Country Wide Infrastructure for Zero Emission Transportation

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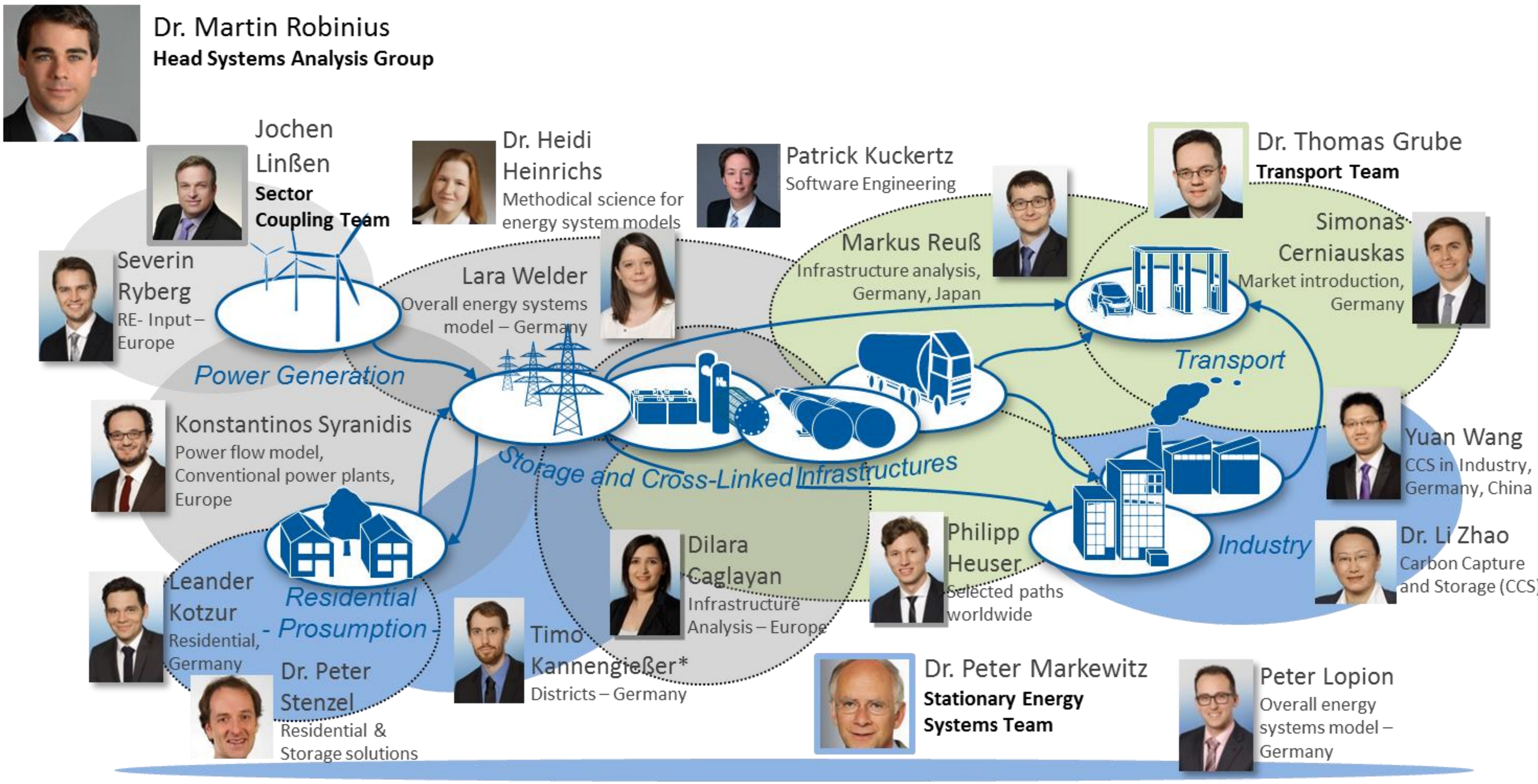
Research Topics within the Techno-Economic Systems Analysis Group



Methodology

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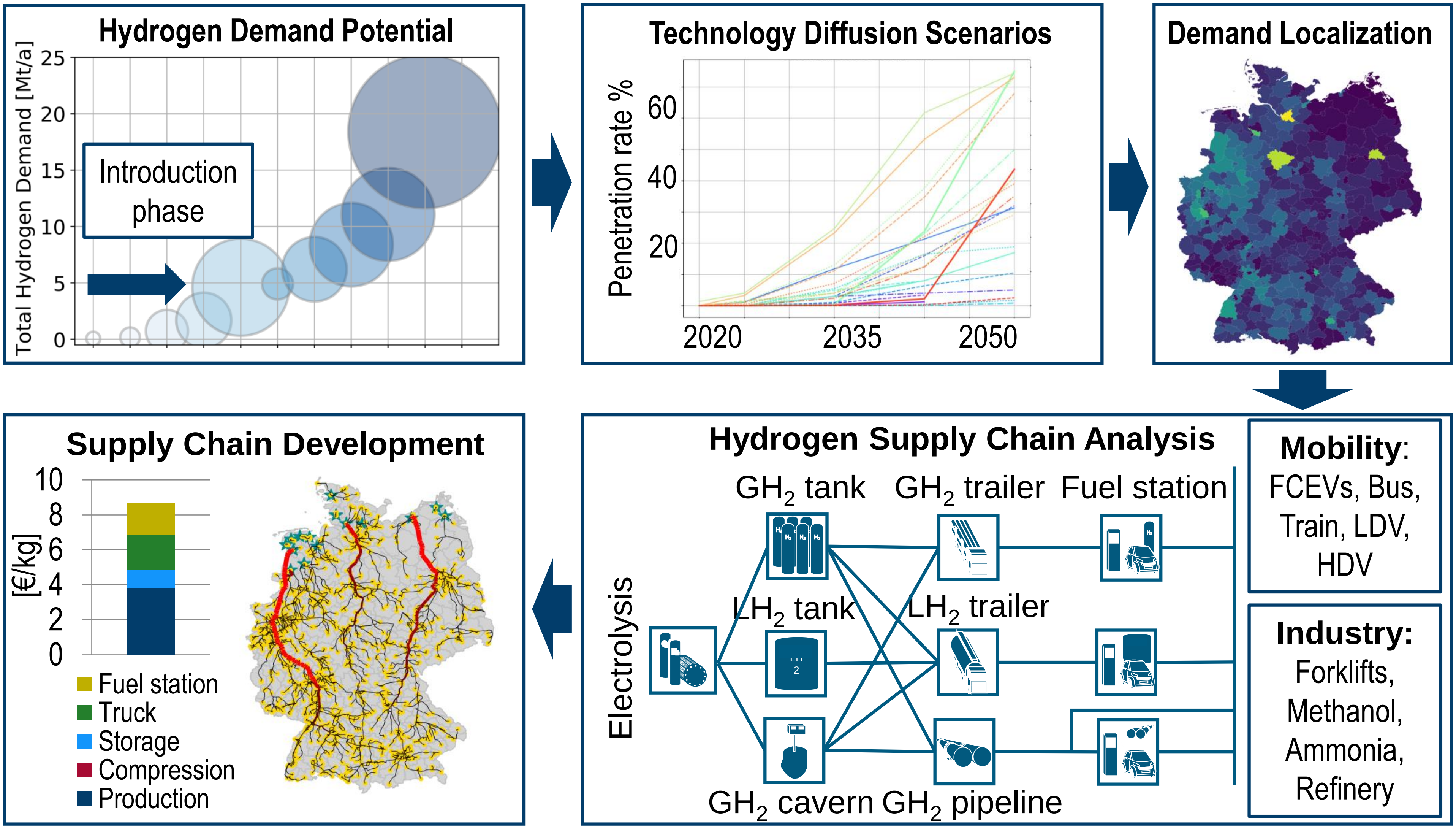
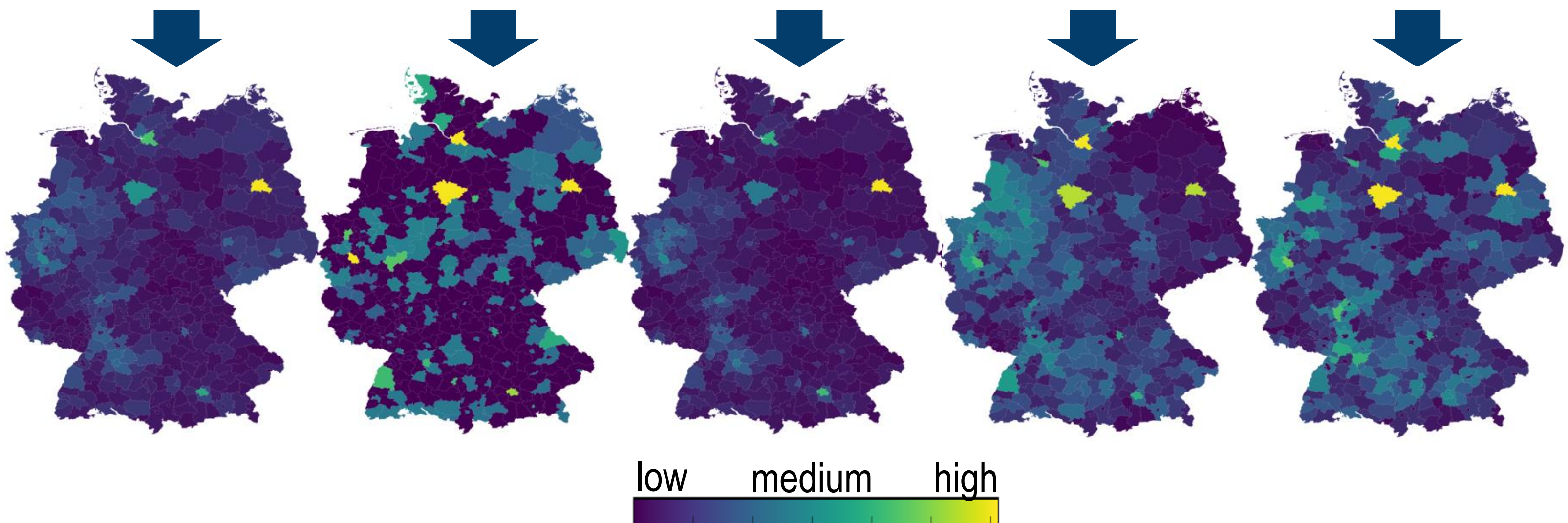


FCEV: Fuel cell electrical vehicle, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,

GH_2: Gaseous Hydrogen, LH_2: Liquid Hydrogen

Methodology: Criteria for Hydrogen Demand Distribution at the County Level

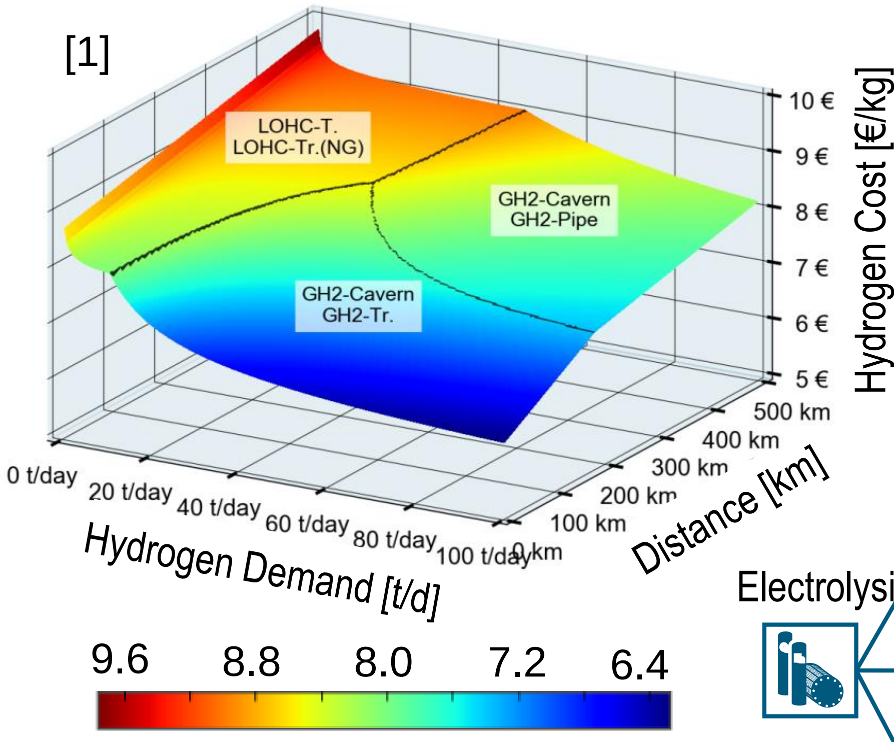
Local bus	Regional train	Passenger car	LDV/HDV	MHV
Population	Diesel train lines	Population	Loaded road freight mass	Logistic space
Federal support	Federal support	Population density	Unloaded road freight mass	Freight intensity
Income	Fuel stations	Income	Fleet size	
		Fleet size		



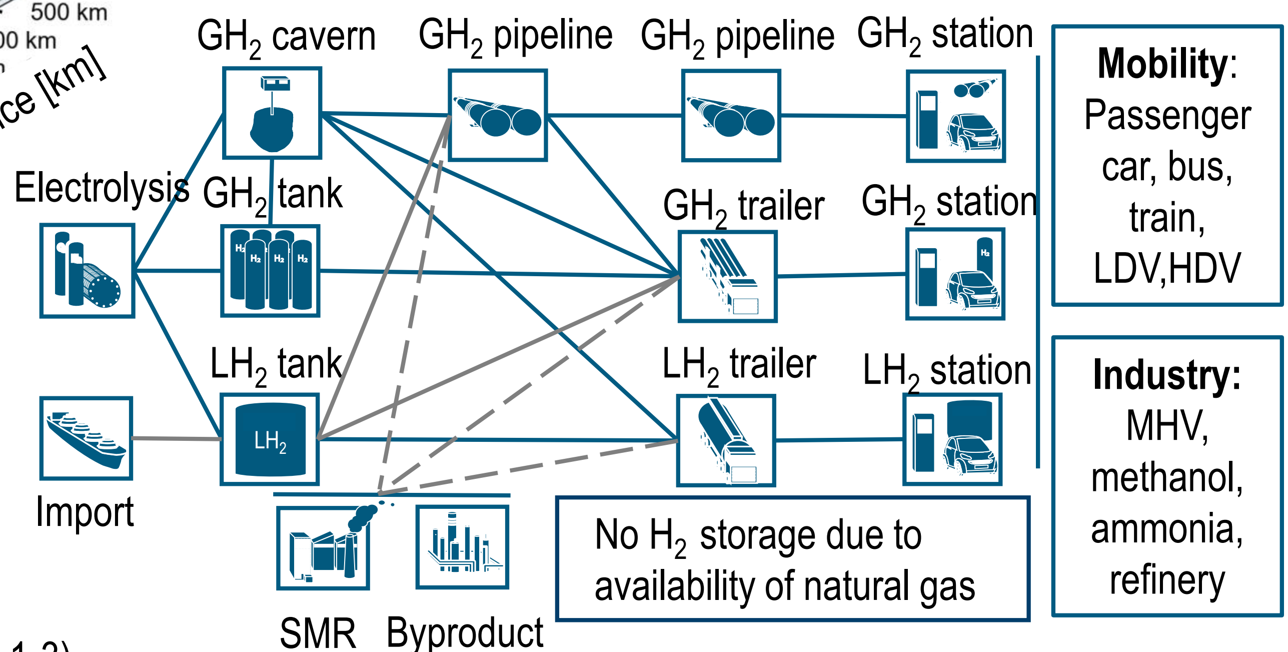
HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3)

Methodology: Hydrogen Supply Chain Analysis

[1]



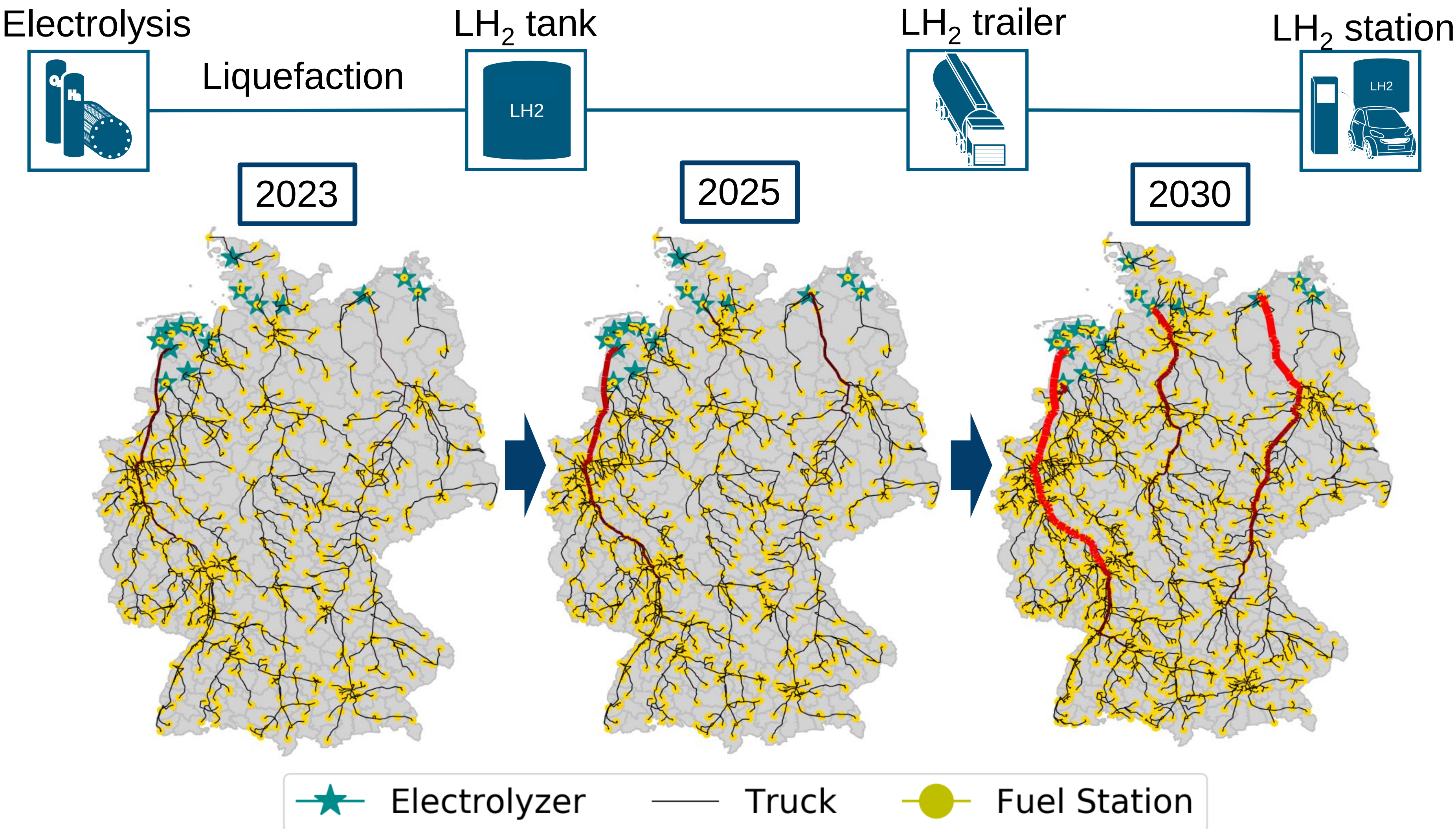
- General model to calculate supply chain costs based on source-sink **distance** and **demand**
- Geo-spatial analysis of relevant **infrastructure constraints**
- Investigation of supply pathways for different **supply** and **demand structures**



GH_2: Gaseous hydrogen
LH_2: Liquid hydrogen
LOHC: Liquid organic hydrogen carrier
HDV: Heavy duty vehicle
LDV: Light duty vehicle
MHV: Material handling vehicle (forklift class 1-3)

[1] Reuss, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied Energy, 200*, 290-302. doi:10.1016/j.apenergy.2017.05.050

Methodology: Supply Chain Development – Example LH_2



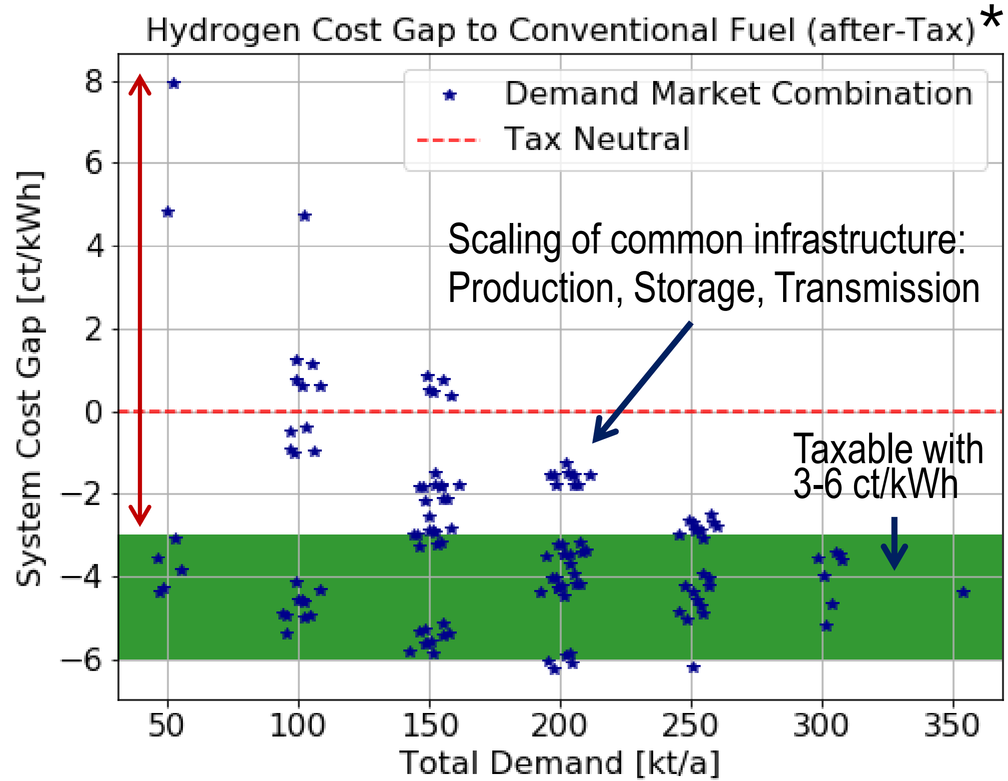
- Electrolysis locations after Robinius, M., et al., *Linking the Power and Transport Sectors-Part 2: Modelling a Sector Coupling Scenario for Germany.* Energies, 2017. **10**(7): p. 23.

What are the impacts on different market segments?

Market Choice: Idealized Mix of Demand Sectors

- Assumptions for **introduction phase**: LCOE = 6 ct/kWh, $CAPEX_{PEM}$= 1500 €/kW, $\eta_{LHV, 2018}$= 67%, Storage = 60 days

- **Approach**:
  - Introduction phase: up to 400 kt p.a.
  - Each technology can be considered either with a demand of **0 or 50 kt p.a.**
  - Evaluate all **2^8 combinations**
  - Calculate the gap to the conventional system for a given market combination



Choice of demand market has a significant impact on system cost

Fuel	pre-Tax	after-Tax*
Gasoline	8 ct/kWh	15,2 ct/kWh

[1]

Demand p.a.	Bus fleet	Train fleet	Public Car	Non-Public Car	Public LDV, HDV	Non-Public LDV, HDV	MHV
50 kt	21%	63%	3%	6%	10%	9%	20%

[1] *Taxing Energy Use*. 2018, Organisation for Economic Co-operation and Development (OECD).
* Including energy related taxes (mineral oil tax), excluding value-added tax

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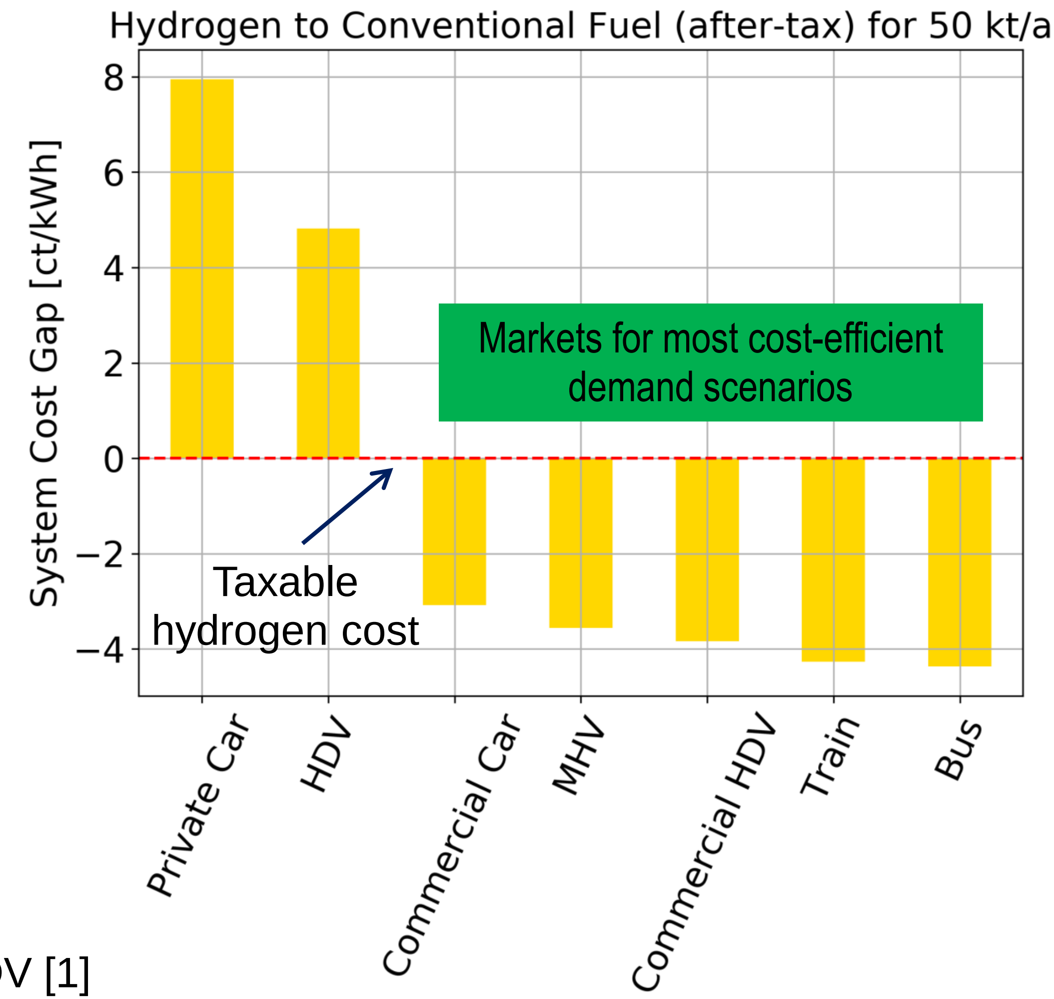
Market Choice: Single Markets in the Introduction Phase (50 kt p.a.)

- Assumptions for **introduction phase**: LCOE = 6 ct/kWh, $CAPEX_{PEM}$= 1500 €/kW, $\eta_{LHV, 2018}$= 67%, Storage = 60 days

- **Assumption**: commercial fleets with access to commercial HRS[1] do not fuel in public HRS
- **Public HRS** introduction strategy requires significantly higher upfront investment per vehicle
- Transportation sectors with **predictable demand and MHV** enable the cost gap to conventional fuels to be significantly reduced



[1]28% of passenger cars and 56% HDV/LDV [1]

*Including energy related taxes (mineral oil tax), excluding value-added tax

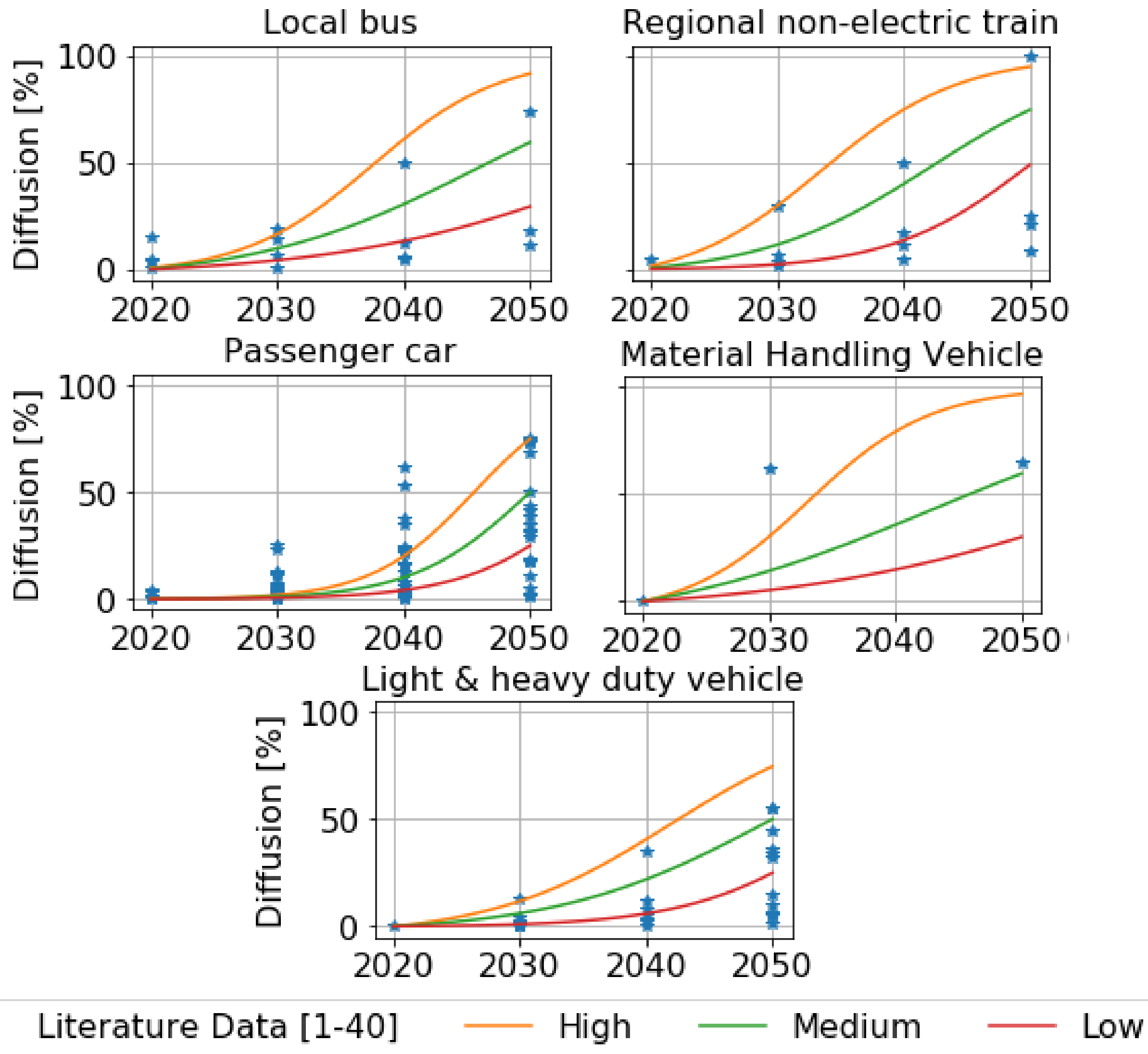
HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3)

HRS: Hydrogen Refueling Station HSC: Hydrogen Supply Chain, HSC: Hydrogen Supply Chain

What is the impact of market growth?

Market Penetration Scenarios

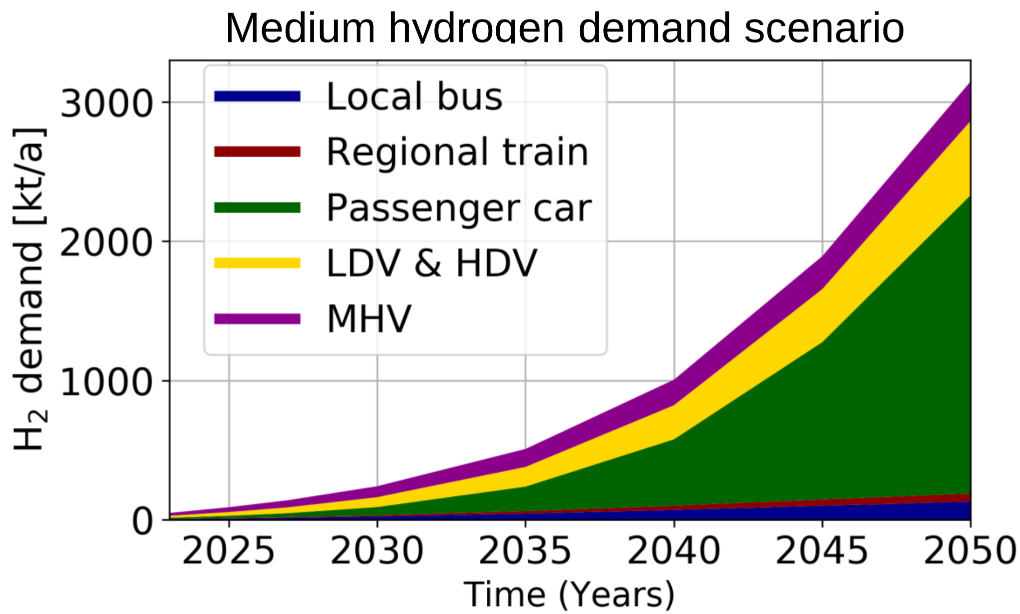
- **Scenario data** base for key technologies and application fields in the introductory phase
- Formulation of **exploratory** scenarios to analyze how hydrogen infrastructure costs might develop
- Formulation of **high**, **medium** and **low diffusion scenarios** for each hydrogen application depending on level of:
  - political support
  - economic incentives
  - technological progress
  - technology acceptance
  - willingness to pay for emission-free applications



Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,
MHV: Material Handling Vehicle (Forklift Class 1-3), Chemical industry: Ammonia, Methanol, Petrochemical industry

Scenario and Input Parameters

Assumption	Value	Unit
WACC	8	%
LCOE	6	ct/kWh
Natural gas cost	4	ct/kWh
Imported H_2 cost	11.7 [1]	ct/kWh
Storage time	60 [2,3]	days
Max. electrolytic H_2 production	3160 [2]	kt/a
Electrolysis efficiency (2050)	70	%
Electrolysis investment (2023)	1500 [4]	€/kW
Electrolysis learning rate	20 [5]	%
Max. SMR H_2 production	96* [6]	kt/a
SMR efficiency	80 [7]	%
Fuel station learning rate	6 [8]	%



- Dominating technology:
  - 2023 - 2030: **LDVs & HDVs, MHVs, public transport**
  - After 2030: **Passenger cars, chemical industry**

* 5 % of todays industrial hydrogen output

Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,
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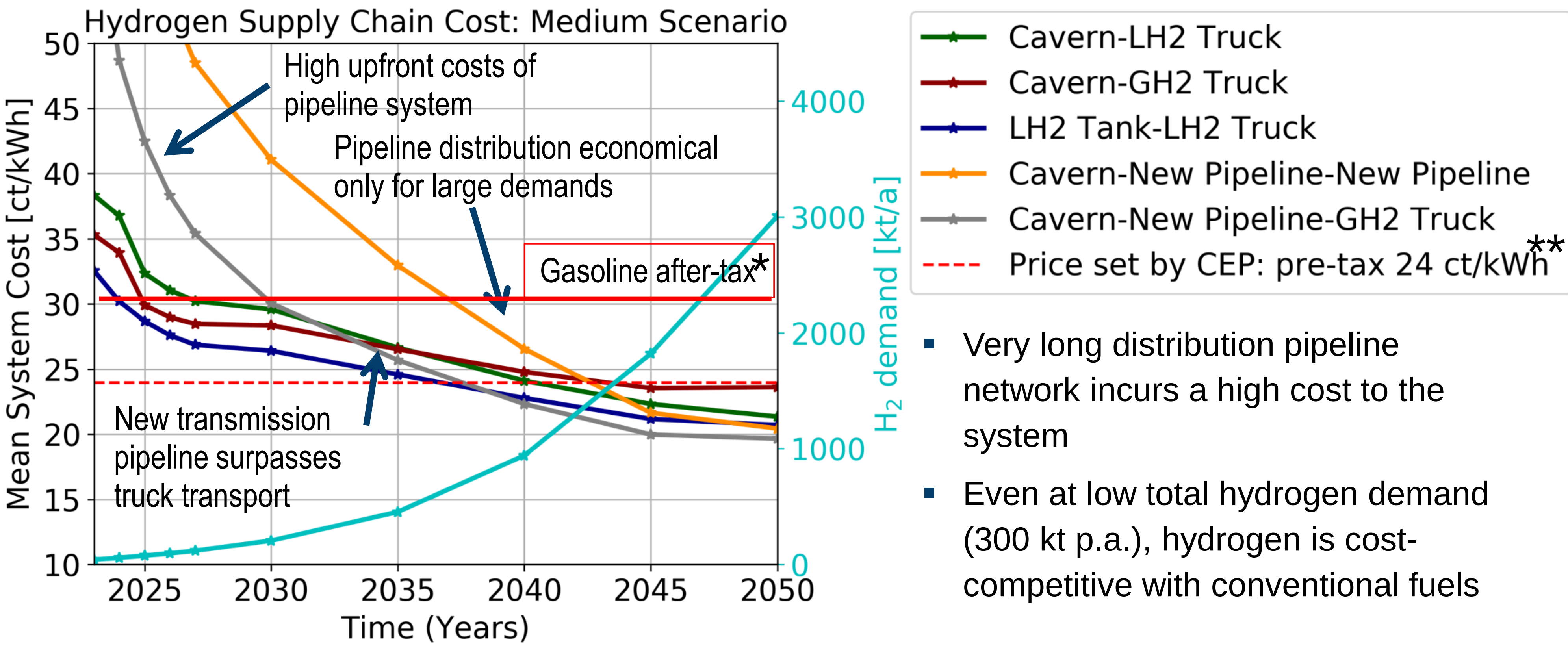
Infrastructure Cost Development: Medium Scenario



- Very long distribution pipeline network incurs a high cost to the system
- Even at low total hydrogen demand (300 kt p.a.), hydrogen is cost-competitive with conventional fuels

- **Hydrogen is cost-competitive with conventional fuels (after-tax) by 2024-2029**

$$^{*}\ \text{Benchmark} = \left(\text{gasoline cost}\left(8\frac{ct}{kwh}\right) + \text{mineral oil tax}\left(7{,}2\frac{ct}{kwh}\right)\right) * \eta_{\text{Fuel Cell}}/\eta_{ICE}$$

**Excluding value-added tax

Summary and Conclusion

Summary and Conclusion

- **High demand potential during the introduction** phase for hydrogen applications with requirements for **high utilization, fast fueling, long range and high power capacity**:
  - Regional non-electrified **trains**
  - Local **busses**
  - **Forklifts** of the class 1 to 3
  - Heavy and light **duty vehicles**
- Focus on **non-public fueling infrastructure** significantly reduces the upfront costs of fuel stations and distribution
- **Choice of demand market segment** has a significant impact on the system cost
- Hydrogen is **cost-competitive with conventional fuels (after-tax) by 2024-2029**

→ **Cost-competitive countrywide hydrogen infrastructures can be developed within 5-10 years of investment**

Thank you for your attention!

Backup

Methodology: Criteria for Hydrogen Demand Distribution at the HRS Level

	Bus HRS	Train HRS	Public HRS: 700 bar	Non-Public HRS: 700 bar	Public HRS: 350 bar	Non-Public HRS: 350 bar	MHV HRS
Max.	402	170	9800	7148	8000	2345	10000
Method	Linearly based on demand	Linearly among existing stations	Minimize investment	Based on commercial area	Minimize investment	Based on the commercial area	Based on the logistic area
Sizes	Predictable demand	Predictable demand	S, M, L, XL, XXL*	Predictable demand	S, M, L, XL, XXL*	Predictable demand	Predictable demand
Early phase	Mean fleet for regional adoption: 25	Mean fleet for regional adoption: 5	Only S until 10 % of FS**	Mean fleet for regional adoption: 50	Only S until 10 % of FS**	Mean fleet for regional adoption: 20	Mean fleet for regional adoption: 70

* S-size: 212 kg/d, M-size: 420 kg/d, L: 1000 kg/d, XL: 1500 kg/d, XXL: 3000 kg/d

** Widely adopted view in the literature regarding the percentage of existing fuel stations for AFVs to reach sufficient infrastructure coverage: 5 - 20% [1-4]

HRS: Hydrogen Refueling Station, MHV: Material Handling Vehicle (Forklift Class 1-3), FS: Fuel Station, AFV: Alternative Fuel Vehicle