Working Paper

Development of Hydrogen Valleys: Defining a Merit-order of End-uses

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Development of Hydrogen Valleys: Defining a Merit-order of End-uses *

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Abstract

Hydrogen valleys, which integrate renewable energy sources, hydrogen infrastructure, and end-use applications, play a crucial role in decarbonizing industrial energy hubs. However, the large-scale deployment of hydrogen is constrained by limited renewable electricity availability and high technology costs. To address these challenges, we develop a framework for optimally allocating renewable hydrogen across end-use sectors to maximize social welfare. A key insight from our analysis is that the merit order of hydrogen end-uses is dynamic, evolving with an increasing Social Cost of Carbon (SCC). When the SCC surpasses a threshold defined by the Social Opportunity Cost of Abatement (SOCA), allocating hydrogen to the most emissions-intensive sector becomes socially optimal, even if that sector has a higher sectoral abatement cost. Additionally, we demonstrate that minimizing welfare losses requires prioritizing sectors with limited viable low-carbon alternatives, ensuring that hydrogen is deployed where it delivers the greatest marginal benefit. A two-period dynamic model further illustrates how investment decisions should prioritize applications with higher learning potential in the initial period to accelerate cost reductions and long-term efficiency gains. We also evaluate second-best policy instruments in scenarios where carbon taxation alone fails to fully internalize externalities. Our findings indicate that demand-side subsidies, which directly support hydrogen adoption in end-use sectors, are more effective than production subsidies in ensuring a better alignment of hydrogen allocation with the social welfare optimum. We calibrate the model to the Industrial-Port-Zone of Marseille-Fos, revealing that sectors with limited low-carbon alternatives, such as chemicals and sectors with high learning potential such as steel industry, rank highest in the merit order for hydrogen deployment.

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Table 1: Table of Abbreviations

Abbreviation	**Full Form**
SMR	Steam Methane Reforming
Bio-SMR	Biomass-based Steam Methane Reforming
BF/BOF	Blast Furnace / Basic Oxygen Furnace
NG-DRI-EAF	Natural Gas-based Direct Reduced Iron with Electric Arc Furnace
CCS	Carbon Capture and Storage
FCEV	Fuel Cell Electric Vehicle
BEV	Battery Electric Vehicle
VLSFO	Very Low Sulfur Fuel Oil
HEFA	Hydroprocessed Esters and Fatty Acids (Biojet Fuel)

1 Introduction

The transition to a low-carbon economy has positioned renewable hydrogen as a key solution for decarbonizing hard-to-abate sectors where direct electrification is not technically feasible. However, hydrogen deployment faces significant economic challenges, including supply chain disruptions, high storage and transportation costs, and delayed policy and regulations (International Energy Agency 2023a). These barriers have slowed investments, delaying many developers' Final Investment Decisions (FIDs). By 2023, only 7% of the announced hydrogen projects became operational (Odenweller and Ueckerdt 2025). Hydrogen Valleys—integrated ecosystems that connect renewable energy sources, hydrogen infrastructure, and multiple end-use applications—offer a promising framework for addressing these challenges (European Commission 2023a). By leveraging economies of scale and reducing reliance on extensive transport infrastructure, these regional hubs can help lower the overall cost of the energy transition.

The challenge regarding those hydrogen valleys is the fact that the high cost of electrolysis and the intermittent availability of the local renewable electricity—especially during peak demand or periods of low generation—create bottlenecks for green hydrogen production, limiting its physical availability. Given this constraint, the limited supply of renewable hydrogen must be allocated in the most cost-efficient manner. While hydrogen may be produced at a uniform cost across the economy, its impact varies by sector due to differences in their abatement potential and end-use sector-specific technologies. A socially suboptimal allocation of hydrogen could significantly increase the cost of the energy transition and the burden of support policies. Therefore, ensuring efficient deployment—through the prioritization and optimization of Hydrogen Valleys—has become critical for resource allocation. As a result, there is a growing call for more targeted policy support mechanisms to enhance the cost-effectiveness of hydrogen integration (European Commission 2023a).

This study is motivated by the European Union's (EU) ambitious climate goals outlined in the European Green Deal and the "Fit for 55" package, which target a 55% reduction in greenhouse gas emissions by 2030, with hydrogen as a key component in this transition (European Commission 2023b). The REPowerEU plan, formulated to address energy security concerns and reduce reliance on fossil fuels, further emphasizes this commitment by setting specific targets for scaling up renewable hydrogen production and utilization. Notably, REPowerEU aims to double the number of Hydrogen Valley announced projects in Europe by 2025 and to establish 100 such hubs by 2030 (European Commission 2023b). To facilitate these goals, the European Commission has dedicated an additional €200 million for Hydrogen Valleys through the Clean Hydrogen Partnership, raising total investment across 16 projects in 15 European countries to over €1 billion. Despite these initiatives, only 32% of Hydrogen Valley projects have reached FID, accounting for a mere 6% of total planned production volume. This limited progress underscores two issues. First, a gap between production costs and buyers' willingness to pay has hindered projects from securing committed offtakers, threatening the stability of the low-emission hydrogen market. Second, the current landscape reveals that mostly smaller-scale, first-mover projects have progressed to construction or operation, leaving the majority of initiatives in a "follower" position. For operational Hydrogen Valleys, showcasing the performance and reliability of key hydrogen technologies is essential to validate the sector's potential and facilitate knowledge transfer to subsequent developers.

To tackle these challenges, Hydrogen Valley developers must implement structured resource allocation strategies and prioritize hydrogen end-uses cost-efficiently. This paper addresses the following question: How should renewable hydrogen be optimally allocated within Hydrogen Valleys given the overall constraint on hydrogen availability at a given point in time? Specifically, we aim to develop a prioritization framework, or "merit order," for end-use sectors within local ecosystems, balancing cost-efficiency with emission reduction potential. This prioritization is essential, as the high cost of hydrogen production and limited renewable electricity supply require careful selection of end uses. Currently, the privately achieved merit order is shaped by the incentives and constraints faced by individual firms or sectors, such as profitability, market prices, capital constraints, and existing policy incentives. However, herein, we consider an optimal merit order for end-uses of hydrogen which is determined by maximizing overall welfare, which involves considering factors like Greenhouse Gas Emissions (GHG) at their social damage costs and technology learning curves that allow accounting for long-term benefits of the renewable hydrogen deployment. Addressing this question could enable policymakers to better design a demand support policy for the hydrogen sector, particularly by targeting the sectors with the highest "merit". Consequently, an optimal policy instrument that supports this prioritized framework should be considered to restore and sustain the optimal merit order across the end-use sectors.

A growing body of research has examined the merit-order of clean hydrogen deployment across end-use sectors, employing various criteria to guide allocation decisions. However, existing studies exhibit several key limitations that constrain their applicability to real-world policy design. One fundamental limitation is that most studies provide broad global-scale guidelines for policymakers (e.g., International Energy Agency 2019, FCH 2 JU 2019, Hydrogen Council 2021), yet they often fail to account for regional economic and environmental heterogeneity. Energy flows, infrastructure availability, and sectoral hydrogen demand vary significantly across regions, meaning that broad assessments may not provide optimal or actionable deployment strategies tailored to specific local conditions. Existing research primarily relies on sector-specific criteria for hydrogen integration, as summarized in Table 2, but does not capture regional variations in market conditions and infrastructure constraints.

Another limitation of existing studies in ranking the end-uses of hydrogen, such as International Energy Agency 2019, FCH 2 JU 2019, and Hydrogen Council 2021, is that while they assess sector-specific criteria to evaluate hydrogen adoption across end-use sectors, their analyses remain largely qualitative and do not offer a comprehensive, quantitatively optimized ranking framework that balances multiple economic and environmental trade-offs. These studies typically assess Technology Readiness Levels (TRLs) of hydrogen-based technologies, along with the cost of transitioning existing infrastructure, leading to recommendations that initially prioritize low-carbon hydrogen deployment in sectors already using fossil fuel-based hydrogen, such as chemical production (i.e. ammonia and methanol) and oil refining. However, their long-term prioritization strategies diverge. For instance, the IEA envisions a high long-term potential for hydrogen in buildings, aligning with its vision of a low-carbon future. In contrast, FCH 2 JU 2019 prioritizes heavy-duty road mobility (i.e. buses, trucks, and vans) over buildings, citing the availability of competitive low-carbon alternatives for heating. Similarly, Hydrogen Council 2021 also emphasizes road mobility, arguing that it relies on higher-emitting fuels like diesel, whereas chemical industries primarily use natural

Table 2: Comparison of Criteria Across Studies

Criteria	International Energy Agency 2019	Hydrogen Council 2021	Bloomberg NEF 2020	FCH 2 JU 2019	Ueckerdt et al. 2021	Geoffron and Appert 2021
Existence of zero and low-carbon alternatives	✓		✓			
Technology Maturity	✓		✓			
Safety Issues						✓
Competitiveness with conventional fossil fuels		✓	✓	✓		✓
Competitiveness with zero and low-carbon alternatives					✓	
Sector-specific deployment cost	✓	✓	✓			✓
Abatement potential	✓				✓	
Existing Public Support			✓	✓		

gas, which has a lower carbon footprint.

While some studies attempt to quantify sectoral prioritization using economic tools, they also exhibit certain shortcomings. Research such as Geoffron and Appert 2021, Ueckerdt et al. 2021, Bloomberg NEF 2020, and Shafiee and Schrag 2024 adopt abatement cost as the primary decision metric, which is the cost of reducing one unit of CO_2 emissions through a decarbonization pathway. This approach follows the methodology introduced by McKinsey & Company 2009 in its Marginal Abatement Cost (MAC) curves, which rank abatement measures from lowest to highest cost. However, these studies yield inconsistent rankings for hydrogen end-use sectors due to variations in how they define abatement costs. For example, Bloomberg NEF 2020 considers only technology costs relative to abatement potential, ranking road mobility first, given its reliance on high-emitting diesel. In contrast, Geoffron and Appert 2021 argues that sectors already using fossil fuel-based hydrogen (chemicals, refineries) incur lower infrastructure transition costs, resulting in a lower abatement cost. Their framework also accounts for safety concerns in mobile and residential hydrogen applications, leading them to rank road mobility and residential heating lower. Ueckerdt et al. 2021 evaluates abatement costs for hydrogen versus electrification within each sector, concluding that direct electrification options in road mobility are more cost-effective than hydrogen. This approach prioritizes hard-to-abate sectors such as aviation and shipping, labeling them as ”no-regret” sectors due to the lack of alternative low-carbon solutions. Shafiee and Schrag 2024 integrates storage, distribution, and refueling costs into the abatement cost framework, ultimately ranking road freight applications lower than industrial uses, which depend less on transportation infrastructure.

Despite the insights provided by ranking the end-use sectors through standard approaches, the main limitation with them is the fact that they fail to account for inter-sectoral impacts and do not optimize the overall energy transition cost at an economy-wide level. The focus on individual sectors leads to potential misallocation of hydrogen resources by overlooking opportunity costs, i.e., the welfare losses incurred by selecting one sector over another when the availability of renewable hydrogen is constrained. Furthermore, these models typically assume static sectoral rankings, ignoring the dynamic evolution of technological progress over time. Consequently, they may misrepresent the long-term economic viability and comparative advantage of hydrogen applications across sectors.

Furthermore, despite growing policy interest in renewable hydrogen deployment, the economic literature on hydrogen support policies remains relatively limited. However, recent studies offer valuable insights into the design and effectiveness of subsidies for renewable hydrogen production. Fell et al. 2024 examine optimal subsidy design for green hydrogen production under the Inflation Reduction Act (IRA) in the United States. Their analysis explores whether differentiated or undifferentiated subsidies based on the electricity source yield the most cost-effective outcomes to expand hydrogen production. Similarly, Hoogsteyn et al. 2025 investigate the interactions and distortions that arise from different hydrogen supply support policies. Their findings suggest that production-based subsidies lead to suboptimal operational decisions for electrolysers, while capacity- and investment-based support schemes introduce a minor technology bias, subtly influencing the adoption of certain electrolyser technologies. Additionally, Chaton and Metta-Versmessen 2023 assess the effectiveness of carbon contracts for differences (CCfDs) as a mechanism to incentivize the decarbonization of hydrogen production. Their findings indicate that CCfDs can help close the cost gap between fossil-based and renewable hydrogen, enhancing the competitiveness of green hydrogen. However, they also highlight key implementation challenges, particularly in determining an appropriate strike price and ensuring long-term policy stability. While these studies contribute significantly to the understanding of hydrogen support mechanisms, they primarily focus on the supply-side—analyzing policies that support hydrogen production. However, they do not explore the economic effectiveness of demand-side subsidies—such as incentives for hydrogen adoption in industry and transport sectors compared with supply-side interventions. This is a critical gap, as the effectiveness of hydrogen deployment depends not only on production incentives but also on how efficiently hydrogen is allocated and utilized across sectors. This gap in the literature is particularly relevant given the findings of Goulder and Parry 2008, who emphasize that untargeted environmental policies tend to be inefficient. In the case of hydrogen, this suggests that a balanced policy mix, combining carbon pricing with both supply- and demand-side support mechanisms, may be essential to minimize market inefficiencies and maximize the decarbonization impact of subsidies.

This study makes several key contributions to the economic literature on hydrogen deployment merit order, addressing certain methodological, normative, and applied gaps in previous research. From a methodological perspective, we develop a novel framework for determining the merit order of renewable hydrogen end-uses. The proposed model incorporates multiple end-use sectors, each with the option to adopt fossil-fuel-based, hydrogen-based, or low-carbon alternative technologies. We minimise the total discounted social cost of the energy transition by identifying the optimal allocation of renewable hydrogen to each end-use sector at a given period of time. A key innovation is the explicit constraint on hydrogen availability, which highlights opportunity costs—the welfare trade-offs between competing sectors under hydrogen scarcity. To quantify this effect, in a simplified setting of the model with only two end-use sectors, we introduce a new metric, the Social Opportunity Cost of Carbon Abatement (SOCA), which captures the implicit cost of prioritizing one sector over another in a constrained hydrogen supply environment. Our findings challenge conventional approaches that prioritize sectors with lower abatement costs, demonstrating that under higher Social Cost of Carbon (SCC) scenarios, optimal hydrogen allocation should favor sectors with greater abatement potential, even if their sectoral abatement cost is higher. We show under which conditions misallocation of hydrogen to a sector with a higher sectoral abatement cost could lead to a loss in social welfare. Furthermore, we extend the analysis to incorporate competition with low-carbon alternatives, showing that hydrogen should be allocated preferentially to sectors with a less competitive low-carbon alternative to maximize social welfare. Finally, we account for technological learning and progress, demonstrating in a two-period dynamic model how long-term discounted benefits can alter the ranking of end-use sectors in the hydrogen merit order.

From a normative policy perspective, this study provides a comparative evaluation of hydrogen support mechanisms, revealing that demand-side subsidies result in greater emissions reductions and lower social costs than production-based subsidies. Our analysis shows that production subsidies alone may lead to misallocation, failing to direct hydrogen toward its most impactful uses. In contrast, demand-side incentives better align hydrogen deployment with decarbonization priorities. These findings provide important policy insights for designing efficient hydrogen deployment strategies that balance market incentives with environmental objectives.

On the applied side, we calibrate our model to the Industrial-Port-Zone of Marseille-Fos, a key hydrogen hub in France that integrates large-scale hydrogen production with diverse end-use applications. This case study incorporates greenhouse gas (GHG) emissions and air pollution, accounting for their social damage costs, as well as sector-specific hydrogen deployment costs, which are often overlooked in existing studies. For instance, mobility applications require higher hydrogen purity for fuel cells, leading to increased costs, while storage and distribution requirements further impact the sector-specific economics of hydrogen deployment. Additionally, we assess the competitiveness of low-carbon alternatives, ensuring a more comprehensive evaluation of hydrogen's role within the energy transition. Even in sectors traditionally classified as "no-regret" options for hydrogen adoption—such as industries currently reliant on fossil-fuel-based hydrogen—alternative decarbonization pathways, such as Carbon Capture and Storage/Utilization (CCS/CCUS) are considered. Additionally, we incorporate emerging applications of hydrogen, such as its role in the steel industry, where the potential for technological learning and cost reductions could significantly impact its long-term competitiveness. By integrating these sectoral trade-offs, our analysis provides a more refined perspective on optimal hydrogen allocation within regional decarbonization strategies. The insights gained from this case study contribute to the broader conversation on hydrogen valleys, a cornerstone of European hydrogen policy, and offer empirical evidence to support the strategic planning of hydrogen infrastructure at both regional and national levels.

The remainder of this paper is structured as follows. Section 2 introduces the general framework of our model, which incorporates multiple end-use sectors and their respective technological choices. To better illustrate the impact of key parameters—such as the Social Cost of Carbon (SCC) and the availability of low-carbon alternatives—on the optimal allocation of hydrogen, we first analyze a simplified two-sector model. This allows us to highlight the opportunity costs associated with hydrogen deployment when supply is constrained.

Furthermore, we extend the analysis to a two-period dynamic model, demonstrating how learning-by-doing and technological progress influence the evolving merit order of hydrogen end-uses over time. We also examine second-best policy instruments, particularly in scenarios where carbon taxation cannot fully internalize the externalities due to political or economic constraints. In such cases, we argue that an optimal policy mix should include learning subsidies alongside targeted supply- and demand-side incentives, comparing the effectiveness of subsidies for hydrogen producers (to reduce production costs) versus subsidies for end-use sectors (to accelerate deployment). In Section 3, we calibrate our model to the Industrial-Port-Zone of Marseille-Fos introducing two different scenarios for the renewable hydrogen availability and production costs. Section 4 presents the numerical results of this case study, providing empirical insights into the optimal allocation of renewable hydrogen under several designed policy pathways. Section 5 discusses the policy implications of our findings, particularly in the context of hydrogen valley development, sector-specific decarbonization strategies, and subsidy design. Finally, Section 6 concludes with recommendations for the development of regional hydrogen ecosystems, emphasizing the need for integrated policy frameworks that balance market incentives, technological progress, and environmental objectives.

2 A Merit-Order Model for Hydrogen Demand

2.1 The General Model

The model considers an economy with S end-use sectors (hereafter referred to as sectors), each of which consumes energy to produce a single good. For simplicity, we assume that each sector i has an inelastic energy demand of $N_{i,t}$ in terms of fossil fuel in each period of time of t. However, this demand can be met using one of the three available technology options.

The first option is a carbon-intensive fossil fuel technology with a sector-specific deployment cost of $K_{F,i,t}$, a fossil fuel price of $C_{F,i,t}$, and an emission intensity of E_i, which incurs a social cost of CO_2 emissions of $p_{CO2,t}$. The second option is a hydrogen-based technology, which involves sector-specific deployment costs denoted by $K_{H,i,t}$ and the cost of renewable hydrogen production $C_{H,i,t}$. The third option is the most competitive carbon-neutral, non-hydrogen alternative available on the market, which may include technologies such as direct electrification, biofuels, or Carbon Capture, Utilization, and Storage (CCUS). This option is associated with deployment costs $K_{A,i,t}$ and the cost of fuel or electricity $C_{A,i,t}$. We assume that both hydrogen-based and alternative technologies are carbon-neutral, with no associated emissions.

The social welfare of sector i at each period of time t is negatively influenced by its social cost (Γ_i), which is expressed as:

$$\begin{aligned}\Gamma_{i,t}(q_{F,i,t}, q_{H,i,t}, q_{A,i,t}) = {} & [p_{CO2,t}E_i + K_{F,i,t} + C_{F,i,t}]q_{F,i,t} \\ & +[K_{H,i,t} + C_{H,t}]q_{H,i,t} + [K_{A,i,t} + C_{A,i,t}]q_{A,i,t} \end{aligned} \tag{1}$$

Here, $q_{F,i,t}$, $q_{H,i,t}$, and $q_{A,i,t}$ represent the annual energy consumption of the fossil fuel-based, hydrogen-based, and carbon-neutral alternative technologies at time t, respectively.

The annualized sector-specific deployment costs of $K_{F,i,t}$, $K_{H,i,t}$, and $K_{A,i,t}$ are expressed per unit of energy consumption and represent the end-use sector-specific adjustment costs of adopting the respective technology, excluding the capital costs associated with energy production.

As the demand for goods in each sector i is assumed to be inelastic, the total energy consumption per sector is fixed. Therefore, the energy consumed by the available technologies must satisfy the following energy balance constraint.

$$N_{i,t} = q_{F,i,t} + \eta_{H,i} q_{H,i,t} + \eta_{A,i} q_{A,i,t}, \quad \forall t.$$

Where $N_{i,t}$ is the total energy demand of the sector expressed in terms of fossil fuel-based technology consumption in the sector i. The parameters $\eta_{H,i}$ and $\eta_{A,i}$ denote the energy efficiency of hydrogen-based and carbon-neutral alternative technologies, respectively, compared to fossil fuel-based technology. While technical advancements could potentially improve energy efficiency over time, for simplicity, we assume these parameters remain constant throughout our model. Replacing this constraint in the social cost of the sector gives:

$$\begin{aligned}\Gamma_{i,t}(q_{H,i,t}, q_{A,i,t}) = [p_{CO2,t}E_i + K_{F,i,t} + C_{F,i,t}](N_{i,t} - \eta_{H,i} q_{H,i,t} - \eta_{A,i} q_{A,i,t}) \\ +[K_{H,i,t} + C_{H,t}]q_{H,i,t} + [K_{A,i,t} + C_{A,i,t}]q_{A,i,t}\end{aligned} \quad (2)$$

The problem is dynamic over T periods, where the social cost of carbon increases according to Hotelling's rule, following the social discount rate r. The cost of hydrogen technology in the sector i ($K_{H,i,t}$) decreases with the cumulative production of hydrogen units $Q_{H,i,t} = \sum_{\tau=0}^{t} q_{H,i,\tau}$, reflecting a learning-by-doing effect at a rate of $\lambda_{H,i}$. Additionally, the cost of hydrogen production C_H is assumed to decrease over time at a rate h. The equation 2 rewrites as:

$$\begin{aligned}\Gamma_{i,t}(q_{H,i,t}, Q_{H,i,t}, q_{A,i,t}) = [E_i p_{CO2}(r,t) + K_{F,i,t} + C_{F,i,t}](N_i - \eta_{H,i} q_{H,i,t} - \eta_{A,i} q_{A,i,t}) \\ +[K_{H,i}(\lambda_{H,i}, Q_{H,i,t}) + C_H(h,t)]q_{H,i,t} + [K_{A,i,t} + C_{A,i,t}]q_{A,i,t}\end{aligned} \quad (3)$$

The social planner's problem is to minimize the aggregate social cost of an economy with S sectors over T periods of time, with $\delta(r,t)$ the discount factor.

$$\min_{\forall i,t,q_{H,i,t},q_{A,i,t}} \Gamma = \sum_{t}^{T} \sum_{i}^{S} \delta(r,t) \Gamma_{i,t}(q_{H,i,t}, Q_{H,i,t}, q_{A,i,t}) \quad (4)$$

under the following constraints

$$\forall i, \forall t, q_{H,i,t} \geq 0; q_{A,i,t} \geq 0 \quad \text{(Non-negative variables)} \quad (5)$$

$$\forall i, \forall t, N_i - \eta_{H_i} q_{H,i,t} - \eta_{A_i} q_{A,i,t} \geq 0 \quad \text{(Saturation of sector } i\text{)} \quad (6)$$

$$\forall i, Q_{H,i,t+1} = Q_{H,i,t} + q_{H,i,t} \quad \text{(Learning-by-doing in sector } i\text{)} \quad (7)$$

$$\forall t, \sum_{i}^{S} q_{H,i,t} \leq H_t < \sum_{i}^{S} N_i \quad \text{(Hydrogen production limit)} \quad (8)$$

Concerning the constraint 8, H_t represents the maximum amount of hydrogen that can be produced *locally* in the economy at time t. It is assumed that at any time t, the total demand for renewable hydrogen across all sectors does not exceed this upper supply limit. This limit is treated as exogenous, meaning it is independent of the cost of hydrogen production. Practically, this means that if the quantity of hydrogen produced is less than H_t, its price is equal to the production cost. However, if the demand exceeds H_t, the price becomes prohibitively high, making any additional hydrogen unavailable. This constraint reflects a physical limitation: the amount of renewable hydrogen production is restricted by the capacity of the local renewable electricity ecosystem. The supply constraint also relates to the concept of merit order: the available renewable hydrogen is limited by factors outside production costs, such as physical and technological constraints. Over time, it is assumed that the maximum supply of hydrogen (H_t) grows at a constant rate h, which aligns with the decrease in C_H. In this way, the availability of hydrogen increases alongside reductions in its cost, but only in the long term.

2.2 A Simple Model with Two End-Use Sectors: Influence of Parameters in a First-Best Setting

This section examines the impact of the model parameters on the optimal allocation of renewable hydrogen in a simplified framework with two end-use sectors ($S = 2$) in single or two-period setting ($T = 0$ or $T = 1$). The following hypothesis will be considered in this section:

Assumption 1 *At any time, the availability of decarbonized hydrogen is constrained such that only one sector can be partially decarbonized using hydrogen:*

$$H_t \leq \min(N_1, N_2)$$

The objective is to determine the merit order for allocating hydrogen under resource constraints, ensuring aggregate social welfare is maximized.

The primary question is: If hydrogen-based technology is the most cost-effective option for decarbonization in each sector, but the availability of renewable hydrogen is constrained, how should hydrogen be allocated to optimize overall welfare? The following subsections analyze the influence of key parameters on this decision, including: the social value of emissions, the existence of alternative carbon-neutral technology, and dynamic effects such as learning-by-doing.

2.2.1 Impact of the Social Value of Emissions

In this section, we assume a single time period ($T = 0$) and no alternative low-carbon technology ($q^*_{Ai} = 0$). These assumptions will be relaxed in the following subsections.

The cost minimization problem in Equation (2) is simplified as:

$$\min_{\forall i, q_{H_i}} \Gamma = \sum_{i=1}^{2} (p_{CO2} E_i + K_{F,i} + C_{F,i})(N_i - \eta_{Hi} q_{H_i}) + (K_{Hi} + C_H) q_{H_i} \tag{9}$$

The first-order conditions (FOC) define **"Abatement Cost"** (AC) as the threshold value for p_{CO2} beyond which sector i adopts renewable hydrogen:

$$AC_i(C_H) = \frac{(K_{H,i} + C_H) - (K_{F,i} + C_{F,i})\eta_{H,i}}{\eta_{H,i}E_i} \tag{10}$$

The *abatement cost* for each end-use sector is the total additional cost per amount of avoided emissions. Without a constraint on total hydrogen availability, the *abatement cost* is a standard benchmark for the sector-specific decision in the deployment of decarbonized resources. If the social value of CO_2 emissions exceeds the abatement cost ($p_{CO2} > AC_i$), the sector partially adopts renewable hydrogen, with demand given by $q_{H,i} = H$. In contrast, if $p_{CO2} < AC_i$ the sector does not deploy renewable hydrogen ($q_{H,i} = 0$).

However, when the economy consists of two end-use sectors ($S = 2$) and the abatement cost of both sectors is lower than the social value of CO_2, but the total hydrogen production is constrained ($q_{H,1} + q_{H,2} = H$), it becomes necessary to establish a merit order for allocating hydrogen between the two sectors to optimize the overall welfare of the economy.

The problem of minimization of the overall social cost of the economy in Equation (4) is simplified to the following:

$$\begin{aligned}\min_{\forall i, q_{H,i}} \Gamma = &[(p_{CO2}E_2 + K_{F,2} + C_{F,2})(N_2 - \eta_{H,2}(H - q_{H,1})) + (K_{H,2} + C_H)(H - q_{H,1})] \\ &+ [(p_{CO2}E_1 + K_{F,1} + C_{F,1})(N_1 - \eta_{H,1}q_{H,1}) + (K_{H,1} + C_H)q_{H,1}].\end{aligned} \tag{11}$$

New threshold value for the social value of emissions which is referred to as the **"Social Opportunity Cost of Abatement"** (SOCA) to arbitrate between the allocation of renewable hydrogen among the sectors.

$$SOCA = \frac{[K_{H,1} - (K_{F,1} + C_{F,1})\eta_{H,1}] - [K_{H,2} - (K_{F,2} + C_{F,2})\eta_{H,2}]}{\eta_{H,1}E_1 - \eta_{H,2}E_2} \tag{12}$$

The following assumption is considered to study interesting cases where abatement costs of both sectors intersect.

Assumption 2 *The abatement cost of hydrogen technology with a zero hydrogen production cost ($AC_i(C_H = 0)$) in sector 1 is less important than that in sector 2, i.e.*

$$AC_1(0) < AC_2(0)$$

However, the adjusted carbon intensity of sector 2 is higher than that of sector 2 ($\eta_{Hi}E_i$), i.e.

$$\eta_{H,1}E_1 < \eta_{H,2}E_2$$

Under Assumption (2), there is a value of C_H for which $AC_1(C_H) = AC_2(C_H) = SOCA$. The corresponding hydrogen production cost is defined as the **Hydrogen Cost at Abatement Cost Parity**, such as:

$$\overline{C_H} = \frac{[K_{H,1} - (K_{F,1} + C_{F,1})\eta_{H,1}]\eta_{H,2}E_2 - [K_{H,2} - (K_{F,2} + C_{F,2})\eta_{H,2}]\eta_{H,1}E_1}{\eta_{H,1}E_1 - \eta_{H,2}E_2} \tag{13}$$

The values of $SOCA$ and $\overline{C_H}$ provide critical insight into hydrogen allocation under constrained supply. The following proposition explains the impact of the evolution of the social value of emissions on the merit order of hydrogen end-uses.

Proposition 1 *Under Assumption (1), if renewable hydrogen can be produced at a cost below the threshold social opportunity cost of hydrogen ($C_H < \overline{C_H}$) and the social value of carbon emissions exceeds the threshold social opportunity cost of abatement ($p_{CO_2} > SOCA$), then renewable hydrogen should be allocated to the sector with the higher abatement potential ($\eta_{H_i} E_i$), even if that sector faces a higher sectoral abatement cost (AC_i).*

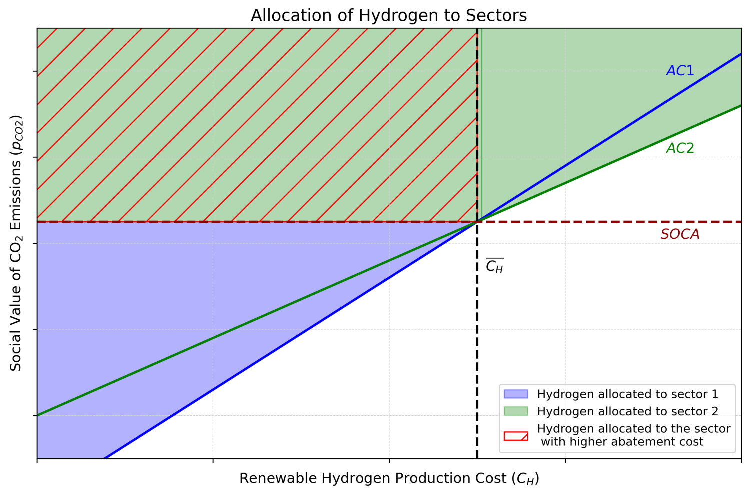

Figure 1: Illustration of Proposition 1

The proof is in the Appendix A.1. As illustrated in Figure 1, the hatched area indicates the allocation of hydrogen to the sector with the higher abatement cost for hydrogen-based technologies. The intuition is as follows: the *abatement cost* ($AC_{H,i}$) represents the sector-specific cost-efficiency of adopting hydrogen, determined by technology costs, energy costs, and emissions intensities. Sectors with lower abatement costs are more likely to adopt hydrogen at lower levels of the social value of emissions (p_{CO2}). However, when hydrogen supply is limited, allocation should prioritize sectors where it delivers the greatest social benefit. For higher levels of p_{CO2} (greater than $SOCA$), the benefit shifts to the allocation of renewable hydrogen to sectors with the highest abatement potential. This shift occurs because, below a critical threshold hydrogen cost ($\overline{C_H}$), the benefits of avoiding large emissions can outweigh the higher deployment costs of hydrogen technology. As a result, prioritizing a sector with a lower abatement cost but a lower abatement potential may not maximize social welfare. The $SOCA$ and $\overline{C_H}$ thresholds capture the trade-offs in these allocation decisions, identifying the critical values of p_{CO2} and C_H at which the optimal allocation shifts between sectors. Balancing the social benefits of abatement with the opportunity costs of allocation, and the cost of hydrogen with the opportunity cost of hydrogen, ensures welfare maximization under resource constraints.

Proposition 1 has two major implications for the optimal social allocation of hydrogen. First, if $C_H < \overline{C_H}$ and $p_{CO2} < SOCA$, the misallocation of hydrogen to the sector with the lower sectoral abatement cost (sector 1) results in a welfare loss, denoted as Δ_1, which is given by:

$$\Delta_1 = [p_{CO_2} \cdot (\eta_{H,2} E_2 - \eta_{H,1} E_1) + (K_{F,2} + C_{F,2})\eta_{H,2} - (K_{F,1} + C_{F,1})\eta_{H,1} + (K_{H,1} - K_{H,2})] \cdot H$$

In the context of a resource with limited short-term availability and inelastic supply, such as renewable hydrogen within a local ecosystem, allocating renewable hydrogen to the sector with the lowest abatement cost can result in a welfare loss. This fact, although already discussed in the literature (Vogt-Schilb et al. 2018), deserves to be emphasized, particularly because abatement costs are often used as a metric to prioritize decarbonization projects. In practice, in cases where we have an inelastic supply of hydrogen, there is a trade-off between minimizing the deployment cost or maximizing the abatement potential to minimize the social cost of emission. The social opportunity cost of abatement helps to determine the most important metrics.

Secondly, by fixing C_H such that $C_H < \overline{C_H}$, the hydrogen merit order reverses with the social cost of carbon : hydrogen should be allocated to the sector with the lowest abatement cost (sector 1) if $p_{CO2} \in [AC_1, SOCA]$, then to the sector with the highest adjusted emission intensity (sector 2) if $p_{CO2} > SOCA$. In the standard marginal abatement cost curves framework (McKinsey & Company 2009), hydrogen must be allocated iteratively to the least expensive options, as the social cost of carbon evolves. By reintroducing the notion of opportunity cost in abatement, the priority sectors for hydrogen allocation change with the social cost of carbon. While abatement costs are central to climate policy design, the opportunity cost of abatement is often overlooked.

2.2.2 Impacts of the Competitive Carbon-Neutral Alternative Technology

In this section, we assume that an alternative non-hydrogen carbon-neutral technology exists, but for simplicity only in the less carbon-intensive sector, i.e. sector 1.

Assumption 3 *In sector 1 with lower emission intensity ($\eta_{H,1}E_1 < \eta_{H,2}E_2$), an alternative carbon-neutral technology exists alongside hydrogen-based technology, i.e. $q_{A_1} \neq 0$. The availability of the carbon-neutral alternative is at least as abundant as the availability of renewable hydrogen.*

In this sector, new first-order conditions emerge as three different technologies compete with each other. The cost-minimization problem for sector 1 in Equation (2) rewrites as:

$$\min_{q_{H,1},q_{A,1}} \Gamma_1 = (p_{CO2}E_1 + K_{F,1} + C_{F,1})(N_1 - \eta_{H,1}q_{H,1} - \eta_{A,1}q_{A,1}) + (K_{H,1} + C_H)q_{H,1} + (K_{A,1} + C_A)q_{A,1} \tag{14}$$

The linearity of the objective function implies that the choice between the hydrogen-based technology and the alternative carbon-neutral technology in this sector is determined solely by their marginal costs weighted by efficiency. This results in a cost-competitiveness threshold cost of hydrogen in sector 1 with the alternative technology, such as:

$$\overline{C^A_{H,1}} = \frac{\eta_{H,1}}{\eta_{A,1}}(K_{A,1} + C_{A,1}) - K_{H,1} \tag{15}$$

This has implications for the above defined metrics. Below the threshold $\overline{C^A_{H,1}}$, hydrogen technology is more competitive than the carbon-neutral alternative technology and the abatement cost of sector 1 is the abatement cost of the hydrogen technology in sector 1,

$AC_{H,1}(C_H)$. Beyond $\overline{C^A_{H,1}}$, the decision is to decarbonize the sector through the carbon neutral alternative, and it becomes the abatement cost of the alternative low-carbon technology, independently of C_H, as expressed in Equation (16).

$$AC_1(C_H) = \begin{cases} \frac{(K_{H,1}+C_H)-(K_{F,1}+C_{F,1})}{E_1\eta_{H1}} & \text{if } C_H < \overline{C^A_{H,1}} \\ \frac{(K_{A,1}+C_{A,1})-(K_{F,1}+C_{F,1})}{E_1\eta_{A,1}} & \text{if } C_H \geq \overline{C^A_{H,1}} \end{cases} \tag{16}$$

Similarly, as there are no more conflicts in hydrogen allocation above $\overline{C^A_{H,1}}$, the social opportunity cost of abatement (SOCA) is no longer defined for values of renewable hydrogen costs beyond the threshold $\overline{C^A_{H,1}}$.

Moreover, if the alternative technology is more cost-effective than the carbon-based option, it should serve as the baseline when assessing opportunity costs. Notably, allocating hydrogen to sector 2 does not imply forgoing abatement in sector 1, as the low-carbon alternative technology remains available. This leads to the following updated social opportunity cost of abatement:

$$SOCA_A = \frac{(K_{H,2} - (K_{F,2} + C_{F,2})\eta_{H,1}) + \frac{\eta_{H,1}}{\eta_{A,1}}(K_{A,1} + C_{A,1}) - K_{H,1}}{\eta_{H,2}E_2} \tag{17}$$

It should be noted that the updated SOCA is lower than the value of SOCA defined in 12, thereby favoring sector 2.

The following proposition further highlights the impact of an additional carbon-neutral alternative technology in the sector with lower emission intensity on the optimal allocation of hydrogen.

Proposition 2 *Under Assumptions (1) and (2), the introduction of an alternative low-carbon technology changes the previously defined merit order if the hydrogen cost at cost parity between the low-carbon technology and the hydrogen technology in sector 1 is lower than the hydrogen cost at abatement cost parity between both hydrogen technologies ($\overline{C^A_{H1}} < \overline{C_H}$).*

The introduction changes the hydrogen allocation in the following three cases:

- ***Case 1:*** *If $p_{CO_2} \in [SOCA_A, SOCA]$ and $C_H < \overline{C^A_{H1}}$, renewable hydrogen should be allocated to the sector without the alternative technology (sector 2), even if its hydrogen technology faces a higher abatement cost.*

- ***Case 2:*** *If $p_{CO_2} \in [AC_2, SOCA]$ and $C_H \in [\overline{C^A_{H1}}, \overline{C_H}]$, renewable hydrogen should be allocated to the sector without the alternative technology (sector 2), even if its hydrogen technology faces a higher abatement cost.*

- ***Case 3:*** *Hydrogen is no longer used if $p_{CO_2} \in [AC_{H1}, AC_{H2}]$ and $C_H \in [\overline{C^A_{H1}}, \overline{C_H}]$*

The demonstration of proposition 2 and welfare losses for the different cases are given in Appendix A.2. Figure 2 highlights the proposition, and represents the optimal allocation of hydrogen with an alternative low-carbon technology in the first sector.

The rectangle (1) represents Case 1, where hydrogen is allocated to sector 2 due to the social opportunity cost, using the low-carbon alternative as the baseline technology.

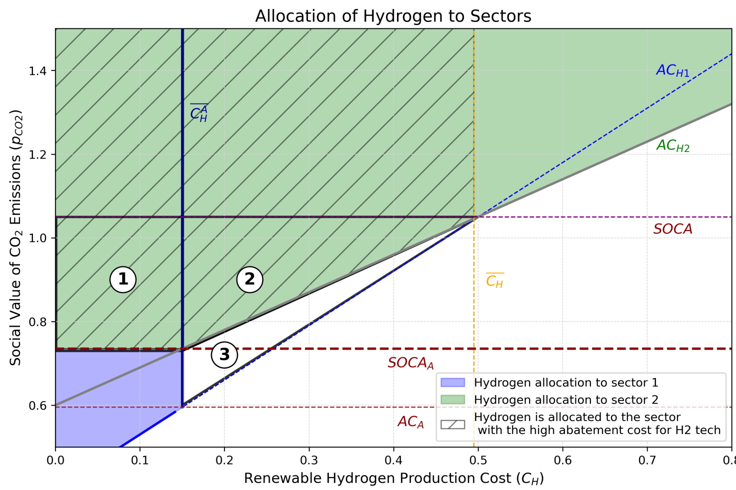

Figure 2: Illustration of Proposition 2

Since both sectors demand hydrogen, but sector 1 can decarbonize without it, even greater priority should be given to sector 2. As a result, hydrogen is allocated to sector 2, even though the low-carbon technology is less efficient than the hydrogen-based technology for these hydrogen cost values. The triangle (2) represents Case 2, where hydrogen is allocated to sector 2 because sector 1 no longer demands hydrogen, as the alternative technology is more cost-competitive. The competition for hydrogen is no longer relevant, whereas it existed prior to the introduction of the alternative technology. In Cases 1 and 2, the welfare loss associated with an allocation based solely on abatement costs is:

$$\begin{aligned}\Delta_2 = [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}}) + (p_{CO2}E_2 + K_{F2} + C_{F2})(-\eta_{H2}H) + (K_{H2})H] \\ -[(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1})H]\end{aligned}$$

Finally, triangle (3) represents case (3), where hydrogen, which was previously allocated solely to sector 1, is no longer used. Since, for these cost values, sector 2 does not demand hydrogen either, no sector requires hydrogen. In this, the welfare loss associated with an allocation based solely on abatement costs is:

$$\Delta_3 = [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H] - [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}})]$$

These different cases represent the three main mechanisms through which the introduction of a low-carbon technology influences the merit order. Overall, this introduction has increased the number of configurations in which the allocation based solely on the abatement cost of hydrogen technologies leads to a welfare loss. This proposition supports the idea of prioritizing hydrogen allocation to sectors that lack viable carbon-neutral alternatives, as highlighted in Ueckerdt et al. 2021.

2.2.3 Impact of Learning-by-doing (LBD)

In this section, we examine the impact of dynamic factors on the merit order. For simplicity, we assume that the sector-specific deployment costs and fuel price of the fossil fuel-based technology and low-carbon alternative are constant over time. However, as the social value of emissions, the cost of hydrogen production, and the cost of hydrogen deployment evolve over time, the merit order of hydrogen applications is likely to change accordingly. The phenomenon of learning-by-doing plays a crucial role in public policy, as investments made today influence future costs and, consequently, the future merit order. Thus, accounting for the future benefits of learning could also change the current merit order of hydrogen applications. Rather than solving the general case of the model, the analysis will focus on a specific question: given that renewable hydrogen will be allocated to the most emission-intensive sector in the long-run, what should be the optimal allocation of hydrogen in the initial period?

To address this question, we simplify the analysis by focusing on a two-period model ($T = 1$). As before, we assume that no alternative carbon neutral technologies are available in both sectors. We further assume a linear evolution of the social value of CO_2 emissions, the hydrogen production cost (C_H), and the deployment cost for hydrogen-based technologies (K_{H_i}). We also extend Assumption 1 to the long-term period, i.e., $H(1+h) < \min(N_1, N_2)$, for simplicity. Under these simplifying assumptions, the social cost for sector i at time t in Equation (3) is expressed as:

$$\Gamma_{i,0}(q_{H,i,0}) = [E_i p_{CO2} + K_{F,i} + C_{F,i}](N_i - \eta_{H,i} q_{H,i,0}) + [K_{H,i} + C_H] q_{H,i,0} \tag{18}$$

$$\begin{aligned}\Gamma_{i,1}(q_{H,i,1}, q_{H,i,0}) = {} & [E_i p_{CO2}(1+r) + K_{F,i} + C_{F,i}](N_i - \eta_{H,i} q_{H,i,1}) \\ & + [K_{H,i}(1 - \lambda_{H,i} q_{H,i,0}) + C_H(1-h)] q_{H,i,1}\end{aligned} \tag{19}$$

$$\Gamma = \sum_i^2 \Gamma_{i,0} + \frac{1}{r} \sum_i^2 \Gamma_{i,1} \tag{20}$$

The two-period problem can be solved by using backward induction. The following hypothesis is proposed:

Assumption 4 *The second period ($t = 1$) is sufficiently far in the future, making the impact of the discount rate (r) significant enough to ensure the following conditions for long-term allocation:*

For each sector i:

$$\forall i, [E_i p_{CO2}(1+r) + K_{F,i} + C_{F,i}]\eta_{H_i} \geq K_{H_i} + C_H(1-h) \tag{21}$$

For Sector 2 versus Sector 1:

$$\begin{aligned}[E_2 p_{CO2}(1+r) + K_{F,2} + C_{F,2}]\eta_{H,2} + K_{H,2}(1 - \lambda_{H,2} N_2) \geq \\ [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}]\eta_{H,1} + K_{H,1}\end{aligned} \tag{22}$$

Equations (21) and (22) imply that hydrogen must be allocated to the sector with the highest carbon intensity, that is, sector 2, in the second period, even if the maximum learning in sector 1 has been achieved in the first period, and the minimum has been achieved in sector 2. The impact of this long-term allocation on the short-term allocation of renewable hydrogen is observed through the first-order conditions. Considering the future benefits on the long-term cost thanks to the initial allocation, **Dynamic Abatement Costs (DAC)** and **Dynamic Social Opportunity Costs of Abatement (DSOCA)** for the initial period be defined as:

$$DAC_{H,2,0} = AC_{H,2,0} - \frac{\lambda_{H,2} K_{H,2} H(1+h)}{(1+r)\eta_{H,2} E_2} \tag{23}$$

$$DSOCA_0 = SOCA_0 - \frac{\lambda_{H,2} K_{H,2} H(1+h)}{(1+r)(\eta_{H,2} E_2 - \eta_{H,1} E_1)} \tag{24}$$

As hydrogen is allocated exclusively to sector 2 in the long term, accounting for learning effects leads to a lower abatement cost value of hydrogen technology in sector 2 ($DAC_{H,0,2} \leq AC_{H,0,2}$), as well as the social opportunity cost of abatement ($DSOCA_0 \leq SOCA_0$). The consideration of dynamic effects does not change the abatement cost for sector 1, which is not used in the long term ($DAC_{H,0,1} = AC_{H,0,1}$). Moreover, we define $\overline{DC_H}$, the hydrogen cost at dynamic abatement cost parity, such that $DAC_{H,0,1}(\overline{DC_H}) = DAC_{H,0,2}(\overline{DC_H})$.

This leads to the following proposition:

Proposition 3 *Under Assumption 4, taking into account future learning-by-doing benefits changes the previously defined merit-order at the initial period in the following cases:*

- ***Case 1:*** *If* $p_{CO_2} \in [max(DSOCA_0, AC_{1,0}), SOCA_0]$ *and* $C_H < \overline{C_H}$*, renewable hydrogen should be allocated to the sector where hydrogen is allocated in the long-term, even if that sector faces a higher sectoral abatement cost of hydrogen at this period.*

- ***Case 2:*** *If* $p_{CO_2} \in [DAC_{2,0}, min(AC_{1,0}, AC_{2,0}]$ *and* $C_H > \overline{DC_H}$*, renewable hydrogen is allocated to sector 2, whereas it would not have been allocated without considering dynamic effects.*

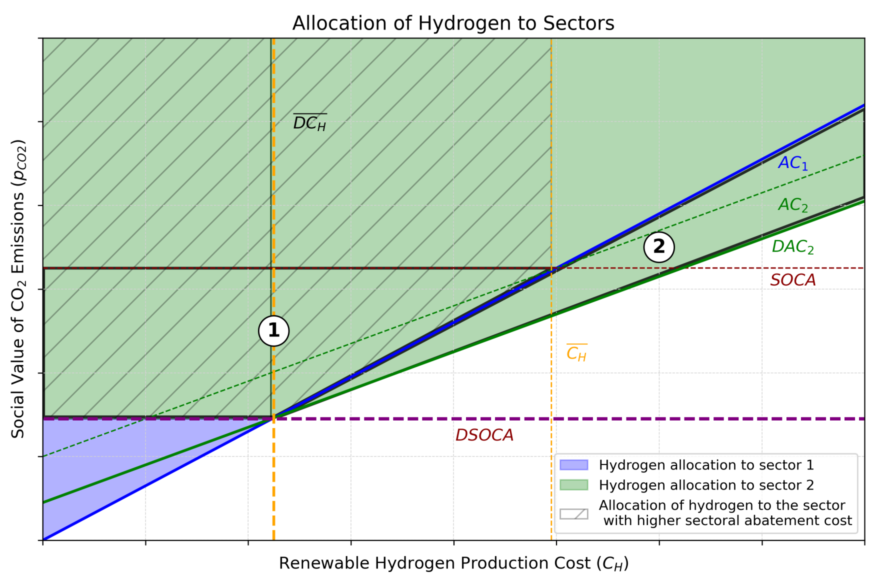

Figure 3: Illustration of Proposition 3

Proposition 3 is demonstrated in Appendix A.3, and Figure 3 illustrates the impact of accounting for dynamic effects. The intuition is straightforward. Since hydrogen will ultimately be directed toward the most emission-intensive sector in the long run, there is an incentive to begin decarbonizing this sector in the first period. In case 1, represented by the area 1, hydrogen is allocated to sector 2 from the first period because the discounted expected learning gains exceed the decarbonization opportunity cost differential between sectors 1 and 2. The welfare loss with an allocation based solely on abatement costs is therefore:

$$\Delta_4 = H[(p_{CO2}E_2 + K_{F2} + C_{F2})\eta_{H2} - (p_{CO2}E_1 + K_{F1} + C_{F1})\eta_{H1} + K_{H1} - K_{H2} \\ - \frac{1}{1+r}(\lambda_{H,2}K_{H,2}H(1+h))]$$

Considering learning effects thus has a conservative impact on the merit order, preventing allocation switching between periods by focusing on a single sector to maximize learning gains. In case 2, represented by the area 2, accounting for future benefits encourages decarbonization in situations where hydrogen would not have been allocated in a static framework. The welfare loss with an allocation based solely on abatement costs is therefore:

$$\Delta_5 = (p_{CO2}E_2 + K_{F2} + C_{F2})(\eta_{H2}H) + (K_{H2} + C_H)H - \frac{1}{1+r}[K_{H,2}\lambda_{H,2}H]H(1+h)$$

Therefore, considering dynamic effects also incentivises earlier decarbonization in certain sectors.

If the amount of hydrogen in the economy is large enough to partially decarbonize the other sector in the second period, the effect of learning on $SOCA$ is ambiguous. In this case, considering the learning effects may no longer have a conservative impact on the merit order. For example, with a large amount of hydrogen available in the economy and a high learning rate in sector 1, taking learning effects into account may result in the merit order changing between the two periods, whereas it remained the same without considering learning by doing. Thus, through the learning-by-doing channel, scenarios of renewable hydrogen production impact the merit order of end-use hydrogen applications. Without considering dynamic learning effects, the value of H and the respective size of the different sectors (N_i) play no role in the merit order of the end-use sectors of hydrogen. With learning-by-doing, the respective production volumes for each sector have an influence on the cost of low-carbon technologies. This will be illustrated further in the numerical analysis.

2.3 Policy Design

Different market imperfections can lead to a socially suboptimal choice in the allocation of hydrogen. First, the social cost of carbon, reflecting the marginal damages of CO_2 emissions on the economy, could differ from the effective carbon taxation in the economy. Second, the market may fail to fully internalize the benefits of learning-by-doing. In the following sections, we will study the design of policies aimed at addressing these two market imperfections.

2.3.1 Policy under Imperfect Carbon Taxation

A Pigouvian tax on CO_2, set at the SCC, is effective in internalizing the negative externalities of emission damages and decentralizing the first-best setting. However, in practice, the effective carbon tax in the economy may deviate from the social value of emissions. Placing a uniform carbon tax across sectors is unlikely at the European level, as evidenced by varied taxation on diesel for mobility and natural gas for industrial applications (EU-ETS). Additionally, carbon taxation may not evolve at the same pace as the social value of emissions. A too-low carbon tax could lead to two main failures on the effective allocation of renewable hydrogen: renewable hydrogen may be used insufficiently in the local ecosystem, or may be miss-allocated between sectors, as seen in proposition 1. In local production ecosystems, local entities cannot unilaterally address the issue of a suboptimal carbon tax without risking carbon leakage to other areas. An alternative approach is to provide subsidies to support existing firms in their decarbonization efforts. We propose two second-best policies in a hydrogen local ecosystem, where the carbon tax is below the social cost of carbon.

Subsidizing the Producers of Renewable Hydrogen To address insufficient carbon taxation, most local ecosystems offer subsidies for hydrogen production (Bloomberg NEF 2020). The advantage of supply subsidy is that it is technologically neutral with respect to the various hydrogen applications. In this section, we explore whether the subsidy for hydrogen production is sufficient to restore the socially optimal allocation of hydrogen.

We consider again the simple two-sector ($S = 2$), single period framework ($T = 0$), without alternative carbon neutral technology ($q_A = 0$), under Assumptions 1 and 2. An agent manages the local hydrogen ecosystem and is subject to a non-optimal carbon tax, called $\tilde{p_{CO2}}$. Hydrogen production subsidies are also allocated, amounting to s per unit of decarbonized hydrogen. The agent faces the following private cost:

$$\begin{aligned}\Gamma_p(\tilde{q_{H_1}}, \tilde{q_{H,2}}, s) = [\tilde{p_{CO2}} E_1 + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}\tilde{q_{H,1}}) + (K_{H,1} + C_H - s)\tilde{q_{H,1}} + \\ [\tilde{p_{CO2}} E_2 + K_{F,2} + C_{F,2}](N_2 - \eta_{H,2}\tilde{q_{H,2}}) + (K_{H,2} + C_H - s)\tilde{q_{H,2}}\end{aligned}$$

The social cost of this hydrogen ecosystem is:

$$\Gamma_s(q_{H,1}, q_{H,2}) = \Gamma_p(q_{H,1}, q_{H,2}) + (p_{CO2} - \tilde{p_{CO2}})[E_1(N_1 - \eta_{H,1}q_{H,1}) + E_2(N_2 - \eta_{H,2}q_{H,2})] + s(q_{H,1} + q_{H,2})$$

The optimal production subsidy level s^* should be set in such a way that the socially optimal hydrogen allocation can be decentralized by the agent managing the local hydrogen ecosystem. In other words, under the optimal subsidy level s^*, allocation of hydrogen should be the same whether minimising $\Gamma_p(q_{\tilde{H},1}, q_{\tilde{H},2}, s^*)$ or $\Gamma_s(q_{H,1}, q_{H,2})$, i.e., $(q_{\tilde{H},1}{}^*, q_{\tilde{H},2}{}^*) = (q^*_{H,1}, q^*_{H,2})$.

In our setting, there are only three possible allocations: either both sectors are not decarbonized ($q_{H,i} = 0$), either only sector 1 is decarbonized ($q_{H,1} = H$), or only sector 2 is decarbonized ($q_{H,2} = H$). According to Proposition 1, different levels of carbon taxation may lead to different hydrogen allocations. The following proposition examines the effectiveness of production subsidies in restoring the optimal allocation.

Proposition 4 *The efficiency of production subsidies in restoring the first-best allocation depends on the relative positions of the social cost of carbon, the effective carbon tax and the social opportunity cost of abatement. In particular, if $\tilde{p_{CO2}} \leq SOCA \leq p_{CO2}$, subsidy to hydrogen production can't restore the socially optimal hydrogen allocation.*

This is demonstrated in Appendix A.4 and illustrated in Figure 4, focusing on the most interesting case where the optimal situation is to allocate hydrogen to sector 2 ($q^*_{H_2} = H$). In the first case (left), production subsidies are efficient to solve the problem of insufficient hydrogen production, by lowering the abatement cost of hydrogen technologies. In the second case (right), where carbon tax and social value of emissions are positioned on either side of the $SOCA$, production subsidies are not capable of inverting the merit order. Since SOCA is independent of C_H, sector 1 ranks first in the merit order regardless of the hydrogen production cost level for this emissions level. It is then necessary to compare the cost of the other hydrogen allocation, to determine whether it is preferable to allocate hydrogen to sector 1 or not to allocate any hydrogen at all. If allocating to sector 1 is preferable, a production subsidy may be considered to achieve the second-best equilibrium.

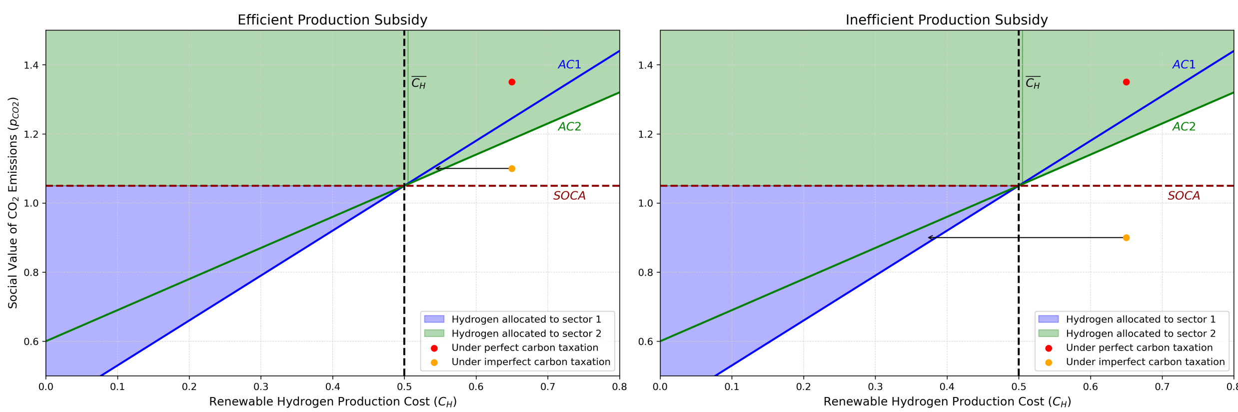

Figure 4: Illustration of efficient and inefficient production subsidy

Subsidizing the End-Use Sectors of Renewable Hydrogen We have shown the impossibility of addressing the hydrogen misallocation problem through a production subsidy, particularly in cases where the social cost of carbon and the effective cost of carbon are on opposite sides of the SOCA. We investigate the efficiency of a direct subsidy targeted at the hydrogen technology in the most meritorious sector. This targeted subsidy could, for instance, take the form of a CAPEX subsidy for the hydrogen technology. By keeping the analytical framework from the previous section, the agent receiving a demand-side subsidy in sector 2 would face the following private cost:

$$\Gamma_p(q_{\tilde{H},1}, q_{\tilde{H},2}, d_2) = [p_{\tilde{CO2}} E_{F,1} + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1} q_{\tilde{H},1}) + (K_{H,1} + C_H) q_{\tilde{H},1} +$$
$$[p_{\tilde{CO2}} E_{F,2} + K_{F,2} + C_{F,2}](N_2 - \eta_{H,2} q_{\tilde{H},2}) + (K_{H,2} - d_2 + C_H) q_{\tilde{H},2}$$

The following proposition provides information on the efficiency of demand subsidies.

Proposition 5 *A direct subsidy to sector 2 can always restore the socially optimal allocation. If production subsidies are ineffective, the optimal subsidy level for sector 2 should be set, such as :*

$$d_2^* = \max(K_{H2} - K_{H1} + (p_{\tilde{CO2}} E_1 + K_{F1} + C_{F1})\eta_{H1} - (p_{\tilde{CO2}} E_2 + K_{F2} + C_{F2})\eta_{H2},$$
$$K_{H2} + C_H - (p_{\tilde{CO2}} E_2 + K_{F2} + C_{F2})\eta_{H2})$$

This proposition is demonstrated in Appendix A.5. Unlike a production subsidy, which affects both sectors, a direct subsidy to the most meritorious demand sector always succeeds in restoring the optimal allocation. This is mainly because it can directly influence SOCA. However, it requires more direct intervention from the social planner, who might instead prefer to allow competition between demand sectors. Moreover, it requires a precise knowledge of the merit order, which can be challenging in the presence of cost uncertainty. We have illustrated the mechanism of these subsidies through a simple example with two sectors and two technologies. The actual efficiency in a more complex case—with multiple sectors, alternative technologies, and learning by doing—is assessed in the numerical analysis.

2.3.2 Learning-by-Doing Policy

In a dynamic framework, learning-by-doing could serve as a rationale for directly subsidizing hydrogen technology in a demand sector. First, the market may fail to fully internalize the benefits of learning, which could spread from one firm to another. Second, learning-by-doing functions similarly to economies of scale, potentially leading to unprofitability along the optimal trajectory and necessitating compensation (Kasser et al. 2024). Moreover, hydrogen valleys are specifically designed to initiate the first experience gains in immature technologies. These gains will be crucial for the future deployment of hydrogen technologies on a larger scale. According to Pigouvian taxation principles, if the end-user does not internalize the benefits of learning, the optimal allocation of hydrogen could be decentralized by combining a subsidy for the learning benefits with a policy instrument addressing the social cost of carbon. For sector i at time t, this subsidy should be equal to the sum of the discounted expected learning benefits along the optimal production path, which is :

$$k_{i,t} = -\sum_{\tau=t}^{T} \frac{1}{(1+r)^\tau} \frac{\partial K_{H_i}(Q_{\tau,H_i}, \lambda_{Hi}, \tau)}{\partial Q_{\tau,H_i}} \tag{25}$$

In the forthcoming numerical section, we will compare various policy mixes, evaluate the optimal level of subsidies, and analyze the costs associated with hydrogen deployment in the most meritorious demand-sectors.

3 Numerical Application: Calibration of the Model to the Industrial Port Zone of Marseille-Fos

We calibrate the model applying it to one of the main prospective hydrogen valleys in France, the industrial-port zone (IPZ) of Marseille-Fos. France's hydrogen strategy outlines a roadmap with seven major clusters projected to meet 85% of national hydrogen demand by 2030 (France Hydrogène 2022). These clusters, identified through a comprehensive process considering the geographical location of announced projects by 2030 and future demand projections, strategically position themselves to meet both production and demand requirements, thus optimizing the supply chain through resource pooling. Figures 5 shows the division of the seven clusters and their potential hydrogen demands for industrial and mobility applications. The IPZ of Marseille-Fos includes seven municipalities of Fos-sur-Mer, Port-Saint-Louis-du-Rhône, Port-de-Bouc, Martigues, Châteauneuf-les-Martigues, and Marignane. This region encompasses more than fifteen industrial sites and six specialized maritime terminals, including the Grand Port Maritime de Marseille (GPMM), which is the largest port in France and the third-largest in the Mediterranean in terms of tonnage of goods (Grand Port Maritime de Marseille 2024). Additionally, the area hosts the Marseille Provence airport, located in the territory of Marignane, serving domestic and international flights.

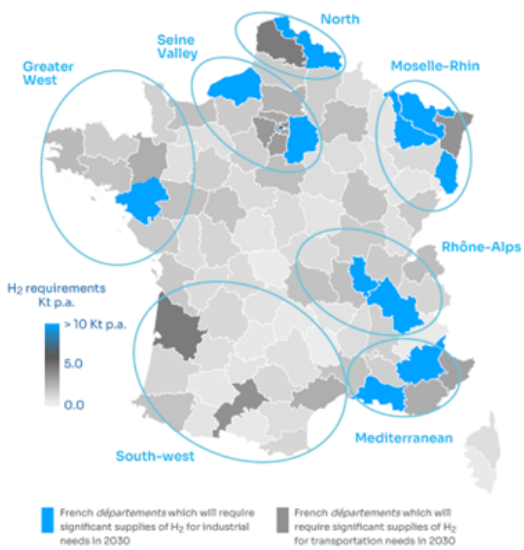

Figure 5: Map of Potential Hydrogen Valleys in France (France Hydrogène 2022)

In model calibration, including several end-use sectors complicates the analytical resolution. Instead, we use a numerical optimization of the model based on the minimization program developed in the former section. The linear optimization program is solved using the MPSolver wrapper and a linear programming solver. The linear optimization solver is Glop, Google's linear programming solver, using Google's OR-Tools in Python.

3.1 Model Inputs

Table 3 provides an overview of the reference fossil fuel-based technologies, renewable hydrogen-based technologies, and primary low-carbon alternatives pertinent to each end-use sector within the region. Further elaboration on these technologies is available in Appendix B.2. Data collection was primarily sourced from the CIGALE database (CIGALE Project 2024), a regional environmental inventory managed by AtmoSud, the certified air quality monitoring association for southern France (i.e. Provence-Alpes-Côte d'Azur). This database provides data on annual energy consumption, greenhouse gas (GHG) emissions, and air pollutants in various sectors and municipalities in the region. However, due to the aggregation of data in the database in end-use sectors, the input values presented in Table 7 were derived using a meticulous data processing procedure, incorporating other available data from the literature, detailed in Appendix B.1.

Table 3: Technological Pathways Across Various End-Use Sectors

End-use Sector	**Reference Fossil Technology**	**Decarbonized Hydrogen Technology**	**Alternative Low-Carbon Technology**
Chemicals (Ammonia and Methanol) and (Bio-)Refinery	SMR	Electrolysis	Bio-SMR
Iron & Steel	BF/BOF	Electrolysis + H2-DRI-EAF	NG-DRI-EAF + CCS
Industrial High Temperature Heat	NG-fired Furnace	Electrolysis + H2-fired Furnace	NG-fired Furnace + CCS
Road Mobility: Trucks	Diesel Engine	Electrolysis + FCEV	BEV
Shipping: Container Ships	VLSFO Engine	Electrolysis + Methanation + E-Methanol	Bio-Methanol
Aviation: Long-haul Aircrafts	Kerosene Engine	Electrolysis + Fischer Tropsch + Kerosene Engine (E-Kerosene)	Biojet Fuel (HEFA)

The techno-economic input data utilized in the model are detailed in Table 8, derived from interviews with regional experts and literature review referenced in this paper.

The social discount rate adopted for this analysis aligns with the prevailing rate in France, set at 3.2%, as recently recommended by France Stratégie, the government's policy analysis body in France (Ni and Maurice 2021). Notably, no inflation rate is considered in this analysis.

The social cost of carbon (SCC) for the year 2030 is set at 250 €/tCO_2-eq, based on the Quinet report (Quinet et al. 2019), the official French assessment of the social value of CO_2 abatement. The SCC trajectory is modeled according to the Hotelling rule, growing at the rate of the social discount rate represented in the Figure 6.

In assessing current carbon pricing policies, we apply differentiated carbon prices across end-use sectors. Industrial, maritime, and aviation sectors are subject to the European Union Emissions Trading System (EU ETS), which, as of 2025, has a market price of approximately 80 €/tCO_2-eq. Projections from the International Energy Agency's Net Zero Emissions pathway suggest this price could reach €250 per tonne by 2050 (International Energy Agency 2024b). For our analysis, we assume a linear progression between these values, as depicted in Figure 6. In contrast, carbon pricing for road transport in France is primarily implemented through fuel excise duties, effectively imposing an implicit carbon tax estimated at around €45 per tonne of CO_2. Additionally, the second European Union's Emissions Trading System for buildings and road transport (EU ETS2), adopted in 2023, is scheduled to be launched in 2027, covering CO_2 emissions from fossil fuels used in road transport, buildings, construction, and small industries. Notably, this system includes a mechanism to address excessive price increases, ensuring that during the initial years, allowance prices do not exceed €45 per tonne of CO_2. For our analysis, we assume a fixed carbon price of 45 €/tCO_2-eq for road mobility until 2030. Post-2030, we project a linear increase in the EU ETS2 price, aligning it with the EU ETS price of 250 €/tCO_2-eq by 2050, illustrated in Figure 6.

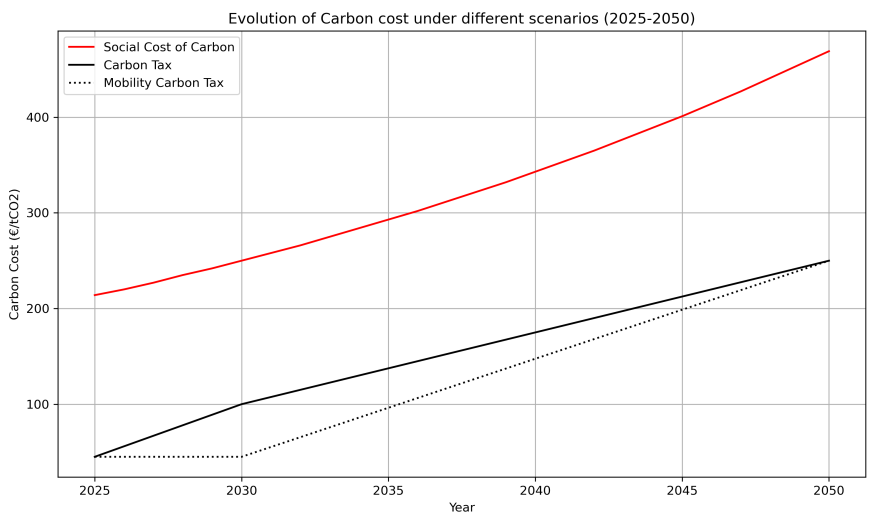

Figure 6: Comparison of the Social Cost of Carbon (SCC) and Differentiated Carbon Tax in France

For the environmental damage costs associated with air pollution, we reference the values estimated in the Environmental Prices Handbook Bruyn et al. 2018, as summarized in Table 4. Following the study's recommendations, these values are assumed to remain constant over time, implying that the overall costs of air pollution are treated as fixed end-use costs of technologies (incorporated into the K parameter in the model setting described in Section 2).

Table 4: Cost of Air Pollutants

Air Pollutant	**Unit**	**Value (€/kg)**
NOX	€/kg	14.8
SO2	€/kg	11.5
CO	€/kg	0.0526
PM 10	€/kg	26.6
PM 2.5	€/kg	38.7
NMVOC	€/kg	1.15

3.2 Scenarios for Hydrogen Valley Development in the Industrial Port Zone of Marseille-Fos

We define two distinct scenarios to account for uncertainty in hydrogen deployment and cost evolution over time. The *Standard* scenario assumes a moderate but sustained scale-up of hydrogen infrastructure, leading to full regional demand coverage by 2050. This scenario benefits from economies of scale and accelerated learning effects in production of renewable hydrogen enabling significant cost reductions. A well-integrated supply chain and a mature renewable energy sector further contribute to driving down hydrogen production costs. Market confidence and investment incentives in this scenario promote efficiency gains, resulting in a lower cost that supports widespread adoption. However, we note that this scenario is not particularly ambitious, given that as of 2025, several announced projects in the region already target supplying approximately 60% of the considered regional demand by 2030.[1] Nonetheless, considering recent trends of delayed Final Investment Decisions (FIDs) for several announced hydrogen projects, a scenario assuming a more gradual deployment remains relevant for assessing market conditions.

In contrast, the *Conservative* scenario reflects a more cautious expansion, where hydrogen availability reaches only 50% of regional demand by 2050. This scenario accounts for potential constraints such as slower infrastructure deployment and weaker investment which can limit economies of scale and delay cost reductions. With a fragmented supply chain and higher capital costs, production remains less efficient, leading to hydrogen costs that are 50% higher than in the *Standard* scenario. These contrasting scenarios allow us to assess the economic implications of hydrogen deployment speed under different market conditions.

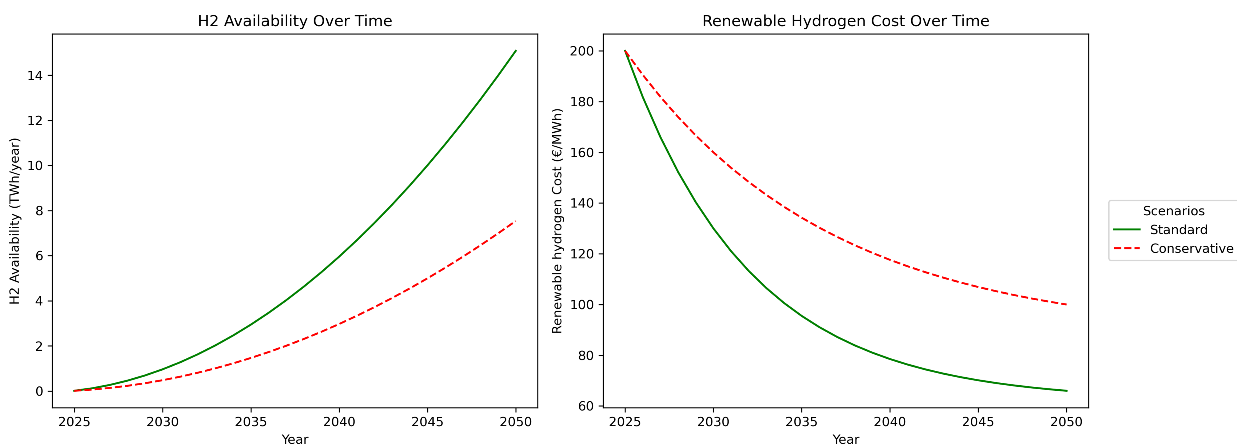

Figure 7: The left panel shows the projected hydrogen availability over time while the right panel illustrates the corresponding cost evolution in the Standard and Conservative scenarios.

[1]Examples of announced projects include the HyAMMED Project (0.365 kt renewable H_2 by 2025), MassHylia Project (11 kt by 2025), H2V Project (28 kt in Phase 1 by 2028 and 56 kt in Phase 2 by 2030), GravitHy Project (120 kt by 2028), and HyGreen Project (30 kt by 2028).

3.3 Results of the Numerical Application

In this section, we establish the ranking of hydrogen end-uses over time in developing a hydrogen valley in the Industrial Port Zone of Marseille-Fos based on our proposed methodology and contrast it with the conventional approach, which prioritizes sectors according to their individual abatement costs. We then determine the optimal allocation of renewable hydrogen across sectors under two distinct scenarios, each varying in terms of the levelized cost of production and the availability of renewable hydrogen. Finally, we examine the design and effectiveness of policy instruments by evaluating optimal carbon pricing and subsidy mechanisms. Specifically, we assess a carbon tax set at the social cost of carbon and explore hybrid policy approaches that combine carbon taxation with subsidies, either directed toward renewable hydrogen producers or directly allocated to end-use sectors. This analysis aims to identify the cost-effectiveness of each policy pathway and its impact on emission reductions.

3.3.1 Ranking of Hydrogen End-Uses Over Time in the Optimal and Standard Approaches

We determine the merit order of hydrogen end-uses and analyze its evolution over time for the numerical application, comparing the standard and proposed methodologies, as illustrated in Figure 8. In both approaches, the CO_2 emissions cost is set equal to the social cost of carbon (SCC) evolving with social discount rate according to Hotelling rule. For the production cost of hydrogen, we consider its evolution under the standard scenario in Figure (7). To establish a merit order in each period, constraint 8 is progressively relaxed by increasing the parameter H from 0 to $\sum N_i/\eta_{h_i}$, implying that renewable hydrogen could eventually become available to fully satisfy sectoral demand. If sector i is allocated by hydrogen in the n-th position, its merit order ranking is also n. Finally, when $H = \sum N_i/\eta_{h_i}$, if no hydrogen is allocated to sector i, it implies that the sector does not demand hydrogen and, consequently, holds no position in the merit order.

The right panel of Figure 8 contrasts our approach with the standard methodology, where the individual abatement costs for each sector are computed at each period without considering learning impacts and in the absence of low-carbon alternatives. Sectors with abatement costs below the SCC in that period are ranked according to their abatement costs, with priority given to the sector with the lowest cost of abatement.

The left panel of this figure presents results from our methodology, referred as socially optimal merit-order, which is derived from the cost minimisation program of Equation 4 in the previous section. Given that the problem is linear,[2] renewable hydrogen is allocated sequentially to each sector. In this ranking, we also consider the existence of low-carbon alternatives to renewable hydrogen as presented in Table (6) of Appendix B.2.

Under the standard approach, the maritime sector consistently holds the highest priority for renewable hydrogen allocation. This is due to the substantial air pollutant emissions

[2] In this formulation, learning effects on the cost of end-use technologies are considered exogenous, meaning they evolve autonomously over time. This contrasts with Equation 4, where learning is endogenous to production stock. Under Learning-by-Doing, the problem ceases to be linear, making it impossible to determine a fixed merit order ranking.

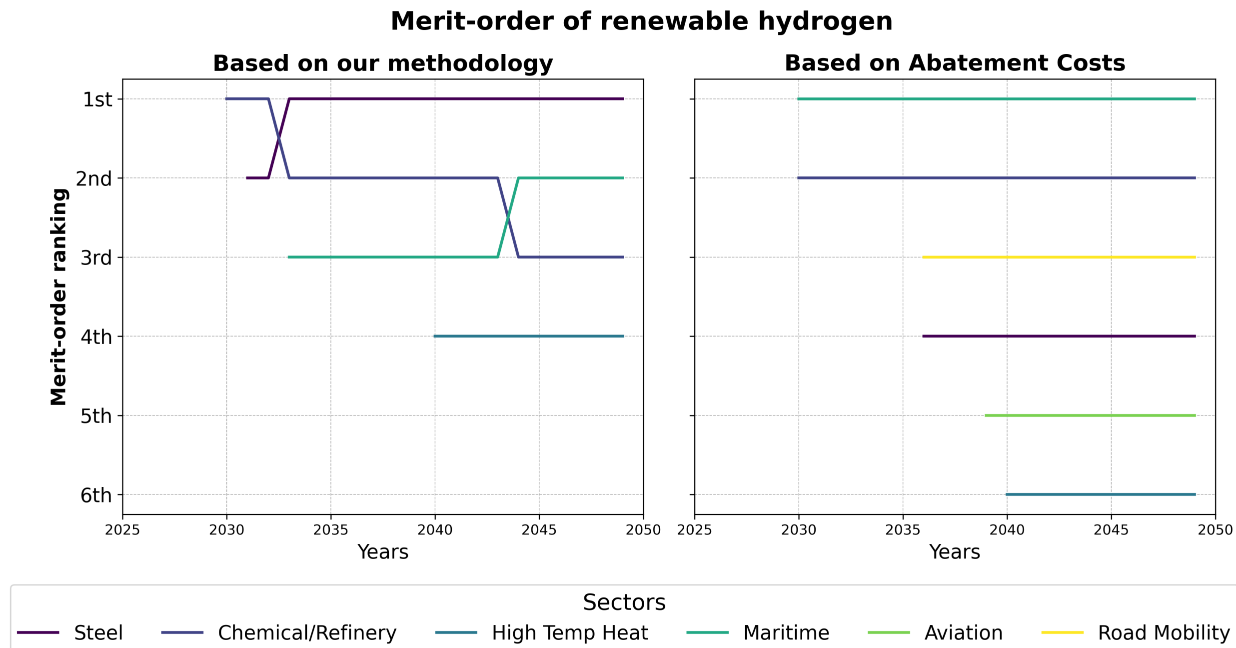

Figure 8: Evolution of merit-order based on our methodology and based on abatement costs

from Ultra-Large Container Vessels (ULCVs) currently utilizing Very Low Sulfur Fuel Oil (VLSFO) as in Table (6) of Appendix B.2. These emissions surpass those of other end-use sectors, resulting in significant benefits from their mitigation through renewable hydrogen adoption. The chemicals and refinery sectors occupy the second position in this approach, owing to their existing use of fossil-fuel-based hydrogen and established end-use infrastructure, which facilitate early adoption of renewable hydrogen. The following is the road mobility sector (heavy-duty trucks), ranking third due to the absence of alternative technologies considered in the standard merit order framework. The steel industry ranks fourth, positioned below the maritime, chemicals, and mobility sectors, as the standard approach overlooks its significant potential for learning-by-doing. However, it ranks above the aviation and industrial high-temperature heating sectors, given the steel industry's reliance on coal—a fuel with high emission intensity—offering greater benefits from emission abatements.

In contrast, the socially optimal merit-order exhibits notable shifts en route to 2050, unlike the static ranking defined by the standard approach that remains unchanged (as demonstrated in Proposition 1). Initially, the chemical and refinery sectors hold the top rank due to their established end-use technology and infrastructure for hydrogen, coupled with the high costs associated with their low-carbon alternatives, which involve the continued use of fossil-fuel-based hydrogen combined with expensive Carbon Capture and Storage (CCS) technology. This case is similar for the steel industry and large-scale industrial high-temperature heating, where CCS serves as the alternative technology. Conversely, the maritime sector's most cost-effective alternative is bio-methanol, which is comparatively less expensive in the region than CCS technologies, resulting in a lower ranking compared to the standard approach that overlooks alternative technologies. In 2032, the steel industry ascends to the top rank, driven by its substantial potential for long-term learning-by-doing and the necessity for early investment. Subsequently, in 2043, the maritime sector surpasses the chemicals and refinery sectors in priority. This shift occurs because the chemicals and refinery sectors have already developed the end-use technology for hydrogen utilization and lack further learning potential on the end-use side, whereas the maritime sector's hydrogen application is an emerging technology with opportunities for learning. Regarding the ranking of heavy-duty road mobility (trucks), the consideration of direct electrification through battery electric vehicles (BEVs) at a lower cost—owing to the avoidance of efficiency losses in converting electricity to hydrogen—results to the fact that this sector is not ranked in the socially optimal merit-order.

3.3.2 Optimal Allocation of Renewable Hydrogen Over Time Considering Different Scenarios and Policy Pathways

In this section, we analyze the optimal allocation of renewable hydrogen over time in the Marseille-Fos area, employing the dynamic optimization framework outlined in Equation 4. Our analysis encompasses two distinct scenarios concerning key parameters of renewable hydrogen cost and availability, as detailed in Section 3.2: the *Conservative* and *Standard* scenarios. Additionally, we evaluate two policy pathways: the *First-Best Policy Pathway*, wherein the carbon price is aligned with the social cost of carbon (SCC) and learning effects are internalized to achieve a socially optimal allocation; and the *Business-as-Usual (BaU) Policy Pathway*, characterized by carbon pricing at the current French tax level and the absence of internalized learning effects, reflecting the anticipated hydrogen allocation without further policy interventions. The combination of these scenarios and policy pathways yields four configurations, as illustrated in Figure 9.

Our findings indicate that the timing, sequence of hydrogen application deployments, and the number of sectors receiving allocations vary depending on the scenarios for availability constraints and production costs of renewable hydrogen, as well as the policy pathways considered.

In the BaU Policy Pathway, without internalizing learning and with insufficient carbon taxation, under the Conservative Scenario (upper-left panel of Figure 9), it is optimal to allocate renewable hydrogen to only two sectors by 2050: the chemical and refinery sectors should launch decarbonization through renewable H_2 around 2040, followed by the maritime sector starting in 2046. Extending the availability and reducing the production cost of renewable hydrogen to their values in the Standard Scenario (upper-right panel of Figure 9) advances the decarbonization of the chemical and refinery sectors by seven years to 2033 and the maritime sector by four years to 2036 compared to BaU-Conservative. Additionally, the steel industry emerges as a third sector for partial decarbonization through renewable hydrogen beginning in 2045 for BaU-Standard.

In contrast, under the First-Best Policy Pathway, with internalized learning and carbon pricing at the SCC level, even within the Conservative Scenario (lower-left panel of Figure 9), decarbonization of the chemical and refinery sectors is advanced by one year more to 2032 compared to BaU-Standard. In 2033, the merit order shifts in favor of the steel industry, attributable to its substantial learning potential. Due to constrained hydrogen availability in this scenario, further decarbonization of the chemical sector through renewable H_2 is deferred until 2043. Expanding hydrogen availability and reducing production costs to their values in the Standard Scenario (lower-right panel of Figure 9) advances decarbonization timelines for the chemical and refinery by four years to 2028, and steel industries by two years in 2032 compared to First-best-Conservative. As hydrogen constraints are alleviated, the chemical and refinery sectors resume decarbonization in 2037, six years earlier than the case for First-best-Standard. The maritime sector's decarbonization advances by four years to 2043 compared to First-best-Conservative, and sufficient hydrogen becomes available to initiate decarbonization in the industrial high-temperature heating sector.

Notably, in none of the configurations are the aviation and road mobility sectors allocated renewable hydrogen by 2050. The deployment of hydrogen under imperfect carbon taxation and without internalizing learning remains significantly below socially optimal levels, underscoring the necessity for effective policy support to promote hydrogen production. Moreover, as the model does not account for the fractional costs of the energy transition, we observe situations where the ranking of end-use sectors fluctuates, leading to back-and-forth shifts in their prioritization—an outcome that may not fully reflect real-world decision-making dynamics.

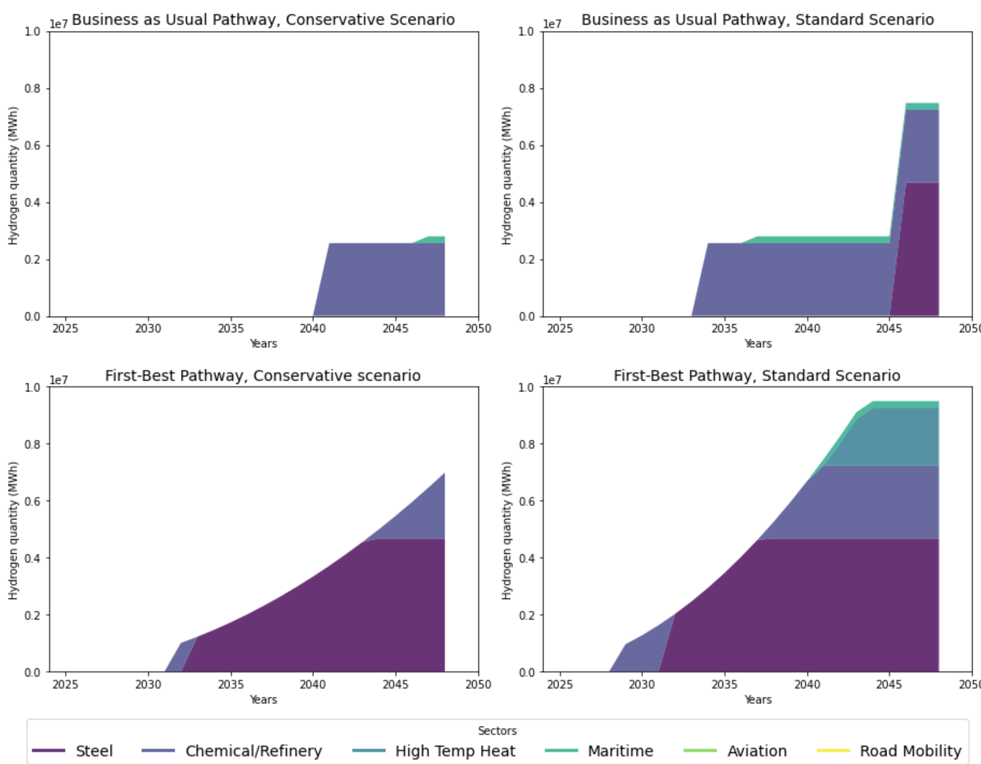

Figure 9: Optimal hydrogen allocation over time across four scenarios. The left column represents a conservative scenario, while the right column illustrates the standard scenario in terms of hydrogen availability and costs. Regarding carbon pricing, the top row corresponds to the Business-as-Usual case under projected carbon prices, whereas the bottom row represents the First-Best scenario under the social cost of carbon.

3.3.3 Optimal Policy

In this section, we conduct a comparative analysis of the previously discussed methodologies and scenarios, assessing their implications for the overall cost and emissions of energy transition pathways. Additionally, we examine the role of public policy interventions, with a particular focus on subsidies designed to support the deployment of a hydrogen valley within the industrial port zone of Marseille-Fos. This analysis is structured around six distinct *Policy Pathways*, which are further elaborated in the following. For analytical clarity, our primary assessment centers on the *Standard* scenario, which reflects baseline assumptions regarding renewable hydrogen availability and production costs. A sensitivity analysis of the *Conservative* scenario is provided in the appendix.

In **Policy Pathway (1)**, hydrogen deployment is optimized using our proposed optimal methodology, under a carbon tax set at the social cost of carbon (SCC) and perfect internalization of learning by agents. This serves as our reference scenario.

In **Policy Pathway (2)**, we examine an alternative optimal allocation methodology based solely on abatement costs, as discussed in Section 3.3.1. Hydrogen allocation is determined by directly comparing the abatement costs of hydrogen-based technologies with the SCC, as well as by comparing the abatement costs of hydrogen-based technologies among themselves.

The following scenarios describe suboptimal trajectories under market failures:

In **Policy Pathway (3)**, we evaluate hydrogen deployment under imperfect carbon taxation and without learning internalization, representing a business-as-usual (BaU) trajectory.

In **Policy Pathway (4)**, a subsidy is introduced into the business-as-usual (BaU) scenario to compensate for the lack of learning internalization. The subsidy amount corresponds to the discounted sum of future benefits from learning-by-doing, as defined by Equation (15).

In **Policy Pathway (5)**, we introduce a renewable hydrogen production subsidy to offset imperfect carbon taxation. This subsidy is cumulative with the learning subsidy from Policy Pathway (4). In each period, the optimal subsidy level is determined by optimizing allocation under different subsidy levels, with the social cost minimization as the criterion.

In **Policy Pathway (6)**, as an alternative to the Policy Pathway (5), a demand-side subsidy for end-use sectors is introduced to compensate for imperfect carbon taxation. This subsidy is also cumulative with the learning subsidy from Policy Pathway (4). In each period, different combinations of subsidy levels for demand sectors are tested, and the optimal combination is the one that minimizes the social cost in that period.

Table 6 compares the key results of the different scenarios, based on the discounted social cost of the trajectories (in €), the total emissions of each trajectory (in $MteqCO_2$), and the total cost of the public policies implemented to address market failures (in €). In Figure 9, we observe the evolution over time of (a) unit subsidies (€ /MWh) for learning in scenarios (4), (5), and (6), (b) production subsidies in scenario (5), and (c) demand-side subsidies in scenario (6).

The First-Best Scenario serves as a theoretical benchmark, yielding the lowest total social cost (€45.3 billion) and CO2 emissions (59.0 MtCO2eq), assuming no market failures. The Abatement Costs-Based Scenario (Scenario 2), which applies an alternative allocation methodology, results in a total social cost of €50.0 billion and emissions of 95.2 MtCO2eq. Compared to the First-Best Scenario, this represents a welfare loss of €4.4 billion and an

Table 5: Comparison of social costs, CO_2 emissions, and policy support costs across policy pathways

	Policy Pathways			**Outcomes**		
#	**Merit-Order Method**	**CO_2 Price**	**Subsidy**	**Total Discounted Social Cost (with SCC) (B€)**	**Cumulative CO_2 Emissions ($MtCO_2eq$)**	**Policy Support Cost (B€)**
(1)	Optimal	SCC	N/A	45.4	59.0	-
(2)	Standard AC	SCC	N/A	49.9	95.2	-
(3)	Optimal	Carbon Tax	N/A	50.0	119.7	-
(4)	Optimal	Carbon Tax	Learning	49.8	115.7	0.03
(5)	Optimal	Carbon Tax	Learning + H_2 Supply-Side	46.8	87.3	2.0
(6)	Optimal	Carbon Tax	Learning + H_2 Demand-Side	45.6	68.2	3.0

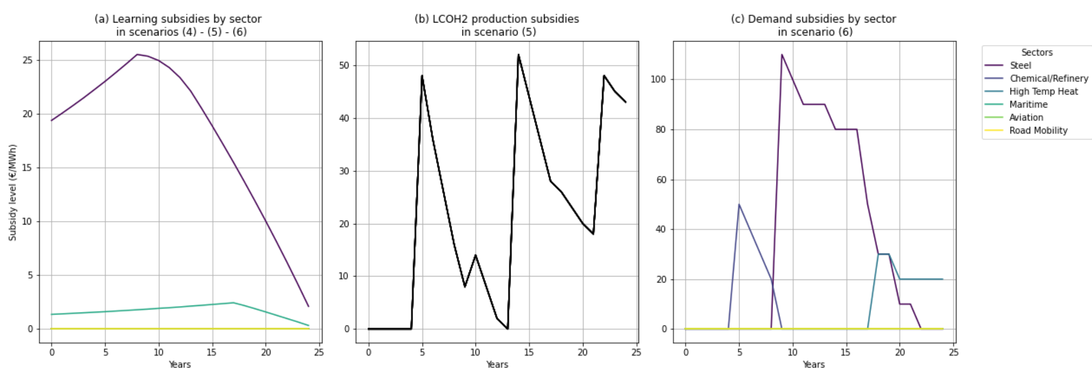

Figure 10: Evolution of learning subsidies, H_2 production subsidies, and demand-side subsidies over time across different policy pathways: (a) unit subsidies (€ /MWh) for learning by sector in pathways (4), (5), and (6), (b) production subsidies in pathways (5), and (c) demand-side subsidies in the pathway (6).

61% increase in emissions, highlighting the inefficiencies of an approach solely based on abatement costs.

The Business-as-Usual Scenario has a total social cost of €50.0 billion, with significantly higher emissions (119.9 MtCO2eq). This highlights the inefficiencies arising from imperfect carbon taxation and the absence of learning internalization. The Learning Subsidies Only Scenario slightly reduces the total social cost to €49.8 billion, with emissions decreasing to 115.7 MtCO2eq, with a relatively low discounted cost of learning policy support (€29.4

million).

Comparing Scenario 5 (Learning Subsidies + Hydrogen Production Subsidies) and Scenario 6 (Learning Subsidies + Demand-Side Subsidies) provides key insights into policy trade-offs. Scenario 5 achieves a total social cost of €46.8 billion while reducing emissions to 87.3 MtCO2eq, at a support cost of €2.0 billion. In contrast, Scenario 6 achieves a slightly lower social cost (€45.6 billion) and significantly greater emissions reductions (68.2 MtCO2eq), though at a higher policy support cost of €3.0 billion. The optimal amount of production subsidy tends to be lower than the optimal amount of demand subsidies: to avoid over-subsidizing non-meritorious sectors, the allocation of production subsidies is too low to restore the first-best allocation, leading to a welfare loss of 1.1 billion.

In our analysis, we assume no transaction costs when subsidies are allocated, so transfers between industry actors and public authorities have a neutral effect on the social cost of the ecosystem. However, in practice, these transfers may be inefficient, which encourages the social planner to choose the most efficient solution. From a cost-effectiveness perspective, Scenario 6 provides greater emission reductions per euro spent than Scenario 5. For an additional €1.0 billion in discounted total policy cost, it enables a further 19.1 MteqCO2 reduction, resulting in an abatement cost of approximately €52/tCO2. This makes it a efficient measure in terms of cost-effectiveness. In the presence of sectoral heterogeneity in carbon intensity, targeted demand-side support address more accurately market distortions than uniform production subsidies.

However, despite these improvements, neither scenario fully restores the social cost efficiency of the First-Best Scenario. The main reason for this discrepancy is that learning subsidies are predetermined based on expected benefits in the First-Best Scenario rather than dynamically adjusted. The interaction between learning subsidies and support for production or demand is not addressed here.

4 Policy Discussion

The merit order guides the optimal allocation of renewable hydrogen by addressing two key questions: Is a sector willing to purchase hydrogen, and does it merit priority from a social perspective? This approach maximizes social welfare and optimally distributes decarbonization efforts. Public policies should ensure that the optimal and effective allocations align.

International Energy Agency 2023b highlights that renewable electrolysis accounts for less than 1% of global hydrogen production. Moreover, hydrogen adoption in emerging applications—such as heavy industry, transportation, and hydrogen-derived fuels—remains minimal, representing less than 0.1% of global demand. This aligns with our scenarios, which suggest that significant demand for renewable hydrogen will only emerge once technological costs reach the projected levels for 2035. However, the cost of some technologies will only decrease if initial high-cost production is undertaken, highlighting the need for pilot projects and local hydrogen ecosystems. These 'learning-by-doing' dynamics justify early deployment, often structured within hydrogen valleys—where large-scale renewable hydrogen production is integrated with multiple end-uses. The Hydrogen Projects Database (International Energy Agency 2024a), covering 429 EU projects, provides key insights into hydrogen demand. It shows that 66% of operational projects involve hydrogen mobility, a share that drops to 30% for future projects. Industrial applications, though representing over 50% of planned projects, account for just 25% of operational ones.

This suggests that the current global allocation of renewable hydrogen may not align with the merit order outlined earlier. While the chemical and steel sectors have the highest merit for hydrogen use at current costs, local hydrogen initiatives seem to favor road mobility, the lowest-ranked sector in the merit order. Our model suggests this misallocation comes from insufficient carbon taxation across sectors. Another potential factor, not explored in this article, is the high fixed costs of deploying hydrogen technologies within local ecosystems. Although certain chemical applications can directly substitute grey hydrogen with renewable hydrogen or gradually integrate green hydrogen, offering greater deployment flexibility, industrial sectors such as steel and glass face a more rigid transition. The fundamental obstacle lies in the need for a full-scale transformation of production assets, which entails substantial fixed costs and delays adoption. By contrast, hydrogen mobility benefits from a modular deployment model, where small-scale production and refueling stations enable incremental expansion. This adaptability may have initially favored mobility over more meritorious applications in early hydrogen ecosystem projects. Public policies must account for these constraints to design effective hydrogen deployment strategies.

Currently, incentives for clean hydrogen use lag behind those for production, as most government funding is concentrated on the supply side. In 2022, only 5.5% of total public funding ($16.7 billion) was directed toward stimulating demand (Bhashyam 2023). Our policy scenario analysis indicates that production subsidies are less effective than direct demand-side subsidies in minimizing the social cost of hydrogen ecosystems. Since the decarbonization potential of hydrogen varies across sectors, demand-side support can better target industries with no viable alternatives, high learning potential, and the greatest decarbonization impact. While optimal demand-side subsidies require greater public investment, they achieve significant emissions reductions at a low cost (€60/tCO2). However, directly targeting end-use sectors carries risks, particularly given the geographic and economic disparities across hydrogen valleys. The merit order established for the Marseille-Fos hydrogen valley, for example, may differ from that of North Sea ecosystems. In a context of uncertainty regarding the costs of low-carbon technologies, production subsidies offer a technology-neutral approach, avoiding premature selection of specific hydrogen applications. Effective demand-side support, by contrast, requires a detailed understanding of cost structures, which may not always be available. In the absence of clear visibility, production subsidies still improve social welfare compared to a business-as-usual scenario. Ultimately, achieving a better balance between production and demand-side subsidies is essential to fostering a hydrogen ecosystem that prioritizes its most impactful uses.

Other mechanisms are also being explored on a larger scale. The EU Hydrogen Bank's auction mechanism serves as an additional tool for allocating renewable hydrogen, extending its deployment beyond hydrogen valleys. The principle is to bridge the gap between the lowest-cost hydrogen producer and the demand sector willing to pay the highest price. The Bank covers the difference, supporting market development. However, this mechanism does not prevent potential misallocations when sectors willing to pay more rank lower in the merit order. For instance, as highlighted in [PtX Hub], auction results suggest that mobility offtakers (€8/kg) may outbid industry (€6/kg), potentially diverting hydrogen towards lower-merit applications. Future discussions must address how to refine this system to better align economic incentives with the most socially beneficial hydrogen uses.

5 Conclusion

This paper has several contributions, which can be summarized as follows.

Firstly, we propose a methodology to define an optimal merit-order for end-uses of hydrogen. Several relevant dimensions to build this merit-order has been chosen: the social cost of carbon, the constraint on hydrogen supply, the cost of renewable hydrogen production, the availability of competing low-carbon technologies, the end-use technology deployment cost, the learning curves of technology, the energy efficiency, and emission intensity factors. This simple modeling approach helps to clarify the question of ranking hydrogen applications in terms of social welfare. Studies ranking the various end-uses of hydrogen have already been conducted, either through a policymaker's approach by reasoning in terms of abatement cost, or through a perspective closer to that of industry stakeholders by considering willingness to pay for hydrogen. Our modeling reconciles these two approaches by jointly considering both the cost of hydrogen production and the social cost of carbon as key variables. To our knowledge, this has not yet been done in the economics or techno-economic literature.

Secondly, several trade-offs are identified in terms of optimal technology choice in a two-sector model. Beyond the classic factors of abatement cost, the concept of social opportunity cost for abatement is highlighted. The merit order of hydrogen end-uses can reverse with the social cost of carbon (SCC): at low SCC, H_2 is allocated to cost-effective sectors, whereas at high SCC, it shifts to emission-intensive sectors. There exist conditions under which it is socially optimal to allocate renewable hydrogen to the sector with the highest abatement potential, even if that sector faces a higher sectoral abatement cost. The presence of alternative low-carbon technologies in some sectors further constrains hydrogen allocation to sectors without low-carbon alternative. Additionally, learning-by-doing reinforces hydrogen deployment in emission-intensive sectors with high cost-reduction potential and creates an incentive to maintain allocation within the same sector over time.

Thirdly, calibrating our model with current data for the case of Marseille-Fos industrial port zone allows us to propose a ranking of different hydrogen applications in terms of merit order. Our results show that the socially optimal merit order for hydrogen allocation differs significantly from the standard allocation approach that ranks the end-use sectors based on abatement costs. While the maritime sector ranks highest under the standard framework due to its high air pollutant emissions, the chemical and refinery sectors take priority initially in our socially optimal ranking, given their reliance on fossil-based hydrogen and costly low-carbon alternatives. By 2032, the steel industry moves to the top position due to its strong learning potential and early investment needs, and by 2043, the maritime sector surpasses chemicals and refineries as its hydrogen applications mature and gain from learning effects.

Finally, a carbon tax aligned with the social cost of carbon (SCC) would ensure optimal hydrogen allocation, but sectoral disparities in taxation lead to inefficiencies. Subsidies are thus needed to prevent underutilization and misallocation of renewable hydrogen. Comparing policy options, demand-side subsidies achieve greater emissions reductions (68.2 MtCO2 eq vs. 87.3 MtCO2 eq) and slightly lower social costs (€45.6 billion vs. €46.8 billion) than production subsidies, despite higher direct policy costs. Production subsidies could fail to correct misallocation, while demand-side support better directs hydrogen to emission-intensive sectors with strong learning potential.

Several limitations are inherent in our study, influencing the robustness and applicability of our findings. Our results are contingent upon a set of assumptions, particularly regarding the number of hydrogen end-use applications analyzed, with power generation and buildings notably excluded. The formalization of technical change through exogenous progress introduces uncertainty into our model. The omission of distribution and logistics costs associated with hydrogen deployment, varying based on production and consumption locations, represents another limitation. Additionally, the study acknowledges the critical impact of energy prices, especially the interplay between electricity and natural gas prices, without a comprehensive exploration of their dynamic relationship. The evolving public policy for the energy transition in electricity production is not explicitly considered. Furthermore, assumptions of inelastic demand for each sector and the absence of market interactions between firms within sectors may oversimplify real-world scenarios. Finally, the merit order approach remains valid as long as hydrogen is a scarce resource but becomes less relevant if its production can scale up rapidly at the local level or if transporting renewable hydrogen between world regions becomes easier. Moreover, the learning subsidy assumes that the planner knows the firm's costs better, which is uncertain. The assumption that the public agency has complete information on the costs of emitting and low-carbon technologies may not reflect the reality of information asymmetry. These limitations underscore the need for further research and refinement to enhance the reliability and practicality of our study's conclusions in navigating the complexities of renewable hydrogen deployment strategies.

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6 Appendix

A Demonstrations

A.1 Demonstration of Proposition 1

SOCA: In the case where hydrogen is constrained, under our different assumptions, there are two unique configurations for the allocation of hydrogen: either it is allocated to sector 1 at cost Γ_1, or it is allocated to sector 2 at cost Γ_2.

$$\Gamma_1 = [(p_{CO2}E_2 + K_{F2} + C_{F2})N_2 + [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H]$$
$$\Gamma_2 = [(p_{CO2}E_1 + K_{F1} + C_{F1})N_1 + [(p_{CO2}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + C_H)H]$$

By comparing Γ_1 and Γ_2:

$$\Gamma_1 - \Gamma_2 = H\left[(p_{CO2}E_2 + K_{F2} + C_{F2})\eta_{H2} - (p_{CO2}E_1 + K_{F1} + C_{F1})\eta_{H1} + K_{H1} - K_{H2}\right]$$

By normalizing with respect to H, we can find the value of p_{CO2} for which there is indifference between the two hydrogen allocations.

$$p_{CO2} = \frac{K_{F2}\eta_{H2} + C_{F2}\eta_{H2} - K_{F1}\eta_{H1} - C_{F1}\eta_{H1} + K_{H1} - K_{H2}}{E_1\eta_{H1} - E_2\eta_{H2}}$$

This value corresponds to the Social Opportunity Cost of Abatement (SOCA). If $p_{CO2} > SOCA$, $\Gamma_1 - \Gamma_2 > 0$, and hydrogen should be allocated to sector 2, and vice versa.

Allocation to sector with higher abatement cost: Following assumption 2, for all C_H lower than the value of $\overline{C_H}$, the abatement cost of sector 1 is lower than that of sector 2.

For $C_H < \overline{C_H}$, do there exist values of p_{CO2} for which hydrogen is allocated to sector 2 ?

We know that abatement cost curves are strictly increasing, that $AC_1(\overline{C_H}) = AC_2(\overline{C_H}) = SOCA$, so for all $C_H < \overline{C_H}$, $SOCA > max(AC_1, AC_2)$. Hence, there exist CO2 prices for which $p_{CO2} > max(AC_1, AC_2)$ (both sectors are willing to adopt hydrogen technology), and $p_{CO2} > SOCA$ (sector 2 is prioritized over sector 1).

Thus, if $C_H < \overline{C_H}$ and $p_{CO2} > SOCA$, hydrogen should be allocated to sector 2, even though the abatement cost for this value of hydrogen cost is higher than that of sector 1.

A.2 Demonstration for Proposition 2

New cost thresholds in sector 1 The social cost of sector 1 with an alternative low-carbon technology is:

$$\min_{q_{H,1},q_{A,1}} \Gamma_1 = (p_{CO2}E_1 + K_{F,1} + C_{F,1})(N_1 - \eta_{H,1}q_{H,1} - \eta_{A,1}q_{A,1}) + (K_{H,1} + C_H)q_{H,1} + (K_{A,1} + C_{A,1})q_{A,1} \quad (26)$$

The first-order conditions for sector 1 give:

$$(p_{CO2}E_1 + K_{F,1} + C_{F,1})\eta_{H,1} = (K_{H,1} + C_H) \quad (27)$$
$$(p_{CO2}E_1 + K_{F,1} + C_{F,1})\eta_{A,1} = (K_{A,1} + C_{A,1}) \quad (28)$$

We obtain the abatement costs of hydrogen technology and the alternative technology in sector 1:

$$AC_{H1} = \frac{(K_{H,1} + C_H) - (K_{F,1} + C_{F,1})}{E_1 \eta_{H1}}$$
$$AC_{A1} = \frac{(K_{A,1} + C_{A,1}) - (K_{F,1} + C_{F,1})}{E_1 \eta_{A,1}}$$

Furthermore, inserting into 27 and 28 and isolating C_H, we obtain the threshold cost of hydrogen for which hydrogen technology and the low-carbon technology are equivalent in terms of costs.

$$\overline{C_{H,1}^{A}} = \frac{\eta_{H,1}}{\eta_{A,1}}(K_{A,1} + C_{A,1}) - K_{H,1} \tag{29}$$

For all $C_H > \overline{C_{H,1}^{A}}$, the reference low-carbon technology becomes the alternative technology, and there is no longer any reason to use hydrogen technology in sector 1.

If $\overline{C_{H,1}^{A}} > \overline{C_H}$, then the introduction of an alternative low-carbon technology has no additional impact, as hydrogen would not be used in sector 1 for all $C_H > \overline{C_H}$.

Let us therefore study the impact of a low-carbon technology if $\overline{C_{H,1}^{A}} < \overline{C_H}$.

Change in allocation due to abatement cost Initially, for all $C_H \in [\overline{C_{H,1}^{A}}, \overline{C_H}]$, sector 1 no longer demands hydrogen. In this case, hydrogen will be used without competition in sector 2, for all $p_{CO2} > AC_2$. Recall that without the alternative technology, sector 1 was prioritized to receive hydrogen for $p_{CO2} \in [AC_1, SOCA]$. This change in allocation is represented by triangle (1) in the figure.

Change in allocation due to social opportunity cost of abatement Next, observe the situations where $C_H < \overline{C_{H,1}^{A}}$. If $p_{CO2} > \max(AC_1, AC_2)$, both sectors demand hydrogen, and an opportunity cost of abatement must be determined. There are four possible configurations, with the following costs:

$$\Gamma_1 = [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H] + [(p_{CO2}E_2 + K_{F2} + C_{F2})N_2]$$
$$\Gamma_2 = [(p_{CO2}E_1 + K_{F1} + C_{F1})N_1 + [(p_{CO2}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + C_H)H]$$
$$\Gamma_3 = [(K_{A1} + C_{A1})(\frac{N_1 - H\eta_{H1}}{\eta_{A1}}) + (K_{H1} + C_H)H] + [(p_{CO2}E_2 + K_{F2} + C_{F2})N_2]$$
$$\Gamma_4 = [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}})] + [(p_{CO2}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + C_H)H]$$

First, if $p_{CO2} < AC_{A,1}$, then $\Gamma_1 < \Gamma_3$ and $\Gamma_2 < \Gamma_4$, so it is a matter of comparing Γ_1 and Γ_2, as in the demonstration of Proposition 1. We retrieve the SOCA, as defined in equation (number).

Second, if $p_{CO2} > AC_{A,1}$, $\Gamma_1 > \Gamma_3$ and $\Gamma_2 > \Gamma_4$, so it is a matter of comparing Γ_3 and Γ_4. We find:

$$\Gamma_3 - \Gamma_4 = H\left[-(K_{A1} + C_{A1})\frac{\eta_{H1}}{\eta_{A1}} + (K_{H1} - K_{H2}) + (p_{CO2}E_2 + K_{F2} + C_{F2})\eta_{H2}\right]$$

For $\Gamma_3 - \Gamma_4 = 0$, isolating p_{CO2}, we define a new threshold value for the opportunity cost of abatement:

$$SOCA_A = \frac{(K_{A1} + C_{A1})\frac{\eta_{H1}}{\eta_{A1}} - (K_{H1} - K_{H2}) - (K_{F2} + C_{F2})\eta_{H2}}{\eta_{H2} E_2} \tag{30}$$

This is a new threshold value of the carbon price to determine the optimal allocation of hydrogen when $p_{CO2} > AC_A$. For $p_{CO2} > SOCA_A$, the optimal allocation is to sector 2.

We observe that $SOCA_A < SOCA$. Furthermore, since $C_H < \overline{C_{H,1}}$, we can also show that $AC_A < SOCA_A < SOCA$.

Thus, ultimately, for all $C_H < \overline{C_{H,1}^A}$, the allocation is as follows. For $p_{CO2} \in [AC_1, SOCA_A]$, hydrogen is allocated to sector 1. For $p_{CO2} > SOCA_A$, the allocation is made to sector 2.

Therefore, we can say that for all $C_H < \overline{C_{H,1}^A}$ and $p_{CO2} \in [SOCA_A, SOCA]$, there is a change in allocation due to the introduction of an alternative low-carbon technology. This change in allocation is represented by the shaded rectangle 2 in the figure.

Welfare loss Ultimately, the introduction of an alternative low-carbon technology increases the number of configurations for which it is optimal not to allocate hydrogen to the sector with the lowest abatement cost hydrogen technology.

The welfare loss when allocating based on abatement costs is:

- In cases 1 and 2: Allocating based on abatement costs leads to cost Γ_1, whereas the optimal cost was Γ_4. The welfare loss is therefore:

$$\begin{aligned}
\Gamma_1 - \Gamma_4 = {} & [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}}) + (p_{CO2}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + C_H)H] \\
& -[(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H + (p_{CO2}E_2 + K_{F2} + C_{F2})N_2] \\
= {} & [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}}) + (p_{CO2}E_2 + K_{F2} + C_{F2})(-\eta_{H2}H) + (K_{H2} + C_H)H] \\
& -[(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H]
\end{aligned}$$

- In case 3: Allocating based on abatement costs leads to cost Γ_1, whereas the optimal cost was Γ_0 (no hydrogen allocation). The welfare loss is therefore:

$$\begin{aligned}
\Gamma_1 - \Gamma_0 = {} & [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H + (p_{CO2}E_2 + K_{F2} + C_{F2})N_2] \\
& -[(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}}) + (p_{CO2}E_2 + K_{F2} + C_{F2})N_2] - \\
= {} & [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H] - [(K_{A1} + C_{A1})(\frac{N_1}{\eta_{A1}})]
\end{aligned}$$

A.3 Demonstration of Proposition 3

Thanks to hypothesis 4, the second period is sufficiently distant for hydrogen to be allocated to sector 2, given that the social cost of carbon represents the majority of the long-term cost. We also assume that in the long term, $H(1 + h) < \min(N_1, N_2)$, for simplification in our example. Therefore, the long-term cost in both sectors, depending on the short-term allocation in sector 2 ($q_{H,2,0}$), is:

$$\Gamma_1(q_{H,2,0}) = [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}]N_1 +$$
$$[K_{H,2}(1-\lambda_{H,2}q_{H,2,0}) + C_H(1-h)]H(1+h) + [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}H(1+h))$$

Under this condition, the discounted cost over the two periods depends only on the optimal short-term allocation:

$$\Gamma(q_{H,1,0}, q_{H,2,0}) = [E_1 p_{CO2} + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}q_{H,1,0}) + [K_{H,1} + C_H]q_{H,1,0}$$
$$+ [E_2 p_{CO2} + K_{F,2} + C_{F,2}](N_2 - \eta_{H,2}q_{H,2,0}) + [K_{H,2} + C_H]q_{H,2,0}$$
$$+ \frac{1}{1+r}[[E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}]N_1 +$$
$$[K_{H,2}(1-\lambda_{H,2}q_{H,2,0}) + C_H(1-h)]H(1+h) + [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}H(1+h))]$$

Dynamic Abatement Costs The first-order conditions regarding the allocation in the first sector ($q_{H,1,0}$) remain unchanged compared to the static version. For the second sector, the condition is:

$$[K_{H,2} + C_H] - [E_2 p_{CO2} + K_{F,2} + C_{F,2}](\eta_{H,2}) - \frac{[K_{H,2}(\lambda_{H,2})]H(1+h)}{(1+r)} = 0$$

Finally, we can define a dynamic abatement cost as follows:

$$p_{CO2} = \frac{[K_{H,2} + C_H] - K_{F,2} + C_{F,2} - \frac{1}{1+r}[K_{H,2}\lambda_{H,2}H(1+h)]}{\eta_{H,2}E_2} = AC_{H,2,0} - \frac{K_{H,2}\lambda_{H,2}H(1+h)}{(1+r)(E_2\eta_{H,2})}$$

Dynamic Social Opportunity Cost of Abatement Furthermore, if both sectors demand hydrogen, then the trade-off occurs between the following two costs:

$$\Gamma_1 = [(p_{CO2}E_2 + K_{F2} + C_{F2})N_2 + [(p_{CO2}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + C_H)H]$$
$$+ \frac{1}{1+r}[[E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}]N_1 + [K_{H,2} + C_H(1-h)]H(1+h)$$
$$+ [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}H(1+h))]$$
$$\Gamma_2 = [(p_{CO2}E_1 + K_{F1} + C_{F1})N_1 + [(p_{CO2}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + C_H)H]$$
$$+ \frac{1}{1+r}[[E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}]N_1 + [K_{H,2}(1-\lambda_{H,2}H) + C_H(1-h)]H(1+h)$$
$$+ [E_1 p_{CO2}(1+r) + K_{F,1} + C_{F,1}](N_1 - \eta_{H,1}H(1+h))]$$

By comparing Γ_1 and Γ_2:

$$\Gamma_1 - \Gamma_2 = H[(p_{CO2}E_2 + K_{F2} + C_{F2})\eta_{H2} - (p_{CO2}E_1 + K_{F1} + C_{F1})\eta_{H1} + K_{H1} - K_{H2}$$
$$- \frac{1}{1+r}(\lambda_{H,2}K_{H,2}H(1+h))]$$

We can find the new value of p_{CO2} for which there is indifference between the two hydrogen allocations ($\Gamma_1 = \Gamma_2$):

$$DSOCA = \frac{(K_{F1} + C_{F1})\eta_{H1} - (K_{F2} + C_{F2})\eta_{H2} + K_{H2} - K_{H1} + \frac{1}{1+r}(\lambda_{H,2}K_{H,2}H(1+h))}{E_2\eta_{H2} - E_1\eta_{H1}}$$

$$= SOCA - \frac{(\lambda_{H,2}K_{H,2}H(1+h))}{(1+r)(E_2\eta_{H2} - E_1\eta_{H1})}$$

According to hypothesis 2, $E_2\eta_{H2} > E_1\eta_{H1}$, so $DSOCA < SOCA$ and $DAC_{H,2,0} < AC_{H,2,0}$. Thus, there exist values of p_{CO2} within the ranges $[DSOCA, SOCA]$ or $[DAC_{H,2,0}, AC_{H,2,0}]$. In these ranges, hydrogen was not allocated to sector 2 when dynamic effects were not considered, but it is allocated when taking these effects into account. Based on the demonstration of Proposition 1, we can show that the regions where hydrogen should not be allocated based solely on the lowest abatement cost increase compared to the static case.

Welfare loss Ultimately, the introduction of an learning-by-doing effects increases the number of configurations for which it is optimal not to allocate hydrogen to the sector with the lowest abatement cost hydrogen technology.

The welfare loss when allocating based on abatement costs is:

- In cases 1: Allocating based on abatement costs leads to cost Γ_1, whereas the optimal cost was Γ_2. The welfare loss is therefore:

$$\Gamma_1 - \Gamma_2 = H[(p_{CO2}E_2 + K_{F2} + C_{F2})\eta_{H2} - (p_{CO2}E_1 + K_{F1} + C_{F1})\eta_{H1} + K_{H1} - K_{H2} - \frac{1}{1+r}(\lambda_{H,2}K_{H,2}H(1+h))]$$

- In case 2: Allocating based on abatement costs leads to cost Γ_0, whereas the optimal cost was Γ_2. The welfare loss is therefore:

$$\Gamma_0 - \Gamma_2 = (p_{CO2}E_2 + K_{F2} + C_{F2})(\eta_{H2}H) + (K_{H2} + C_H)H - \frac{1}{1+r}[K_{H,2}\lambda_{H,2}H]H(1+h)$$

A.4 Demonstration of Proposition 4

Let us examine the effectiveness of production subsidies for the only three possible socially optimal allocations: either both sectors are not decarbonized ($q_{H,i} = 0$), only sector 1 is decarbonized ($q_{H,1} = H$), or only sector 2 is decarbonized ($q_{H,2} = H$).

As proven in Proposition 1, if $p_{CO2} < SOCA$, there are only two socially optimal allocations: $q_{H,i} = 0$ or $q_{H,1} = H$. If $p_{CO2} > SOCA$, the two possible socially optimal allocations are: $q_{H,i} = 0$ or $q_{H,2} = H$.

Faced with a suboptimal carbon tax $\tilde{p_{CO2}}$, the private agent may choose one of the three aforementioned allocations, which may differ from the optimal one. The social planner can provide a production subsidy. The private costs faced are:

$$\Gamma_{0,p} = (\tilde{p_{CO2}}E_2 + K_{F2} + C_{F2})N_2 + (\tilde{p_{CO2}}E_1 + K_{F1} + C_{F1})N_1$$
$$\Gamma_{1,p}(s) = [(\tilde{p_{CO2}}E_2 + K_{F2} + C_{F2})N_2 + [(\tilde{p_{CO2}}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + (K_{H1} + (C_H - s))H]$$
$$\Gamma_{2,p}(s) = [(\tilde{p_{CO2}}E_1 + K_{F1} + C_{F1})N_1 + [(\tilde{p_{CO2}}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + (K_{H2} + (C_H - s))H]$$

No Hydrogen Allocation If the optimal allocation is that both sectors are not decarbonized ($q_{H,i} = 0$), a lower CO2 price $\tilde{p_{CO2}}$ further strengthens the advantage of the allocation at cost $\Gamma_{0,p}$ over the other allocations. Thus, the socially optimal and private allocations coincide.

Socially Optimal Allocation to sector 1 For the case where the socially optimal allocation is that only sector 1 is decarbonized ($q_{H,1} = H$). Necessarily, $p_{CO2} < SOCA$.

- If the privately optimal allocation is to allocate hydrogen to sector 1, then the socially optimal allocation is decentralized without the need for public policy intervention.
- It is not possible for the private allocation to assign hydrogen to sector 2. We know that $p_{CO2} \leq SOCA$. If $\tilde{p_{CO2}} < p_{CO2}$, then $\tilde{p_{CO2}} < SOCA$, and allocation to sector 1 will also be preferred over allocation to sector 2.
- If the privately optimal allocation is not to allocate hydrogen, $\Gamma_{0,p} < \Gamma_{1,p}(0)$. Since it is socially optimal to allocate hydrogen to sector 1, we can define a minimum subsidy amount s^* such that:

$$s = K_{H1} + C_H - (\tilde{p_{CO2}} E_1 + K_{F1} + C_{F1})\eta_{H1}$$

  This subsidy amount ensures that $\Gamma_{0,p} = \Gamma_{1,p}(s^*)$. Moreover, $\Gamma_{1,p}(s^*) - \Gamma_{2,p}(s^*) = \Gamma_{1,p}(0) - \Gamma_{2,p}(0)$. Since $\tilde{p_{CO2}} < SOCA$, then $\Gamma_{1,p}(0) < \Gamma_{2,p}(0)$. Finally, $\Gamma_{0,p} = \Gamma_{1,p}(s^*) < \Gamma_{2,p}(s^*)$. Thus, this amount effectively decentralizes the socially optimal allocation through production subsidies.

Social Optimal Allocation to Sector 2 Regarding the case where the socially optimal allocation is that only sector 2 is decarbonized ($q_{H,2} = H$). Necessarily, $p_{CO2} > SOCA$.

First, suppose that $\tilde{p_{CO2}} > SOCA$.

- If the privately optimal allocation is to allocate hydrogen to sector 2, then the socially optimal allocation is decentralized without the need for public policy intervention.
- If the privately optimal allocation is not to allocate hydrogen, $\Gamma_{0,p} < \Gamma_{2,p}(0)$. As in the previous case, we can define a minimum subsidy amount s^* such that:

$$s = K_{H2} + C_H - (\tilde{p_{CO2}} E_2 + K_{F2} + C_{F2})\eta_{H2}$$

  This subsidy amount ensures that $\Gamma_{0,p} = \Gamma_{2,p}(s^*)$. Moreover, since $\tilde{p_{CO2}} > SOCA$, then $\Gamma_{1,p}(0) > \Gamma_{2,p}(0)$. Finally, $\Gamma_{0,p} = \Gamma_{2,p}(s^*) < \Gamma_{1,p}(s^*)$. Production subsidies enable decentralization of the first-best allocation.

Now, suppose that $\tilde{p_{CO2}} < SOCA$.

- Consider the case where the privately optimal allocation is to allocate hydrogen to sector 1, whereas the socially optimal allocation is to allocate hydrogen to sector 2. In this case, $\Gamma_{1,p}(0) < \Gamma_{2,p}(0)$. We would like to find s such that $\Gamma_{1,p}(s) = \Gamma_{2,p}(s)$. Unfortunately, for any s, $\Gamma_{1,p}(s) - \Gamma_{2,p}(s) = \Gamma_{1,p}(0) - \Gamma_{2,p}(0)$. Thus, it is impossible to find a production subsidy amount that decentralizes the socially optimal allocation.

- Consider the case where the privately optimal allocation is not to allocate hydrogen, whereas the socially optimal allocation is to allocate hydrogen to sector 2. In this case, $\Gamma_{0,p} < \Gamma_{2,p}(0)$. We could define an amount $\tilde{s}$ such that $\Gamma_{0,p} = \Gamma_{2,p}(\tilde{s})$. However, for any $\tilde{s}$, since $p_{\tilde{CO2}} < SOCA$, $\Gamma_{2,p}(\tilde{s}) - \Gamma_{1,p}(\tilde{s}) = \Gamma_{2,p}(0) - \Gamma_{1,p}(0)$, and $\Gamma_{0,p} = \Gamma_{2,p}(\tilde{s}) > \Gamma_{1,p}(\tilde{s})$. Providing production subsidies would therefore incentivize allocating hydrogen to sector 1 rather than sector 2, making it impossible to decentralize the socially optimal allocation.

A.5 Demonstration of Proposition 5

Targeted subsidies are allowed for each sector for hydrogen technologies, with d_1 for sector 1 and d_2 for sector 2. The private cost for the agent becomes:

$$\Gamma_{0,p} = (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})N_2 + (p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})N_1$$
$$\Gamma_{1,p}(d_1) = [(p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})N_2 + [(p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})(N_1 - \eta_{H1}H) + ((K_{H1} - d_1) + C_H)H]$$
$$\Gamma_{2,p}(d_2) = [(p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})N_1 + [(p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})(N_2 - \eta_{H2}H) + ((K_{H2} - d_2) + C_H)H]$$

Let us revisit the case where production subsidies do not restore the merit order. The socially optimal allocation is when only sector 2 is decarbonized ($q_{H,2} = H$), meaning $p_{CO2} > SOCA$. Moreover, $p_{\tilde{CO2}} < SOCA$.

- Consider the case where the privately optimal allocation is to allocate hydrogen to sector 1, whereas the socially optimal allocation is to allocate hydrogen to sector 2. In this case, $\Gamma_{1,p}(0) < \Gamma_{2,p}(0)$. We aim to find $[d_1, d_2]$ such that $\Gamma_{1,p}(d_1) = \Gamma_{2,p}(d_2)$. Consider the following minimum subsidies:

  $$[d_1^*, d_2^*] = [0, K_{H2} - K_{H1} + (p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})\eta_{H1} - (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})\eta_{H2}]$$

  We verify that $\Gamma_{1,p}(d_1) = \Gamma_{2,p}(d_2)$, and $\Gamma_{1,p}(d_1) > \Gamma_{0,p}$, ensuring that these subsidies decentralize the socially optimal allocation, which is to allocate hydrogen to sector 2.

- Consider the case where the privately optimal allocation is not to allocate hydrogen, whereas the socially optimal allocation is to allocate hydrogen to sector 2. In this case, $\Gamma_{0,p} < \Gamma_{2,p}(0)$. The demand subsidy that ensures $\Gamma_{0,p} = \Gamma_{2,p}(d_2)$ is:

  $$[d_1^*, d_2^*] = [0, K_{H2} + C_H - (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})\eta_{H2}]$$

  Now, we must verify that $\Gamma_{1,p}(0) \geq \Gamma_{2,p}(d_2^*)$. The minimum subsidy ensuring $\Gamma_{1,p}(0) = \Gamma_{2,p}(d_2^*)$ is:

  $$d_2^* = K_{H2} - K_{H1} + (p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})\eta_{H1} - (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})\eta_{H2}$$

  Thus, it is sufficient to take the maximum of these two subsidy values to ensure that hydrogen is allocated to sector 2, thereby decentralizing the socially optimal allocation.

  $$d_2^* = \max(K_{H2} - K_{H1} + (p_{\tilde{CO2}}E_1 + K_{F1} + C_{F1})\eta_{H1} - (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})\eta_{H2}, \\ K_{H2} + C_H - (p_{\tilde{CO2}}E_2 + K_{F2} + C_{F2})\eta_{H2})$$

B Numerical Illustration

This numerical illustration focuses on the industrial port area of Marseille-Fos, where a decarbonized hydrogen ecosystem is evolving to replace existing fossil-fuel-based hydrogen use and support new applications. Seven sectors where renewable hydrogen could be deployed are analyzed. Industry and transport represent the main end-use sectors, specifically: heavy-duty road transport (trucks), industry (chemicals, oil refining, iron and steel production, industrial high-temperature heat such as in the glass industry), aviation, and shipping. Below, we explain how the data was processed to derive sector-specific input values and detail the technological pathways for these sectors.

B.1 Data Processing Assumptions

For data collection, we use the CIGALE database of the AtmoSud inventory. The extracted data comprises information on final energy consumption, total greenhouse gas (GHG) emissions, and air pollutants for each end-use and region for the year 2021. Fossil fuel consumption of this database is sourced from the EACEI dataset of INSEE. Regarding pollutant emissions, the database adheres to the recommendations outlined in the PCIT guide (Territorial Inventory Coordination Centre), which was developed jointly with the Approved Associations for Air Quality Monitoring (AASQAs), CITEPA, INERIS and the Laboratory. Air Quality Monitoring Center (LCSQA), and validated by the Ministry in charge of the environment. Energy consumption in CIGALE database is aggregated for all industrial sectors with the total NG consumption of about 7.5 TWh. Several assumptions are made regarding the specific end-use sectors. The estimation for individual industrial end-uses' energy consumption is sourced from a report authored by the energy transition department of Port de Marseille Fos, particularly focusing on the port's strategic vision for hydrogen development. This vision entails the production of 25 kt and 40 kt of hydrogen for the chemicals and refinery sectors, respectively. Assuming the current demand for hydrogen is met entirely through Steam Methane Reforming (SMR) technology, with an energy requirement of 1.34 MWh of natural gas (NG) per 1 MWh of hydrogen produced (as per IEA Assumptions), and employing a lower heating value (LHV) of 33 kWh/kg for hydrogen, it is estimated that the chemicals and refinery end-uses consume approximately 1.1 TWh and 1.8 TWh of NG, respectively. In the steel industry, the primary manufacturing facility operated by ArcelorMittal in the region produces approximately 5 million tons of steel annually utilizing Blast Furnace/Basic Oxygen Furnace (BF/BOF) technology, which relies on both NG and coal. Given the energy requirements of 0.28 MWh of NG and 4.95 MWh of coal per ton of steel produced (according to IEA Assumptions), the steel industry in the region is estimated to consume around 1.2 TWh of NG and 22 TWh of coal. Deducting the NG consumption attributed to chemicals, refinery, and steel industry, it is assumed that half of the remaining NG consumption of the region (approximately 1.7 TWh) is allocated to high-temperature industrial heating purposes. Regarding road mobility, specific vehicle types are not specified in the available database. According to the report from the energy transition of Port de Marseille Fos, the region is estimated to have a total of 350 trucks. Assuming an annual mileage of 158,000 km per truck and a diesel consumption rate of 25 liters per 100 km, with each liter of diesel containing 0.0107 MWh of energy, it is estimated that transportation via trucks consumes approximately 0.15 TWh of diesel annually. Table 7 summerize the sector-specific anuual energy consumption, GHG emissions, and air pollutants in the region.

B.2 Sectoral Technology Pathways

The merit-order model considers three technological pathways for each end-use sector: reference fossil fuel-based technology, hydrogen-based technology, and low-carbon alternative technology. These pathways are elaborated for each specific end-use sector in the region in Table 6. Finally, the techno-economic input values for each technology pathway in end-use sectors are presented in Table 8. The assumptions underlying these technology pathways are derived from a series of structured, face-to-face interviews with regional project developers, during which we posed pre-defined questions regarding their assessments of hydrogen-based technology potential, low-carbon alternatives, and future projections (Grand Port Maritime de Marseille 2024, TotalEnergies and Engie 2025, ENGIE 2025), Gravithy Project 2025).

Table 6: Sectoral Technology Pathways

Sector	**Fossil Fuel-Based Technology**	**Hydrogen-Based Technology**	**Low-Carbon Alternative**
Chemicals/ Refinery	Fossil-fuel-based hydrogen, produced via Steam Methane Reforming (SMR), is currently used in ammonia production (through Haber-Bosch process), in methanol production (through methanation process), and in refining. SMR involves reacting natural gas (or methane) with steam at high temperatures (700-1000°C) to produce hydrogen.	Renewable hydrogen from electrolysis replaces fossil hydrogen production, eliminating SMR.	Natural gas in SMR is substituted with biogas derived from biomass, a process known as bio-SMR.

Sector	Fossil Fuel-Based Technology	Hydrogen-Based Technology	Low-Carbon Alternative
Steel Industry	The traditional steelmaking process uses coal and natural gas in Blast Furnaces (BF) and Basic Oxygen Furnaces (BOF) for reducing iron ore to molten iron and refining it into steel.	Renewable hydrogen replaces coal and natural gas in Direct Reduced Iron (DRI) production, which is then processed in an Electric Arc Furnace (EAF) (H_2-DRI-EAF).	DRI using natural gas (NG-DRI-EAF) with Carbon Capture and Storage (CCS) that could only mitigate about 60% of the CO_2 emissions.
Industrial High-Temperature Heating	Natural gas combustion is widely used to achieve high temperatures in processes like cement production, glass manufacturing, and metal smelting. In this study, we considered only the large-scale furnaces in the region that could not be directly electrified due to heat transfer limitations and need to be replaced by hybrid furnaces.	Hybrid furnaces that use electricity and renewable hydrogen replaces natural gas, achieving high temperatures with significantly lower emissions.	Combustion remains natural gas-based, but CCS captures and stores about 60% of the emitted CO_2.
Heavy-Duty Road Mobility: Trucks	Diesel engines dominate the trucking industry, especially for long-haul transport.	Fuel Cell Electric Vehicles (FCEVs) use renewable hydrogen to generate electricity to power electric motors.	Battery Electric Vehicles (BEVs) rely on electricity stored in large batteries. We assume that the battery can be fully recharged overnight, allowing trucks to cover their daily travel distance.

Sector	Fossil Fuel-Based Technology	Hydrogen-Based Technology	Low-Carbon Alternative
Maritime	In this study, we consider only Ultra-Large Container Vessels (ULCVs) in the maritime sector that primarily use Very Low Sulfur Fuel Oil (VLSFO) for propulsion and power generation.	E-Methanol, derived from renewable hydrogen, is used in existing combustion engines. Therefore, in this study, the cost of end-use technology deployment only accounts for the conversion of renewable hydrogen to E-Methanol.	Biofuels produced from renewable sources like algae, vegetable oils, or waste materials replace fossil fuels in current engines. We assumed there is no cost associated with the end-use technology deployment for the low-carbon alternative technology.
Aviation	In this study, we consider only long-haul aircrafts in the aviation sector that primarily relies on jet fuel and kerosene derived from crude oil.	Renewable hydrogen is used to produce E-kerosene through methanation and Fischer-Tropsch processes, enabling sustainable aviation fuels (SAFs) for existing jet engines. Therefore, in this study, the cost of end-use technology deployment only accounts for the conversion of renewable hydrogen to E-kerosene.	Biojet fuels, such as Hydroprocessed Esters and Fatty Acids (HEFA), are produced from vegetable oils or fats and are compatible with current engines. We assumed there is no cost associated with the end-use technology deployment for the low-carbon alternative technology.

Table 7: Energy Consumption, GHG Emissions, and Air Pollutants by End-Use Sector

End-Use Sector	**Fossil Fuel**	**Energy Consumption (TWh)**	**Total GHG Emissions (M tons of CO_2-eq)**	**NOx (tons)**	**SO_2 (tons)**	**CO (tons)**	**PM10 (tons)**	**PM2.5 (tons)**	**NMVOC (tons)**
Chemical	NG	1.1	0.275	315	5	240	6	5	23
Refinery	NG	1.8	0.450	515	8	393	10	8	38
Steel (NG)	NG	1.2	0.300	343	5	262	7	5	25
Steel (Coal)	Coal	22	7.260	8308	123	6346	160	132	611
Industrial High Temp Heat	NG	1.7	0.425	486	7	371	9	8	36
Maritime	Fuel Oil	0.13	0.035	873	22	82	16	15	31
Trucks	Diesel	0.15	0.234	588	1	252	11	11	55
Aviation	Kerosene	0.23	0.061	228	19	166	1	1	20

Table 8: Parameter Values for Different Sectors

				End-Use Sectors					
End-Use Technology	**Parameter (per Unit of Energy Consumption of Tech)**	**Denotation**	**Unit**	**Steel**	**Chemical/ Refin-ery**	**High Temp Heat**	**Maritime**	**Aviation**	**Trucks**
Fossil Fuel-Based Tech (F-Tech)	End-Use Tech Cost	K_F	€/MWh	69	0	0	0	0	190
	Fuel Price	C_F	€/MWh	15	69	35	46	62	79
	Cost of Air Pollutants	P_F	€/MWh	7.44	3.56	3.56	108.10	15.80	41.71
	GHG Emission Intensity	E_F	tCO_2eq/MWh	0.450	0.339	0.200	0.276	0.301	0.281
H_2-Based Tech (H-Tech)	End-Use Tech Cost @2025	K_H	€/MWh	364	0 5	0	37	46	429
	End-Use Tech Cost @2030	K_H	€/MWh	211	0	0	28	30	233
	Energy Efficiency compared to F-Tech	η_H	-	2.59	1.00	1.00	0.81	0.70	1.22
Low-carbon Alternative (A-Tech)	End-Use Tech Cost	K_A	€/MWh	242	0	100	0	0	335
	Fuel/Electricity Price	C_A	€/MWh	35	180	35	191	154	100
	Energy Efficiency compared to F-Tech	η_A	-	1.25	1.00	1.00	0.81	0.83	1.57
	Cost of Air Pollutants	P_A	€/MWh	2.53	0.00	1.21	0.00	0.00	0.00
	GHG Emission Intensity	E_A	tCO_2eq/MWh	0.07	0.00	0.07	0.00	0.00	0.00