Optimal Design and Operation of Community Hydrogen Generation and Storage Applications

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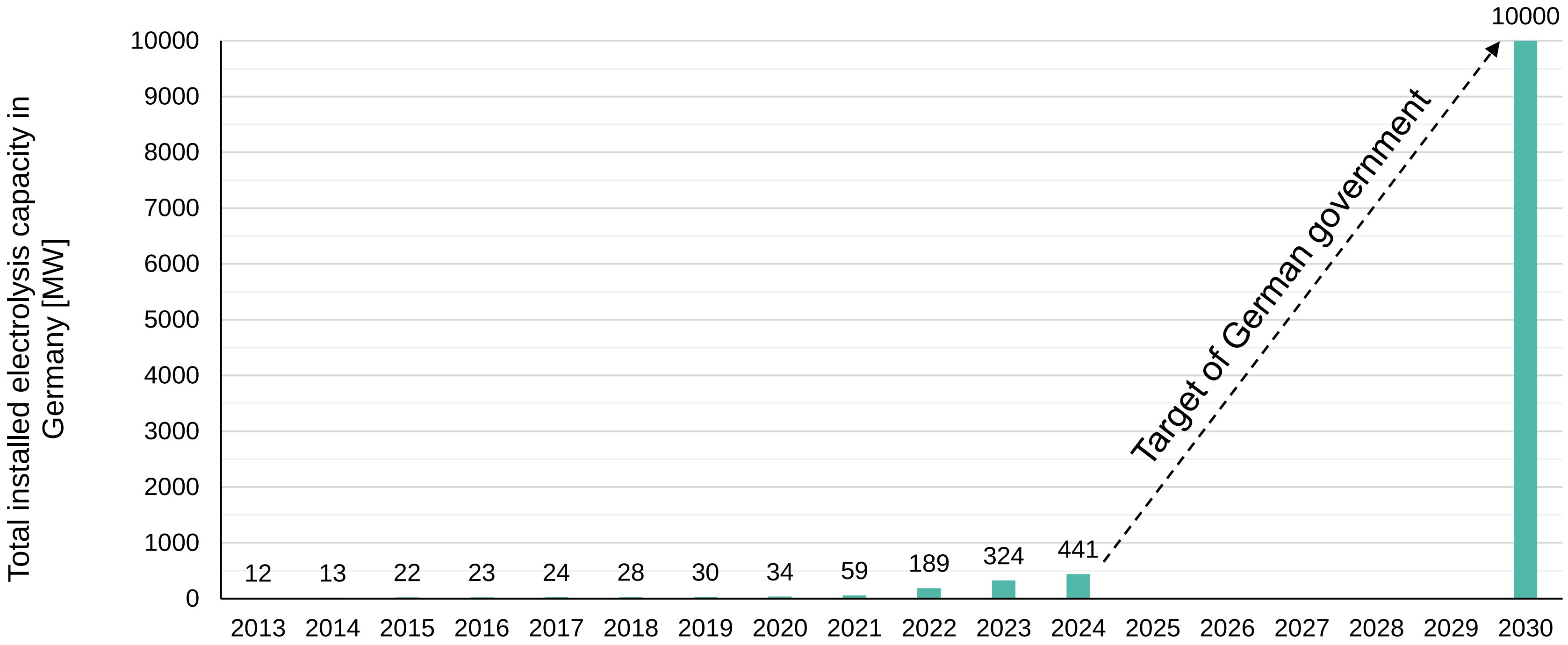
Motivation



Data: Own research; SPD, Die Grünen und FDP, 2021

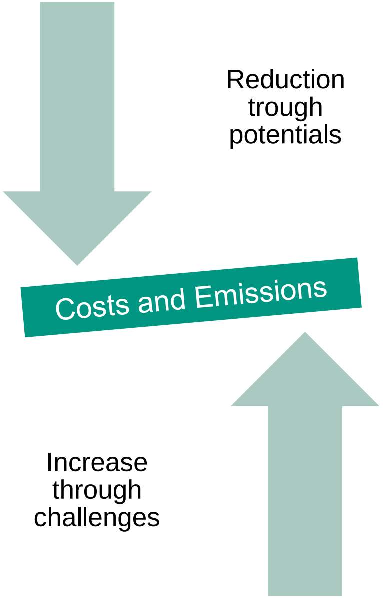
Potentials & Challenges of Seasonal Storage

Potentials

Less activation of fossil power plants

Less shutdowns of renewables

Less heat pump capacity & operation



Challenges

High investment costs

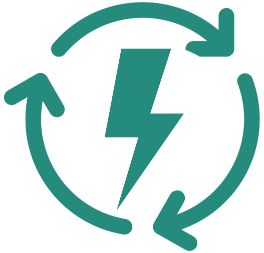
High life cycle greenhouse gas emissions

Operating strategy

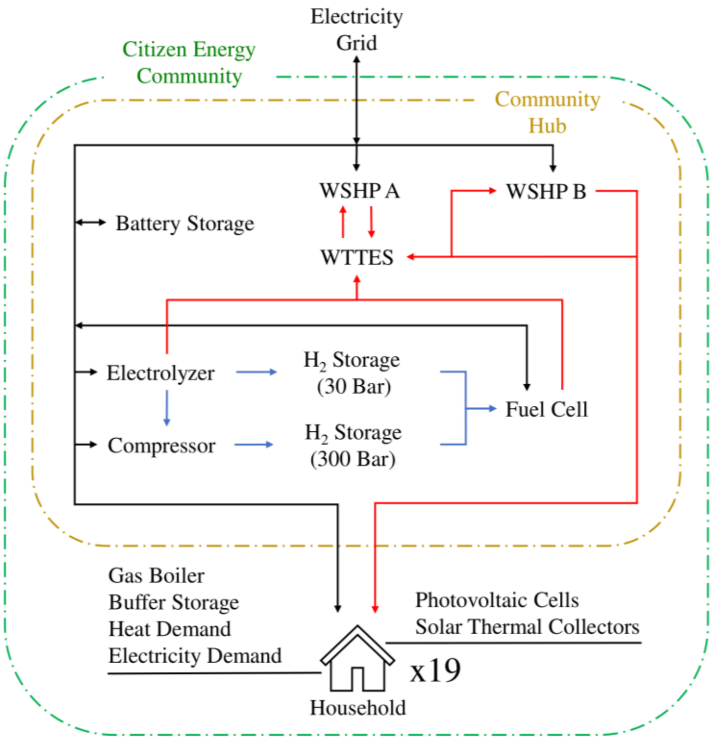
Research Questions

1) What **market, policy, and infrastructural conditions** are required to achieve economic and ecological benefits with a hydrogen system over a 30-year period?

2) How can an **operating strategy** be implemented to achieve these economic benefits in operation?



Layout & Hydrogen Storage Types



Hydrogen storage (30 bar)
Filled with hydrogen at the output pressure of an electrolyzer

Hydrogen storage (300 bar)
Filled with hydrogen at the output pressure of a compressor

Heat Pipe Electricity Line H_2 Pipe

WSHP: Water Source Heat Pump
WTTES: Water Tank Thermal Energy Storage

Challenges for an Operating Strategy

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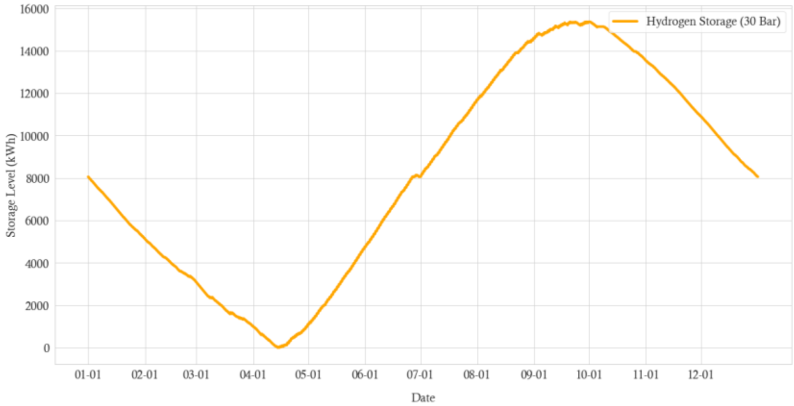
Threoretical Optimum

One 365 days scheduling horizon linear program

→ Seasonal storage curve emerges under suitable conditions



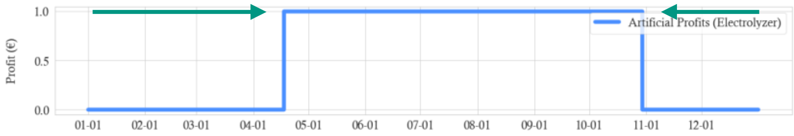
Operating Strategy

Multiple 48 hours scheduling horizon linear programs

→ Lack of incentive for long-term operation of the seasonal storage

Solution:

1) Implement artificial costs and profits for electrolyzer and fuel cell
2) Identifiy cost and profit levels through genetic algorithm and grid search application



Objective, Balance & Energy Capacity

$$\min \sum_{\theta \in \Theta} \sum_{\lambda \in \Lambda} \sum_{k \in K} c_k(\lambda, \theta) \cdot w_k + \sum_{\zeta \in Z} \sum_{t \in T} u(\zeta, t) \cdot M$$

$s.t.$

$$-\sum_{\theta \in \Theta} \zeta^c(\lambda, \theta, \zeta, t) = \sum_{\theta \in \Theta} (\zeta^p(\lambda, \theta, \zeta, t) + \zeta^x(\lambda, \theta, \zeta, t)) \quad \forall \zeta \in Z, \lambda \in \Lambda, t \in T$$

$$\sum_{\zeta \in Z} (\zeta^p(\lambda, \theta, \zeta, t) + \zeta^x(\lambda, \theta, \zeta, t)) \leq e^c(\lambda, \theta) \quad \forall \zeta \in Z, \lambda \in \Lambda, \theta \in \Theta, t \in T$$

$$-\zeta^c(\lambda, \theta, \zeta, t) \leq e^c(\lambda, \theta) \quad \forall \zeta \in Z, \lambda \in \Lambda, \theta \in \{\Theta^d, \Theta^s, \Theta^t\}, t \in T$$

Objective function

Energy system balance

Energy capacity limits carrier production, export & consumption

θ	Technology	ζ	Carrier	Θ^d	Demand technology set	e^c	Energy capacity
Θ	Technology set	Z	Carrier set	Θ^s	Storage technology set	c_k	Technology-related cost or revenue
λ	Location	t	Timestep	Θ^t	Transmission technology set	w_k	Cost class weight
Λ	Location set	T	Timestep set	ζ^c	Consumed carrier quantity (≤ 0)	u	Unsatisfied demand
k	Cost class	Θ^ρ	Resource conversion technology set	ζ^p	Produced carrier quantity	M	Unsatisfied demand penalty factor
K	Cost class set	Θ^ζ	Carrier conversion technology set	ζ^x	Exported carrier quantity		

Resource Conversion, Demand & Transmission

$$\zeta^c(\lambda,\theta,\zeta,t) \geq d(\lambda,\theta,\zeta,t) \qquad \forall \zeta \in Z, \lambda \in H, \theta \in \Theta^d, t \in T$$

$$\frac{\zeta^p(\lambda,\theta,\zeta,t)+\zeta^x(\lambda,\theta,\zeta,t)}{\eta^\rho(\lambda,\theta,\zeta)} \leq \rho^{av}(\lambda,\theta,t) \qquad \forall \zeta \in Z, \lambda \in \Lambda, \theta \in \Theta^\rho, t \in T$$

$$\rho^{av}(\lambda,\theta,t) = \begin{cases} \rho^t(\lambda,\theta,t)\cdot\rho^{ar}(\lambda,\theta), & \text{if } \lambda \in H \text{ and } \theta \in \Theta^\rho \\ \infty, & \text{else} \end{cases} \qquad \forall \lambda \in \Lambda, \theta \in \Theta, t \in T$$

$$\sum_{\theta\in\Theta^\rho} \rho^{ar}(\lambda,\theta) \leq r(\lambda) \qquad \lambda \in H$$

$$\frac{\zeta^p(\lambda,\lambda^t,\theta,\zeta,t)}{\eta^d(\lambda,\theta,t)} = -\,\zeta^c(\lambda,\lambda^t,\theta,\zeta,t) \qquad \forall \lambda,\lambda^t \in \Lambda, \zeta \in Z, \theta \in \Theta^t, t \in T$$

Demand limits carrier consumption

Available resource limits carrier production & export

Available resource is determined by resource quantity per energy capacity & used resource area, which is limited by the roof area

Carrier consumption & production of transmission technologies

θ	Technology	Z	Carrier set	ζ^c	Consumed carrier quantity (≤ 0)	ρ^{av}	Available resource quantity
Θ	Technology set	t	Timestep	ζ^p	Produced carrier quantity	ρ^t	Resource quantity per energy capacity
λ	Location	T	Timestep set	ζ^x	Exported carrier quantity	ρ^{ar}	Used resource area
λ^t	Transmission endpoint	Θ^ρ	Resource conversion technology set	H	Household set	r	Roof area
Λ	Location set	Θ^d	Demand technology set	d	Household demand (≤ 0)	η^d	Energy efficiency per distance
ζ	Carrier	Θ^t	Transmission technology set	η^ρ	Resource efficiency		

Carrier Conversion & Storage

$$\frac{\zeta^p(\lambda,\theta,\zeta^{fo},t)}{\eta^\zeta(\lambda,\theta,\zeta^{fi},\zeta^{fo})} = -\zeta^c(\lambda,\theta,\zeta^{fi},t) \qquad \forall \zeta^{fi},\zeta^{fo} \in Z, \lambda \in \Lambda, \theta \in \Theta^\zeta, t \in T$$

$$\frac{\zeta^c(\lambda,\theta,\zeta^{si},t)}{\zeta^{ri}(\lambda,\theta,\zeta^{fi},\zeta^{si})} = \zeta^c(\lambda,\theta,\zeta^{fi},t) \qquad \forall \zeta^{fi},\zeta^{si} \in Z, \lambda \in \Lambda, \theta \in \Theta^\zeta, t \in T$$

$$\frac{\zeta^p(\lambda,\theta,\zeta^{so},t)}{\zeta^{ro}(\lambda,\theta,\zeta^{fo},\zeta^{so})} = \zeta^p(\lambda,\theta,\zeta^{fo},t) \qquad \forall \zeta^{fo},\zeta^{so} \in Z, \lambda \in \Lambda, \theta \in \Theta^\zeta, t \in T$$

$$s(\lambda,\theta,\zeta,t) = s(\lambda,\theta,\zeta,t-1)\cdot(1-l(\lambda,\theta,\zeta)) + \zeta^c(\lambda,\theta,\zeta,t)\cdot\eta^\zeta(\lambda,\theta,\zeta) - \frac{\zeta^p(\lambda,\theta,\zeta,t)}{\eta^\zeta(\lambda,\theta,\zeta)} \qquad \forall \lambda \in \Lambda, \theta \in \Theta^s, \zeta \in Z, t \in T$$

$$s(\lambda,\theta,t) \le s^c(\lambda,\theta) \qquad \forall \lambda \in \Lambda, \theta \in \Theta^s, t \in T$$

$$s(\lambda,\theta,t) \ge s^d(\lambda,\theta)\cdot s^c(\lambda,\theta) \qquad \forall \lambda \in \Lambda, \theta \in \Theta^s, t \in T$$

$$e^c(\lambda,\theta) \le s^c(\lambda,\theta)\cdot e^s(\lambda,\theta) \qquad \forall \lambda \in \Lambda, \theta \in \Theta^s$$

Relations between consumed input carriers and produced output carriers for carrier conversion technologies

Storage level is determined by the storage level of the previous time step, charged & discharged energy

Storage capacity limits the storage level, for which a lower bound exists

θ	Technology	t	Timestep	ζ^{fi}	First input carrier	Θ^s	Storage technology set	η^ζ	Conversion, charge or discharge efficiency
Θ	Technology set	T	Timestep set	ζ^{fo}	First ouput carrier	Θ^ζ	Carrier conversion technology set		
λ	Location	e^c	Energy capacity	ζ^{si}	Second input carrier	ζ^c	Consumed carrier quantity (≤ 0)		
Λ	Location set	s^c	Storage capacity	ζ^{so}	Second ouput carrier	ζ^p	Produced carrier quantity		
ζ	Carrier	s	Storage level	ζ^{ri}	Relation between ζ^{fi} and ζ^{si}	l	Storage loss rate between $t-1$ and t		
Z	Carrier set	e^s	Maximum e^c per s^c	ζ^{ro}	Relation between ζ^{fo} and ζ^{so}	s^d	Minimum state of charge (fraction of s^c)		

Technology-related Costs

$$c_k(\lambda,\theta) = \begin{cases} c_k^i(\lambda,\theta) + \sum_{t\in T} c_k^v(\lambda,\theta,t), & \text{if } \theta \in \{\Theta^\rho, \Theta^\zeta, \Theta^t, \Theta^s\} \\ 0, & \text{if } \theta \in \Theta^d \end{cases}$$

$$\forall k \in K, \lambda \in \Lambda, \theta \in \Theta$$

$$c_k^i(\lambda,\theta) = c_k^c(\lambda,\theta) + c_k^f(\lambda,\theta) \qquad \forall k \in K, \lambda \in \Lambda, \theta \in \Theta \setminus \Theta^d$$

$$c_k^c(\lambda,\theta) = \begin{cases} d_k(\lambda,\theta)\cdot c_k^e(\lambda,\theta)\cdot e^c(\lambda,\theta), & \text{if } \theta \in \{\Theta^\rho, \Theta^\zeta, \Theta^t\} \\ d_k(\lambda,\theta)\cdot c_k^s(\lambda,\theta)\cdot s^c(\lambda,\theta), & \text{if } \theta \in \Theta^s \end{cases}$$

$$\forall k \in K, \lambda \in \Lambda, \theta \in \Theta \setminus \Theta^d$$

$$c_k^f(\theta) = \begin{cases} c_k^{ef}(\theta)\cdot e^c(\theta), & \text{if } \theta \in \{\Theta^\rho, \Theta^\zeta, \Theta^t\} \\ c_k^{sf}(\theta)\cdot s^c(\theta), & \text{if } \theta \in \Theta^s \end{cases} \qquad \forall k \in K, \theta \in \Theta \setminus \Theta^d$$

Technology-related costs consist of investment & variable costs

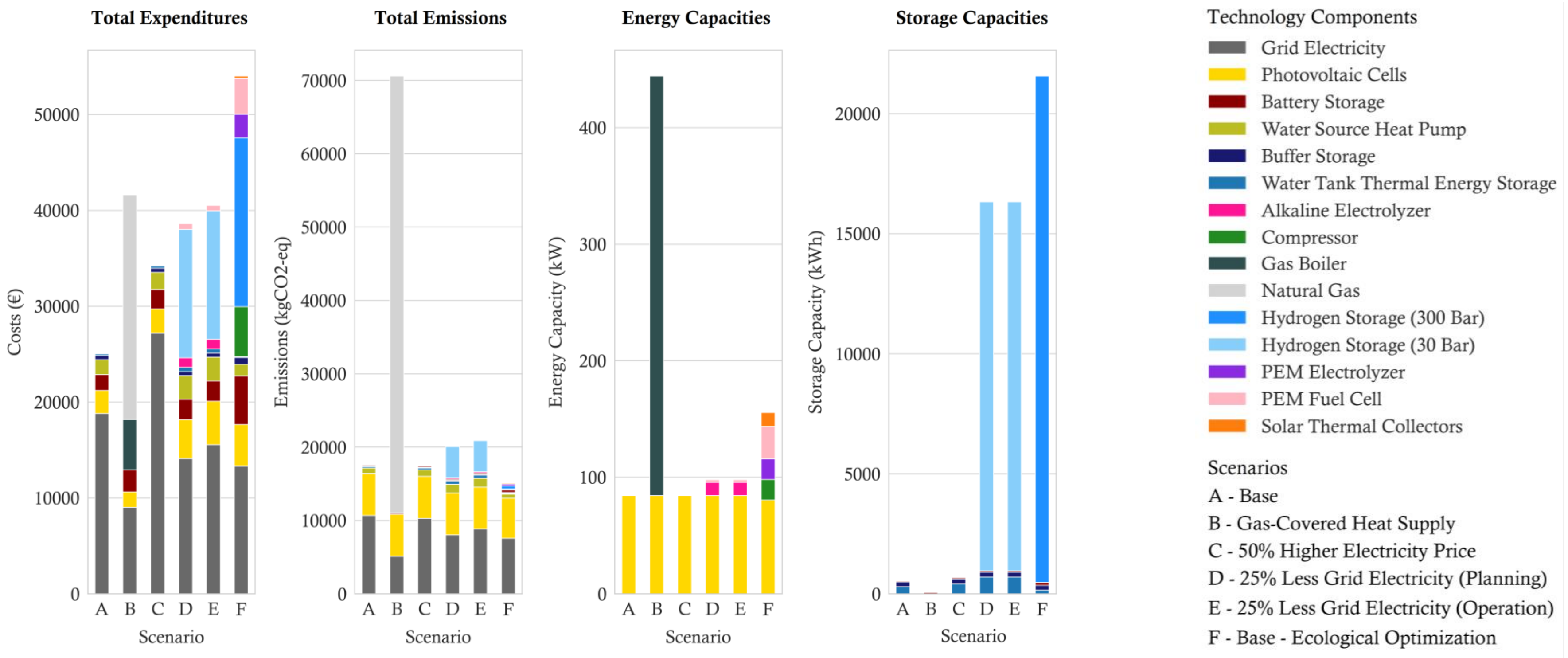
Investment costs embody capacity-related & fixed O&M costs

Capacity-related costs depend on depreciation rate, costs per capacity and used capacity

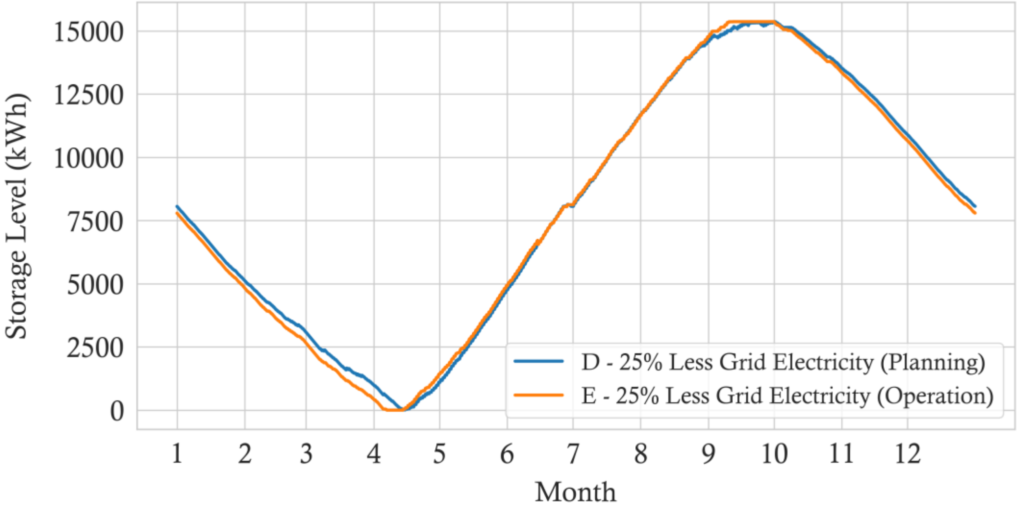
Fixed O&M costs depend on capacity & fixed O&M costs per capacity

θ	Technology	t	Timestep	c_k^c	Capacity-related costs	Θ^ρ	Resource conversion technology set	c_k^s	Capacity-related costs per storage capacity
Θ	Technology set	T	Timestep set	c_k^f	Fixed O&M costs				
λ	Location	e^c	Energy capacity	d_k	Yearly depreciation rate	Θ^ζ	Carrier conversion technology set	c_{km}^{ef}	Fixed O&M costs per energy capacity
Λ	Location set	s^c	Storage capacity	Θ^d	Demand technology set	c_k	Technology-related cost or revenue		
k	Cost class	c_k^i	Investment costs	Θ^s	Storage technology set	c_k^e	Capacity-related costs per energy capacity	c_{km}^{sf}	Fixed O&M costs per storage capacity
K	Cost class set	c_k^v	Variable costs	Θ^t	Transmission technology set				

Expenditures, Emissions and Capacity Results



Optimal Operating Strategy



Genetic Algorithm & Grid Search Results

Charging period: Electrolyzer
Artificial profits of 0.06€ per kWh

Discharging period: Fuel Cell
Artificial costs of 0.20€ per kWh

→ 48 hours of perfect foresight lead to 4.2% higher total expenditures compared to 365 days of perfect foresight

Conclusion – Economical Evaluation

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Economic benefits only in special cases
such as limited access to the electricity grid or the goal of high self-generated electricity consumption

→ Little economic potential in the near future

Interval-based solution of linear programs as basis for operation
Artificial costs and profits enable an efficient seasonal storage integration

→ Forecasts regarding energy prices, weather and energy consumption mainly determine the benefit

Conclusion – Ecological Evaluation

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Hydrogen storage with 300 bar leads to emission reductions
in contrast to a 30 bar storage, which leads to emission increase

➞ Cross-sectoral CO_2 price is more desirable than unspecific subsidies

Comprehensive heat pump and PV expansion has priority

Maximum possible emission reduction is 78.59% compared to gas-fired heat coverage, without hydrogen 75.08% is possible

➞ Non-use of gas brings decisive emission savings

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