



Working Paper

Prioritising Renewable Hydrogen End-Uses: A Merit-Order Framework

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Prioritising Renewable Hydrogen End-Uses: A Merit-Order Framework

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Executive Summary

Renewable hydrogen remains costly and its availability is constrained. Only 10% of planned global clean hydrogen capacity for 2030 has identified buyers. This raises the question of which end-use sectors should be prioritised as deployment progresses. Standard marginal abatement cost (MAC) curves, the dominant policy tool for ranking decarbonisation options, are insufficient for this task: they ignore the opportunity cost of directing hydrogen away from high-emission sectors, fail to account for the existence of competing low-carbon alternatives such as direct electrification or biofuels, and take no account of the long-term cost-reduction benefits generated by early deployment through learning-by-doing.

This paper develops a merit-order framework that incorporates these considerations. By combining the carbon costs, sector-specific deployment costs, energy efficiency ratios, production-to-usage cost disparities, and technology learning curves, it identifies which sectors deserve hydrogen first, and shows how that ranking evolves as the social cost of carbon increases and technology costs fall. In the Marseille-Fos application, chemicals and steel receive priority in the scenarios examined, while road freight is excluded from the optimal allocation because battery-electric alternatives are more competitive.

Regarding policy implications, demand-side subsidies targeted at the most meritorious sectors are approximately 40% more cost-efficient at reducing emissions than undifferentiated production subsidies, yet over 94% of current public hydrogen support is directed at production. The emphasis on road mobility in some early demonstration programmes raises questions about the prioritisation of public support. The paper examines how learning subsidies, targeted demand-side support and production incentives linked to end-use commitments can improve hydrogen allocation.

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1. Introduction: Prioritising Renewable Hydrogen End-Uses

Renewable hydrogen and hydrogen-based fuels (e-fuels) can contribute to decarbonising sectors where direct electrification is difficult, including steelmaking, chemical production, shipping and aviation. Unlike electricity, which can substitute for fossil fuels in heating, light transport and most industrial motor systems, hydrogen offers a pathway to deep decarbonisation where direct electrification is physically infeasible or prohibitively costly: as a feedstock for ammonia and methanol synthesis, as a reducing agent in iron ore processing, and as the basis for synthetic aviation and maritime fuels. European and national hydrogen strategies accordingly identify these hard-to-abate sectors as the primary destination for green hydrogen, with the European Union alone targeting 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030 (EC, 2022). The IEA’s Net Zero Emissions scenario requires low-emission hydrogen to reach roughly 150 Mt per year by 2050, with heavy industry and long-distance transport accounting for the majority of that demand (IEA, 2025). However, committed projects and contracted demand remain well below these objectives.

Insufficient demand at current prices is a major constraint on renewable hydrogen deployment. A global pipeline of roughly 45–47 million metric tonnes (Mt) of annual clean hydrogen capacity has been announced for 2030, representing planned electrolyser investments of hundreds of billions of dollars. Yet as of early 2024, only 12% of that capacity had identified an offtaker, and of that contracted volume, barely one-tenth was under a binding purchase agreement, leaving fewer than 1 Mt per year genuinely committed against a ~45 Mt/yr pipeline (BNEF, 2024). The IEA’s most recent annual review confirms that, of the approximately 520 GW of electrolyser capacity announced globally, only around 4% has reached a final investment decision (IEA, 2025). Odenweller & Ueckerdt (2025) document this as a structural “ambition and implementation gap”: of all green hydrogen capacity announced for delivery in 2023, only 7% was completed on schedule, and closing the gap between stated 2030 targets and committed projects would require roughly \$1.3 trillion in subsidies in the absence of meaningful carbon pricing. Limited demand at current prices contributes to the gap between announced projects and committed investments. Securing long-term purchase commitments is therefore important for financing large-scale renewable hydrogen production.

A second concern is whether early deployment prioritises the sectors in which hydrogen offers the greatest social benefit. The European Union’s Clean Hydrogen Partnership (formerly FCH JU) spent more than a decade funding demonstration projects primarily in mobility: over 1,300 fuel-cell electric vehicles and more than 400 fuel-cell buses were supported through EU programmes between 2005 and 2023 (CHP/JRC, 2024). The flagship JIVE 1 and JIVE 2 programmes deployed approximately 290 fuel-cell buses at 16 European sites, yet the JIVE 2 Best Practice Report acknowledged that “reliability challenges in hydrogen refuelling stations have impacted the availability and business case” of the

buses, and several cities, including Brussels, have since pivoted back to battery-electric alternatives. These programmes raise the question of whether support for industrial applications could have generated greater climate and social benefits. Several studies suggest that renewable hydrogen should be prioritised for feedstocks (ammonia, methanol), steel production, and aviation and maritime e-fuels, where direct electrification is impossible or deeply inefficient, and should be actively discouraged in road transport, building heating, and power generation, where alternatives are commercially mature (Ueckerdt et al., 2021; Terlouw et al., 2025). In the latter sectors, using green hydrogen instead of direct electrification or heat pumps can carry mitigation costs of €800–1,200 per tonne of CO₂ avoided at current costs (Ueckerdt et al., 2021). Such costs raise concerns about the cost-effectiveness of hydrogen in these applications. The concept of a hydrogen “merit order”, ranking end-uses according to their social priority, has been advocated by researchers and practitioners to inform the prioritisation of hydrogen end-uses (Ueckerdt et al., 2021; Liebreich, 2021).

The emphasis on production support may contribute to differences between market allocation and socially preferred end-uses. BloombergNEF’s Hydrogen Subsidies Tracker recorded approximately \$308 billion in announced government hydrogen support globally as of October 2023, of which only \$16.7 billion, roughly 5.4%, targeted demand-side applications; by March 2025, as total announced support fell to ~\$277 billion, the demand share had dropped further to approximately 3% (BNEF, 2023, 2025). The IEA corroborates this imbalance: in a narrower measure covering new policy announcements over a single year, supply-side funding ran approximately 1.5 times the level of demand-side funding (IEA, 2024a). Without targeted demand support, allocation could be driven by private willingness to pay and delivery constraints, which may differ from social priorities. The EU’s recent policy innovations, the Renewable Energy Directive III’s mandate that renewable fuels of non-biological origin (RFNBOs) constitute 42% of industrial hydrogen use by 2030 and 60% by 2035, and the European Hydrogen Bank’s three auction rounds since 2024, represent important steps toward demand-side governance. Yet the Bank’s instrument still pays a fixed premium per kilogramme of hydrogen *produced*, irrespective of the sector that consumes it; the RED III mandate has been transposed by only 4 of 27 Member States as of November 2025 (EHO, 2025); and policies already in force could trigger only ~6 Mt/yr of demand by 2030, roughly half of stated EU demand targets and one-tenth of what the IEA’s Net Zero scenario requires (IEA, 2024a). Demand support must be coordinated with production and infrastructure development within local hydrogen ecosystems.

An allocation framework can help identify priority sectors and guide the calibration of support. Existing approaches have typically relied on qualitative rankings (Liebreich, 2021) or techno-economic life-cycle assessments (Terlouw et al., 2025), without embedding the allocation decision in a welfare-maximising economic framework that can account simultaneously for the social cost of carbon, resource scarcity, competing low-carbon technologies, and the dynamic benefits of early deployment. The standard tool of climate policy, the

Marginal Abatement Cost (MAC) curve, is likewise ill-suited: it ranks decarbonisation options cheapest-first without accounting for the opportunity cost of directing a scarce resource away from high-emission sectors, the existence of alternative low-carbon pathways, or the learning-by-doing effects that early deployment in capital-intensive sectors generates for the entire value chain. Previous multi-sectoral studies (IEA, 2019; FCH 2JU, 2021; Hydrogen Council, 2021; Ueckerdt et al., 2021) have addressed individual dimensions of this problem but not integrated them into a coherent, welfare-maximising allocation model. Dynamic and sectoral approaches have already extended standard abatement-cost assessments. Kasser et al. (2024) account for learning-by-doing and competition between battery-electric and fuel-cell buses, while Sadighi et al. (2026) evaluate glass-industry demonstrators by incorporating knowledge spillovers to subsequent plants. The present study extends these perspectives to the allocation of scarce renewable hydrogen across end-use sectors.

Three key results emerge from our analysis. First, the optimal allocation can *reverse* as the social cost of carbon (SCC) increases: at low SCC levels, hydrogen flows to the cheapest-to-decarbonise sector; at higher SCC levels, priority shifts to the most emission-intensive sector, a reversal captured by the concept of the “Sectoral Opportunity Cost of Abatement” introduced in this paper. Second, the existence of competitive non-hydrogen alternatives caps the social value of hydrogen in certain sectors, changing their rank in the merit order. Third, learning-by-doing in capital-intensive sectors such as steel justifies deploying hydrogen there earlier than current private economics would suggest, because early deployment can reduce technology costs for subsequent adopters. Using sectoral data for the Marseille-Fos industrial port zone, one of France’s seven identified hydrogen valleys, the model produces a changing merit order. The First-Best pathway reduces discounted social costs relative to Business-as-Usual by accounting for the SCC and endogenous learning. The paper concludes with concrete recommendations for a rebalanced policy mix in which demand-side instruments and learning subsidies play a central role alongside production support.

The remainder of the paper is organised as follows. Section 2 reviews the limits of the standard marginal abatement cost approach as a framework for allocating scarce renewable hydrogen. Section 3 develops the stylised merit-order model, introducing the concepts of opportunity cost, competing low-carbon alternatives, learning-by-doing, and sector-specific production-to-usage costs. Section 4 illustrates the methodology through a pedagogical two-sector comparison of heavy-duty road freight and primary steelmaking, showing how each analytical dimension overturns the MAC ranking. Sections 5 and 6 deploy the full framework in the industrial port zone of Marseille-Fos, calibrating the model to sectoral data and deriving a quantitative merit order under alternative carbon pricing and hydrogen deployment scenarios. Section 7 concludes with policy recommendations.

2. The Limits of the Standard Approach

The standard way to rank decarbonisation options is the marginal abatement cost (MAC) curve. For each sector, the cost of replacing the fossil-based technology with a low-carbon option is divided by the emissions avoided. Options are then ranked from the lowest to the highest cost per tonne of CO₂ avoided.

When applied to hydrogen, this approach appears intuitive. A sector should receive renewable hydrogen first if it can reduce emissions at the lowest cost. In its simplest form, the abatement cost of using hydrogen in sector i can be written as:

$$AC_i(C_H) = \frac{C_H - F_i}{e_i} \quad (1)$$

where C_H is the levelised cost of hydrogen, F_i is the cost of the fossil-based technology displaced by one unit of hydrogen, excluding carbon costs, and e_i is the quantity of CO₂ avoided by using one unit of hydrogen in that sector.

This expression deliberately reproduces the logic of a standard MAC curve. It treats hydrogen as if a common hydrogen cost could be compared across sectors and then divided by avoided emissions. This is useful for identifying the carbon price at which hydrogen becomes attractive relative to a fossil benchmark, but it abstracts from the additional costs that arise when hydrogen is made usable in specific sectors.

This metric therefore answers a useful but limited question: *at what social cost of carbon does hydrogen become socially preferable to the fossil technology in a given sector?*

Let p denote the social cost of carbon (SCC), used to value avoided emissions in the social welfare calculation. It differs from the effective carbon price faced by firms through taxes or emissions quotas. The two are assumed equal in the first-best benchmark. Hydrogen becomes socially desirable in sector i when:

$$p > AC_i(C_H). \quad (2)$$

However, this is not the same as answering the allocation question. When renewable hydrogen is scarce, the relevant policy problem is not simply whether hydrogen is socially worthwhile in one sector considered in isolation. It is whether one sector should receive hydrogen *instead of another sector*. In other words, hydrogen allocation is an opportunity-cost problem.

A sector may have a low abatement cost because hydrogen appears cheap relative to its fossil benchmark, but each unit of hydrogen used in that sector is no longer available for a more emission-intensive sector. The MAC curve therefore risks prioritising the sector where hydrogen appears cheapest, rather than the sector where scarce hydrogen delivers the highest social value.

Table 1 summarises four limitations of this approach for allocating renewable hydrogen.

Table 1: *Limitations of the Standard Approach for Ranking the End-Uses*

Limitation	Why It Matters for Hydrogen
It ignores resource scarcity	The MAC curve assumes unlimited supply at a given cost. Renewable hydrogen is physically constrained by renewable electricity availability, electrolyser capacity, storage and transport infrastructure. Allocating it to a sector with low abatement costs may foreclose its use in a sector with higher abatement costs but greater emissions reductions per unit of hydrogen.
It is static	The MAC curve takes a snapshot at one point in time. Hydrogen costs, the Social Cost of Carbon, and alternative technology costs all change. The cheapest sector today may not be the most meritorious in 2035.
It ignores technology competition	The MAC curve compares hydrogen to the fossil fuel baseline. It does not account for the fact that many sectors have non-hydrogen low-carbon alternatives, such as direct electrification, biofuels, or CCS. Allocating hydrogen to a sector with a viable alternative may be socially wasteful.
It treats hydrogen as homogeneous	The MAC curve typically uses a production cost, or a generic delivered cost, for hydrogen. It does not fully account for the sector-specific costs of making hydrogen usable: purity requirements, compression, storage, distribution logistics, conversion equipment, and process adaptation.

The policy implication is that a hydrogen merit order cannot be derived from a static MAC curve alone. A robust merit order must compare the social value of hydrogen across sectors under scarcity. This requires moving from a ranking based on average abatement costs to a ranking based on the marginal social value of scarce hydrogen.

A low abatement cost does not automatically imply high priority for renewable hydrogen. When hydrogen is scarce, the relevant question is where one additional unit of hydrogen creates the largest social gain relative to the next-best use.

3. The Stylised Merit-Order Model

A merit-order framework for hydrogen goes beyond abatement costs by introducing four analytical dimensions: opportunity costs, technology competition, dynamic learning effects, and sector-specific hydrogen usage costs.

Suppose policymakers must allocate a limited quantity of renewable hydrogen across several end-use sectors. We now add the missing sector-specific component that the standard abatement-cost expression abstracts from. Let ν_i denote the sector-specific cost of making hydrogen usable in sector i : purity requirements, compression, storage, distribution logistics, conversion equipment, and process adaptation.

For each sector i , one unit of hydrogen creates a net social value equal to the avoided carbon damage and avoided fossil cost, minus the full cost of using hydrogen in that sector:

$$V_i(p) = pe_i - [(C_H + \nu_i) - F_i]. \quad (3)$$

The term pe_i is the value of avoided CO₂ emissions. The term $(C_H + \nu_i - F_i)$ is the additional non-carbon cost of switching from the fossil technology to hydrogen, including the sector-specific production-to-usage cost gap. A sector should use hydrogen only if $V_i(p) > 0$. But if hydrogen is scarce and several sectors have positive value, hydrogen should be allocated first to the sector with the highest $V_i(p)$.

This expression makes clear why the hydrogen merit order can differ from the standard abatement-cost ranking. The abatement cost in Equation (1) divides the cost premium by emissions avoided. By contrast, Equation (3) measures the total social value of a scarce unit of hydrogen at a given SCC. The ranking therefore depends on the Social Cost of Carbon.

3.1 Resource Scarcity: From Abatement Cost to Opportunity Cost

When hydrogen is scarce, allocating it to one sector necessarily means withholding it from another. This creates an opportunity cost: the social benefit foregone by not using hydrogen in the next-best sector. The merit order must account not just for how cheaply a sector can be decarbonised with hydrogen, but for what is given up by directing hydrogen there rather than elsewhere.

To see this, consider two sectors. Sector 1 has the lower abatement cost, so it would be prioritised by a standard MAC curve. Sector 2 is more emission-intensive, so that $e_2 > e_1$, but it is also more expensive to decarbonise with hydrogen. Hydrogen should be allocated to sector 2 rather than sector 1 when:

$$V_2(p) > V_1(p). \quad (4)$$

Using Equation (3), this condition becomes:

$$p > \frac{[(C_H + \nu_2) - F_2] - [(C_H + \nu_1) - F_1]}{e_2 - e_1} \equiv SOCA_{1 \rightarrow 2}. \quad (5)$$

Because the same production cost C_H applies to both sectors, it cancels from the allocation threshold when one unit of hydrogen is compared across sectors:

$$SOCA_{1 \rightarrow 2} = \frac{(\nu_2 - F_2) - (\nu_1 - F_1)}{e_2 - e_1}. \quad (6)$$

This threshold is the **Sectoral Opportunity Cost of Abatement** (SOCA). It is the SCC level above which the opportunity cost of allocating hydrogen to the cheaper sector becomes too high. Below this threshold, the lower-cost sector may receive priority. Above it, the higher-emission sector should receive hydrogen first, even if its sectoral abatement cost is higher.

A key insight from the model is therefore that the socially optimal allocation can reverse as the Social Cost of Carbon increases. At low SCC levels, hydrogen may be allocated to the sector where decarbonisation is cheapest. As the SCC increases, it becomes progressively more valuable to direct scarce hydrogen toward the most emission-intensive sector, even if that sector's private or sectoral abatement cost is higher.

Standard MAC curve analysis, which orders sectors from cheapest to most expensive and never revises that ranking, can give wrong answers for hydrogen policy. The merit order derived from a welfare-maximising framework, which accounts for opportunity costs, may differ substantially, and will evolve over time as the SCC increases.

3.2 No-Regret Sectors: The Role of Competing Low-Carbon Technologies

The availability and cost of non-hydrogen alternatives also affect sectoral priorities. When direct electrification, biofuels, or carbon capture and storage can decarbonise a sector at comparable or lower cost than hydrogen, the social value of directing hydrogen there is lower.

Let A_i denote the cost of the best non-hydrogen low-carbon alternative in sector i . The value of allocating scarce hydrogen to that sector becomes:

$$V_i^A(p) = \min\{F_i + pe_i, A_i\} - (C_H + \nu_i). \quad (7)$$

The term $\min\{F_i + pe_i, A_i\}$ is the social cost of serving the sector without hydrogen: either society keeps the fossil technology and pays the carbon cost, or it uses the best non-hydrogen low-carbon alternative. Hydrogen is valuable only to the extent that it improves on this next-best option.

Sectors with limited or costly alternatives may therefore receive higher priority as 'no-regret' hydrogen end-uses. Chemicals and steel illustrate this situation. In both cases, alternatives exist, but they are either costly, reliant on uncertain biomass or CO₂ storage

chains, or not yet commercially proven at scale.

The existence of a competitive alternative technology caps the social willingness to pay for hydrogen in a given sector. Once that cap is reached, allocating additional hydrogen to that sector produces no additional social benefit over the alternative pathway. This cap must be incorporated into the merit order.

3.3 Dynamic Merit Order: Learning-by-Doing and the Value of Early Deployment

A framework based only on current costs does not capture the effect of deployment on future technology costs. Hydrogen technologies, from electrolyzers to hydrogen-based direct reduction furnaces for steelmaking, exhibit learning-by-doing. Deployment can reduce future production or deployment costs and generate benefits that extend beyond the deploying firm.

This can be captured by adding a learning value, L_i , to the current social value of hydrogen:

$$V_i^{dyn}(p) = V_i^A(p) + L_i. \quad (8)$$

The term L_i represents the discounted future social benefit generated by one additional unit of hydrogen use in sector i today. Sector-specific learning may arise from improvements in end-use technologies, supply-chain development, and accumulated operating experience.

In the numerical application, this mechanism is represented through end-use technology costs, which decline with cumulative hydrogen use according to $K_{H,i,\tau} = K_{H,i,0} \exp(-\lambda_i X_{i,\tau})$. Here, $X_{i,\tau}$ denotes cumulative past hydrogen use and λ_i is a learning coefficient: a higher coefficient implies faster cost reductions for a given increase in cumulative use. The learning value at date t is then:

$$L_i = \sum_{\tau=t+1}^T \frac{\lambda_i K_{H,i,\tau} D_{i,\tau}}{(1+r)^{\tau-t}}. \quad (9)$$

Here, $D_{i,\tau}$ is future hydrogen use in sector i , r is the discount rate, and T is the final period. Each term combines the marginal reduction in future unit costs, $\lambda_i K_{H,i,\tau}$, with the volume benefiting from that reduction, $D_{i,\tau}$, and discounts the resulting saving to date t . This expression adapts the discounted learning-benefit approach of [Kasser et al. \(2024\)](#) to sector-specific hydrogen use.

In the two-sector case, learning shifts the SOCA threshold:

$$SOCA_{1 \rightarrow 2}^{dyn} = SOCA_{1 \rightarrow 2} - \frac{L_2 - L_1}{e_2 - e_1}. \quad (10)$$

When $e_2 > e_1$, greater learning benefits in sector 2 ($L_2 > L_1$) lower the threshold. Sector 2 therefore takes priority over sector 1 at a lower value of p than in the static model. A

sector with high current costs may thus warrant earlier support if deployment generates sufficiently large future cost savings.

3.4 Accounting for Sector-Specific Hydrogen Costs

An aspect overlooked in hydrogen policy discussions is that hydrogen is not a homogeneous good from the end-user's perspective. The cost of hydrogen at the point of use, the production-to-usage cost gap ν_i , varies significantly across sectors due to differences in required purity, storage and compression needs, distribution logistics, and end-use equipment.

Fuel cell vehicles, for instance, require very high-purity hydrogen and sophisticated on-board storage, which can increase the usage cost beyond the production cost. Industrial processes such as direct reduction of iron ore require large volumes of hydrogen but can sometimes be co-located with production facilities, reducing distribution costs. This is why the model does not rank sectors using the production cost of hydrogen alone. It ranks them using the full sector-specific cost $C_H + \nu_i$.

These cost differences can also change the merit order: in some configurations, it may be socially optimal to allocate hydrogen to a sector with a lower apparent willingness to pay if that sector benefits from a substantially smaller gap between production and usage costs. Conversely, a sector with high abatement potential may move down the merit order if its delivery, purity, compression, or conversion requirements make ν_i too high.

Putting the four channels together, the simplified decision criterion becomes:

$$V_i^{dyn}(p) = \min\{F_i + pe_i, A_i\} - (C_H + \nu_i) + L_i. \quad (11)$$

Scarce hydrogen should be allocated first to sectors with the highest value of $V_i^{dyn}(p)$, subject to hydrogen availability. This rule differs from a standard MAC curve because it accounts for scarcity, competing technologies, learning effects, and the sector-specific production-to-usage cost gap.

Four Factors Affecting Hydrogen Allocation

- **Opportunity Cost:** Allocate hydrogen where the social gain from displacement of fossil fuels is maximised relative to the next-best use, accounting for scarcity.
- **Technology Competition:** Penalise sectors with mature, cost-competitive alternatives. Prioritise sectors where hydrogen is the only, or clearly best, low-carbon pathway.
- **Learning Dynamics:** Weight current deployment decisions by their future cost-reduction benefits, favouring high-learning-potential sectors for early deployment.
- **Production-to-Usage Costs:** Account for sector-specific hydrogen usage costs, captured by ν_i , rather than treating hydrogen as a homogeneous good once produced.

4. An Illustrative Two-Sector Case Study

We illustrate the four analytical dimensions of Section 3 through a stylised comparison of heavy-duty road freight via hydrogen fuel-cell vehicles (FCEV trucks, Sector 1) and primary steelmaking via hydrogen-based direct reduction (H₂-DRI, Sector 2) — the two end-uses that have attracted the largest share of early European hydrogen valley support, yet where the MAC curve and the social merit order point in opposite directions.

Table 2 presents the parameters per unit of energy-used for this case-study. The global LCOH₂ is set at $C_H = 120$ €/MWh, consistent with near-term projections for announced French projects before 2030 (ADEME, 2023; IEA, 2024a). Production-to-usage gaps (ν_i) follow IEA (2019) sector-specific delivery cost estimates: FCEV trucks require 99.97 % purity H₂ at 700 bar ($\nu_1 = 59$ €/MWh) (IEA, 2019); H₂-DRI can be pipeline-supplied at lower purity in co-located facilities ($\nu_2 = 19$ €/MWh) (IEA, 2019). Alternative technology costs and learning values follow Terlouw et al. (2025) and IRENA (2022) respectively. The comparison doesn't take into account assessment of charging infrastructures requirements. Emission intensities and fossil-fuel costs follow the Marseille-Fos calibration in Section 5 (CIGALE Database, 2024). As the reference fossil fuel in steel industry is coal, its emission intensity per MWh of energy-used is higher than the truck sector that uses diesel as the reference fuel ($e_2 = 0.450$ vs. $e_1 = 0.281$ tCO₂/MWh).

Table 2: *Parameters for the two-sector case study ($C_H = 120$ €/MWh)*

Parameter	Sector 1 — Trucks (FCEV)	Sector 2 — Steel (H ₂ -DRI)
Emission intensity e_i (tCO ₂ /MWh)	0.281	0.450
Fossil non-carbon cost F_i (€/MWh)	79 (diesel)	15 (coal/gas)
Prod-to-usage gap ν_i (€/MWh)	59	19
Best alternative A_i (€/MWh)	100 (BEV)	130 (NG-DRI + CCS)
Learning value L_i (€/MWh H ₂)	10	25
MAC at $C_H = 120$ €/MWh (€/tCO₂)	146 → MAC rank #1	233

The MAC methodology that applies the metric of $AC_i = (C_H - F_i)/e_i$ ranks trucks first: diesel's high price makes the hydrogen substitution appear cheaper in road freight, while the coal-heavy fossil baseline in steelmaking looks expensive to abate. Yet steel avoids 60 % more CO₂ per unit of hydrogen deployed. The following subsections show how each merit-order dimension progressively overturns this ranking.

4.1. Opportunity cost of deploying scarce green hydrogen

When the supply of green hydrogen is scarce, the relevant question is not whether trucks or steel individually benefit from hydrogen, but which sector generates the higher social value per unit allocated. Using Equation (4), steel deserves hydrogen over trucks when $V_2(p) > V_1(p)$, i.e. when p exceeds the SOCA. Applying Equation (6):

$$\text{SOCA}_{1 \rightarrow 2} = \frac{(\nu_2 - F_2) - (\nu_1 - F_1)}{e_2 - e_1} = \frac{(19 - 15) - (59 - 79)}{0.450 - 0.281} = \frac{24.4}{0.169} = 144 \text{ €/tCO}_2 \quad (12)$$

Below 144 €/tCO₂ the MAC ranking is correct: trucks should receive hydrogen first. Above this threshold — which falls squarely within the Quinet Commission’s optimal SCC trajectory for 2030–2035 (Quinet, 2019) — steel’s higher emission intensity dominates and the merit order *reverses*. Table 3 quantifies the welfare cost of following the MAC rule: it grows from 1 €/MWh at SCC = 150 €/tCO₂ to 26 €/MWh at SCC = 300 €/tCO₂, per unit of H₂ misallocated to road freight.

Table 3: Social value $V_i(p)$ and welfare cost of MAC misallocation

SCC (€/tCO ₂)	V_1 Trucks (€/MWh)	V_2 Steel (€/MWh)	Optimal Sector	Welfare Loss (MAC) (€/MWh)
50	−85.8	−101.7	Trucks	0 (correct)
100	−71.7	−79.2	Trucks	0 (correct)
150	−57.7	− 56.7	Steel	−1.0 (wrong)
200	−43.6	− 34.2	Steel	−9.4 (wrong)
300	−15.5	+ 10.8	Steel	−26.3 (wrong)

Note: $V_i(p) = p e_i - [(C_H + \nu_i) - F_i]$. Welfare loss = $V_2(p) - V_1(p)$ when MAC incorrectly assigns H₂ to Sector 1 despite $V_2 > V_1$.

4.2. Competing alternatives, learning-by-doing, and the sector-specific costs gap

Three further channels each independently overturn the MAC, and their effects compound.

Alternative technologies The Battery Electric Vehicle (BEV) alternative caps the social value of hydrogen for trucks above $(A_1 - F_1)/e_1 = (100 - 79)/0.281 = 75 \text{ €/tCO}_2$. Above this threshold, according to the equation 7 $V_1^A(p)$ remains constant at $100 - (120 + 59) = -79 \text{ €/MWh}$ once the alternative technology becomes preferable to diesel. Steel’s CCS alternative only caps hydrogen’s social value at $(130 - 15)/0.450 = 256 \text{ €/tCO}_2$. Across the entire policy-relevant range of 75–256 €/tCO₂, hydrogen delivers positive marginal social value in steel but zero in trucks: road freight should transition via BEV, not hydrogen. This result shows that the MAC methodology alone is insufficient for ranking sectors or identifying the most socially valuable allocation of hydrogen.

Learning-by-doing. H₂-DRI is pre-commercial with a higher learning rate ($L_2 =$

25 €/MWh) than near-commercial FCEV trucks ($L_1 = 10$ €/MWh). Accounting for these spillovers via Equation (10):

$$\text{SOCA}_{1 \rightarrow 2}^{\text{dyn}} = \text{SOCA}_{1 \rightarrow 2} - \frac{L_2 - L_1}{e_2 - e_1} = 144 - \frac{25 - 10}{0.169} = 144 - 89 = 55 \text{ €/tCO}_2 \quad (13)$$

The learning externality lowers the SCC threshold at which the relative ranking reverses. At an illustrative SCC of 70 €/tCO₂, the static comparison ranks trucks above steel, while including learning ranks steel above trucks. This illustrates a change in relative priority; with the assumed costs, both social values remain negative at this SCC.

Production-to-usage costs. The MAC treats hydrogen as a homogeneous commodity with a common production cost C_H and cannot detect the 40 €/MWh gap between $\nu_1 = 59$ and $\nu_2 = 19$. This gap is the dominant driver of the SOCA in Equation (12). If trucks were supplied on-site ($\nu_1 \rightarrow 0$), SOCA would rise to 492 €/tCO₂ and trucks would reclaim priority below this higher SCC threshold. At $\nu_1 = 98$, SOCA turns negative and steel is *always* preferred regardless of the SCC. Infrastructure and logistics decisions, not just the SCC, determine the merit order, a dimension that is absent from the MAC framework.

Table 4 collects all four channels.

Table 4: *Comparison of MAC Rankings and Merit-Order Results*

Channel	MAC	Merit order	Switching point
Opportunity cost (SOCA)	Trucks #1	Steel #1	SCC > 144 €/tCO ₂
Competing alternatives (BEV cap)	Trucks #1	Steel always	SCC > 75 €/tCO ₂ (within EU ETS)
Learning-by-doing (dynamic SOCA)	Trucks #1	Steel #1	SCC > 56 €/tCO ₂ (today's ETS price)
Prod-to-usage costs (ν gap)	Trucks #1	Steel #1	Structural; drives SOCA to 144 €/tCO ₂

All four channels reinforce each other. The MAC ranks trucks first at SCC carbon price, yet the opportunity-cost criterion, the BEV alternative, the learning externality, and the production-to-usage cost disparity each independently redirect hydrogen toward steel. Taken together, they imply that the current practice of directing early hydrogen valley support primarily toward road mobility is socially costly. Carbon pricing and targeted support can help align firms' decisions with the socially preferred allocation, as discussed in Section 6. Section 5 extends this logic to the full six-sector landscape of the Marseille-Fos industrial port zone, where the model compares allocation and policy outcomes across six end-use sectors.

5. Application to the Hydrogen Valley of Marseille-Fos

The industrial port zone (ZIP) of Marseille-Fos hosts several major hydrogen projects and potential industrial end-users (see Figure 1). Spanning approximately 10,000 hectares along the Mediterranean coast, it hosts France’s largest port (the Grand Port Maritime de Marseille, third-largest in the Mediterranean by tonnage), over fifteen major industrial sites, the ArcelorMittal steel plant, and several chemical and refinery facilities (Grand Port Maritime de Marseille, 2024). The zone also includes the Marseille Provence international airport.

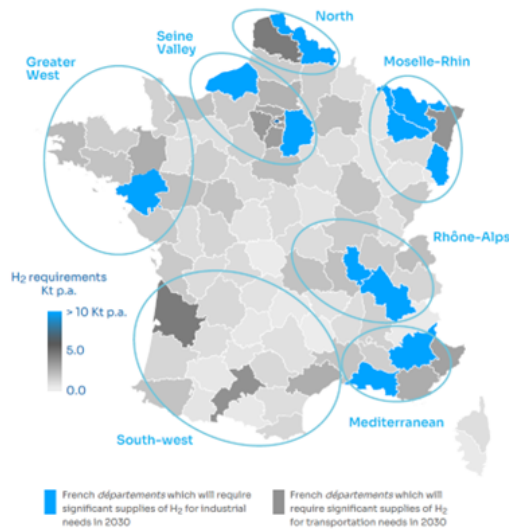


Figure 1: Map of Potential Hydrogen Valleys in France (France Hydrogène, 2022)

This concentration of energy-intensive activities makes Marseille-Fos a relevant case for comparing hydrogen end-uses. The zone has announced a portfolio of significant hydrogen projects for the period to 2030 as detailed in Table 5.

Table 5: Announced hydrogen projects in the Marseille–Fos industrial port (ZIP)

Project	Primary Off-taker	Capacity (H ₂)	Target Date
HyAMMED (Capenergies, 2019)	Heavy-duty road mobility (trucks)	365 t/yr	2022
Masshyla (TotalEnergies, 2024)	Biorefinery (chemicals)	11,000 t/yr	2025
GravithY (ENGIE, 2024)	Steel industry	120,000 t/yr	2027
H2V (H2V, 2024)	Maritime	28,000–84,000 t/yr	2028–2030
HyGreen (Capenergies, 2018)	Gas network injection	30,000 t/yr	2028

5.1. Model Simulations and Inputs

The numerical application distinguishes annual ranking calculations from intertemporal allocation. Annual rankings are computed using linear programs with exogenous technology cost trajectories. First-Best allocations jointly minimize discounted social costs over the study horizon, accounting for endogenous learning in end-use technology costs. Hydrogen production costs and availability remain exogenous. Linear programs are solved using OR-Tools/GLOP, while the nonlinear intertemporal model is implemented in Pyomo and solved using IPOPT. Policy simulations use annual allocation problems with learning subsidies evaluated along the First-Best trajectory.

The model integrates regional energy, emissions, techno-economic, and policy data to assess the social value of renewable hydrogen across major end-use sectors. Table 6 summarizes the fossil reference technologies, hydrogen pathways, and competing low-carbon alternatives considered in the analysis.

The analysis is primarily based on [CIGALE Database \(2024\)](#), maintained by AtmoSud, which provides detailed regional inventories of energy consumption, greenhouse gas (GHG) emissions, and air pollutant emissions for Provence-Alpes-Côte d’Azur. Since these data are reported at an aggregated sectoral level, they are complemented with technology-specific information from the literature to derive the model inputs. The complete data processing methodology and techno-economic assumptions are documented in Appendix.

The numerical application includes fixed annual sectoral demand, which limits how much hydrogen each sector can absorb. Once a priority sector is saturated, additional hydrogen can be allocated to another sector without a reversal of the merit order. With learning-by-doing, deployment volumes also influence future costs and the timing of changes in priority.

Table 6: *Decarbonization pathways considered across end-use sectors.*

End-use Sector	Reference Fossil Technology	Hydrogen Pathway	Competing Low-Carbon Alternative
Chemicals (Ammonia and Methanol) and (Bio-)Refinery	SMR	Electrolysis	Bio-SMR
Iron & Steel	BF/BOF	Electrolysis + H ₂ -DRI-EAF	NG-DRI-EAF + CCS
Industrial High-Temperature Heat	NG-fired Furnace	Electrolysis + H ₂ -fired Furnace	NG-fired Furnace + CCS
Road Freight	Diesel Engine	Electrolysis + FCEV	BEV
Shipping	VLSFO Engine	Electrolysis + Methanation + E-Methanol	Bio-Methanol
Long-Haul Aviation	Kerosene Engine	Electrolysis + Fischer-Tropsch + E-Kerosene	Biojet Fuel (HEFA)

The analysis adopts a social discount rate of 3.2%, consistent with the recommendation of France Stratégie ([Ni and Maurice \(2021\)](#)), and expresses all costs in constant euros.

The social cost of carbon (SCC) is set at 250 €/tCO₂-eq in 2030, following the Quinet report (Quinet, 2019), and is assumed to increase thereafter at the social discount rate according to the Hotelling rule. Allocations are optimized over 2025-2050 in annual steps.

To reflect the prevailing policy environment, the model incorporates differentiated effective carbon prices across sectors. Industrial facilities, shipping, and aviation are assumed to face the EU Emissions Trading System (EU ETS), with allowance prices increasing linearly from approximately 80 €/tCO₂ in 2025 to 250 €/tCO₂ in 2050, consistent with the International Energy Agency’s Net Zero pathway (IEA (2024b)). Road freight is assumed to face an effective carbon price of 45 €/tCO₂ through 2030, reflecting current fuel taxation and the initial price cap under the EU ETS2, before converging linearly to the EU ETS trajectory. Figure 2 compares the assumed effective carbon price trajectories with the SCC.

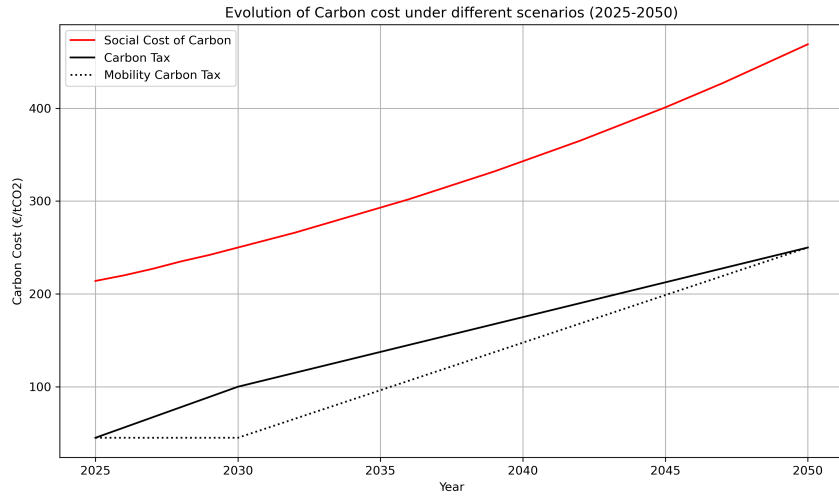


Figure 2: Social cost of carbon and assumed sectoral effective carbon price trajectories.

The model also internalizes local air pollution externalities using marginal damage costs reported in the *Environmental Prices Handbook* (Bruyn et al., 2018). These values are assumed to remain constant over time and enter the objective function as technology-specific external costs. The corresponding damage cost estimates are reported in Appendix.

To capture uncertainty surrounding hydrogen market development, the analysis considers two contrasting deployment scenarios (Figure 3). The *Standard* scenario assumes a sustained expansion of renewable hydrogen production, reaching full regional demand by 2050, accompanied by progressive cost reductions driven by learning effects, economies of scale, and supply-chain maturation. Although this trajectory is relatively conservative given the current pipeline of announced projects in the Marseille–Fos industrial port, it reflects the risk of delays in project execution and final investment decisions. The *Conservative* scenario assumes a slower market development, with hydrogen availability reaching only 50% of regional demand by 2050 and production costs remaining 50% higher than in the Standard scenario because of slower deployment, weaker learning effects, and reduced economies of scale. The two scenarios assess how assumed hydrogen availability

and production costs affect sectoral allocation.

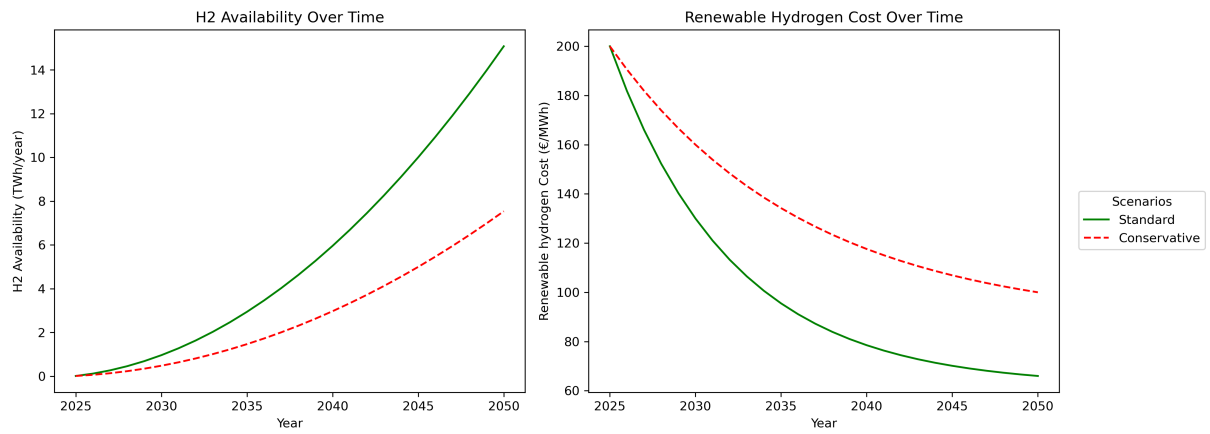


Figure 3: Assumed renewable hydrogen availability (left) and production cost trajectories (right) under the Standard and Conservative deployment scenarios.

5.2. The Merit Order of Green Hydrogen Use in Marseille-Fos ZIP

5.2.1. Ranking of Hydrogen End-Uses Over Time

Figure 4 compares the conventional abatement-cost ranking with an annual merit order based on current social costs. Both approaches use the SCC to value emissions, while hydrogen production costs follow the Standard scenario. End-use technology cost trajectories are exogenous in this exercise: the annual rankings do not internalize the effect of current deployment on future costs.

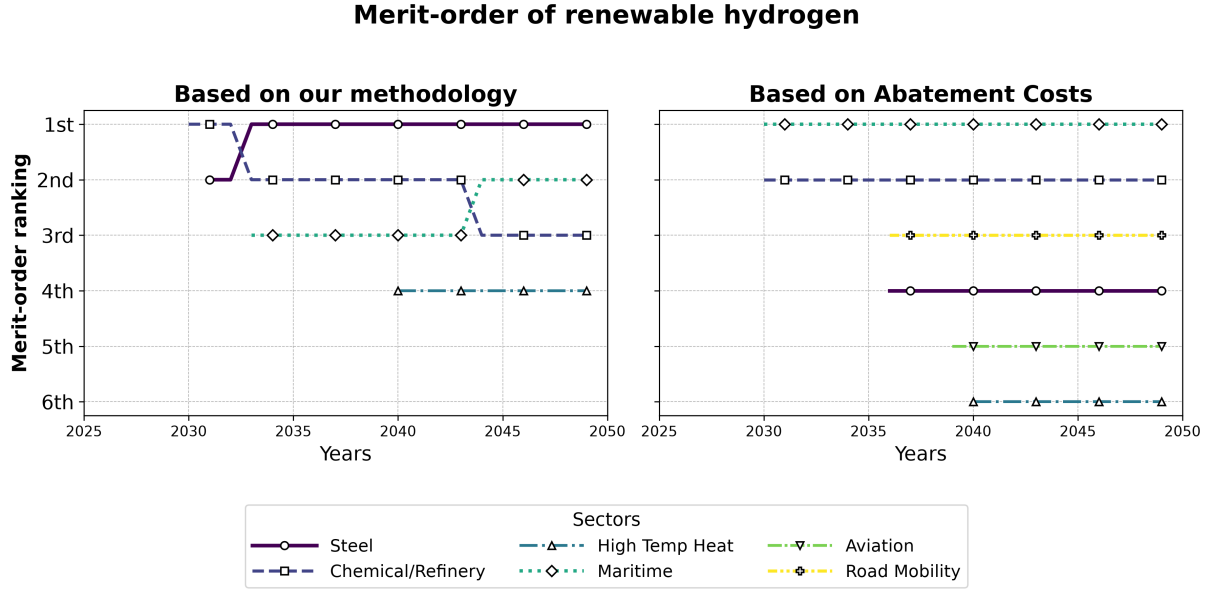


Figure 4: *Evolution of the hydrogen merit order under the proposed social optimization framework and the conventional abatement-cost approach.*

The two approaches produce markedly different sectoral priorities. Under the conventional methodology, the ranking remains unchanged over time, with maritime transport consistently identified as the highest-priority sector, followed by chemicals and refineries, heavy-duty road transport, steel, aviation, and industrial heat. This ordering does not account for technological learning or the availability of competing decarbonization pathways.

By contrast, the socially optimal merit order evolves over time. Chemicals and refineries receive the highest priority during the early deployment phase because hydrogen can be integrated into existing infrastructure while avoiding costly carbon capture alternatives. From 2032 onward, steel becomes the highest-priority sector, reflecting the increasing SCC and assumed decline in hydrogen-based steelmaking costs. Around 2043, maritime transport overtakes the chemical sector as the SCC increases and assumed technology costs decline. Industrial high-temperature heat remains a lower priority throughout the transition, while heavy-duty road transport disappears entirely from the optimal ranking because battery electric vehicles provide a more cost-effective decarbonization pathway. These results demonstrate that sectoral prioritization depends not only on current abatement costs but also on dynamic learning effects and the relative competitiveness of

alternative technologies.

5.2.2. Optimal Allocation of Renewable Hydrogen

Figure 5 presents hydrogen allocation under two deployment scenarios and two policy pathways. The Standard and Conservative scenarios vary exogenous hydrogen availability and production costs. The Business-as-Usual pathway uses assumed effective carbon prices and excludes endogenous learning. The First-Best pathway uses the SCC and accounts for the effect of current deployment on future end-use technology costs through intertemporal optimization.

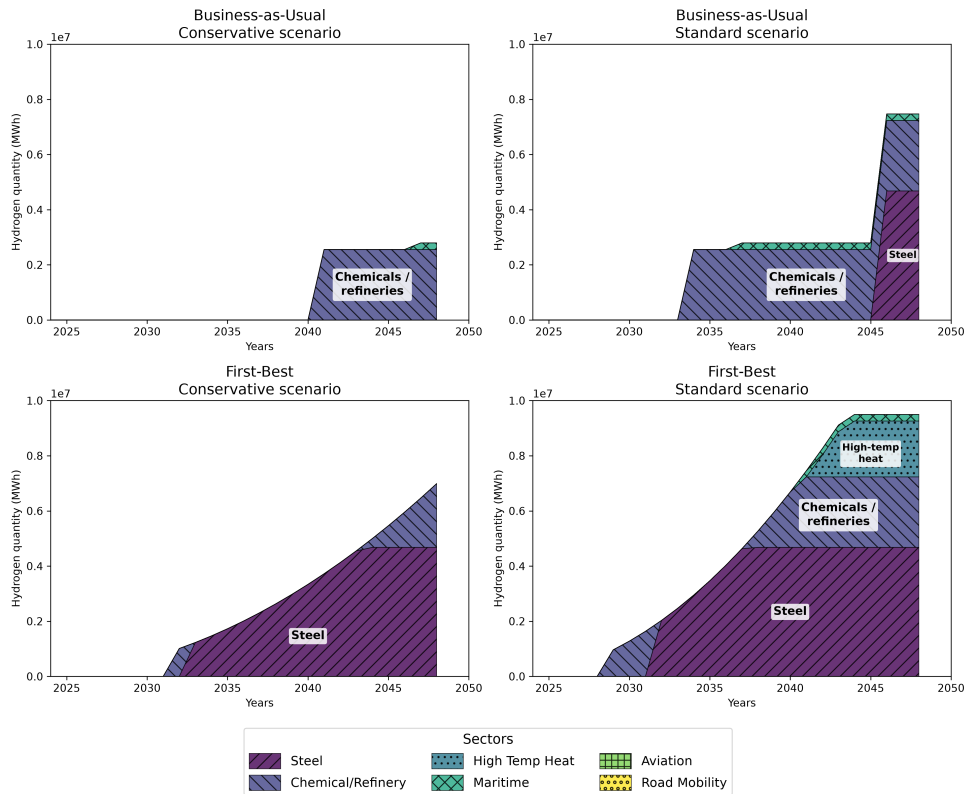


Figure 5: Renewable hydrogen allocation under alternative deployment scenarios and policy pathways. The left column shows the Conservative scenario and the right column the Standard scenario. The upper row shows Business-as-Usual with assumed effective carbon prices and no endogenous learning. The lower row shows First-Best allocation using the SCC and internalizing endogenous learning.

Across all scenarios, hydrogen is first allocated to the chemicals and refinery sector, followed by steel and subsequently maritime transport as hydrogen availability expands and production costs decline. Faster deployment and lower hydrogen costs in the Standard scenario accelerate adoption in all sectors relative to the Conservative scenario and enable hydrogen deployment in industrial high-temperature heat before 2050.

Policy assumptions strongly influence both the timing and scale of deployment. Under Business-as-Usual effective carbon prices, hydrogen adoption is substantially delayed and remains concentrated in a limited number of sectors, particularly under the Conservative scenario. In contrast, aligning effective carbon prices with the social cost of carbon ad-

vances investment decisions, accelerates technology deployment, and expands hydrogen use across sectors. The largest change occurs in the steel industry, where stronger effective carbon pricing makes earlier deployment socially preferable when the resulting reductions in future technology costs are included.

Two sectors consistently remain outside the optimal hydrogen allocation: heavy-duty road transport and aviation. For road freight, battery-electric vehicles outperform hydrogen fuel-cell trucks on both economic and environmental grounds. For aviation, sustainable biofuels remain more competitive than synthetic e-fuels over the study horizon. These findings indicate that renewable hydrogen should be prioritized for hard-to-abate industrial sectors where few economically viable alternatives exist.

Overall, the results highlight three policy implications. First, sectoral prioritization based solely on marginal abatement costs can lead to inefficient hydrogen allocation because it neglects learning effects and competing decarbonization technologies. Second, the value of renewable hydrogen depends on its availability, making sectoral prioritisation relevant during early deployment. Third, ambitious carbon pricing substantially accelerates socially desirable hydrogen deployment but does not alter the conclusion that hydrogen should be concentrated in industrial applications rather than sectors with more competitive electrification pathways.

6. Policy Implications

The merit-order analysis identifies a gap between the socially optimal allocation of renewable hydrogen and its current effective allocation. Bridging this gap requires targeted policy intervention. This section analyses three types of instruments and their relative effectiveness.

6.1. The Insufficiency of Production Subsidies Alone

The dominant form of hydrogen support today, production subsidies, addresses one failure (insufficient quantity of renewable hydrogen) but not another (misallocation across sectors). A uniform production subsidy reduces the levelised cost of hydrogen for all potential off-takers equally. It may therefore increase overall demand without correcting the relative priority given to different sectors.

Our analysis shows that when the effective carbon price is situated on one side of the Sectoral Opportunity Cost of Abatement (SOCA) and the Social Cost of Carbon is on the other, production subsidies cannot correct the allocation failure. The sector that benefits most from the subsidy will simply be whichever has the highest private willingness to pay for hydrogen, not necessarily the sector with the highest social value.

Production subsidies are an appropriate instrument when the primary failure is insufficient total hydrogen demand, that is, when the abatement cost of both candidate sectors exceeds the effective carbon price. In that case, reducing the hydrogen production cost through subsidy can bring both sectors above the threshold and stimulate adoption.

6.2. The Case for Targeted Demand-Side Subsidies

When the most socially meritorious sector is not the one with the highest private willingness to pay, demand-side subsidies targeted at the most deserving sectors are the appropriate instrument.

A targeted demand-side subsidy (for example, a CAPEX subsidy for hydrogen-based technology in a specific sector, or a contract-for-difference that guarantees a minimum carbon value for hydrogen used in that sector) has two advantages over a production subsidy:

- It can correct the allocation distortion by making priority end-uses more competitive relative to others, without reducing hydrogen costs for all end-use sectors.
- It is more cost-efficient at achieving emissions reductions, because it concentrates support where the marginal tonne of CO₂ avoided through hydrogen is highest.

Table 7 compares the outcomes and support costs of the policy pathways in Marseille-Fos.

Table 7: *Comparison of policy pathways under the Standard hydrogen deployment scenario*

Policy Scenario	Total Social Cost	CO ₂ Emissions (2025–50)	Support Cost	Abatement Cost
First-Best (optimal CO ₂ -price + learning)	€34.7 bn	22.1 Mt CO ₂ eq	—	—
Business-as-Usual	€64.9 bn	103.3 Mt CO ₂ eq	—	—
Learning Subsidies Only	€47.0 bn	45.8 Mt CO ₂ eq	€4.1 bn	€71/t
Production Subsidies + Learning	€38.1 bn	15.6 Mt CO ₂ eq	€15.1 bn	€367/t
Demand-Side Subsidies + Learning	€38.1 bn	17.0 Mt CO ₂ eq	€8.6 bn	€156/t

The two subsidy pathways have similar total social costs and emissions levels, but targeted demand-side support requires approximately 43% less public expenditure (€8.6 billion compared with €15.1 billion), with learning support included in both pathways. The support cost per tonne of CO₂ avoided reported in Table 7 is approximately 57% lower (€156 compared with €367). Targeted support directs expenditure towards selected end-uses rather than reducing hydrogen production costs for all sectors.

***Key finding:** In the Marseille-Fos application, targeted demand-side subsidies combined with learning support require approximately 43% less public expenditure than production subsidies combined with learning support, with similar emissions outcomes.*

6.3. Learning Subsidies

A third instrument is a subsidy for learning-by-doing externalities. When firms do not fully internalise the cost reductions their early deployment creates for future adopters, because learning spills over to competitors and to hydrogen ecosystems outside their own firm, they will underinvest in early deployment. This market failure can be corrected by a learning subsidy calibrated to the discounted present value of future cost reductions generated by current deployment.

In the Marseille-Fos analysis, according to Table 7, learning subsidies alone, even without correcting the carbon pricing failure, reduce total social cost by 27% compared to business-as-usual and cut emissions by more than half. The steel sector is the primary beneficiary, because its high learning potential and large expected deployment volumes generate the greatest future cost-reduction externalities.

In this application, learning subsidies have the lowest support cost per tonne of CO₂ avoided among the instruments examined (approximately €71). They compensate for learning benefits that firms do not fully capture, including cost reductions available to subsequent adopters, and can improve outcomes even when effective carbon prices remain below the SCC. They address the learning externality separately from the emissions externality.

6.4. Recommended Policy Mix

Based on the merit-order analysis and the policy instrument evaluation, we recommend a policy mix combining learning subsidies, targeted demand-side support and production support linked to demand commitments, as described in Table 8.

Table 8: *Recommended Policy Instruments*

Instrument	Targeted Failure	Priority Sectors
Learning subsidies calibrated to sector-specific learning rates and deployment volumes	Dynamic externality: firms underinvest in early deployment because learning spills over to other firms	Steel (H ₂ -DRI), Chemicals, Industrial Heat
Demand-side subsidies (CAPEX support or CfDs) targeted at merit-order sectors	Static misallocation: private WtP does not reflect social priority	Steel, Chemicals & Refinery
Production subsidies or hydrogen auctions, conditioned on demand commitments from merit-order sectors	Insufficient total hydrogen quantity	Economy-wide

The proposed instruments address learning externalities, differences between private and social priorities, and the conditions for expanding production. When hydrogen supply is limited, allocation to lower-value uses reduces the quantity available for uses with greater social benefits.

6.5. Implications for Hydrogen Valley Governance

The policy recommendations above have direct implications for how hydrogen valleys are structured and governed. Several practical considerations deserve attention:

- **Off-take agreements should reflect merit-order priorities.** Hydrogen valley governance bodies should require that publicly supported production capacity is matched by demand commitments from merit-order sectors. This reduces the risk of stranded production capacity built without committed industrial buyers.
- **Support programmes should account for differences in project scale and upfront investment requirements.** Road mobility projects tend to be modular and small-scale, making them easier to deploy in demonstration phases. Industrial

hydrogen projects (steel, chemicals) require larger upfront commitments. Without deliberate policy correction, this creates a bias toward mobility at the expense of more meritorious industrial uses.

- **Carbon pricing gaps should be compensated through sectoral support, not uniform instruments.** In sectors where the EU ETS does not apply (road transport) or where effective carbon prices remain below the SCC, sector-specific hydrogen support should be calibrated to bridge the gap between the effective carbon price and the Social Cost of Carbon.
- **Dynamic review mechanisms should be built in.** As technology costs evolve and the Social Cost of Carbon increases, the merit order will shift. Hydrogen valley support programmes should include periodic merit-order reviews, with the ability to redirect support toward newly meritorious sectors.

7. Conclusion

Renewable hydrogen support should consider the social value of end-uses alongside the conditions for market adoption. The social cost of misallocation, directing hydrogen to road mobility rather than steel, or to sectors with viable alternatives rather than those with none, can be as large as the cost of insufficient supply.

A merit-order framework provides the analytical foundation for correcting this misallocation. It goes beyond the static abatement cost curve to incorporate opportunity costs, the availability and cost of alternative low-carbon technologies, and the dynamic benefits of early deployment in high-learning sectors. In the Marseille-Fos application, chemicals and steel receive priority, while road freight is excluded from the optimal hydrogen allocation under the assumptions considered.

The policy toolkit needed to implement this merit order exists. Learning subsidies, demand-side CAPEX support, and sector-specific contracts-for-difference can together correct both the dynamic externality of under-deployment and the static externality of misallocation. They do so at substantially lower fiscal cost than relying on production subsidies alone.

The results support greater differentiation of hydrogen support across end-use sectors. Uniform production support does not directly distinguish between the social value of different end-uses. A merit-order approach requires accepting that some uses of hydrogen are socially more valuable than others, and designing support mechanisms accordingly. In the Marseille-Fos simulations, targeted demand-side subsidies combined with learning support achieve similar emissions outcomes to production subsidies combined with learning support, with approximately 43% lower public expenditure.

The analysis does not assess the macroeconomic effects of carbon pricing and hydrogen

support policies on inflation, interest rates or economic activity. It also abstracts from supply commitments and irreversible investments. In practice, changes in hydrogen allocation should account for existing users' need for predictable supply conditions and continued access to decarbonisation options.

Policy Recommendations

- **Rebalance the hydrogen support mix:** Shift from 94% production / 6% demand to a portfolio that includes substantial demand-side support targeted at merit-order sectors (steel, chemicals, industrial heat).
- **Introduce learning subsidies as a distinct instrument:** Calibrate support to the sector-specific learning potential of hydrogen technologies, prioritising sectors, especially steel, where early deployment generates the largest future cost reductions.
- **Build dynamic merit-order reviews into hydrogen valley governance:** Commission regular updates to the merit-order ranking as technology costs, carbon pricing, and available alternatives evolve, and link public support conditionality to these reviews.

A. Annex: Modelling Data and Calibration

The model is calibrated for the Marseille-Fos industrial port zone using the following primary data sources:

- **Energy consumption and emissions:** [CIGALE Database](#) (2024) of the AtmoSud atmospheric inventory, sourced from the INSEE EACEI dataset for fossil fuel consumption and PCIT guide methodology for pollutant emissions.
- **Technology costs** (CAPEX, OPEX, energy efficiency factors): Expert interviews and published estimates from ADEME, France Hydrogène, ICCT, IEA, Transport & Environment, and DGEC. Costs reflect 2024 estimates with scenario-based projections to 2050.
- **Air pollutant damage costs:** Environmental Prices Handbook EU-28 version (Bruyn et al., 2018), applied to pollutant emissions from the AtmoSud inventory.

Table 9: *Unit environmental damage costs of air pollutants used in the model, based on the Environmental Prices Handbook (Bruyn et al., 2018).*

Air Pollutant	Unit	Value (€/kg)
NO _x	€/kg	14.8
SO ₂	€/kg	11.5
CO	€/kg	0.0526
PM ₁₀	€/kg	26.6
PM _{2.5}	€/kg	38.7
NM VOC	€/kg	1.15

- **Hydrogen cost projections:** ENGIE Research & Innovation projections for PV-powered electrolysis, with two scenarios, Standard (announced projects only through 2030, linear increase to 50% of potential demand by 2050) and Ambitious (full potential demand by 2050).

Table 10: *Key sector-specific input parameters used in the numerical model*

Parameter	Steel	Chem./R	Ind. Heat	Maritime	Aviation	Road Fr.
Emission intensity (tCO ₂ /MWh)	0.31	0.34	0.20	0.28	0.30	0.28
H ₂ efficiency factor (η)	2.59	1.00	1.00	0.81	0.70	1.22
Prod.-to-usage factor (ν)	1.16	1.00	1.16	1.23	1.23	1.49
H ₂ capital cost (€/MWh)	222	0	0	28	30	288
Alt. low-carbon technology	NG-DRI+CC	Bio-SMR	NG+CCs	Bio-MeOH	HEFA	BEV

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Glossary of Acronyms and Abbreviations

Table 11: *Acronyms and abbreviations used in this paper*

Abbreviation	Full Form
BEV	Battery Electric Vehicle
BF/BOF	Blast Furnace / Basic Oxygen Furnace
Bio-SMR	Biomass-based Steam Methane Reforming
CCS	Carbon Capture and Storage
EU ETS	European Union Emissions Trading System
FCEV	Fuel Cell Electric Vehicle
H ₂ -DRI	Hydrogen-based Direct Reduced Iron
HEFA	Hydroprocessed Esters and Fatty Acids (biojet fuel)
LCOH ₂	Levelised Cost of Hydrogen
MAC	Marginal Abatement Cost
NG-DRI-EAF	Natural Gas-based Direct Reduced Iron with Electric Arc Furnace
RFNBO	Renewable Fuels of Non-Biological Origin
SCC	Social Cost of Carbon
SMR	Steam Methane Reforming
SOCA	Sectoral Opportunity Cost of Abatement
VLSFO	Very Low Sulphur Fuel Oil
ZIP	Zone Industriale-Portuaire (Industrial Port Zone)