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ORIGINAL RESEARCH

A game theory approach in hydrogen supply chain resilience: focus on pricing, sourcing, and transmission security

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Abstract

This study examines the pricing and assesses resilience methods in hydrogen supply chains by thoroughly analyzing two main disruption scenarios. The model examines a scenario in which a hydrogen production company depends on a Renewable Power plant (RP) for its electricity supply. Ensuring a steady and efficient hydrogen supply chain is crucial, but outages at renewable power sources provide substantial obstacles to sustainability and operational continuity. Therefore, in the event of disruptions at the RP, the company has two options for maintaining resilience: either sourcing electricity from a Fossil fuel Power plant (FP) through a grid network to continue hydrogen production or purchasing hydrogen directly from another company and utilizing third-party transportation for delivery. Using a game theoretic approach, we examine how different methods affect demand satisfaction, cost implications, and environmental sustainability. The study employs sensitivity analysis to evaluate the impact of different disruption probabilities on each scenario. In addition, a unique sensitivity analysis is performed to examine the resilience of transmission security to withstand disruptions. This study evaluates how investments in security measures affect the strength and stability of the supply chain in various scenarios of disruption. Our research suggests that the first scenario offers greater reliability and cost-effectiveness, along with a higher resilience rate compared to the second scenario. Furthermore, the examination of the environmental impact shows that the first scenario has a smaller amount of CO_2 emissions per kg of hydrogen. This study offers important insights for supply chain managers to optimize resilience measures, hence improving reliability, reducing costs, and minimizing environmental effects.

Keywords Hydrogen supply chain · Resilience · Sustainability · Energy transmission · Pricing · Game theory

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1 Introduction

The rapid increase in the global population has intensified energy demand across all sectors, projecting an increase of approximately 80% by the year 2050 (Alsunousi & Kayabasi, 2024). Global dependence on fossil fuels to meet energy demand has led to significant environmental and economic consequences (Wang & Azam, 2024). The combustion of fossil fuels is a major contributor to the emission of Greenhouse Gases (GHGs), which exacerbates climate change and intensifies air pollution(Alsunousi & Kayabasi, 2024).

Moreover, the finite nature of fossil fuel resources has led to concerns about long-term energy security and price stability (Holechek et al., 2022). As these resources diminish, the search for alternative energy sources has become more urgent (EllabbanAbu-Rub and Blaabjerg, 2014). Shifting from non-renewable, fossil fuel-based energy sources to renewable and sustainable options supports the progression towards an energy transition (Gielen et al., 2019). This comprehensive shift in the energy sector addresses environmental challenges while enhancing energy efficiency, ensuring energy security, and fostering sustainable development (Hassan et al., 2024a).

Hydrogen plays a significant role in the energy transition, a promising alternative to traditional fossil fuels for transportation, industry, etc., due to its high energy content and net-zero emissions when utilizing renewable energy sources for hydrogen production (Yusaf et al., 2024). However, transitioning to a hydrogen-based energy system requires establishing a robust supply chain that includes production, storage, transport, and utilization (Hassan et al., 2024a). A vital component of the hydrogen supply chain is hydrogen production, which can be accomplished through water electrolysis. Water electrolyzers split water into hydrogen and oxygen using electricity (Shiva Kumar & Lim, 2022). The water electrolysis process can be entirely emission-free when powered by renewable energy sources such as solar or wind power (Hassan et al., 2024b). Currently, three main types of water electrolysis techniques are commercially utilized: Solid Oxide Electrolysis Cell (SOEC), Polymer Electrolyte Membrane Water Electrolysis (PEMWE), and Alkaline Water Electrolysis (AWE) (Zhao et al., 2020).

Furthermore, the intermittency and seasonality of renewable energy sources add a layer of complexity (Zheng et al., 2023). For instance, solar and wind energies, while sustainable, do not produce a constant output, which poses a challenge for the continuous operation of electrolyzers (Bareiß et al., 2019). The seasonality of renewable sources means that there are periods of high and low energy production, which do not always align with the demand for hydrogen (Rajabzadeh & Babazadeh, 2022). This mismatch requires innovative solutions to ensure a steady hydrogen supply.

Building resilience in the hydrogen supply chain is crucial for the success of the hydrogen economy (Langen, 2023). It involves optimizing the use of renewable energies and developing a network of infrastructure that can adapt to changes in energy availability and demand (He et al., 2021). The resilience of the hydrogen supply chain is essential for ensuring reliability, affordability, and sustainability of hydrogen as a cornerstone of future energy systems (He et al., 2021).

Due to the gradual energy transition from fossil fuel to renewable or hydrogen, in this study, two hydrogen production companies that benefit from PEM electrolyzers are taken into account. The first one uses renewable electricity sources (RP), which is green but linked to volatile supply, compared to the second company, which supplies electricity through the grid mainly sourced by fossil fuel (FP), a reliable but non-green source. Due to the inherent variability of renewable sources, as explained before, there is a need for innovative approaches to developing resilient energy supply chains. In this regard, this study focuses on developing and evaluating resilient systems using a Game-Theoretic approach to support the widespread adoption of hydrogen, contributing effectively to a secure energy supply.

The rest of this study is organized as follows: Section 2 establishes the definitional, practical, and theoretical foundations. In Section 3, the notation and model description are presented in detail. Section 4 explains the scenarios, profit functions, and optimal values, while chapter 5 includes numerical and sensitivity analyses, along with additional management insights. Finally, Section 6 presents our conclusions and offers suggestions for future research.

2 Literature review

This section delves into the research background of the investigation, including resilient and environmentally sustainable energy supply chains and the importance of energy transmission mostly in a game-theoretical perspective.

2.1 The environmentally sustainable energy supply chain

The quest for an environmentally sustainable energy supply chain has garnered significant attention in the past decade due to increasing concerns over climate change, resource depletion, and environmental degradation (Gawusu et al., 2022). The energy supply chain encompasses the extraction, production, transportation, distribution, and energy consumption (Gold & Seuring, 2011). Traditionally, this supply chain has relied heavily on fossil fuels, contributing significantly to Green House Gas (GHG) emissions and environmental pollution (Arıoğlu AkanDhavale and Sarkis, 2017). Achieving sustainability by prioritizing economic factors, social responsibility, and mitigation of environmental emissions, profoundly impacts all aspects of human behavior and decision-making (Amiri-PebdaniAlinaghian and Safarzadeh, 2022). However, the transition towards sustainable energy sources such as wind, solar, and bioenergy is seen as crucial for mitigating environmental impacts and promoting sustainability (Lu et al., 2020).

Kabeyi and Olanrewaju (2022) argue that sustainable energy supply chains are defined by their ability to meet present energy demands without compromising the ability of future generations to meet their own needs. This involves minimizing environmental impacts, reducing carbon footprints, and ensuring the efficient use of resources (Kabeyi & Olanrewaju, 2022). Accordingly, Saavedra Mde O. Fontes and M. Freires (2018) remarked that renewable energy sources are central to sustainable energy supply chains. Solar and wind energy, in particular, have shown significant potential due to their low environmental impact and decreasing costs. Bioenergy, derived from organic materials, also plays a crucial role, although it comes with challenges related to land use and food security.

Nižetić et al. (2019) highlighted that effective supply chain management is essential for transitioning to sustainable energy. This includes optimizing logistics, enhancing energy efficiency, and reducing waste. Moreover, integrating advanced technologies such as the

Internet of Things (IoT) and blockchain can enhance transparency and efficiency in the energy supply chain (RejebKeogh and Treiblmaier, 2019).

On the other hand, government policies and regulations play a critical role in promoting sustainable energy supply chains. MecklingSterner and Wagner (2017) remarked that incentives for renewable energy development, carbon pricing, and stringent environmental regulations can drive the adoption of sustainable practices. Nevertheless, Wee et al. (2012) identified several challenges that hinder the development of sustainable energy supply chains, including technological limitations, high initial costs, and the intermittency of renewable energy sources. Moreover, Dalton et al. (2015) investigated that socio-economic factors such as public acceptance and employment impacts must be considered.

2.2 Adaptive strategies for managing energy supply chain disruption

Disruptions in the energy supply chain refer to unexpected events or conditions interrupting the regular flow of energy from production to consumption (Craighead et al., 2007). These disruptions can stem from a wide range of factors, including natural disasters, geopolitical conflicts, supply shortages, cyber-attacks, and infrastructure failures. Such events can severely impact national economies, reducing development capacity and affecting key stakeholders like manufacturers and consumers (Jasiūnas, Lund, and Mikkola, 2021; Gupta and Ivanov, 2020). The economic repercussions can be extensive, influencing energy prices, production costs, and even national security (Asif & Muneer, 2007). Understanding and mitigating these disruptions have become critical priorities for both researchers and policymakers.

Recent studies highlight the growing importance of adaptive strategies in enhancing the resilience of energy supply chains. According to Gupta and Ivanov (2020), the capacity to adjust operational tactics quickly is critical for managing supply chain risks in volatile environments. They emphasized that supply chain flexibility, including the ability to modify production schedules and logistics routes, significantly reduces the adverse impacts of disruptions. Similarly, Tufan et al. (2024) argued that companies with agile supply chains recover more rapidly from disruptions, underscoring the need for operational adaptability.

Han et al. (2017) explored the role of strategic reserves in maintaining energy supply stability. Their research suggested that buffer stocks and diversified storage facilities effectively mitigate the risks of supply shortages during emergencies. This is consistent with the findings of Guo et al. (2024), who emphasized the importance of inventory buffers and multi-sourcing strategies to counteract supply chain risks. GreenNewman and Droege (2023) also emphasized the need for redundancy in energy infrastructure, advocating for the development of decentralized and modular energy systems to enhance resilience against localized disruptions.

Resilience in the energy supply chain involves not only redundancy and robust infrastructure but also adaptive strategies and risk management practices (Rajabzadeh and Wiens, 2024). Jasiūnas, Lund, and Mikkola (2021) provided a comprehensive analysis of energy networks' ability to endure and recover from severe disruptions, such as extreme weather events and cyber-attacks. Their research highlights that resilient systems exhibit faster recovery rates and greater adaptability in the face of climate-related challenges. Additionally, GuoKapucu and Huang (2021) emphasized the role of crisis management and governance in enhancing system resilience, pointing out that strong leadership and coordinated responses are essential during major disruptions after COVID - 19.

In the context of predictive analytics, Aljohani (2023) highlighted the potential of data-driven decision-making tools in anticipating supply chain risks. Their findings indicate that advanced modeling techniques, including machine learning algorithms and scenario planning, enable energy companies to proactively manage potential disruptions. This underscores the significance of strong infrastructure and adaptable solutions. Chrisandina et al. (2022) suggested a comprehensive methodology for integrating several scales to enhance the resilience of sustainable energy supply chains against disruptions, such as severe weather. Their strategy encompassed a wide range of levels, from molecule to supply chain, with a focus on decentralized and modular techniques. Furthermore, EmrouznejadAbbasi and Sıcakyüz (2023) introduced a resilience framework that integrates supply chain capabilities with risk management, providing a holistic approach to resilience assessment.

Accordingly, these studies underscore the multifaceted nature of adaptive strategies in energy supply chains. By integrating flexibility and diversification, strategic reserves, infrastructure redundancy, collaborative networks, crisis management, and predictive analytics, organizations can build more resilient and robust supply chains capable of withstanding diverse disruption scenarios. The study emphasized the crucial importance of utilizing data-driven management to improve the resilience of supply chains

2.3 Game theory applications in energy transmission

Efficient energy transmission is vital for improving network efficiency, guaranteeing dependability, and addressing difficulties related to market regulation, the integration of renewable energy sources, and security. Adopting this strategy is crucial for the evolution of energy systems that are both robust and efficient, capable of adjusting to evolving demands and technological progress, and the below-mentioned studies addressed this issue.

The study by HuangWang and Xu (2023) proposed a model for integrating wind, solar, and biomass power stations to enhance renewable energy delivery, maximize profits, reduce carbon emissions, and create jobs. The model uses the ε-constraint method combined with Karush-Kuhn-Tucker conditions to solve the optimization problem. Moreover, Tian and Sun (2022) explored dynamic strategic interactions among regulators, producers, third-party certifiers, and consumers for achieving a low-carbon transition. They applied Lyapunov Stability Theory to identify stable equilibrium points. Proskuryakova (2018), on the other hand, introduced a bi-level multi-objective optimization (BLMO) model to improve the collaboration between hybrid renewable energy systems (HRES) and biomass power stations, ensuring sustainable power generation and addressing economic, environmental, and social objectives. The paper by Tang et al. (2022) proposed a Nash equilibrium-based strategy to optimally allocate electric and hydrogen fuel cell emergency power supply vehicles (EPSVs), balancing Distribution networks (DNs) resilience during hurricanes with economic efficiency. They modeled failure rates using meteorological data and optimized power supply capabilities and simulations showing improved resilience and reduced costs. Caetano and Marques (2023) investigated the strategic interactions in the low-carbon transition among regulators, producers, consumers, and third-party certifiers using an evolutionary game model. The study aims to find an equilibrium point for cooperation to achieve the carbon-neutral target and allows for the continuous revision and improvement of strategies to achieve satisfactory benefits for all parties involved. The paper by MoncecchiMeneghello and Merlo (2020) presented a methodology for forming renewable energy communities (RECs) in Italy, focusing on optimizing energy sharing and distribution using a game theory approach. The methodology used in this study is based on cooperative game theory, particularly focusing on the Shapley value to allocate costs and profits of shared infrastructures fairly among community members.

Regarding the utilization of Game theory approaches in energy systems, the paper by JamaliRasti-Barzoki and Altmann (2023) highlighted an evolutionary game-theoretic approach to analyze the long-term behavior of energy-intensive industries, specifically cement and steel, in Iran regarding their energy procurement strategies from renewable and non-renewable sources. It emphasizes the critical role of governmental subsidies and price discounts in promoting the adoption of renewable energy. Additionally, the study highlighted the importance of energy supply resilience and environmental responsibility in shaping industrial strategies for sustainable development and effective energy transmission. ErdoğanEröz and Grigoriadis (2022) developed a game-theoretic model to analyze green hydrogen transitions, focusing on the strategic dynamics between energy-rich dictatorships and technology-producing democracies. It highlights green hydrogen as a tool for energy independence, environmental sustainability, and geopolitical stability. The study emphasizes EU-Turkey cooperation in the green hydrogen supply chain. It also explores Nash equilibrium outcomes in energy policy decisions.

Moreover, Lei et al. (2023) proposed a Stackelberg game approach to optimize strategic bidding for multiple distributed energy resource (DER) aggregators in electricity markets, considering both market profits and distribution system security. The model integrates a potential game and a data-driven algorithm to achieve equilibrium solutions. Yue and You (2014) presented a bilevel mixed-integer nonlinear programming (MINLP) model for optimizing the biofuel supply chain using a game-theoretic framework, addressing both strategic and operational decisions. The upper level involves the biorefinery investor’s decisions on facility locations and technology, while the lower level encompasses suppliers' and customers' optimization problems. Accordingly, Table 1 presents a summary of the discussed articles and the gaps covered by our study.

Based on the gaps mentioned in Table 1, this study investigates pricing and two sourcing strategies in the presence of two competitive supply chains. Our model considers that company one, as a hydrogen generator, relies on the Renewable Powerplant (RP) for electricity supply in terms of environmental responsibility considerations. On the other hand, the competitor company, company two, benefits from the Fossil fuel-based power plant (FP) in that it supplies electricity and produces hydrogen to sell to the customers, which in this study, for both companies, is assumed to be hydrogen-fueled automobiles. Although the first company is considered environmentally friendly and benefits from governmental subsidies, it may come across interruptions in electricity supply due to the disruption probabilities of the RP. On the other hand, company two, has a non-green electricity supplier but is reliable. As a resilience option, it is assumed that the first company can be resilient in two ways:

- Procuring the rest of the electricity through the second company´s electricity supplier and generating remained hydrogen
- Procuring the hydrogen from the rival company (company 2) and satisfying the disruption affected demand.

Table 1 Summary of investigations in various articles

Article	Price	Environmental responsibility	Transmission Safety/Security	Govern-mental Subsidy	Channel structure		Game structure	
					RS	NR	Nash	Stackelberg
HuangWang and Xu (2023)	✓	✓		✓	✓	✓		✓
Proskuryakova (2018)	✓	✓			✓	✓		✓
JamaliRasti-Barzoki and Altmann (2023)	✓	✓		✓	✓	✓	✓	✓
Tang et al. (2022)	✓				✓	✓	✓	
MoncecchiMeneghello and Merlo (2020)	✓						✓	
Lei et al. (2023)	✓		✓		✓	✓	✓	✓
Yue and You (2014)	✓		✓		✓	✓	✓	
ErdoğanEröz and Grigoriadis (2022)	✓	✓	✓	✓			✓	
Tian and Sun (2022)	✓				✓	✓		
Caetano and Marques (2023)	✓	✓			✓	✓		
This Study	✓	✓	✓	✓	✓	✓	✓	

RS: Renewable sources for energy production, NR: Non-renewable sources for energy production

In the first scenario, it is assumed that the first company procures electricity through a grid network, which causes power loss during electricity transmission; as a result, the security factor is taken into account to reduce this loss. On the other hand, in the second scenario, the produced hydrogen from the second company to the first company is transferred by a truck belonging to a third-party company. Since the hydrogen transmission needs a special environment, the security of the trucks is also taken into account. In the end, the resilience of these two scenarios is investigated using a simultaneous move game (Nash) in a competitive environment between two companies, along with optimal prices, greenness level, and security of electricity and hydrogen transmission.

The primary aims of the study outlined in this paper can be succinctly described as follows:

- **Evaluate the Resilience of Hydrogen Supply Chains:** Evaluate the impact of various resilience strategies for reducing disruption effects on hydrogen supply chains, with a specific emphasis on comparing the efficacy of obtaining electricity from fossil power plants against procuring hydrogen from a secondary company as resilience options.
- **Analyze Economic Implications:** Analyze the economic effects of each resilience

strategy, including the efficiency of costs and pricing methods in the hydrogen supply chain, by employing a game-theoretic methodology to simulate scenarios of competition and cooperation.

- **Investigate Environmental Sustainability:** Analyze the environmental impacts of each resilience strategy, specifically focusing on the carbon dioxide emissions related to various hydrogen supply techniques and energy sources. The objective is to identify more environmentally sustainable practices within the sector.
- **Assess Transmission Security Resilience:** Assess the resilience of transmission security measures and their efficacy in protecting the supply chain from disruptions. This analysis concentrates on assessing how strong security protocols help to sustain uninterrupted operations and reduce risks related to energy transmission.

The aims of this study are to gain a thorough understanding of the operational, economic, and environmental factors involved in maintaining resilient hydrogen supply networks in different disruption scenarios.

3 Notation and model description

3.1 Notation

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

3.2 Model description

In this study, as shown in Fig. 1, two competing hydrogen supply chains are taken into account. The first supply chain consists of one Renewable Powerplant (RP), one hydrogen production company, and their customers. The RP sells the electricity at a price of $\boldsymbol{w}_1^j$ to the first hydrogen-producing company where a company using electricity produces hydrogen. The target customers buy this hydrogen at a price of $\boldsymbol{p}_1^j$. Consumers and governments are progressively emphasizing environmentally sustainable energy sources. The first company utilizes renewable energy for its electrical needs, therefore qualifying for a government subsidy (λ) due to its environmental responsibility, while also enhancing the appeal of their hydrogen to eco-conscious consumers. Company 1, although officially linked to the grid network, is presumed to function on a strategic green contract, procuring energy exclusively from the renewable power plant (RP) under standard terms. This dedication allows the company to get government support and sustain a strong environmental reputation, hence favorably impacting demand in the model. The grid connection is engaged just during RP disturbances, functioning as a resilience mechanism rather than a conventional supply source.

The second supply chain, instead of RP, includes the unlimited capacity fossil fuel powerplant (FP), with a hydrogen-producing company and its customers. To assess the environmental effect of grid-sourced energy, we assume that the electricity provided to Company 2 is produced from fossil fuel power plants. We use emission factors from coal-fired power plants to predict CO_2 emissions, based on data from EIA (2022). Although we recognize that real grid energy comprises a combination of sources (renewable, nuclear, etc.), this cautious

Table 2 Overview of notations

Category	Symbol	Definition
Nomenclatures	$i = \begin{cases} 1 \\ 2 \end{cases}$	Subscript index for 1st supply chain Subscript index for 2nd supply chain
	$j = \begin{cases} SC1 \\ SC2 \end{cases}$	Superscript index for the 1st scenario Superscript index for the 2nd scenario
Parameters	a_i	Market base demand from company in supply chain i
	a_{3p}	Market base demand from third-party
	α^j	The percentage of demand could be satisfied by renewable generated electricity in scenario j
	q	Disruption probability of Renewable powerplant
	β	Own price elasticity
	γ	Rival price elasticity
	ω	The coefficient of security/safety hydrogen transmission on demand
	φ	Own price elasticity of the third party
	τ	Price elasticity of the price of hydrogen which the 2nd company sells to the 1st one
	μ	The sensitivity coefficient amounts of an environmental responsibility per unit of the first company´s product on demand
	λ	The subsidy coefficient of the government for a company´s Environmental responsibility
	f	The electricity consumption of electrolyzers in two companies per kg of hydrogen production
	k_0	The fixed cost of the 1st company´s investment on Environmental responsibility
	k	The investment cost factor of the 1st company on Environmental responsibility
	c_s	The investment cost factor for hydrogen transmission security
	w_i^j	The wholesale price of electricity from powerplant in supply chain i and scenario j
	c_p	Cost of hydrogen production and investment (CAPEX)
	L	The power loss percentage $0 \leq L \leq 1$
	c_0	The fixed investment cost of electricity transmission security
	c_t	The investment cost factor for electricity transmission security
	b_1	The wholesale price of electricity the fossil fuel powerplant sells to 1st company
	b_2	The wholesale price of electricity the fossil fuel powerplant sells to 2nd company to satisfy the hydrogen demand of 1st company
	c_m	Cost of hydrogen transmission by third-party
	n	The number of incidences that may endanger the security/safety of transmission
	ς	Cost of security/safety breach for third-party
Decision variables	p_i^j	The retail price of hydrogen in supply chain i scenario j
	g^j	Environmental responsibility level of 1st company in scenario j,$0 \leq g \leq 1$
	t	The transmission security level of electricity in scenario 1,$0 \leq t \leq 1$
	p_3	The retail price of hydrogen the 2nd company sells to 1st company
	p_{3p}	Transmission price of third-party
	s	Transmission safety/security level of hydrogen in scenario 2,$0 \leq s \leq 1$

Table 2 (continued)

Category	Symbol	Definition
Functions	D_i	Customer demand function in supply chain
	D_H	First company demand function from second company
	D_{3p}	First company demand function from third-party
	π_i^j	Profit function of company in supply chain i scenario j
	π_{3p}	Profit function of third-party
	z_{3p}	The number of successful incidents cause security/safety breach in hydrogen transmission by third-party

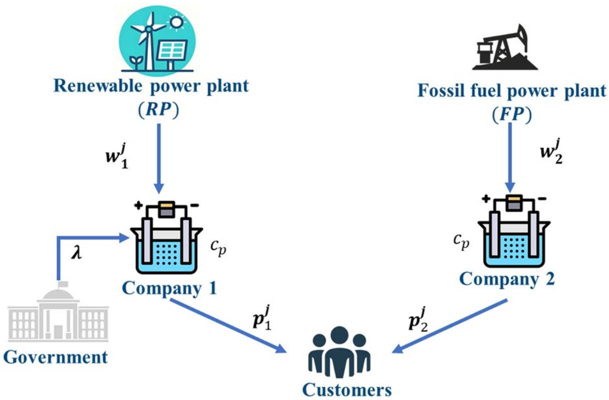


Fig. 1 The graphical representation of the model

assumption enables us to evaluate the most worst environmental scenario and underscore the disparity in sustainability between the two resilience solutions.

Just like the first supply chain, the FP sells the electricity at a price of w_2^j to the second company with an investment and production cost of c_p, produces hydrogen, and sells at a price of p_2^j to its customers.

Both companies benefit from the same electrolyzers to produce hydrogen, which in our study is a PEM electrolyzer with a production and investment cost of c_p. The main reasons why we considered PEM is 1- The PEM electrolyzer is the most compatible with renewable electricity (Shiva Kumar & Himabindu, 2019), and 2- this electrolyzer is capable of producing hydrogen with a purity of around 99.99% (Shiva Kumar & Himabindu, 2019), that is suitable for hydrogen-based vehicles (ISO, 2019) which are considered as our final target customers in our model.

Along with above-mentioned reasons, this research selects PEM electrolyzers because of their operational flexibility and high efficiency, which are essential for hydrogen generation in interruption situations. In scenario 1, detailed in the subsequent section, the capacity of PEM electrolyzers to accommodate variable power inputs from fossil fuel power plants guarantees consistent hydrogen generation (Awad et al., 2024). In scenario 2, detailed in the subsequent section, the acquisition of hydrogen demonstrates that PEM electrolyzers are effective for decentralized hydrogen production systems, diminishing reliance on external providers and strengthening supply chain resilience (Awad et al., 2024). Nonetheless, when hydrogen is procured externally, PEM electrolyzers may experience underutilization, hence impacting operating efficiency.

While PEM electrolyzers have considerable benefits, they also include drawbacks that we have evaluated. Their elevated capital expenditure arises from the use of costly elements such as platinum and iridium (Shiva Kumar & Himabindu, 2019). Durability may be an issue since prolonged high-load operation might reduce their lifetime relative to other technologies (Xu et al., 2024). Their production method incorporates essential elements that may have considerable environmental effects if not acquired responsibly (Shiva Kumar & Himabindu, 2019).

Although the electricity supplied to the first company through the RP is greener and cheaper compared to the FP one, it is more prone to disruption (q) due to the uncertain nature of renewable sources (Wang et al., 2022).In this regard, due to the higher importance of energy supply chain resilience, we have modeled two resiliency options for the first company under two scenarios.

This article defines resilience as the capacity to sustain operations and fulfill demand despite interruptions. This research analyzes two resilience strategies: obtaining energy from an alternative power plant (scenario 1) or procuring hydrogen from another company (scenario 2) as outlined below.

I. **Scenario 1**: The first company procures the rest of the electricity from the FP of the second supply chain to produce hydrogen and satisfy the remaining demand for hydrogen.
II. **Scenario 2**: The first company procures hydrogen directly from the second company to satisfy the remaining demand for hydrogen

Both scenarios are explained comprehensively in the following subsections.

I. Scenario 1

In this scenario, as represented in Fig. 2, the first company that could only satisfy the.

$\boldsymbol{\alpha}^1$ portion of demand for hydrogen through the RP prefers to deal with RP disruption by supplying electricity from the FP of the second supply chain at a price of $\boldsymbol{b}_1 > \boldsymbol{w}_1^j$ to satisfy the rest portion, of the demand $\left(1 - \boldsymbol{\alpha}^1\right)$. Considering the higher distance of FP from the first company and using the electricity grid network for transmission, there is a power loss (L) due to resistance, leakage, and corona discharge in transmission lines (Sadovskaia et al., 2019). Therefore, in terms of reducing the power loss, the first company should invest in increasing the transmission security percentage (t).

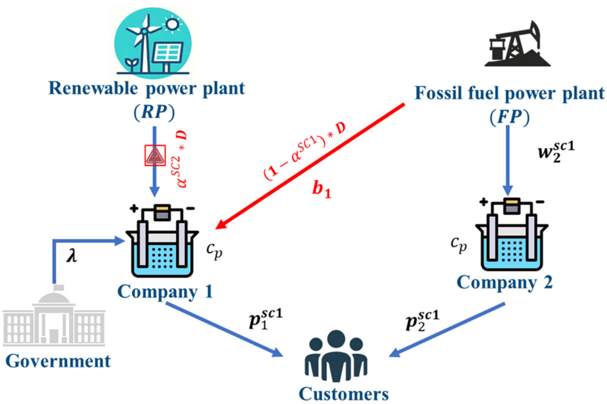


Fig. 2 The graphical representation of scenario I

Transmission In this context, transmission security pertains to the stability and reliability of energy transportation, guaranteeing that power is delivered to its destination securely and effectively.

II. Scenario 2

In this scenario, as shown in Fig. 3, the first company chooses to deal with RP disruption by supplying hydrogen instead of electricity, and the second company satisfies the remaining portion of the demand for hydrogen $\left(1-\boldsymbol{\alpha}^{2}\right)$ for this goal, it orders the unsatisfied demand for the second company to produce and buy at a price of $\boldsymbol{p}_{3}$. In this regard, the second company, along with satisfying its own demand, buys extra electricity from the FP at a price of $\boldsymbol{b}_{2}>\boldsymbol{w}_{2}^{j}$, and generates hydrogen to satisfy the first company´s demand. There is a third party in this scenario that has the responsibility of transporting the required hydrogen by trucks from the second company to the first one, with a transmission price of $\boldsymbol{p}_{3\boldsymbol{p}}$. Trucks carrying hydrogen need a special environment to be safe and secure (Abohamzeh et al., 2021). In this regard, a security level has been taken into account for trucks (s).

Transmission security in scenario 2 pertains to the stability and reliability of hydrogen transport, guaranteeing that hydrogen arrives at its destination securely and effectively.

4 Formulations and optimal values

This section presents the demand and profit functions, followed by an explanation of the solving approach and the optimal values gained for each scenario.

4.1 The demand functions

This model utilizes a price-dependent linear demand function for both customers and the first company. This function, commonly employed by academics as the standard in Industrial Economics and beyond (Allameh & Saidi-Mehrabad, 2021; Tirole, 1988). In this type of demand, demand declines as product prices rise and increases as rival´s price increase.

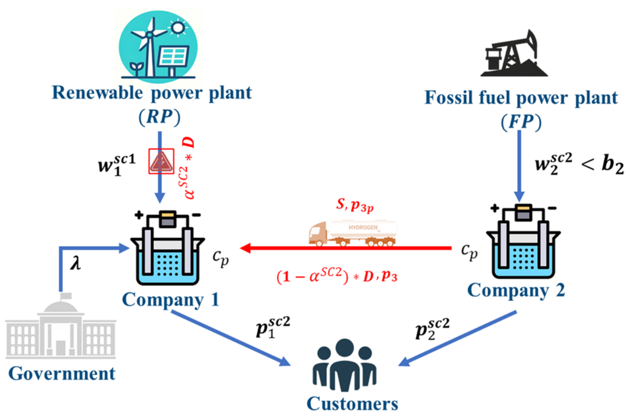


Fig. 3 The graphical representation of -scenario 2

$$D_1 = \left(a_1 - \beta p_1^j + \gamma p_2^j + \mu g^j\right) \tag{1}$$

$$D_2 = \left(a_2 - \beta p_2^j + \gamma p_1^j - \mu g^j\right) \tag{2}$$

D_1 and D_2 represent the customer demand for hydrogen in companies 1 and 2, respectively. In both functions, a_i is the market-based demand, β is the self-price elasticity and, γ is the rival´s price elasticity. Price elasticity (a_i, β) measures the sensitivity of demand to variations in product pricing. In competitive hydrogen marketplaces, price fluctuations substantially influence the demand for hydrogen generated by various enterprises. This aligns with the results of KumarBasu and Avittathur (2018), who emphasize the significance of price elasticity in influencing strategic choices within energy and biofuel supply chains. Allameh and Saidi-Mehrabad (2021) assert that price elasticity is a vital factor in pricing methods for decentralized supply chains that include renewable energy products.

In the end, it is assumed that the environmental responsibility level (g^j) is affecting the demand (JamaliRasti-Barzoki and Altmann, 2023), and it has multiplied by μ, showing the sensitivity coefficient of the customers for the environmental responsibility level. g^j increases the demand for the first company since it supplies electricity from RP and drops the demand from the second company since it supplies from FP as the non-environmentally friendly source.

Understanding of environmental responsibility reflects the influence of sustainability on consumer demand. Contemporary customers emphasize eco-friendly items, as shown by research conducted by JamaliRasti-Barzoki and Altmann (2023) and Nižetić et al. (2019). These works underscore how environmental accountability elevates consumer desire and amplifies demand for sustainable energy alternatives. This is especially important in hydrogen supply chains, where consumers want low-carbon and environmentally friendly manufacturing techniques.

There are also two demand functions for the first company as a customer for hydrogen in disruption mode:

$$D_H = \left(a_2 - \tau p_3 - \varphi p_{3p} - \mu g^{SC2}\right) \tag{3}$$

$$D_{3p} = \left(a_{3p} - \varphi p_{3p} - \tau p_3 - \omega z_{3p}\right) \tag{4}$$

D_H and D_{3p} are the demand functions of the first company for hydrogen from the first company and third party. The demand function shows how the quantity of hydrogen demanded by customers changes based on price, competition, and environmental responsibility. These demands function along with market-based demands as a_2, and a_{3p}, respectively, are negatively affected by the hydrogen price set by the second company to sell to the first one (p_3) and the transmission price of the third-party company (p_{3p}), with price elasticities of τ and φ, respectively. We believe that the rise in each of these prices will decrease the demand from the first company side, normally affecting both demands. D_H is negatively affected by being non-environmental responsible, just like D_2. On the other hand, in a demand function of third-party, there is (ωz_{3p}), which is negatively affecting this demand.

High-pressure storage and flammability are two intrinsic hazards of hydrogen transportation that need strict safety precautions (Ali et al., 2024). The demand for hydrogen obtained via unsafe ways is greatly reduced by numerous occurrences, and customers are very sensitive to these dangers (Di Lullo et al., 2022).

z_{3p} is the number of incidents regarding the security of the trucks which lead to a halt in hydrogen transmission, and ω is the first company´s sensitivity to these security breaches. This is consistent with studies highlighting the importance of transportation reliability and its influence on customer confidence in supply chains.

4.2 Scenario 1

4.2.1 The profit functions

In this scenario, the first company produces hydrogen with power from theRP. Nonetheless, when problems arise in the RP, the company procures energy from a FP to maintain operations. As energy is conveyed over a grid, power loss transpires, prompting the company to invest in transmission security to mitigate this loss.

The profit functions of the first and second companies are outlined as follows.

The profit function of the first company comprises:

- Revenue generated from the sale of hydrogen to clients.
- Expenses associated with hydrogen production, including electricity prices and power loss expenditures.
- Government subsidies are obtained to uphold responsibility for the environment via the use of renewable energy.
- Investment in transmission security, which reduces power loss

The profit function of the second company comprises:

- Revenue generated from the sale of hydrogen to its clients.
- Expenses associated with power acquisition and hydrogen production.

Constraint explanation:

A key constraint guarantees that hydrogen production by RP is the favored and more economical option than FP's.

$$\begin{aligned}\pi_1^{SC1} = &(1-q)\,\alpha^{SC1}\left(p_1^{SC1} - C_P - fw_1\left(1-\lambda g^{SC1}\right)\right)D_1 - (1-q)\left(k(g^{SC1})^2 + k_0\right)\\ &+ q(1-\alpha^{SC1})\left(\left(p_1^{SC1} - fb_1 - C_p - fb_1 l(1-t)\right)D_1 - q\left(c_t t^2 + C_0\right)\right.\end{aligned} \tag{5}$$

$$\begin{aligned}&\text{s.t}\\ &fw_1\left(1-\lambda g^{SC1}\right) \le fb_1 + fb_1 l\,(1-t)\end{aligned}$$

$$\pi_2^{SC1} = \left(p_2^{SC1} - C_P - fw_2\right)D_2 \tag{6}$$

The profit function of the first company includes two main parts.

$$(1-q)\,\alpha^{SC1}(p_1^{SC1} - C_P - fw_1\left(1-\lambda g^{SC1}\right))\,D_1 - (1-q)\left(k(g^{SC1})^2 + k_0\right)$$

$$q(1-\alpha^{SC1})\left(p_1^{SC1}-fb_1-C_p-fb_1l(1-t)\right)D_1-q\left(c_tt^2+C_0\right)$$

The first part, as above, starts with $(1-q)$, representing the non-disruption mode. The $\alpha^{SC1}D_1$ is showing the portion of demand that is satisfied by the RP. The part of income $\left(p_1^{SC1}-C_P-fw_1\left(1-\lambda g^{SC1}\right)\right)$, includes the selling price (p_1^{SC1}), the cost of production and electrolyzer´s investment (C_P), and the government´s subsidy (λ) on the environmental responsibility level (g^{SC1}), which affects the cost of buying electricity from RP, $\left(fw_1\left(1-\lambda g^{SC1}\right)\right)$. Accordingly, f in fw_1, and all equations in this model are defined as the electricity needed by an electrolyzer to produce a kg of hydrogen. $(1-q)\left(k(g^{SC1})^2+k_0\right)$, The first company's investment cost in environmental responsibility is represented as a quadratic function (JamaliRasti-Barzoki and Altmann, 2023), which is only in non-disruption mode due to supplying from RP as an environmentally friendly source.

The second part, as above, starts with q, representing the disruption mode. The $\left(1-\alpha^{SC1}\right)D_1$ is showing the portion of demand that is satisfied by the FP. The part of income, $\left(p_1^{SC1}-fb_1-C_p-fb_1l(1-t)\right)$, includes the selling price (p_1^{SC1}), the electrolyzer´s cost of investment and production (C_P), the cost of buying electricity from FP (fb_1) and the cost of power loss $(fb_1l(1-t))$. The cost of power loss is one of the major costs in electricity transmission through the grid network, as explained in the scenario description section. It means that the amount of electricity sent by the FP is not equal to the amount that the company receives due to resistance, leakage, and corona discharge in transmission lines (Sadovskaia et al., 2019). Therefore, the company needs to pay more to receive the loss of electricity based on power loss level (fb_1l). In this regard, the company invests on security of transmission as a quadratic function $q\left(c_tt^2+C_0\right)$, to reduce the cost of powerloss as shown as fb_1lt.

The constraint is to show that the cost of the first company in disruption mode is higher than in non-disruption mode, making the supply from the RP more favorable and the first choice.

The profit function of the second company consists of only one part where The part of income $\left(p_2^{SC1}-C_P-fw_2\right)$, including the selling price (p_2^{SC1}), the electrolyzers cost of production and investment (C_P), and the cost of buying electricity from FP (fw_2), multipied by the demand of customers for hydrogen from the second company (D_2).

4.2.2 The optimal values

The optimal values of the decision variables in scenario one are gained using a simultaneous moving game solving approach (Nash equilibrium).

Game theory is a mathematical framework used to analyze decision-making in interactive (i.e., competitive) contexts. This research models corporations as actors making strategic choices about price, sourcing, and resilience. A Nash equilibrium in a game occurs when no player can enhance their result by altering their strategy, provided that the strategies of the other players stay unchanged.

This research employs a simultaneous moving game strategy due to the decentralized and competitive characteristics of the examined hydrogen supply chain scenarios.

This game type presupposes that all participants engage in simultaneous strategic decision-making, maximizing their results depending on the anticipated actions of others.

This approach corresponds with the competitive dynamics shown in our research, as businesses autonomously modify their tactics to optimize advantages in a common market context.

Moreover, a simultaneous moving game offers a computationally efficient method for examining strategic interactions, allowing us to concentrate on essential findings pertinent to our study.

The concavity of profit functions regarding the decision variables is investigated as Lemmas below.

- Lemma 1: The profit function of the first company exhibits concavity, respectively, in $p_1^{SC1}, g^{SC1}, \text{and} t$ as its own decision variables under the conditions presented in Appendix 1.
- Lemma 2: The profit function of the second company shows concavity in p_2^{SC1} as its own decision variable in Appendix 1.
- Proposition 1: The solving approach using K.K.T conditions is provided in Appendix 1.

The Karush-Kuhn-Tucker (KKT) method is a mathematical technique used to identify optimum solutions for constrained optimization problems. It assists in identifying optimal values for decision variables (such as pricing, demand, and investments) while guaranteeing compliance with every constraint (for instance, ensuring expenses do not surpass income and that demand is fulfilled).Due to the large number of outcomes, the optimal outcomes for the decision variables of both companies are provided in separate Appendix files.

4.3 Scenario 2

4.3.1 The profit functions

In this scenario, the first company addresses RP disruptions by acquiring hydrogen directly from the second company rather than generating it independently. Hydrogen is then transferred by a third-party logistics operator using specialist hydrogen vehicles, which need secure and regulated settings to guarantee safety.

The profit functions of the first, second, and third-party companies are as follows.

The first company's profit consists of:

- Income generated from the sale of hydrogen to clients.
- Expenses associated with acquiring hydrogen from the second company.
- Expenses incurred for delivery services provided by the third-party company.

The second company's profit consists of:

- Revenue generated from hydrogen sales to its own customers and the first company.
- Expenses associated with hydrogen production, including electricity and operating costs.

The third-party transporter's profit consists of:

- Revenue from hydrogen transportation fees paid by the first company.
- Expenses associated with security expenditures to guarantee secure delivery.
- Possible penalties or losses resulting from transportation failure.

Constraint explanation:

Constraints ensure that:

1. The second company generates sufficient more hydrogen to satisfy the first company's disrupted need.
2. The price at which the second company provides hydrogen to the first company is sufficiently profitable but competitively cheap.
3. The third-party transporter allocates resources to security procedures aimed at minimizing occurrences that may hinder hydrogen delivery

$$\begin{aligned}\pi_1^{SC2} =& (1-q)\,\alpha^{SC2}\left(p_1^{SC2} - C_P - fw_1^{SC2}\left(1-\lambda g^{SC2}\right)\right)D_1 - (1-q)\left(k\left(g^{SC2}\right)^2 + k_0\right)\\ &+ q(1-\alpha^{SC2})\left(p_1^{SC2} - p_3 - p_{3p}\right)D_1\end{aligned} \tag{7}$$

$$\begin{aligned}&S.T.\\ &p_1^{SC2} \geq p_3 + p_{3p}\end{aligned}$$

$$\pi_2^{SC2} = \left(p_2^{SC2} - C_P - fw_2^{SC2}\right)D_2 + q\left(p_3 - C_P - fb_2\right)D_H \tag{8}$$

$$\begin{aligned}&S.T.\\ &D_H \geq (1-\alpha^{SC2})D_2\end{aligned}$$

$$(p_3 - fb_2) \geq \left(p_2^{SC2} - fw_2^{SC2}\right)$$

$$\pi_{3p}^{SC2} = \left(p_{3p} - c_m\right)D_{3p} - \frac{c_s s^2}{2} - \varsigma z_{3p} \tag{9}$$

$$z_{3p} = n\,(1-s)$$

$$\begin{aligned}&S.T.\\ &D_{3p} \geq (1-\alpha^{SC2})D_2\end{aligned}$$

The profit function of the first company includes two main parts.

$$(1-q)\,\alpha^{SC2}\left(p_1^{SC2} - C_P - fw_1^{SC2}\left(1-\lambda g^{SC2}\right)\right)D_1 - (1-q)\left(k\left(g^{SC2}\right)^2 + k_0\right)$$

$$q\left(1-\alpha^{SC2}\right)\left(p_1^{SC2} - p_3 - p_{3p}\right)D_1$$

The first part in non-disruption mode is just like the first part of the first company´s profit function in scenario 1. Then, for brevity, we ignore repetitive explanations.

The second part, as above, starts with q, representing the disruption mode. The $\left(1-\alpha^{SC2}\right)D_1$ is showing the portion of demand that is satisfied by the FP. The part of the income, $\left(p_1^{SC2}-p_3-p_{3p}\right)$, includes two main costs as the price of hydrogen, which the first company buys from the second one (p_3), and the transmission cost (p_{3p}), in which the first company pays the third party to transfer the hydrogen bought from the second company.

The constraint guarantees that the selling price of the hydrogen to the customers by the first company in disruption mode is higher than its costs.

The profit function of the second company in this scenario includes two main parts, as shown below.

$$\left(p_2^{SC2}-C_P-fw_2^{SC2}\right)D_2$$

$$q\left(p_3-C_P-fb_2\right)D_H$$

The first part, as the second company´s income from selling the produced hydrogen to its own customers, is just like its profit in the first scenario with the same explanations.

The new part added to the second company´s profit function is the second part. This part is going to be added when there is a disruption in RP, as shown (q) at the beginning of the second part. In this situation, the first company asks for hydrogen from the second company (D_H), as a result $(p_3-C_P-fb_2)$ is the income of the second company from selling the hydrogen at a price of p_3 with production and investment cost (C_P), and the cost of buying electricity from FP (fb_2).

There are two constraints for the second company´s profit function. The first one, $D_H\geq(1-\alpha^{SC2})D_2$, shows that the hydrogen demand of the first company from the second one is equal to the demand that could not be satisfied due to the RP disruption. The second constraint, $(p_3-fb_2)\geq\left(p_2^{SC2}-fw_2^{SC2}\right)$, is to guarantee a higher profit for the second company when it sells the hydrogen to the first company than selling to its own customers.

The profit function of the third-party company consists of three parts. The first part $(p_{3p}-c_m)D_{3p}$, represent the profit it gains by transferring the hydrogen at the transfer price of p_{3p} and procurement cost of c_m. Due to the higher importance of the truck´s security in hydrogen transmission, the third-party company invests in the security of the trucks as part of two $\frac{c_s s^2}{2}$. Before explaining the third part, we need to explain $z_{3p}=n\left(1-s\right)$. Considering S as the security level of each truck, and n as the incidents that may happen to lead to unsuccessful hydrogen transmission by a truck like high combustibility, natural disaster, etc. (Ali et al., 2024), z_{3p} is the number of successful incidents that cause security/safety breaches leading to unsuccessful hydrogen transmission. The unsuccessfull hydrogen transmission by each truck makes costs to the third party, including loss of cargo, damage to the vehicle, repair or replacement cost, emergency response, etc., which is shown as the third part of the third-party´s profit function (ςz_{3p}). The constraint shows that the first company's hydrogen demand from the third party is equal to the demand that could not be satisfied due to the RP disruption.

4.3.2 The optimal values

Using a backward induction based on game theoretic principles (Aumann, 2019), the optimal values of the decision variables in scenario two are gained in two phases. In the first phase, the optimal values of the third-party´s decision variables are gained after proving the concavity and convexity of the profit function and constraint, respectively, as shown in the lemma below.

•Lemma 3: The profit function of the third-party company exhibits concavity in $p_{3p}, \text{and} s$ as its own decision variables presented in Appendix 1.

In the second phase, After replacing the optimal values of the third-party´s decision variables in the profit functions of the first and second companies. The concavity of profit functions of both companies is investigated. By using a simultaneous moving game between two companies, the optimal values are derived.

- Lemma 4: In terms of p_1^{SC2}, and g^{SC2}, the profit function of the first company shows concavity under conditions provided in Appendix 1.
- Lemma 5: The profit function of the second company shows concavity in p_2^{SC2}, and p_3 decision variable under conditions provided in Appendix 1.
- Proposition 2: The solving approach using K.K.T conditions for each phase are provided in Appendix 1. Due to the large amount of outcomes, the optimal outcomes for the decision variables of both companies are provided as separate Appendix files.

In scenario 1, equilibrium results demonstrate how firms adjust to variable energy supplies and prices from fossil fuel power plants, sustaining hydrogen production while optimizing cost-efficiency and environmental sustainability. Scenario 2 emphasizes the significance of external hydrogen acquisitions and decentralized production options in maintaining supply continuity while addressing hydrogen transmission security concerns. The following section on sensitivity analysis illustrates how fluctuations in critical decision factors, including price and operational modifications, affect resilience and other measures.

5 Analysis and managerial insights

We initially introduce an exemplary set of parametric values inspired by real-world cases or same studies (Table 3). For instance, the cost of production and investment (CAPEX) by a PEM electrolyzer (c_p) is considered 2000 MU /kW based on Shiva Kumar and Himabindu (2019), the amount of electricity needed to produce 1 kg of hydrogen by the PEM electrolyzer (*f*) is considered 57 kWh (Lundberg, 2019), or the power loss percentage (L) is considered 1% which is consistent with data related to Germany grid network (Zweifel et al., 2017).

Based on real-world trends, we assume renewable electricity (w_1^j) to have lower prices due to subsidies and lower operational costs, while fossil fuel electricity is priced higher (w_2^j, b_1, b_2), reflecting generation and emission costs. These assumptions align with examples from EuropeanUnion (2023), IRENA (2023).

Table 3 The values of initial test parameters

Parameter	Value	Parameter	Value
a_i	1000 (kg of H_2)	k_0	1000 (MU)
α^j	0.5	k	3000 (MU)
β	0.05	c_0	1000 (MU)
γ	0.01	c_t	3000 (MU)
ω	0.09	w_1^j	15 (MU /kWh)
φ	0.09	w_2^j	20 (MU /kWh)
τ	0.03	b_1	30 (MU /kWh)
μ	0.01	b_2	35 (MU /kWh)
λ	0.015	c_m	5 (MU /kg)
θ	0.01	ς	1000 (MU /kW)
f	57 (kWh)	n	3
L	0.01	c_s	5000 (MU /kg)
q	0.5	c_p	2000 (ACU/kg)

The parameters a_i market base demand), β (own price elasticity), γ (rival price elasticity), are widely used in renewable energy pricing models to capture market dynamics and customer preferences. The values of these parameters are inspired by studies such as Rajabzadeh and Babazadeh (2022), which explore demand sensitivities and competitive interactions in energy markets.The parameters μ (sensitivity to environmental responsibility), λ (subsidy coefficient), k (investment cost factor for environmental responsibility), and k_0 (fixed investment cost for environmental responsibility) are inspired by studies such as JamaliRasti-Barzoki and Altmann (2023) which analyze market dynamics, customer preferences, and policy impacts in renewable energy.

In whole analyses, it is assumed that the value of α^j (the portion of demand satisfied through RP) equals to 1-q. This is in line with results gained by KumarBasu and Avittathur (2018).

Then, based on the initial data set from Table 3, a sensitivity analysis is conducted to investigate outcomes and insights from various managerial and organizational parameters and their relationships to decision variables and functions. In the end, some managerial insights are provided. All costs are presented in Monetary Units (MU) to allow for general comparison, independent of specific currency effects.

5.1 Sensitivity analysis

5.1.1 Resilience

In the two resiliency scenarios studied in this paper, it seems that company one always has resiliency options to satisfy the unsatisfied demand due to the disruption in RP. In this analysis, we are going to investigate how true this assumption is. In detail, for each scenario in the first place, we have calculated the whole demand when there is no disruption as the maximum demand for company 1. Then, we studied how the overall demand from the first company changes with a change in disruption probability. Finally, we have shown how much of this changed or unchanged demand is satisfied by the resilience options in both scenarios. In other words, how resilient are these two studied scenarios?

In Fig. 4a and b, the gold line shows the maximum customer demand of the first company (D_1) when there is no disruption, which is the optimum demand. The redline shows the change in overall customer demand of the first company (D_1) with a change in disruption probability. The green line represents how much of the total demand changed due to the changes in disruption probability could be satisfied by resilience strategies in each scenario $\left(\left(1-\alpha^j\right) D_1\right)$.

As can be seen from Fig. 4a and b, the overall demand that could be satisfied by the first company in both scenarios when there is no disruption is around 500 kg.

In both scenarios, the rise in q drops the overall demand, which in the second scenario is far sharper than in the first one (redline). In the first scenario, where ithe demand is around 500 kg in the beginning there is a small demand loss around 25 kg when disruption reaches 100%, leaving demand at around 475kg. At the same time, this change is significant in scenario two, where the first company supplies hydrogen from the second company. In this scenario, the demand of 500 kg at the beginning drops sharply to 50 kg at $q = 1$ with 450 kg demand loss. First of all, both redlines show that despite resiliency options for the first company, there is demand loss, and the full demand does not remain. The drop in overall demand in both scenarios due to the rise in q comes from different general and scenario-specific reasons for both scenarios. These evidences are including higher resiliency costs and low greenness level compared to the condition when there is no disruption as general reasons.The competitive environment of both companies in scenario two is the scenario-specific reason which all affects the demand through the rise in final price and drop in environmentally friendly customers due to the lower environmentally responsibility level as illustrated in Fig. 5a and b.

The main reasons for the huge difference between the demand loss in both scenarios could be found in scenario-specific differences that indirectly affect the demand from the first company through the selling price and greenness changes in each scenario, as shown in the figure above. The first difference could be the cost of resilience (Explored in the next analysis). In the first scenario, the first company's costs on resiliency (buying electricity, production cost, and power loss and security) are lower than in scenario two, where it buys the hydrogen from company two, which is the profit maximizer and pays to the third-party for transferring. The second reason could be that the decision variables over which the first company has no control, like the hydrogen price of the second company or the transfer price

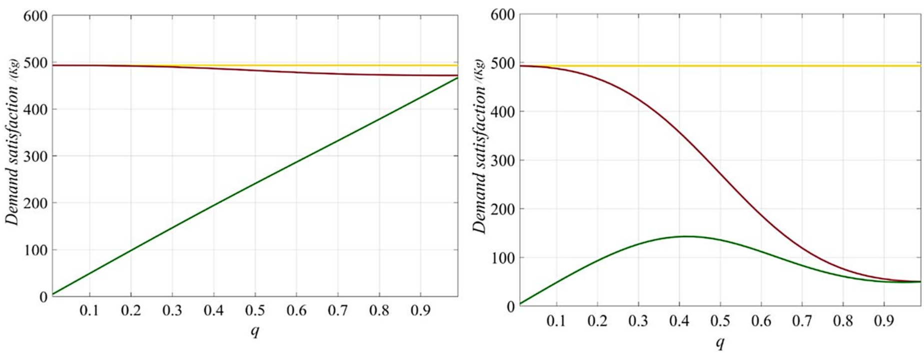


Fig. 4 **a** The resiliency of the 1st scenario. **b** The resiliency of the 2nd scenario

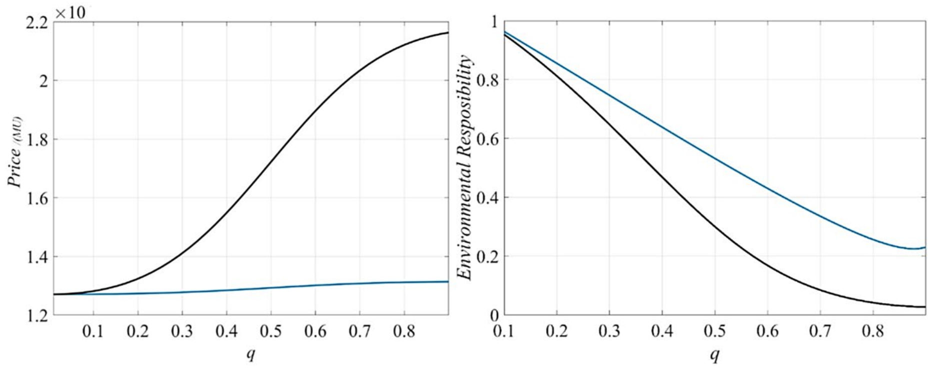


Fig. 5 **a** Change in p_i^j of the 1st and the 2nd companies with change in q. **b** The changes in g^j the 1st and the 2nd companies with change in q

of the third-party company, determined these differentiations in the second scenario. The third reason could be the competitive environment of the two companies. The last one could be derived based on the equations below:

$$\frac{d\pi_1^{SC1}}{dg^{SC1}} = (1-q)\,\alpha^{SC1} f w_1 \lambda D_1 + (1-q)\,\alpha^{SC1}\left(p_1^{SC1} - C_P - f w_1\left(1-\lambda g^{SC1}\right)\right)\mu + q(1-\alpha^{SC1})\left(p_1^{SC1} - f b_1 - C_p - f b_1 l(1-t)\right)\mu - 2\,(1-q)\left(k g^{SC1}\right) > 0$$

$$\frac{d\pi_1^{SC2}}{dg^{SC2}} = (1-q)\,\alpha^{SC2} f w_1 \lambda D_1 + (1-q)\,\alpha^{SC2}\left(p_1^{SC2} - C_P - f w_1\left(1-\lambda g^{SC2}\right)\right)\mu + q(1-\alpha^{SC2})\left(p_1^{SC2} - p_3 - p_{3p}\right)\mu - 2\,(1-q)\left(k g^{SC2}\right) > 0$$

As can be seen from the equations above, the first derivative of the first company's objective function in both scenarios regarding the environmental responsibility level (g^j) is positive, showing that a rise in g^j increases profit. Firstly, as the result of its role as a demand attractor and secondly because of the subsidy (λ) the government grants for environmentally friendly practices. On the other hand, based on Fig. 5b, the rise in q leads to a drop of g^j. This means that the profit of the first company declines due to a drop in demand from environmentally friendly customers and also due to a lower government subsidy. Therefore, the drop in the environmental responsibility is not only directly affected by demand. The indirect way lies in a drop of profits due to the lower subsidy, which urges the first company to increase the price that exerts a second pressure on demand as explained above.

We should not forget that these two companies, along with collaboration, have competition on prices, making the second company always have a lower price advantage, which not only raises the price of the first company but also attracts the first company´s customers as well. All the above-mentioned reasons directly affect the selling price of the first company´s hydrogen in different scenarios (sharp increase in price in scenario two (black line) than scenario one (blue line)) and the environmental responsibility level (significant drop in scenario two (black line) than scenario one,(blue line)) as Fig. 5a and b, respectively regarding their role in demand based on Eq.1. Besides, based on the first order condiotion of the first company in both scenarios regarding the envorinmental responsibility level, it has shown that the drop in the environmentally responsibility level directly affects the demand and price due to drop in subsidy level.

The green line in both scenarios in Fig. 4a and b represents how resilient these two scenarios. In the first scenario, along with increasing the satisfied demand through the electricity supply from FP, with a rise in q, there is a linear correlation between the satisfied demand through the resilience option and disruption probability in a way that, for example, when $q = 0.5$ almost 50% of the demand (around 240kg) is satisfied by the electricity supplied from FP. In the end, when there is a full disruption in RP, the company can satisfy the whole demand with only around a 25kg drop compared to no disruption mode, with the electricity supplied from FP. The main reason for the higher resiliency of the first scenario could be fined in general and scenario-specific reasons mentioned above, where leading to the lowest price and environmental responsibility level change with increasing q as shown in Fig. 5a and b. With a simple calculation considering the 500 kg demand as the maximum when there is no disruption and the satisfied demand of almost 475 kg when disruption is 100%, it can be concluded that this scenario is 95% resilient.

In the second scenario, from the beginning till q reaches around 0.45, the rise in disruption gives rise to higher supply from the second company (green line). But from $q = 0.45$ onwards a drop in overall demand, the hydrogen supply also drops. Although the supply from the second company drops after $q = 0.45$, resiliency (the gap between the red and green lines) decreases due to the sharper drop in overall demand.

The main reason why the supply from the second company drops at around $q = 0.45\mathrm{on}$ would be due to the fact that the first company sees the drop in overall demand with increasing disruption and the rise in hydrogen supply cost from the second company due to all the above-mentioned costs related to this scenario, and in terms of preventing more profit loss and demand loss it drops the supply from the second company. In the end, by considering the ideal demand as 500kg and those satisfied at maximum disruption probability (around 50), it can be calculated that this scenario is 10% resilient.

Managerial insights:

The assessment of resilience in hydrogen supply chains underscores the strategic superiority of scenario 1, whereby procuring energy from a Fossil Power Plant (FP) during disruptions guarantees enhanced dependability and improved demand satisfaction. Conversely, scenario 2 (acquisition of hydrogen from a secondary supplier) demonstrates diminished resilience owing to external coordination challenges and elevated logistical expenses.

- **Investment Decision:** Supply chain managers need to invest in robust energy infrastructure to diminish dependence on external providers and alleviate disruptions. Investments in green energy may also support government subsidies and maintain consumer demand.
- **Policy Advocacy:** Policymakers have to promote grid security and energy storage options while optimizing subsidy frameworks to ensure companies retain environmental incentives during disruptions.
- **Operational Adjustment:** Fortifying supplier alliances and diversifying energy sources may augment flexibility, assuring production consistency and mitigating demand loss attributable to price volatility.

5.1.2 Cost of resilience

The previous analysis has shown that the first scenario has higher resiliency. But how much do the two resilience options cost for the first company? In other words, which of the resilience scenarios is profitable for the first company? In this regard, the resiliency cost of the first company for the two scenarios is derived based on profit functions 5 and 7, for scenarios 1 and 2, respectively, as below.

$$C^{sc1} = q\left(1-\alpha^{SC1}\right)\left(C_p + fb_1 + fb_1 l\left(1-t^*\right)\right)D_1 + q\left(c_t t^{*2} + C_0\right)$$

$$C^{sc2} = q\left(1-\alpha^{SC2}\right)\left(p_3^* + p_{3p}^*\right)D_1$$

The first part of C^{sc1}, $q\left(1-\alpha^{SC1}\right)C_pD_1$, represents the cost of hydrogen production by PEM electrolyzer to satisfy the demand. The second part, $q\left(1-\alpha^{SC1}\right)fb_1D_1$, represents the buying cost of electricity from the FP. The third part, $q\left(1-\alpha^{SC1}\right)\left(fb_1 l\left(1-t^*\right)\right)D_1$, shows the cost of power loss during electricity transmission and the effect of transmission security on power loss. The last part, $q\left(c_t t^{*2} + C_0\right)$, represents the variable and fixed costs as investments in the security of transmission.

C^{sc2}, related to the cost of the second resilience scenario, has only two parts. The first one, $q\left(1-\alpha^{SC2}\right)\left(p_3^*\right)D_1$, is the cost of buying hydrogen from the second company, and the second one, $q\left(1-\alpha^{SC2}\right)\left(p_{3p}^*\right)D_1$, relates to the cost of hydrogen transmission from the second company to the first one by the third party.

In the first place, Fig. 6 shows the increase in resilience costs for two scenarios (blue line and red line for scenario 1 and 2, respectively) by increasing the disruption probability, which is sensible since the rise in q increases the dependency of the first company on FP and the second company in scenarios 1 and 2, respectively. The findings show that the resilience cost in scenario two (red line), even at lower values of q where the satisfied demand through both scenarios is almost equal, is far higher than in scenario one.

The interesting point is that at around $q = 0.55$ the cost of resilience in scenario 2, with only 125kg hydrogen demand satisfaction (Fig. 4b) is equal to scenario one at $q = 0.9$ with 250kg demand satisfaction (Fig. 4a). This shows that, even if the second scenario has the same resiliency as scenario one, it would have far higher resiliency costs. It is worth men-

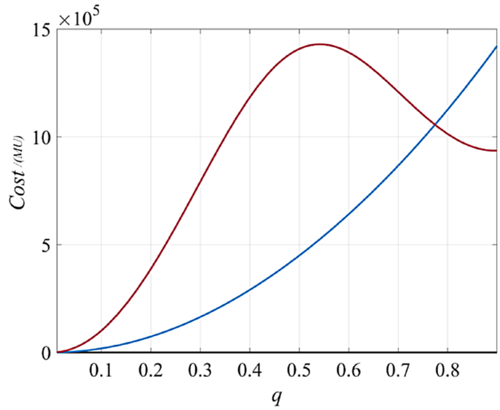


Fig. 6 The resilience cost of two scenarios in various q.

tioning that the drop in resilience cost of the second scenario is based on the drop in demand from the second company, as explained in the first section of the analysis (Resilience).

There are a number of reasons why the resilience cost in scenario 2 is higher. The main reason is that the cost of electricity supply from FP and hydrogen production in scenario 1 is less than buying hydrogen from the second company. This is because the second company sets a higher selling price, along with buying electricity from the same source at a higher price and producing the hydrogen (hydrogen production cost) to guarantee its profit. The second reason is the competition between these two companies. The competitive dynamics affect the hydrogen price that the second company sells to the first. This makes the first company to set a higher price. Another reason is the transmission cost, in which the first company must pay to the third party, making its expenditure on resiliency too much compared to the first resilience scenario where the electricity transmission compared to hydrogen transmission cost is negligible.

5.1.2.1 Resilience costs components In terms of a deeper analysis of costs related to resilience, in the second phase of this sensitivity analysis, we have investigated the costs for each resilience scenario separately.

As presented in C^{sc1}, the resilience cost in scenario one includes three main different costs.

1. Cost of hydrogen production:

$$q\left(1-\alpha^{SC1}\right)\left(C_p\right)D_1+q\left(c_t t^{*2}+C_0\right)$$

2. Purchase cost of electricity from fossil fuel sources:

$$q\left(1-\alpha^{SC1}\right)\left(fb_1\right)D_1+q\left(c_t t^{*2}+C_0\right)$$

3. And the cost of electricity transmission, power loss, and security:
4. $q\left(1-\alpha^{SC1}\right)\left(fb_1 l\left(1-t^*\right)\right)D_1+q\left(c_t t^{*2}+C_0\right).$

Which is shown in Fig. 7a as orange, green, and yellow lines, respectively. As C^{sc2} in the second scenario, the resilience cost of the first company encompasses two components.

1. Purchase cost of hydrogen from the second company

$$q\left(1-\alpha^{SC2}\right)\left(p_3^*\right)D_1$$

2. Transmission cost of hydrogen by third-party

$$q\left(1-\alpha^{SC2}\right)\left(p_{3p}^*\right)D_1$$

Which is demonstrated in Fig. 7b as blue and black lines, respectively. The red line in both Figs is the overall costs of resilience in both scenarios, just as shown in Fig. 6.

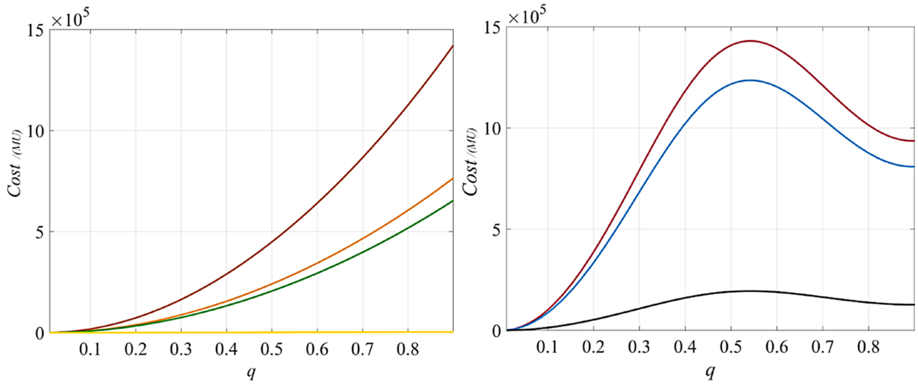


Fig. 7 **a** Resilience cost components of first scenario. **b** Resilience cost components of second scenario

From Fig. 7a, it can be understood that the major resilience cost in scenario 1 is the cost of production, leaving the electricity purchase cost with a minimal difference in the second place. The production cost is high because the PEM electrolyzer has the highest production and maintenance cost (Vincent & Bessarabov, 2018), compared to other electrolyzers.

The cost of electricity purchase is high as well, since to produce a kg of hydrogen by PEM electrolyzer; there is a need for 57 kw/h electricity. The lowest cost is related to the cost of power loss and the security of electricity transmission. This is the lowest cost since only a small percentage of electricity loss happens (in our study, 1%). Therefore, the investment in security is not that much.

In the second scenario, the major cost is the hydrogen purchase cost due to the first and the second reasons explained for the higher resilience cost of the second scenario in Fig. 7b explanation. Meanwhile, the hydrogen transmission cost has less impact on the resilience cost of the second scenario.

Managerial Insights:

This analzye demonstrates that procuring power from FP during disruptions is not only more resilient but also more economical than acquiring hydrogen externally.

- **Investment Decision:** Managers must assess cost structures while choosing electrolyzer technology. For example, transitioning from PEM electrolyzers (2000 MU/kg) to Alkaline electrolyzers (800 MU/kg) (Vincent & Bessarabov, 2018) may decrease production costs while preserving high hydrogen purity (99.97%).
- **Policy Advocacy:** Governments need to endorse investments in cost-effective electrolyzer technology by providing subsidies for more economical and scalable hydrogen generation techniques.
- **Operational Adjustment:** Companies should implement real-time cost monitoring to dynamically modify power sourcing and hydrogen procurement in response to price variations, therefore maintaining an ideal equilibrium between cost and resilience.

5.1.3 Sustainability

In this analysis, both scenarios' sustainability is investigated in terms of CO_2 emission levels regarding resilience-related activities with a rise in disruption probability. For the first and second scenarios, the resilience activities emitting CO_2 are considered as below:

$$S^1 = \left(f\left(1-\alpha^1\right)\left(1+l\left(1-t\right)\right)D_1 * \left(\begin{array}{c} CO_2 emmission by FP per \\ kwhelectricity production \end{array}\right)\right)$$

$$S^2 = f\left(1-\alpha^2\right)D_1 * \left(\begin{array}{c} CO_2 emmission\ by\ FP\ per \\ kwhelectricity\ production \end{array}\right) + \frac{\left(1-\alpha^2\right)D_1}{Truck\ capacity} * \left(CO_2 emmission\ by\ Truck\ per\ km\right) * \left(1st\ and\ 2nd\ company\ dis\tan ce\left(km\right)\right)$$

For the first scenario, the only resilient activity is considered to be FP's electricity production based on the required demand and power loss.

For the second scenario, two parts of resilience activities are considered that emit CO_2. The first part is the required electricity from FP to produce hydrogen by the second company, and the second part represents the CO_2 emissions by transferring trucks based on the distance between the companies.

For this analysis, we have tried to use values based on real-world examples. We have considered two hydrogen filling stations from H2Mobility in Germany as our company 1 and 2 (H2, 2024). The station located in Neuruppin is considered as the first company (H2, 2024b), and that located in Berlin– Heer Street as the second company (H2, 2024b), assuming each of which, uses the same electrolyzers. The distance between these two stations is around 72km (GoogleMap, 2024).

The station located in Berlin is assumed to use electricity generated by the Berlin-Klingenberg Power Plant, the largest power plant in Berlin that burns coal (Wikipedia, 2018). It is assumed that for 1 kWh of electricity generation by the coal-based powerplant, an amount of around 1kg CO_2 is emitted (EIA, 2022). Just like the study by Di Lullo et al. (2022) for hydrogen transmission, Conventional diesel trucks typically drive at an average speed of 65 km/h, consume fuel at a rate of 39.2 L/100 km, and have a capacity of approximately 380 kg (Energy, 2024). Each Diesel motor emits around 1.5-2.5 kg CO_2 per Liter, depending on the size of the vehicle (Commission, 2021).

Based on the provided information, the CO2 emission of each scenario is gained, as shown in Fig. 8.

The brown line shows the CO_2 emission of the first scenario with increasing q. It can be seen that with increasing demand from FP, the CO_2 emission increases as well since the FP emits more CO_2 with increasing electricity production. In the end, when there is full disruption, the CO_2 emission reaches around 22,000 kg to satisfy around 475 kg of hydrogen (Based on the satisfied demand gained in the first analysis). In other words, each kg of hydrogen satisfied through the first scenario resilience emits around 46 kg CO_2.

On the other hand, the blue line illustrates the CO_2 using the second scenario resilience option. Based on the Fig. 8, the CO_2 emission increases with a rise in q. But around $q = 0.5$ it drops gradually to stop at around 300 kg CO_2 emission when there is full disruption. The main reason why it drops at $q = 0.5$ is due to the demand drop explained in the first analyse (Resilience section). Since the demand drop in scenario two is sharper than in scenario one,

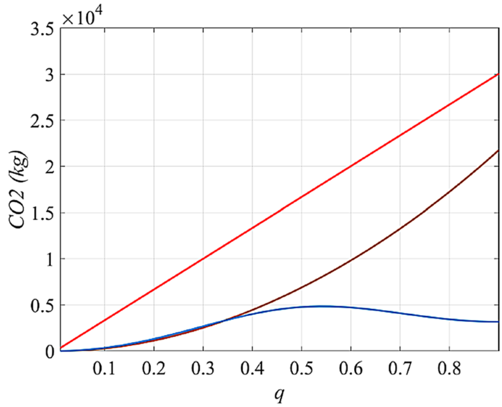


Fig. 8 The relation between CO_2 emission and q

as shown in the first analyse, it cannot be concluded that the second scenario is more sustainable than the first one due to less CO_2 emission. In other words, in the same q the satisfied demand in scenario one is far more than in scenario two due to a drop in demand. Then, less demand will lead to less CO_2 emission, making these two scenarios uncomparable in terms of sustainability.

In this regard, we have assumed that in the second scenario, the satisfied demand, $\left(1-\alpha^2\right)D_1,$ is equal to 475 kg of hydrogen, just as in the first scenario to compare CO_2 emissions in a fair environment, and it has shown as the red line in Fig. 8. Based on this line, if the second scenario can satisfy the demand as the amount the firs scenario can, when there is a full disruption, it emits around 30,000 kg CO_2. This amount is 8,000 kg more than in the first scenario. It is worth mentioning that when using electricity from coal fired powerplants, the overall emission level is higher than in the case of direct production of hydrogen from fossil fuels through steam methane reforming or coal gasification.

It can be concluded that, even if the second scenario is as resilient as the first one, it is less sustainable by emitting around 63 kg CO_2 per kg of hydrogen demand satisfaction compared to the first scenario with 46 kg CO_2 emission.

The main reason for this difference is the hydrogen transfer method since the powerplant, and the amount of electricity needed to produce hydrogen in both companies are the same.

Managerial Insights:

This analysis highlights the need for cohesive environmental planning, prompting managers to reconcile cost-effectiveness with environmental sustainability.

- **Investment Decision:** Managers need to include renewable energy sources into their resilience strategy to reduce emissions while ensuring cost-effectiveness.
- **Policy Advocacy:** Policymakers have to establish carbon pricing strategies and green energy incentives to promote low-emission hydrogen generation.
- **Operational Adjustment:** Investing in energy-efficient electrolyzers, streamlined logistics, and carbon footprint monitoring may improve resilience and sustainability, integrating long-term strategic objectives with environmental obligations.

5.1.4 Transmission Security

In this study along with investigating the hydrogen supply chain resilience, the resilience of transmission security is taken into account as well. In this analyse we have explored how responsible firms for transferring electricity in scenario 1 and hydrogen in scenario 2 are resilient against incidents in various disruption probabilities. In other words, how their investment in security in both scenarios made them resilient.

In this regard, as we defined before, the first company is responsible for the security of the electricity transmission grid network (t) against power loss as incidents, which is denoted as level (L). On the other hand, the third-party company in scenario two has this responsibility (s) against various incidents, which is denoted as number (n), may happen to the hydrogen-transferring trucks.

In this analysis, the simultaneous effect of the rise in disruption probability (q), and the change in the level of power loss (L) in scenario one and the number of incidents that may halt hydrogen trucks (n) in scenario two, on the security levels of each scenario, $t and s$, respectively, is investigated as below. It must be noted that the power loss level is considered 0.01–0.21 as the lower and higher percentages exist in the real-world (World, 2020).

As shown in Fig. 9 in the first scenario, the rise in q and L solely gives rise to an increase in t. at lower values of q, the rise in L makes the first company increase the security less due to the fact that at lower q, the supply from FP is low. At lower values of L, the rise in q increases the security level, but again, not so much since the grid network has less power loss level to need to improve. At higher values of both q and L, the rise in each increases the security sharply. This is because when q is high, it means that the first company needs much electricity through this grid network, and higher L means a higher level of power loss; therefore, the first company invests much in the security to have safer electricity transmission with a low level of power loss which increases the security level. This is why when the L reaches 21% and q is around 100%, the security is at its maximum level.

For the second scenario, where the third-party company is responsible for the hydrogen transmission, as shown in Fig. 10 the rise in q has no effect on s. This is because it does not matter how much hydrogen is needed to be transferred; the trucks all have a minimum safety or security level, around 20% based on Fig. 10, which is dependent on n than the volume of needed hydrogen in various q. In other words, all trucks with a specific level of s, mostly

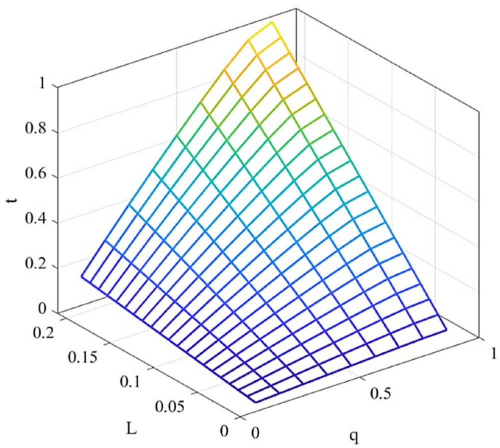
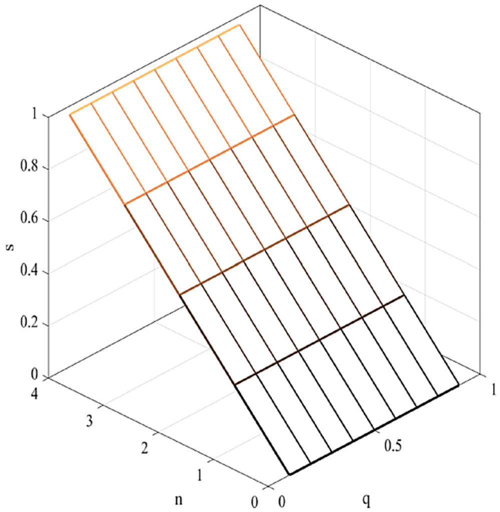


Fig. 9 The effect of q and l on t

Fig. 10 The effect of q and n on s



in terms of combustion, are prepared for the normal situation, and the number of incidents and their effect in severe situations like natural disasters affect the s. This is sensible due to the fact that the route, geographical, and weather situations, along with other factors, are more determinative in hydrogen transmission by a truck than the volume of the hydrogen. As a result, the rise in n makes the third-party company to invest more in security and be resilient against these incidents. Furthermore this action is sensible in terms of the profit which third-party gains through safe transmission of hydrogen and the cost function for any defects (ςz_{3p}).This may raise the question of why the rise in q in scenario one increases the t while in scenario two, it has no effect on s. This is because, at even a secure grid network, there is at least 1% power loss because of resistance, leakage, and corona discharge, which increases at higher electricity transmission volume.

Managerial insights

This analyse highlights the need of substantial security expenditures to strengthen supply chain resilience.

- **Investment Decision:** Supply chain managers must prioritize investments in physical infrastructure, intelligent monitoring systems, and cybersecurity to reduce risks associated with power outages and transportation interruptions.
- **Policy Advocacy:** Governments need to provide risk assessment frameworks and subsidy initiatives for companies adopting hydrogen transport security protocols.
- **Operational Adjustment:** Companies must use adaptive security measures, invest in cutting-edge transportation technology, and educate staff to effectively react to changing risk situations, therefore assuring continuous hydrogen supply chain operations.

6 Conclusion

This paper has thoroughly evaluated the reliability of resilience strategies based on factors including resilience level, the cost of resiliency, and the sustainability of each resilience strategy in hydrogen supply chains under two primary disruption scenarios. The model considers a situation where a hydrogen production company relies on a Renewable Power plant (RP) for electricity. When disruptions occur at the RP, the company can choose between two resilience strategies:

1- Sourcing electricity from a fossil power plant (FP) of the second company to continue hydrogen production as scenario 1.
2- Purchasing hydrogen directly from a second company and utilizing third-party transportation for delivery, as the second scenario.

By employing a game theoretic approach, we analyzed the impacts of these strategies on demand satisfaction, cost implications, and environmental sustainability. Then we have investigated the security resilience transmission methods in each scenario. Our findings indicate that, in the case of supply disruptions, sourcing electricity from the FP is more reliable, cost-effective, and environmentally sustainable than the alternative strategy of purchasing hydrogen from the second company. Specifically, the FP sourcing strategy maintains higher resiliency, ensuring a more stable supply chain with minimal loss in customer demand even under high disruption probabilities. This strategy incurs lower overall costs due to more manageable production and transmission expenses and fewer dependencies on external suppliers and logistics.

Moreover, sourcing electricity from the FP results in lower CO_2 emissions per unit of hydrogen compared to the second scenario, primarily due to the reduced need for third-party transportation, which adds significant emissions. The FP sourcing strategy effectively meets demand even in disruption conditions, whereas purchasing hydrogen from the second company suffers significant demand loss under similar conditions. Additionally, sourcing electricity from the FP gives the first company more control over critical variables such as electricity prices and transmission security investments, enhancing overall supply chain robustness.

Furthermore, it has shown that in contrast to electricity transmission security, which is affected by both disruption likelihood and powerloss degree, hydrogen transmission security is mostly sensitive to the incidents that may happen to the trucks rather than the volume of the hydrogen needed from the second company by the first one which varies with disruption probability

6.1 Potential applications of this model

- **Supply Chain Optimization for Energy Companies:** Energy firms can utilize this model to enhance their supply chain strategies by evaluating the reliability and cost-efficiency of various resilience options, such as obtaining electricity from different power plants or procuring hydrogen from external sources.
- **Disruption Management for Hydrogen Production:** Hydrogen production firms

can utilize this concept to create resilient plans for managing disruptions effectively. Through the assessment of probable disruptions in renewable energy sources, analysts may ascertain the most effective techniques to ensure a steady supply of hydrogen and fulfill customer demand.

- **Environmental Impact Assessment:** Environmental regulators and policymakers can employ this model to evaluate the environmental consequences of various hydrogen supply chain strategies. Through the comparison of CO_2 emissions and other environmental criteria, it is possible to encourage the adoption of sustainable practices within the hydrogen energy sector.
- **Investment Decision Support:** Investors and stakeholders in the energy sector can utilize this model to make well-informed investment decisions. Through the examination of the financial consequences and long-term viability of different solutions to enhance the resilience of the supply chain, organizations can allocate resources in a more efficient manner and prioritize projects that are more dependable and have a reduced environmental footprint.

6.2 Guide for future research

Future research on hydrogen supply chains needs to apply a comprehensive strategy that includes technological, economic, and policy dimensions to improve resilience and efficiency. Investigating electrolyzer technologies, such as Alkaline, Solid Oxide, and Anion Exchange Membrane electrolyzers, will yield insights into techno-economical and dependable hydrogen production techniques. Furthermore, the integration of machine learning-driven predictive analytics and stochastic modeling might facilitate the anticipation and mitigation of disturbances, hence maintaining supply chain stability. An extensive assessment of hydrogen transport techniques, including pipelines, compressed gas trailers, and liquid hydrogen tankers, will help clarify the most efficient and sustainable alternatives. Incorporating game-theoretic techniques, vertical integration, and cooperative supply chains into the discussion on market structures eventually provides strategic improvements with respect to resource allocation and resilience. Analyzing collaborative supply chain models devoid of competition may uncover benefits in cost minimization, demand satisfaction, and overall stability. Enhancing the policy framework through the examination of strategic reserves, hydrogen certification, carbon pricing, and governmental incentives will foster a conducive regulatory environment. Future research must concentrate on the integration of hydrogen with renewable energy, smart grids, and decentralized production centers to improve flexibility and efficiency. Creating advanced optimization models that consider changing market dynamics, variable customer demand, and unexpected interruptions can furnish supply chain managers with effective decision-making tools. A comprehensive approach that integrates technological innovations, economic strategies, and governmental measures will provide a robust and sustainable hydrogen supply chain.

Appendix

Lemma 1 *The profit function of the first company exhibits concavity, respectively, in* p_1^{SC1}, g^{SC1}, $andt$ *as its own decision variables under the conditions.*

Proof The profit function of the first company in the first scenario, denoted as(π_1^{SC1}), exhibits concavity in the variables p_1^{SC1}, t, andg^{SC1}. The Hessian matrix of π_1^{SC1} with respect to these variables is as follows:

$$H_{\pi_1^{SC1}(p_1^{SC2},g^{SC1})} = \begin{vmatrix} -2(1-q)\alpha^{SC1}\beta - 2q\left(1-\alpha^{SC1}\right)\beta & (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu & -q(1-\alpha^{SC1})fb_1 l\beta \\ (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu & 2\,(1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\mu - 2\,(1-q)\,k & q(1-\alpha^{SC1})fb_1 l\mu \\ -q(1-\alpha^{SC1})fb_1 l\beta & 2(1-q)\alpha^{SC1} fb_1 l\mu & -2qc_t \end{vmatrix} < 0 \tag{A.1}$$

Since $\left|-2(1-q)\alpha^{SC1}\beta - 2q(1-\alpha^{SC1})\beta\right| < 0$, the following two determinants must be in positive and negative, respectively

$$\begin{vmatrix} -2(1-q)\alpha^{SC1}\beta - 2q\left(1-\alpha^{SC1}\right)\beta & (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_2\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu \\ (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_2\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu & 2\,(1-q)\,\alpha^{SC1} fw_2\lambda\mu - 2\,(1-q)\,k \end{vmatrix} > 0,$$

$$\begin{vmatrix} -2(1-q)\alpha^{SC1}\beta - 2q\left(1-\alpha^{SC1}\right)\beta & (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu & -q\left(1-\alpha^{SC1}\right) fb_1 l\beta \\ (1-q)\,\alpha^{SC1}\mu - (1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\beta + q\left(1-\alpha^{SC1}\right)\mu & 2\,(1-q)\,\alpha^{SC1} fw_1^{SC1}\lambda\mu - 2\,(1-q)\,k & q\left(1-\alpha^{SC1}\right) fb_1 l\mu \\ -q\left(1-\alpha^{SC1}\right) fb_1 l\beta & 2\,(1-q)\,\alpha^{SC1} fb_1 l\mu & -2qc_t \end{vmatrix} < 0$$

In terms of constraint:
Let $s^{sc1} = fw_1\left(1-\lambda g^{SC1}\right) - \left(fb_1 + fb_1 l\,(1-t)\right)$.
Where, $s^{sc1} \geq 0$.
We find that g^{sc1} is convex.

Lemma 2 *The profit function of the second company shows concavity in p_2^{SC1} as its own decision variable.*

Proof The profit function of the second company in the first scenario (π_2^{SC1}) also shows concavity in p_2^{SC1}. Accordingly, the hessian of the second profit function in p_2^{SC1} is as follows.

$$H_{\pi_2^{SC1}(p_2^{SC1})} = [-2\beta] \tag{A.2}$$

Since $|-2\beta| < 0$, the profit function of π_2^{SC1} hessian shows its concavity.

Proposition 1 *The solving approach using K.K.T conditions is provided below. Due to the large amount of outcomes, the optimal outcomes for the decision variables of both companies are provided as separate Appendix files available upon your request.*

The K.K.T. conditions for first company´s profit function in first scenario are as follows:

$$\nabla \pi_1^{SC1}\left(p_1^{SC1}, g^{SC1}, t\right) = \sum_i u_i^{sc1} g_i\left(p_1^{SC1}, g^{SC1}, t\right).$$

$$\begin{aligned} &(1-q)\,\alpha^{SC1}\left(a_1 - \beta p_1^{SC1} + \gamma p_2^{SC1} + \mu g^{SC1}\right) \\ &-(1-q)\,\alpha^{SC1}\left(p_1^{SC1} - C_P - f w_1\left(1 - \lambda g^{SC1}\right)\right)\beta \\ &+q\left(1-\alpha^{SC1}\right)\ \left(a_1 - \beta p_1^{SC1} + \gamma p_2^{SC1} + \mu g^{SC1}\right) \\ &+q\left(1-\alpha^{SC1}\right)\left(p_1^{SC1} - f b_1 - C_p - f b_1 l\,(1--t)\,\beta\ = -u_2^{sc1}\right. \end{aligned} \tag{A.3}$$

$$\begin{aligned} &(1-q)\,\alpha^{SC1} f w_1 \lambda\left(a_1 - \beta p_1^{SC1} + \gamma p_2^{SC1} + \mu g^{SC1}\right) \\ &+(1-q)\,\alpha^{SC1}\left(p_1^{SC1} - C_p - \mu f b_1\left(1 - \lambda g^{SC1}\right) + q\left(1 - -\alpha^{SC1}\right)\right) \\ &-f b_1 - C_P + \left(p_1^{SC1} - f b_1 l\,(1-t)\right)\mu \\ &-(2-2q)\,k g^{SC1} = -u_1^{sc1} f \lambda w_1 - u_3^{sc1} \end{aligned} \tag{A.4}$$

$$q\left(1-\alpha^{SC1}\right) f b_1 l\left(a_1 - \beta p_1^{SC1} + \gamma p_2^{SC1} + \mu g^{SC1}\right) - 2q C_P t = u_1^{sc1} f b_1 l - u_4^{sc1} \tag{A.5}$$

$$u_1^{sc1}\left(f w_1\left(1 - \lambda g^{SC1}\right) - \left(f b_1 + f b_1 l\,(1-t)\right)\right) = 0 \tag{A.6}$$

$$u_2^{sc1}\left(-p_1^{SC1}\right) = 0 \tag{A.7}$$

$$u_3^{sc1}\left(-g^{SC1}\right) = 0 \tag{A.8}$$

$$u_4^{sc1}\,(-t) = 0 \tag{A.9}$$

$$\left(f w_1\left(1 - \lambda g^{SC1}\right) - \left(f b_1 + f b_1 l\,(1-t)\right)\right) \le 0 \tag{A.10}$$

$$-p_1^{SC1} \le 0 \tag{A.11}$$

$$-g^{SC1} \le 0 \tag{A.12}$$

$$-t \le 0 \tag{A.13}$$

$$u_i^{sc1} \ge 0 i = 1, 2, 3, 4 \tag{A.14}$$

$$\frac{\partial \pi_2^{SC1}}{\partial p_2^{sc1}} = \left(a_1 - \beta p_1^{SC1} + \gamma p_2^{SC1} + \mu g^{SC1}\right) - \beta\left(p_2^{SC1} - f b_1 - C_p\right) \tag{A.15}$$

The answer was chosen from the simultaneous solving of Karush-Kuhn-Tucker (K.K.T), and Eq (A.15). covers all the constraints and assumptions of the model.

Lemma 3 *The profit function of the third-party company exhibits concavity in* p_{3p}, $ands$ *as its own decision variables.*

Proof The profit function of the third party in the second scenario, exhibits concavity in the variables p_3^{SC2}, and S. The Hessian matrix of π_2^{SC2} with respect to these variables is as follows:

$$H_{\pi_3^{SC2}\left(p_3^{SC2},S\right)} = \begin{bmatrix} -2\varphi & \omega n \\ \omega n & -1 \end{bmatrix} \tag{A.16}$$

Since $|-2\varphi| < 0$,then the only condition for the profit function of the second company in the second scenario hessian to be concave is:
$\begin{vmatrix} -2\varphi & \omega n \\ \omega n & -1 \end{vmatrix} > 0.$

Let $S_{3p}^{sc2} = (1-\alpha^{SC2})D_2 - fD_{3p}$.

Where, $S_{3p}^{sc2} \geq 0$.

We find that S_{3p}^{sc2} is convex.

The K.K.T. conditions for thirdßparty company´s profit function in second scenario are as follows:

$$\nabla\pi_{3p}^{SC2}\left(p_{3\text{p}}^{SC2}, s\right) = \sum_i v_i^{sc2} g_i\left(p_{3\text{p}}^{SC2}, s\right).$$

$$-\omega n(1-S) - \tau p_3^{SC2} - \varphi p_3^{SC2} + a_3 - \varphi\left(p_3^{SC2} - C_m\right) = v_1^{sc2}\varphi - v_2^{sc2} \tag{A.17}$$

$$\left(p_3^{SC2} - C_m\right)\omega n - S + \varsigma n = -v_1^{sc2}\omega n - v_3^{sc2} \tag{A.18}$$

$$v_1^{sc2}\left(\left(1-\alpha^{SC2}\right)\left(a_2 - \beta p_1^{SC2} + \gamma p_2^{SC2} + \mu g^{SC2}\right) - \left(a_3\varphi p_3^{SC2} - \omega z_3 - \tau p_3^{SC2}\right)\right) = 0 \tag{A.19}$$

$$v_2^{sc2}\left(-p_{3\text{p}}^{SC2}\right) = 0 \tag{A.20}$$

$$v_3^{sc2}(-s) = 0 \tag{A.21}$$

$$\left(1-\alpha^{SC2}\right)\left(a_2 - \beta p_1^{SC2} + \gamma p_2^{SC2} + \mu g^{SC2}\right) - \left(a_3\varphi p_3^{SC2} - \omega z_3 - \tau p_3^{SC2}\right) \leq 0$$

-(A.22)

$$-p_{3\text{p}}^{SC2} \leq 0 \tag{A.23}$$

$$-s \leq 0 \tag{A.24}$$

$$v_i^{sc2} \geq 0 i = 1,2,3 \tag{A.25}$$

The optimal value is chosen from solving of Karush-Kuhn-Tucker (K.K.T), covers all the constraints and assumptions.

After replacing the optimal values of the third-party´s decision variables in profit functions of the first and second company. The concavity of profit functions of both companies are investigated.

Lemma 4 *In terms of* p_1^{SC2}*, and* g^{SC2}*,The profit function of the first company shows concavity under conditions provided in Appendix 1.*

The profit function of the first company in the second scenario, denoted as (π_1^{SC2}), exhibits its concavity in the variables p_1^{SC2}, and g^{SC2}. The Hessian matrix of π_1^{SC2} with respect to these variables is as follows:

$$H_{\pi_1^{SC2}(p_1^{SC2},g^{SC2})} = \begin{bmatrix} -2(1-q)\alpha^{SC2}\beta - 2q\left(1-\alpha^{SC2}\right)\beta & (1-q)\alpha^{SC2}\mu - (1-q)\alpha^{SC2} fw_2\lambda\beta + q\left(1-\alpha^{SC2}\right)\mu \\ (1-q)\alpha^{SC2}\mu - (1-q)\alpha^{SC2} fw_2\lambda\beta + q\left(1-\alpha^{SC2}\right)\mu & 2(1-q)\alpha^{SC2} fw_2\lambda\mu - 2(1-q)k \end{bmatrix} \tag{A.26}$$

Since $\left|-2(1-q)\alpha^{SC2}\beta - 2q\left(1-\alpha^{SC2}\right)\beta\right| < 0$,then the only condition for the profit function of the first company in the second scenario hessian to be concave is:

$$\begin{vmatrix} -2(1-q)\alpha^{SC2}\beta - 2q\left(1-\alpha^{SC2}\right)\beta & (1-q)\alpha^{SC2}\mu - (1-q)\alpha^{SC2} fw_2\lambda\beta + q\left(1-\alpha^{SC2}\right)\mu \\ (1-q)\alpha^{SC2}\mu - (1-q)\alpha^{SC2} fw_2\lambda\beta + q\left(1-\alpha^{SC2}\right)\mu & 2(1-q)\alpha^{SC2} fw_2\lambda\mu - 2(1-q)k \end{vmatrix} > 0$$

Let $S_1^{sc2} = p_3 + p_{3p} - p_1^{SC2}$.

Where, $S_1^{sc2} \geq 0$.

We find that S_1^{sc2} is convex.

Lemma 5 *The profit function of the second company show concavity in* p_2^{SC2}*, and* p_3 *decision variable under conditions below.*

The profit function of the second company in the second scenario, denoted as (π_2^{SC2}), exhibits concavity in the variables p_2^{SC2}, and p_3^{SC2}. The Hessian matrix of π_2^{SC2} with respect to these variables is as follows:

$$H_{\pi_2^{SC2}(p_2^{SC2},p_3^{SC2})} = \begin{bmatrix} -2\beta & 0 \\ 0 & 2q\left(-\tau - \frac{c_s\tau\varphi}{n^2\omega^2 - 2c_s\varphi}\right) \end{bmatrix} \tag{A.27}$$

Since $|-2\beta| < 0$,then the only condition for the profit function of the second company in the second scenario hessian to be concave is:

$$\begin{vmatrix} -2\beta & 0 \\ 0 & 2q\left(-\tau - \frac{c_s\tau\varphi}{n^2\omega^2 - 2c_s\varphi}\right) \end{vmatrix} > 0.$$

Let $S_{2,1}^{sc2} = (1-\alpha^{SC2})D_2 - D_H$

$$S_{2,2}^{sc2} = \left(p_2^{SC2} - fw_2^{SC2}\right) - (p_3 - fb_2)$$

where, $S_{2,1}^{sc2}, and S_{2,2}^{sc2} \geq 0$.

We find that $S_{2,1}^{sc2}, and S_{2,2}^{sc2}$ are convex.

The K.K.T. conditions for first and second company´s profit functions in second scenario are as follows:

$$\nabla\pi_1^{SC2}\left(p_1^{SC2}, g^{SC2}\right) = \sum_i y_i^{sc2} g_i\left(p_1^{SC2}, g^{SC2}\right).$$

$$\begin{aligned}&(1-q)\,\alpha^{SC2}\left(a_2 - \beta p_1^{SC2} + \gamma p_2^{SC2} + \mu g^{SC2}\right) - (1-q)\,\alpha^{SC2}\left(p_1^{SC2} - fw_2^{SC2}\left(1-\lambda g^{SC2}\right)\right)\beta \\ &+q\left(1-\alpha^{SC2}\right)\left(a_2 - \beta p_1^{SC2} + \gamma p_2^{SC2} + \mu g^{SC2}\right) - q\left(1-\alpha^{SC2}\right) \\ &\left(-p_3^{SC2} - \left(\frac{n^2\omega^2 C_{m-} n^2\omega\varsigma + \omega n + \tau p_3^{SC2} - \varphi C_m - a_3}{n^2\omega^2 - 2\varphi}\right) + p_1^{SC2}\right)\beta = -y_1^{sc2} - y_2^{sc2}\end{aligned} \tag{A.28}$$

$$\begin{aligned}&(1-q)\,\alpha^{SC2} fw_2^{SC2}\lambda(\left(a_2 - \beta p_1^{SC2} + \gamma p_2^{SC2} + \mu g^{SC2}\right) - (1-q)\,\alpha^{SC2}\left(p_1^{SC2} - fw_2^{SC2}\left(1-\lambda g^{SC2}\right)\right)\mu \\ &+q\left(\frac{n^2\omega^2 C_{m-} n^2\omega\varsigma + \omega n + \tau p_3^{SC2} - \varphi C_m - a_3}{n^2\omega^2 - 2\varphi}\right)\left(1-\alpha^{SC2}\right)\mu - (2-2q)\,k g^{SC2} = -y_3^{sc2}\end{aligned} \tag{A.29}$$

$$y_1^{sc2}\left(p_3^{SC2} + \left(\frac{n^2\omega^2 C_{m-} n^2\omega\varsigma + \omega n + \tau p_3^{SC2} - \varphi C_m - a_3}{n^2\omega^2 - 2\varphi}\right) - p_1^{SC2}\right) = 0 \tag{A.30}$$

$$y_2^{sc2}\left(-p_1^{SC2}\right) = 0 \tag{A.31}$$

$y_3^{sc2}\left(-g^{SC2}\right) = 0$(A.32

$$\left(p_3^{SC2} + \left(\frac{n^2\omega^2 C_{m-} n^2\omega\varsigma + \omega n + \tau p_3^{SC2} - \varphi C_m - a_3}{n^2\omega^2 - 2\varphi}\right) - p_1^{SC2}\right) \leq 0 \tag{A.33}$$

$$-p_1^{SC2} \leq 0 \tag{A.34}$$

$$-g^{SC2} \leq 0 \tag{A.35}$$

$$y_i^{sc2} \geq 0 i = 1, 2, 3 \tag{A.36}$$

$$\nabla\pi_2^{SC2}\left(p_2^{SC2}, p_3\right) = \sum_i o_i^{sc2} g_i\left(p_2^{SC2}, p_3\right).$$

$$-\beta p_2^{SC2} + \gamma p_1^{SC2} - \mu g^{SC2} + \alpha_1 - \left(-fw_2^{SC2} - c_p + p_3\right) = o_1^{sc2}\gamma(1-\alpha^{SC2}) + o_2^{sc2} - o_3^{sc2} \tag{A.37}$$

$$q\left(\alpha^{SC2}-\tau p_3^{SC2}-\left(\frac{n^2\omega^2 C_{m-}n^2\omega\varsigma+\omega n+\tau p_3^{SC2}-\varphi C_m-a_3}{n^2\omega^2-2\varphi}\right)-g^{SC2}\mu\right)$$
$$+q\left(-fw_2^{SC2}+p_3^{SC2}\right)\left(-\tau-\frac{\tau\varphi}{n^2\omega^2-2\varphi}\right)=o_1^{sc2}\left(\tau+\frac{\tau\varphi}{n^2\omega^2-2\varphi}\right)+o_2^{sc2}-o_4^{sc2} \tag{A.38}$$

$$o_1^{sc2}\left(\left(1-\alpha^{SC2}\right)\left(a_2-\beta p_1^{SC2}+\gamma p_2^{SC2}+\mu g^{SC2}\right)\right.$$
$$\left.-\left(a_2\tau p_3^{SC2}-\mu g^{SC2}-\left(\frac{n^2\omega^2 C_{m-}n^2\omega\varsigma+\omega n+\tau p_3^{SC2}-\varphi C_m-a_3}{n^2\omega^2-2\varphi}\right)\varphi\right)\right)=0 \tag{A.39}$$

$$o_2^{sc2}\left(\left(p_2^{SC2}-fw_2^{SC2}\right)-\left(p_3^{SC2}-fw_3^{SC2}\right)\right)=0 \tag{A.40}$$

$$o_3^{sc2}\left(-p_2^{SC2}\right)=0 \tag{A.41}$$

$$o_4^{sc2}\left(-p_3\right)=0 \tag{A.42}$$

$$\left(\left(1-\alpha^{SC2}\right)\left(a_2-\beta p_1^{SC2}+\gamma p_2^{SC2}+\mu g^{SC2}\right)\right.$$
$$\left.-\left(a_2\tau p_3^{SC2}-\mu g^{SC2}-\left(\frac{n^2\omega^2 C_{m-}n^2\omega\varsigma+\omega n+\tau p_3^{SC2}-\varphi C_m-a_3}{n^2\omega^2-2\varphi}\right)\varphi\right)\leq 0\right)$$
-(A.43)

$$\left(\left(p_2^{SC2}-fw_2^{SC2}\right)-\left(p_3^{SC2}-fw_3^{SC2}\right)\right)\leq 0 \tag{A.44}$$

$$-p_2^{SC2}\leq 0 \tag{A.45}$$

$$-p_3\leq 0 \tag{A.46}$$

$$o_i^{sc2}\geq 0 i=1,2,3,4 \tag{A.47}$$

From the simultaneous solving of Karush–Kuhn–Tucker (K.K.T) of both profit functions, the sets of optimal values gained which the best set covers all the constraints is chosen.

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