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Government Interventions in a Hydrogen Supply Chain: a Bi-criteria, Game-theoretic Approach

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Abstract The German government attributes a crucial role to green hydrogen in the energy transition, as it has the potential to reduce greenhouse gas emissions when used as an energy carrier. However, currently, green hydrogen is not yet competitive. On the one hand, its production is costly, and on the other, current electrolysis capacities are insufficient to meet the potential demand. Therefore, at least during a transitional period, green hydrogen must compete with gray hydrogen produced from fossil energy sources. In this paper, we examine three government instruments aimed at increasing the market share of green hydrogen: taxes on gray hydrogen, subsidies for the green retailer, and financial support for expanding green hydrogen production capacities. In a bi-criteria, game-theoretic model, in which the government acts as the Stackelberg leader, we observe that all three measures can improve the position of green hydrogen on the market. Notably, the state's sole intervention can significantly increase the sales volume of green hydrogen. However, if the state's main focus is on balancing its net gain from hydrogen market interventions, it should concentrate on taxes. If finances and the sales volume of green hydrogen are equally important, the state will increasingly focus on positive measures and support capacity expansions. In contrast, if the state's expenditures do not matter, the additional use of subsidies leads to maximizing the market share of green hydrogen.

Keywords Game theory · Hydrogen supply chain · Green supply chain · Government interventions · Bi-criteria optimization

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1 Introduction

In recent years, and in light of the consequences of climate change, there has been a growing global awareness regarding the necessity of transitioning to sustainable and renewable energy sources. The need arises to reduce reliance on fossil fuels and to embrace cleaner alternatives. In this context, green hydrogen is attributed a crucial role, as it has the potential to initiate a profound change in our energy systems.

Green hydrogen is a clean, emission-free energy carrier produced by renewable energy sources. Furthermore, hydrogen can also be used to provide storable energy (Andersson and Grönkvist 2019). This is especially relevant for energy produced by renewable sources like wind or solar power, which can experience substantial fluctuations due to varying weather conditions.

Although green hydrogen thus represents an alternative to other conventional energy sources such as gas, coal, or oil, its most immediate role lies in replacing gray hydrogen in existing industrial applications. Green hydrogen can be directly utilized here without technological adjustments and by leveraging the existing infrastructure. However, using green hydrogen as an energy carrier is still in an early stage, leading to several challenges. Currently, the production of green hydrogen is still significantly more expensive than that of other types of hydrogen, as, for example, expanding the capacities of renewable energy sources is associated with large investments. In addition, production capacities are limited, as the availability and efficiency of electrolyzers are currently insufficient. Conventional methods of producing hydrogen from gas are presently more efficient and cost-effective (Ajanovic et al. 2022).

Consequently, it is expected that, at least for a transitional period, the demand for hydrogen will also have to be met by hydrogen produced by non-green energy sources. However, the European Union and national institutions such as the German government aim to make green hydrogen, as a low-carbon alternative to gray hydrogen, competitive in the future through several funding programs (BMBF 2025). We adopt these ideas by analyzing the intra-hydrogen competition between gray hydrogen, as the currently dominant form of hydrogen production, and green hydrogen, representing the most promising alternative to support the energy transition. The aim of the paper is to model the current state of the hydrogen market using game theory and to determine how the use of green hydrogen can be promoted from today's perspective. Hence, we consider a two-echelon hydrogen supply chain consisting of a green hydrogen center and a gray hydrogen manufacturer, along with retailers for both green and gray hydrogen variants. Each supplier produces hydrogen in its respective color and sells it to the corresponding retailer. Because of limited production capacities on the green hydrogen side, market demand cannot always be met. In order to increase the share of green hydrogen sales in the market, we consider various governmental supporting instruments. On the one hand, these are investments aimed at expanding capacities for green hydrogen production. On the other hand, as another positive measure to advance the market diffusion of green hydrogen, we also want to consider the possibility of subsidies to supply chain members. In contrast, we analyze the impact of taxes on CO₂ emissions as a negative instrument.

Aligned with most existing literature in Green Supply Chain Management (see, e.g., Barman et al. 2021), we first consider a simple two-stage game featuring a passively acting state. This enables us to conduct a precise marginal analysis of how players respond to alterations in the parameter settings. However, in an extension of the two-stage game and in contrast to existing literature, we treat the state as an actively involved player and Stackelberg leader, pursuing its own goals and resulting in a three-stage game. Additionally, we investigate the advantageousness of governmental interventions in a bi-criteria context, taking into account not only the sales volume of green hydrogen but also the net gain from hydrogen market interventions as possible objectives of the government. Given its increased complexity compared to the two-stage game, the game is analyzed numerically.

We aim to answer the following research questions:

- How do players and consumers behave under exogenously given government measures, assuming the government is not actively participating in a two-stage supply chain?
- Which government measures are best suited
 - a) to increase the market share of green hydrogen,
 - b) to maximize the government's net gain from hydrogen market interventions, considering the government to be an actively involved player?
- What are the results compared to the case where no government intervention occurs?

The remainder of this paper is organized as follows. In Section 2, we provide a literature review, focusing on the papers most pertinent to our research. Section 3 presents the two-stage supply chain model, where the government initially assumes a non-active role. After providing a solution approach, managerial insights are derived through a sensitivity analysis. In the extension of the two-stage supply chain model, in Section 4, the government participates in the game as the Stackelberg leader and has two different objective functions. This leads to increasing complexity, so the game is solved and analyzed numerically. Section 5 summarizes managerial insights and concludes the paper.

2 Literature Review

In principle, while the game-theoretic analysis of hydrogen supply chains is still at an early stage and research in this area is limited, various optimization approaches are commonly employed to analyze hydrogen supply chains. Due to methodological distinctions from our study, we will refer to these approaches without delving into detailed comparisons. Li et al. 2019 offer a comprehensive review of optimization-focused literature in the realm of hydrogen supply chains that examines, for example, MILP models. In a literature review, Liu and Ma 2020 also present various problem formulations in hydrogen supply chains, objective functions, and solution methods.

In the following, we focus on the game-theoretic analysis of hydrogen supply chains. At the same time, parallels to our paper can also be found with papers

in the field of green supply chain management, which, therefore, also served as the basis for the model under consideration. The literature review comprehensively addresses both streams, particularly emphasizing government interventions designed to enhance sustainability.

A game-theoretic analysis of hydrogen supply chains is elaborated, for instance, in the research conducted by Guo et al. 2021, who analyze an equilibrium model considering peer-to-peer contracts between suppliers who produce hydrogen from renewable energy sources and retailers to capture strategic behaviors of market participants. The MILP model they present is reformulated using the Karush-Kuhn-Tucker conditions. Other complex hydrogen supply chain structures are also modeled as bi-level problems. For example, Cao et al. 2022 consider hydrogen as a byproduct of chemical plants. A transportation problem occurs between chemical plants in the framework of a cooperative game. In contrast, the relationship between chemical plants and a salt cavern for hydrogen storage is modeled as a Stackelberg game. Zwickl-Bernhard and Auer 2022 consider a bi-level optimization problem consisting of a hydropower plant owner who produces hydrogen and a transportation firm acting as a hydrogen consumer. They find that only a sufficiently high CO₂ price makes green hydrogen competitive. Pan et al. 2020 also examine a bi-level optimization problem between a power-to-hydrogen and methane plant and multiple markets. Zhang et al. 2021, e.g., consider different business models in hydrogen energy systems, including different investors, operators, and investment shares. The choice of the business model comes in the form of a multi-objective optimization problem, which is solved using a dragonfly algorithm. Jafari et al. 2022 consider a supply chain for hydrogen-powered cars. They examine government incentives in a game-theoretic context in the form of subsidies and tax rebates for the car manufacturer, which increase demand. However, the government does not participate in the game as an active player; tax rates and subsidies are exogenous parameters. Beranek et al. 2023 consider a hydrogen supply chain consisting of one retailer and three hydrogen manufacturers. Within this setup, there is both a fixed green and gray manufacturer, as well as a mixed manufacturer seeking to establish its position in the market. They find that the mixed manufacturer is more inclined to produce green hydrogen under positive incentives, such as a subsidized retailer, than in situations where the gray manufacturer is subject to tax penalties. However, the government is not an actively involved player.

The literature from the Green Supply Chain Management field is also pertinent to the model under consideration in our paper. Many of these studies focus on the competition between general green and non-green products, see, e.g., Mondal et al. 2022, meaning the models can potentially be adapted for hydrogen supply chains with competing product types. For a comprehensive overview of green supply chain research, see, e.g., Carter and Liane Easton 2011, Min and Kim 2012, Tseng et al. 2019, and Khan et al. 2021. Nielsen et al. 2019 investigate a two-period green supply chain under government incentives. Their study reveals that the optimal greening level is achieved when the government subsidizes total research and development costs rather than providing incentives per unit. Notably, the government plays a non-active role in their game. The same applies to the work of Yi and Wen 2023; however, instead of directly covering research and development costs, the state provides a sub-

sity based on the greening level of the manufacturer. Similarly, Barman et al. 2021 explore a passively acting government in a Stackelberg model. In their scenario, the government subsidizes green products and imposes taxes on non-green products. Ma et al. 2021 consider a subsidized manufacturer investing in green emission reduction technology in a sustainable supply chain. They find that these subsidies can lead to emissions reductions. A similar model is also analyzed by Ruidas et al. 2022, including inventory decisions and imperfect production processes. Mondal and Giri 2022 as well as Yang and Xiao 2017 consider a subsidized manufacturer where the level of greening directly impacts the amount of subsidies. A penalty is incurred if the greening level falls below a minimum acceptable threshold that the government sets. In contrast, Madani and Rasti-Barzoki 2017 view the government as a Stackelberg leader, responsible for setting subsidies and tax rates for a competitive green and non-green supply chain. The government's objective is to maximize its profit. Also Hadi et al. 2020 incorporate the government as an active player, responsible for determining the optimal tax and subsidy rates for both green and non-green products supplied by the manufacturer. They consider three distinct government objectives, including environmental protection, revenue maximization, and a combination of both, determining the optimal government interventions for each scenario separately. Similarly, Mahmoudi and Rasti-Barzoki 2018 examine three governmental scenarios within a sustainable supply chain, involving taxes and subsidies designed to maximize profits, minimize the environmental impact, or achieve a combination of both objectives, as also considered by Giri et al. 2019. In the paper of Zolfagharinia et al. 2023, the government aims at maximizing social benefits by subsidizing a single manufacturer for increasing its greening level.

Other studies examine more specific products, such as the work by Amiri-Pebdani et al. 2022, which analyzes the pricing of green and conventional energy under the impact of government taxes and subsidies. The government aims to maximize revenue and social welfare and minimize environmental impact.

Table 1 displays a comparative overview of the literature most relevant to our paper. We extend the existing Green Supply Chain Management literature models by addressing hydrogen-specific characteristics. For instance, the production volume of green hydrogen is currently limited by the availability of electrolyzers or infrastructure, necessitating consideration regarding capacity constraints. The government aims to increase the sales volume of green hydrogen, and, therefore, can intervene in the supply chain using three instruments: Providing subsidies to the green hydrogen retailer, implementing taxation measures on gray hydrogen, and offering financial support for research and development costs to establish green hydrogen production capacities. Moreover, as an extension of the two-stage supply chain setting, we incorporate the government as an active player by considering its interests in a bi-criteria context. This approach goes beyond merely maximizing sales volume and also includes financial criteria in the profit function. In contrast to the previously cited literature, we do not limit ourselves to separate scenarios but employ a weighted-sum approach to generate points on the Pareto frontier.

Table 1 Comparison of relevant related literature

Authors	Application area	Number of SC-parties	Government as player	Subsidies	Taxes	R&D investments	Capacity restrictions	Multi-objective approach	Stackelberg model
Amiri-Pebdani et al. 2022	Energy Supply Chain	2M	✓	C	C			✓	✓
Barman et al. 2021	Green SC	2M, 1R		C	C				✓
Beranek et al. 2023	Hydrogen SC	3M, 1R		R	M				✓
Giri et al. 2019	Green SC	2M, 1R	✓	M	R				✓
Hadi et al. 2020	Green SC	1S, 1M	✓	C	C				✓
Ma et al. 2021	Green SC	1M, 1R		M	M				✓
Madani and Rasti-Barzoki 2017	Green SC	2M, 2R	✓	C	C				✓
Mahmoudi and Rasti-Barzoki 2018	Green SC	Multiple M, R	✓	M	M				✓
Mondal and Giri 2022	Green Closed-loop SC	2M, 1R		M					✓
Nielsen et al. 2019	Green SC	1M, 1R				✓			✓
Yang and Xiao 2017	Green SC	1M, 1R		M					✓
Yi and Wen 2023	Green SC	1M, 1R		M		✓			✓
Zhang et al. 2021	Hydrogen SC	1M, 1R						✓	✓
Zolfaghariania et al. 2023	Green SC	1M	✓	M					✓
This paper	Hydrogen SC	2M, 2R	✓	R	M	✓	✓	✓	✓

SC Supply Chain, M Manufacturer, R Retailer, C Customer, S Supplier

Table 2 Notations in the two-stage supply chain model

Notation	Description	Domain
<i>Parameters</i>		
c_g	Production costs of green hydrogen	$0 \leq c_g \leq 1$
c_n	Production costs of gray hydrogen	$0 \leq c_n \leq 1$
η	Cost coefficient for capacity expansions	$0 \leq \eta \leq 1$
δ	Parameter to express the valuation of the gray product	$0 < \delta < 1$
γ	Financial support provided by the government to the costs of capacity expansions	$0 \leq \gamma \leq 1$
G_s	Government's subsidies	$0 \leq G_s \leq 1$
G_t	Government's tax rate	$0 \leq G_t \leq 1$
Cap_{g0}	Green basic capacity	$0 \leq Cap_{g0} \leq 1$
ϕ	Willingness-to-pay for green product	$0 \leq \phi \leq 1$
<i>Decision variables</i>		
Cap_g	Green capacity enhancement	$0 \leq Cap_g \leq 1$
m_{Rg}	Retailer's margin for green hydrogen	$0 \leq m_{Rg} \leq 1$
m_{Rn}	Retailer's margin for gray hydrogen	$0 \leq m_{Rn} \leq 1$
w_g	Green manufacturer's wholesale price	$0 \leq w_g \leq 1$
w_n	Gray manufacturer's wholesale price	$0 \leq w_n \leq 1$
<i>Other variables</i>		
D_g	Demand for green hydrogen	$0 \leq D_g \leq 1$
D_n	Demand for gray hydrogen	$0 \leq D_n \leq 1$
λ	Lagrange multiplier	$0 \geq \lambda$
π_{Mg}	Green manufacturer's profit	$0 \geq \pi_{Mg}$
π_{Mn}	Gray manufacturer's profit	$0 \geq \pi_{Mn}$
π_{Rg}	Green retailer's profit	$0 \geq \pi_{Rg}$
π_{Rn}	Gray retailer's profit	$0 \geq \pi_{Rn}$
U_g	Customer's utility from buying the green product	$0 \geq U_g$
U_n	Customer's utility from buying the non-green product	$0 \geq U_n$

3 Two-stage Game

3.1 Assumptions

We describe the two-stage hydrogen supply chain model and its associated assumptions in the following. All notations used in the paper are presented in Table 2.

- We examine a hydrogen supply chain comprising a green hydrogen center, a gray hydrogen manufacturer, and two retailers for green and gray hydrogen, respectively. For simplicity, the terms green manufacturer and hydrogen center are used interchangeably in this paper. The hydrogen center concept is to be understood as a cooperation between electrolyzer and green hydrogen manufacturers. In Germany, for example, there is a cooperation agreement between the energy company ENERTRAG and the electrolyzer manufacturer Sunfire to establish a joint hydro-

gen center, seen as an ideal platform for testing new technologies related to the energy transition (Sunfire 2021).

- The hydrogen center and the gray manufacturer compete by offering substitute hydrogen products within this supply chain. Specifically, the hydrogen center produces green hydrogen (g), which is hydrogen produced through electrolysis using electricity from renewable sources and causes the lowest carbon emissions among all types of hydrogen. In our paper, we employ the simplifying assumption of zero emissions, as discussed in Liu and Ma 2020, and do not account for emissions that may arise during transportation, for instance. In contrast, gray hydrogen (n) is typically produced through steam reforming from fossil energy sources or coal gasification (Ajanovic et al. 2022) and is assumed to be supplied by the gray hydrogen manufacturer. It carries the highest carbon emissions among all hydrogen types.
- Green hydrogen is exclusively marketed through a green retailer, while gray hydrogen is distributed via a gray retailer.
- We assume that the hydrogen center and the gray hydrogen manufacturer possess market power over the retailers. This reflects the existing supply oligopoly within the hydrogen market (Wietschel et al. 2021), where few manufacturers hold vast amounts of hydrogen (Beranek et al. 2023). Furthermore, considering the high dependence of hydrogen prices on current raw material costs, the manufacturers should be in the position to be the first in the supply chain to set their prices.
- The retailers purchase their respective types of hydrogen, denoted as g and n , at wholesale prices, w_g and w_n , respectively. They then add their margins, m_{Rg} and m_{Rn} , before distributing the hydrogen to the customers (see, e.g., Choi 1996; Aust and Buscher 2012; Beranek and Buscher 2021). The retailers could, for example, be the operators of hydrogen filling stations. For instance, the ENERTRAG and Sunfire hydrogen center supplies an exclusive green hydrogen filling station, while most other hydrogen filling stations in Germany predominantly provide gray hydrogen.
- We assume that the customers' willingness-to-pay, denoted as ϕ , for the green product is uniformly distributed between 0 and 1, i.e., $\phi \sim U[0, 1]$, and $F(\phi) = \phi$ (Souza 2013). In this setup, each customer purchases either green or gray hydrogen, and the market size is normalized to one. Additionally, we assume that the willingness-to-pay for gray hydrogen is lower than that of green hydrogen, i.e., $\delta\phi$, where $0 < \delta < 1$ (Souza 2013; Vorasayan and Ryan 2006).

From this, we can derive the conditions under which each type of hydrogen is sold. If the customer's utility U_g for purchasing the green product is larger the utility U_n for purchasing the gray product, i.e., $U_g > U_n$, the green product is sold, i.e.

$$U_g = \phi - (w_g + m_{Rg}) \geq 0 \quad (1)$$

$$U_g = \phi - (w_g + m_{Rg}) > U_n = \delta\phi - (w_n + m_{Rn}) \quad (2)$$

must hold.

On the other hand, the customer opts for gray hydrogen if $U_g < U_n$, i.e.

$$U_n = \delta\phi - (w_n + m_{Rn}) \geq 0 \quad (3)$$

$$U_g = \phi - (w_g + m_{Rg}) < U_n = \delta\phi - (w_n + m_{Rn}). \quad (4)$$

By solving the equations for ϕ , we obtain the following demand functions:

$$D_g = 1 - \frac{(w_g + m_{Rg}) - (w_n + m_{Rn})}{1 - \delta} \quad (5)$$

$$D_n = \frac{(w_g + m_{Rg}) - (w_n + m_{Rn})}{1 - \delta} - \frac{(w_n + m_{Rn})}{\delta}. \quad (6)$$

Note that the fraction of customers who will not make any purchase is $\frac{(w_n + m_{Rn})}{\delta}$ (Vorasayan and Ryan 2006). The resulting linear demand functions are established in the hydrogen literature despite the simplification of real demand patterns, see, e.g., Li and Mulder 2021, Veenstra and Mulder 2024, as they provide an analytically tractable representation of price-dependent demand.

Based on the assumption of a market size of one, we further normalize all other input parameters to values between 0 and 1, as shown in Table 2.

- The unit manufacturing costs for green and gray hydrogen are denoted as c_g and c_n , respectively. The Hydex, a cost-based spot price index for hydrogen developed by E-Bridge Consulting GmbH, provides an orientation to determine the specific value for the parameters (E-Bridge 2023). It is based on the short-term prices of electricity, gas, and European Emission Allowances without capital costs (energate GmbH 2023). Currently, lower production costs and, consequently, lower prices are being observed for gray hydrogen; see also Ajanovic et al. 2022. However, in our paper, we refrain from specifying a fixed relationship between c_g and c_n . This allows us to map potential future cost developments in the model and the sensitivity analysis.

Transportation costs are simplistically considered identical for both manufacturers, thereby not being decision-relevant and not being considered.

- Steam reforming is the predominant method of hydrogen production worldwide (Bullmann et al. 2020). Therefore, we assume that the manufacturing process at the gray hydrogen manufacturer is technologically mature (Ajanovic et al. 2022) and that the manufacturer can satisfy its typical market demand. Even with increasing future demand, no capacity constraints are expected, despite the limited availability of fossil energy sources (Newborough and Cooley 2020). Therefore, no capacity restrictions are considered on the part of this manufacturer in our paper.

In contrast, producing green hydrogen by electrolysis is currently less prevalent. For instance, only 7% of the hydrogen demand in Germany is met through hydrogen produced by electrolysis processes (Bullmann et al. 2020). The production capacity of green hydrogen is significantly influenced by factors such as the capacity, efficiency, and quantity of electrolyzers in operation. To expand production

capabilities, investments are required to manufacture more electrolyzers and conduct research to improve their efficiency.

In our paper, we therefore assume that the capacity of the green manufacturer is defined as

$$Cap_{g0} + Cap_g \quad (7)$$

where Cap_{g0} represents the existing basic capacity of the green manufacturer, while Cap_g is the additional capacity that can be established through investments in capacity expansions. The cost associated with a capacity expansion is represented by

$$\eta Cap_g^2 \quad (8)$$

where η represents a cost coefficient. Quadratically increasing investment costs reflect the current market conditions, where large-scale electrolyzers are still technologically immature and limited, and critical components or infrastructure remain scarce, leading to rising costs with increasing capacity. See also, e.g., Nielsen et al. 2019 and Yi and Wen 2023, who consider quadratically increasing research and development investment costs.

Depending on the investments and the prevailing market conditions, the demand for green hydrogen could still surpass the production capacity of the green manufacturer. In such a scenario, only the maximum feasible supply quantity, which aligns with the capacity limit, can be sold. This circumstance is addressed in the solution process using a case distinction.

- Green hydrogen is regarded as indispensable for realizing the desired energy transition in many countries. However, green hydrogen is currently not competitive due to its high price and limited manufacturing capacities. To incentivize the widespread diffusion of green hydrogen, we examine the application of three different governmental instruments: taxes, subsidies, and financial support for capacity expansions. Firstly, we assume the imposition of taxes on CO₂ emissions. This practice is prevalent in countries like Germany, where companies are required to acquire emission rights through certificates. In our paper, only the gray hydrogen manufacturer causes CO₂ emissions. Therefore, this manufacturer alone incurs taxes, denoted as G_r . This tax rate represents a standardized rate applicable to the carbon emissions generated while producing a single unit of gray hydrogen. On the other hand, we consider subsidies to be a positive measure to support the distribution of green hydrogen. For instance, the German government has planned an investment of almost one billion euros in the funding program ‘H2Global’ (Bollerhey et al. 2023), with one of its objectives being to provide subsidies to intermediaries such as retailers. This is considered crucial, as the production costs of green hydrogen are relatively high in the initial phase, and potential losses could be expected without such support. These subsidies only apply to the sale of green hydrogen (ntv 2021). Hence, in our paper, we adapt this idea and examine subsidies G_s per unit that the green retailer receives for the sale of green hydrogen.

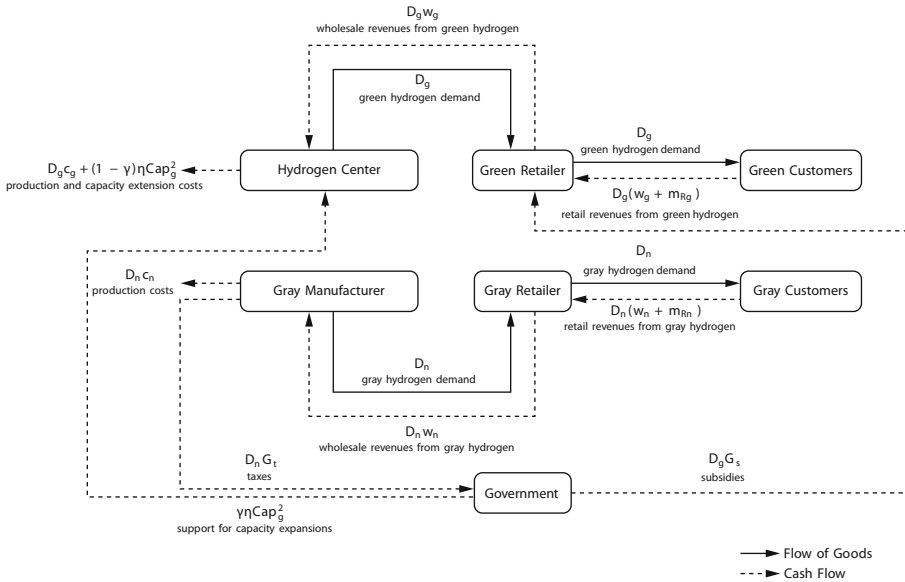


Fig. 1 Flow of goods and cash flow in the hydrogen supply chain

The third instrument under examination involves providing financial support for capacity expansions at the green hydrogen center. In a joint declaration made during the 2022 European electrolyzer Summit, electrolyzer manufacturers in Europe committed to increasing their electrolyzer manufacturing capacity tenfold to 17.5 GW by 2025 in order to align with the EU’s climate objectives. These manufacturers consider substantial investments and uncertainty about future market demand as one of the most significant hurdles. Consequently, the European Commission aims to encourage the advancement of hydrogen technologies through funding programs, such as the Horizon Europe Clean Hydrogen Partnership (European Clean Hydrogen Alliance 2022). In our paper, we therefore consider the coefficient γ to reflect the portion of capacity investments covered by the government. Hence, the investments of the government are $\gamma\eta Cap_g^2$, leaving the hydrogen center with a share of $(1 - \gamma)\eta Cap_g^2$, see also Nielsen et al. 2019)

The structure of the hydrogen supply chain and its material and cash flow are illustrated in Fig. 1, taking all considerations above into account.

3.2 Profit Functions

Considering all previous assumptions, we obtain the following profit functions for the players.

3.2.1 Manufacturers

The hydrogen center supplies the requested quantity of green hydrogen, which is limited to its available capacity. On the other hand, the gray manufacturer meets the market demand in full. In addition to manufacturing costs, the gray manufacturer also bears taxes at the rate of G_t per unit sold, while the hydrogen center may incur expenses related to capacity expansions. Therefore, we derive the hydrogen center's profit π_{Mg} and the gray manufacturer's profit π_{Mn} as follows:

$$\pi_{Mg} = (w_g - c_g) \cdot D_g - (1 - \gamma) \cdot \eta \cdot z^2 \quad (9)$$

$$\pi_{Mn} = (w_g - c_n - G_t) \cdot D_n \quad (10)$$

where

$$z = \begin{cases} 0 & \text{if } D_g \leq Cap_{g0} \\ Cap_g = D_g - Cap_{g0} & \text{if } D_g > Cap_{g0}. \end{cases} \quad (11)$$

Using the auxiliary variable z , we consider an upper limit on the sales volume of green hydrogen, which is contingent on the green manufacturer's capacity. If there is less demand than the basic capacity Cap_{g0} , no capacity expansion is required, and the quantity demanded, D_g , is produced. However, if demand surpasses the existing capacity, the required capacity extension is determined by the difference between the demand D_g and the basic capacity Cap_{g0} , i.e., $z = D_g - Cap_{g0}$.

3.2.2 Retailers

The retailers procure their respective types of hydrogen from the manufacturers and add their margin to the prices. The state supports the sale of green hydrogen with G_s subsidies per unit:

$$\pi_{Rg} = (m_{Rg} + G_s) \cdot D_g. \quad (12)$$

In contrast, the sale of gray hydrogen is not subsidized, leading to the following equation:

$$\pi_{Rn} = m_{Rn} \cdot D_n. \quad (13)$$

3.3 Solution

As previously noted, it is necessary to distinguish the scenario for the green manufacturer based on whether the demand for green hydrogen exceeds its basic capacity. If not, no capacity expansion is performed, i.e., $Cap_g = 0$. To analytically derive the equilibrium solution of the game, we first consider the unrestricted (interior) solution in Case I. Subsequently, we assess whether the corresponding demand ex-

ceeds the green manufacturer's capacity. If it does, Case II, the restricted solution, applies. Here, prices are set to align customers' demand with the capacity limit.

3.3.1 Retailers

We apply backward induction to determine the players' optimal strategies. The retailers act as the Stackelberg followers, determining their optimal retail margins m_{Rg} and m_{Rn} simultaneously for each of the hydrogen types sold, given any decisions made by the manufacturers:

$$\max_{m_{Rg}} \pi_{Rg} = (m_{Rg} + G_s) \cdot D_g = (m_{Rg} + G_s) \cdot \left[1 - \frac{(w_g + m_{Rg}) - (w_n + m_{Rn})}{1 - \delta} \right] \quad (14)$$

$$\max_{m_{Rn}} \pi_{Rn} = m_{Rn} \cdot D_n = m_{Rn} \cdot \left[\frac{(w_g + m_{Rg}) - (w_n + m_{Rn})}{1 - \delta} - \frac{(w_n + m_{Rn})}{\delta} \right]. \quad (15)$$

To determine the Nash equilibrium, we have to solve the equation system $\frac{\partial \pi_{Rg}}{\partial m_{Rg}} = 0$, and $\frac{\partial \pi_{Rn}}{\partial m_{Rn}} = 0$, i.e.

$$\frac{\partial \pi_{Rg}}{\partial m_{Rg}} = \frac{2m_{Rg} - m_{Rn} + \delta + w_g + G_s - w_n - 1}{\delta - 1} = 0 \quad (16)$$

$$\frac{\partial \pi_{Rn}}{\partial m_{Rn}} = \frac{-\delta(m_{Rg} + w_g) + 2m_{Rn} + w_n}{(\delta - 1)\delta} = 0. \quad (17)$$

We obtain

$$m_{Rg} = -\frac{-2\delta + (\delta - 2)w_g - 2G_s + w_n + 2}{\delta - 4} \quad (18)$$

$$m_{Rn} = \frac{\delta(\delta - w_g + G_s - 1) - (\delta - 2)w_n}{\delta - 4}. \quad (19)$$

To ensure the concavity of the profit functions with respect to the decision variables, we verify the second-order conditions:

$$\frac{\partial^2 \pi_{Rg}}{\partial m_{Rg}^2} = -\frac{2}{1 - \delta} < 0 \quad (20)$$

$$\frac{\partial^2 \pi_{Rn}}{\partial m_{Rn}^2} = -\frac{2}{\delta} - \frac{2}{1-\delta} < 0. \quad (21)$$

Since $0 < \delta < 1$, both conditions are always satisfied, and we obtain a unique equilibrium solution.

3.3.2 Manufacturers

Next, we analyze the manufacturers' decisions, who operate in a non-cooperative manner and act simultaneously, thus resulting in a Nash equilibrium between them.

Case I: $D_g \leq Cap_{g0}$

Taking into account the reactions of the retailers (Eqs. 18 and 19), the following optimization problem occurs:

$$\max_{w_g} \pi_{Mg} = (w_g - c_g) \cdot D_g \quad (22)$$

$$\max_{w_n} \pi_{Mn} = (w_n - c_n - G_t) \cdot D_n \quad (23)$$

s.t. (18)–(19). Please note that in the case of the unrestricted solution, we first ignore the capacity constraint and check it afterward.

To determine the Nash equilibrium, the equation system $\frac{\partial \pi_{Mg}}{\partial w_g} = 0$, and $\frac{\partial \pi_{Mn}}{\partial w_n} = 0$ needs to be solved. We obtain

$$w_g = \frac{2(\delta - 2)^2 c_g - (\delta - 2)c_n + 3\delta^2 - 11\delta + (\delta(2\delta - 9) + 8)G_s - \delta G_t + 2G_t + 8}{\delta(4\delta - 17) + 16} \quad (24)$$

$$w_n = \frac{-\delta(\delta - 2)c_g + 2(\delta - 2)^2 c_n + 2(\delta - 3)(\delta - 1)\delta + \delta(\delta - 2)G_s + 2(\delta - 2)^2 G_t}{\delta(4\delta - 17) + 16}. \quad (25)$$

To ensure the concavity of the profit functions with respect to the decision variables, we verify the second-order conditions:

$$\frac{\partial^2 \pi_{Mg}}{\partial w_g^2} = \frac{2(\delta - 2)}{\delta^2 - 5\delta + 4} < 0 \quad (26)$$

$$\frac{\partial^2 \pi_{Mn}}{\partial w_n^2} = \frac{2(\delta - 2)}{(\delta - 4)(\delta - 1)\delta} < 0. \quad (27)$$

Given that $0 < \delta < 1$, both conditions are always satisfied, resulting in a unique equilibrium solution.

The solution is feasible only if $D_g \leq Cap_{g0}$.

Case II: $Cap_{g0} < D_g$

If the green demand exceeds the basic capacity, a capacity expansion Cap_g must be carried out to align demand with the total capacity, i.e., $D_g = Cap_{g0} + Cap_g$.

To solve the problem, we set up the following Lagrangian function for the green manufacturer:

$$\mathcal{L} = (w_g - c_g)D_g - (1 - \gamma)\eta Cap_g^2 + \lambda(Cap_{g0} + Cap_g - D_g). \quad (28)$$

The manufacturers act non-cooperatively and simultaneously, thus resulting in a Nash equilibrium between them. Hence, the following optimization problem occurs:

$$\max_{\lambda, w_g, Cap_g} \mathcal{L} = (w_g - c_g)D_g - (1 - \gamma)\eta Cap_g^2 + \lambda(Cap_{g0} + Cap_g - D_g) \quad (29)$$

$$\max_{w_n} \pi_{Mn} = (w_n - c_n - G_t)D_n \quad (30)$$

s.t. (18)–(19).

To determine the Nash equilibrium, we have to solve the equation system $\frac{\partial \mathcal{L}}{\partial \lambda} = 0$, $\frac{\partial \mathcal{L}}{\partial w_g} = 0$, $\frac{\partial \mathcal{L}}{\partial Cap_g} = 0$, and $\frac{\partial \pi_{Mn}}{\partial w_n} = 0$. We obtain

$$w_g = \frac{\begin{pmatrix} 4(\gamma - 1)(\delta - 4)(\delta - 2)^2(\delta - 1)\eta Cap_{g0} \\ + (\delta - 1)(3\delta - 8)(2(\gamma - 1)(\delta - 2)\eta + \delta^2 - 5\delta + 4) \\ + 2(\delta - 4)(\delta - 2)^2(\delta - 1)c_g \\ - (\delta - 2)c_n(2(\gamma - 1)(\delta - 2)\eta + \delta^2 - 5\delta + 4) + 4\gamma\delta^3\eta G_s \\ - 26\gamma\delta^2\eta G_s + 52\gamma\delta\eta G_s - 32\gamma\eta G_s - 4\delta^3\eta G_s + 26\delta^2\eta G_s + 2\delta^4 G_s \\ - 19\delta^3 G_s + 61\delta^2 G_s - 52\delta\eta G_s - 76\delta G_s + 32\eta G_s + 32G_s - 2\gamma\delta^2\eta G_t \\ + 8\gamma\delta\eta G_t - 8\gamma\eta G_t + 2\delta^2\eta G_t - \delta^3 G_t + 7\delta^2 G_t - 8\delta\eta G_t \\ - 14\delta G_t + 8\eta G_t + 8G_t \end{pmatrix}}{2(\gamma - 1)(\delta - 2)(\delta(2\delta - 9) + 8)\eta + 4\delta^4 - 37\delta^3 + 117\delta^2 - 148\delta + 64} \quad (31)$$

$$Cap_g = \frac{\begin{pmatrix} (\delta - 2)((\delta(2\delta - 9) + 8)c_g + (\delta - 2)c_n - 3\delta^2 + 11\delta) \\ + ((9 - 2\delta)\delta - 8)G_s + \delta G_t - 2G_t - 8) \\ - (\delta - 4)(\delta - 1)(\delta(4\delta - 17) + 16)Cap_{g0} \end{pmatrix}}{2(\gamma - 1)(\delta - 2)(\delta(2\delta - 9) + 8)\eta + 4\delta^4 - 37\delta^3 + 117\delta^2 - 148\delta + 64} \quad (32)$$

$$\lambda = \frac{\begin{pmatrix} 2(\gamma - 1)\eta((\delta - 4)(\delta - 1)(\delta(4\delta - 17) + 16)Cap_{g0} \\ - (\delta - 2)((\delta(2\delta - 9) + 8)c_g + (\delta - 2)c_n - 3\delta^2 + 11\delta \\ + ((9 - 2\delta)\delta - 8)G_s + \delta G_t - 2G_t - 8)) \end{pmatrix}}{2(\gamma - 1)(\delta - 2)(\delta(2\delta - 9) + 8)\eta + 4\delta^4 - 37\delta^3 + 117\delta^2 - 148\delta + 64} \quad (33)$$

Table 3 Results of the sensitivity analysis: Case I

	δ	c_n	c_g	G_t	G_s
w_g	\pm	+	+	+	+
w_n	\pm	+	+	+	-
mRg	\pm	+	-	+	-
mRn	\pm	-	+	-	-
D_g	\pm	+	-	+	+
D_n	\pm	-	+	-	-

$$w_n = \frac{\begin{pmatrix} -2(\gamma - 1)(\delta - 4)(\delta - 2)(\delta - 1)\delta\eta Cap_g 0 \\ +2(\delta - 4)(\delta - 1)\delta ((\gamma - 1)(\delta - 2)\eta + \delta^2 - 4\delta + 3) \\ -(\delta - 4)(\delta - 2)(\delta - 1)\delta c_g \\ +2(\delta - 2)^2 c_n ((\gamma - 1)(\delta - 2)\eta + \delta^2 - 5\delta + 4) + \delta^4 G_s - 7\delta^3 G_s \\ +14\delta^2 G_s - 8\delta G_s + 2\gamma\delta^3 \eta G_t - 12\gamma\delta^2 \eta G_t + 24\gamma\delta \eta G_t - 16\gamma \eta G_t \\ -2\delta^3 \eta G_t + 12\delta^2 \eta G_t + 2\delta^4 G_t - 18\delta^3 G_t + 56\delta^2 G_t - 24\delta \eta G_t \\ -72\delta G_t + 16\eta G_t + 32G_t \end{pmatrix}}{2(\gamma - 1)(\delta - 2)(\delta(2\delta - 9) + 8)\eta + 4\delta^4 - 37\delta^3 + 117\delta^2 - 148\delta + 64} \tag{34}$$

The bordered Hessian matrix equals

$$\bar{H}(\mathcal{L}) = \begin{pmatrix} 0 & \frac{\partial^2 \mathcal{L}}{\partial \lambda \partial w_g} & \frac{\partial^2 \mathcal{L}}{\partial \lambda \partial Cap_g} \\ \frac{\partial^2 \mathcal{L}}{\partial \lambda \partial w_g} & \frac{\partial^2 \mathcal{L}}{\partial w_g^2} & \frac{\partial^2 \mathcal{L}}{\partial w_g \partial Cap_g} \\ \frac{\partial^2 \mathcal{L}}{\partial \lambda \partial Cap_g} & \frac{\partial^2 \mathcal{L}}{\partial Cap_g \partial w_g} & \frac{\partial^2 \mathcal{L}}{\partial Cap_g^2} \end{pmatrix} \tag{35}$$

$$= \begin{pmatrix} 0 & \frac{2-\delta}{\delta^2-5\delta+4} & 1 \\ \frac{2-\delta}{\delta^2-5\delta+4} & \frac{2(\delta-2)}{\delta^2-5\delta+4} & 0 \\ 1 & 0 & 2(-1 + \gamma)\eta \end{pmatrix} \tag{36}$$

Given that

$$\det \bar{H}(\mathcal{L}) = -\frac{2(\delta - 2) [(\gamma - 1)(\delta - 2)\eta + \delta^2 - 5\delta + 4]}{(\delta^2 - 5\delta + 4)^2} > 0 \tag{37}$$

we can be sure to obtain a maximum via the first-order partial derivatives of the green manufacturer’s profit function.

Given that the second-order condition of the gray manufacturer’s profit function

$$\frac{\partial^2 \pi_{Mn}}{\partial w_n^2} = \frac{2(\delta - 2)}{\delta(\delta^2 - 5\delta + 4)} < 0 \tag{38}$$

is consistently met, the gray manufacturer’s profit function is also concave in w_n .

Table 4 Results of the sensitivity analysis: Case II

	δ	c_n	c_g	G_t	G_s	η	γ	Cap_{g0}
w_g	\pm	+	+	+	+	\pm	\pm	–
w_n	\pm	+	+	+	–	\pm	\pm	–
mR_g	\pm	+	–	+	–	\pm	\pm	+
mR_n	\pm	–	+	–	–	\pm	\pm	–
D_g	\pm	+	–	+	+	\pm	\pm	+
D_n	\pm	–	+	–	–	\pm	\pm	–
Cap_g	\pm	+	–	+	+	\pm	\pm	–

3.4 Sensitivity Analysis

To analyze the impact of the parameters on the variables, the derivatives of the symbolic variable expressions with respect to each parameter are computed for each case. All derivatives are provided in the Appendix (available as Supplementary Material). The impacts of the parameters on the variables are presented in Table 3 for Case I and Table 4 for Case II. Please note that the parameters η , γ , and Cap_{g0} are exclusive to Case II, and similarly, the variable Cap_g is specific to Case II. Concerning the remaining parameters, it has been determined that their impact on the variables is consistent across both Case I and Case II. If a specific derivative is greater than zero, this is denoted by ‘+’ in the table, meaning the variable increases in the considered parameter. Conversely, if it is less than zero, this is represented by ‘–’, indicating that the variable decreases in the considered parameter. For some cases, where the expression is complex, and the parameter’s impact relies on specific values of other parameters, no definite statement can be made. This situation is denoted with ‘ \pm ’ in the tables in such a case. This applies to the parameters δ in both Case I and Case II, as well as the parameters η and γ in Case II.

From the analysis, we find that increasing manufacturing costs, regardless of the hydrogen type, increase wholesale prices for both hydrogen manufacturers. The manufacturer impacted by the cost increase naturally needs to raise the selling price of its product to compensate. Conversely, the unaffected manufacturer experiences an increase in demand and subsequently can raise its prices as well. Furthermore, the hydrogen retailer that is not affected by the cost increase can charge a higher margin. If the production costs of green hydrogen increase, the retailer dealing with gray hydrogen increases its margin, and vice versa. Otherwise, in the case of higher production costs of its respective product, the retailer must reduce its margins to offset the manufacturer’s price increases and the decline in demand. The capacity extension Cap_g is a decision variable only in Case II. In this scenario, increasing production costs of gray hydrogen lead to larger capacity expansions, resulting in amplified sales volumes of green hydrogen due to the increased demand for it. Conversely, if the production costs of green hydrogen rise, capacities are downscaled as a consequence.

The basic capacity Cap_{g0} is a relevant parameter only in Case II. Interestingly, a higher basic capacity triggers increased demand for green hydrogen since the green manufacturer can reduce its capacity expansions and related expenditures. This, in

turn, leads to decreasing prices for all players, except the green hydrogen retailer, which has the leeway to set a higher margin.

For taxes G_t , it appears that their impact on the variables mirrors that of the production costs c_n . When taxes rise, wholesale prices increase, lowering the gray retailer's margin and reducing the demand for gray hydrogen. Conversely, subsidies G_s for the green retailer enable it to reduce its margin without compromising profitability, thereby amplifying the demand for green hydrogen and diminishing the market share of gray hydrogen. This shift necessitates the gray retailer also to decrease its margin to offset potential profit loss, consequently leading to a drop in the wholesale price of the gray manufacturer to counterbalance the increase in demand for green products. Meanwhile, the green manufacturer gains the ability to command higher prices in the market.

From the analysis, we therefore observe that both taxes and subsidies are suitable instruments to increase the sales volume of green hydrogen. However, if we compare the two derivatives of $\partial D_g / \partial G_t$ and $\partial D_g / \partial G_s$ (A. 24 and A.25 for Case I, and A.77 and A.78 for Case II in the Appendix), we find that $\partial D_g / \partial G_t < \partial D_g / \partial G_s$. That means that subsidies can be used more effectively to stimulate an increase in demand for green hydrogen. On the other hand, the use of subsidies is opposed by the fact that they incur costs for the state. Taxes, on the other hand, represent revenue for the state. Hence, it seems reasonable to determine the optimal combination and level of these governmental instruments. Therefore, in the next section, as an extension of the two-stage supply chain model, the perspective of the state will be taken. It is integrated as an active player in the game and determines its optimal tax rate and subsidies. In addition, we also consider the parameter γ , the state's contribution to capacity expansions, as a decision variable.

4 Extension: Three-stage Game

4.1 Profit Functions

When the government is an active player in the game, we consider it a three-stage game, and since it can pursue various goals, it is a bi-objective optimization problem. Furthermore, taxes and subsidies have been considered parameters for the manufacturers and the retailer, and they are now handled as variables. On the one hand, the government wants to promote the diffusion of green hydrogen. Therefore, it is in its interest to maximize the amount of green hydrogen sold in the market:

$$\max_{\gamma, G_t, G_s} \pi_{Ga} = D_g. \quad (39)$$

However, the government is interested in keeping its expenditures as low as possible and, on the other hand, benefits from high tax revenues. Hence, a second objective is to maximize the government's profit, resulting from the difference between tax revenues and investments in subsidies and additional capacity:

$$\max_{\gamma, G_t, G_s} \pi_{Gb} = G_t D_n - G_s D_g - \gamma \eta Cap_g^2. \quad (40)$$

4.2 Solution

The government acts as the Stackelberg leader. We now delve into a bi-objective optimization problem on the government's side, employing the weighted-sum approach to merge the government's optimization problems into a single objective function, denoted by π_G . For this purpose, both objective functions need to be normalized, taking into account the minimum and maximum possible values of each individual objective function:

$$\max_{\gamma, G_t, G_s} \pi_G = \alpha \frac{\pi_{Ga} - \min(\pi_{Ga})}{\max(\pi_{Ga}) - \min(\pi_{Ga})} + \beta \frac{\pi_{Gb} - \min(\pi_{Gb})}{\max(\pi_{Gb}) - \min(\pi_{Gb})} \quad (41)$$

where $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$, and $\alpha + \beta = 1$ represent weights for the objective functions. The government seeks to find the optimal combination of γ , G_t , and G_s that maximizes the weighted objective function (41). Due to the model's complexity, it is not possible to determine symbolic closed-form expressions for the government's decision variables.

In this section, we have therefore opted for a numerical solution approach. To determine the minimum and maximum expressions of each objective function and the optimal values of the government decision variables, G_s , G_t , and γ are varied in small increments. The optimal reactions of the other players are thereby taken into account (Eqs. 18 and 19 and (24) and (25), as well as (31)–(34)). Furthermore, the government must consider that the hydrogen center will only opt for capacity expansions if they are more advantageous in terms of profit than no capacity expansion. In addition, only those solutions were considered feasible which led to positive decision variables and demands.

4.3 Numerical Analysis

The following parameter values (see Table 5) are used as the basis for the subsequent numerical and sensitivity analysis.

The selection of parameters aimed to mirror the prevailing conditions in the hydrogen market. The value of δ , which indicates the appreciation of gray hydrogen compared to the green one, was reasonably estimated based on studies indicating a 39% higher willingness to pay for green products in the transportation sector from globally surveyed customers (Pieters et al. 2023), while Koreans would be willing to pay 28.5% higher fuel costs when switching to green hydrogen (Park et al. 2022). The production costs of gray and green hydrogen can vary significantly, with gray

Table 5 Numerical example

Parameters	δ	c_n	c_g	η	Cap_{g0}
Values	0.7	0.1	0.2	1	0.1

Table 6 Results of decision variables and profits without government intervention

Decision variables	Results	Profits	Results
w_g	0.5260110	π_{Rg}	0.0108845
w_n	0.2723880	π_{Rn}	0.0219610
Cap_g	0.0904777	π_{Mg}	0.0539117
m_{Rg}	0.0571433	π_{Mn}	0.0557471
m_{Rn}	0.0679103		

hydrogen ranging from 0.8 to 2.1 € per kg and green hydrogen from 2.2 to 8.2 € per kg (Ajanovic et al. 2022). This means that green hydrogen can be approximately equally expensive or up to ten times more expensive than gray hydrogen. For the basic example, we make a rather optimistic estimate and assume a price that is twice as high. However, as part of the sensitivity analysis, both prices are varied to capture potential future developments and price fluctuations. Moreover, the expenses associated with capacity expansions are currently high, prompting us to establish the cost coefficient η at its maximum value of 1. Given the limited current production capacity of green hydrogen, we assume a low basic capacity of $Cap_{g0} = 0.1$.

In order to have a comparison regarding the effectiveness of the government measures, we first consider the situation that would occur without government intervention. For this purpose, we set $\gamma = G_t = G_s = 0$ and obtain the results displayed in Table 6.

These lead to a demand of $D_g = 0.190478$ and $D_n = 0.323382$. Gray hydrogen's low assumed production costs lead to a small selling price and an increased demand for it, mirroring a market situation that closely resembles the present state. This illustrates the need for government measures to change this situation and make green hydrogen more competitive and affordable.

We therefore now take the function in Eq. 41 and determine the optimal decisions γ , G_r , and G_s of the state for varying weights α and β assigned to the objective functions π_{Ga} and π_{Gb} . The solutions illustrated in Fig. 2 appear as points on a Pareto frontier, representing scenarios where the government, without specific preferences, remains indifferent. Since current production costs can be an important factor influencing the players' decisions, we vary them exemplarily and observe a vertical down shift of the Pareto frontier, with a smaller number of distinct feasible solutions for higher production costs of green hydrogen. The cause of this is the lower demand for green hydrogen, the higher the production costs, and, consequently, the prices for green hydrogen are.

However, if we consider a government with a high willingness to invest in favor of maximizing the sales volume of green hydrogen, i.e., $\alpha = 1$ and $\beta = 0$, the demand for green hydrogen can be increased up to $D_g = 0.449932$. The state must then bear expenses resulting in a profit of $\pi_{Gb} = -0.179964$. Another extreme point can be reached for $\alpha = 0$ and $\beta = 1$. Here, the government focuses on profits rather than a greater market diffusion of green hydrogen. This results in a demand of $D_g = 0.217846$ and $\pi_{Gb} = 0.034563$. Here, the government relies heavily on high taxes on gray hydrogen to increase its revenues, which leads to a decrease in demand for gray hydrogen and, thus, indirectly to an increase in green hydrogen.

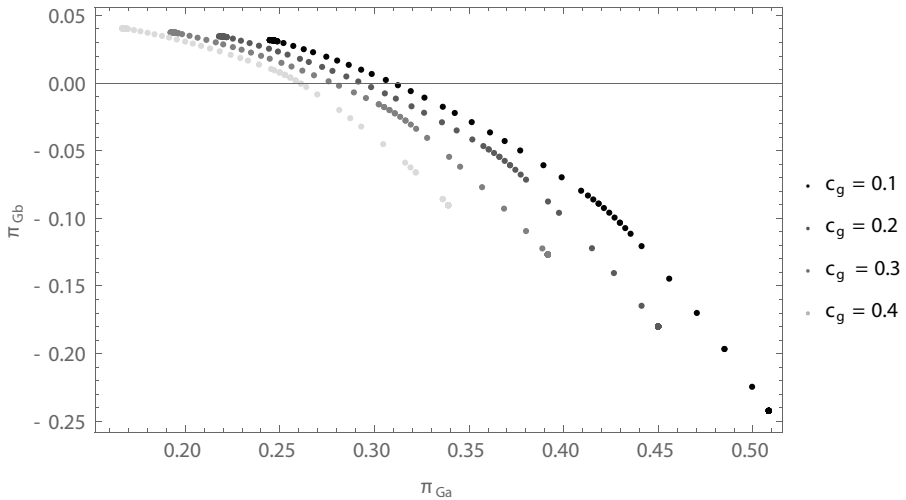


Fig. 2 Pareto frontier for different values of c_g

Hence, we observe that government intervention alone, even without a strict focus on strengthening the sales volume of green hydrogen, leads to increases in green demand compared to the benchmark case of $\gamma = G_t = G_s = 0$.

Similar to the two-stage supply chain model, we aim to discern the parameters' impact on the players' choices. Since only a numerical analysis is possible in this game, we incrementally vary the parameter values from Table 5. We consider three representative points on the Pareto frontier, namely

- the extreme point of $\alpha = 0$ and $\beta = 1$ (hereafter also referred to as situation (a)),
- an interior point with identical weights for both objective functions, i.e., $\alpha = 0.5$ and $\beta = 0.5$ (situation (b)),
- and the other extreme point of $\alpha = 1$ and $\beta = 0$ (situation (c)).

The parameter δ was one of the parameters in the two-stage supply chain model for which no clear statement could be made based on the symbolic expression of the derivative regarding its effect on the decision variables. Figure 3, 4 and 5 display the results after numerical variation. If δ increases, customers show a greater preference for gray hydrogen, resulting in a general increase in its demand. For our basic example, we see that for situation (a), where only the government's profit is in focus, this situation is utilized to increase the tax rate G_t solely with a higher value δ . The government decides against subsidies and against covering the costs of capacity expansions. However, the more important the dissemination of green hydrogen is to the state, the more it relies on positive, supportive measures, and the less on tax revenues. In situation (b), the state thus funds the hydrogen center's investments in capacity expansions, while in situation (c), additional subsidies come into effect. If δ is small and customer preference leans towards green hydrogen, less state support in the form of subsidies or taxes is required. Instead, support for capacity expansions is necessary to meet the increased demand for green hydrogen.

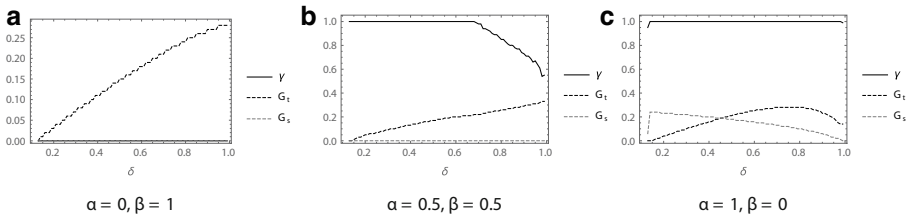


Fig. 3 Government's decision variables under variations of δ

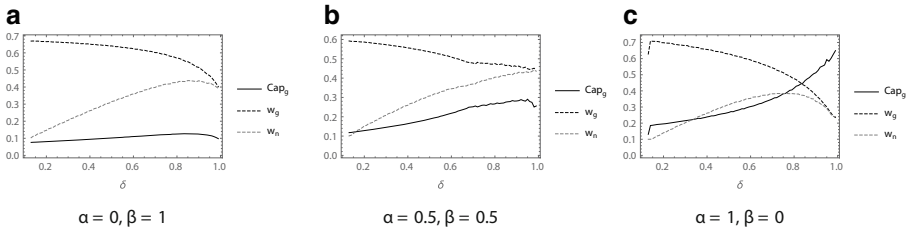


Fig. 4 Manufacturers' decision variables under variations of δ . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

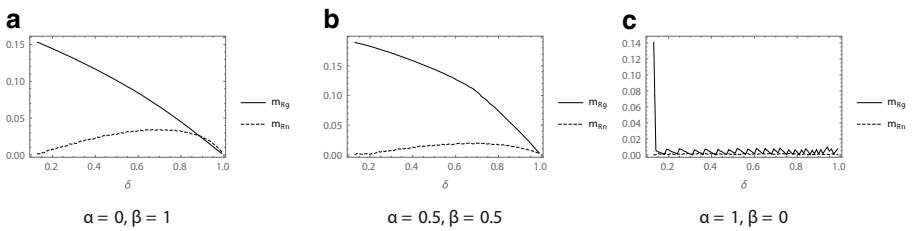


Fig. 5 Retailers' decision variables under variations of δ . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

Accordingly, the green manufacturer also increasingly expands its capacity as the state subsidizes the green retailer or the manufacturer (see Fig. 4). While the wholesale price w_n tends to increase with a higher δ in all three situations, that of the green one w_g decreases. It can be seen from Fig. 5 that the green retailer has to reduce its margin at a higher δ . In situation (c), on the other hand, the margin of the green retailer remains almost consistently at a very low level. This is due to the additional subsidies that enable the retailer to set lower prices. To avoid formally negative margins, the government must, as shown in Fig. 3, reduce its subsidies when δ increases. Each time the government reduces its subsidies by a certain value, the green margin rises shortly before falling again with a higher appreciation for the green product. This results in the zigzag pattern, which can be seen in Fig. 5c.

Rising manufacturing costs of the gray manufacturer (c_n) generally lead to a lower demand for gray hydrogen. For our example, we observe that solutions with $c_n \geq 0.53$ are not feasible and are, therefore, not displayed in Figs. 6, 7 and 8. The costs are too high for the players to determine positive prices in these situations.

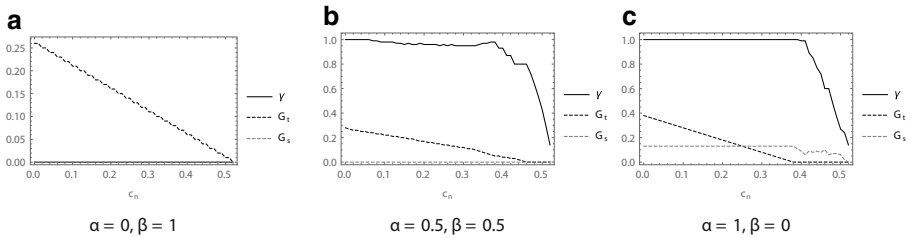


Fig. 6 Government's decision variables under variations of c_n . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

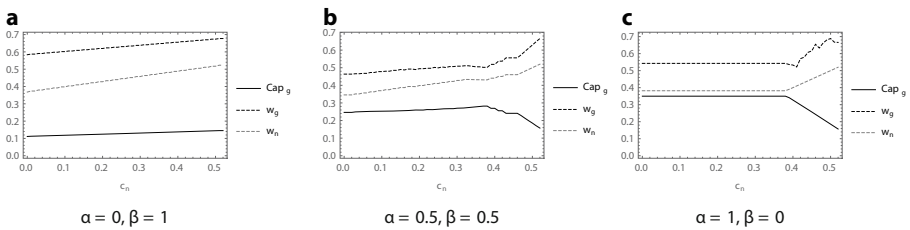


Fig. 7 Manufacturers' decision variables under variations of c_n . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

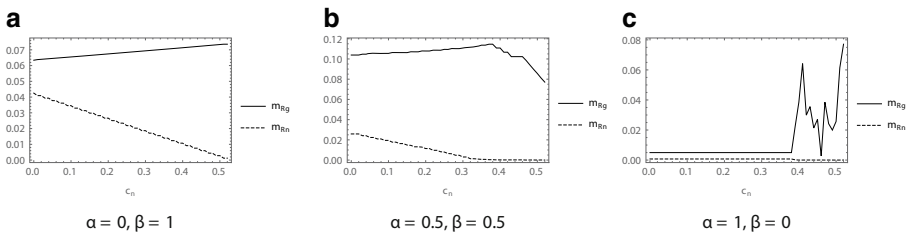


Fig. 8 Retailers' decision variables under variations of c_n . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

Furthermore, we observe that high manufacturing costs on the part of the gray manufacturer reduce the need for government intervention. As already observed in the two-stage supply chain model, the manufacturing costs c_n have a similar impact as the taxes G_t on the decision variables of the players since taxes are also added directly to the unit costs of gray hydrogen.

If the government focuses on profit (situation (a)), then as c_n increases, the government must reduce its tax rate to avoid exacerbating the decline in demand due to rising production costs with higher taxes. Both manufacturers choose higher wholesale prices w_n and w_g —the gray manufacturer to compensate for the higher production costs, and the green manufacturer to capitalize on the higher market share of green hydrogen. Hence, its capacity investments also increase. The green manufacturer also benefits from this and sets a higher margin, whereas the gray one has to reduce its margin. The retailer of gray hydrogen bears the burden of the manufacturers' price increases. The retailer reduces its margin to avoid a too strong

decrease in demand for gray hydrogen. This, in turn, allows the green retailer to increase its margin.

If the sales volume of green hydrogen is equally important to the government as the profit (situation (b)), the government financially supports the green manufacturer in the capacity expansions. Again, the green retailer’s margins increase while the gray retailer’s margins decrease with a larger c_n , and the difference between the two margins is more pronounced compared to scenario (a)—the green margin is larger due to the additional support from the state, and the gray margin is smaller. To avoid negative margins of the gray retailer, i.e., infeasible solutions, the intensity of the government’s measures decreases with a larger c_n , especially the support of capacity expansions.

In situation (c), the government again uses subsidies to increase the market share of green hydrogen further. This greatly reduces the green retailer’s margin compared to the other situations. Due to the low gray demand, the margin of the gray retailer also decreases. With rising costs c_n , taxes decrease to avoid infeasible solutions with negative margins m_{Rn} . Up to $c_n = 0.38$, the situation occurs that wholesale prices, capacity expansions, and margins remain at a constant level after each incremental tax reduction. After this point, further tax reduction is not possible, as they have already fallen to zero. Hence, the state reduces its financial support for capacity expansions, leading to shrinking manufacturing capacities for green hydrogen, rising wholesale prices, and just leaving the gray retailer with a margin of 0. If manufacturing costs c_n continue to rise, various combinations of γ and G_s lead to such a zero margin m_{Rn} . This results in a somewhat erratic behavior pattern for the green retailer’s margin, which can both rise and fall for $c_n \geq 0.38$.

Figures 9, 10 and 11 show the different behaviours of the players under variations of c_g . Generally, rising manufacturing costs of the green manufacturer lead to increasing wholesale prices w_g and, therefore, lower demand for green hydrogen D_g in all considered situations, see Fig. 10. Capacity expansions are restricted. This, in turn, allows the gray manufacturer to increase its wholesale price as it experiences rising demand. No capacity expansions are carried out once the production costs reach $c_g \geq 0.66$ in the situation (a), so the optimal solution is then found under Case I. In situation (b), this is the case for $c_g \geq 0.73$ and in situation (c) for $c_g \geq 0.82$. Hence, the more important the diffusion of green hydrogen to the state, the later capacity expansions are abandoned despite rising manufacturing costs.

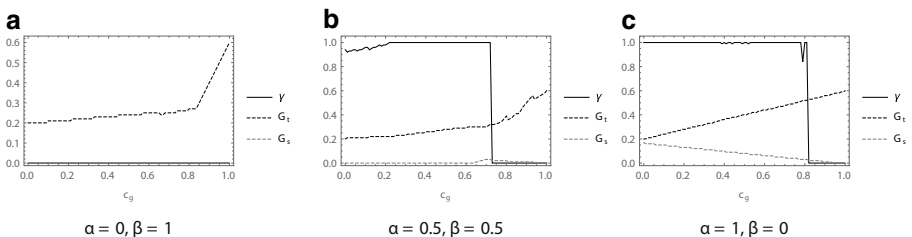


Fig. 9 Government’s decision variables under variations of c_g . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

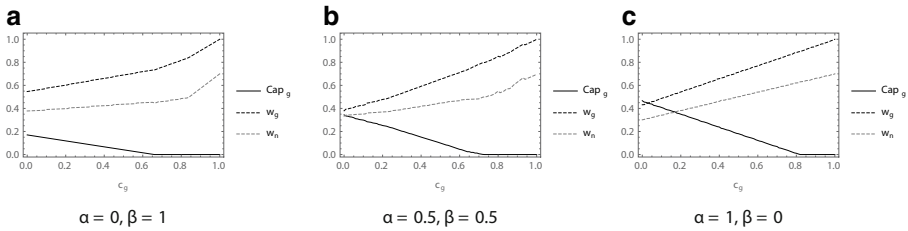


Fig. 10 Manufacturers' decision variables under variations of c_g . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

Like the other parameters, the government focuses on taxes in situation (a), taking advantage of the increasing demand for gray hydrogen. The green retailer suffers from higher manufacturing costs and has to reduce its margin, whereas the gray retailer can increase its margin. To avoid negative margins on the side of the green retailer, the state counteracts with more sharply increasing taxes from $c_g \geq 0.84$. From this point on, the margin of the gray retailer also decreases.

In situation (b), similar behavior is observed, except that the government also provides additional financial support for capacity expansions due to the increased importance of the diffusion of green hydrogen. However, these are dropped when demand falls below the basic capacity.

In situation (c), when the government focuses solely on maximizing the amount of green hydrogen D_g , the green retailer is additionally subsidized. However, these subsidies decrease with rising costs c_g , allowing the green retailer to lower its margin, hence avoiding infeasible solutions with formally negative margins. Each time the government reduces its subsidies G_s , the green retailer's margin increases temporarily to compensate before falling again at a constant subsidy level due to rising manufacturing costs. Once again, a zigzag pattern emerges; see Fig. 11.

The parameter η , the cost coefficient for capacity expansions, is the second parameter in the two-echelon supply chain model about which no clear statement could be made regarding its effect on the decision variables based on the symbolic expressions of the derivatives. Figures 12, 13 and 14 display the results after numerical variation. If the government only focuses on profit (situation (a)), taxes are once again the means of choice. The other two government instruments (γ and G_s) do not come into effect. Since an increasing value of η is associated with rising costs

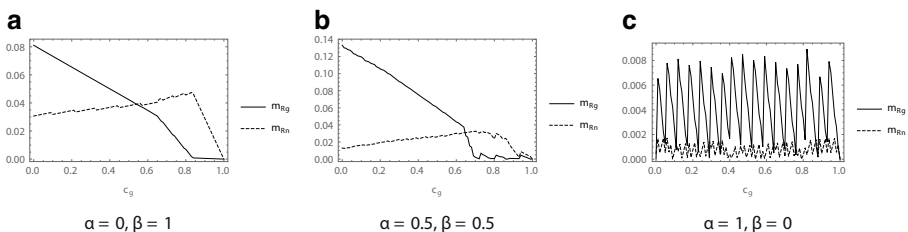


Fig. 11 Retailers' decision variables under variations of c_g . (a) $\alpha = 0, \beta = 1$, (b) $\alpha = 0.5, \beta = 0.5$, (c) $\alpha = 1, \beta = 0$

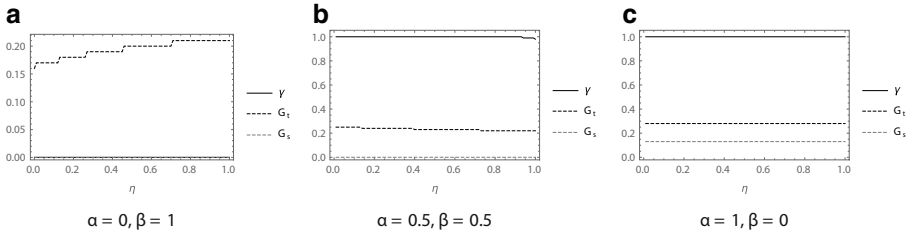


Fig. 12 Government's decision variables under variations of η . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

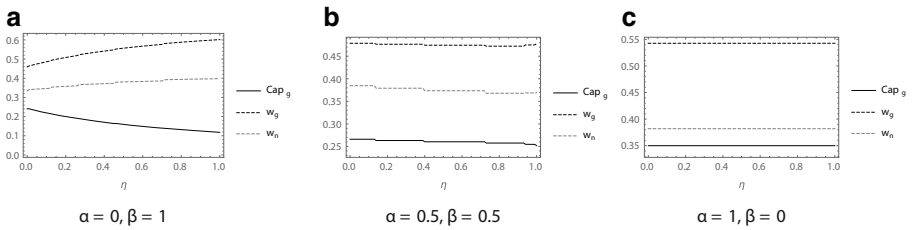


Fig. 13 Manufacturers' decision variables under variations of η . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

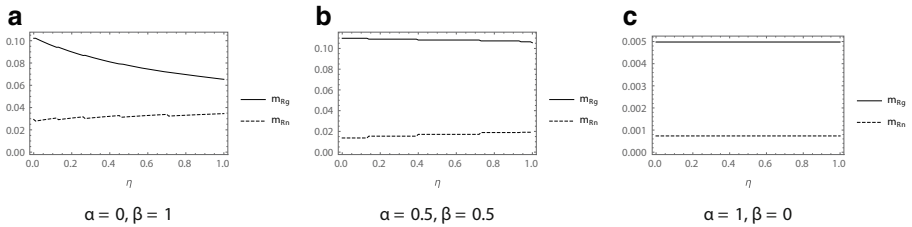


Fig. 14 Retailers' variables under variations of η . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

for capacity expansions for the green manufacturer, the capacity expansions, Cap_g , decrease (see Fig. 13), and fewer units of green hydrogen can be sold. The wholesale price of the green manufacturer increases to compensate for the financial losses. At the same time, this allows the gray manufacturer to increase its market share and its prices. The green retailer suffers from the manufacturer's price increases and has to reduce its margin, while the gray retailer can increase its margin. These effects can be counteracted to some extent by the government's use of taxes, which maximizes the government's profit in situation (a) while avoiding a sharp decrease in the sales volume of green hydrogen.

In situation (b), however, where the sales volume of green hydrogen and the government's profit are equally important, financial support will again be provided for capacity expansions. Except for extremely high values of η , these are at the maximum possible level. Compared to the situation (a), the decreases in capacity

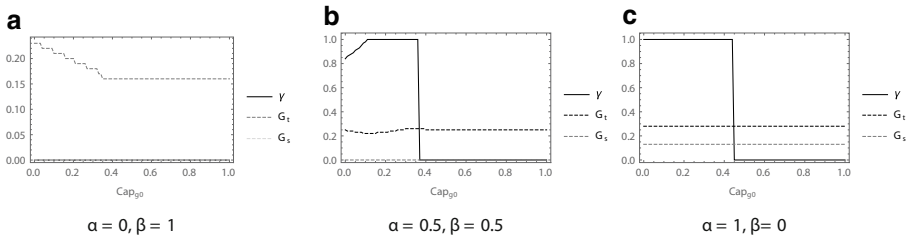


Fig. 15 Government's decision variables under variations of Cap_{g0} . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

expansions can be nearly offset, resulting in only slight changes in the players' variables.

Situation (c), when the government focuses solely on the sales volume of green hydrogen, looks very similar, but subsidies are also applied. However, through this targeted additional use of subsidies, the government achieves that all decision variables have constant values independent of η .

A larger basic capacity Cap_{g0} reduces the need for capacity expansions on the manufacturer's side in all situations (a)–(c); see Fig. 16. From certain points, the basic capacity exceeds the demand for green hydrogen, so the optimal solution is found under Case I, the unrestricted case. In situation (a), this is the case for $Cap_{g0} \geq 0.35$, in situation (b) for $Cap_{g0} \geq 0.37$, and in situation (c) for $Cap_{g0} \geq 0.45$. From then on, the players' decisions remain constant as a higher basic capacity becomes irrelevant.

In situation (a), the government again focuses on taxes as the optimal instrument; see Fig. 15. With a low basic capacity and thus a high demand for gray hydrogen, taxes are higher than with a large basic capacity. Furthermore, a rising basic capacity leads in situation (a) to both manufacturers lowering their wholesale prices. The gray manufacturer, in order to offset its demand losses, and the green manufacturer, as it has fewer expenses for capacity expansions. This allows the green retailer to increase its margin without loss of demand—in fact, the demand for green hydrogen increases with a larger basic capacity. The gray retailer, however, has to decrease its margin to offset the decline in the demand for gray hydrogen, see Fig. 17.

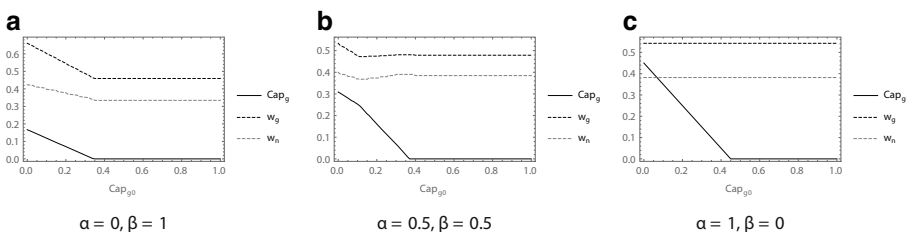


Fig. 16 Manufacturers' decision variables under variations of Cap_{g0} . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

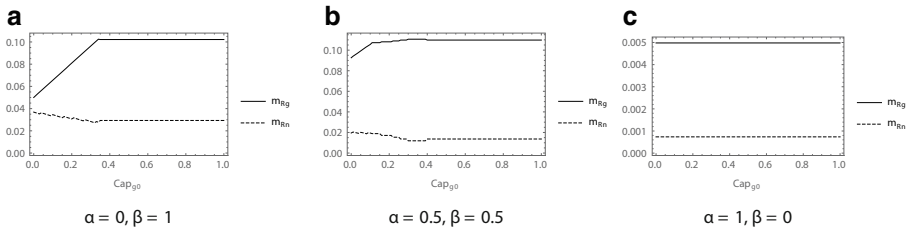


Fig. 17 Retailers' decision variables under variations of Cap_{g0} . (a) $\alpha = 0, \beta = 1$. (b) $\alpha = 0.5, \beta = 0.5$. (c) $\alpha = 1, \beta = 0$

In situation (b), the government again supports the green manufacturer with capacity expansions until the demand exceeds the basic capacity. For the other variables, a similar behaviour as in situation (a) can be observed.

In situation (c), the state aims at maximizing the amount of green hydrogen sold. As already observed for the other parameters, all three government instruments are now being used. Hence, the green retailer is additionally subsidized. Irrespective of the specific value of Cap_{g0} , the demand for green hydrogen remains at a constant, maximum possible level using these three instruments. Further intervention, e.g., increasing subsidies, would lead to infeasible solutions. Therefore, all variables remain constant, apart from the capacity expansions of the green manufacturer and the government support for these. As soon as the basic capacity exceeds demand, these are reduced again.

5 Managerial Insights and Conclusion

In this paper, we introduced a hydrogen supply chain featuring competition between a green and a gray hydrogen manufacturer, and selling their products to the respective retailer. The capacity of the green manufacturer is limited, which may necessitate expansion to meet demand. In the future, green hydrogen should be more competitive than it is currently. We therefore examined three government instruments: subsidies to the green retailer, taxes on gray hydrogen, and support for the green manufacturer's capacity expansion costs.

In the two-stage supply chain model, we treated the state as a passive player to answer the first research question, considering state measures as exogenous parameters. This approach facilitated a sensitivity analysis utilizing symbolic expressions. Our findings indicated that both taxes and subsidies can potentially increase the sales volume of green hydrogen, with subsidies exhibiting a more pronounced impact. However, conclusive statements regarding supporting capacity investments could not be drawn.

As an extension of the two-stage model, we considered the state an active player, aiming to promote the diffusion of green hydrogen and minimize expenditures. Therefore, a bi-criteria approach was developed and presented to solve the model. To answer the second and third research questions, we conducted a numerical analysis.

In summary, it can be said that the market position of green hydrogen can be strengthened through

- a) a state intervention in general. Regardless of the state's preferences (increase in demand vs. profit maximization) and the specific nature of government measures, the supply chain benefits from the government's involvement from an ecological perspective.
- b) an increase in the cost of gray hydrogen production. This can be achieved by demanding taxes per unit produced, mirroring the impact of elevated production costs. In other words, the state could also intervene in the raw materials market in a regulatory manner. Such interventions prove particularly effective when the state's primary concern is limiting financial resources or maximizing profit.
- c) implementing positive, supportive measures, such as subsidies for the retailer and financial support for capacity expansions. The more important it is to the state to maximize the sales volume of green hydrogen, the more important the use of subsidies as an instrument becomes. On the other hand, if the goal is to maximize the quantity of green hydrogen while simultaneously limiting expenses (equally weighted objectives), the state should prioritize support for capacity expansion.

While we have considered capacity constraints on the green manufacturer's side, extending the model could involve incorporating the electricity supplier's perspective. Notably, electricity generated from renewable sources experiences fluctuations in both availability and prices. Integrating the supply side and the uncertainties associated with it into the model has the potential to yield additional insightful observations. Furthermore, the model could be expanded by examining multiple manufacturers and retailers of each type, providing a more comprehensive representation of the hydrogen market. Although green hydrogen is currently regarded as the most promising type of hydrogen, blue hydrogen, which involves the use of carbon capture and storage technologies, can also be of interest during a transitional phase. Future models could analyze this as an additional alternative to gray hydrogen. Another interesting aspect for further investigation lies in the examination of competing products not only within the hydrogen market but also with other energy carriers. For instance, Zwickl-Bernhard and Auer 2022 examine green hydrogen competing with conventional fuels. These studies could be expanded by including governmental interventions to gain further insights.

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Conflict of interest M. Beranek and U. Buscher declare that they have no competing interests.

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