Interplay of a Network of Hydrogen Refuelling Stations (HRS) for Heavy-Duty Vehicles (HDV) and the Power System in Germany in 2050

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Fraunhofer ISI

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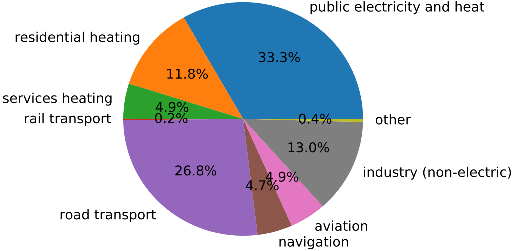
Karlsruhe Institute of Technology

The Global Carbon Dioxide Challenge...

... is not just about electricity!

EU28 CO_2 emissions in 2015:

(total 3.2 Gt CO_2, 8% of global)



Heavy-duty vehicles:

- a quarter of CO_2 emissions from road transport

Source: EEA; Tom Brown

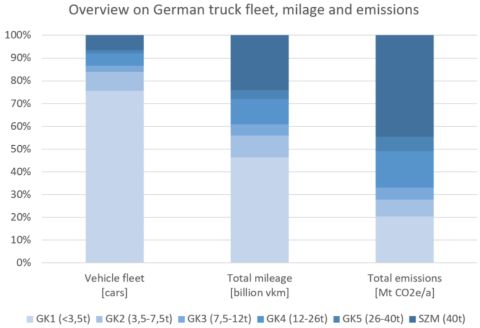
Focus: Reducing GHG emissions from German road freight transport

Role of HDV in the Transport Sector

- Of today's **170 Mt/a CO_2** emissions in transport, **40 Mt** are caused by heavy commercial vehicles (>3.5t)
- Growth of road freight transport volume
- Limited relocation potential on rail

Take-Away Message

- Especially **heavy trucks (40t)** cause disproportionately high emissions due to typically high mileages and vehicle weight.



Previous Work: A Viable Network of Hydrogen Refuelling Stations

HRS locations were determined using a Node-Capacitated Fuel Refuelling Location Model (NC-FRLM) that minimizes the number of stations to cover the hydrogen demand.

Inputs

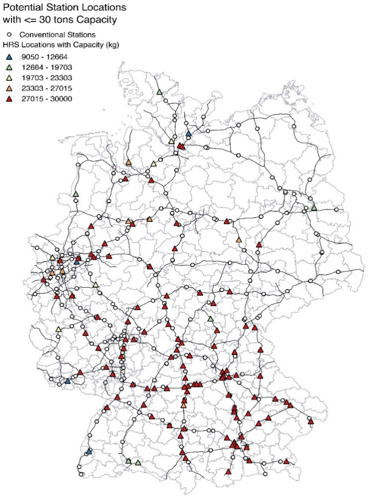
- HDV traffic density per section in the German highway network from a traffic census (BASt)
- Forecast of HDV traffic volume until 2050 (IEA)
- Driving profiles (origin-destination) for NUTS3 regions
- Technical parameters (e.g. range and consumption rates)
- Assuming 100% market diffusion of FC-HDV
- Discrete set of station sizes and sites *(7.5t, 15t, 30t)*

Outputs

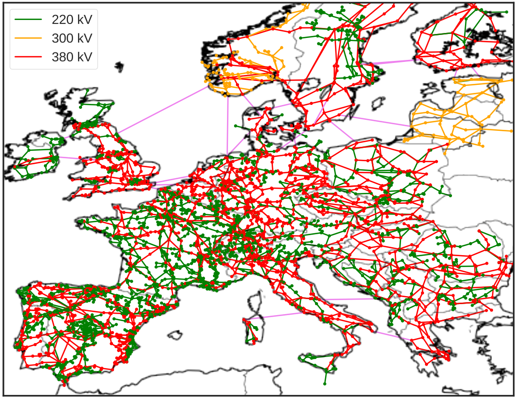
- Minimum viable set of HRS locations and sizes to serve HDV hydrogen demand **with onsite electrolysis**.

Results (2050)

- HRS network for FC-HDV-based road freight traffic consists of **142 stations** with maximum capacity of 30t/d.
- **Number of required HRS** depends on maximum capacity.



Methodology: Open Energy System Modelling with PyPSA-Eur (1/3)



- Grid data based on **GridKit** extraction of ENTSO-E interactive map
- **powerplantmatching** tool combines open databases using matching algorithm DUKE
- Renewable energy time series from open **atlite**, based on Aarhus University REatlas
- Geographic potentials for RE from land use databases processed with **glaes**
- Optional: time series aggregation with **tsam**
- Basic **validation** performed in Hörsch et al 'PyPSA-Eur: An Open Optimisation Model of the European Transmission System'
- `https://github.com/PyPSA/pypsa-eur`

Source: Tom Brown

Methodology: Open Energy System Modelling with PyPSA-Eur (2/3)

Find the long-term cost-optimal energy system, including investments and short-term costs:

$$\text{Minimise}\left(\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right) = \sum_{n}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right) + \sum_{n,t}\left(\begin{array}{c}\textbf{Marginal}\\ \textbf{costs}\end{array}\right)$$

subject to

- meeting **energy demand** at each node n (e.g. region) and time t (e.g. hour of year)
- **transmission constraints** between nodes and (linearised) power flow
- wind, solar, hydro (variable renewables) **availability time series** $\forall\ n, t$
- (installed capacity) $\leq$ (**geographical potentials** for renewables)
- **CO_2 constraint** (e.g. 30 Mt/a CO_2-Cap)
- **Dispatchability** from gas plants, battery storage, hydrogen storage, HVDC links

Source: Tom Brown

Methodology: Open Energy System Modelling with PyPSA-Eur (3/3)

Find the long-term cost-optimal energy system, including investments and short-term costs:

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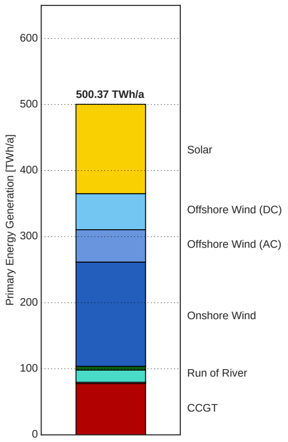
Model Scope

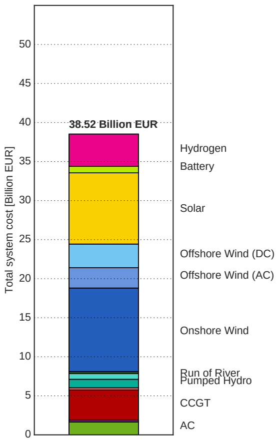
- German extract of European model
- Temporal resolution of **2 hours** (4380 snapshots)
- Spatial resolution of **333 nodes**
- max. **30 Mt/a** CO_2 emissions

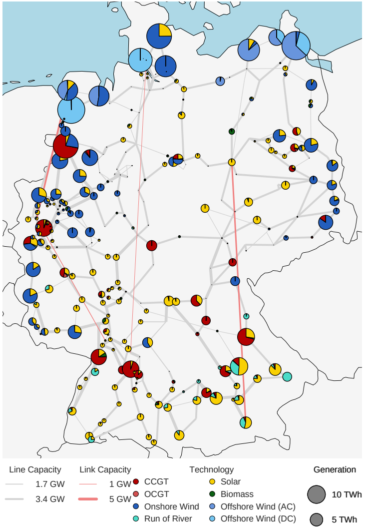
Experimental Setup

- greenfield optimisation
- power plants are extendable
- excluding nuclear and coal power plants
- transmission grid is extendable
- HVDC links route options from TYNDP
- hydrogen and battery storage options

The German Power System without HRS (30 Mt/a CO_2-Cap)







76.98 EUR/MWh

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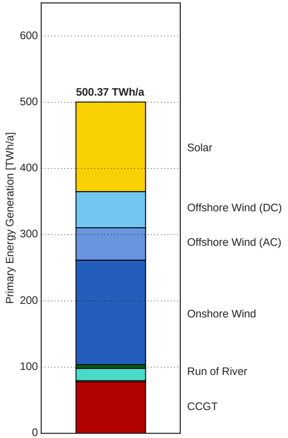

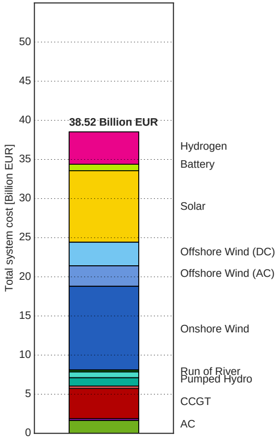

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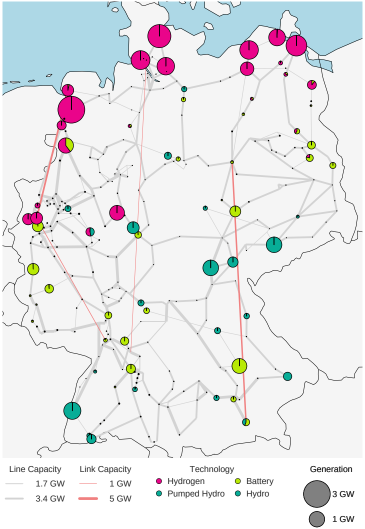


Two HRS Dimensioning Scenarios for Power System Integration

Scenario:
System-Ignorant Investment in HRS

- locally optimal station size
- minimise capital expenditures (CAPEX)

Scenario:
System-Aware Investment in HRS

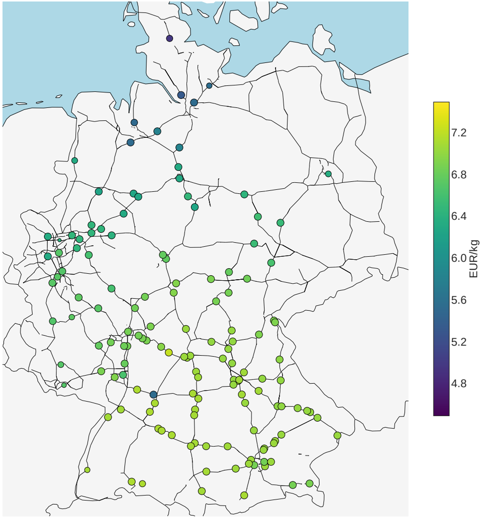
- globally optimal station size
- serve to minimise total system costs

In both scenarios...

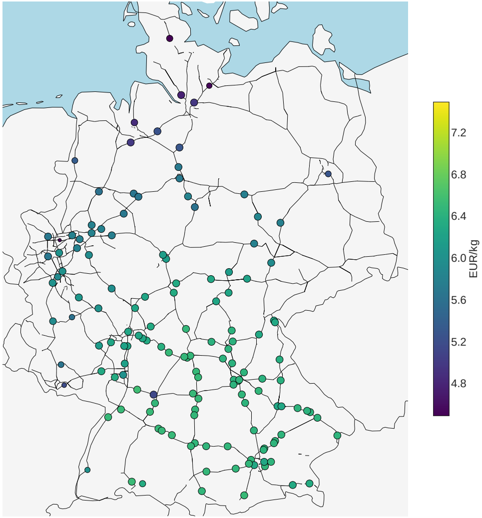
- local hydrogen demand must be met,
- no reconversion of hydrogen to power is allowed at HRS,
- maximum hydrogen storage capacity is 30 tonnes (1000 MWh),
- connection cost of electrolyser is proportional to distance to nearest (U-)HV-substation,
- CO_2-emissions for electricity sector plus refuelling infrastructure must not exceed 30 Mt/a.

Levelised Cost of Hydrogen – A North-South Divide

System-Ignorant HRS

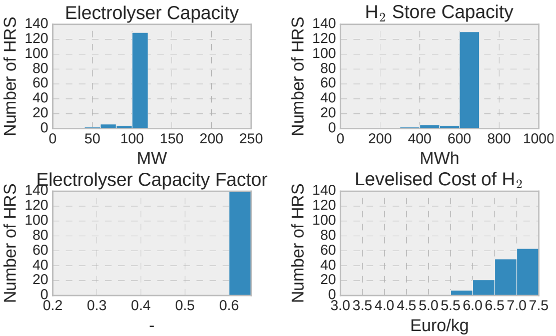


System-Aware HRS



Let's look at this from another perspective...

System-Ignorant HRS



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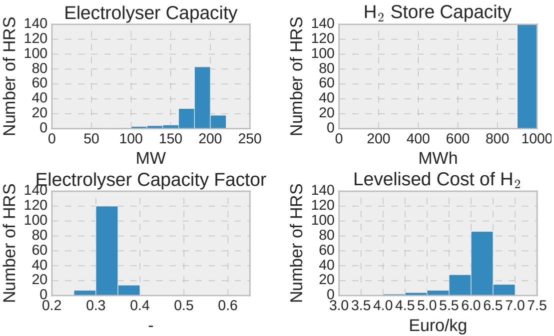
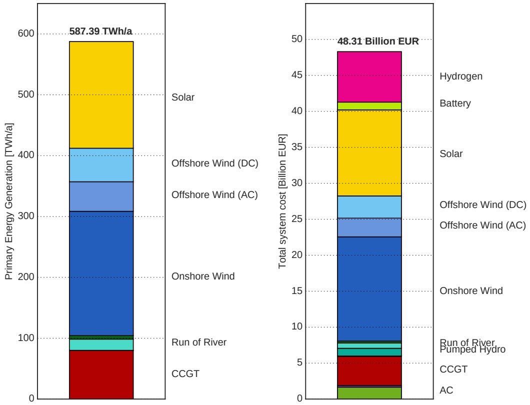


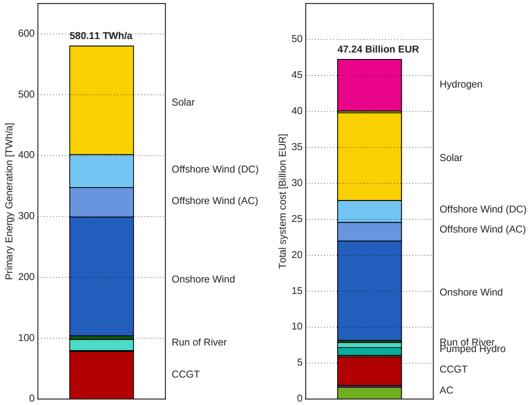
How Does Total System Cost Change with More Flexible HRS?

System-Ignorant HRS



Average: **82.25 EUR/MWh**

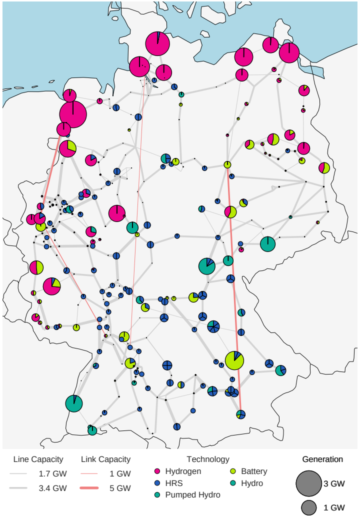
System-Aware HRS



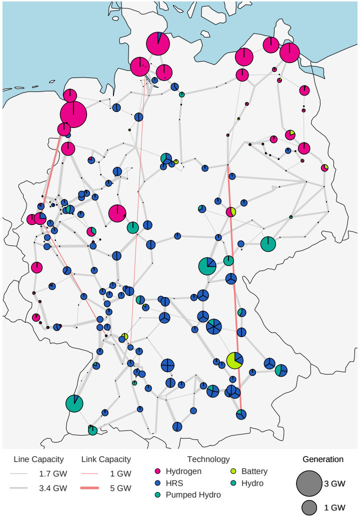
Average: **81.43 EUR/MWh**

How did System-Aware HRS Sizing Change Storage Placement?

System-Ignorant HRS



System-Aware HRS



In a Nutshell...

	Without HRS	System-Ignorant	System-Aware
Annual Electricity Demand [TWh]	463	537	537
– Hydrogen Refuelling	–	74	74

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LCOH [EUR/kg]	–	6.66	5.97
– CAPEX Share [%]	–	9.6	20.0
Electrolyser Capacity Factors [-]	–	0.61	0.33

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Total System Cost [EUR/MWh]	77.0	82.3	81.4
Total System Cost [bn EUR]	38.5	48.3	47.2
– HRS Electrolysis	–	1.0	1.8
– HRS Storage	–	0.2	0.3
– Other Storage (Battery, Hydro & Hydrogen)	6.0	8.0	6.4

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Generation Fleet [GW]	304	381	383
HRS Electrolysers [GW]	–	13.9	25.6
HRS Hydrogen Storage [GWh]	–	93	142

Can Modelling and Analysis Still Improve? Always!

On finding a suitable HRS network...

- Better data on trips and refuelling profiles (national)
- European road freight traffic
- Pipeline transport of hydrogen

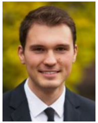
On analysing the grid impact...

- Allow reconversion of hydrogen
- Analyse with fully sector-coupled model (heat, industry, transport, power)
- Extend to European model

What are the Take-Away Messages?

1. A **node-capacity limit** has a major impact on the number of refuelling stations required.
2. **Levelised Cost of Hydrogen (LCOH) vary regionally** depending on local cost of electricity production.
3. **System-aware dimensioning** of hydrogen refuelling infrastructure reduces LCOH (0.7 EUR/kg_{H_2}) as well as total system cost (1 Billion EUR/a).
4. **Co-optimization of multiple energy sectors** is important for planning to exploit synergies and cost reduction potentials.
5. **Nodal pricing** can forward useful information about total system cost.

Contact Details



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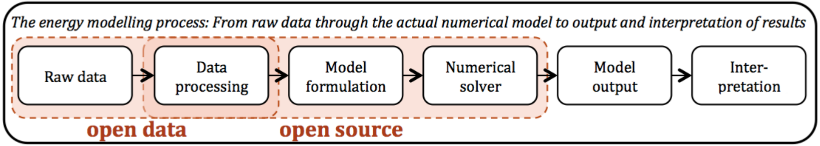
Idea of Open Energy Modelling

The whole chain from raw data to modelling results should be open:



Open data + free software $\Rightarrow$ Transparency + Reproducibility

There's an initiative for that! Sign up for the mailing list / come to the next workshop:

openmod open energy modelling initiative

openmod-initiative.org

Source: Tom Brown, openmod

Assumptions of Fuel Refuelling Location Model

- A vehicle drives along a single OD path that is determined as the shortest path from the centre of the origin area to the centre of the destination area.
- The traffic volume on a single OD path is known in advance.
- A station will only be located at one of the nodes that is part of the highway network.
- The distance travelled is proportional to the fuel consumption.
- Only trips with a distance greater than 50 km need refuelling.
- The drivers have full knowledge about the location of AFS along the path and refuel efficiently to complete a single trip.
- The maximum driving range that can be achieved for each single refuelling is similar for each vehicle.
- Each vehicle starts and ends its trip with the same fuel level, which is sufficient 136 for a specific range.
- Nodes and AFS are capacitated.

NC-FRLM

Table 1. Formulation of the NC-FRLM

General Formula (Flow Refueling Location Model; FRLM):

Objective :

$$Min \sum_{i \in N} z_i \quad (1)$$

Subject to:

$$\sum_{i \in K^q_{j,k}} z_i \geq y_q, \forall q \in Q, a_{j,k} \in A_q \quad (2)$$

$$\sum_{q \in Q} f_q y_q \geq S \quad (3)$$

$$y_q, z_i \in \{0,1\}, \forall q \in Q, i \in N \quad (4)$$

Additional Constraints for Node-Capacitated FRLM (NC-FRLM):

$$\sum_{q \in Q} f_q (e_{iq} + r_{iq}) \cdot p \cdot y_q \cdot g_{iq} \cdot x_{iq} \leq c \cdot z_i, i \in N \quad (5)$$

$$\sum_{i \in K^q_{j,k}} x_{iq} = y_q, \forall q \in Q, a_{j,k} \in A_q \quad (6)$$

$$x_{iq} \leq z_i, i \in N, q \in Q \quad (7)$$

$$0 \leq x_{iq} \leq 1 \quad (8)$$

Table 2: Nomenclature for sets, parameters and decision variables of the NC-FRLM

Sets and Indices:

A_q	Set of directional arcs on the shortest path q, sorted from the origin to the destination.
K^q_{jk}	Set of all potential refuelling station sites / nodes that can refuel the directional arc $a_{j,k}$ in A_q
N	Set of all nodes that built the highway network, N = {1,…n}
Q	Set of all OD pairs
i,j,k	Indices of potential facilities at nodes
q	Index of OD pairs

Parameters:

$a_{j,k}$	Unidirectional arc from node j to node k
f_q	Total vehicles flow per OD trip refuelled
S	Objective percentage of the traffic flow refuelled
c	Capacity at node i
e_{iq}	Distance from origin point to node i in path q
r_{iq}	Distance from node i to destination point in path q
p	Fuel consumption
g_{iq}	Potential location indicator, 1 if node i is in path q, 0 if otherwise

Variables:

z_i	z_i = 1 if a refuelling station is built at node i. z_i = 0 if otherwise
y_q	y_q = 1 if the flow on path q is refuelled. y_q = 0 if otherwise
X_{iq}	Proportion of vehicles in path q that refuel in node i, 0<= x_{iq} <= 1

Python for Power System Analysis (PyPSA)

Our free software PyPSA is online at https://pypsa.org/ and on github. It can do:

- Static **power flow**
- **Linear optimal power flow** (LOPF) (multiple periods, unit commitment, storage, coupling to other sectors)
- **Security-constrained LOPF**
- Total electricity system **investment optimisation**

It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables and sector coupling.

Source: Tom Brown

PyPSA: Linear power flow

The linearised **power flows** f_ℓ for each line $\ell \in \{1, \dots L\}$ in an AC network are determined by the nodal power injections p_i, the **reactances** x_ℓ of the transmission lines by enforcing Kirchhoff's Current Law (energy conservation), then Voltage Law (angle differences around closed cycles) **directly on cycles** $C_{\ell c}$ rather than using auxilliary angle variables θ_i:

$$\sum_\ell C_{\ell c} K_{i\ell} \theta_i = \sum_\ell C_{\ell c} x_\ell f_\ell = 0$$

This solves faster and more stably than the angle formulation using commercial LP solvers.

Transmission flows cannot exceed the capacities $\bar{P}_\ell$ of the transmission lines (with buffer $s_{N-1} = 0.7$ to approximate $N-1$ security):

$$|f_{\ell,t}| \leq s_{N-1} \cdot \bar{P}_\ell$$

Since the impedances x_ℓ change as capacity $\bar{P}_\ell$ is added, we do multiple runs and iteratively update the x_ℓ after each run, rather than risking a non-linear (or MILP) optimisation.

Source: Tom Brown

PyPSA: Model Inputs and Outputs

Inputs	Description
$d_{i,t}$	Demand (inelastic)
$G_{i,s,t}$	Per unit availability for wind and solar
$\hat{G}_{i,s}$	Generator installable potentials
various	Existing hydro data
various	Grid topology
η_*	Storage efficiencies
$c_{i,s}$	Generator capital costs
$o_{i,s,t}$	Generator marginal costs
c_ℓ	Line costs

$\rightarrow$

Outputs	Description
$G_{i,s}$	Generator capacities
$g_{i,s,t}$	Generator dispatch
F_ℓ	Line capacities
$f_{\ell,t}$	Line flows
λ_*, μ_*	Lagrange/KKT multipliers of all constraints
f	Total system costs

Source: Tom Brown

Costs and assumptions for the electricity sector (projections for 2030)

Quantity	Overnight Cost [EUR]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40

Interest rate of 7%, storage efficiency losses, only gas has CO_2 emissions, gas marginal costs.

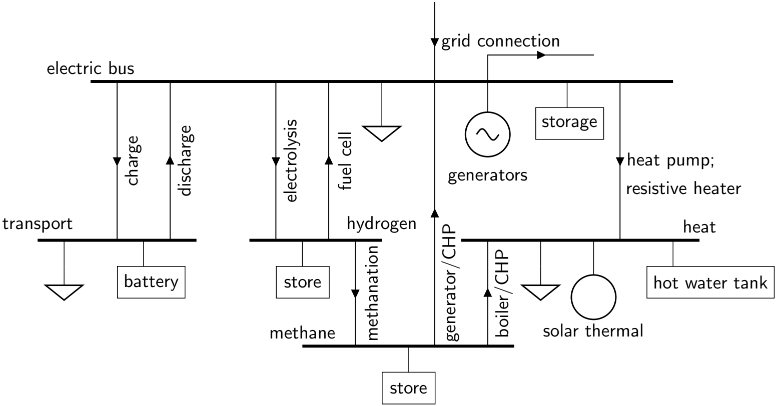
Batteries can store for 6 hours at maximal rating (efficiency 0.9×0.9), hydrogen storage for 168 hours (efficiency 0.75×0.58).

Source: Tom Brown

Costs and assumptions for Hydrogen Refuelling Stations

Quantity	CAPEX [EUR]	Unit	FOM [%/a]	Lifetime [a]	η [%]	r [%]
Electrolyser	510	kW_{el}	4	20	68	7
Hydrogen Store	19	kWh	1	20	100	7
Grid Connection	400	MWkm	2	20	100	7

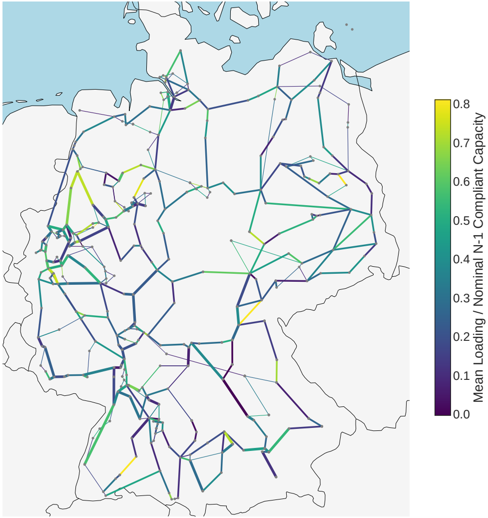
Sector coupling: A new source of flexibility



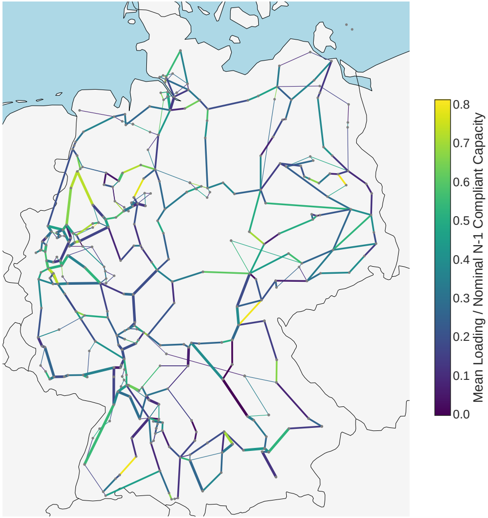
Source: Tom Brown

Network impact of HRS is very limited: mean AC-line loading

System-Ignorant HRS

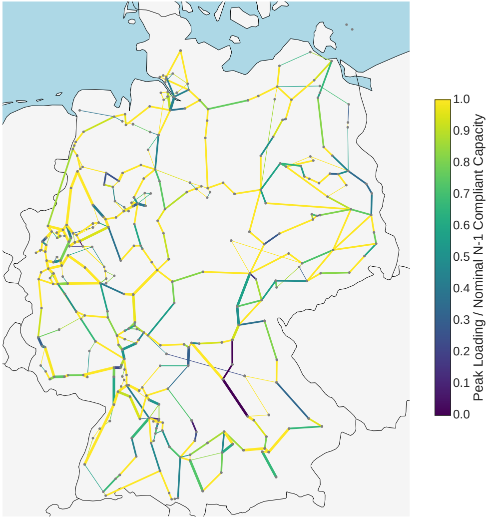


System-Aware HRS



Network impact of HRS is very limited: peak AC-line loading

System-Ignorant HRS



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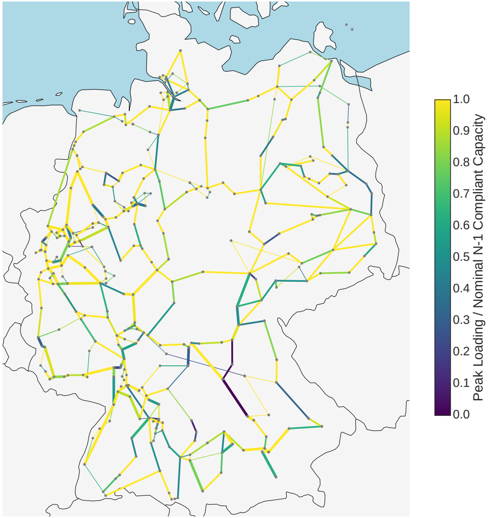
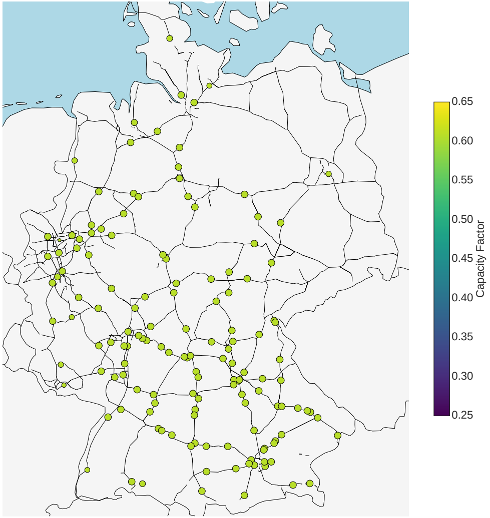


Capacity Factors of Onsite Electrolysers decrease with oversizing

System-Ignorant HRS



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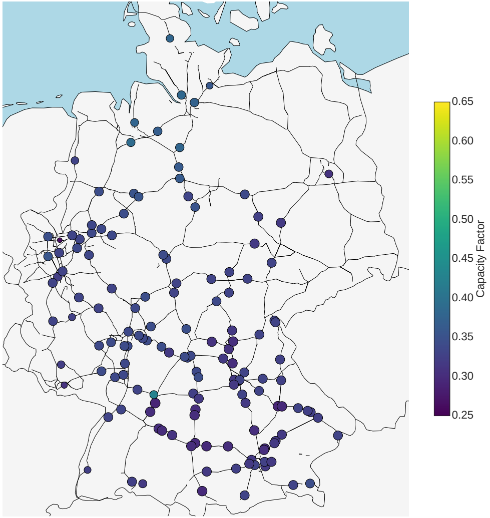
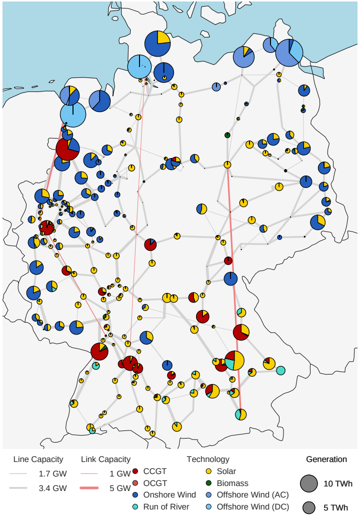


Does the Regional Generation Mix Change with Flexible HRS?

System-Ignorant HRS



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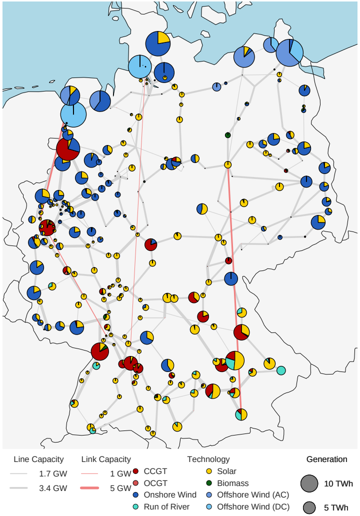
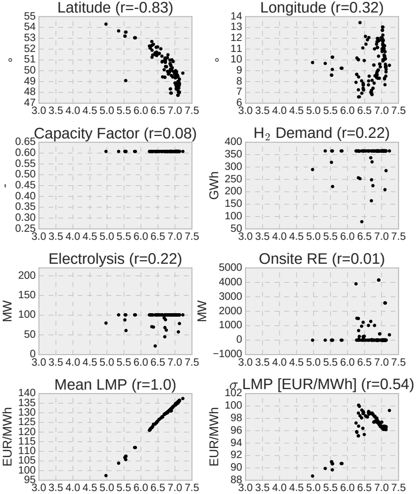


What Characteristics are Correlated to the Cost of Hydrogen?

System-Ignorant HRS



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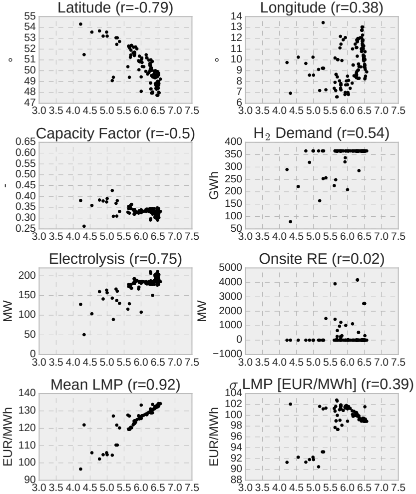
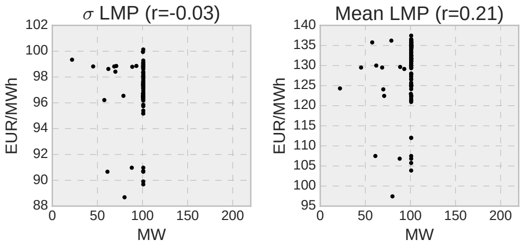
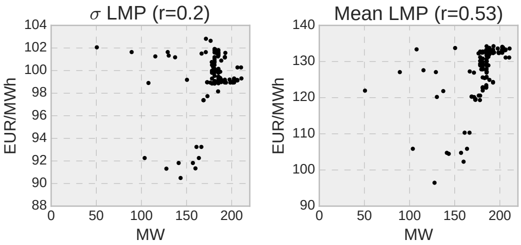


How do Electrolyser Capacity and Price Characteristics Correlate?

System-Ignorant HRS



System-Aware HRS



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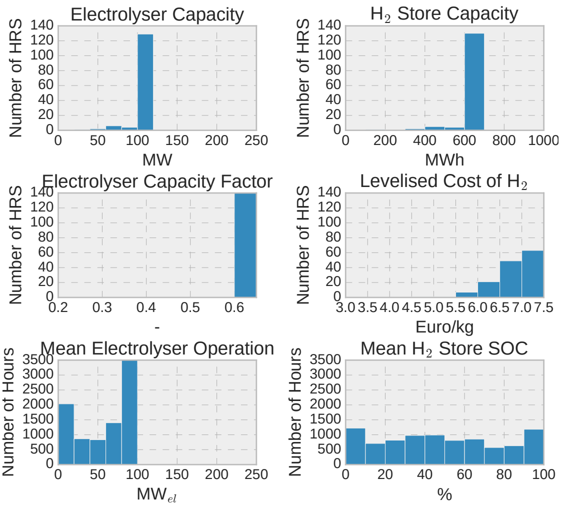

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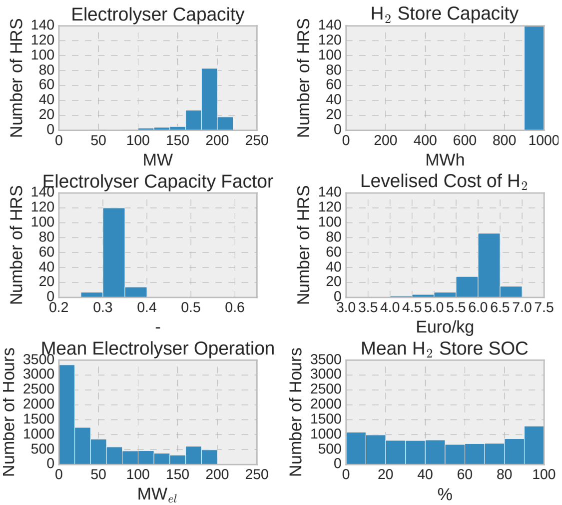
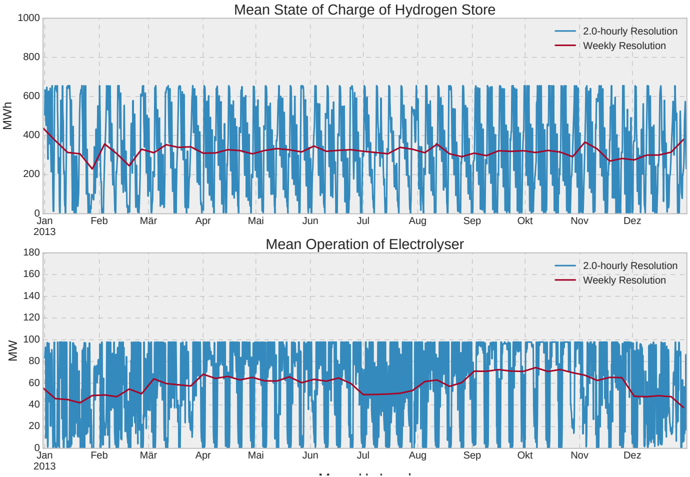


Timeseries: System-Ignorant HRS



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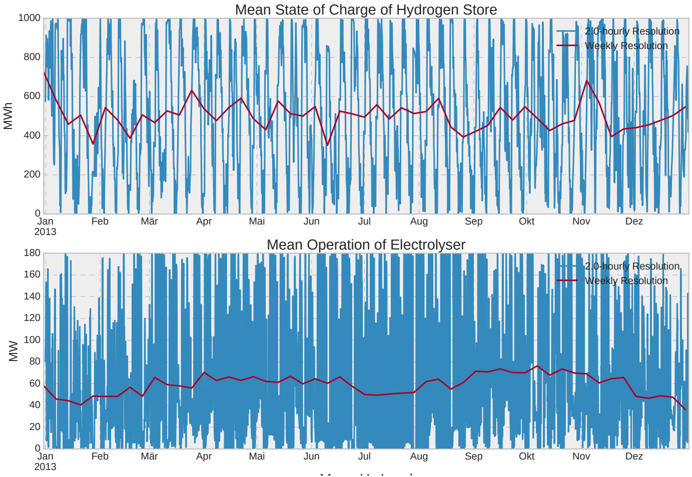
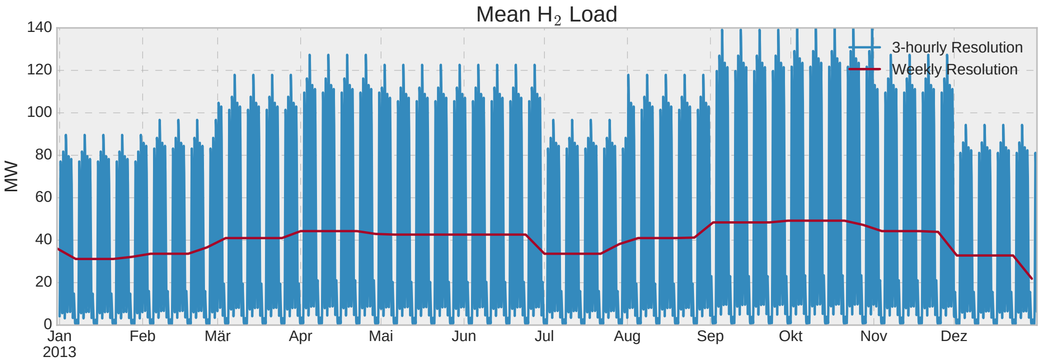


Timeseries: Hydrogen Demand



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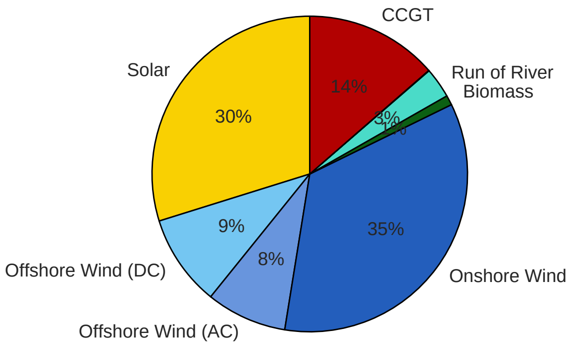

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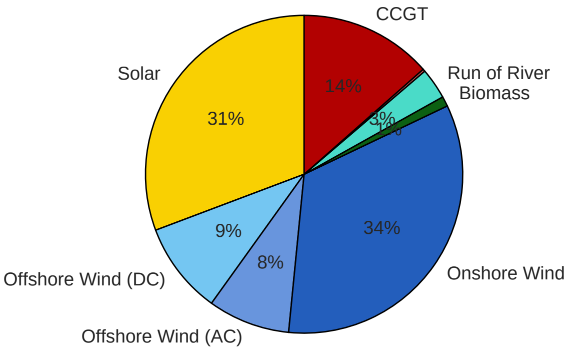

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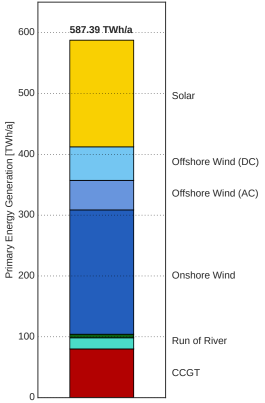
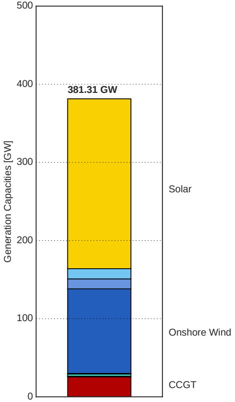
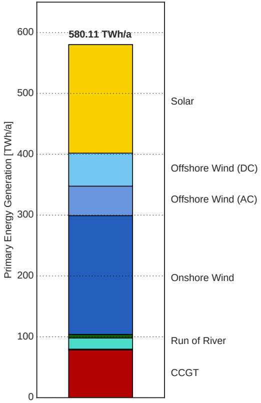
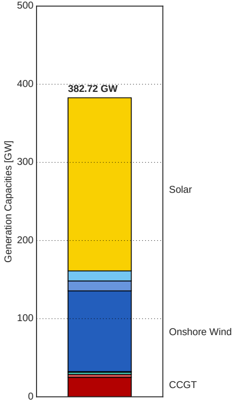




82.25 EUR/MWh

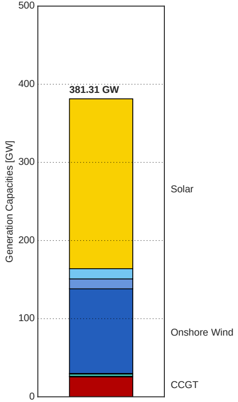
System-Aware HRS

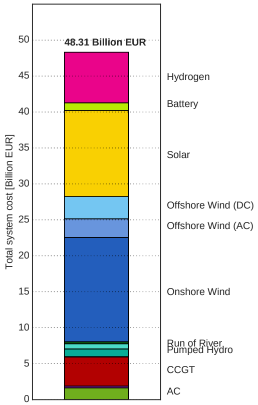




81.43 EUR/MWh

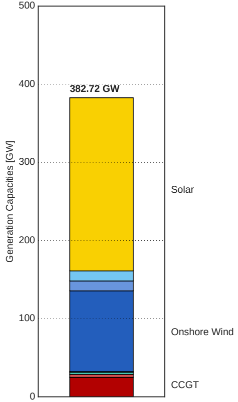
System-Ignorant HRS

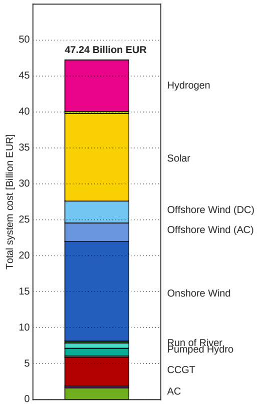




82.25 EUR/MWh

System-Aware HRS





81.43 EUR/MWh

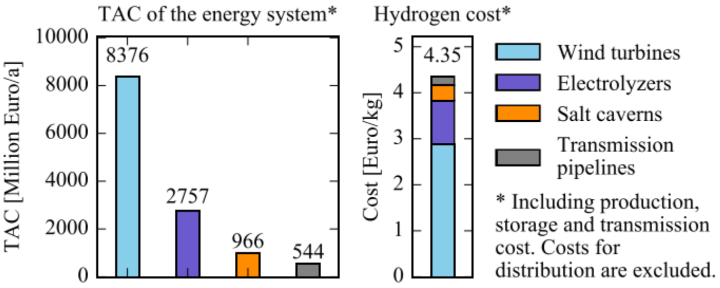


Figure 10: Total annual cost of the energy supply system (left) and mass specific hydrogen cost (right) in the hydrogen-to-mobility scenario.

Welder, L., Ryberg, D. S., Kotzur, L., Grube, T., Robinius, M., & Stolten, D. (2018). Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy, 158, 1130–1149.

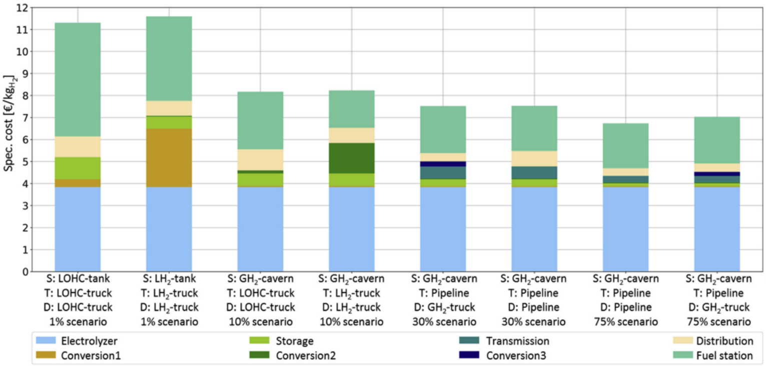


Fig. 8 – Specific H_2 costs as a function of market scenarios, technology pathways and infrastructural components.

Emonts, B., Reuß, M., Stenzel, P., Welder, L., Knicker, F., Grube, T., & Stolten, D. (2019). Flexible sector coupling with hydrogen: A climate-friendly fuel supply for road transport. International Journal of Hydrogen Energy.

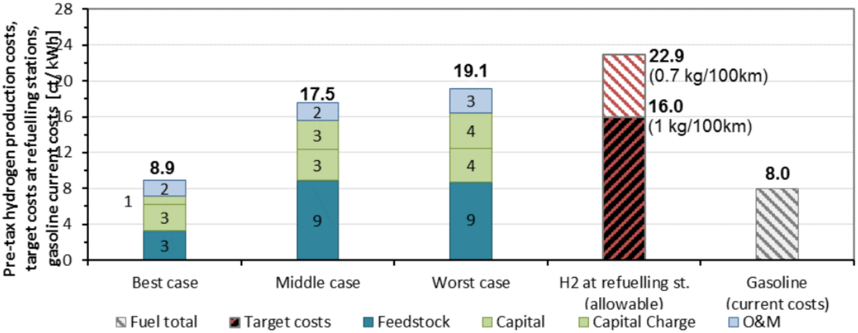


Figure 16. Pre-tax cost analysis for the three cases from Table 2.

Robinius, M., Otto, A., Syranidis, K., Ryberg, D. S., Heuser, P., Welder, L., Stolten, D. (2017). Linking the power and transport sectors - Part 2: Modelling a sector coupling scenario for Germany. Energies, 10(7), 1–23.

Table 2. Input values of pre-tax hydrogen cost analysis of the updated energy concept from the IEK-3, compare Figure 16.

Input-Data	Best Case	Middle Case	Worst Case
Electricity costs (ct/kWh)	2.4	5.8	6
Weighted average cost of capital (WACC) (%)	3	8	8
Electrolysis:			
Investment costs (€/kW)	446	500	500
Efficiency (%)	76	70	70
Operating costs as a share of the investment costs (%)	0.4	3	3
Hydrogen Storage (Salt Caverns):			
Size (TWh)	15	48	90
Costs (Bil. €)	2.7	8	15
Hydrogen Pipeline Grid:			
Peak hydrogen demand (Mil. t)	2.9	2.9	2.9
Costs transmission pipeline (Bil. €)	5.4	6.7	8.3
Costs distribution pipeline (Bil. €)	10.1	12	14.6
Hydrogen Fuelling Station:			
Costs per fuelling station (Mil. €)	2	2	2

Robinius, M., Otto, A., Syranidis, K., Ryberg, D. S., Heuser, P., Welder, L., Stolten, D. (2017). Linking the power and transport sectors - Part 2: Modelling a sector coupling scenario for Germany. Energies, 10(7), 1–23.