-term environmental sustainability goals.

Summary of important findings:

1- In terms of resilience, the collaboration scenario always performs better than the non-collaboration scenario (Figure 6).
2- In terms of sustainability, the non-collaboration scenario performs better than collaboration. Since, in time of disruption, all demand is satisfied by the FPP, while in scenario 1 the disruption leads to loss of demand (Figure 7).
3- In terms of the manufacturer's profitability in RS strategy in non-disruption mode, the non-collaboration scenario is always profitable. While in disruption, the collaboration results in higher profit for the manufacturer. In DS strategy, it depends on the games between PPS. In RL game mode, the collaboration scenario is profitable till $q = 0.64$, while in FL and Nash, this scenario is profitable till $q = 0.65$ and 0.61, respectively. On average, it could be said that the collaboration scenario is profitable for the manufacturer from δ=0.29 to 0.63. After 0.63, the disruption mode of non-collaboration leads to a higher profit level (Figure 9).
4- In terms of PPs profitability, in RS strategy, the collaboration scenario is always profitable. This is partially true for the DS strategy as well till $q = 0.7$, where the non-collaboration scenario becomes better.

7.2 Model applications

On a large scale, the situation where European countries dependent on Russian gas, like Germany, faced an energy shortage due to disruptions in the supply chain during the Russia-Ukraine conflict is a pertinent example of the challenges that can occur in the real world. In this situation, Germany has lost its main energy supplier and needed to find suitable alternatives in terms of being resilient. But how these resilient options are effective in terms of resilience and environmental sustainability must be taken into account, and here, our model will find promising application. In a small-scale application, Volkswagen serves as a pertinent example. Volkswagen's main facility in Germany relies on two coal-fired power plants as backups while heavily investing in renewable energy (Christian Schiebold 2023). They've partnered with projects like the WPD wind farm in Sweden and a significant solar plant in Germany, emphasizing their commitment to renewables (Dr. Christoph Ludewig 2021). Given the uncertainties in renewable energy, such as biomass, wind, and sunlight variations etc. (Hamed Rajabzadeh and Reza Babazadeh 2022), this model finds relevance not only in the automotive industry but also in sectors facing similar disruptions and environmental sustainability challenges.

Another exemplary real-world application that closely corresponds to both scenarios elucidated in our study is Johns Hopkins University and Hospital. In the context of Scenario One, Johns Hopkins University stands out as an insightful illustration. The university has proactively invested in sustainable practices, with its primary power sources being solar panels. Fossil fuel-based electricity serves as a backup, echoing the dynamics of our initial scenario and highlighting the crucial role of dual sourcing from both renewable and non-renewable sources (JHU 2022). Transitioning to Scenario Two, Johns Hopkins Hospital perfectly embodies the outlined conditions. Relying on solar panels as the primary renewable energy source, the hospital employs fossil fuel as a backup. Given the critical nature of uninterrupted power supply in healthcare settings, including Johns Hopkins, the imperative for 100% resilience resonates profoundly, closely aligning with the specifications of our second scenario (JHU 2022; Anderson 2016). This real-world application exemplifies the practicality and relevance of our model in diverse and vital contexts.

Our model enhances performance indicators by providing a resilient energy supply chain. It optimizes dual-sourcing strategies and fosters collaboration between power plants, ensuring energy availability and security. Importantly, it aligns with environmental sustainability goals by primarily relying on renewables while using fossil fuels only when necessary. This approach empowers cost-efficiency and effective decision-making. It is valuable for industries and regions seeking reliable, cost-effective, and environmentally responsible energy solutions during disruptions and uncertainties.

The potential application of our model in other industries could be summarized below:

1. **Manufacturing:** Industries that engage in continuous production processes, such as automotive or electronics manufacturing, can utilize the model to ensure a consistent energy supply. Interruptions can lead to costly downtime, and the model's dual-sourcing strategies offer resilience while balancing environmental sustainability.

2. **Data Centers:** Data centers are critical for modern businesses, and any interruption in power can have severe consequences. The model's approach can be applied to maintain uninterrupted data center operations, where reliability and environmental sustainability are paramount.

3. **Healthcare:** Hospitals and healthcare facilities require a constant and reliable power supply. Implementing our model can help them remain operational during energy disruptions, ensuring patient care and safety.

4. **Agriculture:** In precision agriculture, where technology is essential for optimizing crop yields, consistent power is crucial. The model's strategies can assist in ensuring that farms have access to power, even in rural or remote areas.

5. **E-commerce and Retail:** With the growth of online shopping and automated warehousing, the retail industry relies heavily on energy. Our model can help e-commerce companies maintain their operations during energy disruptions.

6. **Transportation:** Electric vehicles and public transportation systems are becoming increasingly important. The model can be applied to electric vehicle charging infrastructure and public transit systems to ensure consistent service.

7.3 Guidance for future studies

Future research directions following our work include exploring advanced multi-objective optimization models considering resilience, environmental sustainability, cost, and social impact. Additionally, investigating more intricate game theoretic approaches, real-time decision support systems, and integrating energy storage technologies can enhance supply chain agility and reliability. Furthermore, extending the research to analyze policy impacts, conducting industry-specific case studies, and considering global supply chain resilience are promising avenues. Addressing behavioral aspects in decision-making and devising strategies to reduce carbon emissions during disruptions are also crucial areas for future investigation. These research directions aim to deepen our understanding of energy supply chain management and environmental sustainability, providing valuable insights for academia and industry.

Disclosure of Interest:

The authors report that there are no competing interests to declare.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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Appendix

Appendix (A)

1. Non-collaboration scenario (Scenario 1)

1.1 Game models and optimal values in DS strategy

In this sub-section, considering the manufacturer as the overall leader, three games, including I) the renewable power plant as a leader, II) the fossil fuel power plant as a leader, and III) the Nash game, are done between renewable and fossil fuel power plants.

I) The renewable power plant as a leader

In this model of the game, the renewable power plant's decision power is higher than the fossil fuel power plant. As a result, the renewable power plant makes a decision on his own wholesale price first, and then the fossil fuel power plant decides on his own wholesale price.

Using $\frac{\pi_{1,m}^{DS}}{\pi_{1,r}^{DS}} \geq \tau_1$ the optimal value of $w_{1,r}^{DS}$ is obtained. Since $\pi_{1,r}^{DS}$ is linearly increasing in $w_{1,r}^{DS}$ it can be said that the optimal value of $w_{1,r}^{DS}$ is its highest possible value.

$$w_{1,r}^{DS*} = \frac{(q-1)\left(\left(w_{1,f}^{*} + \tau_1 c_r\right)\alpha_1^{*} + p_{1,n}^{DS*} - w_{1,f}^{*}\right) D_{1,n}^{DS} + qD_{1,d}^{DS}\left(w_{1,f}^{*} - p_{1,d}^{DS*}\right)}{D_{1,n}^{DS}\alpha_1^{*}(1+\tau_1)(q-1)} \qquad \text{(A.1)}$$

The optimal wholesale price of the fossil fuel power plant by considering that the $w_{1,f}$ gives rise to a linear increase in $\pi_{1,f}^{DS}$, and using $\frac{\pi_{1,r}^{DS}}{\pi_{1,f}^{DS}} \geq \tau_2$ it gained as Eq. (A.2).

$$w_{1,f}^{*} = \frac{\left(c_f(1+\tau_1)(\alpha_1^{*}-1)\tau_2 + c_r\alpha_1 - p_{1,n}^{DS*}\right)(q-1)D_{1,n}^{DS} + \left(c_f(1+\tau_1)\tau_2 + p_{1,d}^{DS*}\right)qD_{1,d}^{DS}}{(1+(1+\tau_1)\tau_2)\left((q-1)(\alpha_1-1)D_{1,n}^{DS} + qD_{1,d}^{DS}\right)} \quad \text{(A.2)}$$

By substituting Eqs. (A.1) and (A.2) In the manufacturer's profit function, the concavity condition of the profit function with respect to the $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ is investigated.

Lemma 1. *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail prices.*

Proof*:* the manufacturer's hessian in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ is as follows.

$$H_{\pi_{1,m}^{DS}(p_{1,n}^{DS},p_{1,d}^{DS})} = \begin{bmatrix} \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS}\partial p_{1,d}^{DS}} \\ \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS}\partial p_{1,n}^{DS}} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} \end{bmatrix} = \begin{bmatrix} \frac{2\tau_2(q-1)b\tau_1}{1+\tau_1\tau_2+\tau_2} & 0 \\ 0 & -\frac{2\tau_2 q b\tau_1}{1+\tau_1\tau_2+\tau_2} \end{bmatrix} \quad \text{(A.3)}$$

Since $\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} = \frac{2\tau_2(q-1)b\tau_1}{1+\tau_1\tau_2+\tau_2} < 0$ and $\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right) - \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS}\partial p_{1,n}^{DS}}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS}\partial p_{1,d}^{DS}}\right) = \frac{2{\tau_2}^2(1-q)b^2{\tau_1}^2 q}{(1+\tau_1\tau_2+\tau_2)^2} > 0$, the profit function of the manufacturer is concave in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$.

With considering $g\left(p_{1,n}^{DS}, p_{1,d}^{DS}\right) = (1-\alpha_1^{*})\left(a - bp_{1,n}^{DS*}\right) - \left(a - bp_{1,d}^{DS*}\right) \geq 0$ it is obvious that the constraint is convex in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$.

Proposition 1. *The best answers for retail prices and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.9-11). The optimal value of the dual variable for the constraint is*: $\mu_1^{*} = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1\tau_2+\tau_2}$.

Proof: Putting Eqs. (A.1) and (A.2) in the manufacturer's profit function ($\pi_{1,m}^{DS}$) it is defined below

$$\emptyset = \pi_{1,m}^{DS} + \mu_1\left[(1-\alpha_1)\left(a - bp_{1,n}^{DS}\right) - \left(a - bp_{1,d}^{DS}\right)\right] \quad \text{(A.4)}$$

Using KKT conditions, we get,

$$\frac{\partial\emptyset}{\partial p_{1,n}^{DS}} = -\frac{\tau_1(q-1)\left(-b(\alpha_1-1)c_f - 2bp_{1,n}^{DS} + b\alpha_1 c_r + a\right)\tau_2}{1+\tau_1\tau_2+\tau_2} + \mu_1 b(\alpha_1 - 1) \quad \text{(A.5)}$$

$$\frac{\partial\emptyset}{\partial p_{1,d}^{DS}} = -\frac{\tau_1 q\left(\left(2p_{1,d}^{DS} - c_f\right)b - a\right)\tau_2}{1+\tau_1\tau_2+\tau_2} + \mu_1 b \quad \text{(A.6)}$$

$$\frac{\partial\emptyset}{\partial \alpha_1} = -\frac{\left(a - bp_{1,n}^{DS}\right)\left(\left(\left(\mu_1 + (q-1)c_f + (1-q)c_r\right)\tau_1 + \mu_1\right)\tau_2 + \mu_1\right)}{1+\tau_1\tau_2+\tau_2} \quad \text{(A.7)}$$

$$\frac{\partial\emptyset}{\partial \mu_1} = \left[(1-\alpha_1)\left(a - bp_{1,n}^{DS}\right)\right) - a + bp_{1,d}^{DS}\right] \quad \text{(A.8)}$$

When we solve the four Eqs. (A.4-8), we get the values as Eqs. (A.9-11) and $\mu_1^* = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1\tau_2+\tau_2}$.

$$p_{1,n}^{DS*} = \frac{bc_r + a}{2b} \quad \text{(A.9)}$$

$$p_{1,d}^{DS*} = \frac{bqc_r - bc_r + bc_f + qa}{2bq} \quad \text{(A.10)}$$

$$\alpha_1^* = \frac{\left(c_f - c_r\right)b}{q(a - bc_r)} \quad \text{(A.11)}$$

It is clear that $\alpha_1^* = 1$ implies that the manufacturer supplies only from the renewable power plant (RS), therefore, by solving the $\alpha_1^* = \frac{(c_f - c_r)b}{q(a - bc_r)} = 1$ with respect to the q, we gain the specific point of q which we called critical disruption probability earlier ($\delta_1 = \frac{(c_f - c_r)b}{(a - bc_r)}$). As a result, in situations where $q \leq \delta_1$, the manufacturer prefers the RS strategy while in the range of $\delta_1 < q < 1$ the dual sourcing strategy is its choice.

2) *The fossil fuel power plant as a leader*

In this model of the game, the fossil fuel power plant's decision power is higher than the renewable power plant. As a result, the fossil fuel power plant makes a decision on its own wholesale price first, and then the renewable power plant decides on its own wholesale price.

Using $\frac{\pi_{1,m}^{DS}}{\pi_{1,f}^{DS}} \geq \tau_1$ the optimal value of $w_{1,f}^{DS}$ is obtained. Since $\pi_{1,f}^{DS}$ is linearly increasing in $w_{1,f}$ it can be said that the optimal value of $w_{1,f}$ is its highest possible value.

$$w_{1,f}^* = \frac{\left(c_f \tau_1 (\alpha_1^* - 1) - p_{1,n}^{DS*} + \alpha_1^* w_{1,r}^{DS*}\right)(q-1) D_{1,n}^{DS} + q D_{1,d}^{DS}\left(p_{1,d}^{DS*} + c_f \tau_1\right)}{(1+\tau_1)\left((\alpha_1^* - 1)(q-1) D_{1,n}^{DS} + q D_{1,d}^{DS}\right)} \tag{A.12}$$

The optimal wholesale price of the renewable power plant by considering that the $w_{1,r}^{DS}$ gives rise to a linear increase in $\pi_{1,r}^{DS}$, and using $\frac{\pi_{1,f}^{DS}}{\pi_{1,r}^{DS}} \geq \tau_2$ is gained as Eq. (A.13).

$$w_{1,r}^{DS*} = \frac{\left(\alpha_1^* c_r \tau_2 (1+\tau_1) + p_{1,n}^{DS*} - c_f + c_f \alpha_1^*\right)(q-1) D_{1,n}^{DS} + q D_{1,d}^{DS}(c_f - p_{1,d}^{DS*})}{D_{1,n}^{DS} \alpha_1^* (1 + (1+\tau_1)\tau_2)(q-1)} \tag{A.13}$$

By substituting Eqs. (A.12) and (A.13) In the manufacturer's profit function, the concavity condition of the profit function with respect to the $p_{1,n}^{DS}$ *and* $p_{1,d}^{DS}$ is investigated.

Lemma 2 *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail prices.*

Proof: the manufacturer's hessian in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ is as follows.

$$H_{\pi_{1,m}^{DS}(p_{1,n}^{DS},p_{1,d}^{DS})} = \begin{bmatrix} \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS} \partial p_{1,d}^{DS}} \\ \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS} \partial p_{1,n}^{DS}} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} \end{bmatrix} = \begin{bmatrix} \frac{2\tau_2(q-1)b\tau_1}{1+\tau_1\tau_2+\tau_2} & 0 \\ 0 & -\frac{2\tau_2 q b\tau_1}{1+\tau_1\tau_2+\tau_2} \end{bmatrix} \quad \text{(A.14)}$$

Since $\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} = \frac{2\tau_2(q-1)b\tau_1}{1+\tau_1\tau_2+\tau_2} < 0$ and $\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right) - \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS} \partial p_{1,n}^{DS}}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS} \partial p_{1,d}^{DS}}\right) = \frac{2{\tau_2}^2(1-q)b^2{\tau_1}^2 q}{(1+\tau_1\tau_2+\tau_2)^2} > 0$, the profit function of the manufacturer is concave in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$. With considering $g\left(p_{1,n}^{DS}, p_{1,d}^{DS}\right) = (1-\alpha_1^*)\left(a - bp_{1,n}^{DS*}\right) - \left(a - bp_{1,d}^{DS*}\right) \geq 0$ it is obvious that the constraint is convex in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$.

Proposition 2. *The best answers for retail prices and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.20-22). The optimal value of the dual variable for the constraint is*: $\mu_1^* = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1\tau_2+\tau_2}$.

Proof: Putting Eqs. (A.12) and (A.13) in the manufacturer's profit function ($\pi_{1,m}^{DS}$) it is defined as below

$$\emptyset = \pi_{1,m}^{DS} + \mu_1\left[(1-\alpha_1)\left(a - bp_{1,n}^{DS}\right) - \left(a - bp_{1,d}^{DS}\right)\right] \quad \text{(A.15)}$$

Using KKT conditions, we get,

$$\frac{\partial\emptyset}{\partial p_{1,n}^{DS}} = -\frac{\tau_1(q-1)\big(-b(\alpha_1-1)c_f - 2bp_{1,n}^{DS} + b\alpha_1 c_r + a\big)\tau_2}{1+\tau_1\tau_2+\tau_2} + \mu_1 b(\alpha_1 - 1) \quad \text{(A.16)}$$

$$\frac{\partial\emptyset}{\partial p_{1,d}^{DS}} = -\frac{\tau_1 q\left(\big(2bp_{1,d}^{DS} - c_f\big)b - a\right)\tau_2}{1+\tau_1\tau_2+\tau_2} + \mu_1 b \quad \text{(A.17)}$$

$$\frac{\partial\emptyset}{\partial \alpha_1} = -\frac{\big(a - bp_{1,n}^{DS}\big)\left(\left(\big(\mu_1 + (q-1)c_f + (1-q)c_r\big)\tau_1 + \mu_1\right)\tau_2 + \mu_1\right)}{1+\tau_1\tau_2+\tau_2} \quad \text{(A.18)}$$

$$\frac{\partial\emptyset}{\partial \mu_1} = \left[(1-\alpha_1)\big(a - bp_{1,n}^{DS}\big) - a + bp_{1,d}^{DS}\right] \quad \text{(A.19)}$$

When we solve the four Eqs. (A.15-19), we get the values as Eqs. (A.20-22) and $\mu_1^* = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1\tau_2+\tau_2}$.

$$p_{1,n}^{DS*} = \frac{bc_r + a}{2b} \quad \text{(A.20)}$$

$$p_{1,d}^{DS*} = \frac{bqc_r - bc_r + bc_f + qa}{2bq} \quad \text{(A.21)}$$

$$\alpha_1^* = \frac{\big(c_f - c_r\big)b}{q(a - bc_r)} \quad \text{(A.22)}$$

We gained the specific point of q which we called critical disruption probability earlier ($\delta_1 = \frac{(c_f - c_r)b}{(a - bc_r)}$) as explained in previous section considering the renewable power plant as a leader.

3) *The Nash game*

In this model, the decision power of the renewable power plant and the fossil fuel one are equal. Therefore they decide on their own wholesale prices independently and at the same time. Since $\pi_{1,r}^{DS}$ is linearly increasing in $w_{1,r}^{DS}$ just like $\pi_{1,f}^{DS}$ in $w_{1,f}$, the best answers for $w_{1,r}^{DS}$ and $w_{1,f}$ using the same methods conducted in previous game models are derived as Eqs. (A.23-24).

$$w_{1,r}^{DS*} = \frac{(q-1)\left(\left(\tau_1 c_r + c_f + c_r\right)\alpha_1^* + p_{1,n}^{DS*} - c_f\right) D_{1,n}^{DS} + q D_{1,d}^{DS}(c_f - p_{1,d}^{DS*})}{D_{1,n}^{DS}\alpha_1^*(\tau_1 + 2)(q-1)} \tag{A.23}$$

$$w_{1,f}^{*} = \frac{(q-1)(\left((\alpha_1^* - 1)(1+\tau_1)c_f - p_{1,n}^{DS*} + \alpha_1^* c_r\right) D_{1,n}^{DS} + q D_{1,d}^{DS}\left((1+\tau_1)c_f - p_{1,d}^{DS*}\right)}{(2+\tau_1)\left((q-1)(\alpha_1^* - 1)D_{1,n}^{DS} + q D_{1,d}^{DS}\right)} \tag{A.24}$$

By substituting Eqs. (A.23) and (A.24) In the manufacturer's profit function, the concavity condition of the profit function with respect to the $p_{1,n}^{DS}$ *and* $p_{1,d}^{DS}$ is investigated.

Lemma 3 *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail prices.*

Proof*:* the manufacturer's hessian in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ is as follows.

$$H_{\pi_{1,m}^{DS}(p_{1,n}^{DS}, p_{1,d}^{DS})} = \begin{bmatrix} \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS}\partial p_{1,d}^{DS}} \\ \frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS}\partial p_{1,n}^{DS}} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} \end{bmatrix} = \begin{bmatrix} \frac{2(q-1)b\tau_1}{2+\tau_1} & 0 \\ 0 & -\frac{2qb\tau_1}{2+\tau_1} \end{bmatrix} \tag{A.25}$$

Since $\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2} = \frac{2(q-1)b\tau_1}{2+\tau_1} < 0$ and $\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial {p_{1,n}^{DS}}^2}\right) - \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,d}^{DS}\partial p_{1,n}^{DS}}\right)\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial p_{1,n}^{DS}\partial p_{1,d}^{DS}}\right) = \frac{4(1-q)b^2{\tau_1}^2 q}{(2+\tau_1)^2} > 0$, the profit function of the manufacturer is concave in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$. With considering $g\left(p_{1,n}^{DS}, p_{1,d}^{DS}\right) = (1-\alpha_1^*)\left(a - bp_{1,n}^{DS*}\right) - \left(a - bp_{1,d}^{DS*}\right) \geq 0$ it is obvious that the constraint is convex in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$.

Proposition 3. *The best answers for retail prices and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.31-33). The optimal value of the dual variable for the constraint is*: $\mu_1^* = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1}$.

Proof: Putting Eqs. (A.23) and (A.24) in the manufacturer's profit function ($\pi_{1,m}^{DS}$) it is defined as below

$$\emptyset = \pi_{1,m}^{DS} + \mu_1\left[(1-\alpha_1)\left(a - bp_{1,n}^{DS}\right) - \left(a - bp_{1,d}^{DS}\right)\right] \quad \text{(A.26)}$$

Using KKT conditions, we get,

$$\frac{\partial\emptyset}{\partial p_{1,n}^{DS}} = -\frac{\left(\left((-2p_{1,n}^{DS} + (c_r - c_f)\alpha_1 + c_f)q + 2p_{1,n}^{DS} + (c_f - c_r)\alpha_1 + c_f\right)b + a(q-1)\right)\tau_1}{2+\tau_1} - \mu_1 b(1-\alpha_1) \quad \text{(A.27)}$$

$$\frac{\partial\emptyset}{\partial p_{1,d}^{DS}} = -\frac{\tau_1\left(\left(2bp_{1,d}^{DS} - c_f\right)qb - qa\right)}{2+\tau_1} + \mu_1 b \quad \text{(A.28)}$$

$$\frac{\partial\emptyset}{\partial \alpha_1} = -\frac{\left(a - bp_{1,n}^{DS}\right)\left(\left(\mu_1 + (q-1)c_f + (1-q)c_r\right)\tau_1 + 2\mu_1\right)}{2+\tau_1} \quad \text{(A.29)}$$

$$\frac{\partial\emptyset}{\partial \mu_1} = \left[(1-\alpha_1)\left(a - bp_{1,n}^{DS})\right) - a + bp_{1,d}^{DS}\right] \quad \text{(A.30)}$$

When we solve the four Eqs. (A.26-30), we get the values as Eqs. (A.31-33) and $\mu_1^* = -\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1+\tau_1}$.

$$p_{1,n}^{DS*} = \frac{bc_r + a}{2b} \quad \text{(A.31)}$$

$$p_{1,d}^{DS*} = \frac{bqc_r - bc_r + bc_f + qa}{2bq} \quad \text{(A.32)}$$

$$\alpha_1^* = \frac{\left(c_f - c_r\right)b}{q(a - bc_r)} \quad \text{(A.33)}$$

We gained the specific point of q which we called critical disruption probability earlier ($\delta_1 = \frac{(c_f - c_r)b}{(a - bc_r)}$) as explained in previous section considering the renewable power plant as a leader.

1.2 Game models and optimal values in RS strategy

In this sub-section, considering the manufacturer as the overall leader, there is only one game.

I) The manufacturer as a leader

Using $\frac{\pi_{1,m}^{RS}}{\pi_{1,r}^{RS}} \geq \tau_1$ the optimal value of $w_{1,r}^{RS}$ is obtained. Since $\pi_{1,r}^{RS}$ is linearly increasing in $w_{1,r}^{RS}$ it can be said that the optimal value of $w_{1,r}^{RS}$ is its highest possible value.

$$w_{1,r}^{RS*} = \frac{\left(\tau_1 c_r + p_{1,n}^{RS*}\right)}{(\tau_1 + 1)} \tag{A.34}$$

By substituting Eq. (A.34) In the manufacturer's profit function, the concavity condition of the profit function with respect to the $p_{1,n}^{RS}$ is investigated.

Lemma 4 *The profit function of the manufacturer is concave in retail price*.

Proof*:* the manufacturer's hessian in $p_{1,n}^{RS}$ is as follows.

$$H_{\pi_{1,m}^{RS}(p_{1,n}^{RS})} = \left[\frac{\partial^2 \pi_{1,m}^{RS}}{\partial {p_{1,n}^{RS}}^2}\right] = \frac{2(q-1)b\tau_1}{1+\tau_1} \tag{A.35}$$

Since $\frac{\partial^2 \pi_{1,m}^{RS}}{\partial {p_{1,n}^{RS}}^2} = \frac{2(q-1)b\tau_1}{1+\tau_1} < 0$ the profit function of the manufacturer is concave in $p_{1,n}^{RS}$.

Proposition 4. *The best answer for retail price gained as Eq. (A.37).*

Proof: After putting Eq. (A.34) in the manufacturer's profit function ($\pi_{1,m}^{RS}$) we calculate first derivative regarding $p_{1,n}^{RS}$ as below

$$\frac{\partial \emptyset}{\partial p_{1,n}^{RS}} = -\frac{\tau_1(q-1)\left(\left(-2bp_{1,n}^{RS} - c_r\right)b + a\right)}{1+\tau_1} \tag{A.36}$$

When we solve the Eq. (A.36), we get the value as Eq. (A.37).

$$p_{1,n}^{RS*} = \frac{bc_r + a}{2b} \tag{A.37}$$

2. Collaboration scenario (Scenario 2)

2.1 Game models and optimal values in DS strategy

In this sub-section, considering the manufacturer as the overall leader, three game models, including I) the renewable power plant as a leader, II) the fossil fuel power plant as a leader, and III) the Nash game, are done between renewable and fossil fuel power plants to gain the wholesale prices . Besides, in each game models, one game considering the fossil fuel power plant as a leader in Stackelberg game between the renewable and the fossil fuel power plant is taken into account to gain optimal price of the energy produced by the fossil fuel power plant and sold to the renewable one. The main reason why we considered one game between two power plants is to reduce the complexity of the model and considering that the fossil fuel power plant has the primary capability to generate energy during disruptions when the renewable power plant may not be able to meet the demand. Besides, the fossil fuel power plant, as an established energy source, may have better market knowledge, pricing information, and experience in energy trading.

I) The renewable power plant as a leader

In this model of the game, the renewable power plant's decision power is higher than the fossil fuel power plant. As a result, the renewable pow plant makes a decision on his own wholesale price first, and then the fossil fuel power plant decides on his own wholesale price.

Using $\frac{\pi_{2,m}^{DS}}{\pi_{2,r}^{DS}} \geq \tau_1$ the optimal value of $w_{2,r}^{DS}$ is obtained. Since $\pi_{2,r}^{DS}$ is linearly increasing in $w_{2,r}^{DS}$ it can be said that the optimal value of $w_{2,r}^{DS}$ is its highest possible value.

$$w_{2,r}^{DS*} = \frac{\left(\left(\left(\left(v + b_f{}^* - c_r\right)q + c_r\right)\tau_1 + w_{2,f}^*\right)\alpha_2{}^* + p_2^{DS*} - w_{2,f}^*\right)D_2^{DS} + \tau_1 qc}{D_2^{DS}\alpha_2{}^*(1+\tau_1)} \tag{A.38}$$

The optimal wholesale price of the fossil fuel power plant by considering that the $w_{2,f}^{DS}$ gives rise to a linear increase in $\pi_{2,f}^{DS}$, and using $\frac{\pi_{2,r}^{DS}}{\pi_{2,f}^{DS}} \geq \tau_2$, $w_{2,f}$ is gained as Eq. (A.39).

$$w_{2,f}^* = \frac{\left(\left(\left(b_f{}^* - c_f\right)q + c_f\right)(1+\tau_1)\tau_2 + \left(v + b_f{}^* - c_r\right)q + c_r\right)\alpha_2{}^* - \tau_2 c_f(1+\tau_1) - p_2^{DS*})D_2^{DS} + qc\right)}{D_2^{DS}(\alpha_2{}^* - 1)(1 + \tau_2(1+\tau_1))} \tag{A.39}$$

By substituting Eqs. (A.38) and (A.39) In the renewable and fossil fuel power plants' profit functions in a disruption mode, a game conducted between these two power plants with a leadership of the fossil fuel power plant to gain optimal price of the power generated by the fossil fuel power plant and sold to the renewable one (b_f).

The optimal b_f by considering that the b_f gives rise to a linear increase in the second part of $\pi_{2,f}^{DS}$ (disruption mode), and using $\frac{\pi_{2,f}^{DS}}{\pi_{2,r}^{DS}} \geq \tau_3$, b_f is gained as Eq. (A.40).

$$b_f{}^* = \frac{\tau_3 c + v\tau_3 D_2^{DS}\alpha_2{}^* - \tau_3 X_1 D_2^{DS}\alpha_2{}^* - c_f D_2^{DS}\alpha_2{}^*}{D_2^{DS}\alpha_2{}^*(q\tau_3 - \tau_3 - 1))} \tag{A.40}$$

The value of X_1 is as below.

$$X_1 = \frac{\begin{array}{c}\left(\left((v - c_r)q + c_r\right)\tau_1\tau_2 + \left(c_f - qc_f\right)\tau_2 + (v - c_r)q + c_r\right)D_2^{DS}\alpha_2{}^* \\ -\tau_2\left(c_f - p_2^{DS*}\right)D_2^{DS} + qc(\tau_1\tau_2 + 1)\end{array}}{D_2^{DS}\alpha_2{}^*(1 + \tau_2 + \tau_1\tau_2)}$$

By substituting Eqs. (A.38-40) In the manufacturer's profit function, the concavity condition of the profit function with respect to the p_2^{DS} is investigated.

Lemma 5. *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail price.*

Proof*:* the manufacturer's hessian in p_2^{DS} is as follows.

$$H_{\pi_{2,m}^{DS}(p_2^{DS})} = \left[\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2}\right] = -\frac{2\tau_2 b \tau_1}{1+\tau_1\tau_2+\tau_2} \quad \text{(A.41)}$$

Since $\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2} = -\frac{2\tau_2 b\tau_1}{1+\tau_1\tau_2+\tau_2} < 0$ the profit function of the manufacturer is concave in p_2^{DS}. With considering $g(p_2^{DS}) = q\alpha_1^*(a - bp_2^{DS*}) - \beta \geq 0$ it is obvious that the constraint is convex in p_2^{DS}.

Proposition 5. *The best answers for retail price and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.46-47). The optimal value of the dual variable for the constraint is:* $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$.

Proof: Putting Eqs. (A.38-40) in the manufacturer's profit function ($\pi_{2,m}^{DS}$) it is defined as below

$$\emptyset = \pi_{2,m}^{DS} + \mu_2\left[q\alpha_2^*\left(a - bp_2^{DS*}\right) - \beta\right] \quad \text{(A.42)}$$

Using KKT conditions, we get,

$$\frac{\partial \emptyset}{\partial p_2^{DS}} = -\frac{\tau_1\left(-b\left(c_f - c_r + v\right)q - c_f + c_r\right)\alpha_2 - a + bp_2^{DS} - \left(c_f - p_2^{DS}\right)b\Big)\tau_2}{1+\tau_1\tau_2+\tau_2} - \mu_2 b\alpha_2 q \quad \text{(A.43)}$$

$$\frac{\partial \emptyset}{\partial \alpha_2} = -\frac{\tau_2\tau_1\left(a - bp_2^{DS}\right)\left(\left(c_f - c_r + v\right)q - c_f + c_r\right)}{1+\tau_1\tau_2+\tau_2} + \mu_2 q\left(a - bp_2^{DS}\right) \quad \text{(A.44)}$$

$$\frac{\partial \emptyset}{\partial \mu_2} = \left[q\alpha_2\left(a - bp_2^{DS}\right)\right) - \beta\right] \quad \text{(A.45)}$$

When we solve the three Eqs. (A.43-45), we get the values as Eqs. (A.46-47) and $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$

$$p_2^{DS*} = \frac{bc_f + a}{2b} \quad \text{(A.46)}$$

$$\alpha_2^* = \frac{2\beta}{q\left(a - bc_f\right)} \quad \text{(A.47)}$$

It is clear that $\alpha_2^* = 1$ implies that the manufacturer supplies only from the renewable power plant (RS), therefore, by solving the $\alpha_2^* = \frac{2\beta}{q(a-bc_f)} = 1$ with respect to the q, we gain the specific point of q which we called critical disruption probability earlier ($\delta_2 = \frac{2\beta}{(a-bc_f)}$). As a result, in situations where $q \leq \delta_2$, the manufacturer prefers RS strategy while in the range of $\delta_2 < q < 1$ the dual sourcing strategy is its choice.

2) *The fossil fuel power plant as a leader*

In this model of the game, the fossil fuel power plant's decision power is higher than the renewable power plant. As a result, the fossil fuel power plant makes a decision on his own wholesale price first, and then the renewable power plant decides on his own wholesale price.

Using $\frac{\pi_{2,m}^{DS}}{\pi_{2,f}^{DS}} \geq \tau_1$ the optimal value of $w_{2,f}$ is obtained. Since $\pi_{2,f}^{DS}$ is linearly increasing in $w_{2,f}$ it can be said that the optimal value of $w_{2,f}$ is its highest possible value.

$$w_{2,f}^{DS*} = \frac{\left(\left((1-q)c_f + qb_f{}^*\right)\tau_1 + w_{2,r}^{DS*}\right)\alpha_2{}^* - p_2^{DS*} - \tau_1 c_f}{(\alpha_2{}^* - 1)(1+\tau_1)} \quad \text{(A.48)}$$

The optimal wholesale price of the renewable power plant by considering that the $w_{2,r}^{DS}$ gives rise to a linear increase in $\pi_{2,r}^{DS}$, and using $\frac{\pi_{2,f}^{DS}}{\pi_{2,r}^{DS}} \geq \tau_2$, $w_{2,r}^{DS}$ is gained as Eq. (A.49).

$$w_{2,r}^{DS*} = \frac{((1+\tau_1)q\tau_2 + q)b_f^{\ *}}{(1+\tau_2+\tau_1\tau_2)} + X_2 \tag{A.49}$$

The value of X_2 is as follow:

$$X_2 = \frac{\left(\left((\tau_1+1)\left((v-c_r)q+c_r\right)\tau_2 - qc_f + c_f\right)\alpha_2^{\ *} - c_f + p_2^{DS*}\right)D_2^{DS} + \tau_2 qc(\tau_1+1)}{D_2^{DS}\alpha_2^{\ *}(1+\tau_2+\tau_1\tau_2)}$$

By substituting Eqs. (A.48) and (A.49) In the renewable and fossil fuel power plants' profit functions in a disruption mode, a game conducted between these two power plants with a leadership of the fossil fuel power plant to gain optimal price of the power generated by the fossil fuel power plant and sold to the renewable one (b_f).

The optimal b_f by considering that the b_f gives rise to a linear increase in the second part of $\pi_{2,f}^{DS}$ (disruption mode), and using $\frac{\pi_{2,f}^{DS}}{\pi_{2,r}^{DS}} \geq \tau_3$, b_f is gained as Eq. (A.50).

$$b_f^{\ *} = \frac{\tau_3 c + v\tau_3 D_2^{DS}\alpha_2^{\ *} - \tau_3 X_2 D_2^{DS}\alpha_2^{\ *} - c_f D_2^{DS}\alpha_2^{\ *}}{D_2^{DS}\alpha_2^{\ *}(q\tau_3 - \tau_3 - 1))} \tag{A.50}$$

By substituting Eqs. (A.48-50) In the manufacturer's profit function, the concavity condition of the profit function with respect to the p_2^{DS} is investigated.

Lemma 6. *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail price.*

Proof: the manufacturer's hessian in p_2^{DS} is as follows.

$$H_{\pi_{2,m}^{DS}(p_2^{DS})} = \left[\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2}\right] = -\frac{2\tau_2 b\tau_1}{1+\tau_1\tau_2+\tau_2} \quad \text{(A.51)}$$

Since $\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2} = -\frac{2\tau_2 b\tau_1}{1+\tau_1\tau_2+\tau_2} < 0$ the profit function of the manufacturer is concave in p_2^{DS}. With considering $g(p_2^{DS}) = q\alpha_1^*(a - bp_2^{DS*}) - \beta \geq 0$ it is obvious that the constraint is convex in p_2^{DS}.

Proposition 6. *The best answers for retail price and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.56-57). The optimal value of the dual variable for the constraint is:* $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$.

Proof: Putting Eqs. (A.48-50) in the manufacturer's profit function ($\pi_{2,m}^{DS}$) it is defined as below

$$\emptyset = \pi_{2,m}^{DS} + \mu_2\left[q\alpha_2^*\left(a - bp_2^{DS*}\right) - \beta\right] \quad \text{(A.52)}$$

Using KKT conditions, we get,

$$\frac{\partial\emptyset}{\partial p_2^{DS}} = -\frac{\tau_1\left(-b\left(c_f - c_r + v\right)q - c_f + c_r\right)\alpha_2 - a + bp_2^{DS} - (c_f - p_2^{DS})b\big)\tau_2}{1+\tau_1\tau_2+\tau_2} - \mu_2 b\alpha_2 q \quad \text{(A.53)}$$

$$\frac{\partial\emptyset}{\partial \alpha_2} = -\frac{\tau_2\tau_1\left(a - bp_2^{DS}\right)\left(\left(c_f - c_r + v\right)q - c_f + c_r\right)}{1+\tau_1\tau_2+\tau_2} + \mu_2 q\left(a - bp_2^{DS}\right) \quad \text{(A.54)}$$

$$\frac{\partial\emptyset}{\partial \mu_2} = \left[q\alpha_2\left(a - bp_2^{DS}\right)\right) - \beta\right] \quad \text{(A.55)}$$

When we solve the three Eqs. (A.53-55), we get the values as Eqs. (A.56-57) and $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$.

$$p_2^{DS*} = \frac{bc_f + a}{2b} \tag{A.56}$$

$$\alpha_2^* = \frac{2\beta}{q\left(a - bc_f\right)} \tag{A.57}$$

We gained the specific point of q which we called critical disruption probability earlier ($\delta_2 = \frac{2\beta}{(a-bc_f)}$) as explained in previous section considering the renewable power plant as a leader.

3) *The Nash game*

In this model, the decision power of the renewable power plant and the fossil fuel one are equal. Therefore they decide on their own wholesale prices independently and at the same time. Since $\pi_{2,r}^{DS}$ is linearly increasing in $w_{2,r}^{DS}$ just like $\pi_{2,f}^{DS}$ in $w_{2,f}$, the best answers for $w_{2,r}^{DS}$ and $w_{2,f}$ using the same methods conducted in previous game models are derived as Eqs. (A.58-59).

$$w_{2,r}^{DS*} = \frac{qb_f{}^*\left(D_2^{DS}\alpha_2{}^*(2+\tau_1)\right) + X_3}{D_2^{DS}\alpha_2{}^*(2+\tau_1)} \tag{A.58}$$

$$w_{2,f}^* = \frac{\left(\begin{array}{c}\left(\left(\left(b_f{}^* - c_f\right)\tau_1 + 2b_f{}^* - c_f + v - c_r\right)q + c_f + \tau_1 c_f + c_r\right)\alpha_2{}^* \\ -p_2^{DS*} - \tau_1 c_f - c_f\end{array}\right)D_2^{DS} + qc}{D_2^{DS}(\alpha_2{}^* - 1)(2+\tau_1)} \tag{A.59}$$

The value of X_3 is presented as below:

$$X_3 = \left(\left(\left((v - c_r)\tau_1 + v - c_r - c_f\right)q + \tau_1 c_r + c_f + c_r\right)\alpha_2{}^* + p_2^{DS*} - c_f\right)D_2^{DS} + qc\,(1+\tau_1)$$

By substituting Eqs. (A.58-59) In the renewable and fossil fuel power plants' profit functions in a disruption mode, a game conducted between these two power plants with a leadership of the fossil fuel power plant to gain optimal price of the power generated by the fossil fuel power plant and sold to the renewable one (b_f).

The optimal b_f by considering that the b_f gives rise to a linear increase in the second part of $\pi_{2,f}^{DS}$, and using $\frac{\pi_{2,f}^{DS}}{\pi_{2,r}^{DS}} \geq \tau_3$, b_f is gained as Eq. (A.60).

$$b_f{}^* = \frac{\left(\left(c + vD_2^{DS}\alpha_2{}^*\right)\tau_1 - X_3 + 2vD_2^{DS}\alpha_2{}^* + 2c\right)\tau_3 - c_f D_2^{DS}\alpha_2{}^*(2+\tau_1)}{D_2^{DS}\alpha_2{}^*(q\tau_3 - \tau_3 - 1))(2+\tau_1)} \tag{A.60}$$

By substituting Eqs. (A.58-60) In the manufacturer's profit function, the concavity condition of the profit function with respect to the p_2^{DS} is investigated.

Lemma 7 *The profit function of the manufacturer and its constraint are concave and convex, respectively, in retail prices.*

Proof: the manufacturer's hessian in p_2^{DS} is as follows.

$$H_{\pi_{2,m}^{DS}(p_2^{DS})} = \left[\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2}\right] = -\frac{2b\tau_1}{2+\tau_1} \tag{A.61}$$

Since $\frac{\partial^2 \pi_{2,m}^{DS}}{\partial {p_2^{DS}}^2} = -\frac{2b\tau_1}{2+\tau_1} < 0$ the profit function of the manufacturer is concave in p_2^{DS} . With considering $g(p_2^{DS}) = q\alpha_1^*(a - bp_2^{DS*}) - \beta \geq 0$ it is obvious that the constraint is convex in p_2^{DS}.

Proposition 7. *The best answers for retail prices and the order split are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A.66-67). The optimal value of the dual variable for the constraint is:* $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(2+\tau_1)}$.

Proof: Putting Eqs. (A.58-60) in the manufacturer's profit function ($\pi_{2,m}^{DS}$) it is defined as below

$$\emptyset = \pi_{2,m}^{DS} + \mu_2\left[q\alpha_2^*\left(a - bp_2^{DS*}\right) - \beta\right] \tag{A.62}$$

Using KKT conditions, we get,

$$\frac{\partial \emptyset}{\partial p_2^{DS}} = -\frac{\tau_1\left(-\left(\left(c_f - c_r + v\right)q - c_f + c_r\right)b\alpha_2 - a + bp_2^{DS} - (c_f - p_2^{DS})b\right)\tau_2}{2+\tau_1} - \mu_2 b\alpha_2 q \quad \text{(A.63)}$$

$$\frac{\partial \emptyset}{\partial \alpha_2} = -\frac{\tau_1\left(a - bp_2^{DS}\right)\left(\left(c_f - c_r + v\right)q - c_f + c_r\right)}{2+\tau_1} + \mu_2 q\left(a - bp_2^{DS}\right) \quad \text{(A.64)}$$

$$\frac{\partial \emptyset}{\partial \mu_2} = \left[q\alpha_2\left(a - bp_2^{DS}\right)\right) - \beta\right] \quad \text{(A.65)}$$

When we solve the three Eqs. (A.63-65), we get the values as Eqs. (A.66-67) and $\mu_2^* = \frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$.

$$p_2^{DS*} = \frac{bc_f + a}{2b} \quad \text{(A.66)}$$

$$\alpha_2^* = \frac{2\beta}{q\left(a - bc_f\right)} \quad \text{(A.67)}$$

We gained the specific point of q which we called critical disruption probability earlier ($\delta_2 = \frac{2\beta}{(a-bc_f)}$) as explained in previous sections.

2.2 Game models and optimal values in RS strategy

In this sub-section, considering the manufacturer as the overall leader, there is only one game.

I) The manufacturer as a leader

Using $\frac{\pi_{2,m}^{RS}}{\pi_{2,r}^{RS}} \geq \tau_1$ the optimal value of $w_{2,r}^{RS}$ is obtained. Since $\pi_{2,r}^{RS}$ is linearly increasing in $w_{2,r}^{RS}$ it can be said that the optimal value of $w_{2,r}^{RS}$ is its highest possible value.

$$w_{2,r}^{RS*} = \frac{\left(\left(\left(v + b_f{}^* - c_r\right)q + c_r\right) D_2^{RS} + qc\right)\tau_1 + p_2^{RS*} D_2^{RS}}{D_2^{RS}(1+\tau_1)} \quad \text{(A.68)}$$

By substituting Eq. (A.68) In the renewable power plant profit function in a disruption mode, a game conducted between these two power plants with a leadership of the fossil fuel power plant to gain optimal price of the power generated by the fossil fuel power plant and sold to the renewable one (b_f).

The optimal b_f by considering that the b_f gives rise to a linear increase in the second part of $\pi_{2,f}^{RS}$, and using $\frac{\pi_{2,f}^{RS}}{\pi_{2,r}^{RS}} \geq \tau_3$, b_f is gained as Eq. (A.69).

$$b_f{}^* = \frac{-\left(\left(\left((X_4 - v)D_2^{RS} - c\right)\tau_3 + D_2^{RS} c_f\right)(1+\tau_1)\right)}{D_2^{RS}\left((q\tau_1 - \tau_1 - 1)\tau_3 - 1 - \tau_1\right)} \quad \text{(A.69)}$$

The value of X_4 is presented as below:

$$X_4 = \frac{\left(\left((v + c_r)q + c_r\right)D_2^{RS} + qc\right)\tau_1 + p_2^{RS*} D_2^{RS}}{D_2^{RS}(1+\tau_1)}$$

By substituting Eqs. (A.68-69) In the manufacturer's profit function, the concavity condition of the profit function with respect to the p_2^{RS} is investigated.

Lemma 8. *The profit function of the manufacturer is concave in retail price.*

Proof*:* the manufacturer's hessian in p_2^{RS} is as follows.

$$H_{\pi_{2,m}^{RS}(p_2^{RS})} = \left[\frac{\partial^2 \pi_{2,m}^{RS}}{\partial {p_2^{RS}}^2}\right] = -\frac{2(\tau_3 q - 1 - \tau_3)b\tau_1}{\tau_1\tau_3 q - \tau_1 - \tau_3 - \tau_1\tau_3 - 1} \quad \text{(A.70)}$$

Since $\frac{\partial^2 \pi_{2,m}^{RS}}{\partial {p_2^{RS}}^2} = -\frac{2(\tau_3 q - 1 - \tau_3) b \tau_1}{\tau_1 \tau_3 q - \tau_1 - \tau_3 - \tau_1 \tau_3 - 1} < 0$ the profit function of the manufacturer is concave in p_2^{RS} .

Proposition 8. The best answer for retail price as Eq. (A.72) derived.

Proof: After putting Eqs. (A.68-69) in the manufacturer's profit function ($\pi_{2,m}^{RS}$) we calculate first derivative regarding p_2^{RS} as below

$$\frac{\partial \emptyset}{\partial p_2^{RS}} = -\frac{\tau_1 \left(-(q-1)(\left(\left(c_r - 2p_2^{DS} \right) b + a \right) \tau_3 + \left(\left(c_f - c_r + v \right) q - 2p_2^{DS} + c_r \right) b - a \right)}{\tau_1 \tau_3 q - \tau_1 - \tau_3 - \tau_1 \tau_3 - 1} \quad \text{(A.71)}$$

When we solve the Eq. (A.71), we get the value as Eq. (A.72).

$$p_2^{RS*} = \frac{\left(\tau_3 c_r (q-1) + \left(c_r - c_f - v \right) q - c_r \right) b + a\left((q-1)\tau_3 - 1 \right)}{b((q-1)\tau_3 - 1)} \quad \text{(A.72)}$$

Tables

Table 1. Comparison of the related articles

Article	Pricing	Sust	Res	Channel Structure		Collab		Method	Game structure	
				Sg	Du	yes	no		Nash	Stackelberg
(Jamali, Rasti-Barzoki, and Altmann 2023)			✓		✓			Game theory		✓
(Babaei, Zhao, and Liu)			✓	✓				Game theory and stochastic optimization	✓	
(Namdar et al. 2018)			✓	✓	✓	✓		mixed integer linear programming		
(Liu Xiang 2020)			✓			✓		Optimization algorithms		
(Maddouri, Elkhorchani, and Grayaa 2020)	✓	✓						Game theory and Hybrid Genetic algorithm	✓	
(Jamali and Rasti-Barzoki 2022)	✓				✓	✓		Game theory	✓	✓
(Yang, Tang, and Nehorai 2012)	✓							Game theory	✓	
(Hamed Rajabzadeh and Reza Babazadeh 2022)	✓		✓		✓		✓	Game theory	✓	✓
(Noorollahi, Pourarshad, and Veisi 2021)		✓						Scenario-based mathematical model		
This Study	✓	✓	✓	✓	✓	✓	✓	Game theory	✓	✓

Sust: Sustainable, Collab: Collaboration, Sg: Single, Du: Dual, Res: Resilience,

Table 2. Notations used for model and formulation

Category	Symbol	Definition
Nomenclatures	m	The manufacturer
	r	The renewable power plant (RPP)
	f	The fossil fuel power plant (FPP)
	$i = \begin{cases} n \\ d \end{cases}$	Non-disruption Disruption
	$j = \begin{cases} DS \\ RS \end{cases}$	Dual sourcing Sourcing from the renewable power plant
	$l = \begin{cases} 1 \\ 2 \end{cases}$	The Scenario 1: Non-collaboration The Scenario 2: Collaboration
Parameters	c_r	Power generation cost of renewable power plant
	c_f	Power generation cost of fossil fuel power plant
	v	The variable cost of power supply from fossil fuel power plant for renewable power plant
	c	The fix cost of power supply from fossil fuel power plant for renewable power plant
	a	The market potential of the manufacturer
	b	Own price elasticity of the manufacturer
	β	Minimum critical needed power by the manufacturer
	q	The disruption probability of renewable power plant $0 < q < 1$
Decision variables	$w_{l,r}^{j}$	The wholesale power price of the renewable power plant in scenario l strategy j
	$w_{l,f}$	The wholesale power price of the fossil fuel power plant in scenario l strategy j
	$p_{l,i}^{j}$	The retail price of the manufacturer in scenario l mode i strategy j
	b_f	The fossil fuel power plant backup power price
	α_l	The split of the order to the renewable power plant in scenario l $0 < \alpha_l \leq 1$, where $\alpha_l = 1$ implies RS.
	μ_l	K.K.T coefficient in scenario l
Functions	$D_{l,i}^{j}$	Customer demand function in scenario l mode i strategy j
	$\pi_{l,m}^{j}$	Manufacturer profit function for scenario l strategy j
	$\pi_{l,r}^{j}$	Renewable power plant profit function for scenario l strategy j
	$\pi_{l,f}^{j}$	Fossil fuel power plant profit function for scenario l strategy j

Table 3. The optimal values of the decision variables

		Optimal values in DS strategy	
Game	***Variable***	***SC1***	***SC2***
RL	$w_{l,r}^{DS*}$	$\frac{(q-1)\left(\left(w_{1,f}^{*}+\tau_1 c_r\right)\alpha_1^{*}+p_{1,n}^{DS*}-w_{1,f}^{*}\right)D_{1,n}^{DS}+qD_{1,d}^{DS}\left(w_{1,f}^{*}-p_{1,d}^{DS*}\right)}{D_{1,n}^{DS}\alpha_1^{*}(1+\tau_1)(q-1)}$	$\frac{\left(\left(\left(\left(v+{b_f}^{*}-c_r\right)q+c_r\right)\tau_1+w_{2,f}^{*}\right){\alpha_2}^{*}+p_2^{DS*}-w_{2,f}^{*}\right)D_2^{DS}+\tau_1 qc}{D_2^{DS}{\alpha_2}^{*}(1+\tau_1)}$
	$w_{l,f}^{*}$	$\frac{\left(c_f(1+\tau_1)(\alpha_1^{*}-1)\tau_2+c_r\alpha_1-p_{1,n}^{DS*}\right)(q-1)D_{1,n}^{DS}+\left(c_f(1+\tau_1)\tau_2+p_{1,d}^{DS*}\right)qD_{1,d}^{DS}}{(1+(1+\tau_1)\tau_2)\left((q-1)(\alpha_1-1)D_{1,n}^{DS}+qD_{1,d}^{DS}\right)}$	$\frac{\left(\left(\left({b_f}^{*}-c_f\right)q+c_f\right)(1+\tau_1)\tau_2+\left(v+{b_f}^{*}-c_r\right)q+c_r\right){\alpha_2}^{*}-\tau_2 c_f(1+\tau_1)-p_2^{DS*})D_2^{DS}+qc}{D_2^{DS}({\alpha_2}^{*}-1)(1+\tau_2(1+\tau_1))}$
	${b_f}^{*}$	-	$\frac{\tau_3 c+v\tau_3 D_2^{DS}{\alpha_2}^{*}-\tau_3 X_1 D_2^{DS}{\alpha_2}^{*}-c_f D_2^{DS}{\alpha_2}^{*}}{D_2^{DS}{\alpha_2}^{*}(q\tau_3-\tau_3-1))}$
	$p_{l,n}^{DS*}$	$\frac{bc_r+a}{2b}$	$\frac{bc_f+a}{2b}$
	$p_{l,d}^{DS*}$	$\frac{bqc_r-bc_r+bc_f+qa}{2bq}$	
	α_l^{*}	$\frac{\left(c_f-c_r\right)b}{q(a-bc_r)}$	$\frac{2\beta}{q\left(a-bc_f\right)}$
	δ_l	$\frac{\left(c_f-c_r\right)b}{(a-bc_r)}$	$\frac{2\beta}{\left(a-bc_f\right)}$
	μ_l^{*}	$-\frac{(c_f q-c_r q+c_r-c_f)\tau_1\tau_2}{1+\tau_1\tau_2+\tau_2}$	$\frac{(c_f q-c_r q+qv+c_r-c_f)\tau_1\tau_2}{q(1+\tau_1\tau_2+\tau_2)}$
FL	$w_{l,r}^{DS*}$	$\frac{\left(\alpha_1^{*}c_r\tau_2(1+\tau_1)+p_{1,n}^{DS*}-c_f+c_f\alpha_1^{*}\right)(q-1)D_{1,n}^{DS}+qD_{1,d}^{DS}(c_f-p_{1,d}^{DS*})}{D_{1,n}^{DS}\alpha_1^{*}(1+(1+\tau_1)\tau_2)(q-1)}$	$\frac{((1+\tau_1)q\tau_2+q){b_f}^{*}}{(1+\tau_2+\tau_1\tau_2)}+X_2$
	$w_{l,f}^{*}$	$\frac{\left(c_f\tau_1(\alpha_1^{*}-1)-p_{1,n}^{DS*}+\alpha_1^{*}w_{1,r}^{DS*}\right)(q-1)D_{1,n}^{DS}+qD_{1,d}^{DS}\left(p_{1,d}^{DS*}+c_f\tau_1\right)}{(1+\tau_1)\left((\alpha_1^{*}-1)(q-1)D_{1,n}^{DS}+qD_{1,d}^{DS}\right)}$	$\frac{\left(\left((1-q)c_f+q{b_f}^{*}\right)\tau_1+w_{2,r}^{DS*}\right){\alpha_2}^{*}-p_2^{DS*}-\tau_1 c_f}{({\alpha_2}^{*}-1)(1+\tau_1)}$
	${b_f}^{*}$	-	$\frac{\tau_3 c+v\tau_3 D_2^{DS}{\alpha_2}^{*}-\tau_3 X_2 D_2^{DS}{\alpha_2}^{*}-c_f D_2^{DS}{\alpha_2}^{*}}{D_2^{DS}{\alpha_2}^{*}(q\tau_3-\tau_3-1))}$
	$p_{l,n}^{DS*}$	$\frac{bc_r+a}{2b}$	

	$p_{l,d}^{DS*}$	$\frac{bqc_r - bc_r + bc_f + qa}{2bq}$	$\frac{bc_f + a}{2b}$
	α_l^*	$\frac{(c_f - c_r)b}{q(a - bc_r)}$	$\frac{2\beta}{q(a - bc_f)}$
	δ_l	$\frac{(c_f - c_r)b}{(a - bc_r)}$	$\frac{2\beta}{(a - bc_f)}$
	μ_l^*	$-\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1 + \tau_1\tau_2 + \tau_2}$	$\frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(1 + \tau_1\tau_2 + \tau_2)}$
Nash	$w_{l,r}^{DS*}$	$\frac{(q-1)\left(\left(\tau_1 c_r + c_f + c_r\right)\alpha_1^* + p_{1,n}^{DS*} - c_f\right)D_{1,n}^{DS} + qD_{1,d}^{DS}(c_f - p_{1,d}^{DS*})}{D_{1,n}^{DS}\alpha_1^*(\tau_1 + 2)(q-1)}$	$\frac{qb_f{}^*\left(D_2^{DS}\alpha_2{}^*(2+\tau_1)\right) + X_3}{D_2^{DS}\alpha_2{}^*(2+\tau_1)}$
	$w_{l,f}^*$	$\frac{(q-1)(\left((\alpha_1^* - 1)(1+\tau_1)c_f - p_{1,n}^{DS*} + \alpha_1^* c_r\right)D_{1,n}^{DS} + qD_{1,d}^{DS}\left((1+\tau_1)c_f - p_{1,d}^{DS*}\right)}{(2+\tau_1)\left((q-1)(\alpha_1^* - 1)D_{1,n}^{DS} + qD_{1,d}^{DS}\right)}$	$\frac{\left(\left(\left((b_f{}^* - c_f)\tau_1 + 2b_f{}^* - c_f + v - c_r\right)q + c_f + \tau_1 c_f + c_r\right)\alpha_2{}^* - p_2^{DS*} - \tau_1 c_f - c_f\right)D_2^{DS} + qc}{D_2^{DS}(\alpha_2{}^* - 1)(2+\tau_1)}$
	$b_f{}^*$	-	$\frac{\left((c + vD_2^{DS}\alpha_2{}^*)\tau_1 - X_3 + 2vD_2^{DS}\alpha_2{}^* + 2c\right)\tau_3 - c_f D_2^{DS}\alpha_2{}^*(2+\tau_1)}{D_2^{DS}\alpha_2{}^*(q\tau_3 - \tau_3 - 1))(2+\tau_1)}$
	$p_{l,n}^{DS*}$	$\frac{bc_r + a}{2b}$	$\frac{bc_f + a}{2b}$
	$p_{l,d}^{DS*}$	$\frac{bqc_r - bc_r + bc_f + qa}{2bq}$	
	α_l^*	$\frac{(c_f - c_r)b}{q(a - bc_r)}$	$\frac{2\beta}{q(a - bc_f)}$
	δ_l	$\frac{(c_f - c_r)b}{(a - bc_r)}$	$\frac{2\beta}{(a - bc_f)}$
	μ_l^*	$-\frac{(c_f q - c_r q + c_r - c_f)\tau_1\tau_2}{1 + \tau_1}$	$\frac{(c_f q - c_r q + qv + c_r - c_f)\tau_1\tau_2}{q(2 + \tau_1)}$
Optimal values in RS strategy			
ML	$w_{l,r}^{RS*}$	$\frac{(\tau_1 c_r + p_{1,n}^{RS*})}{(\tau_1 + 1)}$	$\frac{\left(\left((v + b_f{}^* - c_r)q + c_r\right)D_2^{RS} + qc\right)\tau_1 + p_2^{RS*}D_2^{RS}}{D_2^{RS}(1+\tau_1)}$

$b_f{}^*$	-	$\frac{-\left(\left((X_4-v)D_2^{RS}-c\right)\tau_3+D_2^{RS}c_f\right)(1+\tau_1)}{D_2^{RS}\left((q\tau_1-\tau_1-1)\tau_3-1-\tau_1\right)}$
$p_{l,n}^{RS*}$	$\frac{bc_r+a}{2b}$	$\frac{\left(\tau_3 c_r(q-1)+\left(c_r-c_f-v\right)q-c_r\right)b+a\left((q-1)\tau_3-1\right)}{b((q-1)\tau_3-1)}$

RL: Renewable power plant as a leader, FL: Fossil fuel power plant as a leader, ML: Manufacturer as a leader

Table 4. The values of initial test parameters

Parameter	Value	Parameter	Value
c_f	300	τ_1	1.5
c_r	150	τ_2	1.3
v	20	τ_3	1.1
c	10	a	1000
β	80		
q	0.5		
b	1.5		

Table 5. The expected and satisfied demand in both scenarios

SC1																		
q	0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9	
Expected Demand	388		388		388		388		388		388		388		388		388	
Disruption mode	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D
Satisfied demand	388	0	388	0	388	8	388	104	388	163	388	200	388	228	388	247	388	263
SC2																		
q	0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9	
Expected Demand	388		381		275		275		275		275		275		275		275	
Disruption mode	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D
Satisfied demand	388	388	381	381	275	275	275	275	275	275	275	275	275	275	275	275	275	275

ND: Non- Disruption, D: Disruption

Figures

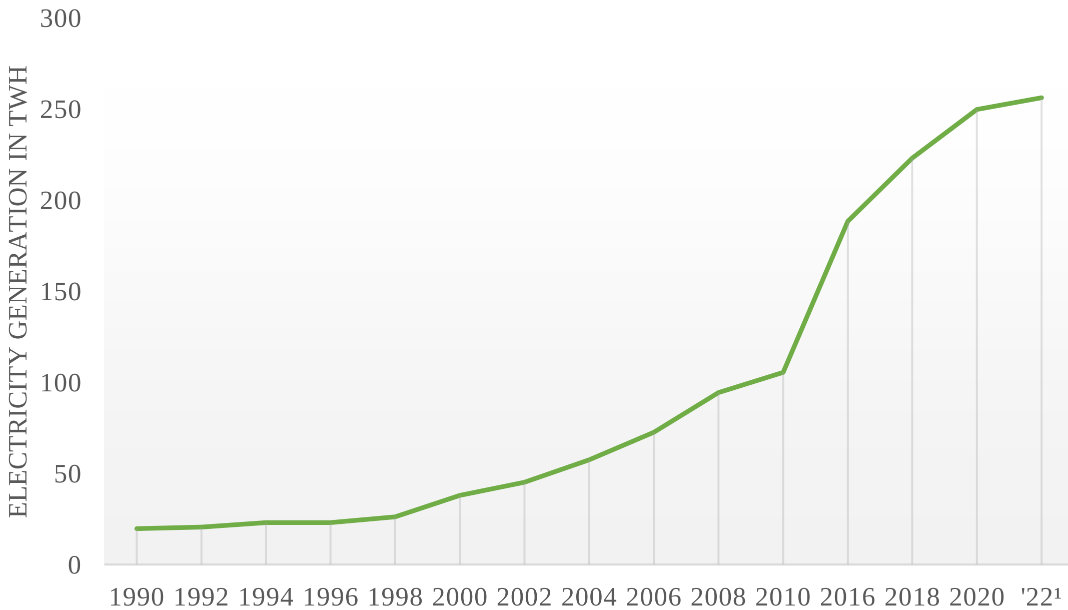

Figure 1. Gross electricity generation from renewable energy in Germany from 1990 to 2022(in terawatt hours)

Figure 1 Alt text: The Figure 1 is showing the rise in the electricity generation from renewable sources in Germany from 1990 till 2022. Although in 1990 the electricity generated from the renewable sources was arounf 20 TWH, with a sharp increase in 2010-2016 it has reached almost 250 TWH in 2022.

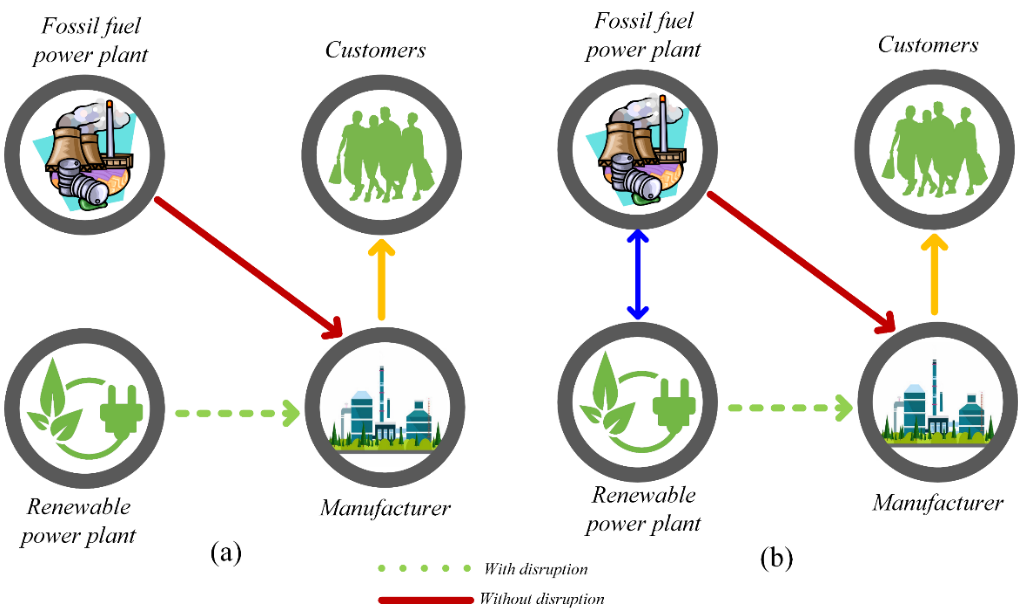

Figure 2. The graphical representation of the model in (a) Non-collaborative, and (b) Collaborative environment

Figure 2 Alt text: Figure 2 represents the fossil fuel and renewable powerplants supplying power to the manufacturer for product production purposes considering the renewable powerplant supply may come across disruption . While the Figure 2 (a) showing the no collaboration between powerplants , the Figure 2 (b) represents the model considering collaboration between powerplants.

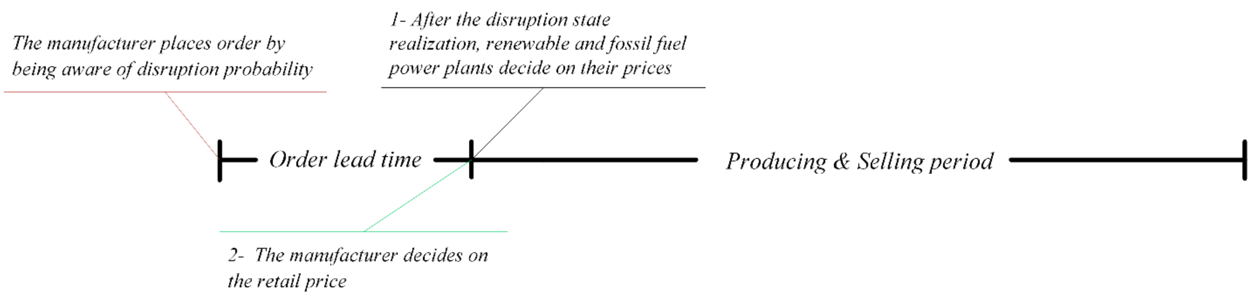

Figure 3. General Timeline of the Events

Figure 3 Alt text: The time line showing the sequence of events in the model starting from placing order to the both suppliers based on disruption probability at the beginning of the order lead time. At the end of order lead time considering whether disruption occurred or not based on power prices supplied from powerplants, the manufacturer decides on its retail price and sells products during selling period.

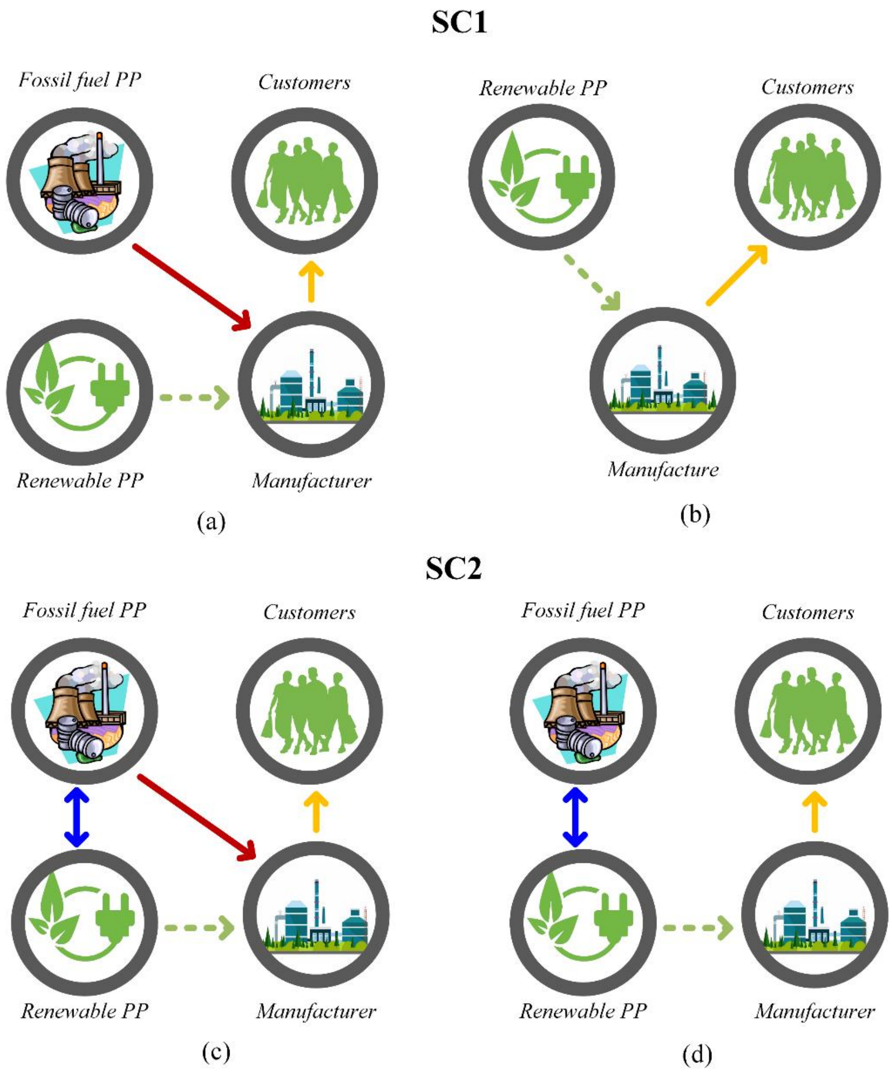

Figure 4. Sourcing strategies in scenarios 1 and 2

Figure 4 Alt text: The Figure 4 (a) and (b) are respectively representation of dual and single sourcing strategies of the manufacturer in the first scenareio where there is no collaboration between powerplants. In Figure 4 (a) it is assumed $\delta < q < 1$ and the manufacturer prefers DS strategy while in the (b) $q \leq \delta$ and there is only single sourcing from renewable power plant. The Figure 4 (c) and (d) are showing the same for the collaboration scenario.

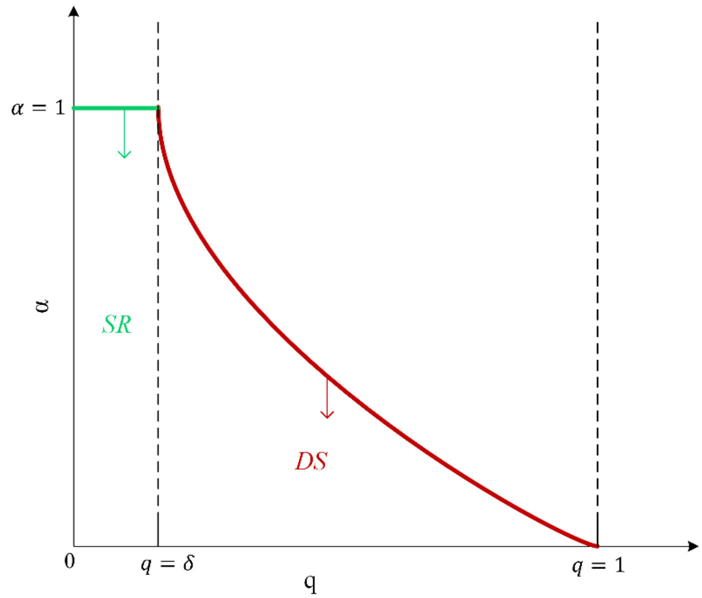

Figure 5. The relationship between α_l and q

Figure 5 Alt text: Figure 5 is showing the relationship between the split of the order and the disruption probability. It has shown that when $q \leq \delta$, the manufacturer gives order to only the renewable powerplant. With increasing q, the manufacturer prefers dual sourcing by splitting order to both renewable and fossil fuel power plants.

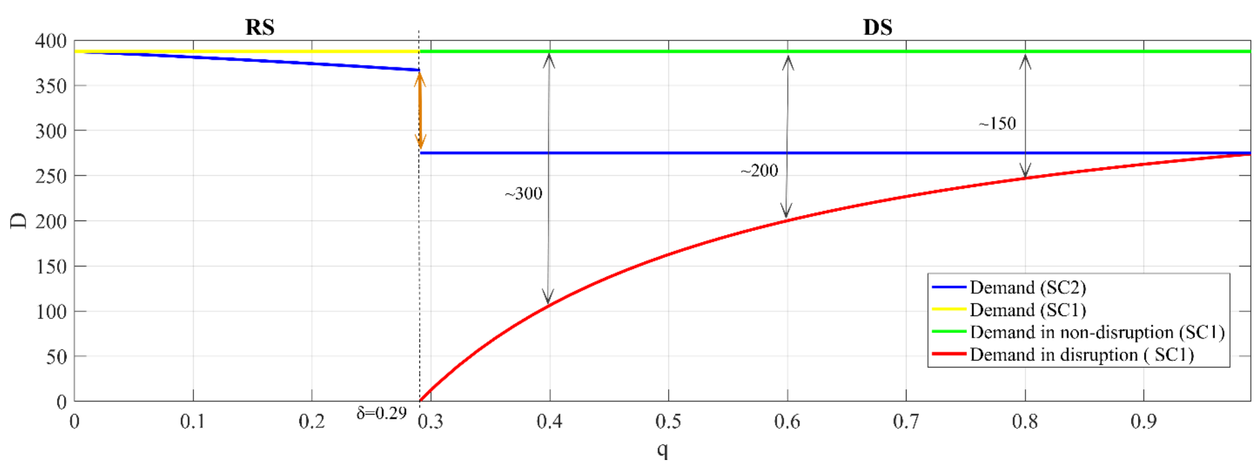

Figure 6. The demand satisfaction in different values of disruption probability

Figure 6 Alt text: The demand satisfaction regarding disruption probability is shown in Figure 6. While in RS strategy in both scenarios the demand satisfaction is in the peak, in DS strategy no matters disruption happens or not the demand satisfaction in scenario 2 is constant. On the other hand in scenario 1 if disruption happens the rise in disruption probability rises the demand satisfaction as well with supplying more from fossil fuel power plant , but the highest demand satisfaction occurs when there is no disruption in scenario 1.

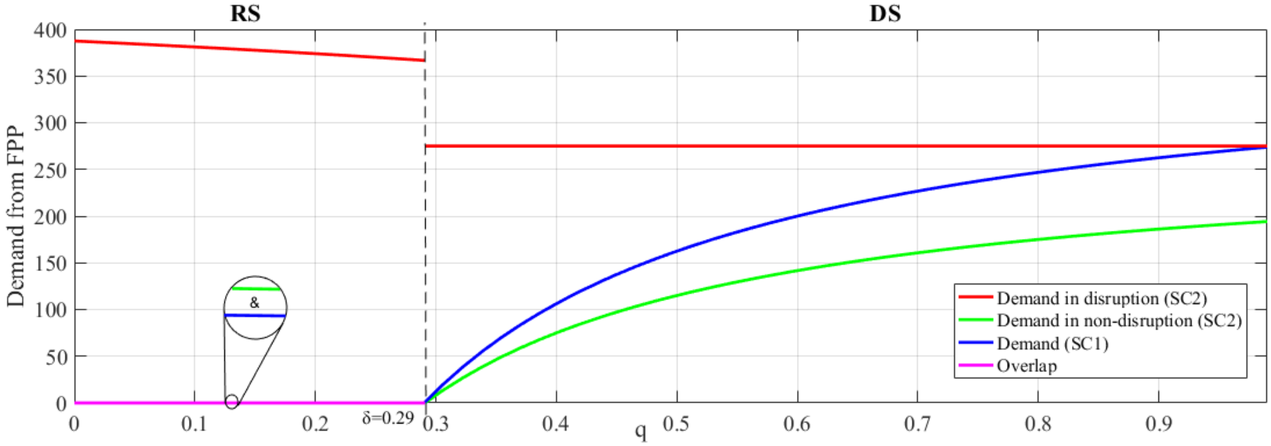

Figure 7. The demand from the fossil fuel power plant in different values of disruption probability

Figure 7 Alt text: Figure 7 illustrates that in scenario 1 (RS approach), sustainability is high as the manufacturer exclusively relies on RPP, resulting in no FPP demand. However, scenario 2 exhibits varying sustainability: it's most sustainable under non-disruption conditions but becomes less so as q increases due to rising FPP demand. In cases of RPP disruption, scenario 2 has the lowest sustainability as FPP supplies both RPP and manufacturer needs, aligning FPP demand with q.

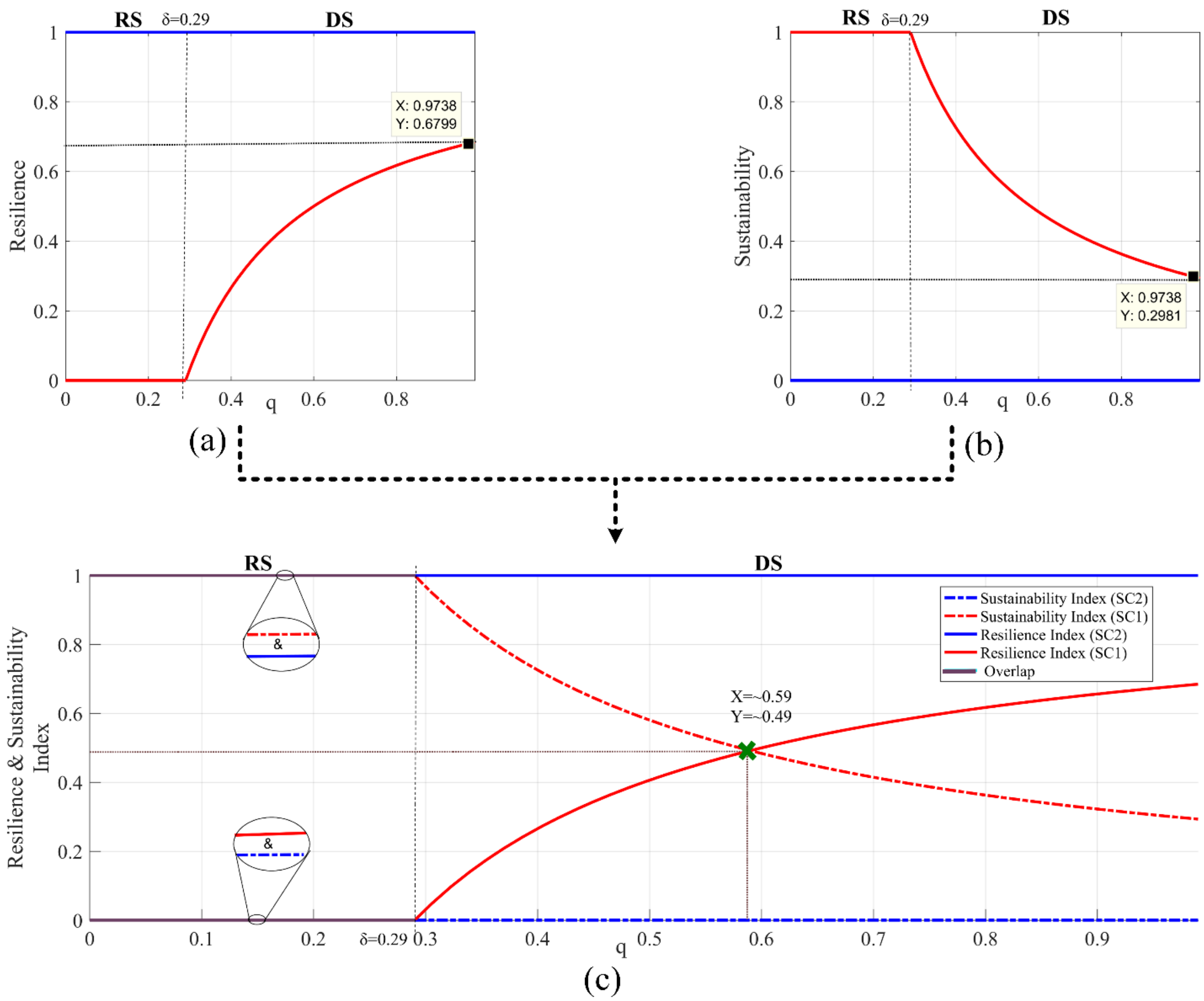

Figure 8. (a): The change in the Resilience index, (b): The change in the Sustainability index, (c): The change in the Resilience/Sustainability index in different values of disruption probability.

Figure 8 Alt text: Based on defined RI and SI Figures 8 (a) and (b) gained which their combinantion resulted in (c). The Figure 8 (a) showing the resilice of both scenarios in disruption sitiation which in RS strategy the scenario 1 has the least resilience while in DS with a rise in disruption probability its resilience rise as well. For the 2nd scenario in both RS and DS strategies the resilience is always on top. On the other hand the Figure 8 (b) shoeing the least sustainability for scenario 2 in both sourcing strategies whilr in scenario 1 in RS the sustainability is highest and decreases with the rise in disruption probability in DS strategy.

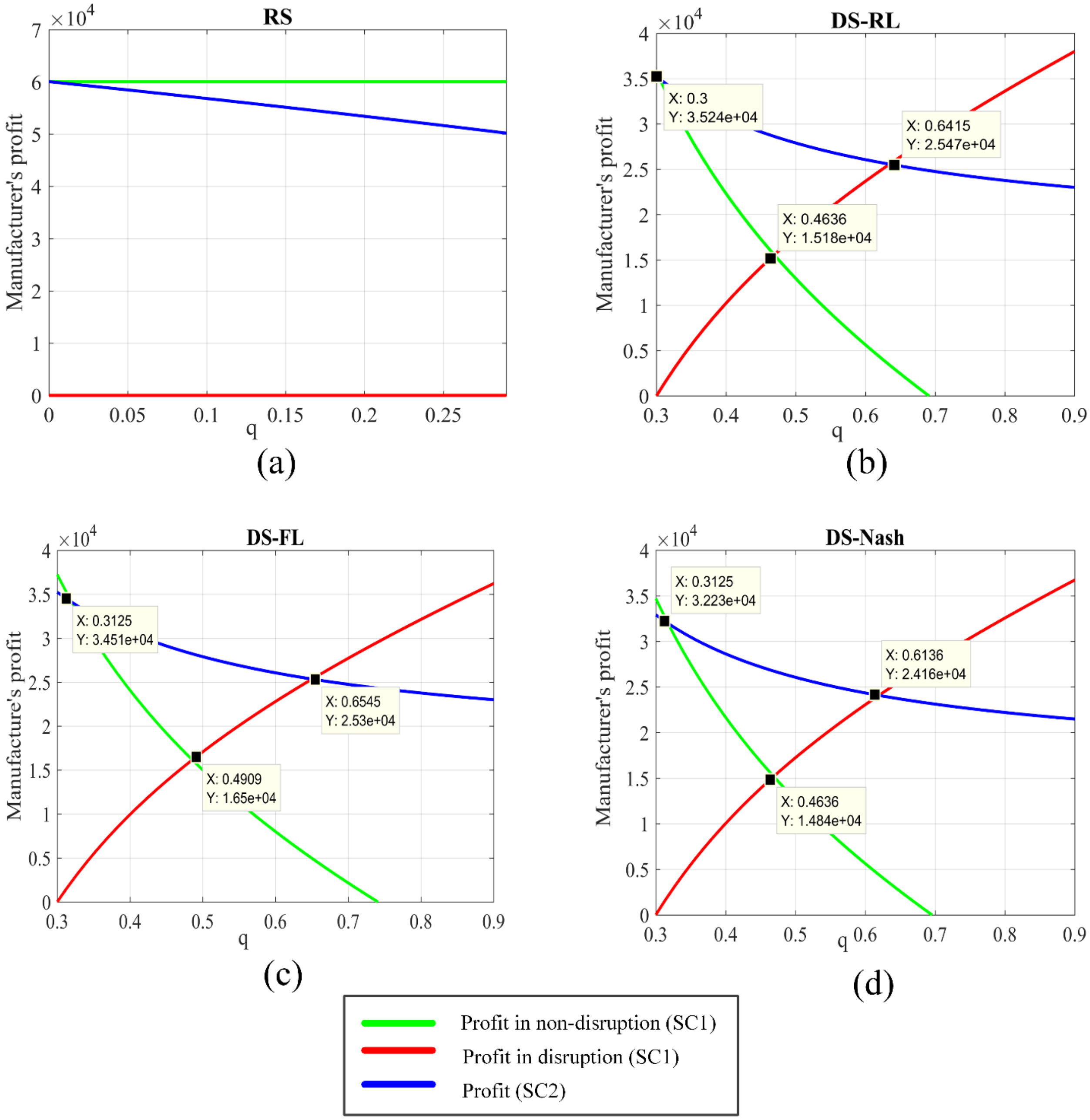

Figure 9. The change in manufacturer's profit in different values of disruption probability (a): In RS strategy, (b): In an RL game of DS strategy, (c): In an FL game of DS strategy, (d): In a Nash game of DS strategy

Figure 9 Alt text: In Figure 9(a), scenario 1's manufacturer profits most in non-disruption mode but zero in disruptions. Scenario 2 peaks at low q. Initially, all DS strategies yield similar profit patterns across scenarios. In scenarios 1 and 2, manufacturer profit decreases with rising q in non-disruption. In scenario 1's disruption mode, profit rises with q. Intersection points for manufacturer profit in disruption vs. non-disruption for RL, FL, and Nash games in scenario 1 DS are (0.46, 15100), (0.49, 16000), and (0.46, 148000), respectively. FL game at q=0.49 reaches the highest profit of 16000. In scenario 2, Nash game has the steepest profit decline with increasing q. Comparing all scenarios, scenario 2's initial profit aligns with scenario 1's non-disruption. RL, FL, and Nash intersect at (0.64, 25000), (0.65, 25000), and (0.61, 24000) in scenario 2 and scenario 1 (disruption mode).

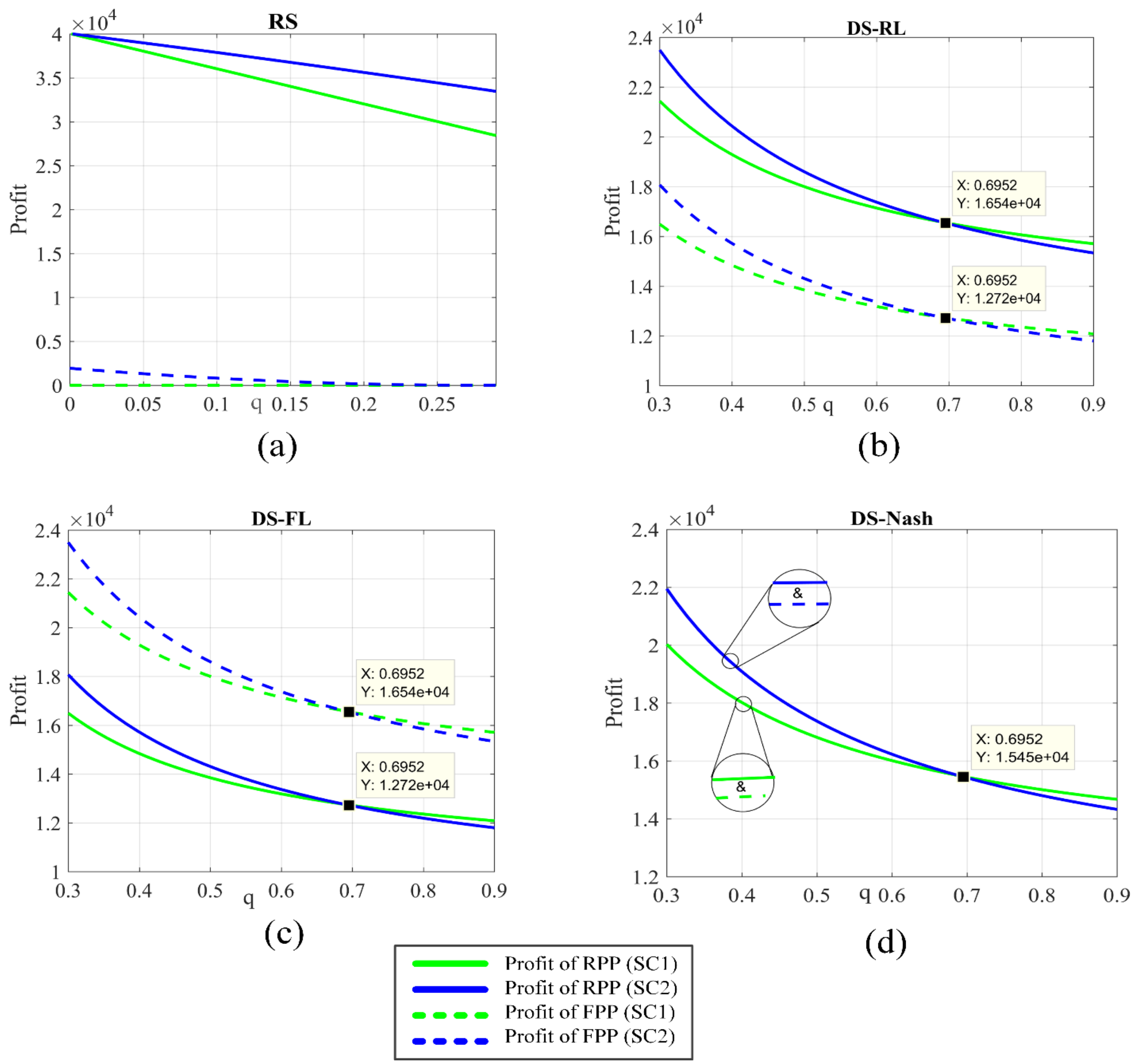

Figure 10. The change in PP's profit in different values of disruption probability (a): In RS strategy, (b): In an RL game of DS strategy, (c): In an FL game of DS strategy, (d): In a Nash game of DS strategy

Figure 10 Alt text: Figure 10(a) reveals that in scenario 2's RS strategy, both RPP and FPP profits decrease as q rises. Conversely, in scenario 1's RS strategy without PP collaboration, FPP profit remains at zero, while RPP profit decreases with increasing q. In all scenarios, higher q leads to reduced profits for both

FPP and RPP. However, switching demand from RPP to FPP doesn't improve FPP's profitability. As expected, in DS strategy games, the leader consistently earns more profit, while Nash games result in equal profits for both PPs. Collaboration is not profitable for both RPP and FPP in all game models. Scenario 1 benefits both FPP and RPP after q reaches approximately 0.7, at which point their profits intersect. At q=0.7, both PPs might choose to discontinue collaboration.

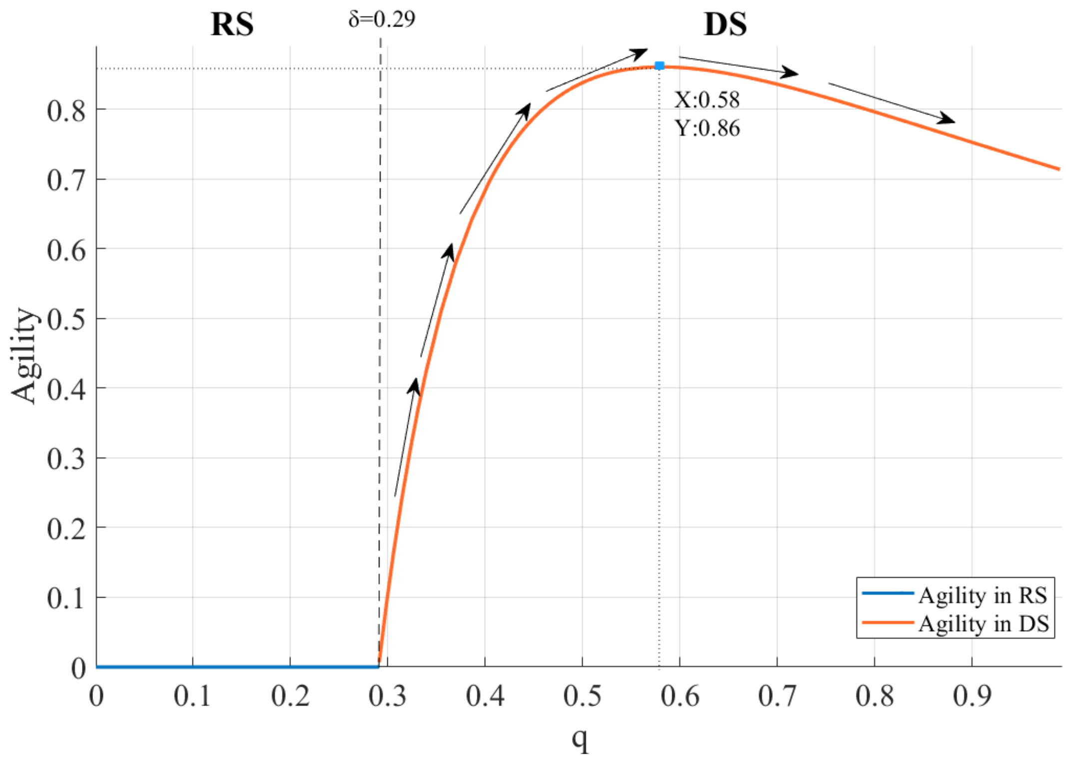

Figure 11: the change in agility with disruption probability

Figure 11 Alt text: The agility, as defined in our paper, exhibits a consistent pattern in both scenarios across different game models, as depicted in Figure 11. Notably, agility remains at zero in the RS strategy. However, once the disruption probability surpasses the critical threshold (δ) and the manufacturer opts for the DS strategy, agility begins to increase with rising q until it reaches q=0.58, after which it gradually declines.