Electricity and Gas Market Design to Supply the German Transport Sector with Hydrogen

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Strommarkttreffen zum Thema „Marktdesign“, 13. Mai in Berlin

Institute of Electrochemical Process Engineering (IEK-3)

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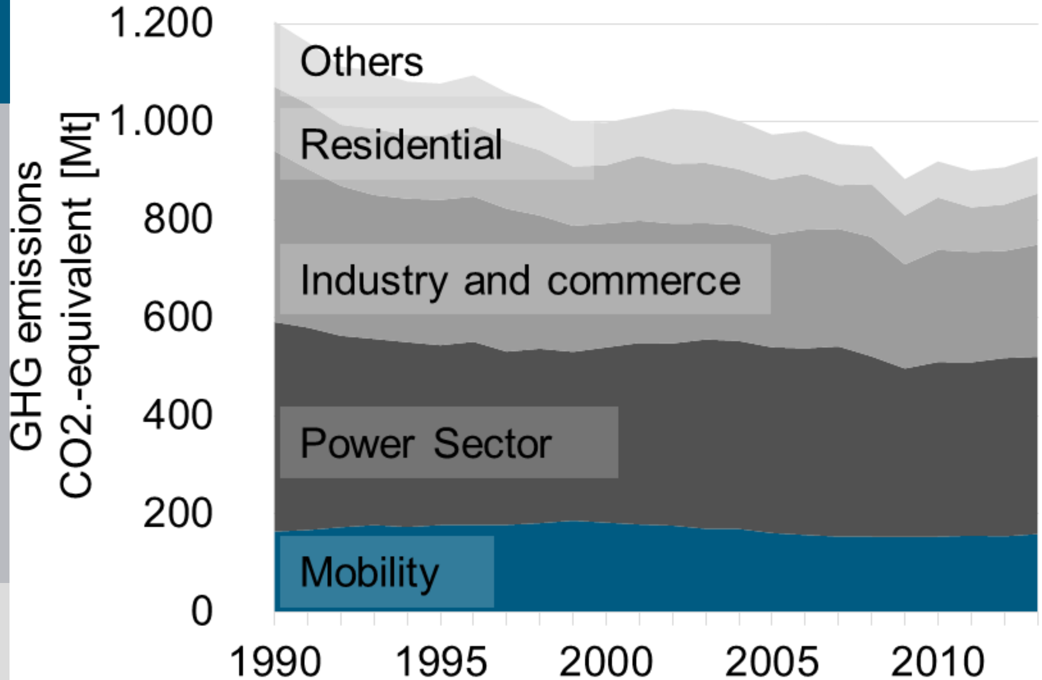
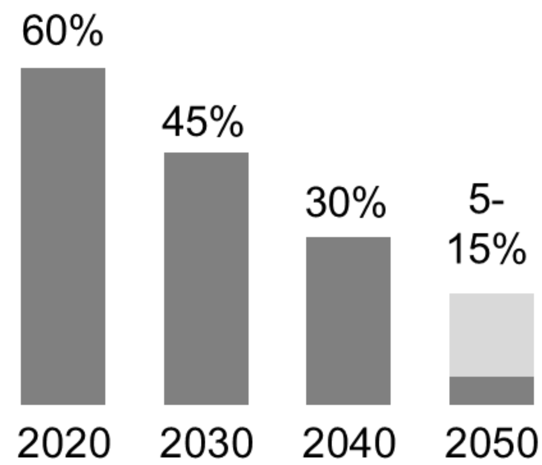
The Overall GHG Emission Goals of the German Government Require a Holistic Transformation of all Sectors

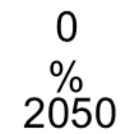
GHG Emissions in Germany since 1990 [1]



Goals of the BRD in reference to 1990 [2]

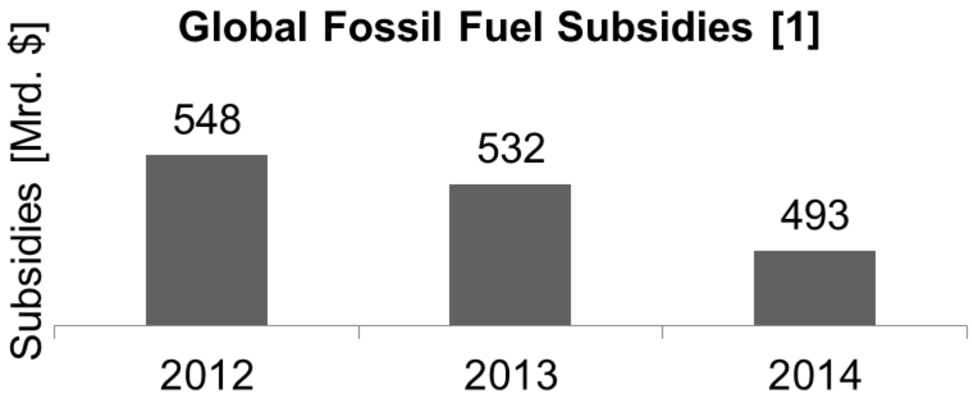


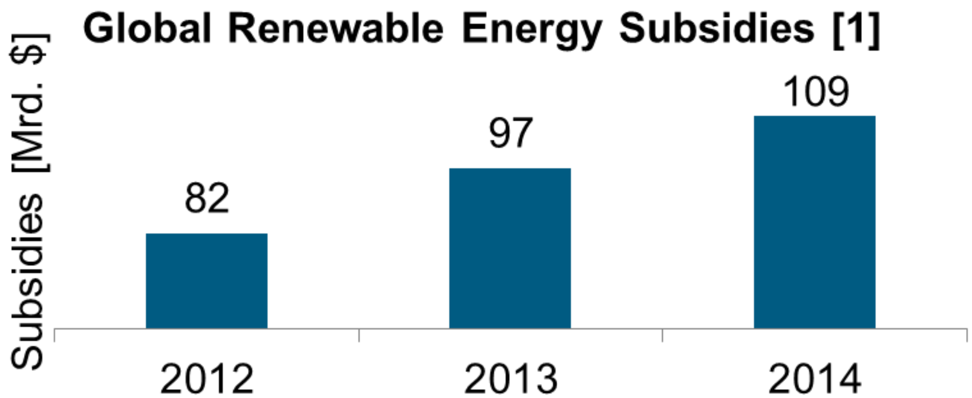
COP21 Paris [3]

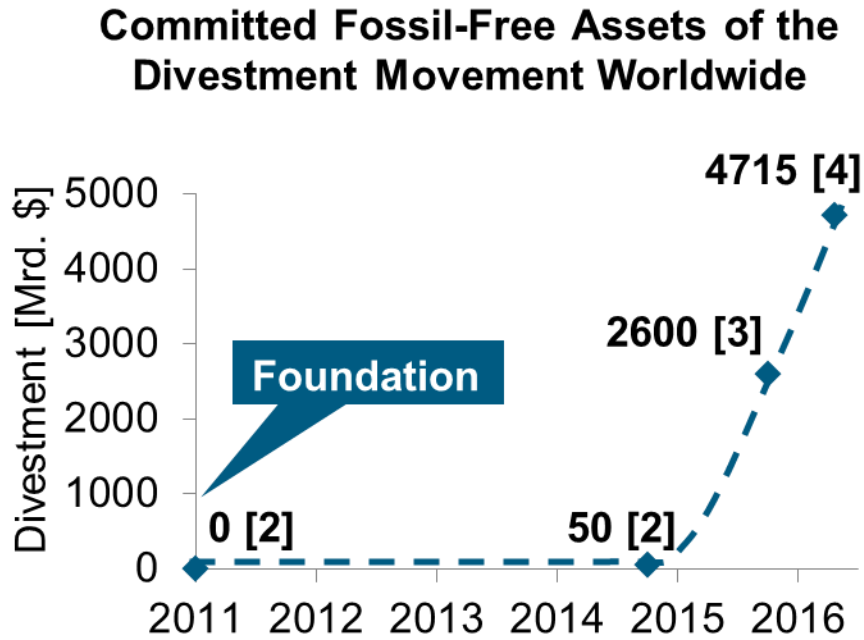


[1] BMWi, *Zahlen und Fakten Energiedaten - Nationale und Internationale Entwicklung*. 2016, Bundesministerium für Wirtschaft und Energie: Berlin. [2] BRD, *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*, Bundeskabinett. 2010: Berlin. [3] UN, *Paris Agreement - COP21*, United Nations Framework Convention on Climate Change 2015: Paris.

Transition of Financial Interests from Fossil Energies towards Renewable Energies







'Energy Giant Peabody Enters Bankruptcy'

- Wall Street Journal (13/04/2016)

[1] International Energy Agency, *World Energy Investment Outlook*, 2014,
URL: https://www.iea.org/publications/freepublications/publication/WEIO2014.pdf
[2] Arabella Advisors, *Measuring the Global Divestment Movement*, 2014,
URL: http://www.arabellaadvisors.com/wp-content/uploads/2014/09/Measuring-the-Global-Divestment-Movement.pdf
[3] Arabella Advisors, *Measuring the Growth of the Divestment Movement*, 2015,
URL: http://www.arabellaadvisors.com/wp-content/uploads/2015/09/Measuring-the-Growth-of-the-Divestment-Movement.pdf
[4] DivestInvest, URL: http://divestinvest.org/individual/ (access date: 19/04/2016, 4:30 pm)

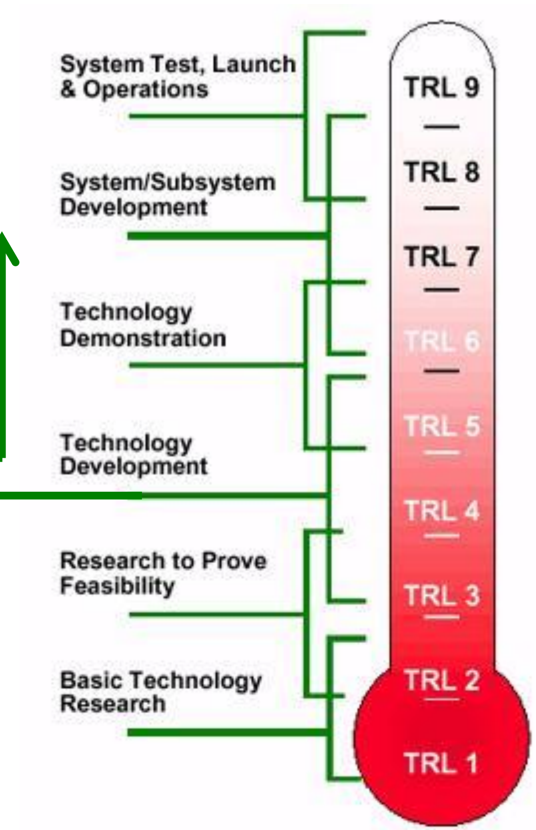
Timeline for Energy Research and Deployment to Meet the 2050 Goals

- **2050:** 80% reduction goal fully achieved
- **2040:** start of market penetration
- **2030:** research finalized for 1st generation technology

Development period: until 2040

Research period: until 2030

⇒ 16 years left for research => TRL 4 and higher (> validated in the lab)



This is not to say research at lower TRL levels is not useful, it will just not contribute to the 2050 goal

TRL: Technology Readiness Level; cf. h2020-wp1415-annex-g-trl_en.pdf; issued by EU

FCV Market Introduction has Started

JÜLICH FORSCHUNGSZENTRUM

1994 MB NECAR 1 (H_2)

1999 Honda FCX V1 (H_2)

2002 Honda FCX-V4: 1st FCV commercially certified *

2004 Clean Energy Partnership (D)

Hyundai ix35 FCEV
1st manufact. plant

Toyota Mirai
2nd series prod.

Fuel cell APUs for passenger cars, trucks, train, ships & airplanes

60s | 70s | 80s | 1990s | 2000s | 2010s

1966 GM Electrovan (H_2, AFC)

First FCV

2001 MB NECAR 5.2, methanol reformer

GM Chevrolet S-10 gasoline reformer

2001 Cold start at -20°C (GM)

2006 HT-PEM (Volkswagen)

2008-2009 **Small series for demonstration projects**

MB B-Class F-Cell

GM HydroGen4

Honda FCX Clarity

Aromatic membrane -30…95 °C

* First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use

MB: Mercedes-Benz; GM: General Motors

All cars with PEFC except GM Electrovan with AFC

Select Improvements Hydrogen can Deliver on

Worldwide:
Reduction of CO_{2eq} emissions: mitigation of sea level rise, future storm intensity, floods, droughts etc.
Impact on all countries; high vulnerability of lower income countries

Middle income countries*, particularly upper middle income countries:
PM10, PM2.5, NO_x, SO_2, etc., particularly in sprawling urban centers; change of attitude with upper and middle class city dwellers & expatriates (e.g. China), change of policies (e.g. China)

Yet there are still massive emissions issues in
High income countries:
NO_x (and hence O_3), PM10, PM2.5 in urban centers

Low income countries:
Hardly accessible with new expensive technology, particularly if massive infrastructure is needed
Example: more people own cell phones worldwide than have access to toilets**

The world is very diverse and bears stunning discrepancies
This study focuses on Germany as a starting point
& is going to be extended to further countries

* World Bank classification; comparison of classifications cf. IMF working paper WP/11/31; Lynge Nielssen 2011
** http://www.un.org/apps/news/story.asp?NewsID=44452&Cr=sanitation&Cr1=#.UU_G_BySV3-

The Year 2050

The Year 2050 – Energy Concept 2.0

Assessment based on municipal level and an hourly resolution of grid load and RES feed-in

Power-Sector

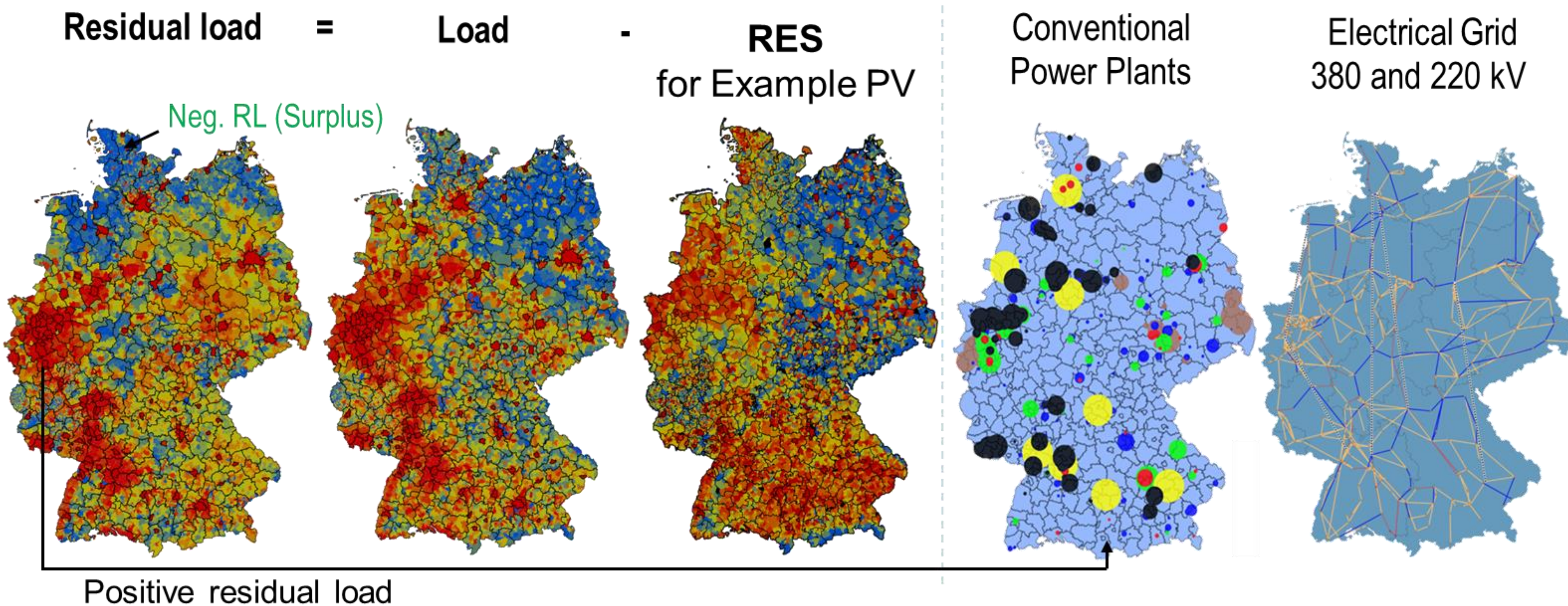
RES power [GW | TWh]: onshore: 170 | **350**; offshore: 59 | **231**; PV: 55 | **47**; hydro: 6 | **21**; bio: 7 | **44**

Further assumptions: grid electricity: **528 TWh**; imports: 28 TWh; exports: 45 TWh; pos. residual: natural gas

„Copper plate" & 40 GWh pumped hydro: **191 TWh (→ 4.0 million t_{H2})**

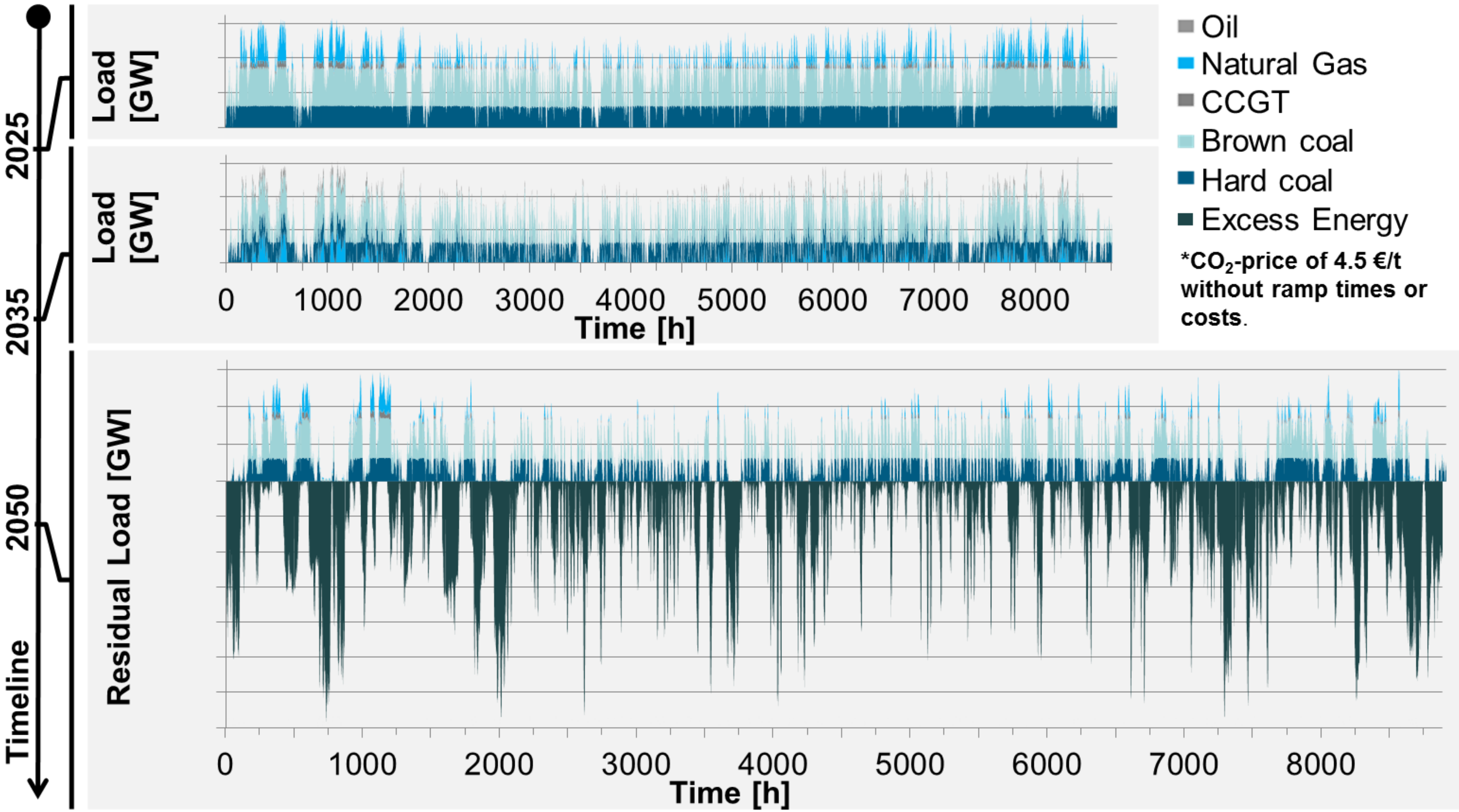
Grid capacity constraints considered: **293 TWh (→ 6.2 million t_{H2})**

RES: Renewable Energy Sources



All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen University, ISBN: 978-3-95806-110-1

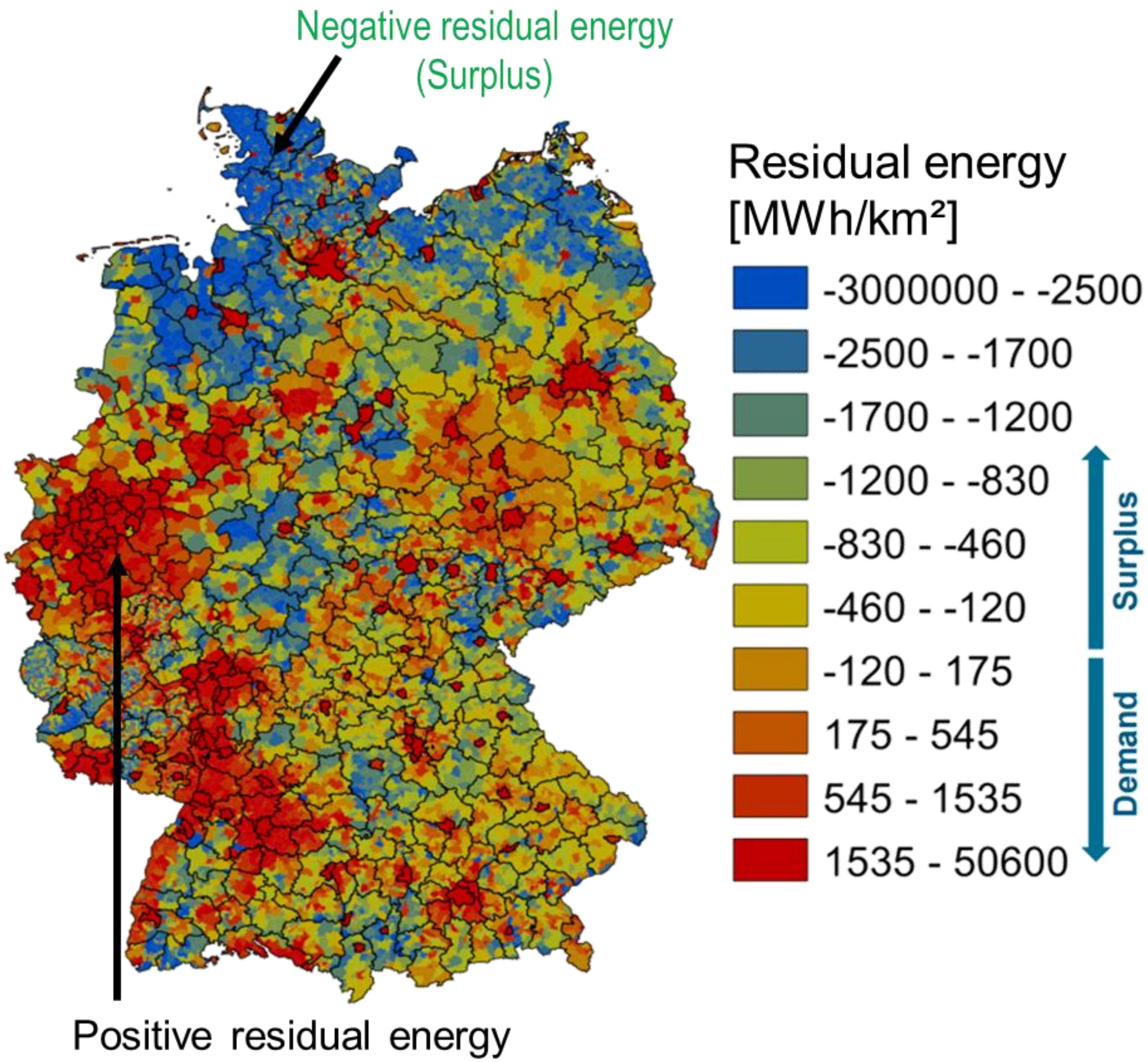
Effect of a Renewable Energy Scenario on the Operation of Conventional Power Plants*

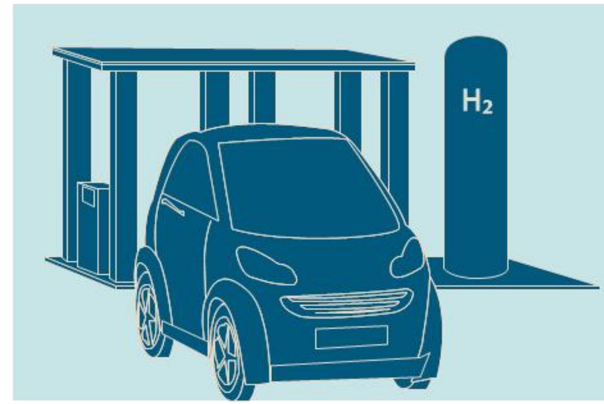


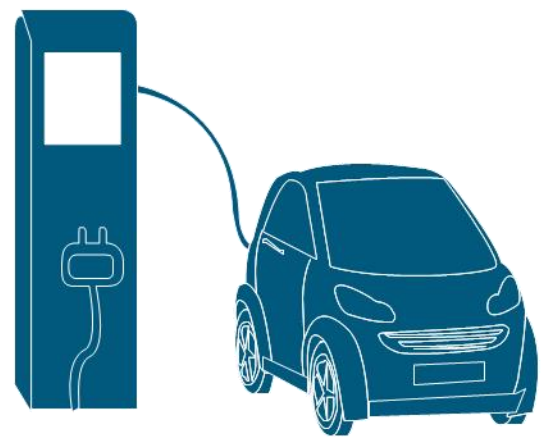
*CO_2-price of 4.5 €/t without ramp times or costs.

Installed capacity regarding to [1] Übertragungsnetzbetreiber (2015): Netzentwicklungsplan Strom 2025
[2] Bartels, S (2016): Simulationsmodell regional aufgelöster Residuallasten in Deutschland, Masterthesis
[3] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.

Linking the Power and Transport Sector



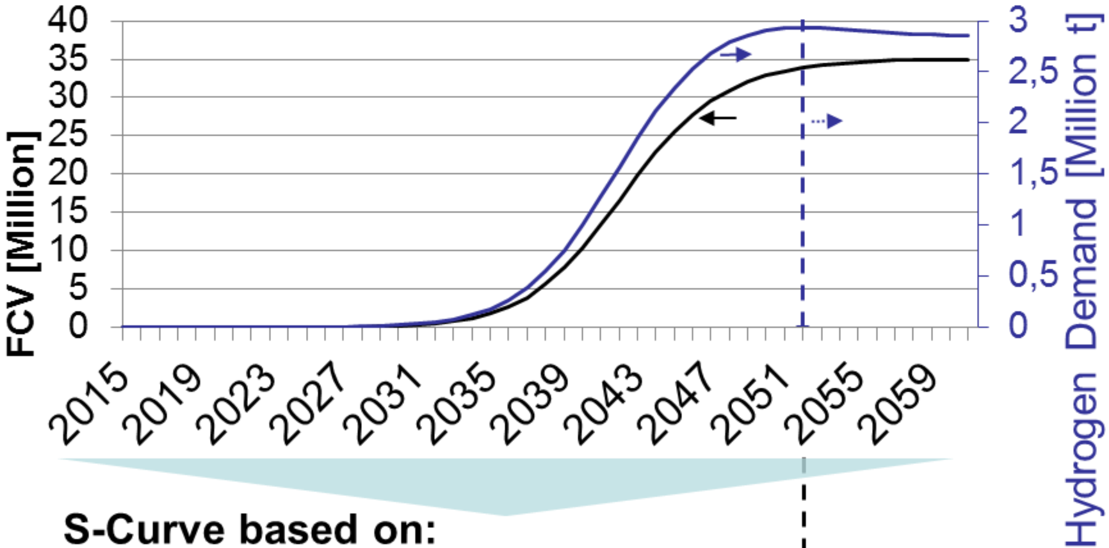


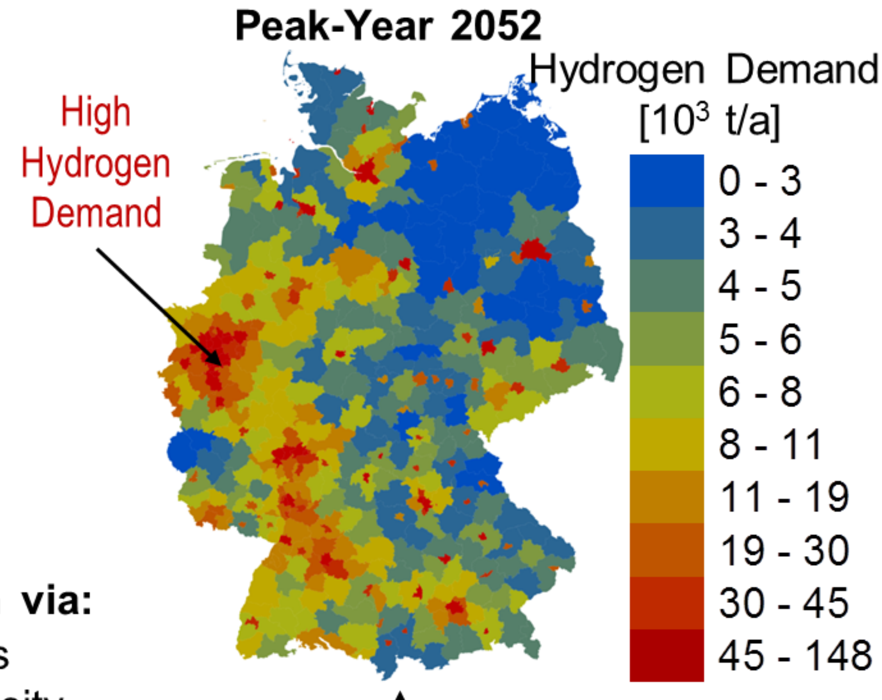


Energy Concept 2.0

Assessment based on counties level

H_2 Demand/a		
	FCV [kg/100 km]:	**0.92** (2010) → **0.58** (2050) [1], linear decrease
	FCV fleet:	curve fit; until 2033 according to [2]; maximum share in 2050: 75 % of German fleet
	Further assumptions:	**14,000** km annual mileage **12 years** lifetime; total vehicle stock: **44 million cars**
	Peak annual H_2 demand:	**2.93 million t_{H2} (2052) (Surplus 2050 Copper plate scenario → 4.0 million t_{H2})**





S-Curve based on:

- Target is 75 % of total passenger cars are FCV
  → 32.9 million FCV in 2050
- Reference points are based on H2Mobility

Disintegration via:

Number of cars
Population density
Useable income of private households …

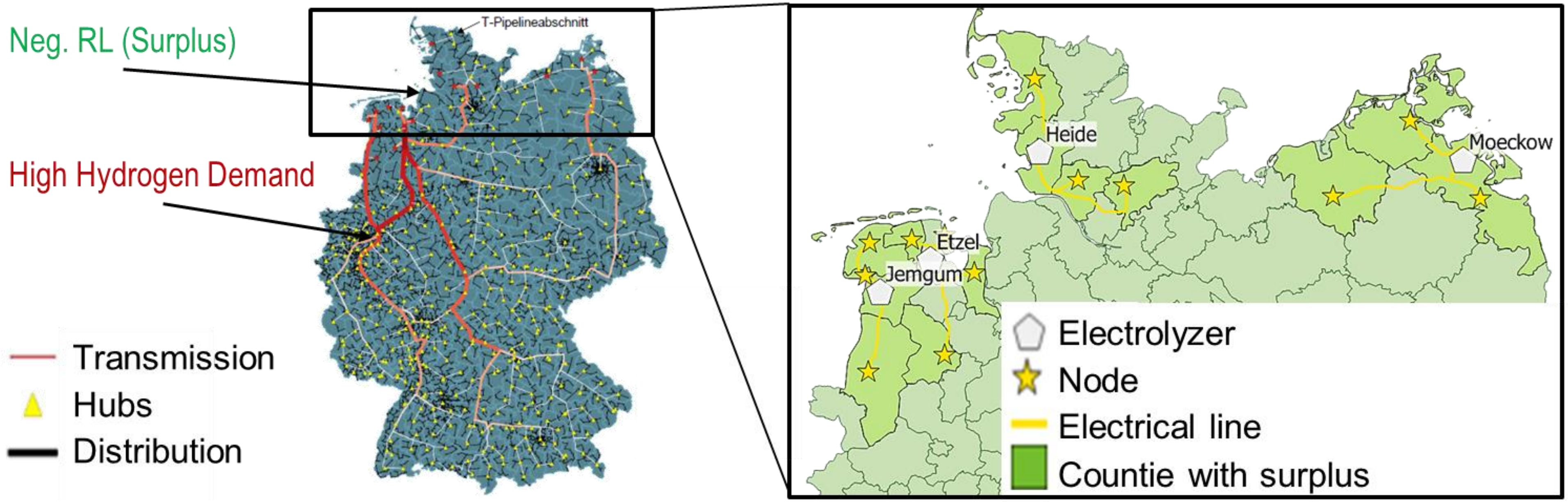
All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff and Tietze, V.: Techno-ökonomische Bewertung von pipelinebasierten Wasserstoffversorgungssystemen für den deutschen Straßenverkehr, to be published except: [1] GermanHy (2009), Scenario "Moderat" [2] H2-Mobility, time scale shifted 2 years into the future [3] Krieg, D. (2012), Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.

Energy Concept 2.0

Assessment based on counties level

Results

H_2 sources:	**28 GW** electrolysis power in 15 districts in Northern Germany, **15 billion €**
H_2 sinks:	**9,968 refueling stations** with averaged sales of 803 kg/d, **20 billion €**
H_2 storage:	**48 TWh** (incl. 60 day reserve), **8 billion €**
Pipeline invest [3]:	**6.7 billion €** (12,104 km transmission grid); **12 billion €** (29,671 km distribution grid)
Electricity cost:	LCOE Onshore: **5.8 ct/kWh**;
Total H_2 cost (pre-tax):	**17.5 ct/kWh** WACC: 8 %



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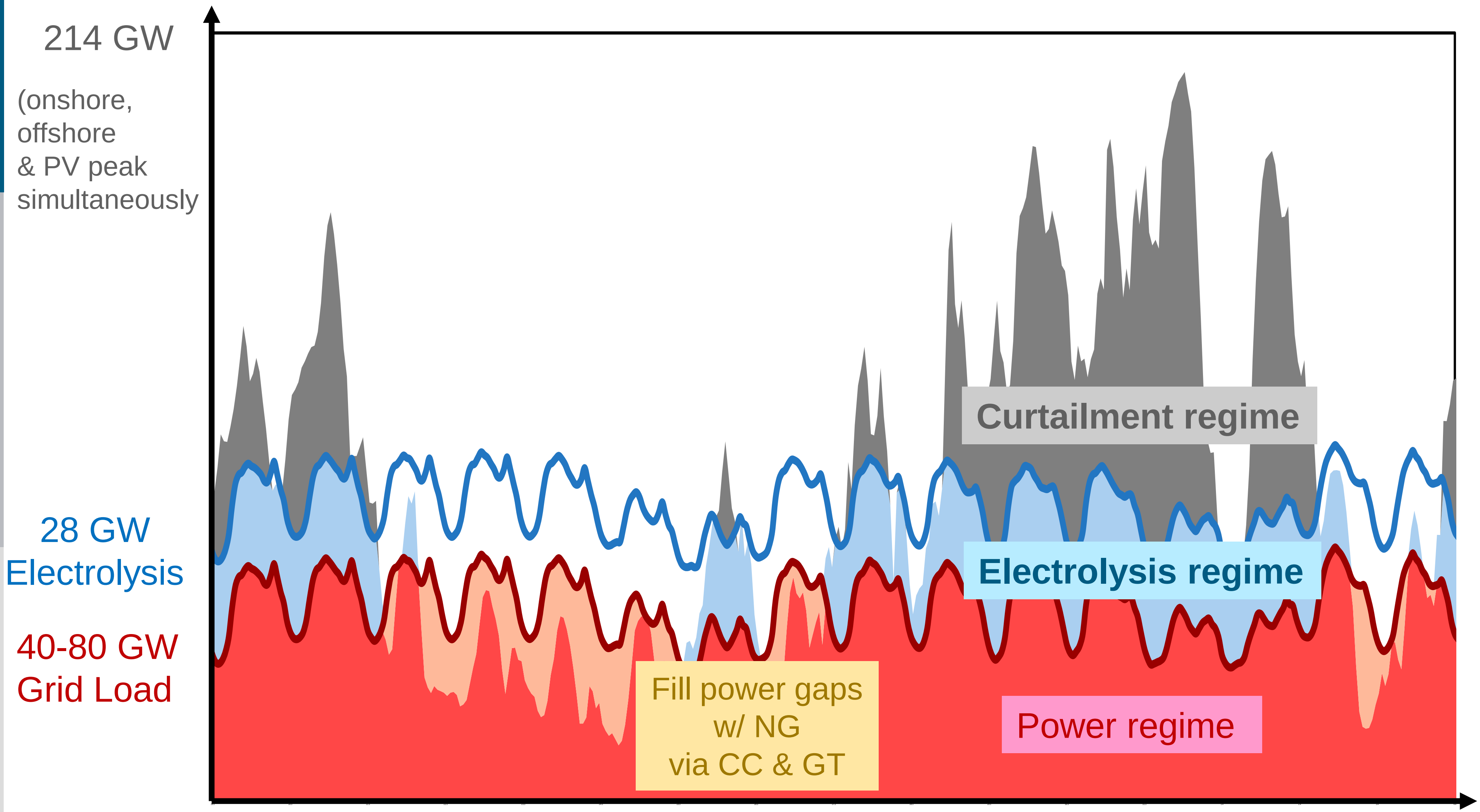
[4] Tietze, V.: Techno-ökonomische Bewertung von pipelinebasierten Wasserstoffversorgungssystemen für den deutschen Straßenverkehr, to be published

Principle of a Renewable Energy Scenario with Hydrogen

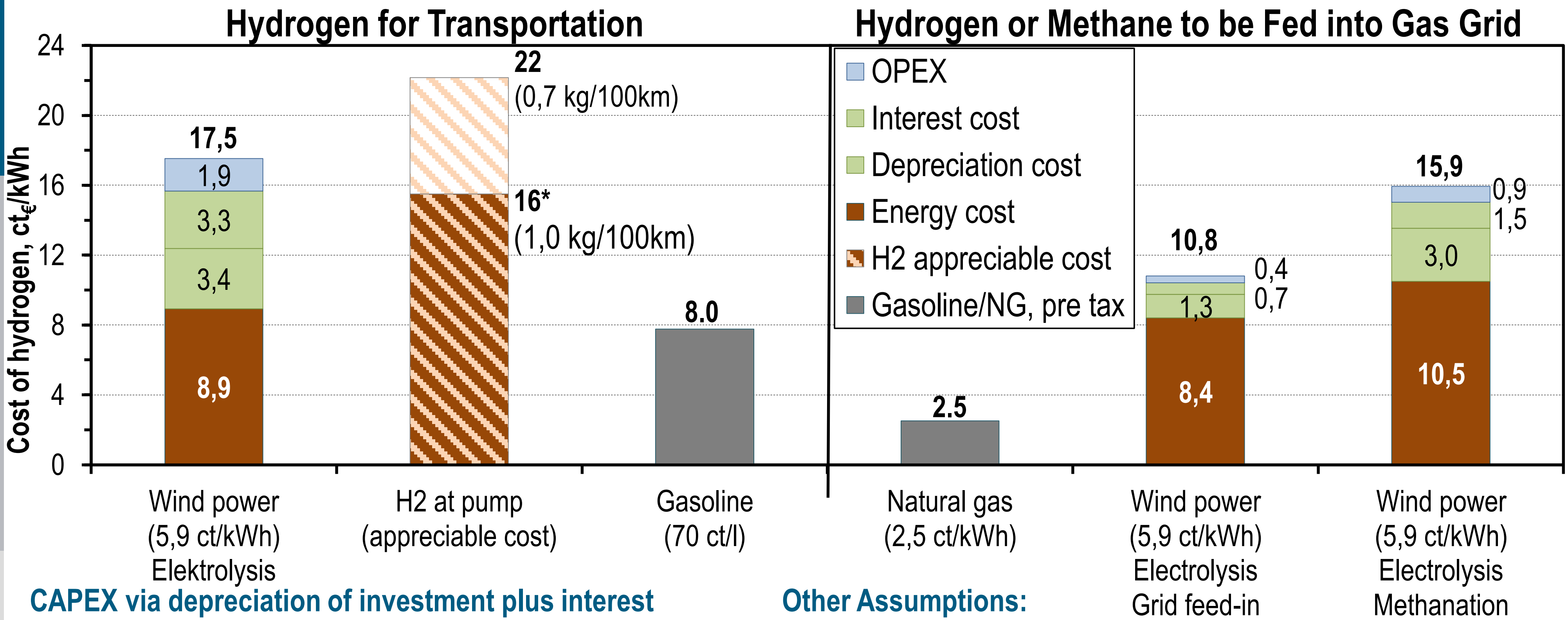
Hydrogen as an Enabler for Renewable Energy



* based on Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. PhD thesis

Cost Comparison of Power to Gas Options – Pre-tax

Hydrogen for Transportation with a Dedicated Hydrogen Infrastructure is Economically Reasonable



CAPEX via depreciation of investment plus interest

- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid and refueling stations
- Interest rate 8.0 % p.a.

Other Assumptions:

- 2.9 million t_{H2}/a from renewable power via electrolysis
- Electrolysis: η = 70 $\%_{LHV}$, 28 GW; investment cost 500 €/kW
- Methanation: η = 80 $\%_{LHV}$

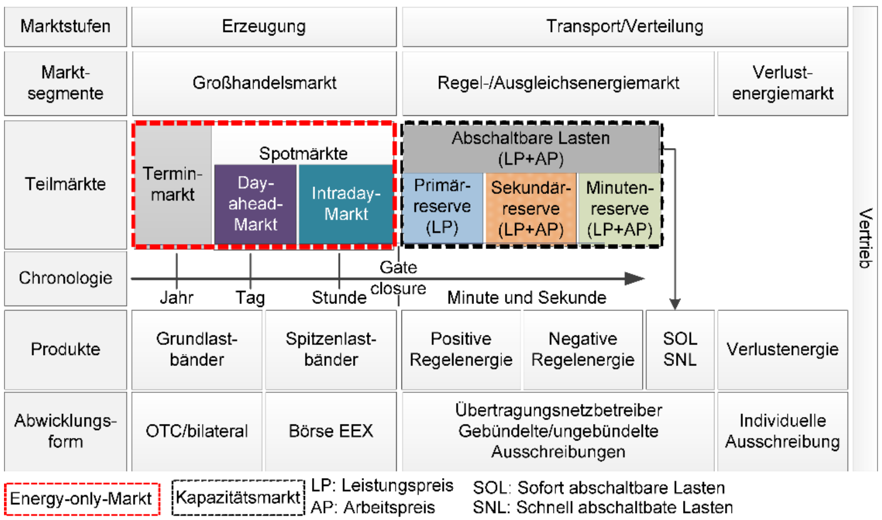
- Appreciable cost @ half the specific fuel consumption

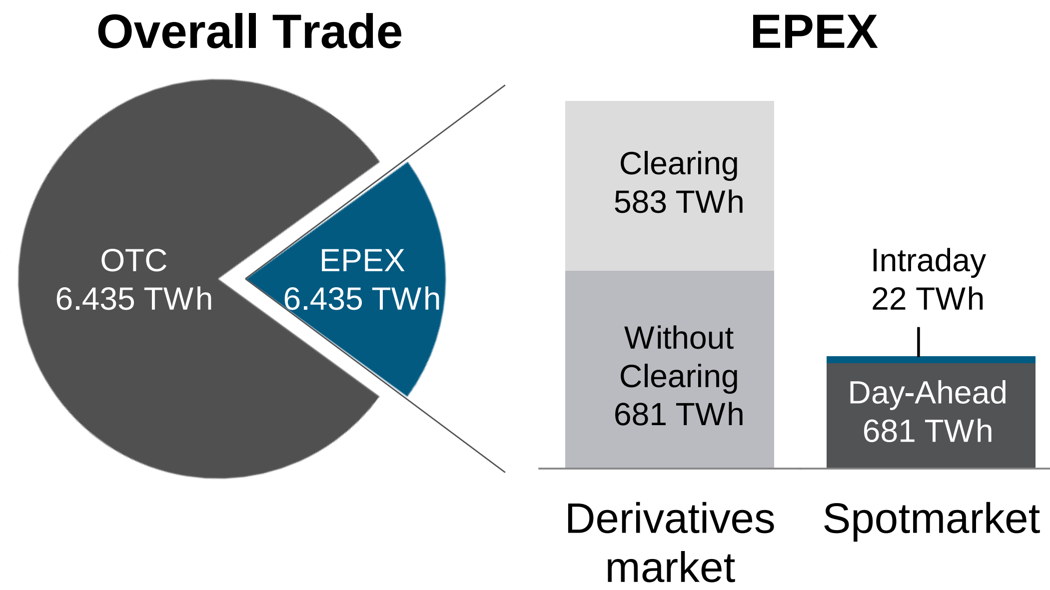
[1] Energy Concept 2.0

The Markets and Share- and Stakeholder

Electricity Market

Description of the current state:





Analysis of alternative market designs:
Capacity markets & congestion management

Choice of suitable market designs:

- Integrated energy market design: *If required: electrolysis units can reduce their promised load and safe achievement certificates*
- Zonal or nodal pricing: *Local price signals, in comparison to the actual copper plate model*

“Grid expansion is required for the preservation of a single price zone” [1]

[1] Ein Strommarkt für die Energiewende (Weißbuch). Ergebnispapier des Bundesministeriums für Wirtschaft und Energie Juli 2015, S. 19. [2] Wend, A., Modellierung des deutschen Strommarktes unter Verwendung der Residuallast, in Institut für Brennstoffzellen. 2014, RWTH Aachen. [3] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. PhD thesis

Gas Market

Description of the current state :

- Worldwide analysis of hydrogen market:
  - *Hydrogen production from 45 to 65 million tons per year*
  - 48% from natural gas steam reforming
  - 4% from alkaline electrolysis
  - No market for the hydrogen supply of Fuel Cell Vehicles (FCV)
    - German natural gas market as reference market

Analysis of alternative market designs:

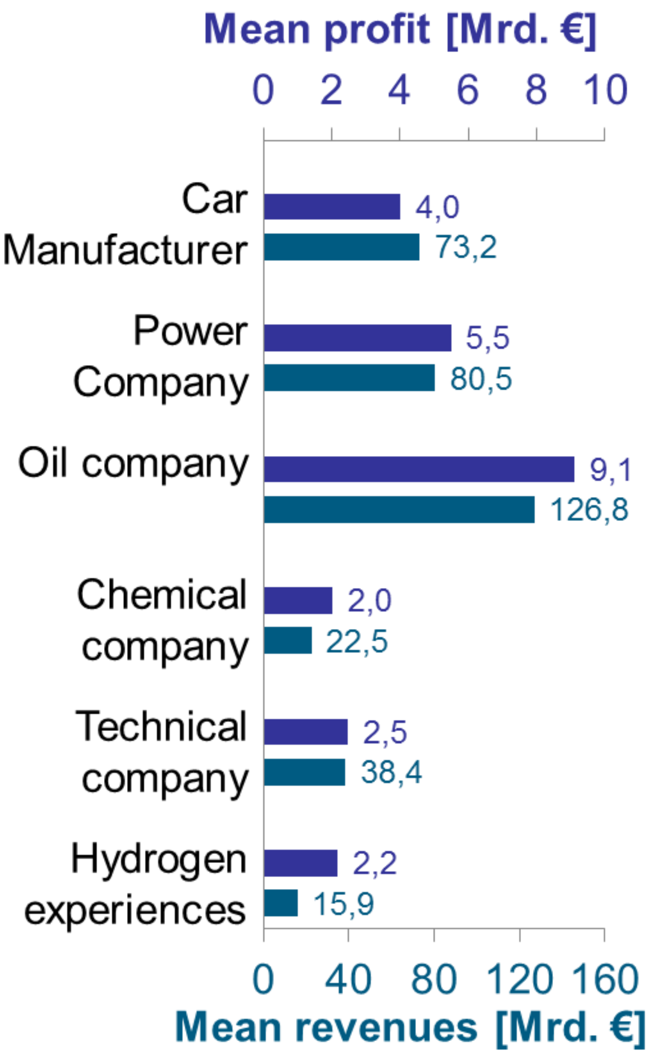
- Contract-Path-Model
- Bathtub-Model
- Control-Area-Model

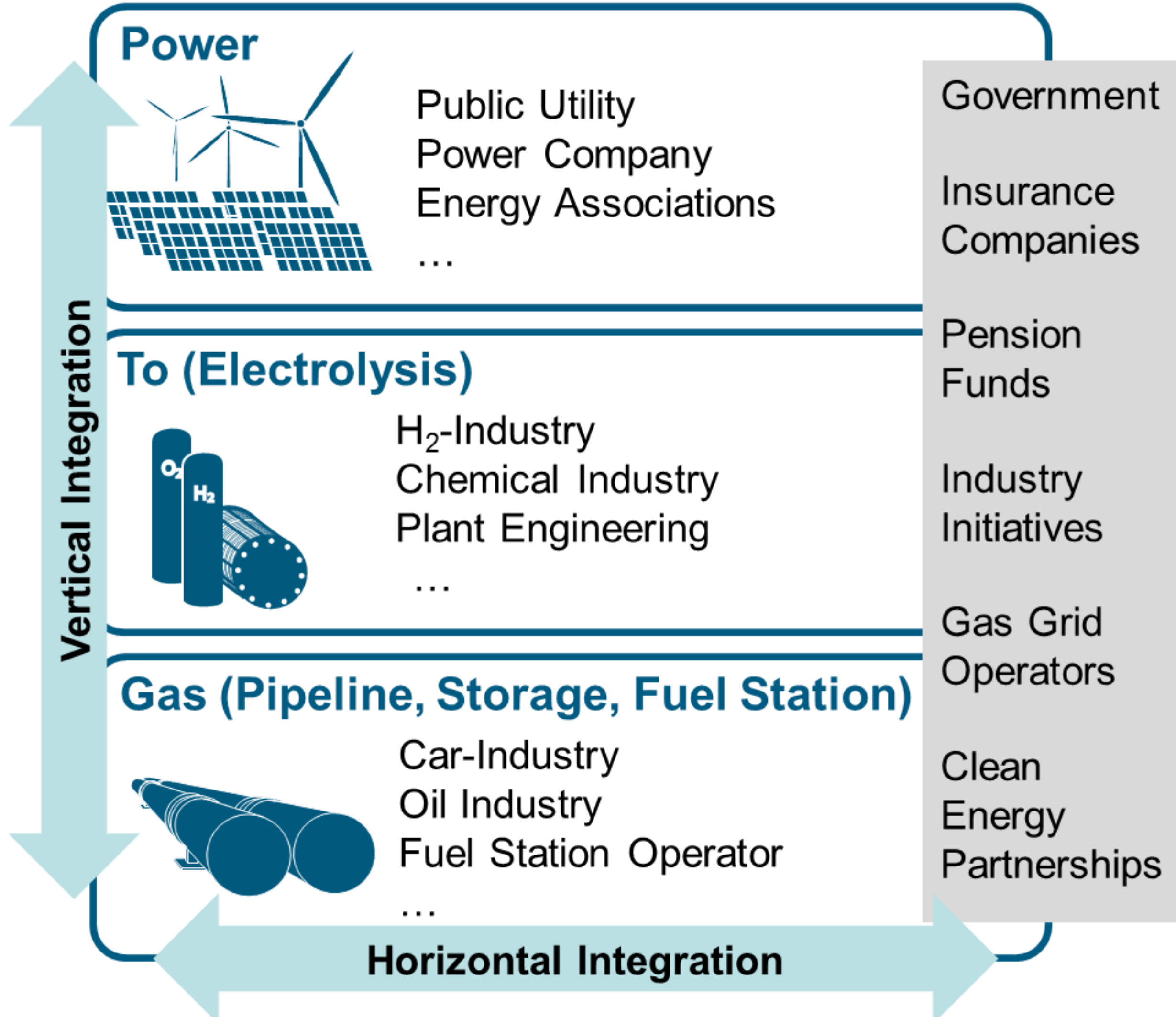
Choice of suitable market designs:

- Contract-Path-Model: *Effective during pipeline development due to specific source-sink relations*
- Entry-Exit-Model: *Comparable to natural gas market, reasonable for highly meshed grids*

[1] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. PhD thesis

Share- and Stakeholer Analysis





Industry co-operations can accelerate the development of an hydrogen infrastructure

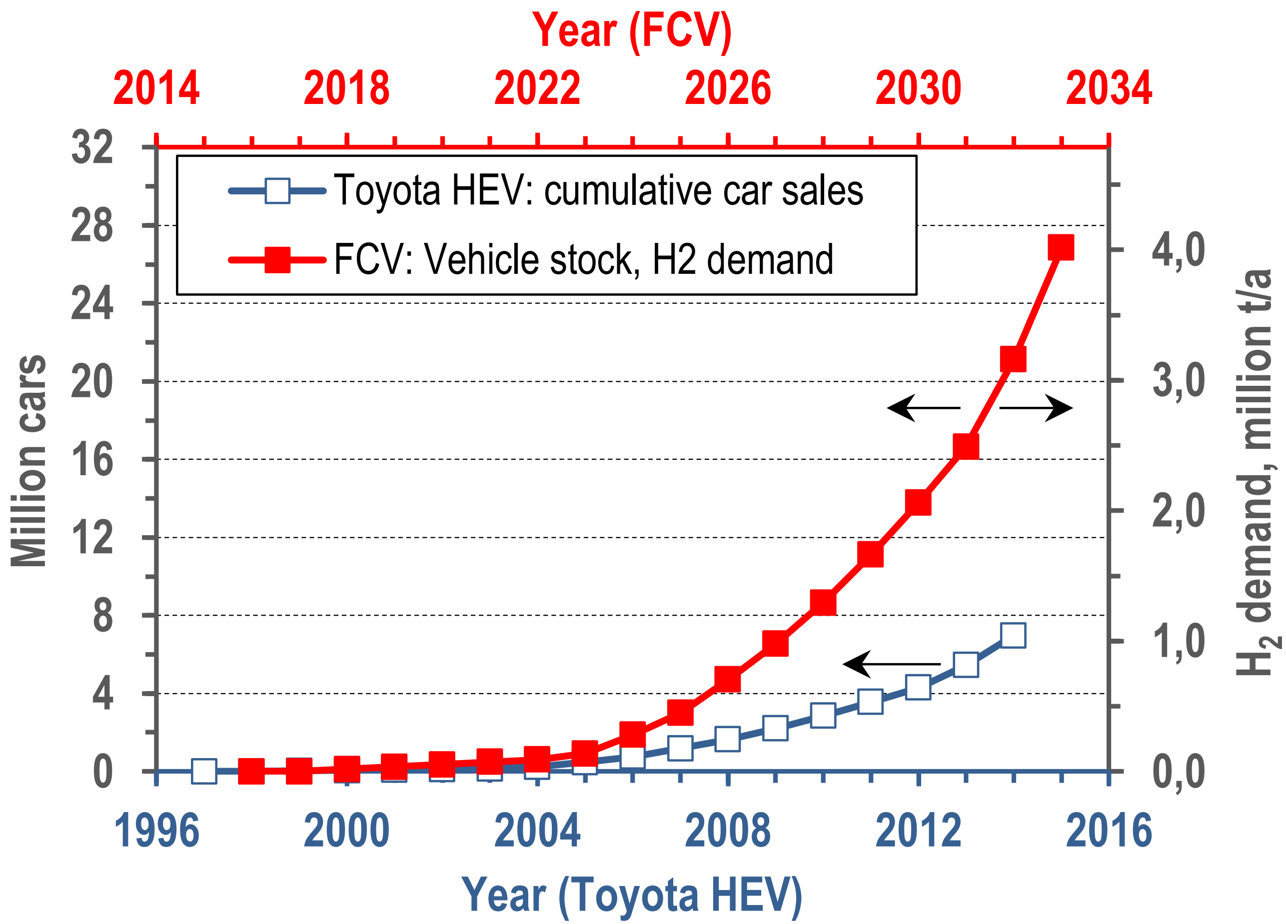
[1] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. PhD thesis

Mass Market Introduction of Hydrogen

No Barrier, just a Challenge

Estimated Worldwide Fuel Cell Car Population Build-up
Energy Concept 1.0

Based on Toyota's Hybrid Cars / Assuming Fourfold Build-up-power for FCV Cars

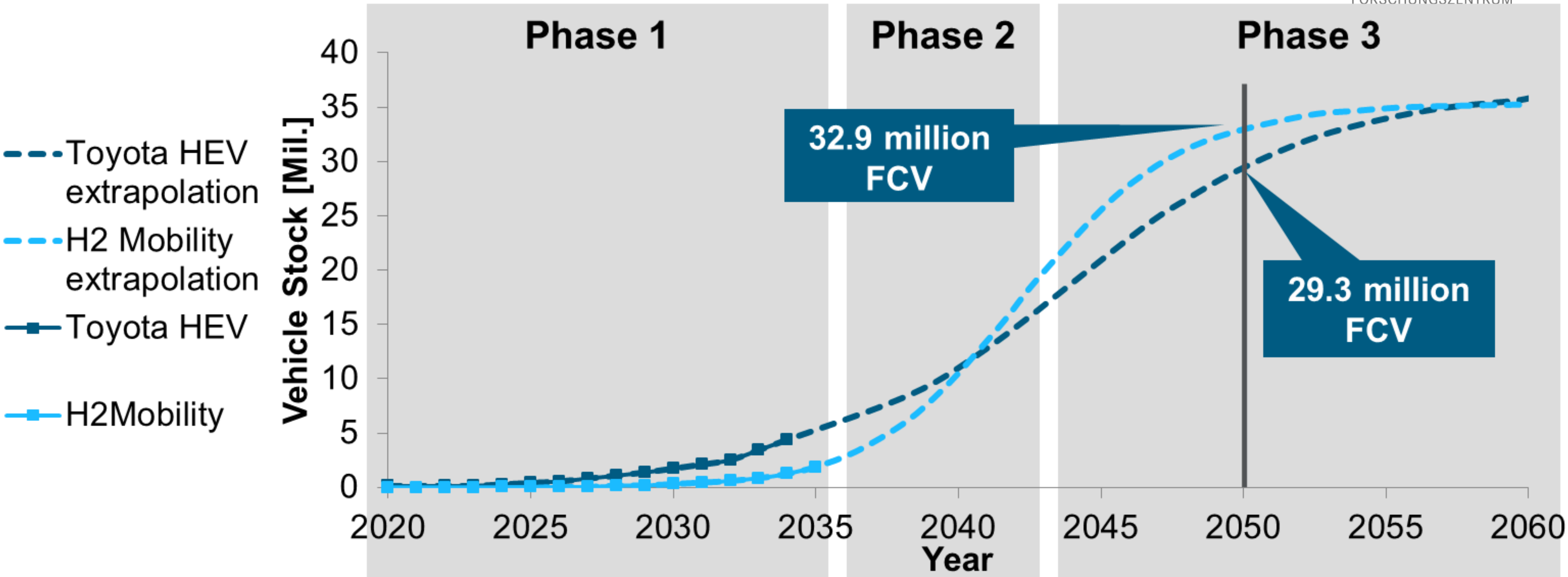


Assumptions
(based on Toyota HEV data [1])

- the same market penetration
- **four-fold sales** (four OEMs: Daimler/Ford, Honda/GM, Hyundai, Toyota)
- Vehicle lifetime of 10 years considered
- **FCV with fleet average** (cars, light trucks and busses) according to **GermanHy**: 1.17 kg (100 km)$^{-1}$ fuel use 15,170 km a^{-1} annual mileage
- Passenger cars (GermanHy): **1.0 kg (100 km)$^{-1}$** fuel use **14,900 km a^{-1}** annual mileage, mix of gasoline and diesel cars

[1] **Hirose (2014)**: *Toyota's Effort toward Sustainable Mobility 2015 FCV and Beyond*. In Proceedings: 20th World Hydrogen Energy Conference 2014, Gwangju, Korea.

Comparison of FCV market introduction scenarios

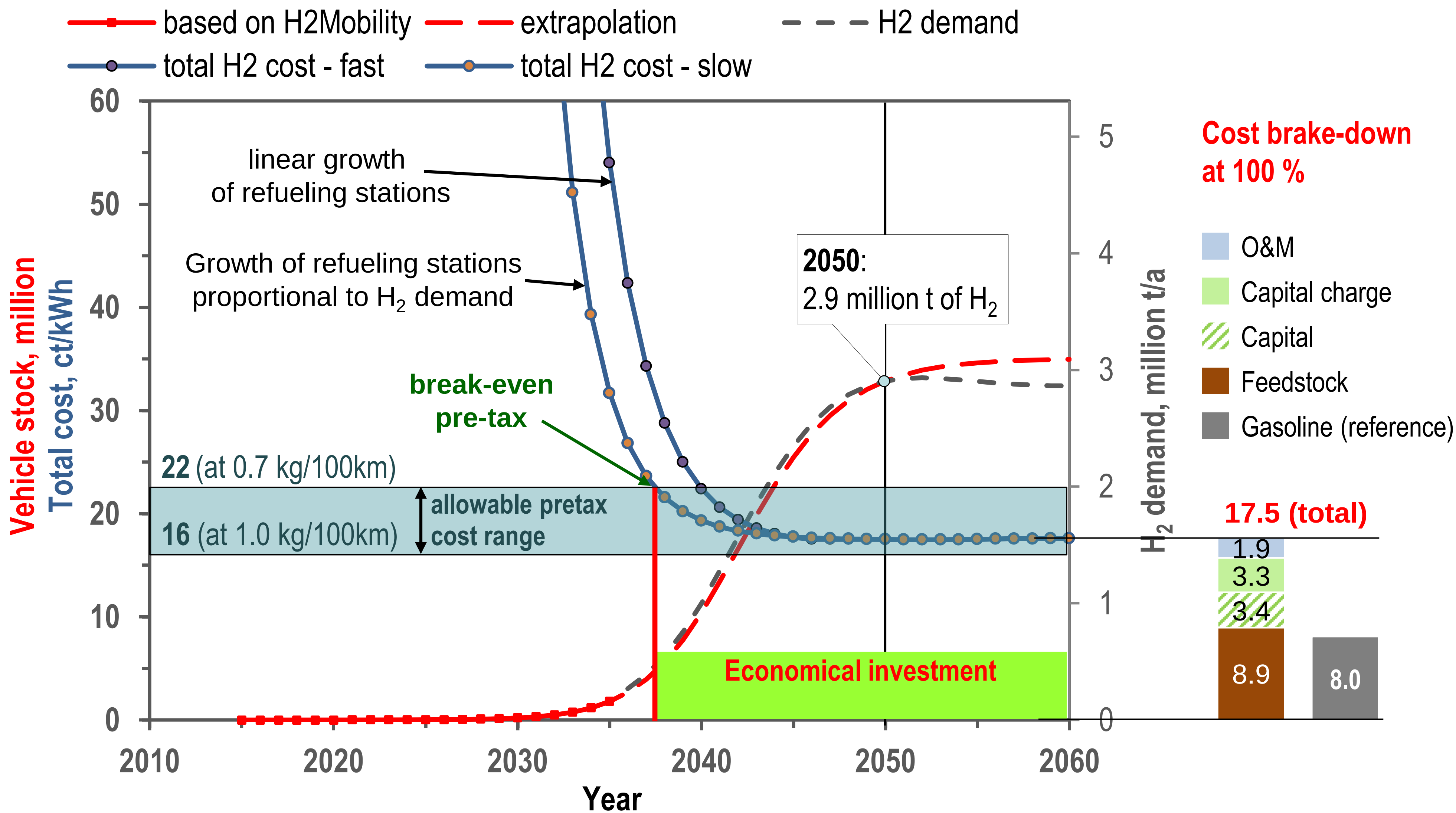


	Phase 1	Phase 2	Phase 3
Power Source:	Reserve market, EEX, negative prices	**Transition**	Reserve market, EEX. Surplus RES, LCOE
Hydrogen Production:	Decentralized (~kW)		Centralized (~GW)
Hydrogen Transport:	Trailer, None → on-site		Pipeline, Trailer
Hydrogen Demand:	Urban		Everywhere
Hydrogen Storage:	Hydrogen Pressure Vessels		Hydrogen Pressure Vessels, Salt caverns

Energy Concept 2.0 (H2Mobility): Target is 75 % of total passenger cars are FCV, Fuel consumption improves over time, Reference points are based on H2Mobility; Energy Concept 1.0 (Toyota): Target 2050 is based on available hydrogen, fuel consumption assumed constant, Reference points are based on development of Toyota HEV

FCV Market Introduction in Germany 2.0

H_2-cost evolution for full-fledged transmission grid, with demand-driven installation of electrolysers, storage capacities, distribution grid and fueling stations; **Pre-tax**



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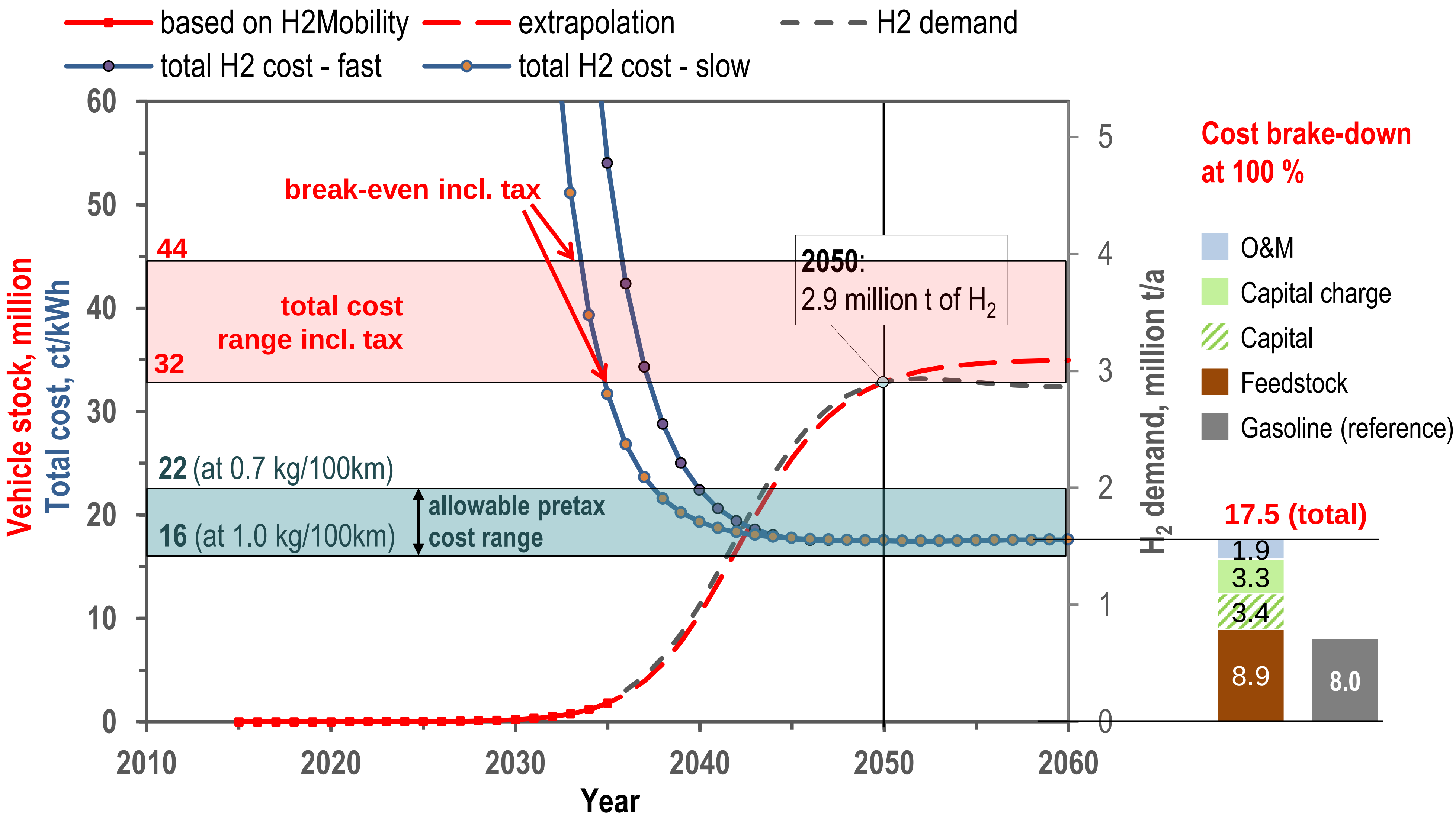

Conclusion

Fuel cell vehicles are at the brink of market introduction; main remaining issues are

- Cost & Durability

Use of gaseous hydrogen at 700 bar as a transportation fuel represents a robust strategy

- Methanol and gasoline Fcs with reforming have been explored
- Liquid hydrogen has been explored
- 350 vs. 700 bar units have been explored
- Hydrogen as a transportation fuel is much more cost-effective than for stationary use
- Hydrogen as a fuel will be cost effective enough to allow for taxation
- A hydrogen infrastructure will need tax breaks in the early stages

Hydrogen fuel for transportation is an enabler for renewable energy owing to its storage option & transportation represents a high-price sink

For sake of cost effectiveness and energy efficiency energy strategies are to be cast across the traditional sectors of

- Power supply & transportation
- Residential energy supply
- Industry

The infrastructure for FCVs has been proven to be no impediment

Feasibility of energy strategies includes proof of

Physics, technology, **economics** (micro- and macro-economics), acceptance

Thank You for Your Attention

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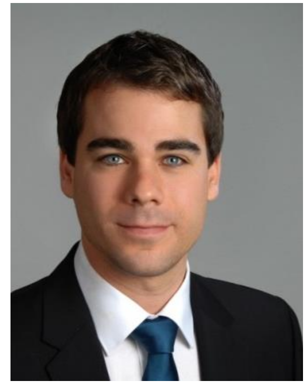

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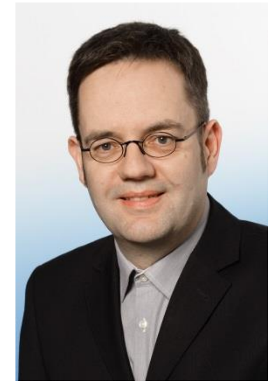

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