Wasserstofftransport im Gas-Fernleitungsnetz: Eine techno-ökonomische Bewertung

05.08.2020 I DETLEF STOLTEN, BASTIAN GILLESSEN, JOCHEN LINSSEN, TOBIAS TRIESCH, MARTIN ROBINIUS

Öffentlicher Workshop Netzentwicklungsplan Gas 2020-2030

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IEK-3: Institute of Techno-economic Systems Analysis

Guiding Questions

… What does an appropriate hydrogen infrastructure look like covering the transformation pathway toward a very low carbon energy system?

… Which gas transmission pipelines could be used for hydrogen transport?

… What are suitable reassignment options for NG pipelines to H_2?

… Which alternative is most economical?

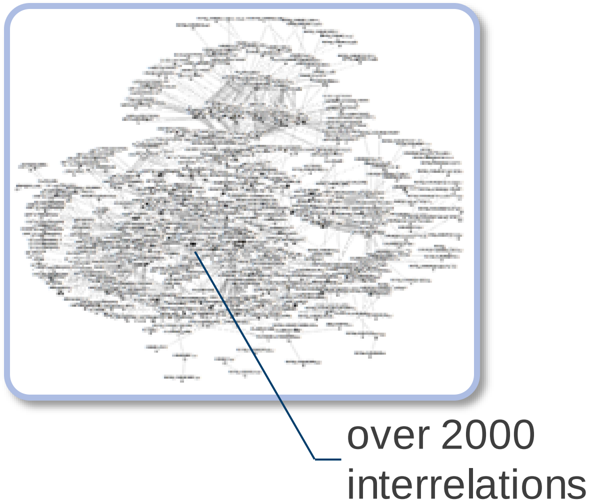
… How do the alternatives compare techno-economically?

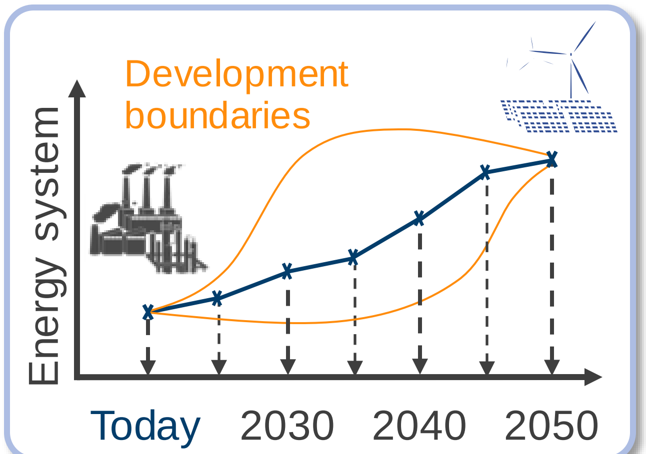
Setting the Scene

Hydrogen Demand and Infrastructure over Time in Germany According to the ES 2050 Study*

Wege für die Energiewende – Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050. Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt/Energy & Environment, Band/Volume 499; Robinius M., Markewitz P., Lopion P., Kullmann F., Heuser P.-M., Syranidis K., Cerniauskas S., Schöb T., Reuß M., Ryberg S., Kotzur L., Caglayan D., Welder L., Linßen J., Grube T., Heinrichs H., Stenzel P., Stolten D.: https://juser.fz-juelich.de/record/877960/files/Energie_Umwelt_499.pdf

Approach: Cross-sectoral Cost-optimization of the Entire Energy System under CO_2-Emission Constraints from Today through 2050





Transformation Strategy:

- Cross-sectoral
- Cost-optimal
- Technologically unbiased

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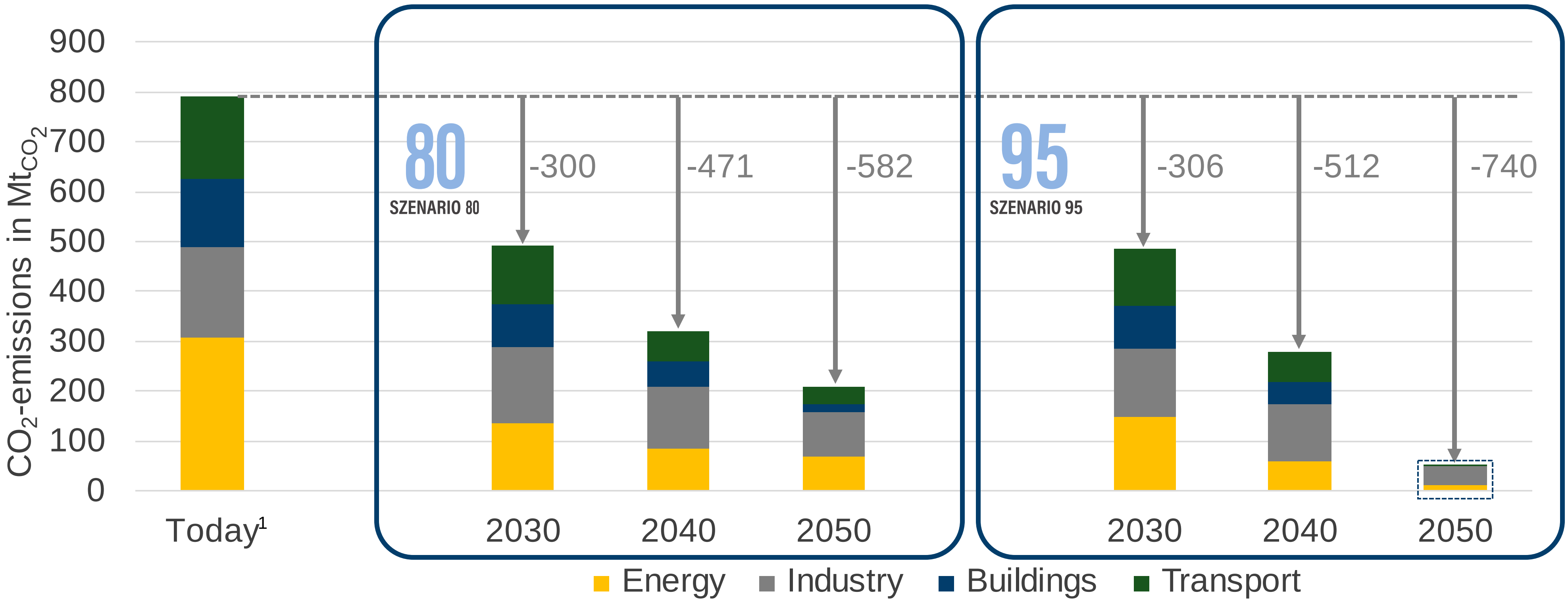
CO_2 Emissions per Sector until 2050



[1] Umweltbundesamt 2019. https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland

- Transformation strategies for a 80 %- and 95 %- CO_2-reduction are noninterchangeable
- Paris climate accord requires a greenhouse gas reduction of at least 95 %

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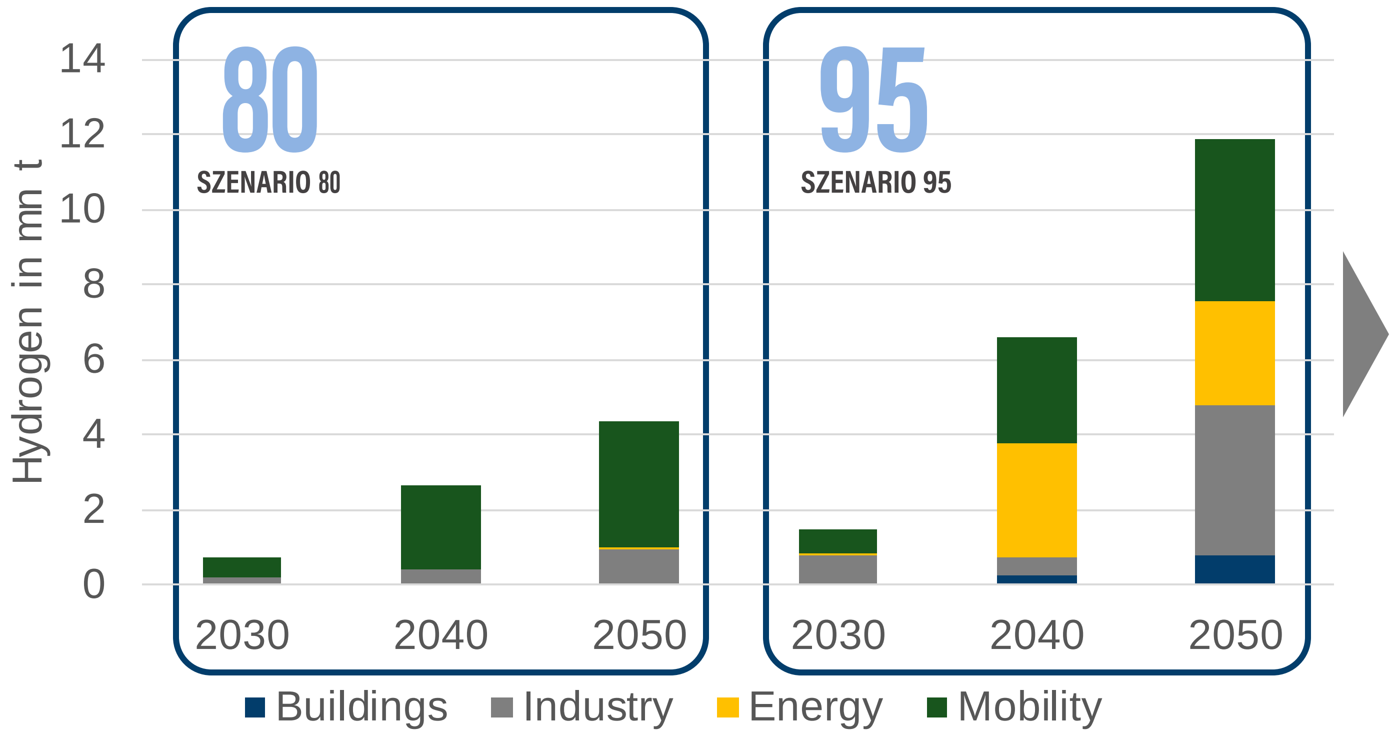
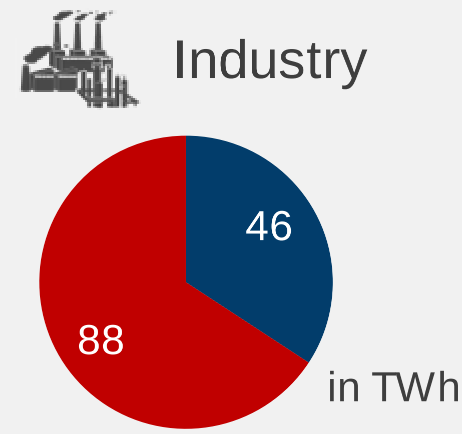
Hydrogen Demand Triples for the 95% Scenario





- Scenario 80: Hydrogen demand of 4 mn t (mostly transport and industry)
- Scenario 95: Hydrogen demand of 12 mn t across all sectors (incl. process heat)

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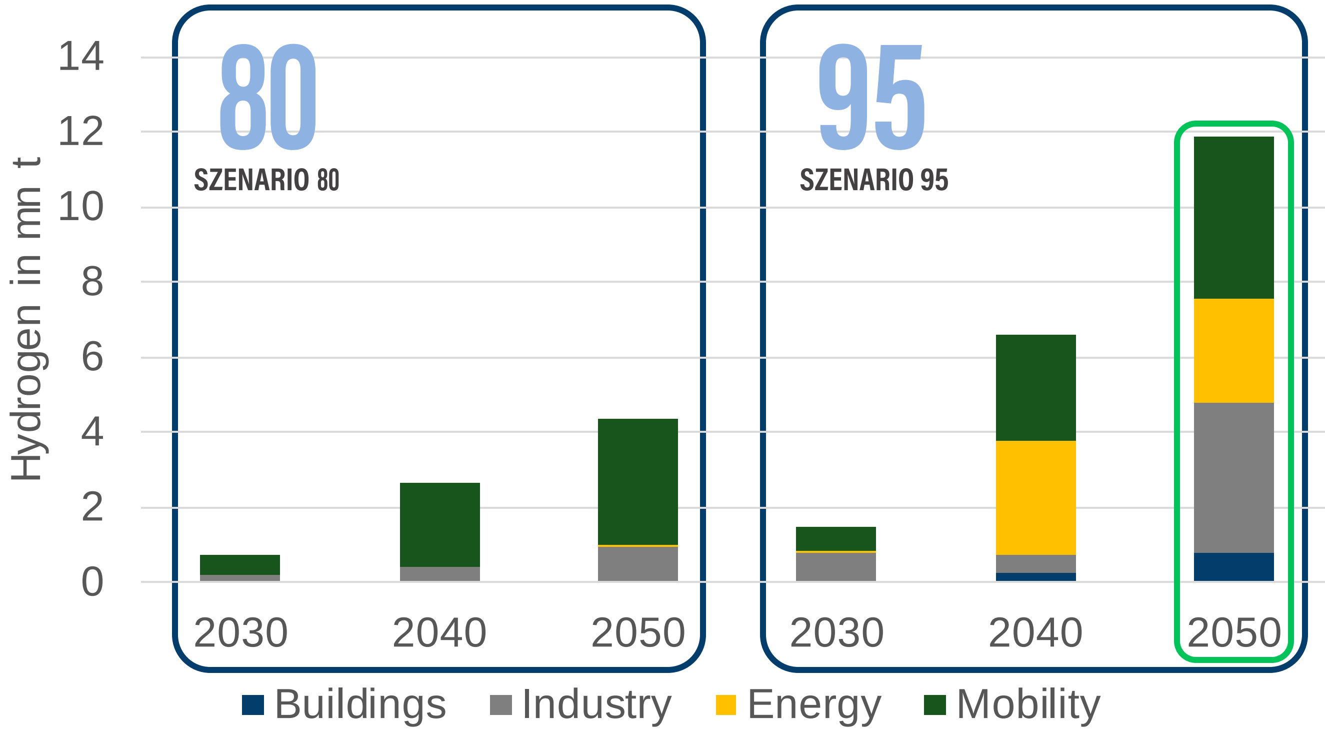
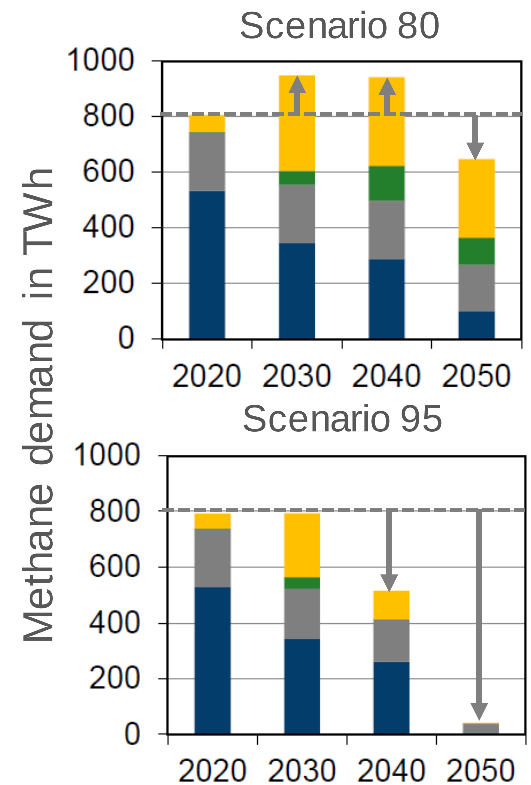
Hydrogen and Methane Demand





- Scenario 80: Hydrogen occurs in mobility and industry only,
  NG demand rises in between before dropping in 2050
- Scenario 95: H_2 in all sectors ➔ infrastructure development & supply chain analysis needed

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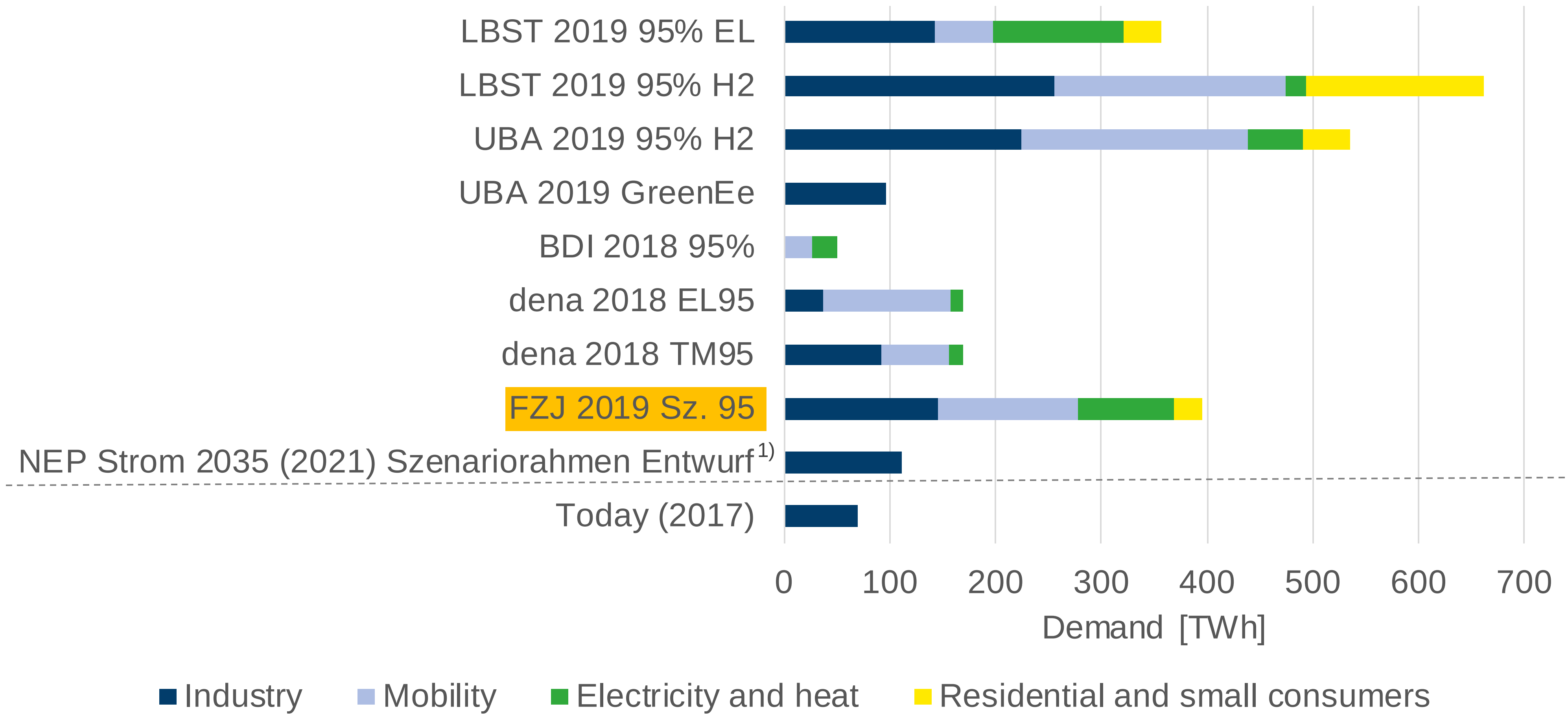
Comparison of Existing Hydrogen Scenarios: Demand 2050



1) Entwurf Szenariorahmen, 17.1.2020: H_2 consumption for steel industry not considered

Micellaneous

Colors of Hydrogen

2050 needs CO_2-free H_2

Green H_2 : long-term solution

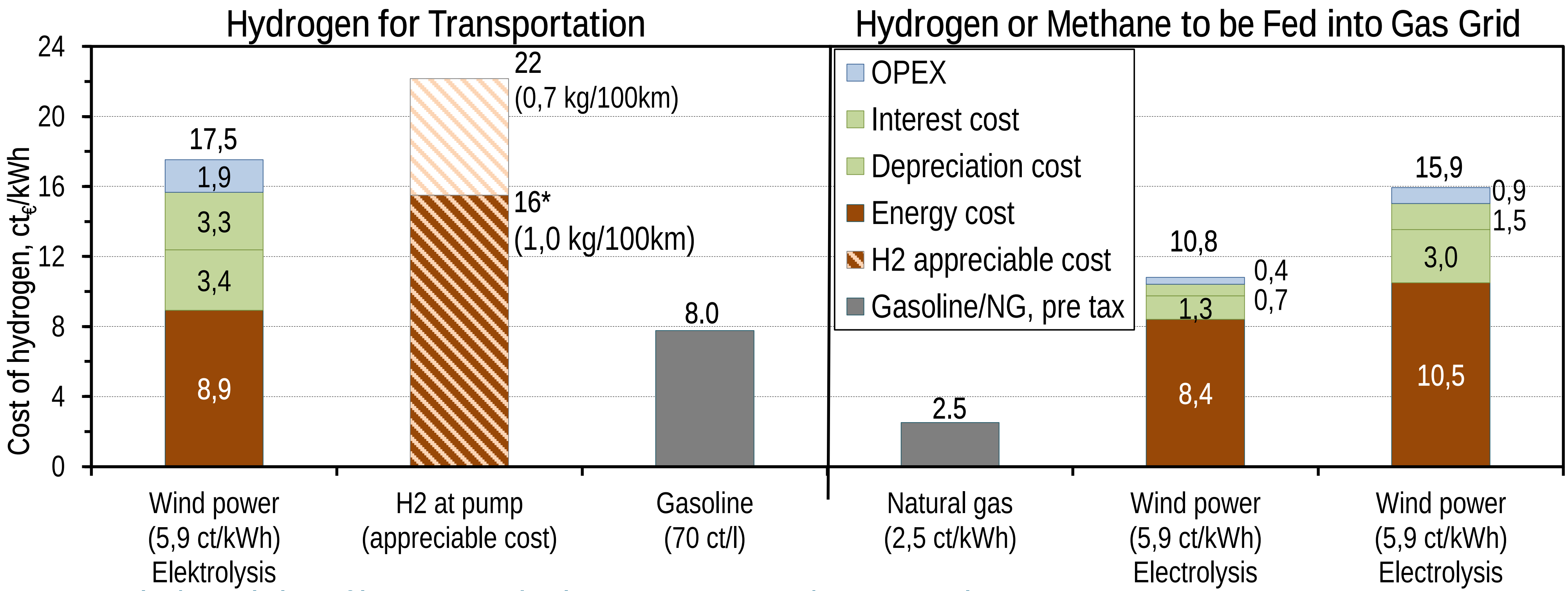
Blue H_2 : suitable for the transition; CO_2 separation degree between 70-80% to be consic
separation technology to be further developed
suggested to be phased out by 2040

Turquoise H_2 : carbon separation at an early stage (TRL 3/4)

Nuclear H_2 : depends on nuclear discussion, not on H_2 related issues

Cost Comparison of Power to Gas Options – Pre-tax V2.0

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:

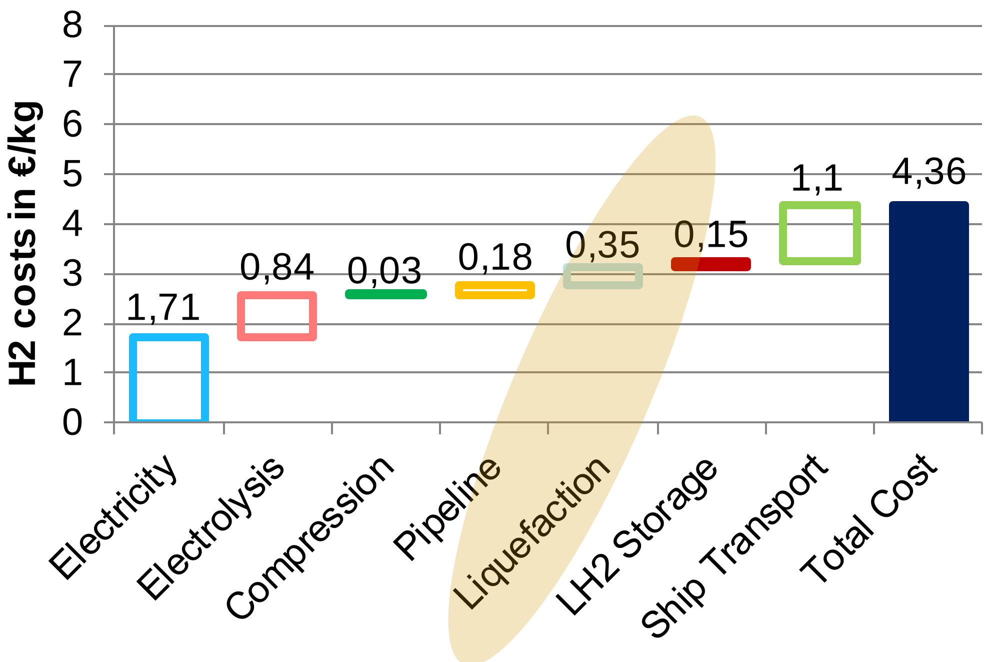
- 2.9 million t_{H2}/a from renewable power via electrolysis
- **Electrolysis: η = 70 %$_{LHV}$**, 28 GW; investment cost 500 €/kW
- **Methanation: η = 80 %$_{LHV}$**

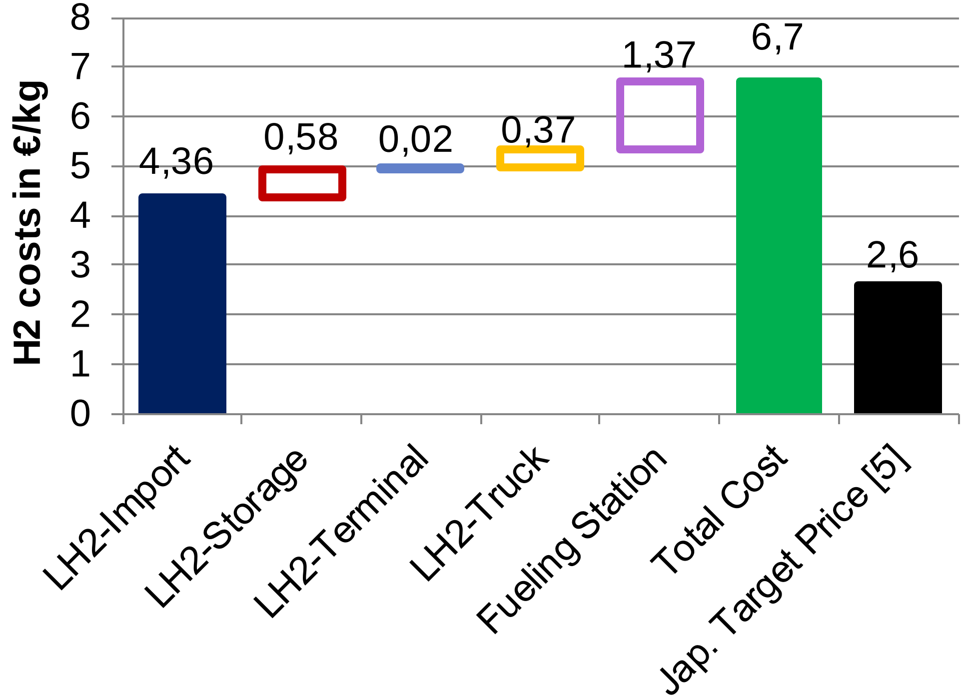
- Appreciable cost @ half the specific fuel consumption

[1] Energy Concept 2.0

Global Energy Supply Systems

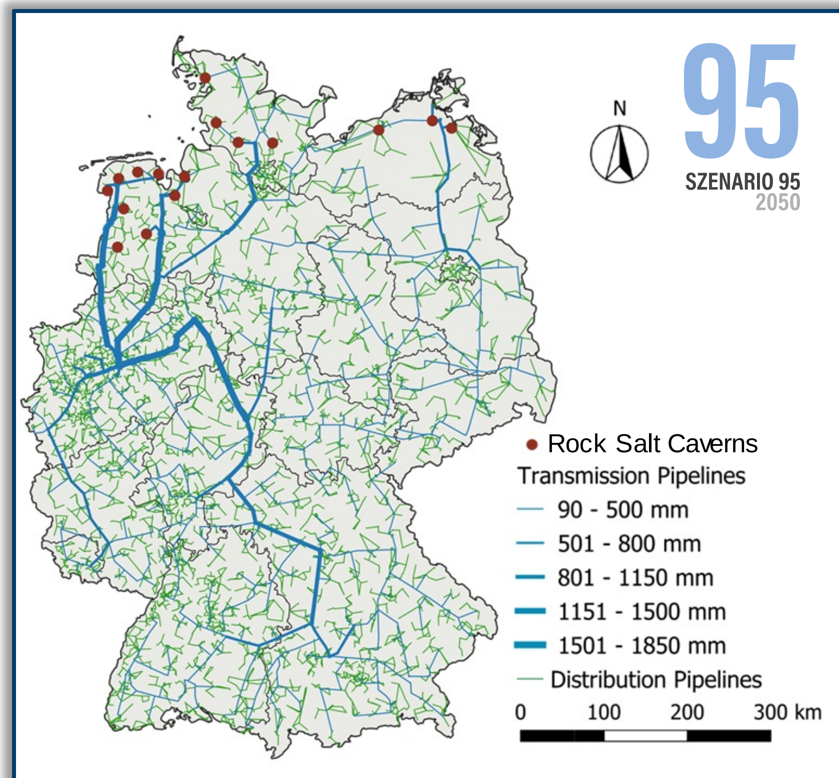
- **International Trade of H_2 is Most Cost Effective via Liquid H_2**
- Hence, according to Scenario 95, 6 mn t in DE in 2050 will be liquid; 6 mn t gaseous





Pipeline Infrastructure

Cost-optimal Virtual H_2-Pipeline Design for Germany as per Scenario 95



Optimized H_2-pipeline infrastructure for Germany

- Cost-optimal hydrogen pipeline infrastructure; 100% green field w/ full cost
  → Advantage of reassignment of natural gas pipelines to be assessed
- Salt caverns in northern Germany for long-term storage

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Modeling of Hydrogen Infrastructure (HyInfraGis)

Key Features

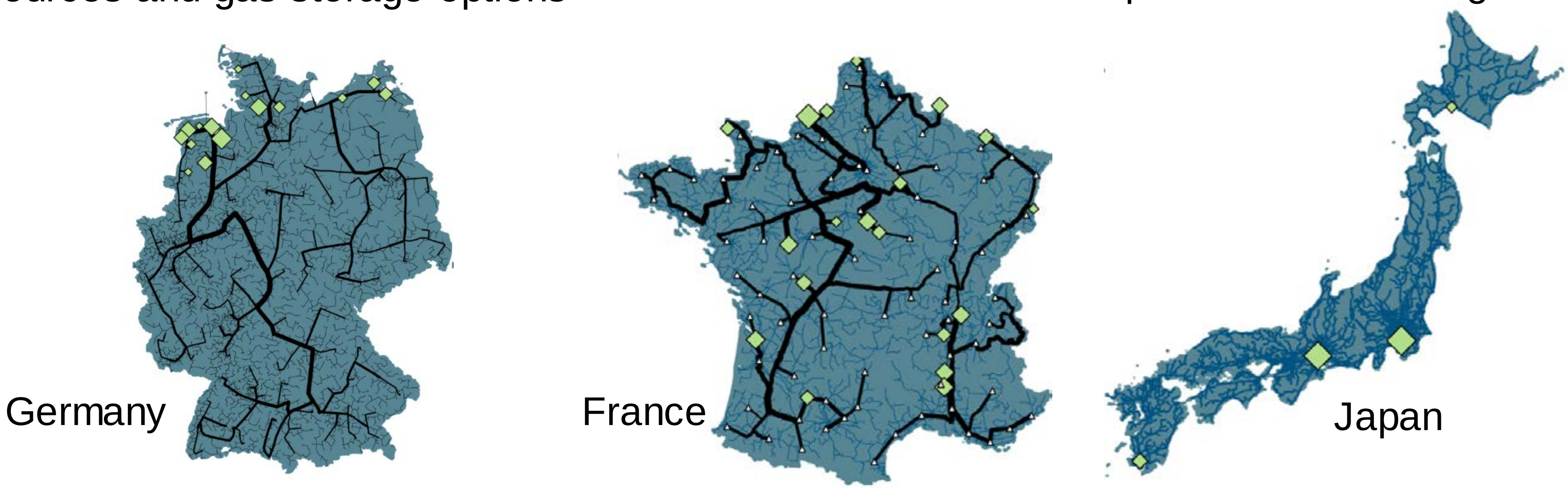
- Techno-economic analysis of hydrogen pathways (pipeline, truck) with high spatial resolution
- Analysis of transmission and distribution of hydrogen
- Determination of pipeline topology and hydrogen flow, diameter sizing based on pressure drop

Model characteristics

- Generic modeling of hydrogen infrastructure for any region and transportation mode
- Consideration of candidate grids, sinks, sources and gas storage options

Model applications

- Design of hydrogen pathway scenarios for Germany, France and Japan
- Reassignment of gas pipelines and analysis of truck transportation on existing roads

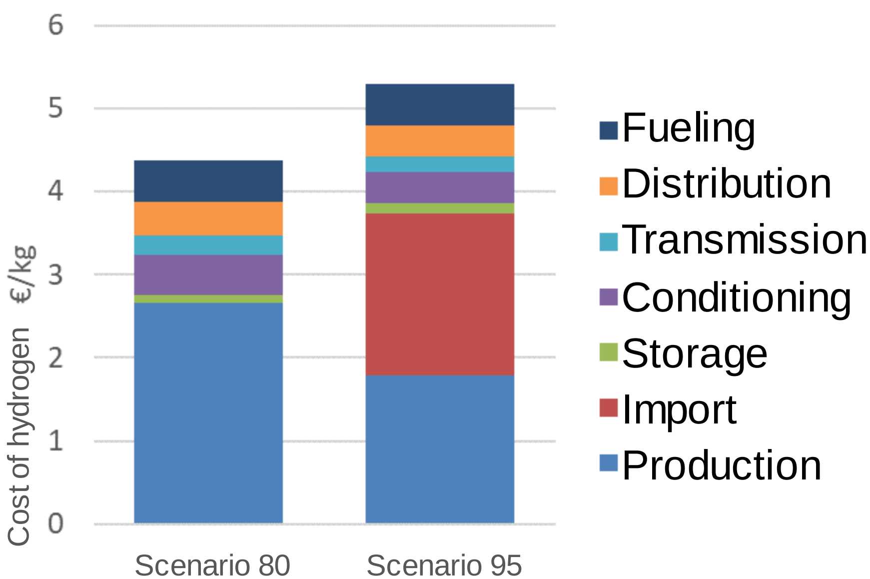


[1] Reuß M., Grube T., Robinius M., Stolten D.: A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies. Applied Energy. 2019

[2] Reuß M.: Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur. Dissertation RWTH Aachen University. 2019.

Costs of Hydrogen Production, Transport and Distribution

		Scenario 80	*Scenario 95*
Hydrogen demand	Mio. t	4	12
Length of transmission grid	km	12,500	12,200
Number compressor stations	-	180	220
Storage capacity (caverns)	TWh	3	67
Cost incl. infrastructure (large consumer)	$€_{ct}$/KWh	10.4	13.3

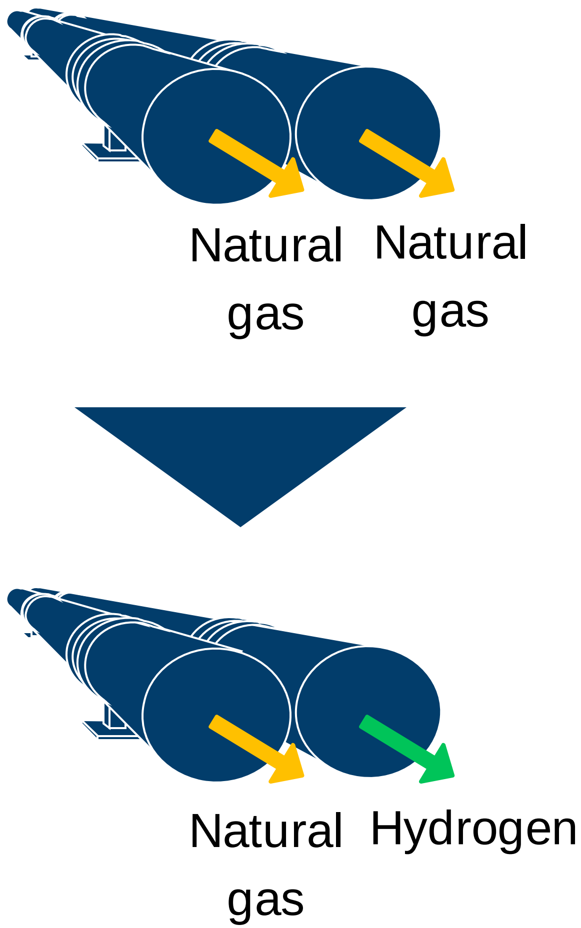


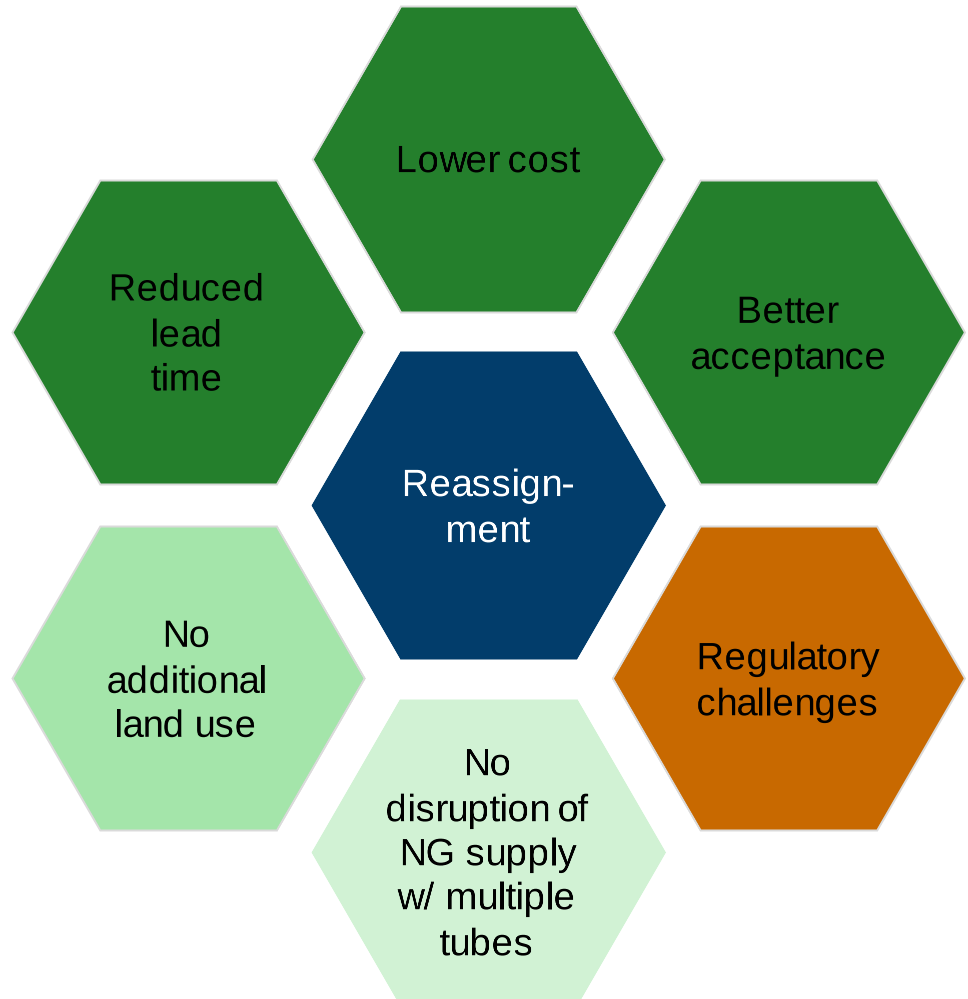
- High hydrogen import in **Scenario 95**
- **Scenario 80:** Savings in production have the biggest cost impact
- **Scenario 95:** Savings in import and production are most impactful

Robinius M., Markewitz P., Lopion P., Kullmann F., Heuser P.-M., Syranidis K., Cerniauskas S., Reuß M., Ryberg S., Kotzur L., Caglayan D., Welder L., Linßen J., Grube T., Heinrichs H., Stenzel P., Stolten D. (2019): Cost-efficient and Climate Friendly Transformation Strategies for the German Energy System Until 2050. (Detailed Results)

Pipeline Reassignment

From Green Field to Brown Field: NG-Pipeline Reassignment to Hydrogen

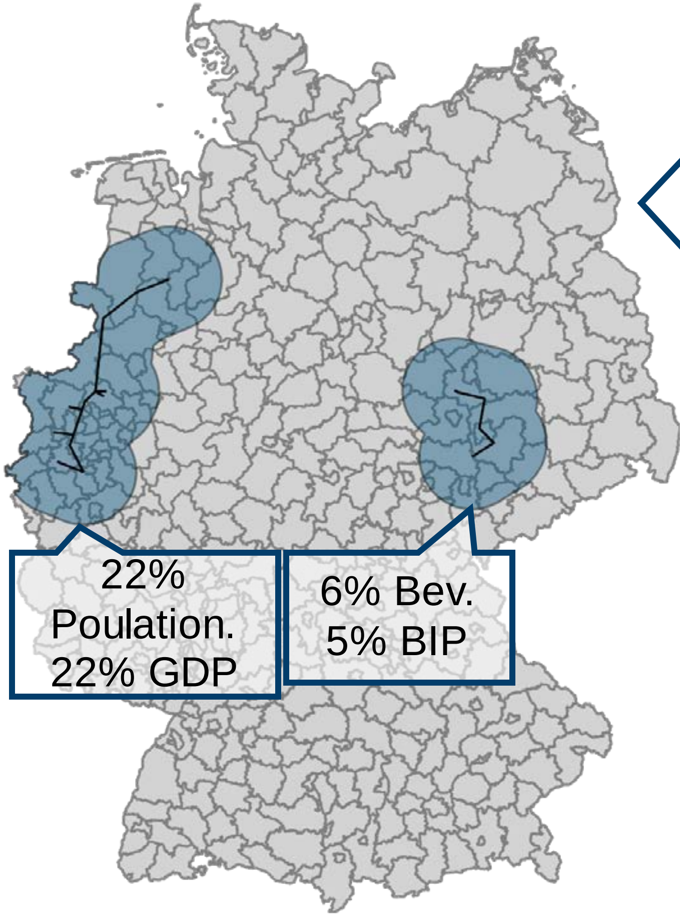




Example NG Pipeline Reassignment Potential for Germany

Only Multiple Tube Pipelines Considered; Market Introduction

Distance: ~420 km
2020-2025



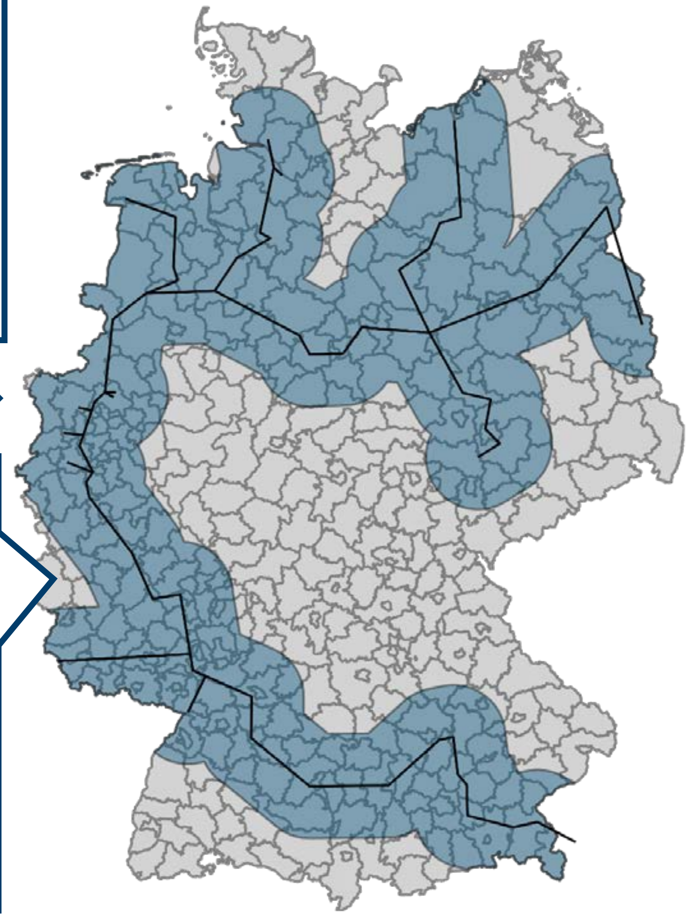
22%
Poulation.
22% GDP

6% Bev.
5% BIP

Markpotenzial
(Umkreis 50km):
Bevölkerung (2017):
~23,5 Mio. (~28%)
BIP (2017):
~800 Mrd. € (~27%)

Markpotenzial
(Umkreis 50km):
Bevölkerung (2017) [1]:
~67 Mio. (~81%)
BIP (2017) [2]:
~2.500 Mrd. € (~83%)

Distance: ~2600 km
2035-2040



[1] Eurostat (2018). Bevölkerung am 1. Januar nach Altersgruppen, Geschlecht und NUTS 3 Regionen.
[2] Eurostat (2018). Bruttoinlandsprodukt (BIP) zu laufenden Marktpreisen nach NUTS-3-Regionen.

Reassignment of Natural Gas Pipelines: Options

Pipeline Reassignment

Pipeline w/o modification	Coating	Inhibitors	Pipe-in-pipe
Additional maintenance and repair procedures	Additional safety layer limits hydrogen adsorption	supplement the gas stream undermining reactions	outer pipe for stability/safety, inner pipe for H_2 transport

- **Technically:** Pros and Cons to all of these options
- **Economically:** Options differ in cost-structure

➔ **Challenge:** balancing these aspects against each other to find the most promising solution

Current contribution to Energiewirtschaftliche Tagesfragen 7-8/2020 ;
Gillessen, B., Cerniauskas, S., Linßen J., Grube T., Robinius M., Stolten D. (2020): Umstellung von Erdgaspipelines auf Wasserstoff – eine wirtschaftliche Alternative für Deutschland?

Strengths and Weaknesses of Pipeline Reassignment Options

	Strengths	Weaknesses
Pipeline w/o modification	**Few modifications**	Increases material degradation
	Limited material fracturing under static load	
Coating	Specific protection layer against H_2 embrittlement	No established on-site coating procedures
	Developed industrial processes on metal surfaces	**Excavation of pipelines probably required**
Inhibitors (O_2, CO, SO_2)	**Limited modifications are required**	Toxicity and security risks
	Protection layer undermining hydrogen permeation	Purity requirements of hydrogen and fuel cells
Pipe-in-pipe	Combined benefits from inner and outer pipeline	Required additional material
		Excavation of pipelines probably required

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Cost Components of Most Appropriate Reassignment Options

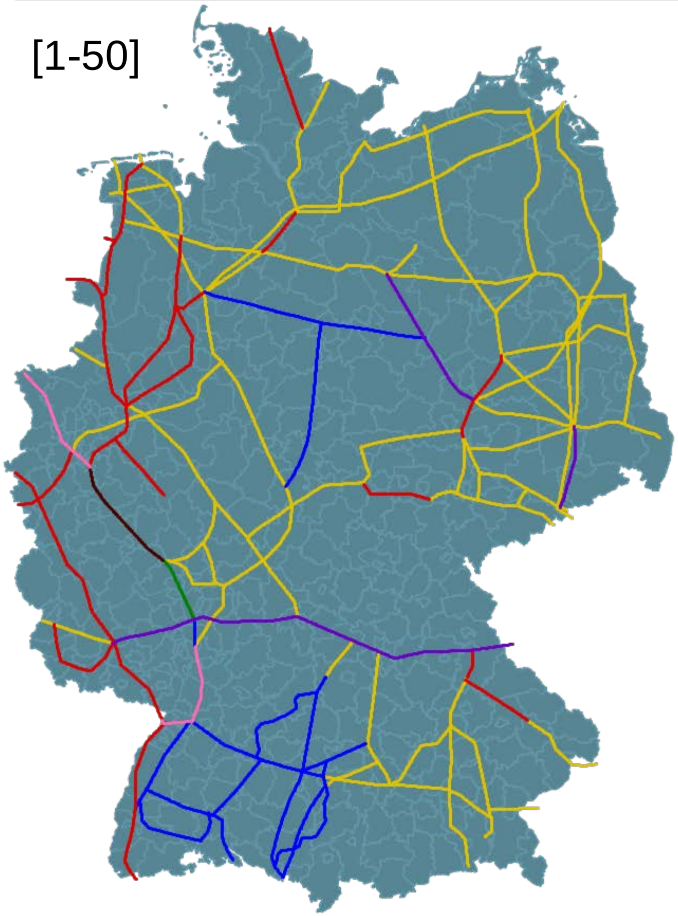
Cost component	Pipeline w/o modification		Inhibitors (O_2, CO, SO_2)	
	CAPEX	OPEX	CAPEX	OPEX
Pipeline	No	Yes	No	Yes
Compressor stations	Yes	Yes	Yes	Yes
Gas pressure regulation	Yes	Yes	Yes	Yes
Inhibitor	---	---	No	Yes
Purification	---	---	Yes	Yes
Compressor at purification facility	---	---	Yes	Yes

- No adaption of pipeline operating pressure level necessary (≈ 70 - 100 bar)
- Yet, static pressure level needed (+- some bar)
- Inhibitor is admixed to hydrogen stream and has to be removed at the hydrogen extraction point via a purification
- Inhibitors require an additional compressor due to low purification output pressure of 40 bar

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Reassignment of Natural Gas Pipelines: Technical Potential

[1-50]



	Strings	Pressure	Material	% of total length	Total
Convertible for hydrogen transport	1	> 70 bar	X70/L485	42.96 %	81.96 %
	2	> 70 bar	X70/L485	25.89 %	
	3	> 70 bar	X70/L485	13.11 %	
Non-Convertible for hydrogen transport	1	< 70 bar	X60/L415	10.72 %	18.04 %
	1	< 70 bar	X70/L485	0.90 %	
	1	> 70 bar	X60/L415	0.17 %	
	2	< 70 bar	X70/L485	1.41 %	
	2	> 70 bar	X60/L415	2.44 %	
	3	> 70 bar	X60/L415	2.40 %	

Cerniauskas S., Grube T., Robinius M., Stolten D. (2020): Reassignment Options to Use the German Natural Gas Transmission Grid for Hydrogen Transport – Final Results. 6. ESI Coordination Meeting: WP1. 12.11.2019, Frankfurt.

Reassignment of Natural Gas Pipelines: Options

Pipeline Reassignment
Semi static operation assumed
Exchange of compressor station assumed

Pipeline w/o modification	Coating	Inhibitors	Pipe-in-pipe

- Additional monitoring

- Approach is straight forward
- Comparably low investment with higher future O&M cost compared to current O&M
- Short time-to-operation

➔ Techno-economically most promising

Current contribution to Energiewirtschaftliche Tagesfragen 7-8/2020 ;
Gillessen, B., Cerniauskas, S., Linßen J., Grube T., Robinius M., Stolten D. (2020): Umstellung von Erdgaspipelines auf Wasserstoff – eine wirtschaftliche Alternative für Deutschland?

Reassignment of Natural Gas Pipelines: Options

Pipeline Reassignment
Semi static operation assumed
Exchange of compressor station assumed

Pipeline w/o modification	Coating	Inhibitors	Pipe-in-pipe
	▪ Additional safety layer limits hydrogen adsorption		▪ outer pipe for stability/safety, inner pipe for H_2 transport

- No established coating method ➔ renders further cost investigation infeasible
- Pipe-in-pipe approach likely needs excavation ➔ no benefit compared to newly-built

➔ Both approaches excluded from further investigation

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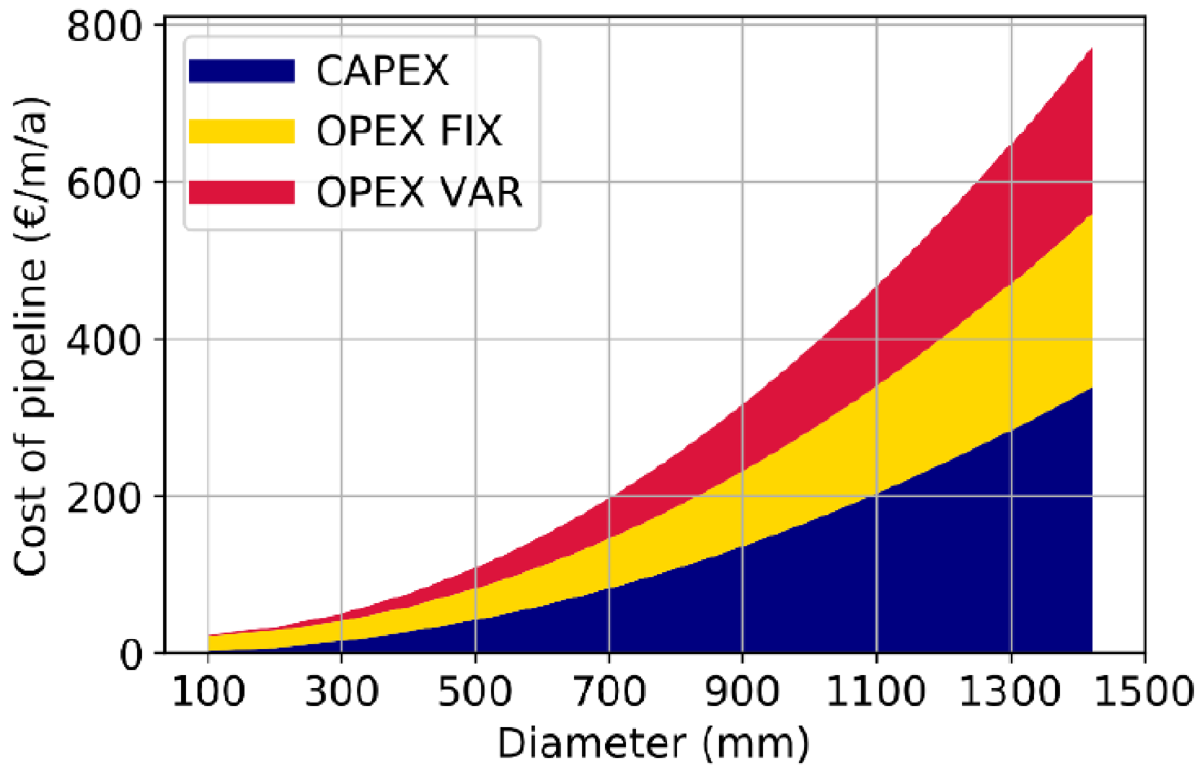
Cost Structure of Reassignment Option "Pipeline w/o Modification"

- CAPEX only for compressor and gas pressure regulation station
- OPEX FIX is primarily operation and maintenance
- OPEX VAR is the cost of recompression
- Assumption:
  Static pipeline load



- CAPEX share increases with diameter
- In case of wider diamaters CAPEX and OPEX for reassignment are almost equal

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Options for Reassignment of Natural Gas Pipelines

Pipeline Reassignment
Semi static operation assumed
Exchange of compressor station assumed

Pipeline w/o modification (PWM)	Coating	Inhibitors	Pipe-in-pipe

- supplement the gas stream undermining reactions

- Inhibitors prolong life-time of pipelines made of steels with limited suitability
- Viability depends on purity requirements of end-use technologies and inhibitor cost

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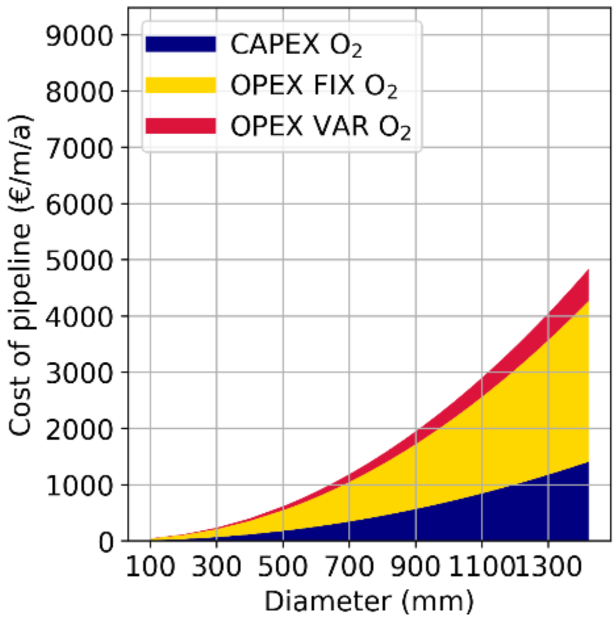
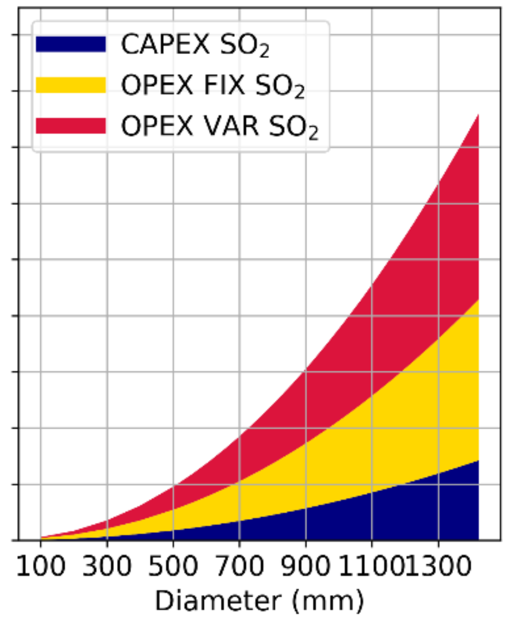
Cost Structure of Reassignment Option "Inhibitors"

Oxygen (O_2)



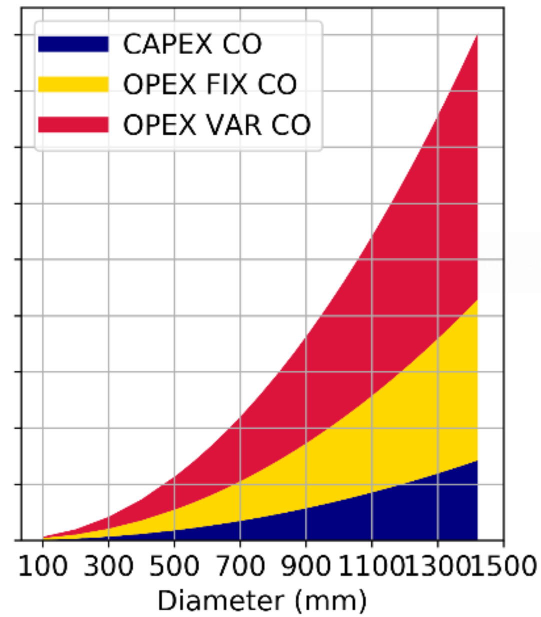
150 ppm needed
vs 4% explosive limit
Catalytic cleanup

Sulphur dioxide (SO_2)



Fuel cell poison
Cleanup via adsorption

Carbon monoxide (CO)

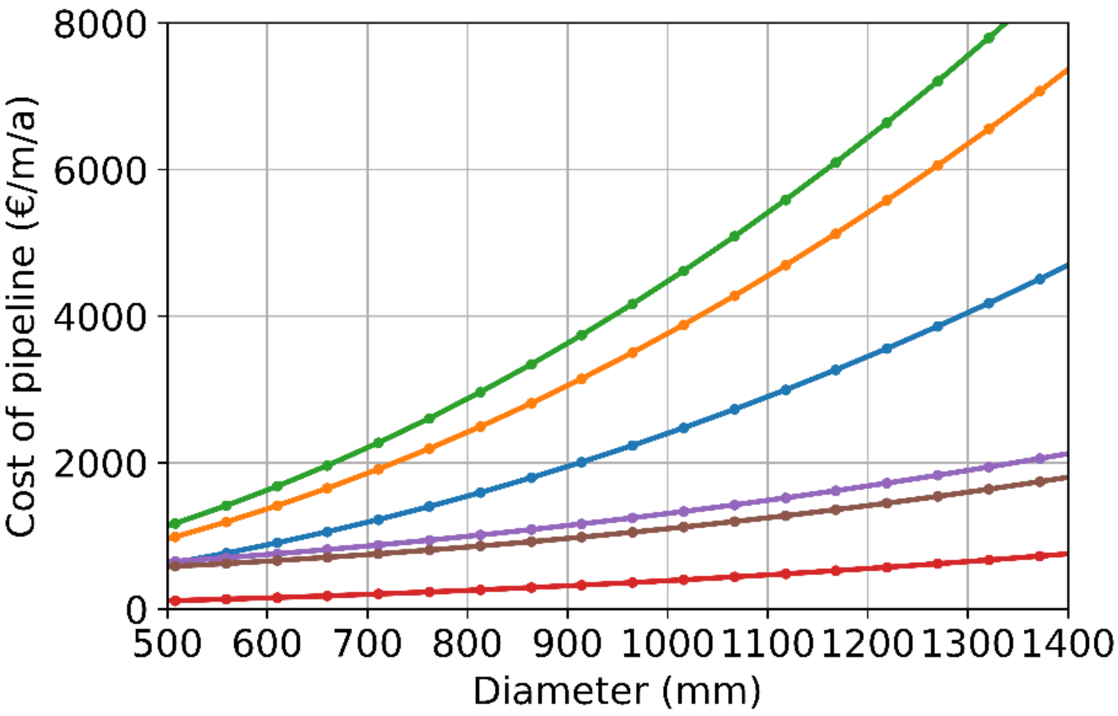


Fuel cell poison
Cleanup via adsorption

- Reassignment costs dominated by OPEX (hydrogen purification, compression & inhibitor expenditures)

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Cost Comparison of the Reassignment Alternatives and New H_2 Pipelines



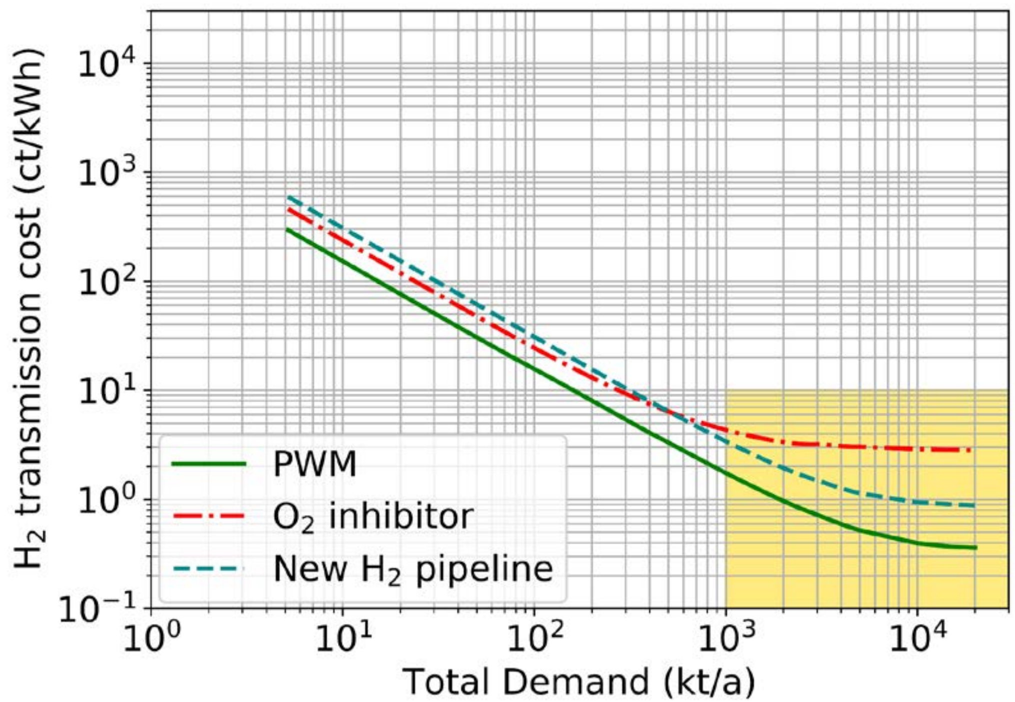
H_2 -pipeline cost for new pipelines including compressor and gas pressure regulation every 250 km

- No cost reduction for inhibitor admixture over new pipelines due to high purification cost
- Significant cost reduction for reassignment w/o modification

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Comparison of National H_2 Transmission Cost

- Overall technical reassignment potential is used, thus displaying an optimistic scenario
- Rapid cost reduction of a countrywide H_2 pipeline system with increasing demand



- Only for small overall hydrogen demand (< 250 kt p.a.); O_2 as an inhibitor provides a good pipeline reassignment option
- With sufficient market size, cost-competitive network costs of 0.6-1 ct / kWh can be achieved
- O_2 inhibition and PWM reassignment lead to cost reductions of up to 20% and 60%

Cerniauskas, S., Junco A.J.C., Grube T., Robinius M., Stolten D. (2020): Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. International Journal of Hydrogen Energy 45(21).

Thank you for your attention!

Prof. Dr. Detlef Stolten
Director of IEK-3

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