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Technology learning and innovation for industrial decarbonization



Daniela Toribio
February 09th, 2026
Future of Energy Seminar

Content of the presentation

- Background
- Technology learning and innovation
- Modeling technology learning and innovation
- Study cases
- Questions

Cumulative installed capacity per scenario



Technology learning and innovation

Learning rates per technology

Change in energy system (i.e., policy)

Demands
Techno-economic data
Constraints
Policies

Production levels
Technology options
Energy and CO_2 prices

Process design
Equipment cost correlations
Energy and material prices



Macroeconomic level
General equilibrium model

GDP
Employment



National level
LP cost optimization

Investments
Operation
Energy & CO_2 prices
Trade



Cluster level
MILP optimization

Optimal cluster configuration
Investments
Operation
Intro-cluster exchanges



Process level
Techno-economic model

Process design
Efficiency and conversions
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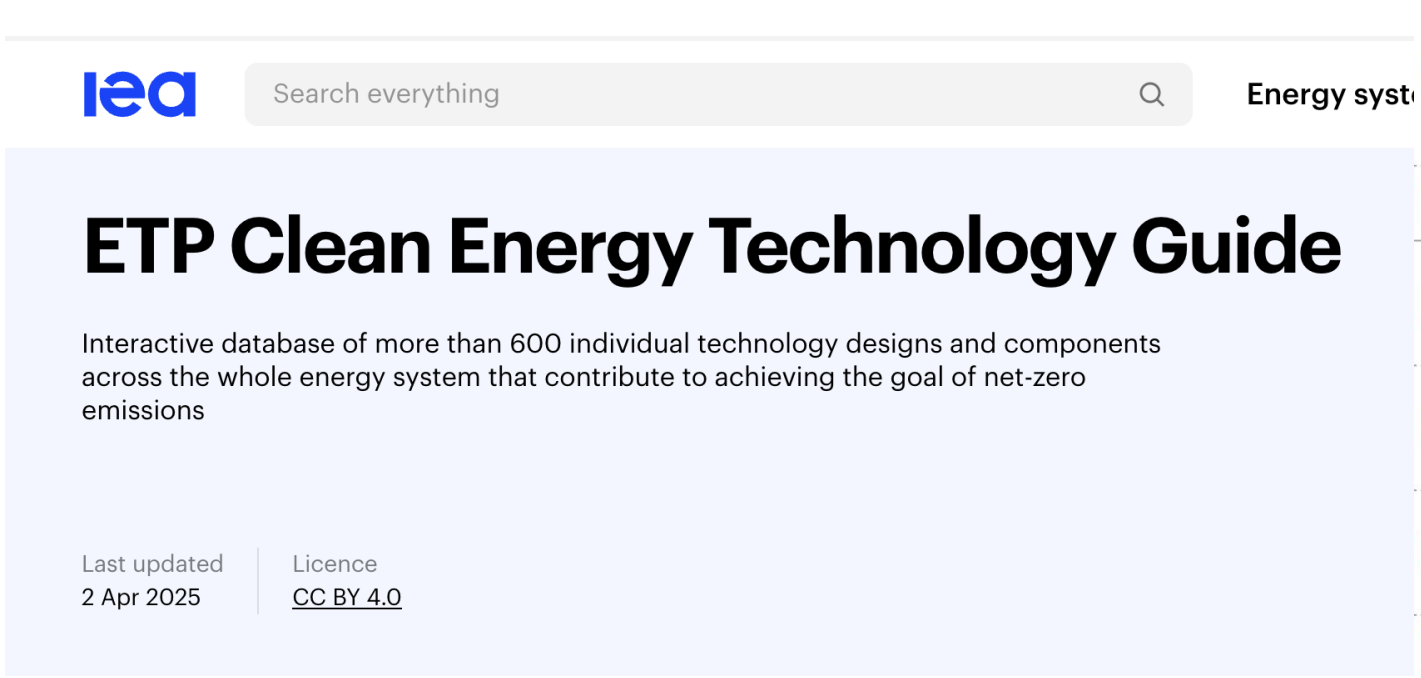
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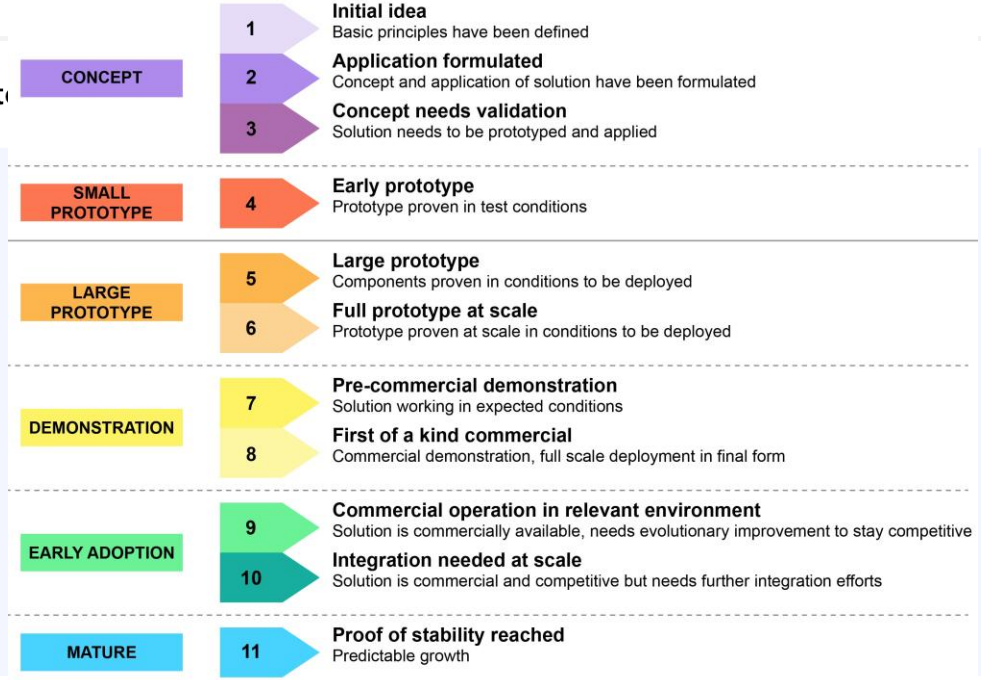


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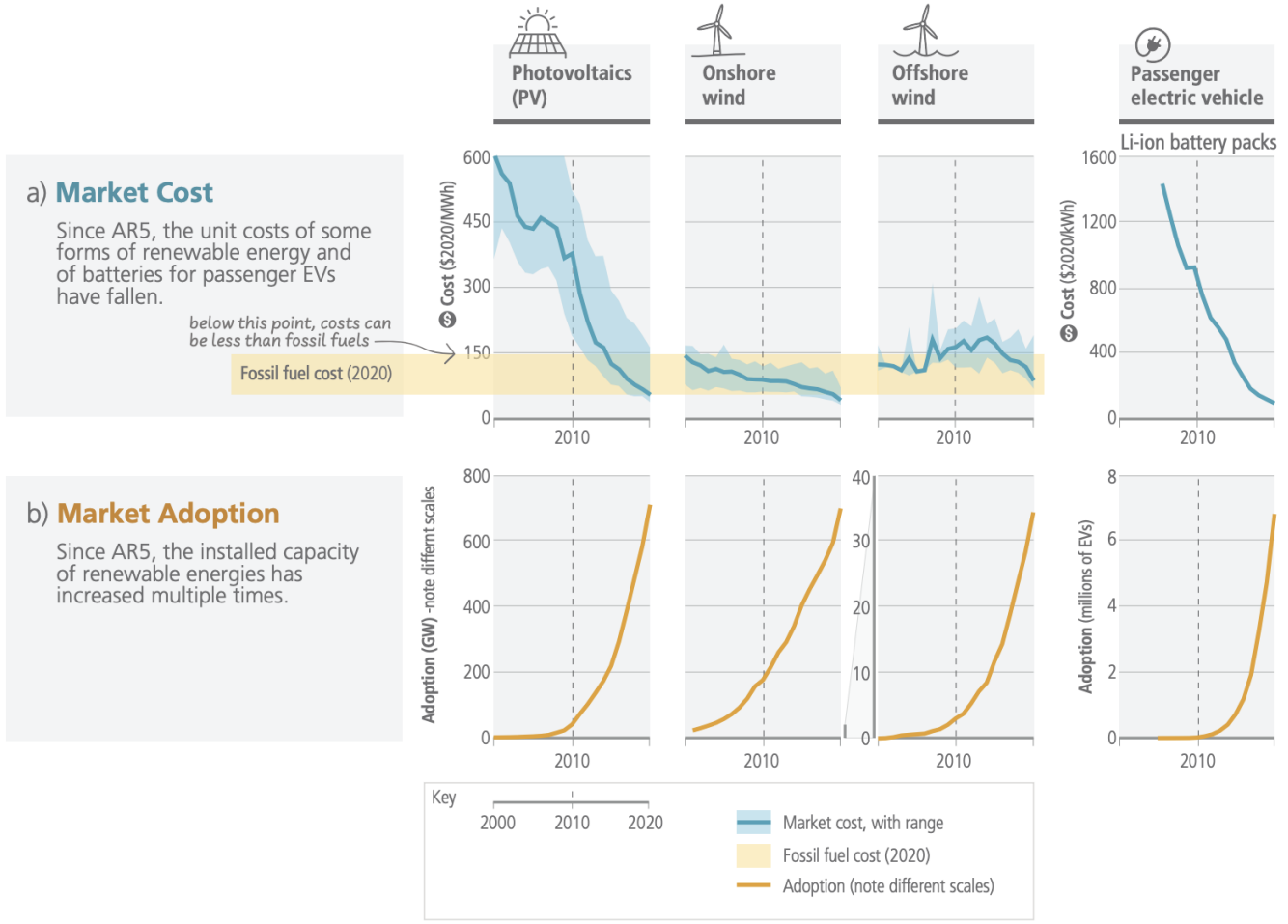
There are more than 600 new technologies available to help achieve the net-zero emissions goals, but most of them are in the early development stages.





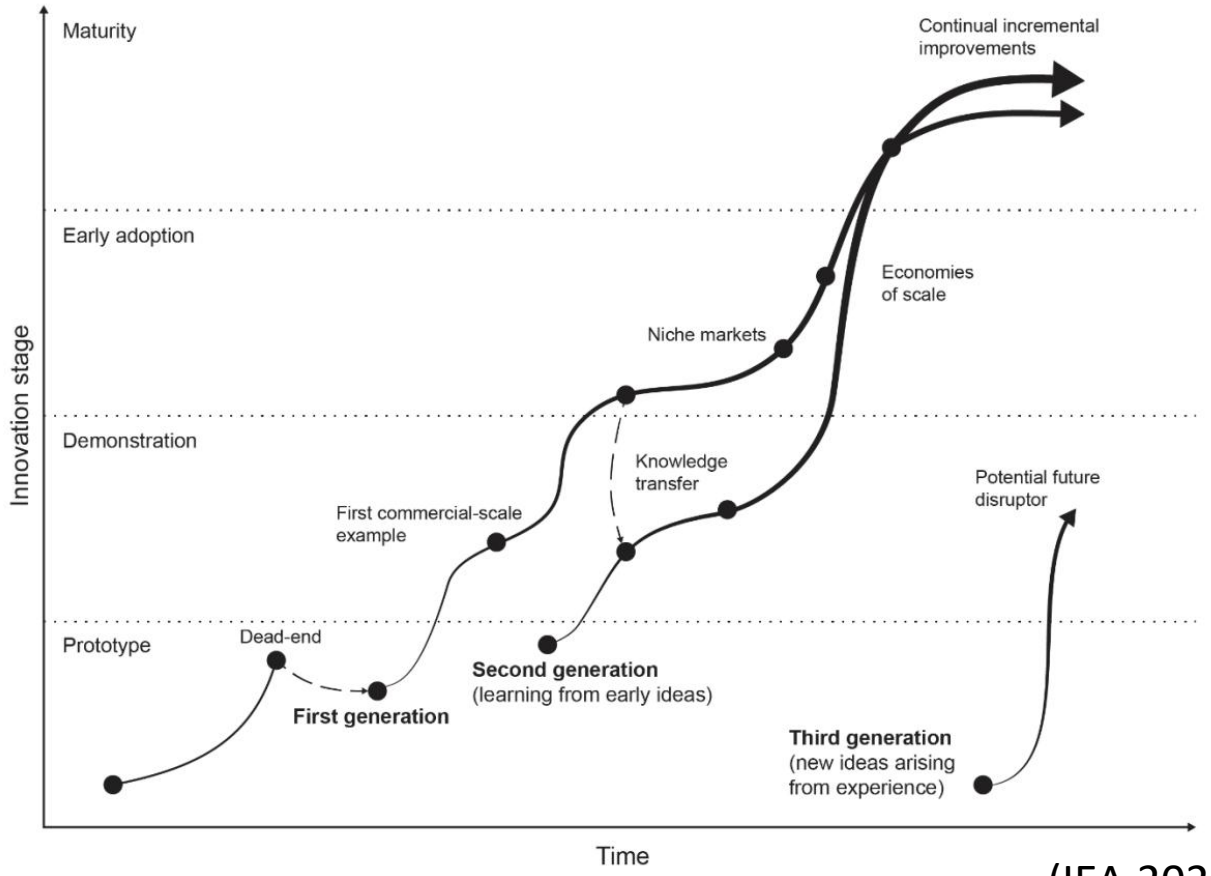
International Energy Agency. Tracking Clean Energy Progress 2023 – Analysis - IEA. https://www.iea.org/reports/tracking-clean-energy-progress-2023 (2023).

It is possible to drive down the cost of renewable technologies and become cost-competitive with fossil fuel.



IPCC. *Climate Change 2022 Mitigation of Climate Change Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg3/ (2022).

Understanding the innovation process can help accelerate and guide the transition toward a sustainable energy system.



(IEA,2020)

Intrinsic characteristics of the existing industrial sector affect the widespread adoption of new low-carbon technologies.



Large-scale processing plants with high upfront costs and long investment cycles.



Large multinational firms with significant market power.



Highly globalized and price competitive markets with low profit margins.



Preference towards incremental innovations.

Wesseling, J. H. *et al.* The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews* **79**, 1303–1313 (2017).

Research goal

The goal of this work is to quantitatively describe and project cost developments of low-carbon technologies, which are expected to support the energy transition in the industry.

How to model technology learning and innovation?

Learning curves
- One factor
- Multi-factor
- Multi-component

Bottom-up cost model

Socio-technical transitions theories
- Multi-level perspective
- Technological innovation systems

Expert elicitation

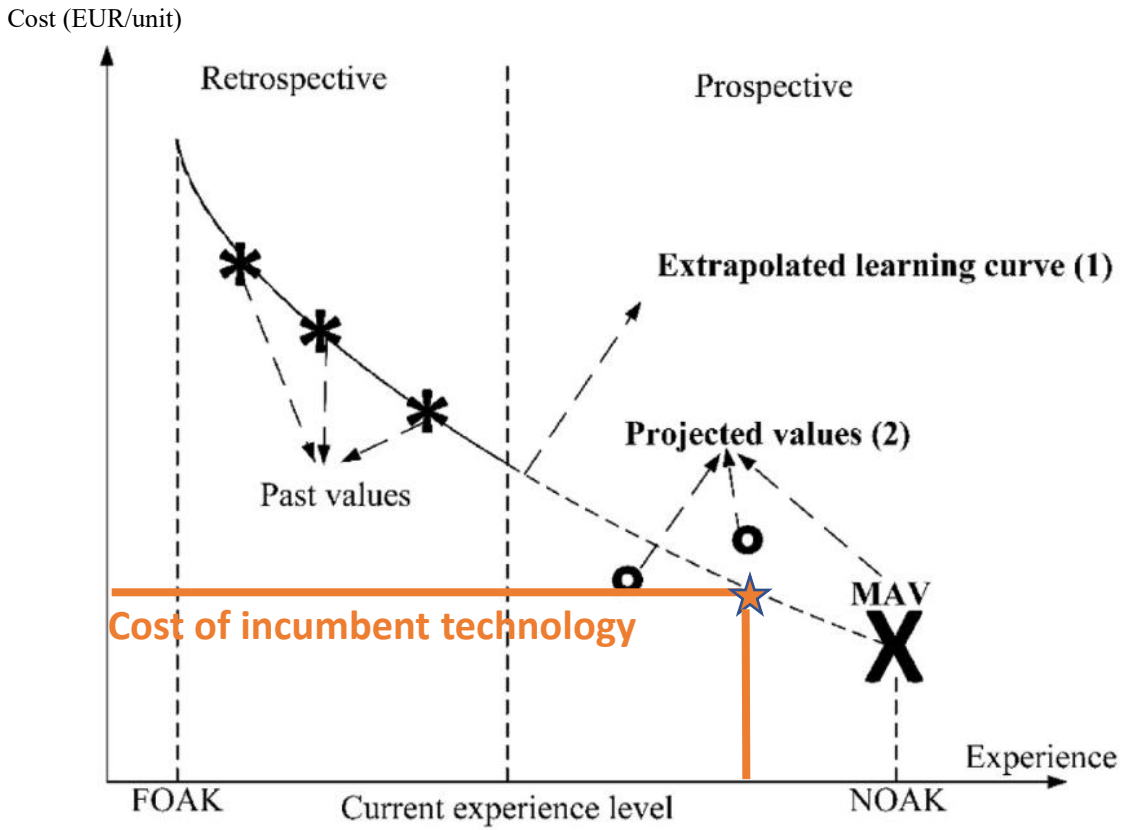
Patent analysis

Policy intervention studies

Toribio-Ramirez, D.A., van der Zwaan, B. C. C., Detz, R. J., & Faaij, A. (2025). A review of methods to analyze technological change in industry. *Renewable and Sustainable Energy Reviews*, *212*, 115310. https://doi.org/10.1016/j.rser.2024.115310

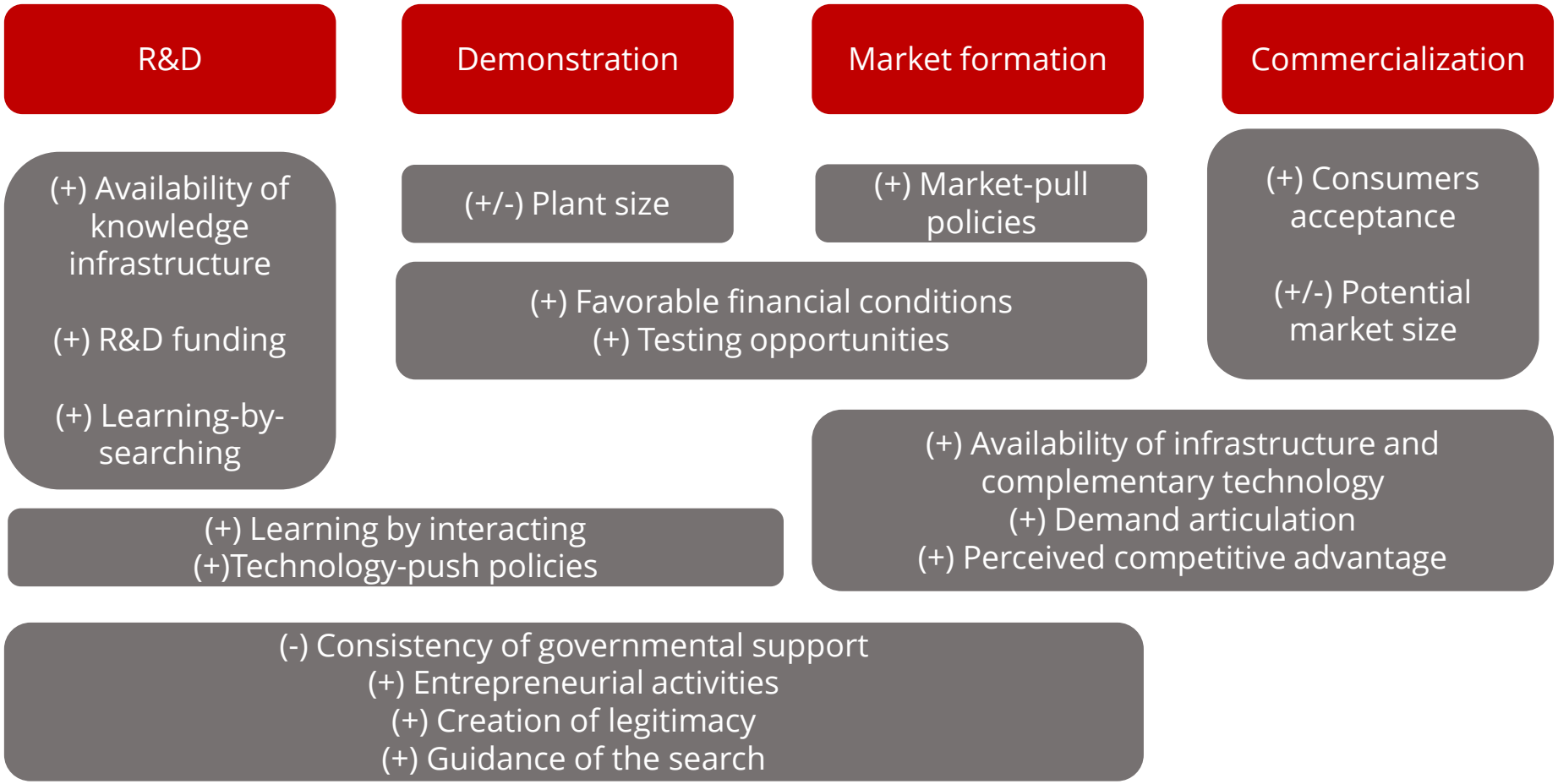
Learning curves

- ***Empirical model*** quantifying cost reductions in as a function of cumulative output (Wright, 1936; Arrow, 1962).
- ***One-factor learning curve (LC)***: it is obtained by plotting a performance metric (e.g., unit cost) against an experience metric (e.g., cumulative installed capacity).
- ***Two-factor learning curve (2FLC) & Multi-factor learning curve (MFLC)***: further generalizes the framework by integrating learning-by-doing, learning-by-searching, scale effects, and input price dynamics, etc. (Nemet, 2006; Yeh & Rubin, 2012).



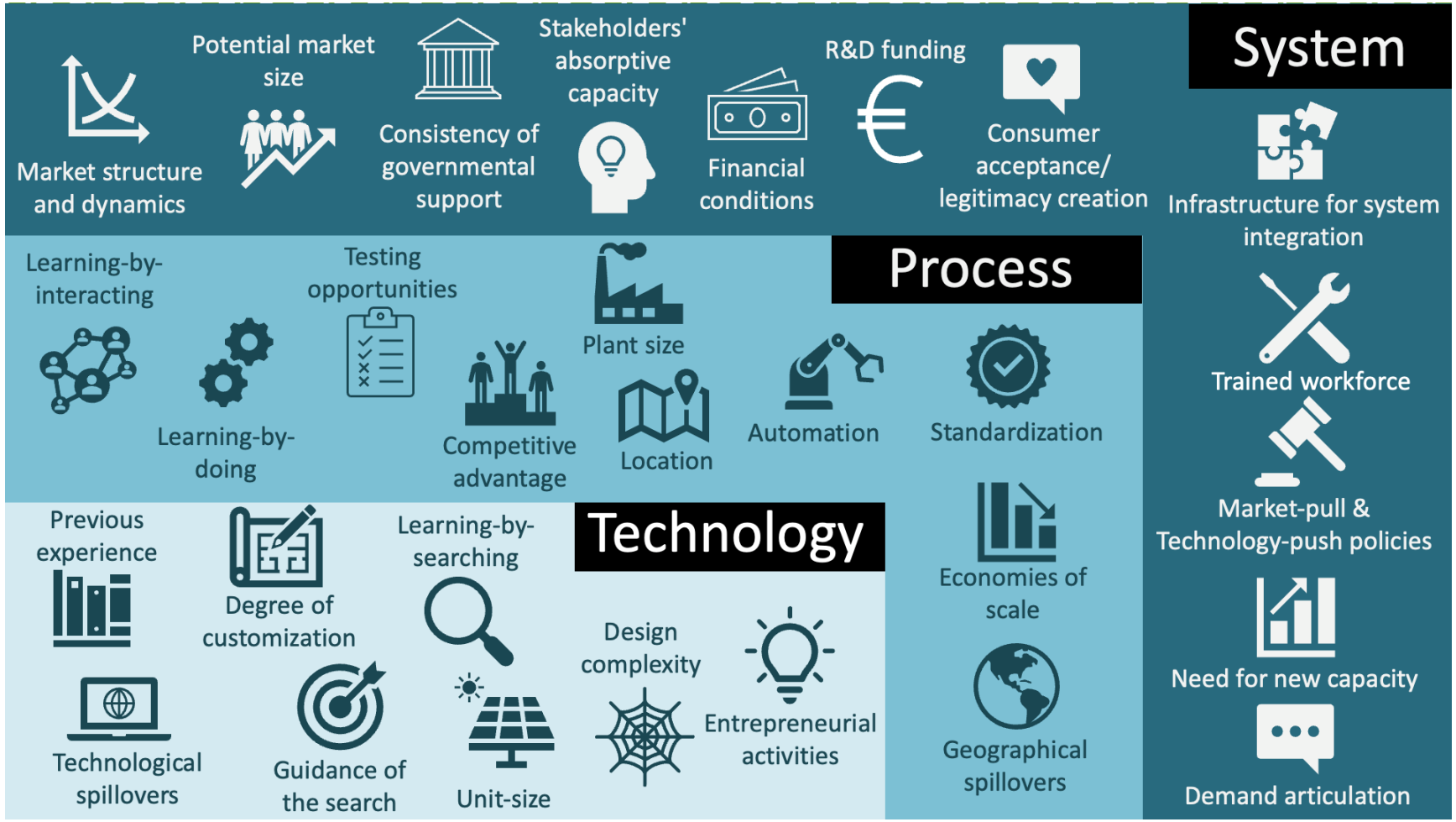
(Thomassen, 2020)

We identify factors that drive or hinder energy technological change.



Toribio-Ramirez, D.A., van der Zwaan, B. C. C., Detz, R. J., & Faaij, A. (2025). A review of methods to analyze technological change in industry. *Renewable and Sustainable Energy Reviews*, *212*, 115310. https://doi.org/10.1016/j.rser.2024.115310

We present a framework to study cost reductions of low-carbon industrial processes.



Toribio-Ramirez, D.A., van der Zwaan, B. C. C., Detz, R. J., & Faaij, A. (2025). A review of methods to analyze technological change in industry. *Renewable and Sustainable Energy Reviews*, *212*, 115310. https://doi.org/10.1016/j.rser.2024.115310

Our 3-level framework is applied to four different study cases



Cost reduction analysis for sustainable ethylene production technologies.



Exploiting niche markets to enable competitive renewable DME production.



From Design to Deployment: cost reduction pathways for bio-degradable polyester production.



Photo-electrochemical reactors in the future energy system.

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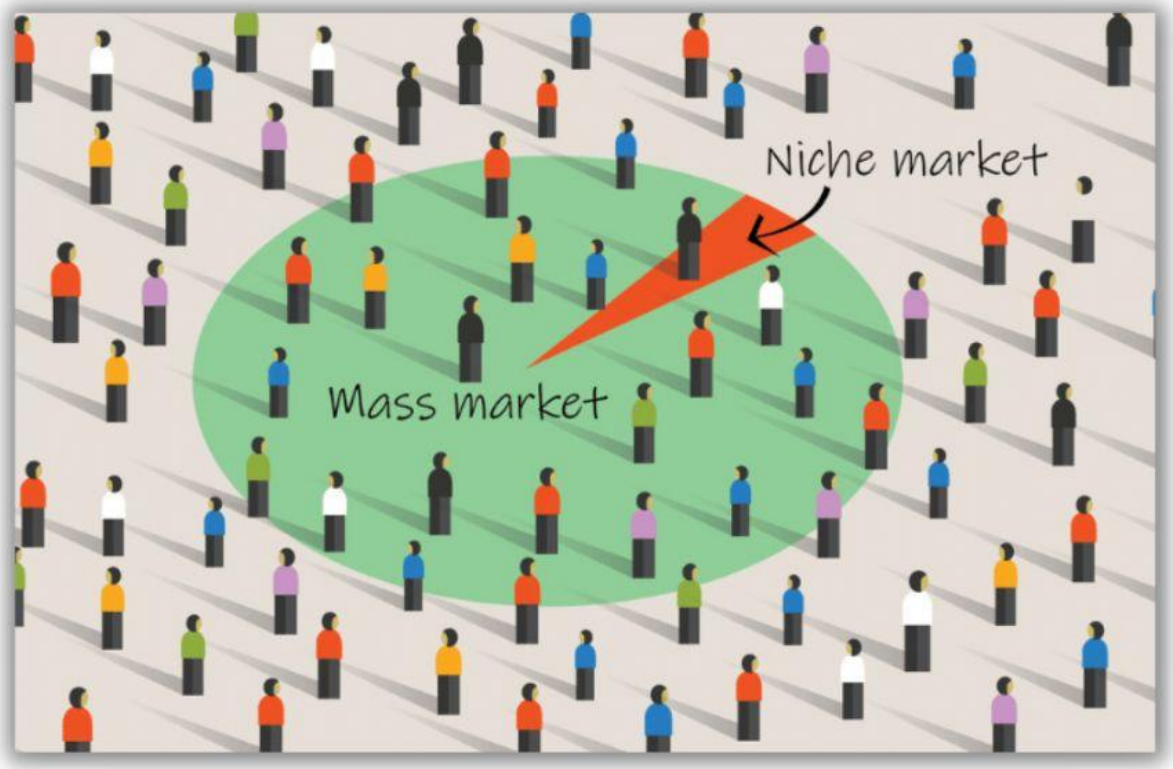
Exploiting niche markets to enable competitive renewable DME production

Toribio Ramirez, D.A., Detz, R.,Boon, J., Faaij,A., and van der Zwaan, B.



Creation of niche markets: a strategy supporting technology innovation.

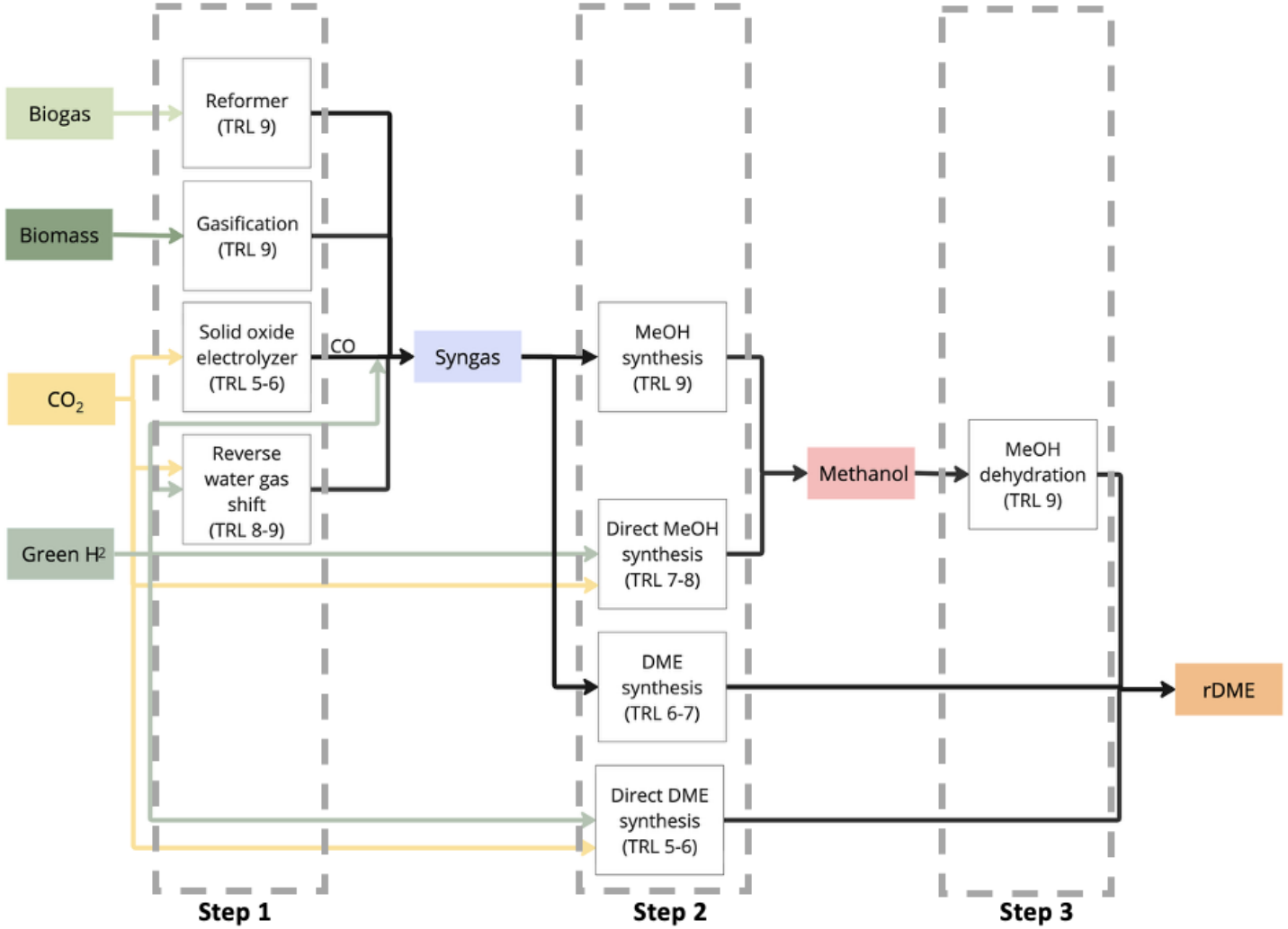
- **Protected spaces of the broader market** in which emerging technologies can be tested without immediate exposure to the competitive pressures of established systems.
- By enabling real-world learning and performance validation, niches **reduce technological and market uncertainties**.
- They also **help build the institutional, financial, and organizational capacities** needed to advance a technology toward commercial viability.



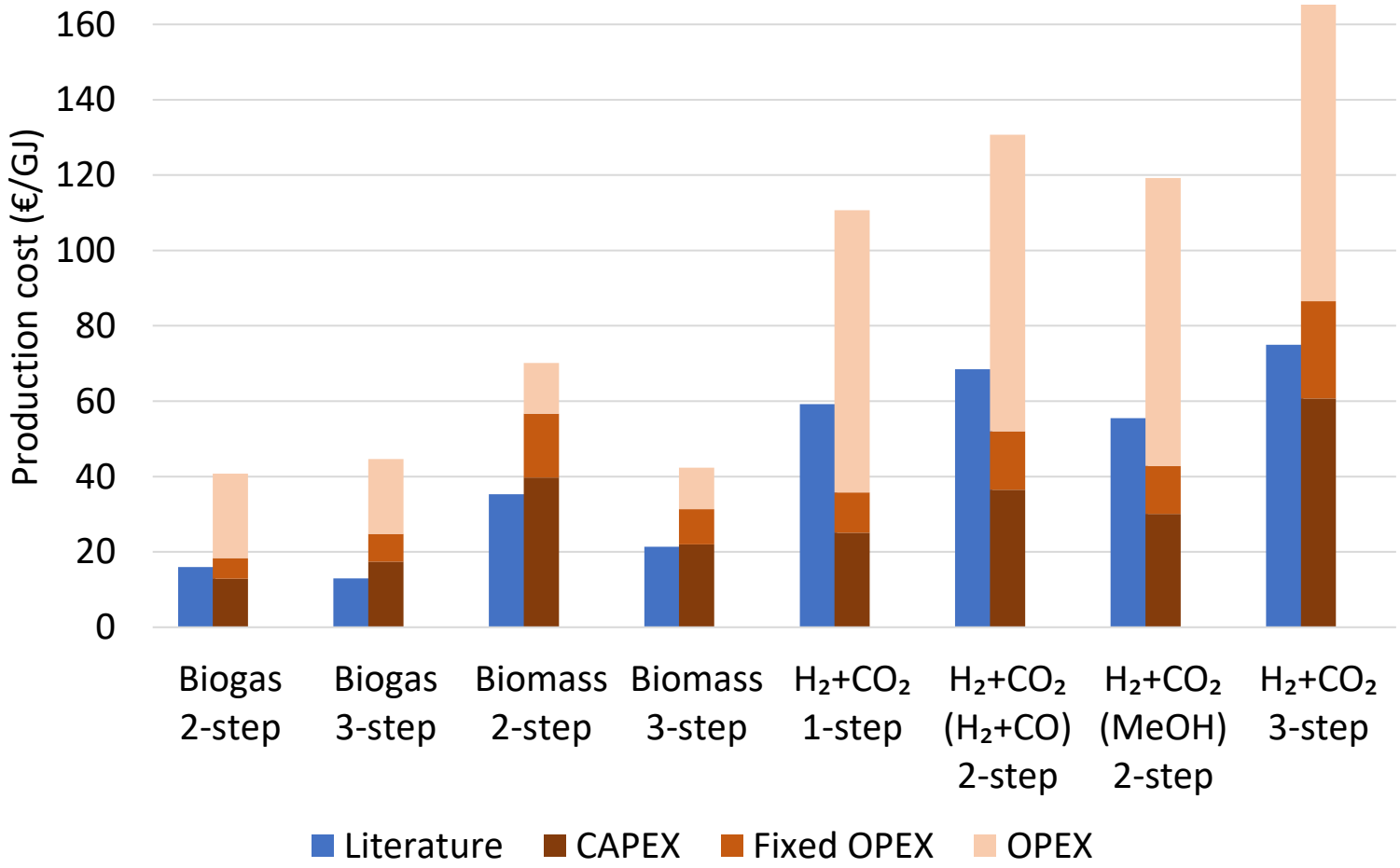
Research goal

The goal of this work is to determine the production cost in the early deployment stage, and project potential cost reduction of rDME by 2050 driven by demand in smaller segments of the broader market (niche market).

We studied eight different rDME production pathways.

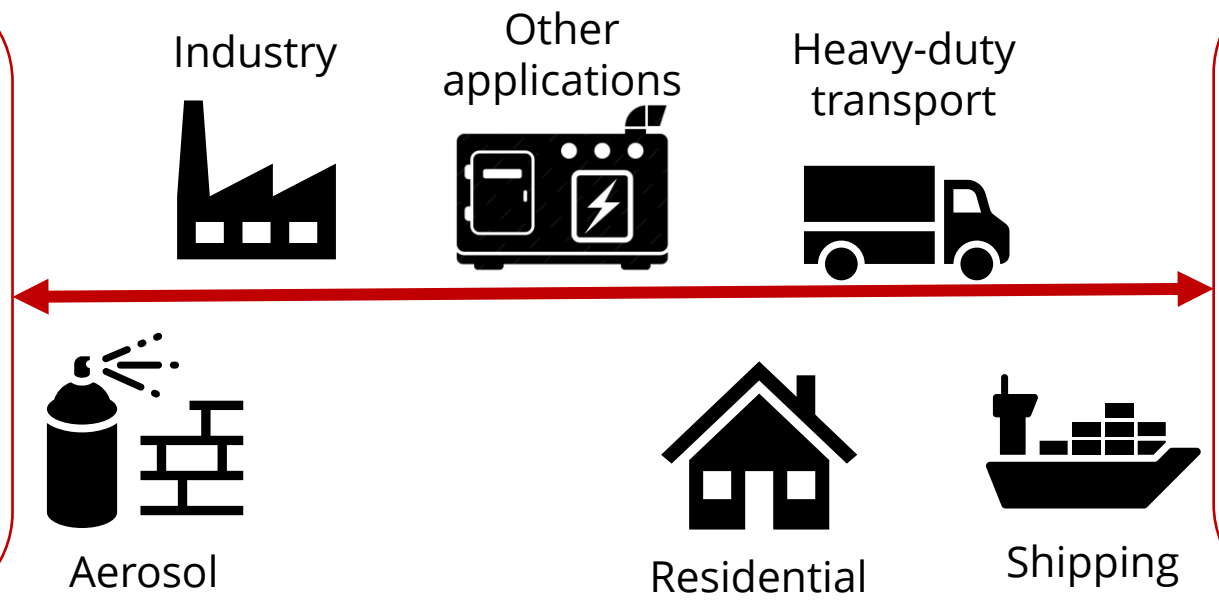


We calculated the production cost of each pathway, considering the cost of the FOAK plant.



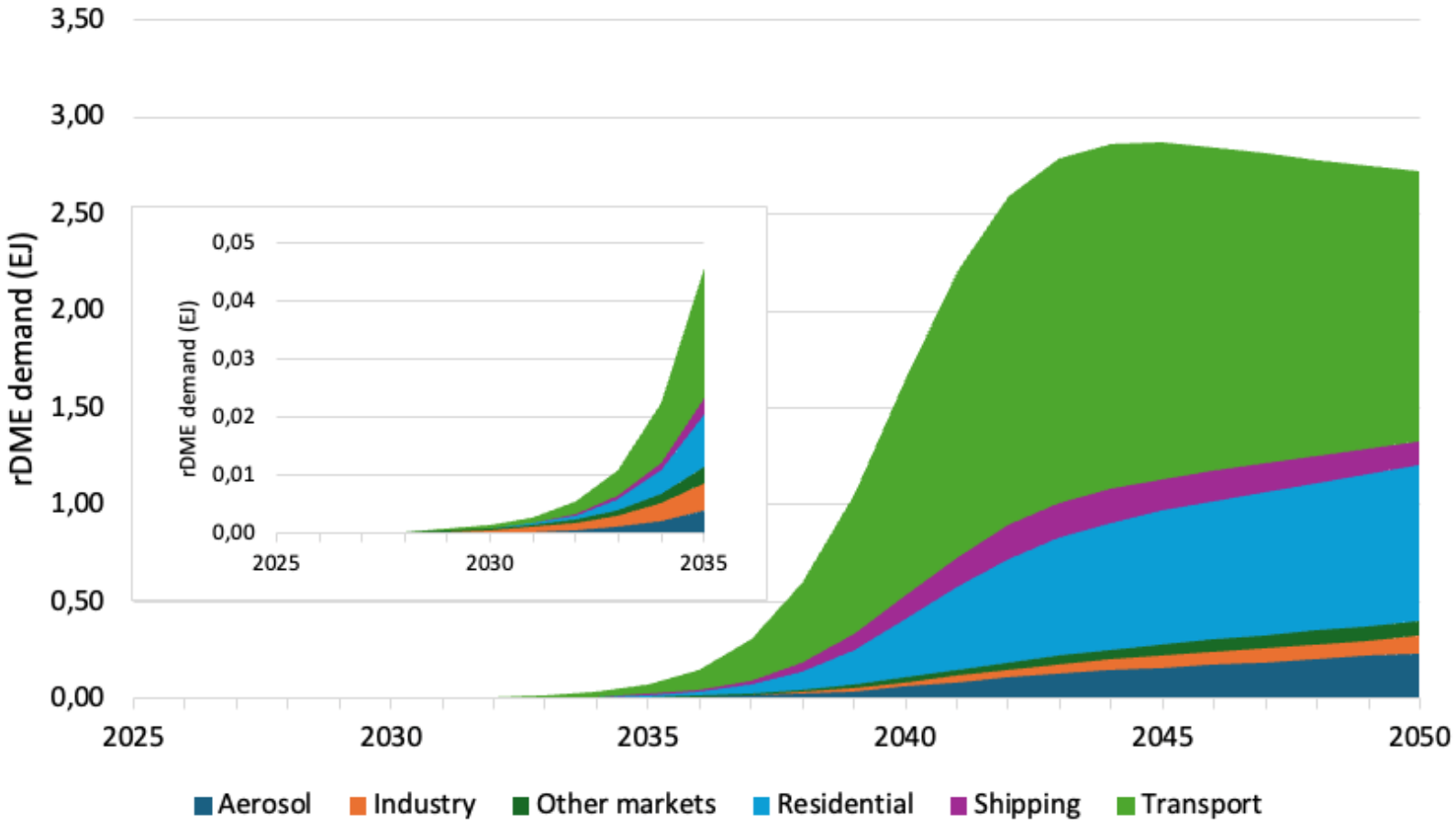
We categorized the different applications depending on their market maturity.

Established markets
An application in which DME is already in use, has established supply chains, infrastructure, and there is significant regulatory support for rDME.

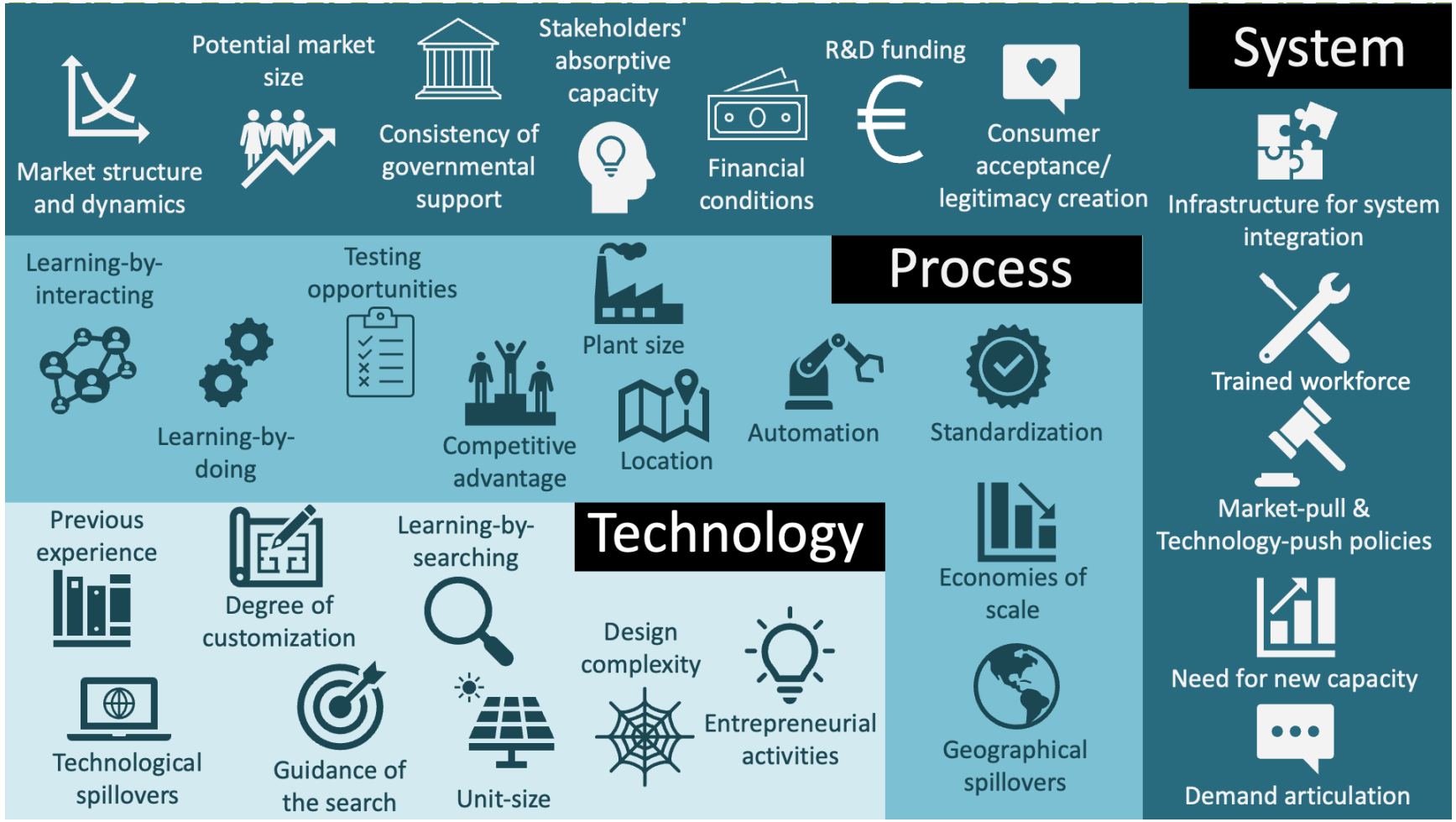


New markets
An application for which the renewable option is not yet widely used, and for which supply chains, infrastructure and regulation are missing.

Based on the market analysis, we formed stylistic assumptions and estimated rDME demand.



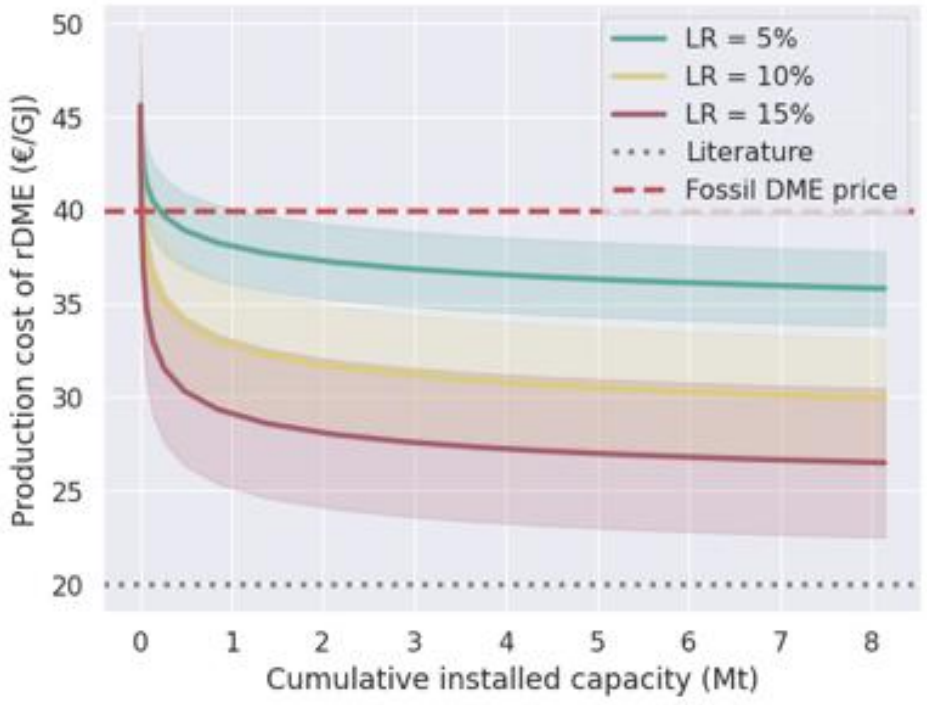
We model cost reductions at the process level.



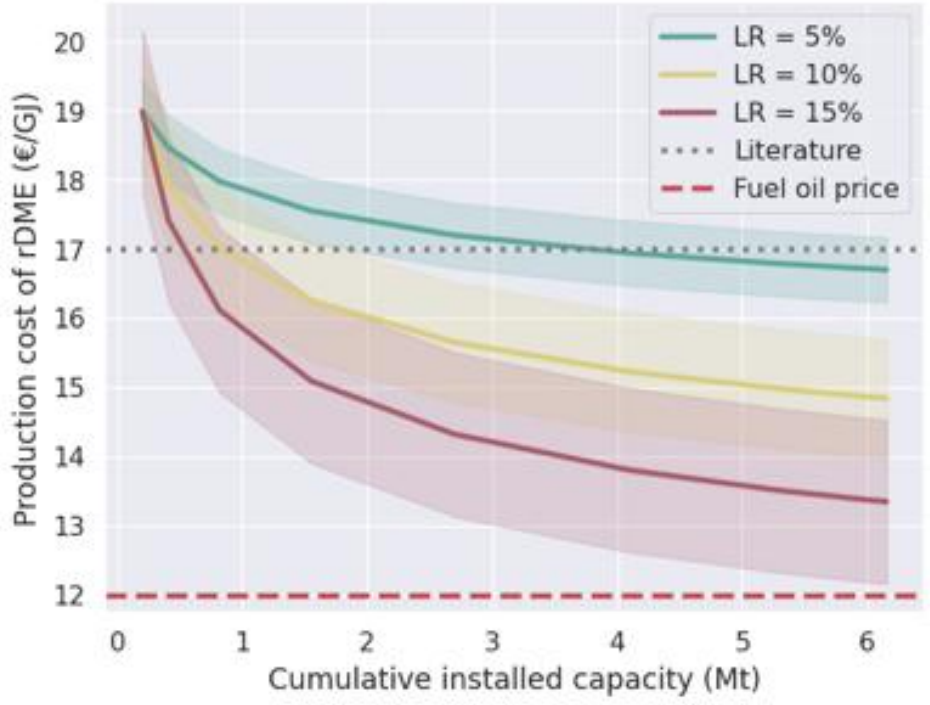
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Biogas and biomass rDME pathways can be cost-competitive in new and established markets by 2050.

Pathway: Biogas 3-step
Market: Aerosol (established)

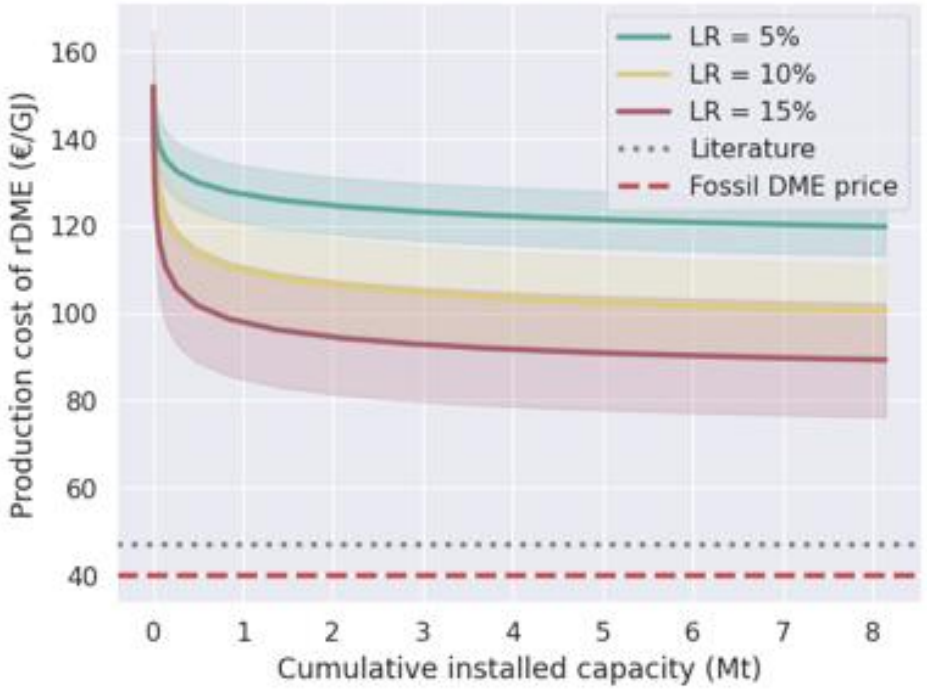


Pathway: Biomass 3-step
Market: Shipping (new)

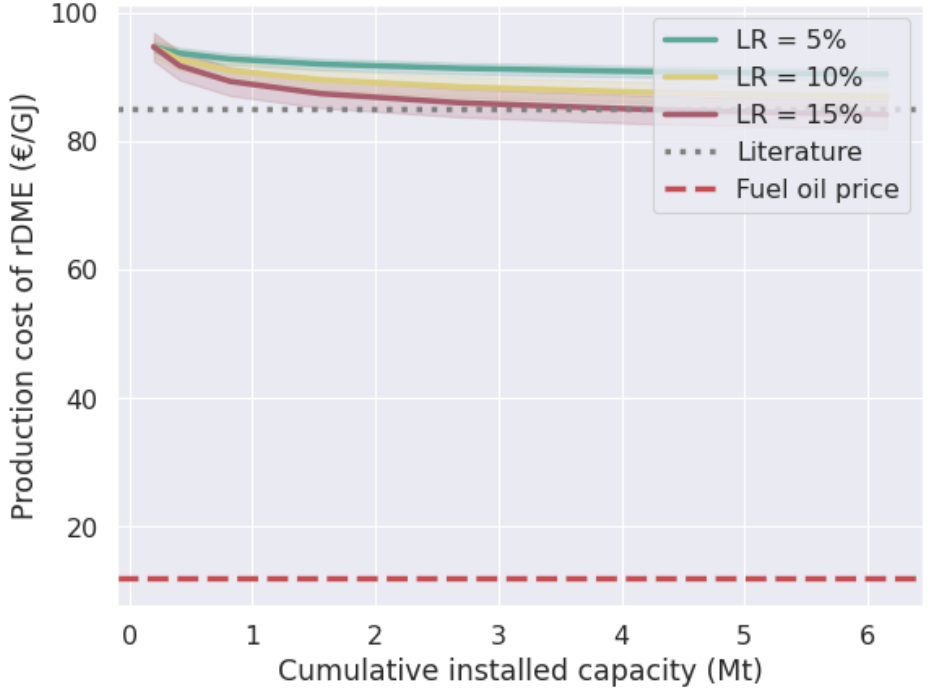


H_2 based rDME production pathways need a 30–85 €/GJ premium to be cost-competitive in 2050.

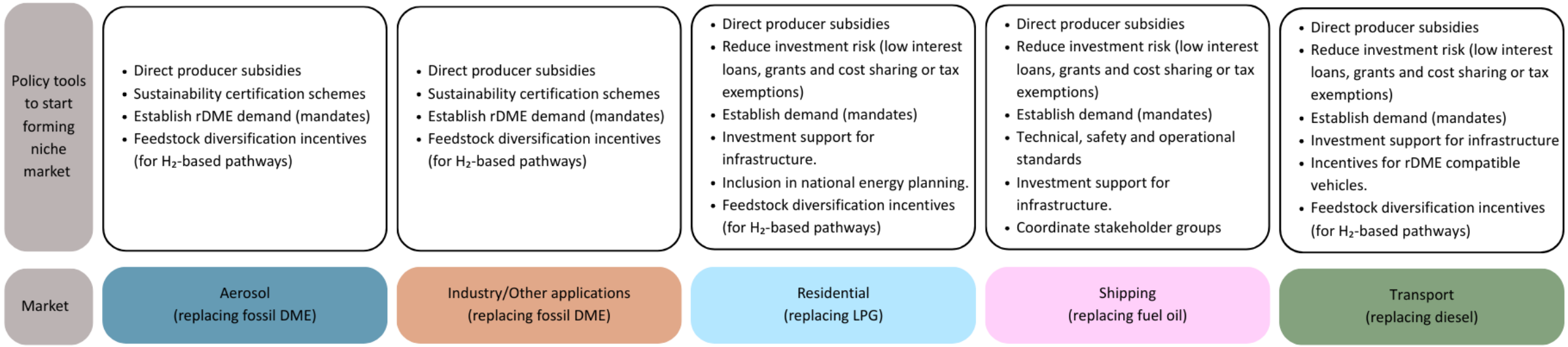
Pathway: H_2+CO_2 1-step
Market: Aerosol (established)



Pathway: H_2+CO_2 3-step
Market: Shipping (new)



Mandates complemented with other policies are required to develop niche markets for rDME.



Final remarks

- Our analysis highlights the **critical importance of niche markets** in providing protected spaces **for learning, reducing technological and market uncertainties**, and enabling FOAK plants to progress toward commercial-scale deployment.

- The optimal scale of FOAK plants must **balance economies of scale, investment risk, and learning opportunities**, with smaller plants enabling faster cumulative learning but at higher specific investment costs.

- **Systematic knowledge transfer** from FOAK projects, **collaborations with industrial partners**, and the **establishment of centralized project databases** will be crucial to accelerating the commercialization of rDME, contributing to the broader goal of achieving net-zero emissions by 2050.

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Questions

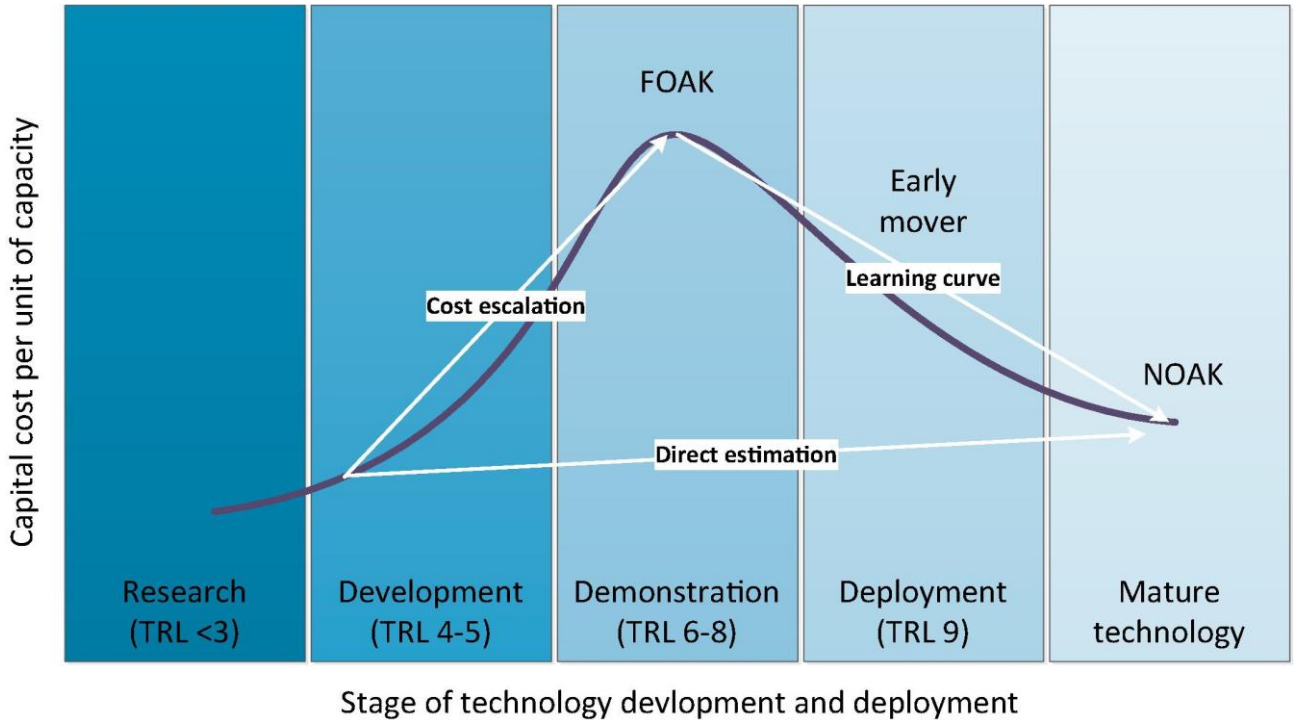


Cost misestimation for First of a Kind (FOAK) plants

- Based on cost data from 44 chemical plants, the RAND group found that **early project cost estimates are frequently underestimated** due to technology complexity and limited early data.

- Beiron and Johnsson (2024) report a cost **overrun of 100%-200%** when comparing real project data with reported plant cost estimates.

- Eblé and Weeda (2024) found that costs of existing electrolysis projects are **roughly double than cost estimates** reported in the literature.



van der Spek et al. 2017