UNIVERSITÄT DUISBURG ESSEN

Chair for Management Sciences and
Energy Economics
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# Efficient storage capacity in power systems with thermal and renewable generation

Transatlantic Infraday FERC
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# wind is a powerful source of energy...

# ... but occasionally not

# Integration of RES motivates the re-evaluation of storage

- High-pace transition of generation landscape
  - 20% RES by 2020 (RES-directive 2001/77/EC)
  - 35% RES by 2020 and 80% by 2050 (EEG-2012, § 2 Abs. 2)
- Integration of intermittent renewables being a challenge
  - Wind and PV with very low capacity credit
  - Availability of controllable thermal capacity not evident
- Electricity storage as natural complement – really?
  - Extension of storage capacities vowed by politicians
  - Surge of pumped-hydro storage projects in Germany
  - However, only one option next to thermal "backup" plants

➡ **Efficient storage capacity to be determined**

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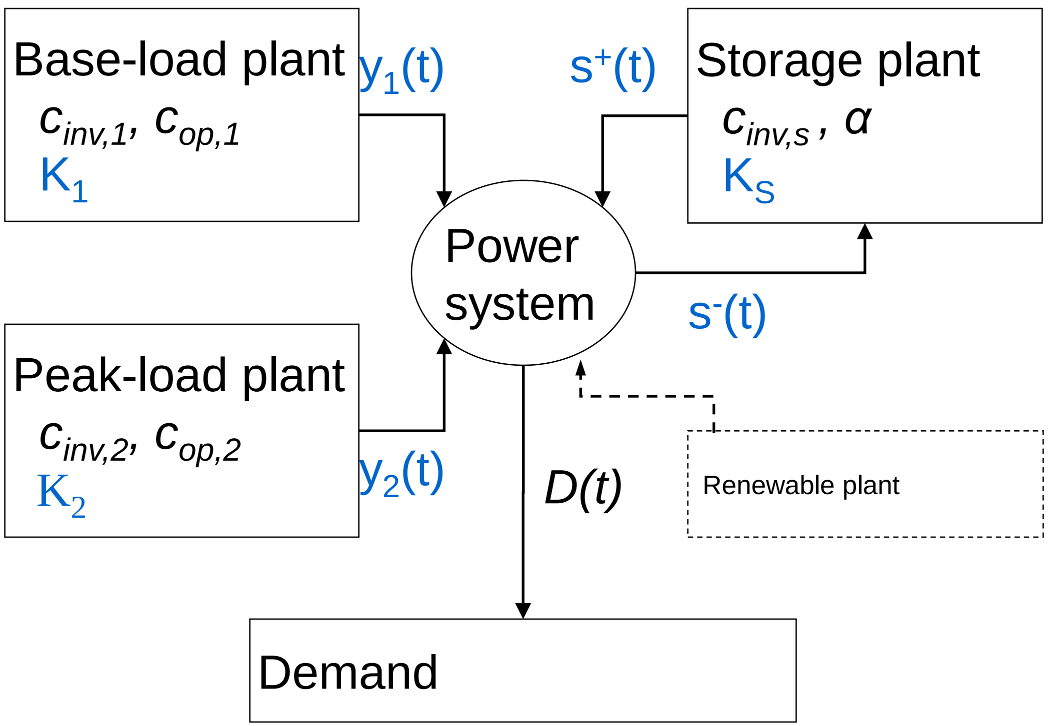
# Model builds on peak-load-pricing literature

- Goal: Analytical derivation of **efficient storage capacity**
  - Large-scale storage
  - Turbine/pumping power
  - Social optimum
- Theoretical literature
  - Two-period peak-load-pricing models: Jackson (1973), Gravelle (1976)
  - Optimizing individual plant's profit, e.g. Horsley and Wrobel (2002)
  - Efficient storage operation: Crampes and Moreaux (2010)
- Contribution
  - Efficient storage capacity in view of RES and controllable plants
  - Departure from two-period setup

# Load is met by two thermal technologies, RES and storage




*Given parameters*
Optimization variables

$$t \in [0; T]$$

$$D : [0; T] \to \mathbb{R}_+, t \mapsto D(t)$$

$$D_{max} = D(0)$$

$$C_{inv,i} = c_{inv,i} K_i$$

$$C_{op,i} = c_{op,i} Q_i$$

$$c_{inv,1} > c_{inv,2}$$

$$c_{op,2} > c_{op,1}$$

$$\alpha Q_s$$

$$\alpha > 1$$

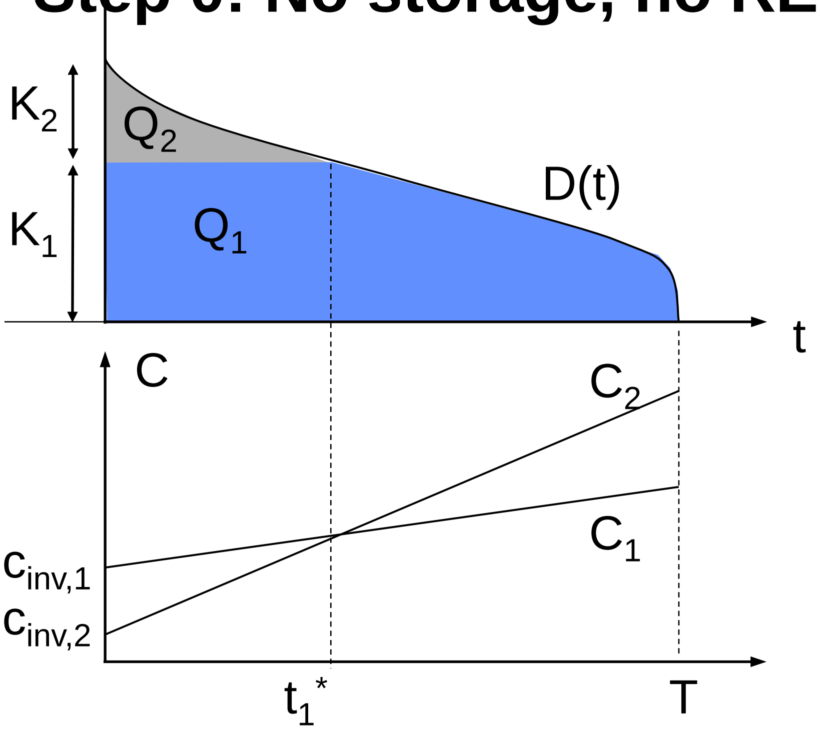
# Welfare optimum obtained by minimization of total costs

$$\min_{y_i(t),K_i,K_s} C\left(y_i(t),K_i,K_s\right) = \int_0^T \sum_i y_i(t)c_{op,i}\,dt + \sum_i K_i c_{inv,i} + K_s c_{inv,s} \quad (1a)$$

s.t.

$$\begin{aligned}
K_i - y_i(t) &\geq 0 && \forall\, i,t && (1b)\\
K_s - s^+(t) &\geq 0 && \forall\, t && (1c)\\
K_s + s^-(t) &\geq 0 && \forall\, t && (1d)\\
\int_0^T s^+(t)\,dt &= -\alpha \int_0^T s^-(t)\,dt && && (1e)\\
\sum_i y_i(t) + s^+(t) + s^-(t) &= D(t) && \forall\, t && (1f)\\
K_i, K_s, y_i(t), s^+(t), -s^-(t) &\geq 0 && \forall\, i,t. && (1g)
\end{aligned}$$

# Step 0: No storage, no RES



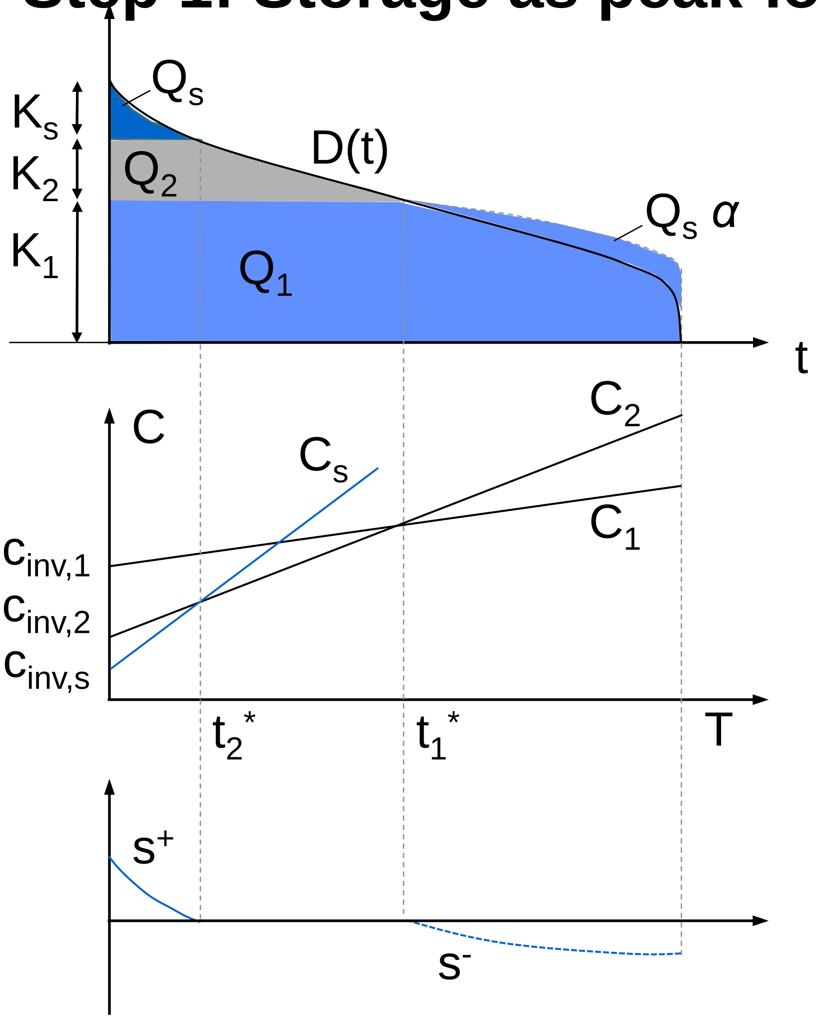

$$Q_2 = \int_0^{t_1} D(t)dt - t_1 K_1$$

$$Q_1 = Q_E - Q_2$$

$$K_1^* = D(t_1^*),$$

$$K_2^* = D_{max} - D(t_1^*)$$

# Step 1: Storage as peak-load plant ( $c_{inv,s} < c_{inv,2}$ ), no RES yet




$$\min_{K_i,K_s} C(K_i,K_s)$$

$$= \sum_i K_i c_{inv,i} + K_s c_{inv,s} + \sum_i Q_i c_{op,i} + Q_s \,\alpha\, c_{op,1}$$

$$\text{s.t.} \qquad K_i, K_s \geq 0 \qquad \forall\ i,$$

$$Q_s = \int_0^{t_2} D(t)dt - t_2(K_1 + K_2)$$

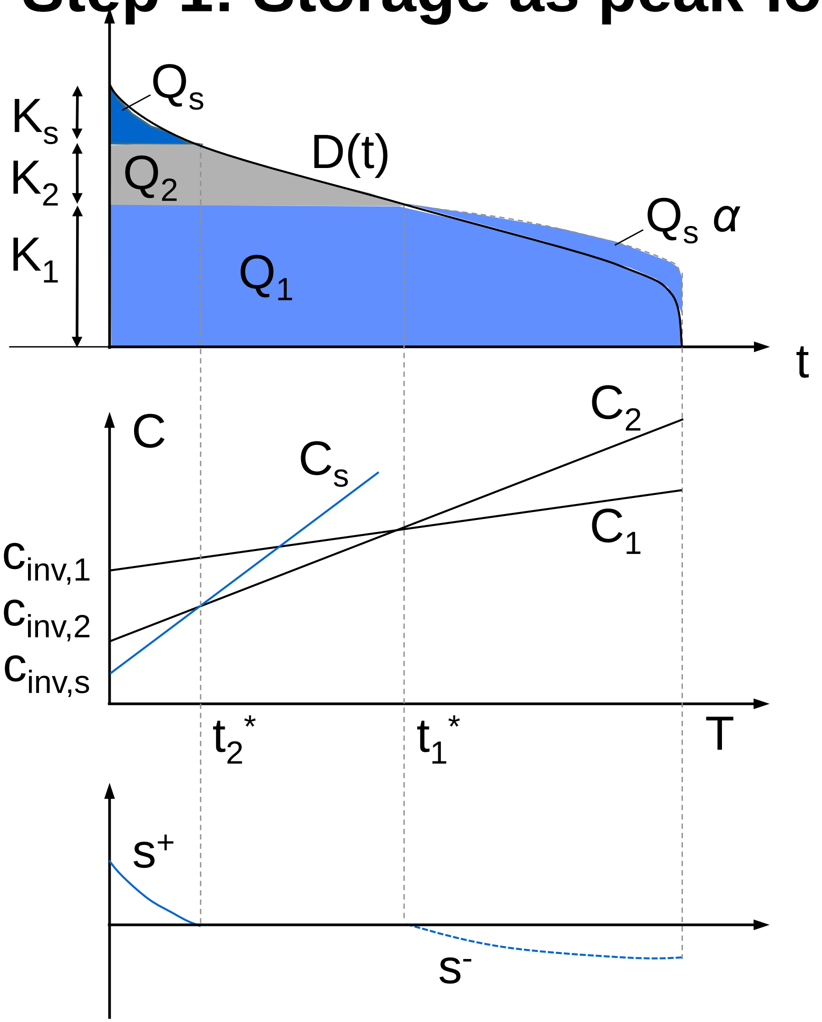
$$Q_2 = \int_0^{t_1} D(t)dt - t_1 K_1 - Q_s$$

$$Q_1 = Q_E - Q_s - Q_2$$

$$K_1 = D(t_1), \qquad K_2 = D(t_2) - D(t_1)$$

$$K_s = D_{max} - D(t_2)$$

# Step 1: Storage as peak-load plant ($c_{inv,s} < c_{inv,2}$), no RES yet




$$\frac{\partial C(t_2, t_1)}{\partial t_2} \geq 0, \quad \perp \quad t_2 \geq 0$$

$$K_s^* = D_{max} - D(t_2^*), \qquad t_2^* = \frac{c_{inv,2} - c_{inv,s}}{\alpha\, c_{op,1} - c_{op,2}}$$

$$\frac{\partial K_s^*}{\partial c_{inv,s}} < 0, \qquad \frac{\partial K_s^*}{\partial \alpha} < 0$$

$$\frac{\partial K_s^*}{\partial c_{inv,2}} > 0, \qquad \frac{\partial K_s^*}{\partial c_{op,2}} > 0$$

$$\frac{\partial K_s^*}{\partial c_{inv,1}} = 0, \qquad \frac{\partial K_s^*}{\partial c_{op,1}} < 0.$$

$$c_{inv,2} - c_{inv,s} = t_2^* \left(\alpha\, c_{op,1} - c_{op,2}\right)$$

# Step 2: Constraints for mid-merit storage ($c_{inv,2} < c_{inv,s} < c_{inv,1}$)

## A. Storage part of portfolio

- Round-trip efficiency

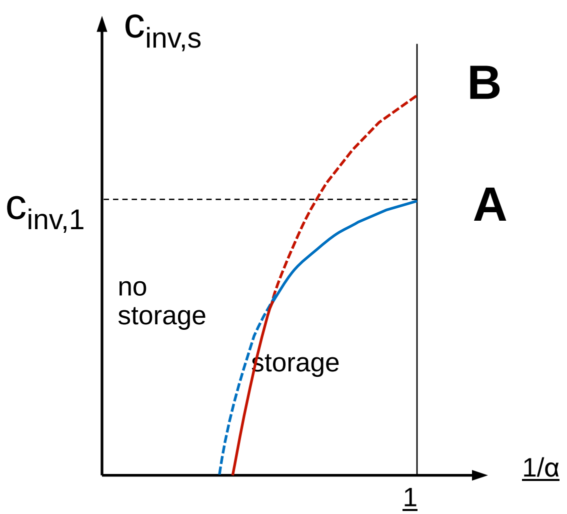
$$\alpha\, c_{op,1} < c_{op,2} \quad \leftrightarrow \quad \frac{1}{\alpha} > \frac{c_{op,1}}{c_{op,2}}$$

- Investment cost disadvantage

## B. Maximum generation time

- Round-trip efficiency

$$t_s^* < \frac{T}{1+\alpha}$$




**B** $$c_{inv,s} < c_{inv,2} + T\frac{c_{op,2} - \alpha\, c_{op,1}}{1+\alpha}$$

**A** $$c_{inv,s} < c_{inv,1} + \tilde{t}_1^* c_{op,1} - \alpha\, \tilde{t}_1^* c_{op,1}, \qquad \tilde{t}_1^* = \frac{c_{inv,1} - c_{inv,2}}{c_{op,2} - c_{op,1}}$$

# Step 2: Solution for mid-merit storage ( $c_{inv,2} < c_{inv,s} < c_{inv,1}$ )

$$
\begin{aligned}
Q_2 &= \int_0^{t_s} D(t)dt - t_S(K_1 + K_s) \\
Q_s &= \int_0^{t_1} D(t)dt - t_1 K_1 - Q_2 \\
Q_1 &= Q_E - Q_2 - Q_s
\end{aligned}
$$

$$K_1 = D(t_1)$$

$$K_s = D(t_s) - D(t_1)$$

$$K_2 = D_{max} - D(t_s)$$

$$
\begin{aligned}
\frac{\partial C(t_s, t_1)}{\partial t_s} &\geq 0, \quad \perp \quad t_s \geq 0 \\
\frac{\partial C(t_s, t_1)}{\partial t_1} &\geq 0, \quad \perp \quad t_1 \geq 0
\end{aligned}
$$

$$K_s^* = D(t_s^*) - D(\min\{t_1^*, t_1^{max}\})$$

$$t_s^* = \frac{c_{inv,s} - c_{inv,2}}{c_{op,2} - \alpha\, c_{op,1}}$$

$$t_1^* = \frac{c_{inv,1} - c_{inv,s}}{(\alpha - 1)\, c_{op,1}}$$

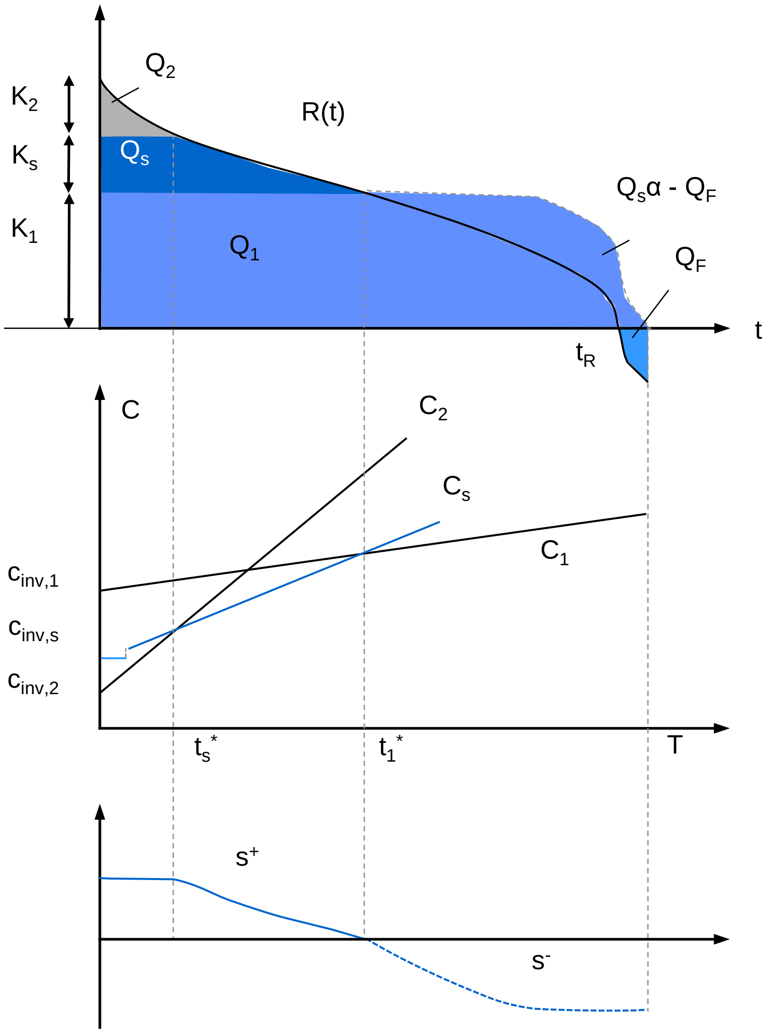
$$t_1^{max} = \frac{T}{1 + \alpha}$$

$$\frac{\partial K_s^*}{\partial c_{inv,s}} < 0, \qquad \frac{\partial K_s^*}{\partial \alpha} < 0$$

$$\frac{\partial K_s^*}{\partial c_{inv,2}} > 0, \qquad \frac{\partial K_s^*}{\partial c_{op,2}} > 0$$

$$\frac{\partial K_s^*}{\partial c_{inv,1}} \geq 0, \qquad \frac{\partial K_s^*}{\partial c_{op,1}} < 0$$

# Final step: Introducing renewables




$$R : [0;T] \to \mathbb{R}, t \mapsto R(t)$$

$$t_r \le T$$

$$Q_F = -\int_{t_r}^{T} R(t)dt$$

$$\min_{K_i,K_s} C(K_i,K_s) =$$

$$\sum_i K_i c_{inv,i} + K_s c_{inv,s} + \sum_i Q_i c_{op,i} + (\alpha Q_s - Q_F)\, c_{op,1}$$

$$\text{s.t.} \qquad \alpha Q_s - Q_F \ge 0$$

$$K_i, K_s \ge 0 \qquad \forall\, i$$

$$K_s^* = R(t_s^*) - R(t_1^*)$$

$$t_s^* = \frac{c_{inv,s} - c_{inv,2}}{c_{op,2} - \alpha\, c_{op,1} + \lambda}, \qquad t_1^* = \frac{c_{inv,1} - c_{inv,s}}{(\alpha - 1)c_{op,1} - \lambda}$$

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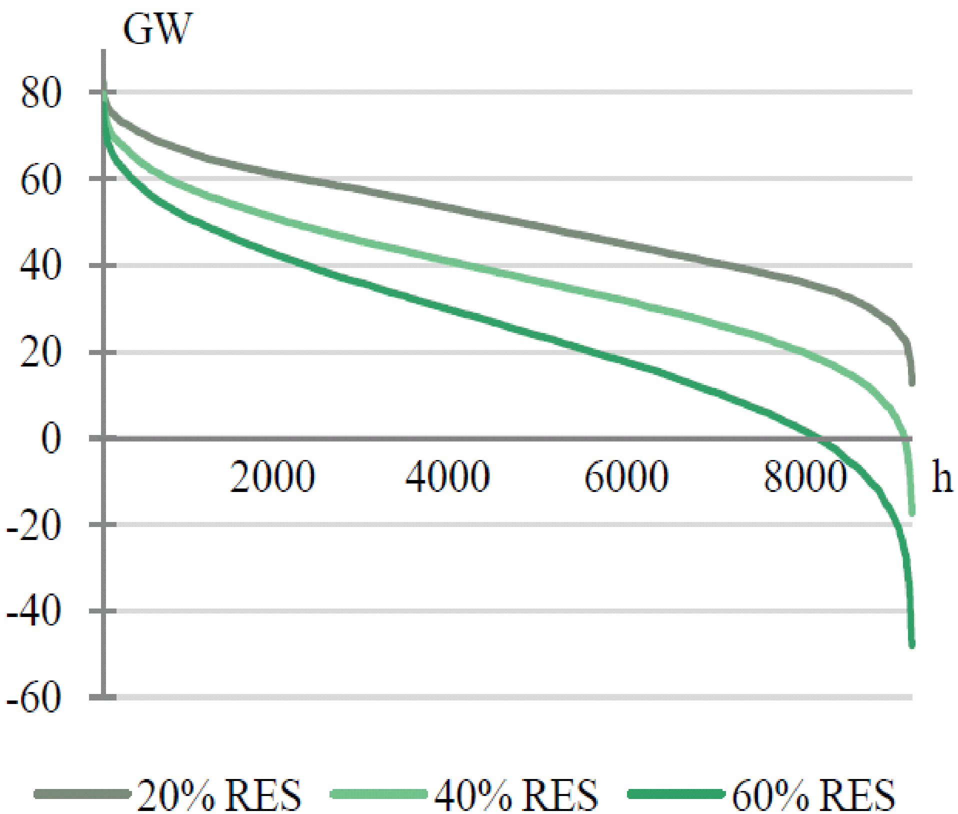
# High shares of RES generation cause steep residual LDC

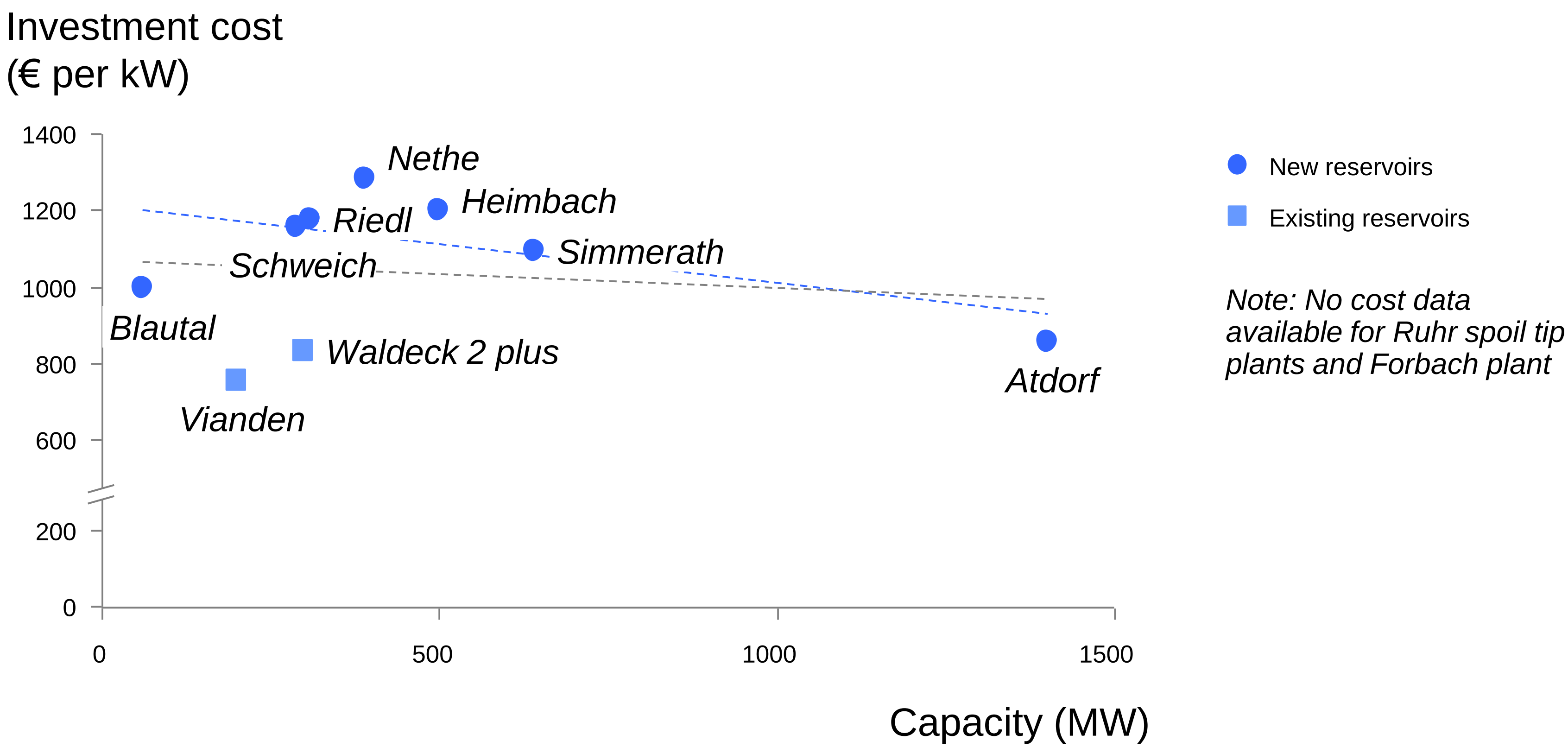


# Five controllable generation technologies considered

| Parameter | Unit | Lignite | Hard coal | CCGT | OCGT | PHS |
|---|---|---|---|---|---|---|
| Thermal efficiency | $MWh_{el}$ / $MWh_{th}$ | 0.43 | 0.46 | 0.56 | 0.34 | |
| Round-trip efficiency | $MWh_{out}$ / $MWh_{in}$ | | | | | 0.80 |
| Carbon emission rate | t $CO_2$ / $MWh_{el}$ | 0.99 | 0.75 | 0.37 | 0.60 | 0 |
| Technical lifetime | years | 45 | 45 | 30 | 25 | 50 |
| Total investment costs | €/kW | 1934 | 1419 | 608 | 456 | 961 |
| Fixed O&M, overhead | €/kW a | 43.26 | 36.06 | 13.97 | 9.69 | 9.61 |
| Variable O&M, transport | €/$MWh_{el}$ | 1.7 | 2.9 | 13.1 | 19.6 | 0 |

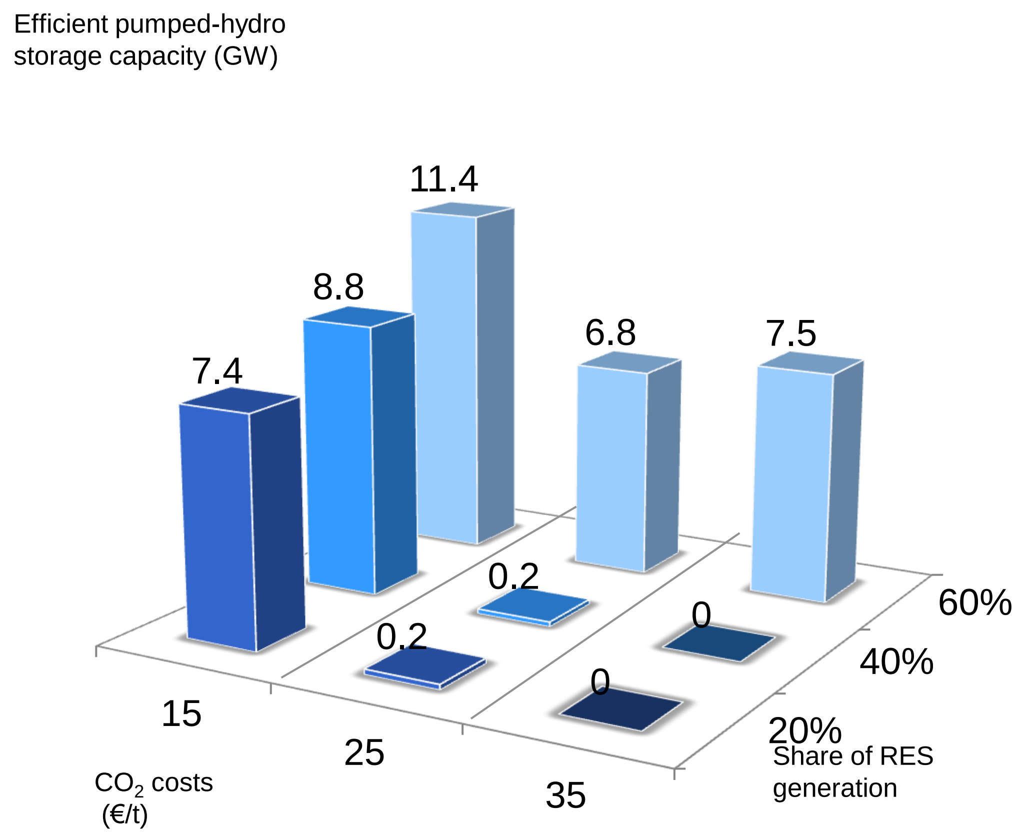
| Fuel | €/$MWh_{th}$ |
|---|---|
| Lignite | 4.28 |
| Hard coal | 9.94 |
| Gas | 21.90 |

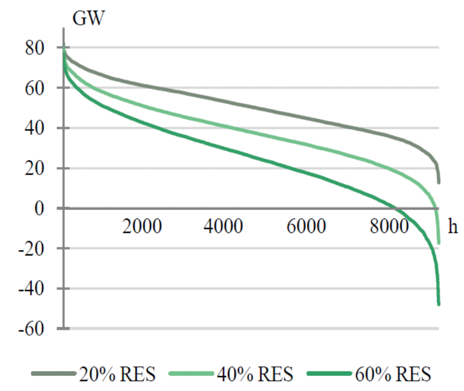
# Investment costs of German pumped-hydro projects




| Model specification | N | coefficient | t-statistic |
|---|---|---|---|
| All projects | 9 | -.209 | -1.94 |
| New build projects only | 7 | -.318 | -5.98 |
| New build projects only, excluding Atdorf | 6 | -.142 | -.63 |

# Result: Growing storage capacity with RES share – as long as $CO_2$ prices are not too high



# Summary and conclusion

- Peak-load-pricing based on load duration curve provides unifying framework for storage efficiency evaluation in the presence of RES and controllable plants
  - Critical cost level for storage being part of the portfolio
  - Influence of central cost parameters on storage capacity
  - Role of RES: excess generation vs. shape of residual load duration curve
- Case study for Germany shows high dependency on $CO_2$ costs
  - Efficient storage capacity 50% with higher RES generation, despite lower peak load
  - However, inefficient with $CO_2$ costs of from € 25, except with RES share above 40%
  - Surge of German pumped-hydro projects coming too early?
- Trade-off between larger turbines and larger reservoirs still has to be evaluated
  - Load duration curve as basis has no information on cyclicality
  - Optimal reservoir capacity to be evaluated in a next step

# Thank you for your attention!

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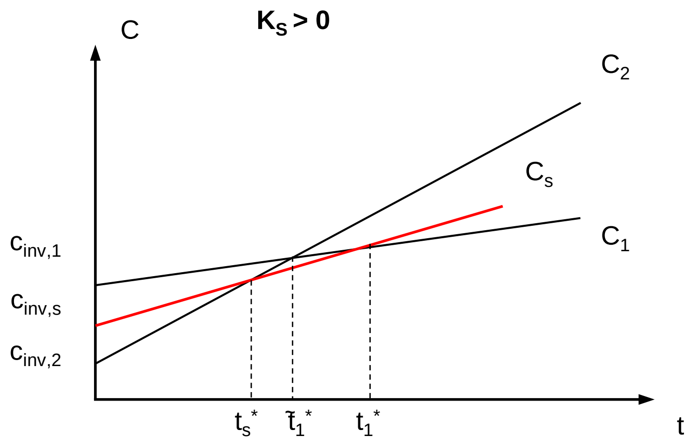
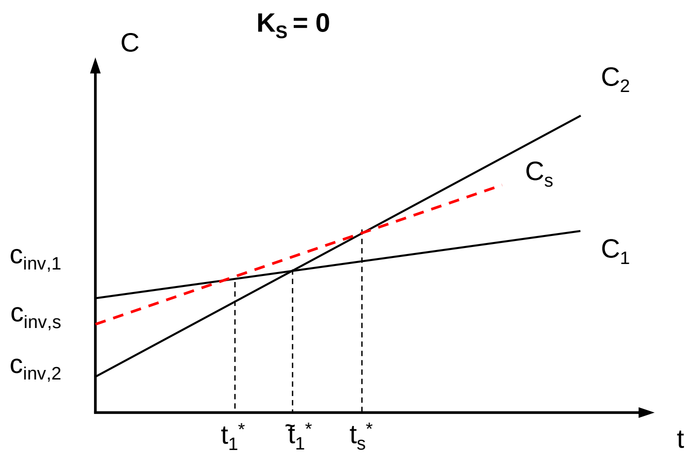
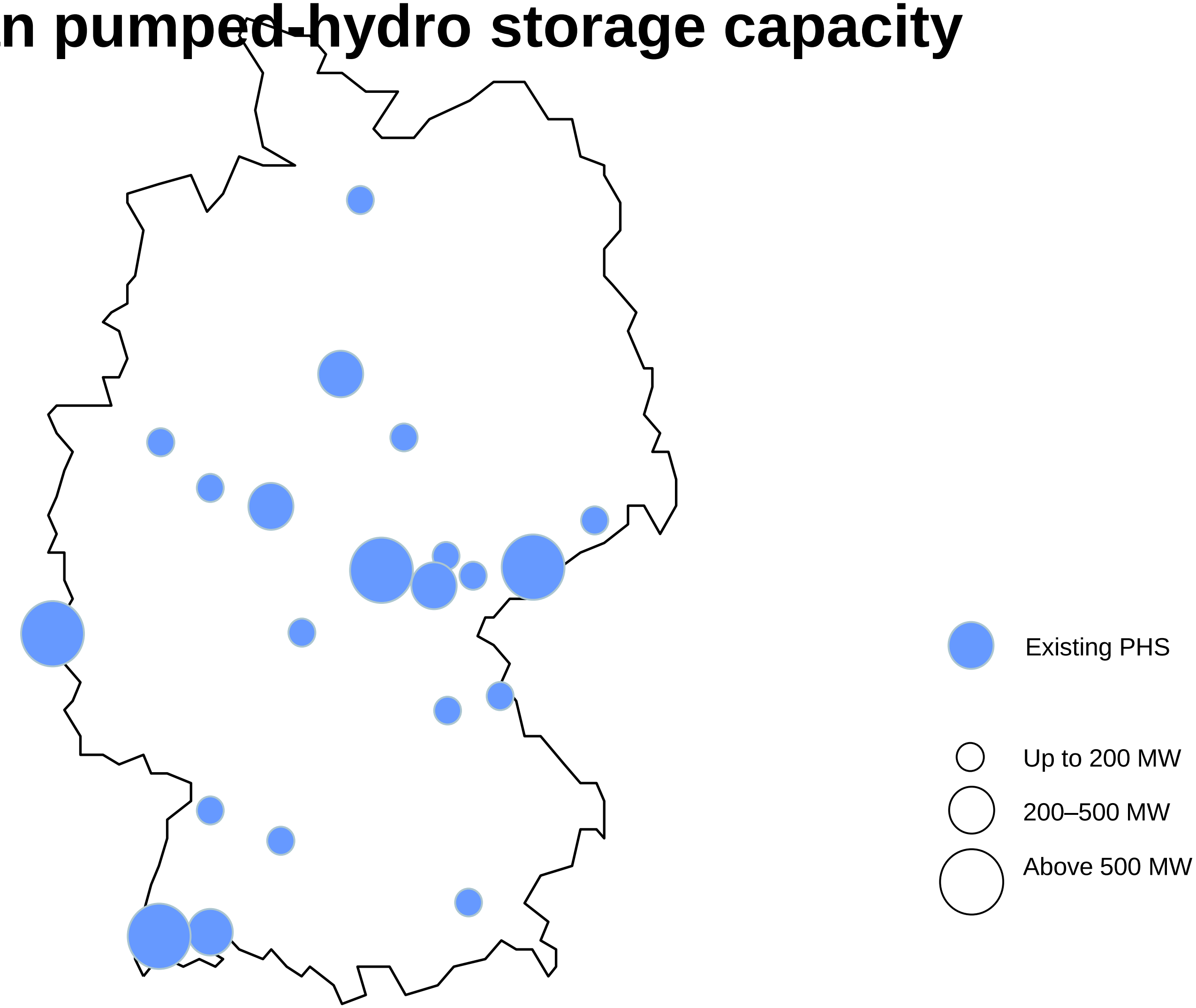
# Condition for mid-merit storage being part of the portfolio



# German pumped-hydro storage capacity



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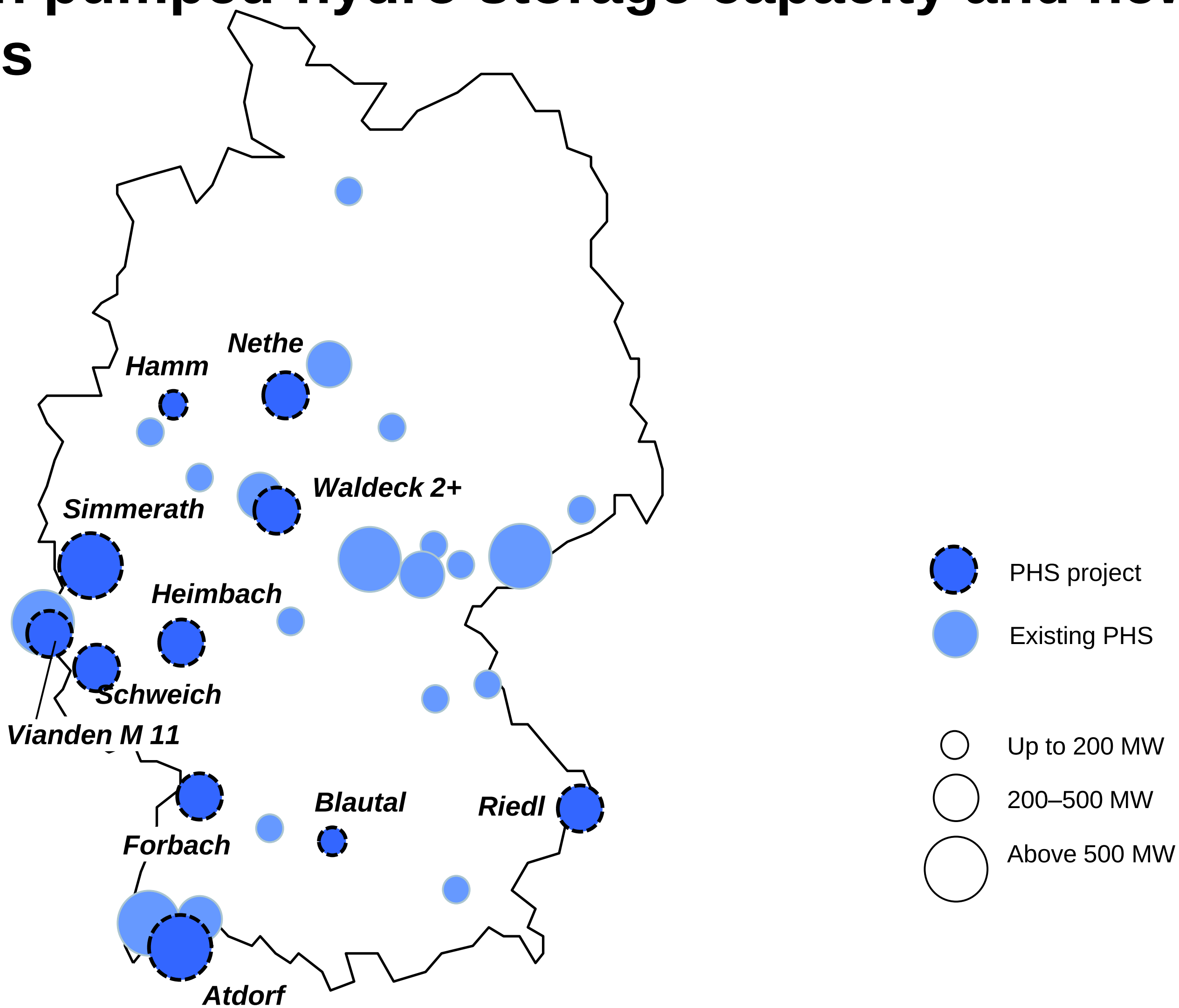
# German pumped-hydro storage capacity and new projects



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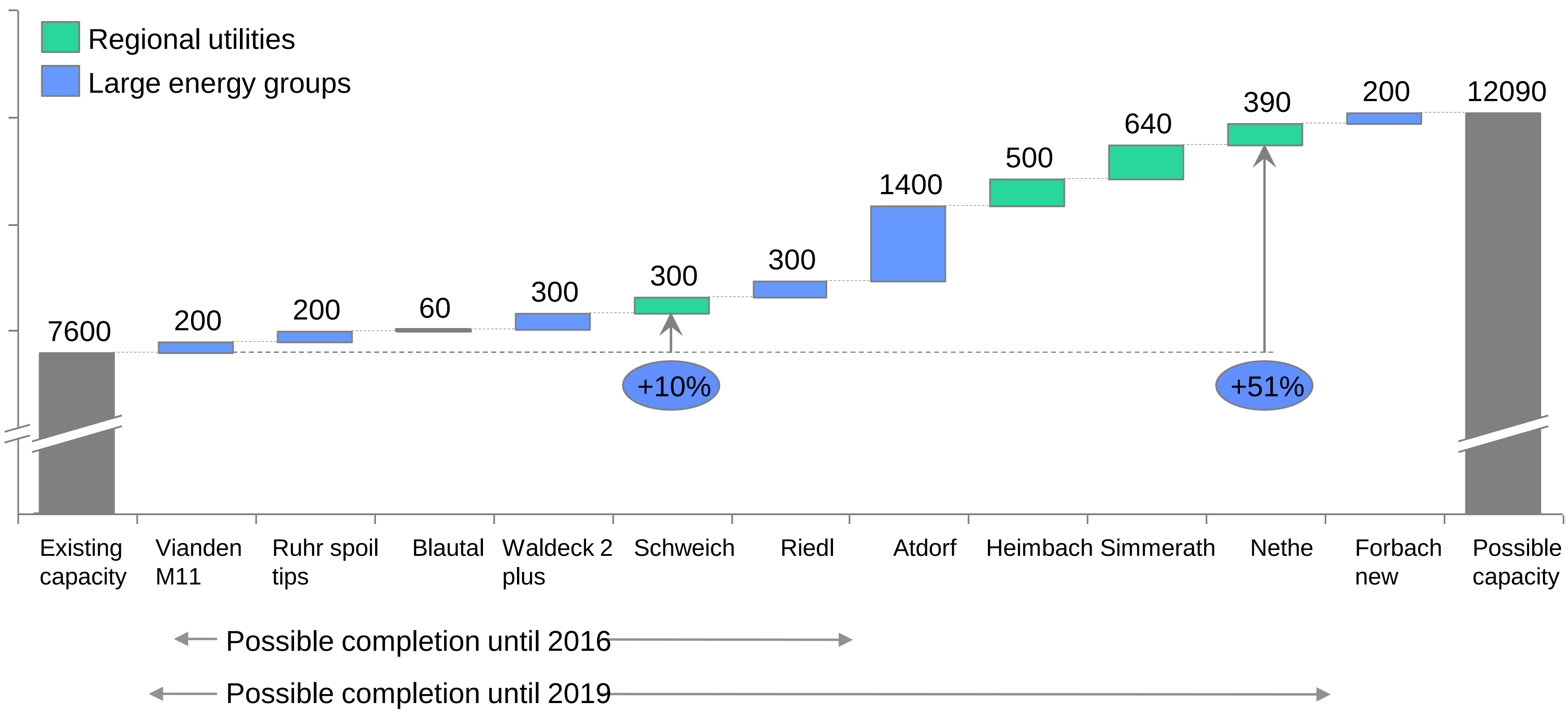
# German pumped-hydro storage projects until 2019

PHS turbine capacity (MW)



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# Parameters of German pumped-hydro storage projects

| Plant project | State[a] | Head (m) | Capacity (MW) | Costs (€M) | Planned completion |
|---|---|---|---|---|---|
| Vianden M 11 | (Lux.) | 280 | 200 | 155 | 2013 |
| Ruhr spoil tip plants | NW | 50–100 | 15/200[b] | n.a. | 2014/n.a.[b] |
| Blautal (Ulm) | BW | 170 | 60 | 60 | 2015–2016 |
| Waldeck 2 plus | HE | 360 | 300 | 250 | 2016 |
| Schweich (Trier) | RP | 200 | 300 | 300–400 | 2015–2017 |
| Riedl | BY | 350 | 300 | 350 | 2018 |
| Atdorf | BW | 600 | 1400 | 1200 | 2019 |
| Forbach | BW | 320 | 200 | n.a. | n.a. |
| Heimbach (Mainz) | RP | 500 | 400–600 | 500–700[c] | 2019 |
| Simmerath | NW | 240 | 640 | 700 | 2019 |
| Nethe (Höxter) | NW | 220 | 390 | 500+ | 2019 |

[a] BW=Baden-Wuerttemberg, BY= Bavaria, HE= Hesse, Lux.= Luxembourg, NW= North Rhine-Westphalia, RP= Rhineland-Palatinate

[b] Pilot plant/all planned plants

[c] Cost range of "comparable plants" as provided by project developer

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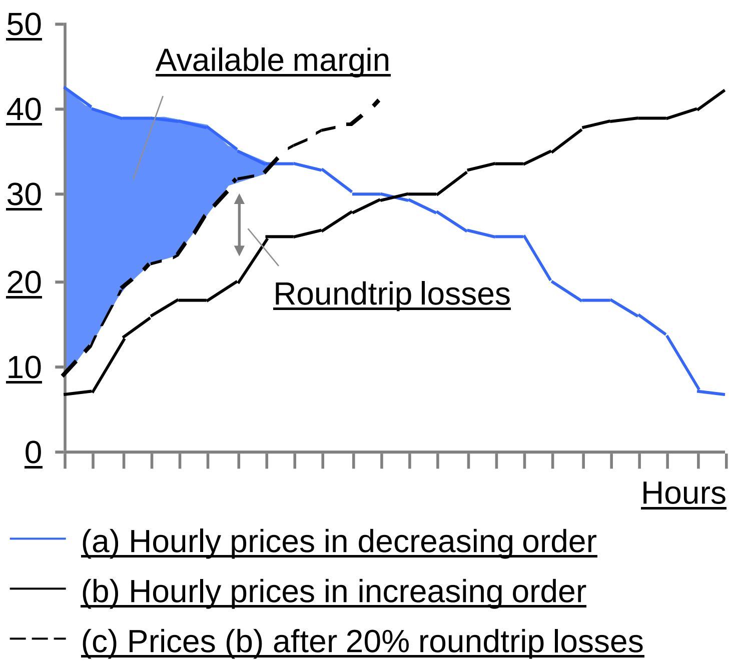
# Estimate of time spread arbitrage potential in German

## Logic

Price duration curves EPEX Spot, 01/08/2010
€/MWh




## Results 2002–2010

Available margin from times spread arbitrage
€/MW per year