Energy Transition Dynamics: Unlocking Synergies for Low-emission Hydrogen Deployment

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Outline

Context and definitions

Low-emission hydrogen: produced via electrolysis using low-emission electricity (renewables, nuclear...).

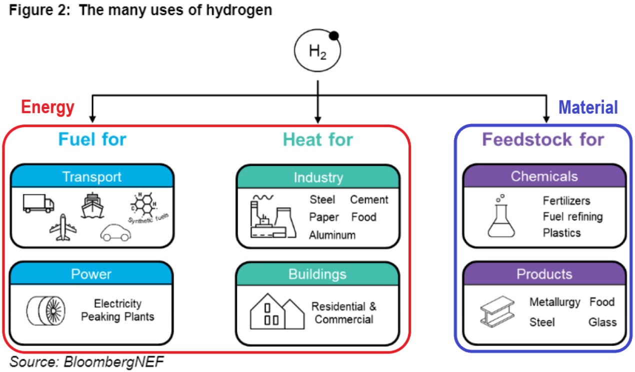


Figure: Hydrogen demand sectors for energy or material uses
Adapted from *Hydrogen Economy Outlook, BloombergNEF (2020)*

Research question

- **Context:** 2°C goal of the Paris Agreement → **cap** on cumulative GHG emissions.
- Two end-use sectors for hydrogen: **material-use sector** (ex. industry) and **energy-use sector** (ex. transport, heating...).
  - For material uses, hydrogen is non-substitutable.
  - For energy uses, hydrogen is in competition with other low-emission alternatives (ex. electricity in batteries, biofuels...).
- Expected **learning-by-doing** and **diseconomies of scale** for low-emission hydrogen.

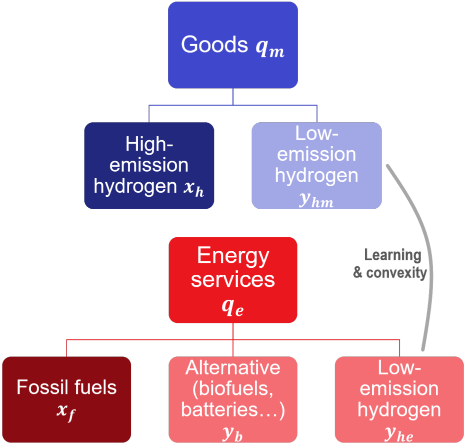
What is the added value of considering cross-sectoral ineractions between material and energy uses of low-emission hydrogen on its deployment and the overall energy transition dynamics?

Literature review

- Green innovation
  - Inter-sectoral knowledge spillovers (R&D) (Stephan et al., 2021; Dugoua et al., 2024)
  - Learning-by-doing (Arrow, 1962; Creti et al., 2018)
- Hydrogen deployment (techno-economics)
  - Sector-specific optimization models (Schneider, 2022)
  - Contribution of hydrogen within energy models (Hanley et al., 2018)
- **Methodology:** Energy transition macro-dynamic models à la (Hotelling, 1931), variants by Chakravorty, Moraux and co-authors:
  - Allocation of a shared scarce resource across sectors (land for food and bioenergy) (Chakravorty, Magné, et al., 2008)
  - Low-emission backstop with learning and convexity effects (Chakravorty, Leach, et al., 2012)
  - Scarce and renewable backstops (CCS) (Amigues, Lafforgue, et al., 2016)
  - Volume and blend clean energy mandates (Amigues, Chakravorty, et al., 2022)

General framework

- Two sectors: material-use (produces goods) and energy-use (produces energy services).
- $q_m(t) = x_h(t) + y_{hm}(t)$
- $q_e(t) = x_f(t) + y_b(t) + y_{he}(t)$
- Unitary output per unit of input.
- Perfect substitution between inputs.



General framework

- Additive utility $U = u_m(q_m) + u_e(q_e)$, where $u_i(q_i)$ is strictly increasing, strictly concave, and satisfying the Inada conditions.
- $Z(t)$: cumulative GHG emissions at time t.
- α and β: quantities of GHG emissions released into the atmosphere per unit of fossil fuel or high-emission hydrogen consumed respectively.
- Dynamics of emissions: $\dot{Z}(t) = \alpha x_f(t) + \beta x_h(t)$.
- Emissions cap $Z(t) \leq \overline{Z}$.

Figure: Utility function

Costs

- No infrastructure costs.
- $g(y_h, Y_h)$ unit cost of low-emission H_2, where $y_h(t) = y_{hm}(t) + y_{he}(t)$ and Y_h is the cumulative intersectoral production of low-emission H_2 $Y_h(t) = Y_{h0} + \int_0^t y_h(\tau)\,\mathrm{d}\tau$.
- g experiences **learning-by-doing** and **diseconomies of scale**.
- Constant average costs per unit of output for the other options c_i, $i \in \{h, b, f\}$.

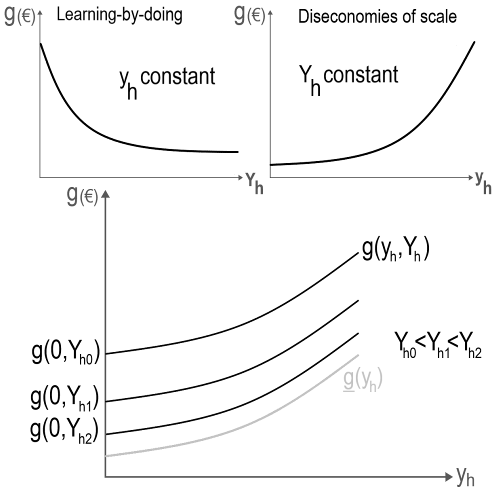


Figure: Cost function g of low-emission hydrogen, adapted from (Chakravorty, Leach, et al., 2012)

Planner's problem

$$\max_{\{x_h;y_{hm};y_{he};y_b;x_f\}} \int_0^{+\infty} \{u_m(x_h + y_{hm}) + u_e(y_{he} + y_b + x_f) - c_h x_h \\ - g(y_h, Y_h)y_h - c_b y_b - c_f x_f\} e^{-\rho t} \,\mathrm{d}t \quad (1)$$

where $y_h = y_{hm} + y_{he}$, and subject to

$$\dot{Y}_h(t) = y_h(t) \quad (2)$$

$$\dot{Z}(t) = \alpha x_f(t) + \beta x_h(t) \quad (3)$$

$$\overline{Z} - Z(t) \geq 0 \quad (4)$$

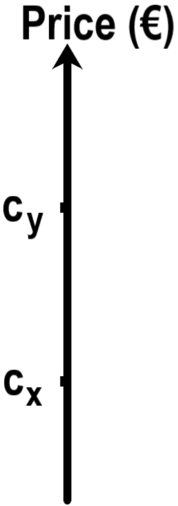
$$x_i \geq 0, i \in \{h, f\}; y_i \geq 0, i \in \{hm; he; b\} \quad (5)$$

with the initial conditions $Y_h(0) = Y_{h0} = 0$ and $Z(0) = 0$.

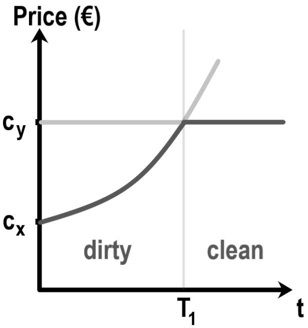
Social marginal costs

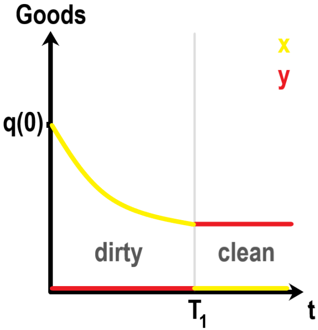
- The costate variables λ and μ are the shadow prices associated with the learning-by-doing and environmental constraints respectively.
- Social marginal costs are $c_f + \mu\alpha$ for fossil fuels, $c_h + \mu\beta$ for high-emission hydrogen and $\frac{\partial g}{\partial y_h} y_h + g - \lambda$ for low-emission hydrogen.
- $$\lambda(t) = \int_t^{+\infty} -\frac{\partial g}{\partial Y_h} y_h e^{-\rho(\tau - t)} \, \mathrm{d}\tau \tag{6}$$
- The learning rent λ at time t is > 0 and represents the cumulative discounted sum of all future marginal cost cuts allowed by a slight accumulation of experience.

Mechanisms

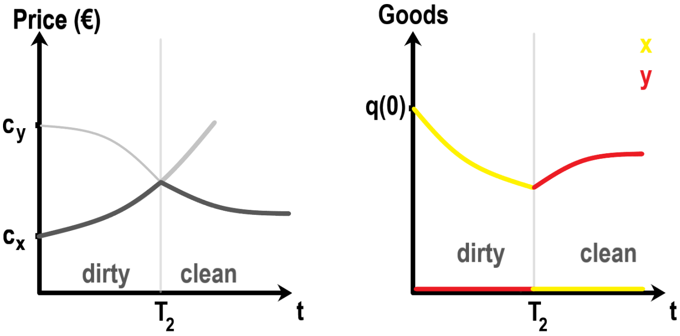


Emissions cap

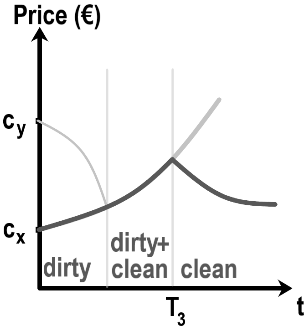


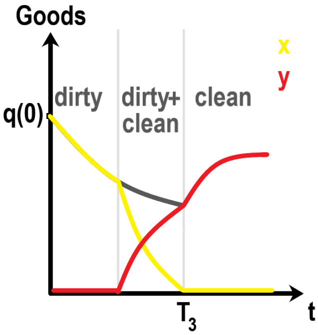


Emissions cap + learning-by-doing

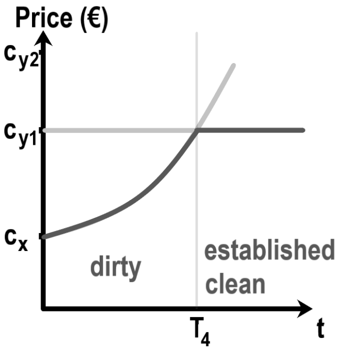


Emissions cap + learning-by-doing + diseconomies of scale

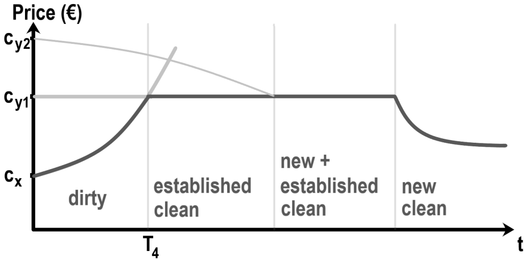


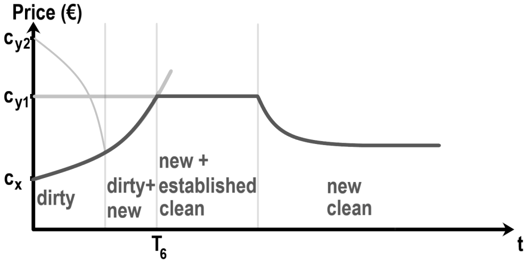


Two clean inputs

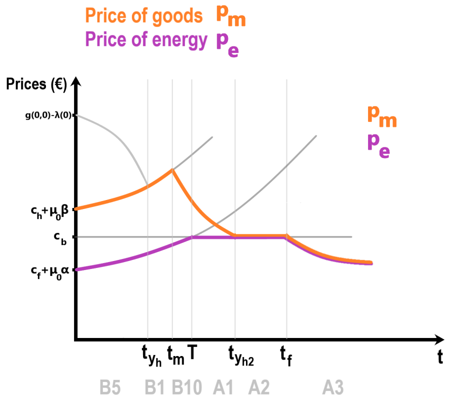


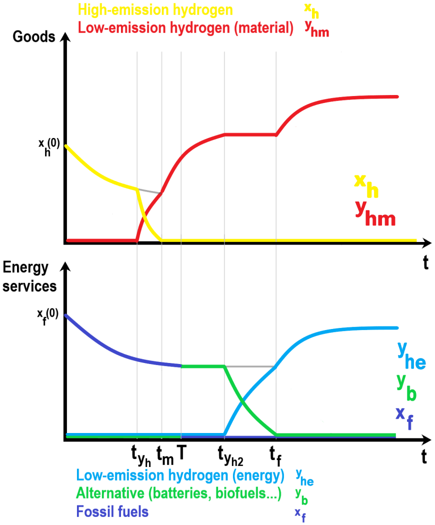
Two clean inputs





Benchmark: optimal paths of prices and quantities





Conclusion

Results:

- Price paths in the material-use sector may present a second peak or stagnate after its clean transition due to diseconomies of scale from energy uses.
- Compared to a separate sector study, the linked framework leads to an earlier introduction of low-emission hydrogen for material uses, lower prices of goods, and higher utility.
- The timing of the introduction of low-emission hydrogen in the energy-use sector in the linked study relies on *realized* not *anticipated* cost reductions from learning.

Limits: infrastructure constraints, perfect input substitution, constant costs...
Extension: effect of a share mandate on low-emission for material uses.
Takeaways: Inter-sectoral effects can significantly impact deployment trajectories $\rightarrow$ need for more holistic modeling approaches which combine material and energy uses.

Questions?

Thanks for your attention.
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Summary

Research question: What is the added value of considering cross-sectoral ineractions between material and energy uses of low-emission hydrogen on its deployment and the overall energy transition dynamics?

Contribution: Exploring both *material* and energy uses, focusing on the *intersectoral synergies*.

Method: Analytical dynamic model (optimal control).

Framework:

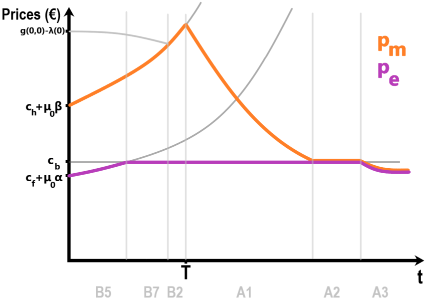
- Two end-use sectors for H_2: **material-use sector** (ex. industry) where H_2 is non-substitutable and **energy-use sector** (ex. transport, heating) where H_2 is in competition with other low-emission alternatives.
- Cap on cumulative GHG emissions. Learning-by-doing and diseconomies of scale for low-emission H_2.

Results:

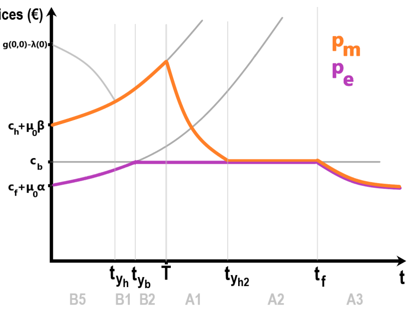
- Price paths in the material-use sector may present a second peak or stagnate after its clean transition due to diseconomies of scale from energy uses.
- Compared to a separate sector study, the linked framework leads to an earlier introduction of low-emission hydrogen for material uses, lower prices of goods, and higher utility.

6 **Appendix**

Benchmark variants - no mandate

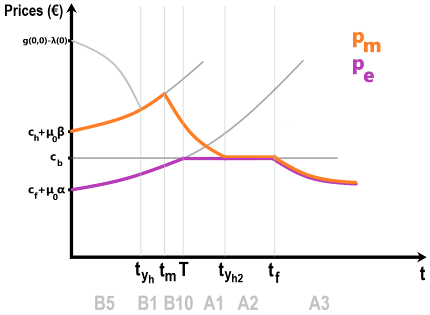


(a) Weak LBD, any DOS

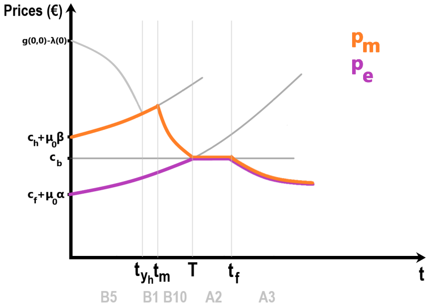


(b) Moderate LBD, strong DOS

Benchmark variants - no mandate

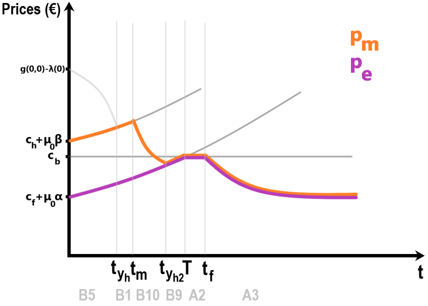


(a) Main : Moderate LBD, moderate DOS

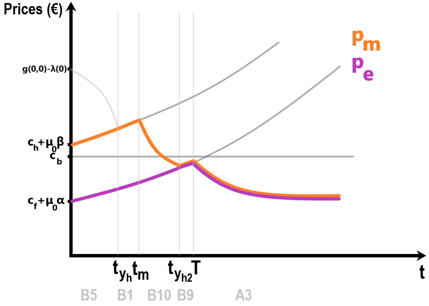


(b) Moderate LBD, weak DOS

Benchmark variants - no mandate



(a) Strong LBD, weak DOS



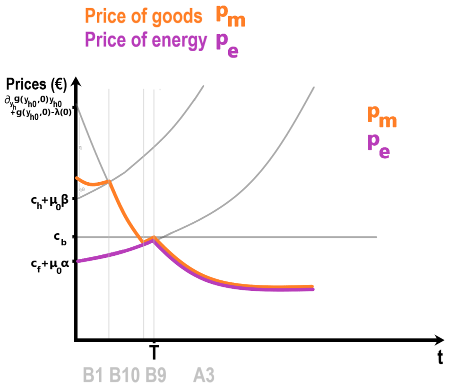
(b) Strong LBD, very weak DOS

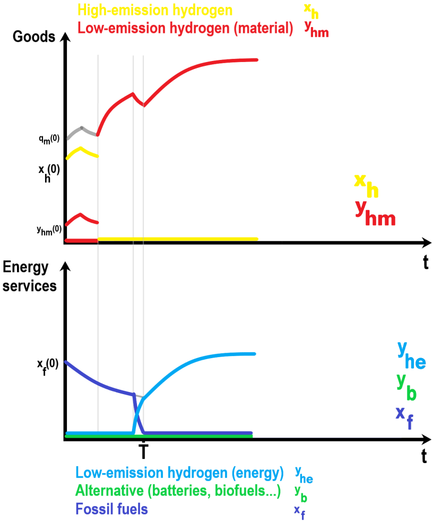
Defining the share mandate

Imposed minimum share $0 < \sigma < 1$ of low-emission hydrogen in the material-use sector:

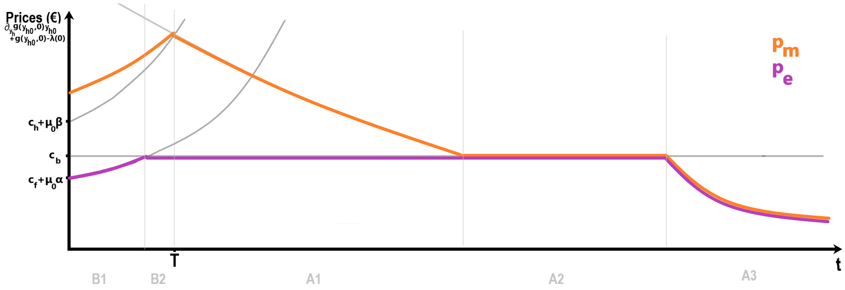
$$y_{hm} \geq \sigma(x_h + y_{hm}) \tag{7}$$

Benchmark: optimal paths - share mandate



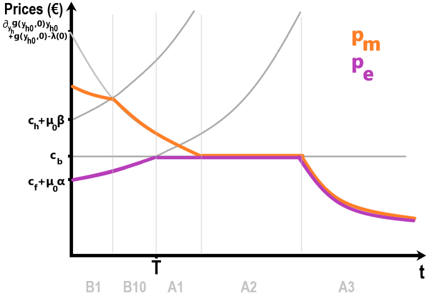


Benchmark variants - share mandate

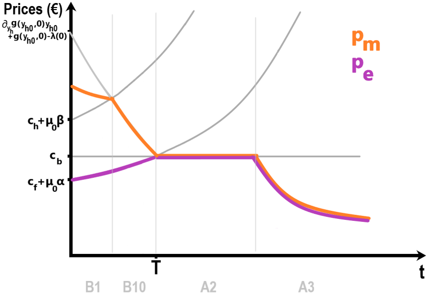


(a)

Benchmark variants - share mandate

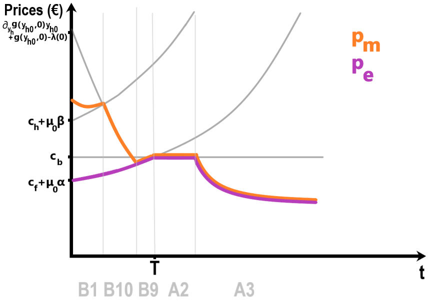


(a)

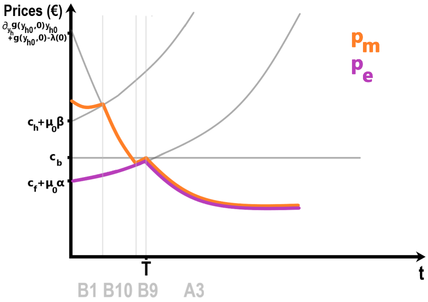


(b)

Benchmark variants - share mandate



(a)



(b) Main

Hydrogen production paths

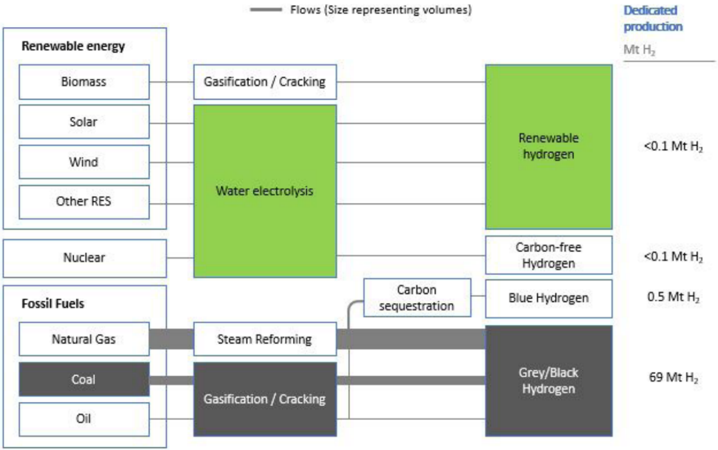


Figure: Global hydrogen production paths in 2019 (De Blasio et al., 2020)

Hydrogen production paths

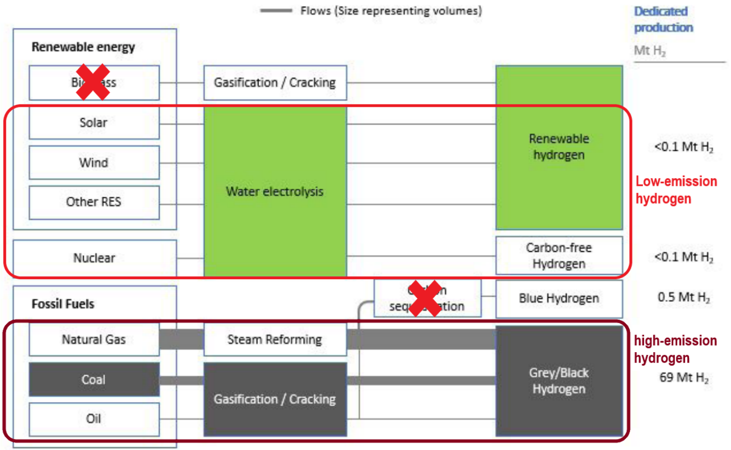


Figure: Global hydrogen production paths in 2019. Adapted from (De Blasio et al., 2020)

Hydrogen end-uses

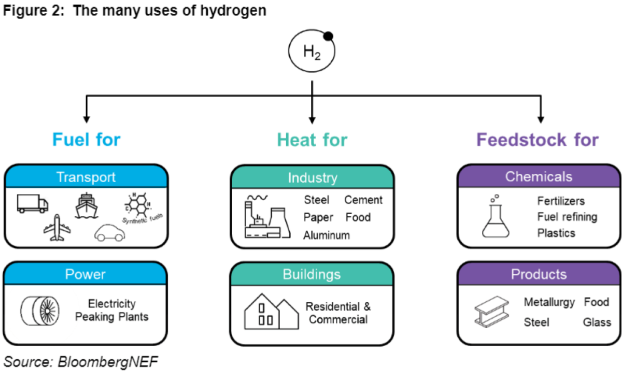


Figure: Hydrogen demand sectors for energy or material uses (Bhavnagri et al., 2020)

Hydrogen end-uses

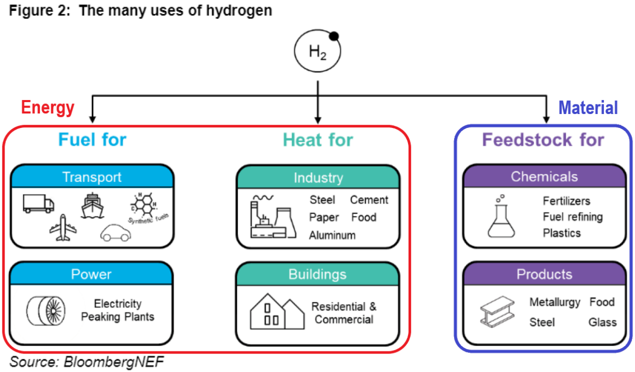


Figure: Hydrogen demand sectors for energy or material uses. Adapted from (Bhavnagri et al., 2020)

Example on material uses: ammonia

- Around a third of hydrogen demand in 2020 was for ammonia production.
- Around 70% of ammonia NH_3 is used to make nitrogen fertilizers, to feed close to half of the world's population.
- Ammonia is produced via the Haber-Bosch process.
- The chemical reaction $N_2 + 3H_2 \longrightarrow 2NH_3$ cannot take place without hydrogen inputs.
- Hydrogen is a non-substitutable material input in ammonia production.

Projections on Hydrogen demand in France for 2050

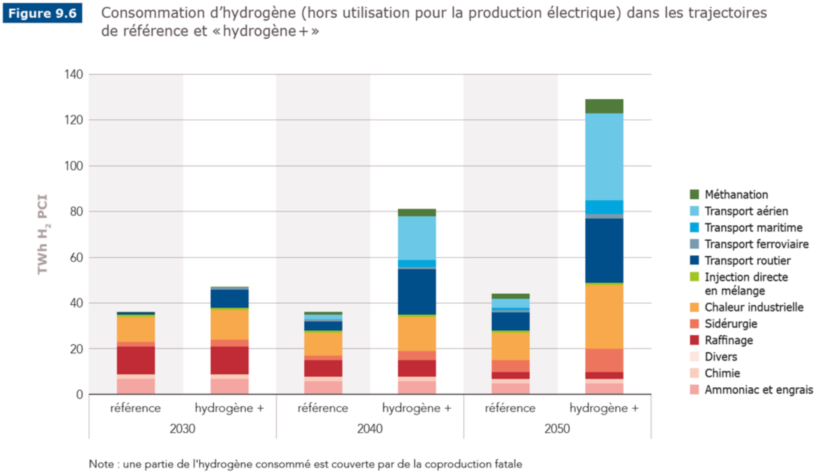


Figure: Hydrogen demand projections for 2050 in France outside electricity production (RTE, 2022)

Projections on Hydrogen demand in France for 2050

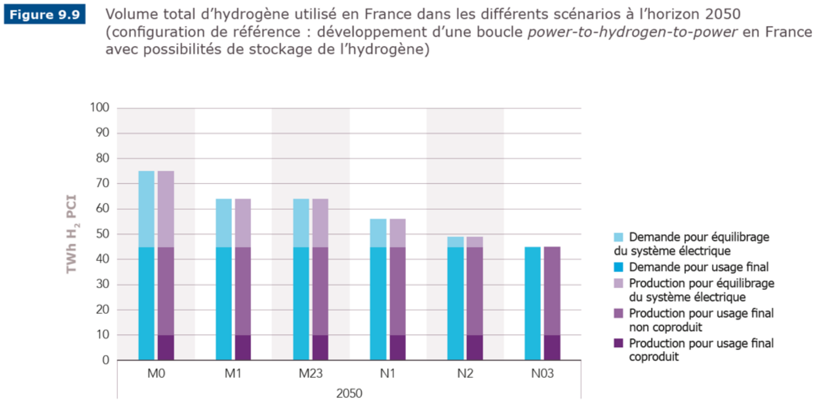


Figure: Hydrogen demand and production projections for 2050 in France for all uses (RTE, 2022)

Ph.D. topic

- **Ph.D. topic:** Conditions for the development of a low-emission energy carrier (hydrogen): techno-economic analysis focusing on the transport and industry sectors in France.
- Areas of attention:
  - the demand side
  - territorial aspects
  - pure economic and techno-economic modeling approaches
- **Supervisors:** Mouez Fodha (PSE), Elisabeth Le Net (CEA I-Tésé), Valérie Seguin (CEA I-Tésé), and Oualid Gharbi (CEA I-Tésé).

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