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# A MERIT-ORDER FOR END-USES OF LOW-CARBON HYDROGEN

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# Context: Why a «Merit-Order of Renewable Hydrogen for End-Uses»?

- **"Merit-Order of Hydrogen" for end-uses: how to optimally allocate renewable hydrogen among end-use sectors**
  - **Availability** of renewable hydrogen is constrained and uncertain
  - There is a **loss of efficiency** in converting renewable electricity to hydrogen/e-fuels
- **Why do the end-use sectors have different priorities to deploy hydrogen?**
  - **Competitive low-carbon technology alternatives** might **not exist** for some applications ➔ **no-regret sectors** for hydrogen
  - Sectors vary in the **costs associated with implementing hydrogen technologies**
  - Sectors vary in the **most competitive reference fossil fuels**
  - Sectors vary in their **potential for reducing emissions**
  - Implementing hydrogen in some sectors/aggregation of some sectors might generate a **higher learning spillover impact**
  - **Technology Readiness Level (TRL)** of $H_2$-based technology is different for each sector
  - Some sectors have **higher safety issues** to deploy hydrogen (e.g. mobile applications)

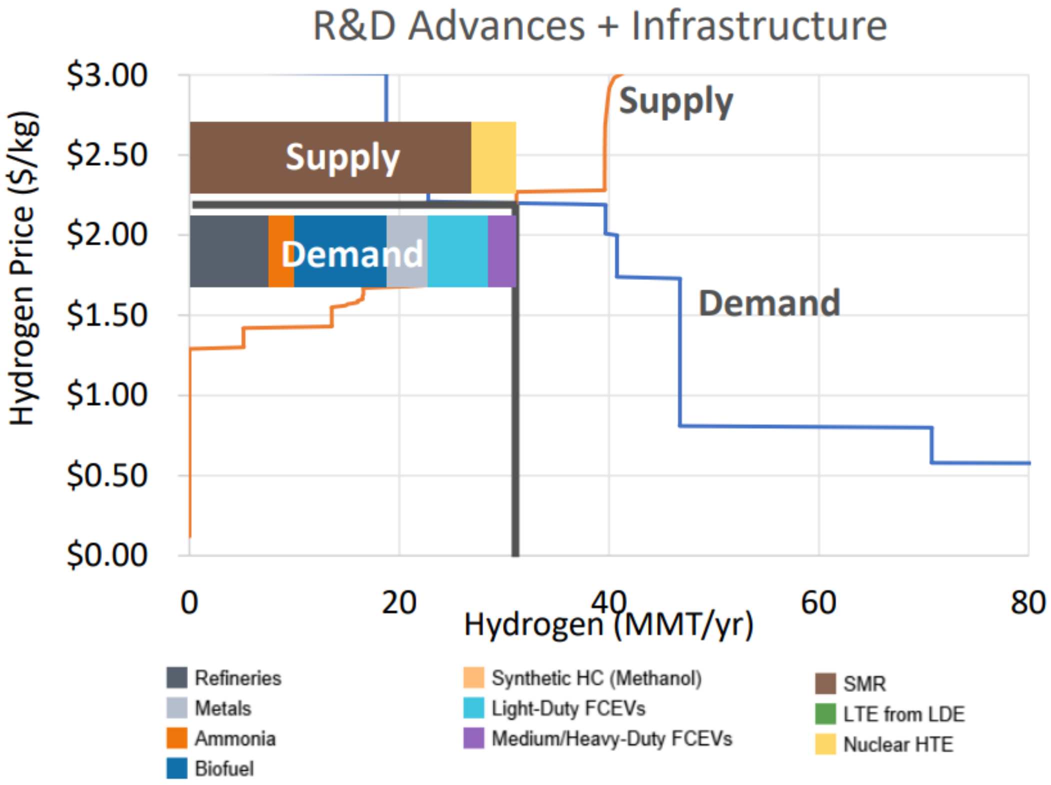
# Motivation: Several approaches exist for allocating hydrogen among sectors, but sectoral interactions and competitive alternatives are overlooked

- **Conventional MAC Curves:** similar to *McKinsey & Company (2010) "Global GHG Abatement Cost Curve v2.1"*: prioritize sectors with the lowest abatement costs (some studies for $H_2$ such as *BloombergNEF (2020) "Hydrogen Economy Outlook"*)

- **MAC over the low-carbon alternative:** *Ueckerdt et al. (2021) "Potential and risks of hydrogen-based e-fuels in climate change mitigation", Nature Climate Change:* prioritizes e-fuels for sectors that are inaccessible to direct electrification.

- **Multi-criteria analysis:** *Appert and Geoffron (2021) "What merit order for hydrogen development?"*: considers factors beyond just abatement cost, including the availability of alternatives and safety concerns.

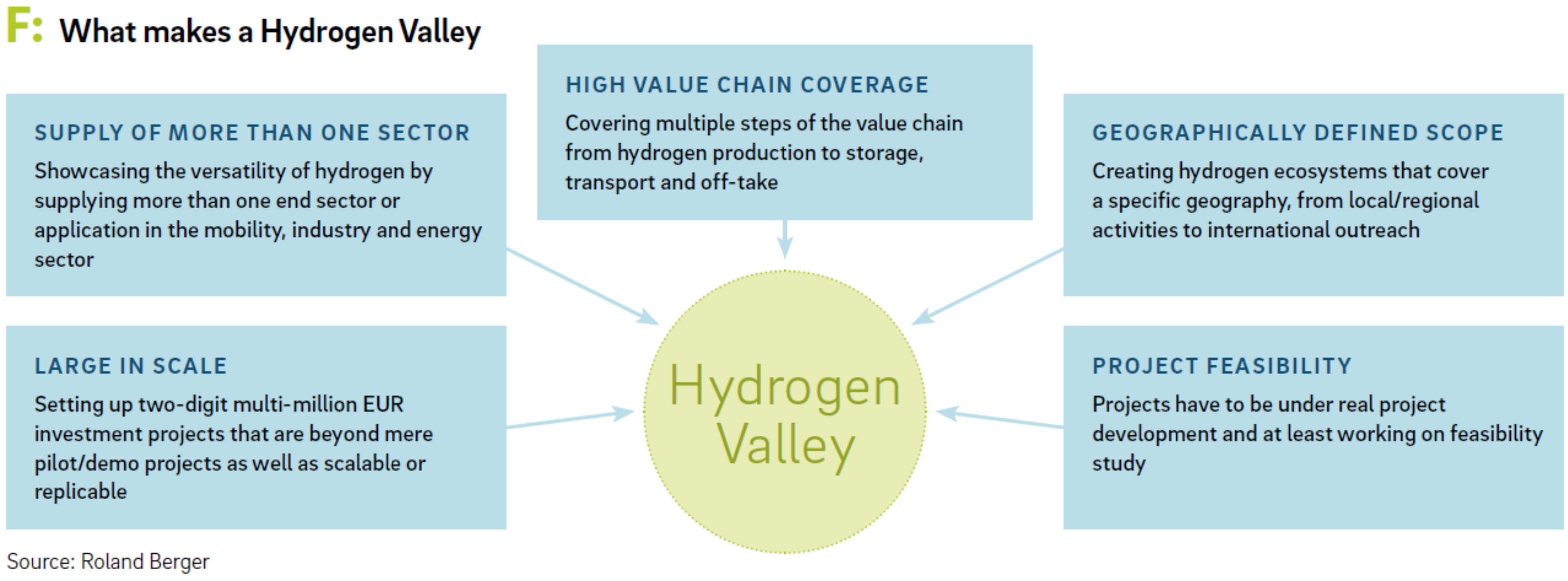
- **Equilibrium of Supply and Demand:** *M.F. Ruth et al (@NREL). (2020), "The Technical and Economic Potential of the H2@Scale Concept within the United State"*: defines optimal quantity where the demand price is equal to the supply price of hydrogen.




Source: NREL, The Technical and Economic Potential of the H2@Scale Concept within the United State, 2020

# Scope: Hydrogen Valleys: Stepping Stones in the Development of a Global Hydrogen Ecosystem

- **What is a Hydrogen Valley?**
  - First regionally integrated hydrogen ecosystems, so-called **hydrogen hubs**, **hydrogen clusters** or **“Hydrogen Valleys”** pave the way for the setup of regional 'mini hydrogen economies' by combining or pooling hydrogen supply and demand to increase scale, maximize asset utilization and bringing down costs.
- **What makes a Hydrogen Valley?**




Roland Berger (2022), Hydrogen Valleys Insights into the emerging hydrogen economies around the world

# Overview of the Paper

## Research Question

- What is the **optimal merit-order** for end-uses of low-carbon hydrogen in a local ecosystem?

## Methodology

- **Dynamic optimization** of the **overall welfare of a hydrogen ecosystem**
- **Calibration of parameters**
- **Sensitivity Analysis**

## Contributions

- Applied Economy of low-carbon Hydrogen
- Climate policy: the optimal policy design to acheive the socially optimal merit-order

## Main Findings

- We propose a methodology to define an optimal "Merit-Order for End-Uses of Hydrogen" considering additional dimensions: the constraint on hydrogen supply in short-term, competition among different zero and low-carbon technologies, the interactions between sectors to handle economies of scale, as well as the time perspective.
- The optimal policy to achieve the socially optimal merit order in a local ecosystem is designed

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# Defining the merit-order

What factors impact the demand for low-carbon hydrogen?

# Demand Side: Abatement Cost and Willingness-to-Pay (WtP)

The economic **Welfare (** $W_{Di}$ **)** of a **«No-Regret»** End-user of Hydrogen (no low-carbon alternative exists):

$$W_{Di} = \Pi_i - (p_{CO2}E_i + C_{Fi} + p_{Fi})(N_i - q_i) - \frac{1}{\eta_{Hi}}(C_{Hi} + p_H)q_i \qquad 0 < q_i < H < N_i$$

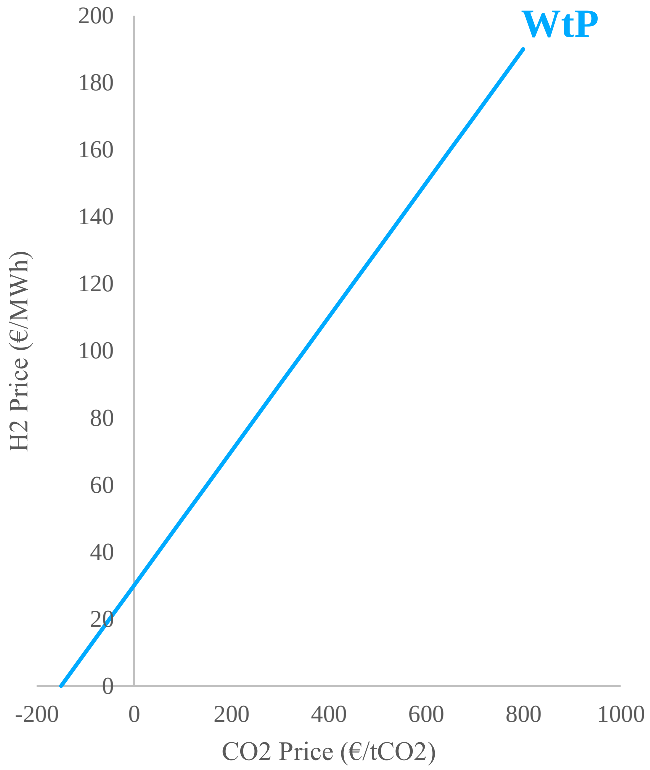
| | | | | | |
|---|---|---|---|---|---|
| $\Pi_i$ | Total Profit of End-user | $p_{Fi}$ | Price of fossil fuel (€/MWh) | $C_{Hi}$ | Cost of deployment of H2 based technology (€/MWh) |
| $p_{CO2}$ | Price of CO2 (€/tCO2) | $N_i$ | Total demand of the end-user (MWh) | $p_H$ | H2 price (€/MWh) |
| $E_i$ | Emission intensity of fossil based technology (€/MWh) | $q_i$ | Quantity of H2 uptake (MWh) | | |
| $C_{Fi}$ | Cost of deployment of fossil based technology (€/MWh) | $\eta_{Hi}$ | Efficiency of H2 based technology | | |

$$\max_{q_i} W_{Di}: \begin{cases} q_i = H & if\ p_{CO2} > \Delta_i \\ q_i = 0 & if\ p_{CO2} < \Delta_i \end{cases}$$

**Abatement Cost:** $\Delta_i = \frac{(C_{Hi} + p_H) - (C_{Fi} + p_{Fi})}{\eta_{Hi} E_i}$

$$\max_{q_i} W_{Di}: \begin{cases} q_i = H & if\ p_{H2} < WtP_i \\ q_i = 0 & if\ p_{H2} > WtP_i \end{cases}$$

**Willingness-to-Pay (WtP):** $WtP_i = (p_{CO2}E_i + C_{Fi} + p_{Fi}) - \frac{1}{\eta_{Hi}} C_{Hi}$




Numerical illustration of a valley with an ammonia production plant

$p_{CO2} = \Delta_i$ or $p_{H2} = WtP_i$: The end user is indifferent to using fossil or H2-based technology

# Demand Side: Abatement Cost and Willingness-to-Pay (WtP)

**Total Welfare of the Demand Side of a Two-End-User Ecosystem**:

$$W_T = W_{D1} + W_{D2} \qquad 0 < q_i < H < N_i$$
$$0 < q_1 + q_2 < H$$

$$\max_{q_i} W_T: \begin{cases} q_1 = H, & q_2 = 0 & \text{if } p_{CO2} > \Delta_{opp} \\ q_1 = 0, & q_2 = H & \text{if } p_{CO2} < \Delta_{opp} \end{cases}$$

**Opportunity Cost of Abatement:**

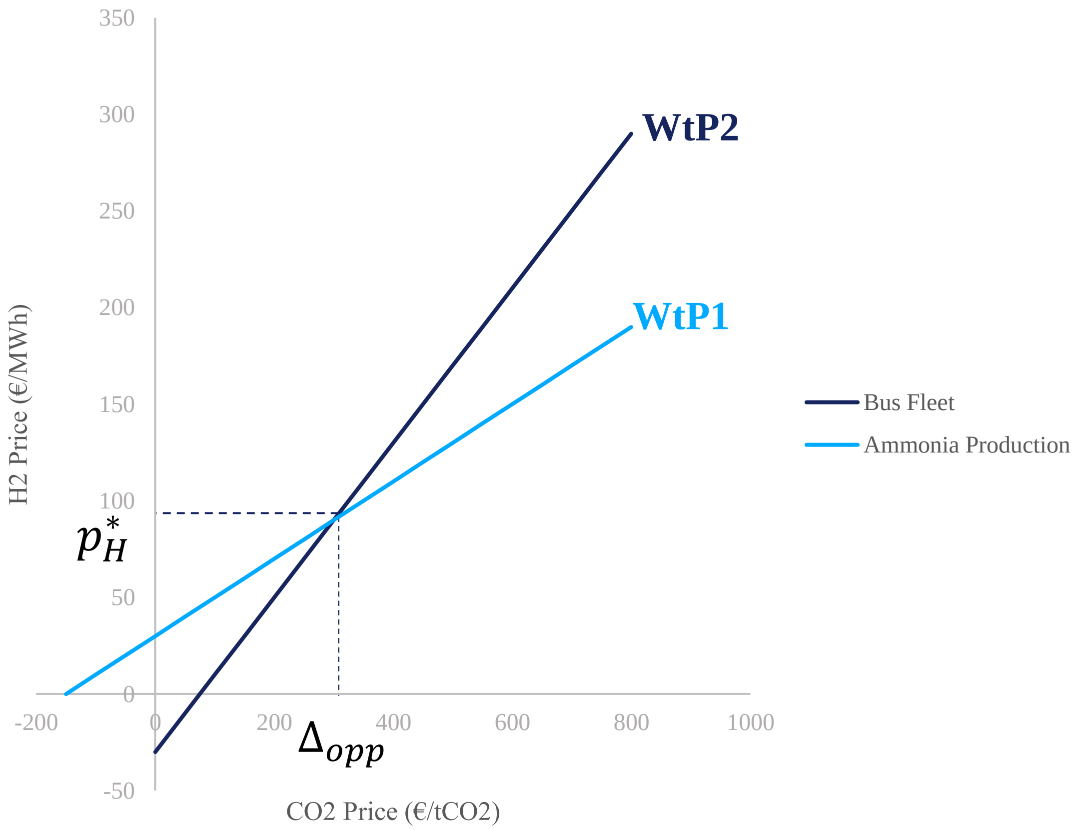
$$\Delta_{opp} = \frac{(C_{H1} - C_{F1} - p_{F1}) - (C_{H2} - C_{F2} - p_{F2})}{\eta_{H1}E_1 - \eta_{H2}E_2}$$

$$\max_{q_i} W_T: \begin{cases} q_1 = H, & q_2 = 0 & \text{if } p_H > p_H^* \\ q_1 = 0, & q_2 = H & \text{if } p_H < p_H^* \end{cases}$$

**Opportunity Price of Hydrogen:**

$$p_H^* = \frac{(C_{H1}-C_{F1}-p_{F1})-(C_{H2}-C_{F2}-p_{F2})}{\eta_{H1}-\eta_{H2}E_2/E_1} + C_{F1} + p_{F1} - \frac{1}{\eta_{H1}}C_{H1}$$

$\Delta_{opp}, p_H^*$ → **The switch point of WtP of the actors**




Numerical illustration of a valley with a bus fleet and an ammonia production plant

# Demand Side: Abatement Cost and Willingness-to-Pay (WtP)

The economic Welfare of an End-user **with a low-carbon alternative for hydrogen**:

$$W_{Di} = \Pi_i - (p_{CO2}E_i + C_{Fi} + p_{Fi})(N_i - (q_{Hi} + q_{Ai})) - \frac{1}{\eta_{Hi}}(C_{Hi} + p_H)q_{Hi} - \frac{1}{\eta_{Ai}}(C_{Ai} + p_A)q_{Ai}$$

$\eta_{Ai}$ Efficiency of low-carbon alternative based technology

$C_{Ai}$ Cost of deployment of alternative low-carbon based technology (€/MWh)

$p_A$ Price of low-carbon alternative (€/MWh)

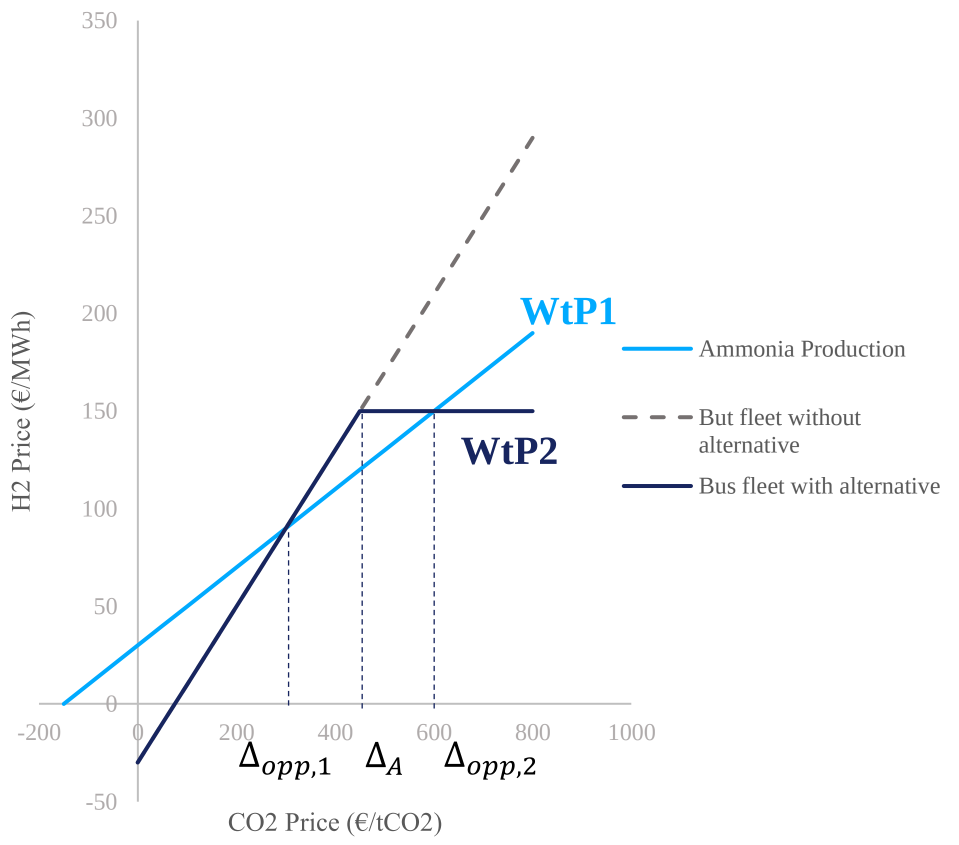
$q_{Ai}$ Quantity of low-carbon alternative uptake (MWh)

$$\begin{cases} \text{WtP} = (p_{CO2}E_i + C_{Fi} + p_{Fi}) - \frac{1}{\eta_{Hi}}C_{Hi} & \text{if} \quad p_{CO2} < \Delta_A \\ \text{WtP} = \frac{1}{\eta_{Ai}}(C_{Ai} + p_A) - \frac{1}{\eta_{Hi}}C_{Hi} & \text{if} \quad p_{CO2} > \Delta_A \end{cases}$$

**Abatement cost of alternative low-carbon technology:**

$$\Delta_A = \frac{(C_{Ai} + p_A) - (C_{Fi} + p_{Fi})}{\eta_{Ai}E_i}$$

$\Delta_A$ → The end user is indifferent to using fossil or alternative low-carbon technology




Numerical illustration of a valley with a bus fleet and an ammonia production plant

# Demand Side: Abatement Cost and Willingness-to-Pay (WtP)

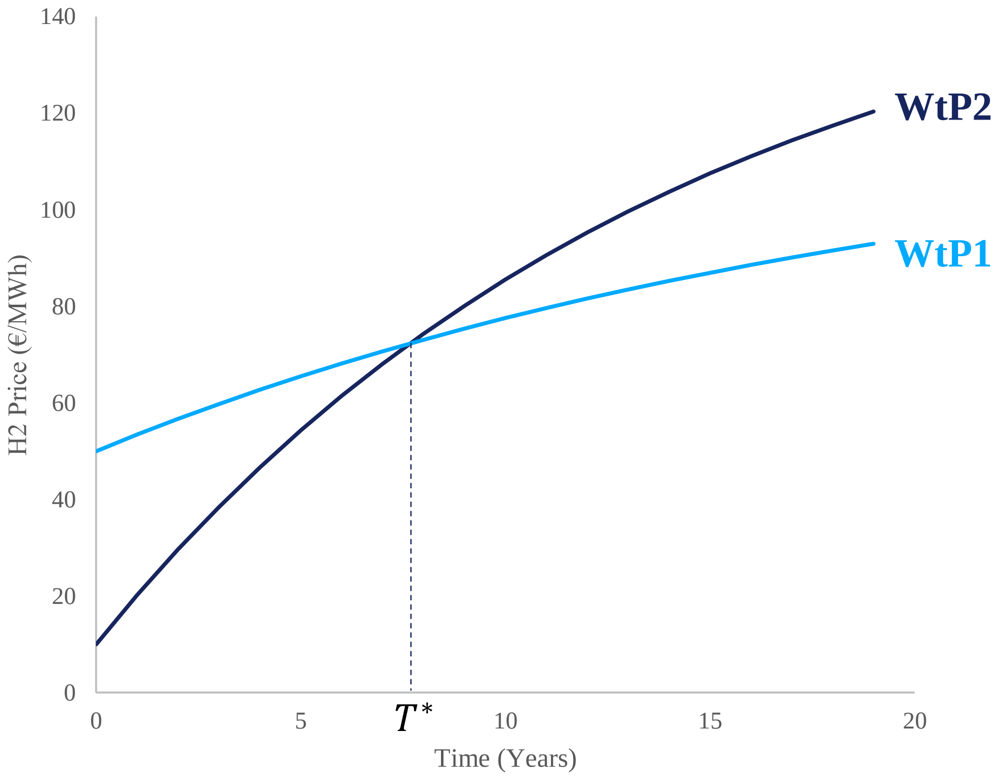
$$W_{Di} = \Pi_i - (p_{CO2}E_i + C_{Fi} + p_{Fi})(N_i - q_i) - \frac{1}{\eta_{Hi}}(C_{Hi} + p_H)q_i$$

Cost of deployment of low-carbon technology could be subjected to **learning**:

$$C_{Hi} = e^{-(r+\gamma_i)T}\ C_{Hi0}$$

| | |
|---|---|
| $r$ | Discount Rate |
| $\gamma_i$ | Learning Rate |
| T | Time |
| $C_{Hi0}$ | Cost of deployment of H2 technology at T=0 |

$T^*$ → **The switch point of WtP of the actors**



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# A Market equilibrium in the Hydrogen valley

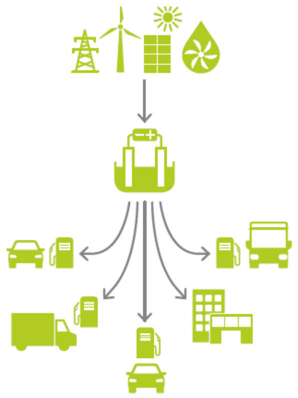
Which supply-demand market equilibrium in hydrogen valleys ?

Which market failures in hydrogen valley and what are their implications ?

# Scope: Hydrogen Valleys: Stepping Stones in the Development of a Global Hydrogen Ecosystem

- Three different archetypes for **Hydrogen Valleys (Roland Berger, 2021)**

### Archetype 1



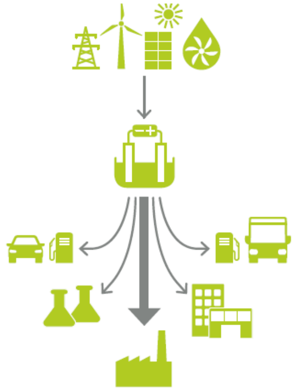
**Smaller-scale local mobility-centred Hydrogen Valleys (typically 1–10+ MW of local electrolyser capacity**

Typically combine the decarbonization efforts of various regional mobility fleets (hydrogen fuel cell trucks, buses, trains, etc.).

**Project examples:**

- Zero Emission Valley Auvergne-Rhône-Alpes (FR)
- Hydrogen Valley South Tyrol (IT)
- Hydrospider project (CH).

### Archetype 2



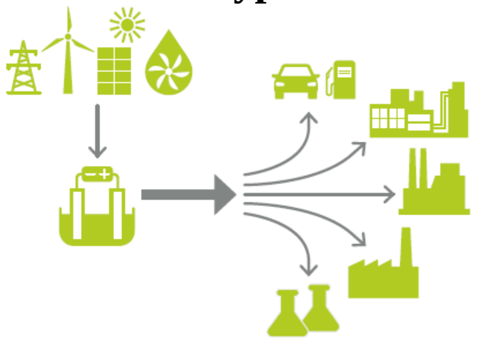
**Medium-scale Hydrogen Valleys focusing on industrial decarbonisation (typically 10-300+ MW of local electrolyser capacity):**

One or more large industrial consumers serving as "anchor load". Around this anchor load, mobility off-takers and their hydrogen assets are added benefitting from lower hydrogen supply costs.

**Project examples:**

- Hydrogen Holland 1 (NL)
- Basque Hydrogen Corridor (ES)
- HyNet North-West England (UK)

### Archetype 3



**Large-scale and ultimately export-oriented Hydrogen Valleys (typically 250-1,000+ MW of local electrolyser capacity):**

Focusing on low-cost production of clean hydrogen for local off-take, but ultimately mainly regional and international export to connect supply and demand centers on a global scale.

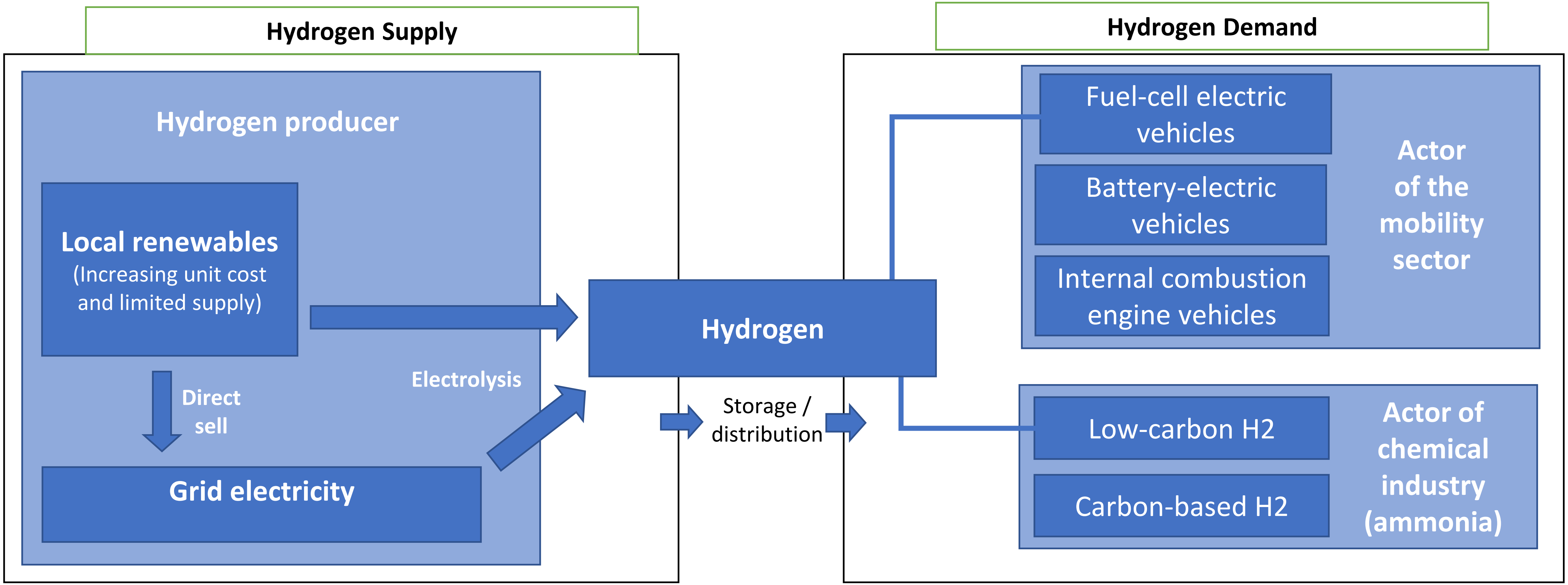
**Project examples:**

- NEOM (KSA)
- Aqua Ventus (DE)
- H2 Magallanes (CL)
- Pilbara Hydrogen Hub (AU)

# A simplified hydrogen valley model

**Objective function:** Maximization of the aggregated welfare

**Time-scale: Year**
**Time-horizon: 2030 -2040**




**Energy actor:** Maximize its profit by:
- producing renewable electricity
- choosing between selling it directly to the grid or producing renewable hydrogen

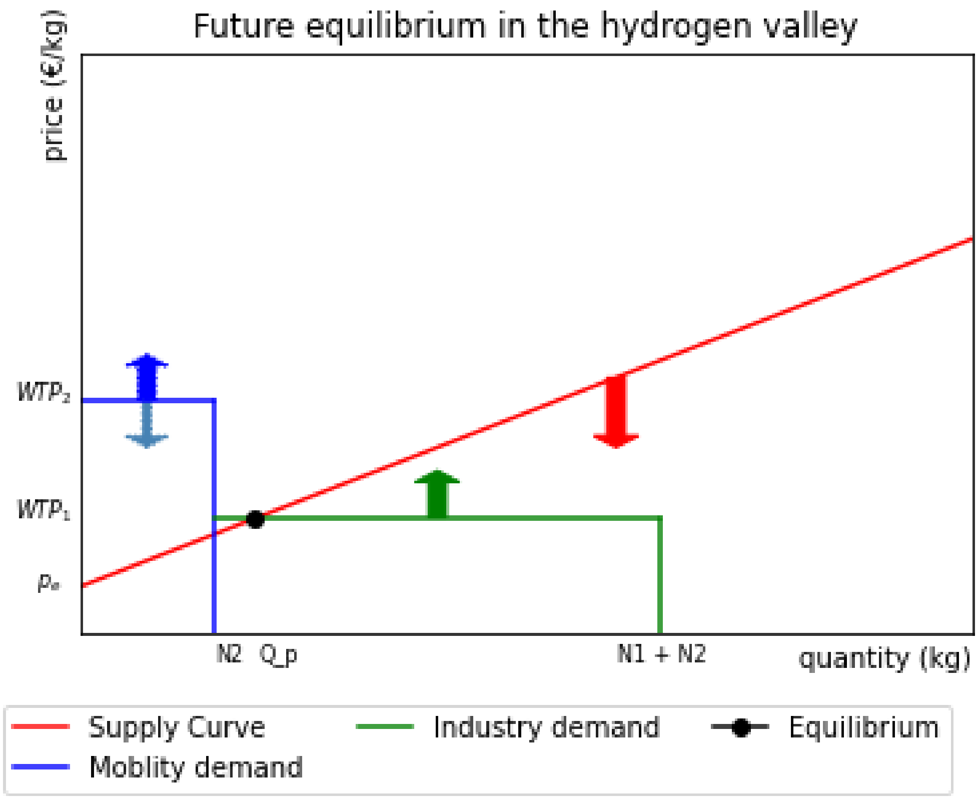
**Output:** H2 price and quantity

**Input:** H2 price and quantity

**Mobility actor:** Maximize its profit by choosing between two low-carbon technologies and one carbon-based technology to meet a fixed demand

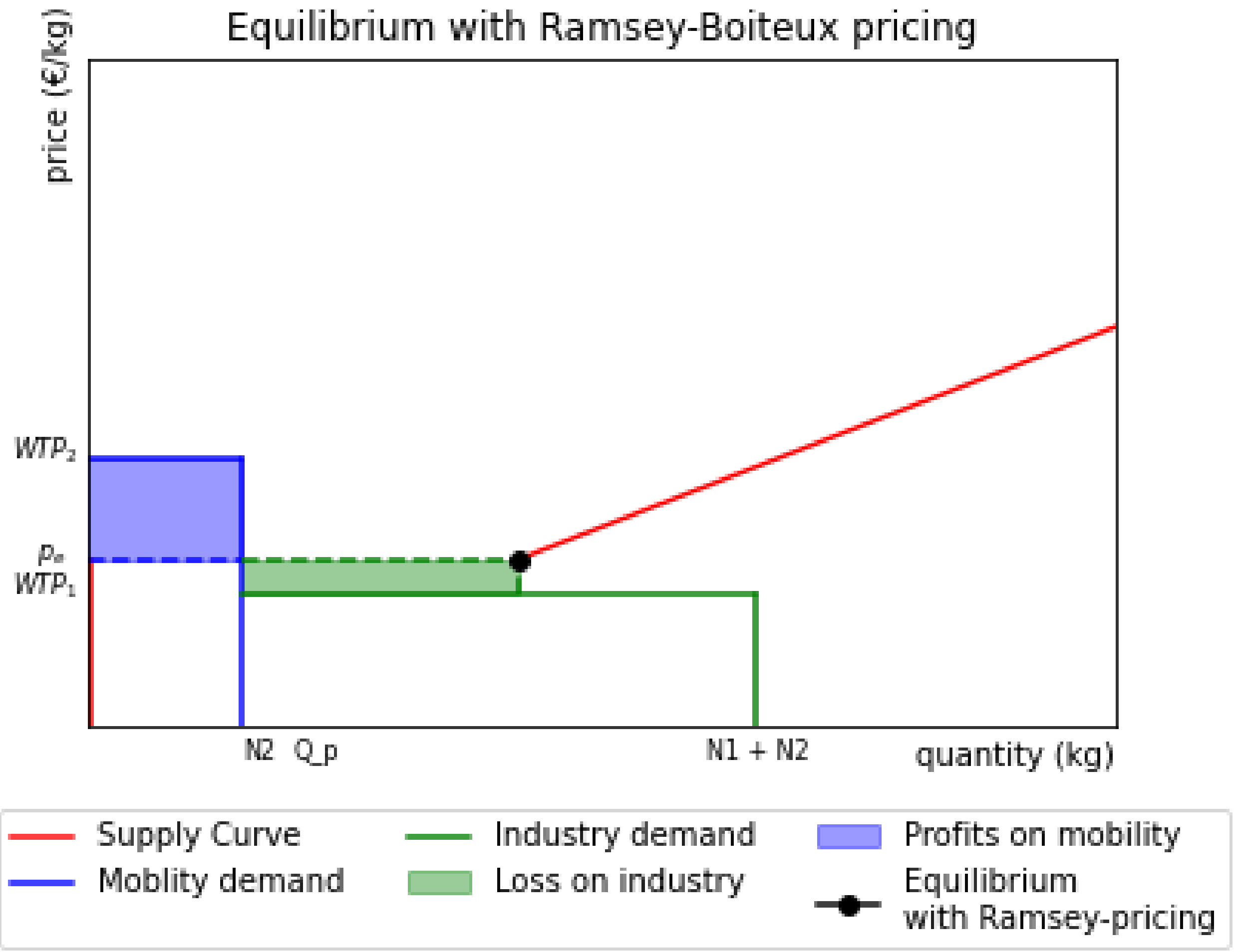
**Industry actor:** Maximize its profit by choosing between one low-carbon technology and one carbon-based technology to meet a fixed demand

# Standard Market Equilibrium in the hydrogen valley




- **Supply curve in H2 valley**
  - Trade-off between selling renewable electricity to the grid and producing renewable hydrogen
- **Demand-curve**
  - **Mobility** have high willingness-to-pay but low demand level
  - **Industry** have low willingness-to-pay but high demand level
- **Long-term equilibrium:**
  - Reduced electrolysis cost: **lower supply curve**
  - Increasing social cost of carbon: **higher WtP**
  - Decreasing cost of hydrogen technologies: **higher WtP**
  - ⚠ **:** Decreasing cost of alternative low-carbon technologies in mobility: **lower WtP for H2**

# Economies of scale and its implication (work in progress)




**scale for large-scale electrolysers (electricity price 100€/MWh)**

**Sources of economies of scale:**

- The CAPEX of large-scale electrolysers represents a fixed cost in a H2 valley

**Consequences on the market equilibrium**

- The producer only agrees to produce hydrogen if the quantity is large enough to amortize the CAPEX (otherwise it sells its electricity directly).
- Without intervention, an equilibrium might not be found, which means no hydrogen production in the valley.

$\Rightarrow$ **Ramsey-Boiteux problem (1956) applied to a local monopoly**

**Ramsey-Boiteux pricing:**

- Both sectors are priced at their own WtP level
- Profit made on mobility sector = Loss made on the industry sector ?

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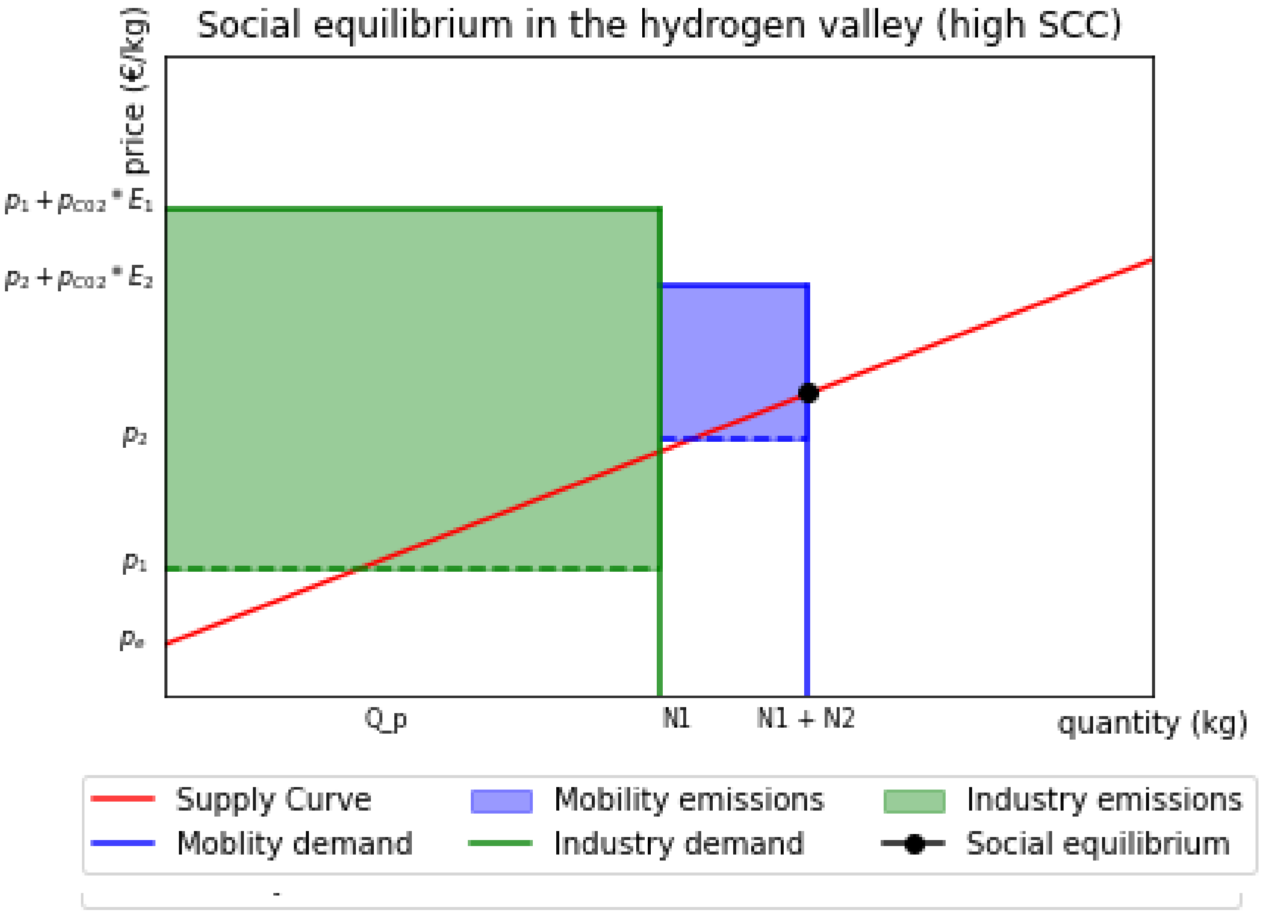
## Hydrogen-end uses and public policy instruments

What are the implications of insufficient carbon taxation?

Which public policy instruments to reach the socially optimal allocation of hydrogen?

# Insufficient carbon taxation leads to inefficient H2 allocation




**Private equilibrium without climate policy**

**With a social cost of carbon lower than the opportunity cost of abatement:**

- Insufficient hydrogen production
- Limited welfare loss

**With a social cost of carbon higher than the opportunity cost of abatement:**

- Non-meritorious hydrogen allocation
- Significant welfare loss

**First-best policy:**

- A Pigouvian tax on emissions is efficient to decentralize the first-best scenario
- **However, a uniform carbon tax across sector is unlikely to emerge at the European level**
- For example: high taxation on diesel (mobility) and low taxation on natural gas (industry)

# First and second-best policy ranking (work in progress)

**Comparing second-best policy:**

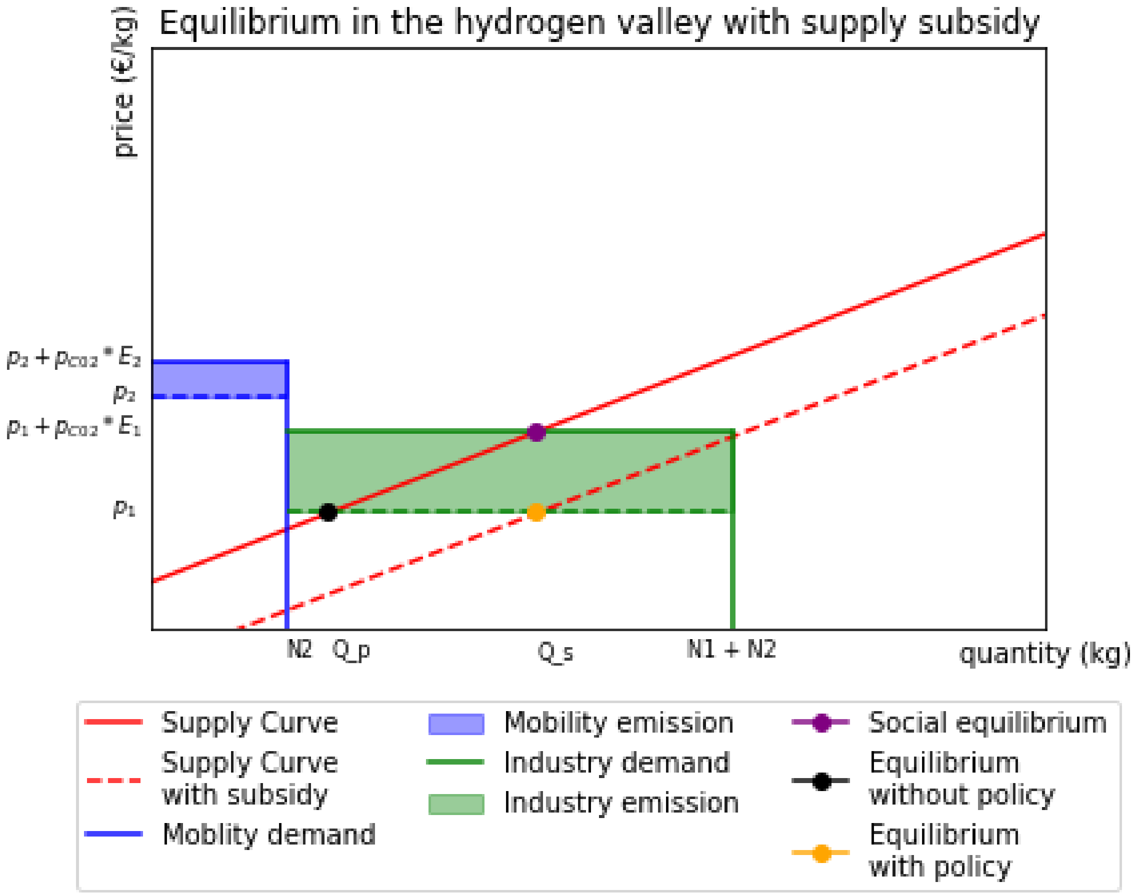
- Subsidy to hydrogen production
- Subsidy to one demand sector (mobility or industry)
- Joint subsidy to demand and production sector

**Preliminary results:**

- Subsidy to hydrogen production can create a windfall effect (unnecessary mobility support)
- Direct subsidy to a hydrogen option in a sector with a low-carbon alternative may distort the competition between low-carbon technologies
- The best policy depends on the position of the social cost of carbon in comparison to the opportunity cost of abatement

**Objective:**

- For each instrument, determine the welfare-maximizing policy level, and indicate the quantity of hydrogen produced, its price and allocation
- Extend this analysis in the context of discriminatory pricing



# Conclusion and next steps

## Preliminary conclusion

- We propose a methodology to define an optimal “Merit-Order for End-Uses of Hydrogen” based on the notion of MACC considering additional dimensions: *the constraint on hydrogen supply in short-term, competition among different zero and low-carbon technologies, the interactions between sectors as well as the time perspective.*
- This approach is applied to define the optimal allocation of renewable hydrogen in a hydrogen valley (or hydrogen hub). Some market failures (economies of scale, insufficient carbon taxation) are identified, and public policies to address them are derived.

## Next steps and extensions:

- Calibration of the model, based on data from local hydrogen valleys
- Introducing hydrogen storage and distribution in the model
- Introducing the option of hydrogen import in the hydrogen valley, as well as hydrogen export (archetype 3)
- Introducing other criteria to define a a merit-order for end-uses of renewable hydrogen (TRL, safety issues)

**Thank you so much for your attention!**