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# A Long-Term Analysis of the System Value of Power Storage under Renewable Integration

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## MOTIVATION

- **In the long term, very high shares of fluctuating renewables are required**
  - Because of climate change and security of supply
  - Limited potentials of dispatchable renewables in Germany and many other countries
- **Appropriate mix of different generation technologies and dedicated flexibility options is necessary:**
  - Power storage
  - Demand-side measures
  - Flexible thermal generators
- **We set up a dispatch and investment model to study the role of power storage:**
  - In a greenfield perspective (around 2050)
  - From a power system perspective (no decentralized or micro-economic optimization)
  - In the context of other flexibility options
- **Extensive sensitivity analyses to address long-run parameter uncertainty**

**For further details and policy conclusions please see also::**

Zerrahn, A., Schill, W.-P. (2015): A greenfield model to evaluate long-run power storage requirements for high shares of renewables. DIW Discussion Papers 1457.

Schill, W.-P. et al. (2015): Stromspeicher: eine wichtige Option für die Energiewende. DIW Wochenbericht 10/2015

Schill, W.-P. et al. (2015): Power Storage: an Important Option for the German Energy Transition. DIW Economic Bulletin 10/2015.

## STATE OF THE LITERATURE

- Many studies with different modeling approaches:
  - Investment models
  - Pure dispatch models
  - Agent-based models
  - Time-series and theoretical approaches
- So far, no coherent evidence, but broad common findings
  - Up to around 50-70% RES penetration, only moderate storage requirement
  - Longer-term projections vary widely
- For example, gray literature for Germany:
  - VDE (2012): 36 and 68 GW short- and long-term storage for 100% RES
  - "Roadmap Storage" (2014): 0-20 GW short-term storage for 88% RES
  - Agora (2014): 7 and 16 GW short- and long-term storage for 90% RES
- Results depend on model assumptions:
  - Cost parameters
  - Considered flexibility options
  - In particular, DSM and international balancing

## METHODOLOGY

**Minimization of total system costs:**
- Sum of annualized investments, fixed costs, variable costs
- Decision variables: capacities and dispatch of all technologies
- Subject to numerous constraints

**Numerical solution:**
- Linear program
- Implemented in GAMS
- Solved with commercial solver CPLEX

**Time resolution:**
- Hourly resolution, 8760 hours
- Solved for one year (~2050, long-run equilibrium)

**Reserves:**
- Endogenous requirements (PR, SR, MR)
- Provision and activation (deterministic)

**Other features:**
- Up to seven power storage technologies
  - Baseline: Li-ion, PHS, Power-to-gas
- Innovative DSM formulation for shifting and curtailment
- Linearized load change costs of thermal generators

**Objective function:**

$$
\begin{aligned}
C = \sum_h \Bigg[ & \sum_{con} \left( c^m_{con} G^l_{con,h} + c^+_{con} G^+_{con,h} + c^-_{con} G^-_{con,h} \right) + \sum_{res} c^{cu}_{res} CU_{res,h} \\
& + \frac{1}{2} \sum_{sto} c^m_{sto} \left( S^{out}_{sto,h} + S^{in}_{sto,h} \right) + \frac{1}{2} \sum_{ls} c^m_{ls} \left( DSM^{d+}_{ls,h} + DSM^{d-}_{ls,h} \right) + \sum_{lc} c^m_{lc} DSM^{cu}_{lc,h} \Bigg] \\
& + \sum_{con} \left[ \left( c^i_{con} + c^{fix}_{con} \right) N_{con} \right] + \sum_{res} \left[ \left( c^i_{res} + c^{fix}_{res} \right) N_{res} \right] \\
& + \sum_{sto} \left[ \left( c^{iP}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^P_{sto} + \left( c^{iE}_{sto} + \frac{1}{2} c^{fix}_{sto} \right) N^E_{sto} \right] \\
& + \sum_{lc} \left[ \left( c^i_{lc} + c^{fix}_{lc} \right) N_{lc} \right] + \sum_{ls} \left[ \left( c^i_{ls} + c^{fix}_{ls} \right) N_{ls} \right] \\
& + \frac{1}{2} \sum_r \sum_h \alpha_{r,h} \left[ \sum_{sto} c^m_{sto} P_{r,sto,h} + \sum_{ls} c^{sh}_{ls} P_{r,ls,h} \right] \\
& + \sum_{lc} \sum_h c^{cu}_{lc} \left( P_{SR+,lc,h} \alpha_{SR+,h} + P_{MR+,lc,h} \alpha_{MR+,h} \right)
\end{aligned}
$$

**Model application:**
- Stylized system, loosely calibrated to Germany
- Time-series for demand and RES feed-in from 2013
- Potential restrictions to biomass, offshore wind, pumped hydro, demand-side management
- Cost parameter estimates for 2050

**Baseline and numerous sensitivities:**
- Availability and costs of different power storage technologies
- Variations of DSM potentials
- Costs, availabilities and feed-in patterns of renewables
  - Including biomass and "dark winter doldrums"
- Different reserve requirements
- (Different base years)

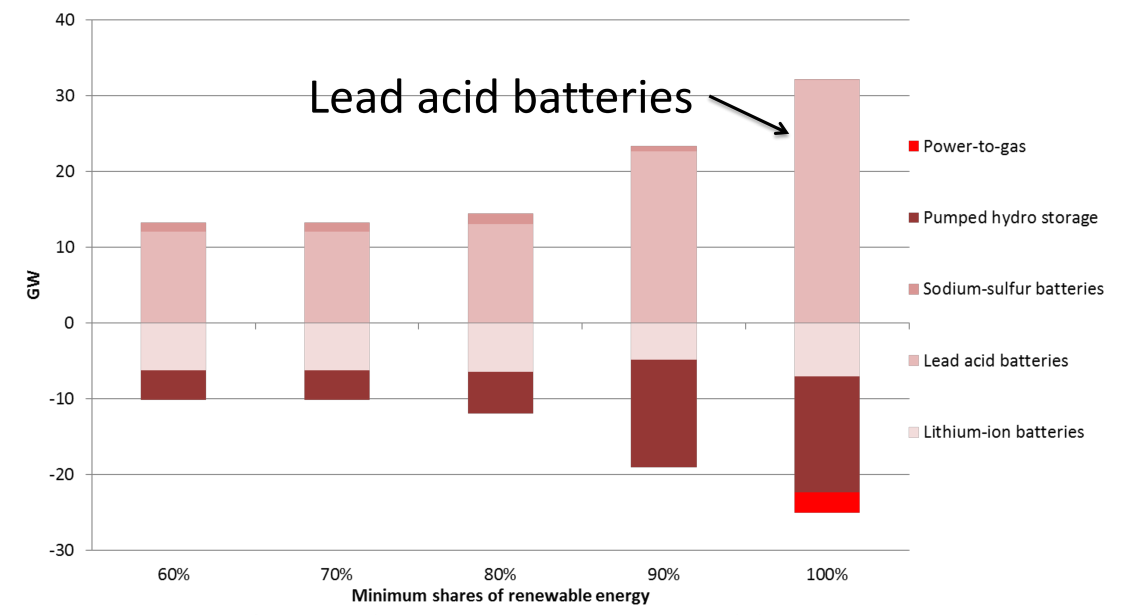
## RESULTS: BASELINE AND SELECTED SENSITIVITIES

**Baseline:**
- High shares of onshore wind and PV
- Capacities increase strongly towards 100% RES
- Power storage:
  - Moderate in 80% case
  - 100%: 34 GW overall (24 GW PHS)
  - Hardly any power-to-gas
  - E/P ratios (100%): 3 for Li-ion, 12 for PHS, 42 for P2G
  - Important role in reserve provision, particularly for batteries
- Sources of flexibility:
  - CCGT plants and biomass "oversizing"
  - Curtailment of fluctuating RES
  - DSM: longer-term shifting and curtailment

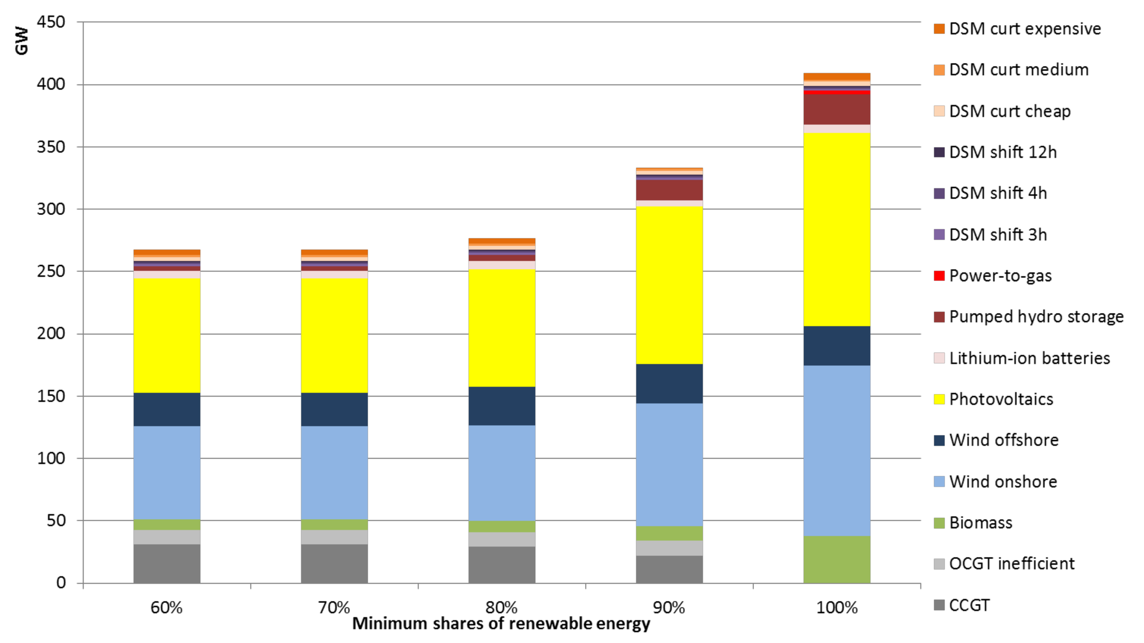
**Technology portfolio of "Roadmap Storage":**
- Lead acid batteries substitute PHS and Li-ion batteries
- Without lead acid: dominant role for NaS
- Redox flow batteries and AA-CAES always inferior

**No biomass**
- Case for power-to-gas in 100% scenario
- Along with excessive onshore wind deployment and curtailment
- Much-increased costs

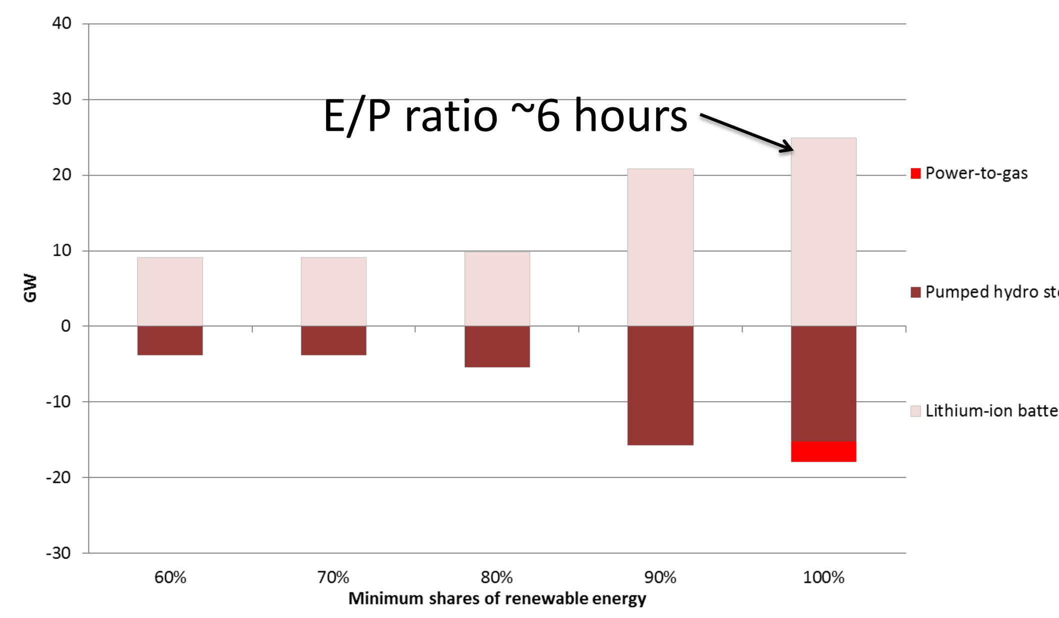
**Half specific investments costs for lithium-ion batteries:**
- Li-ion batteries substitute other storage technologies
- PHS still at energy cap in 100% case, but higher E/P ratio (33 hours)



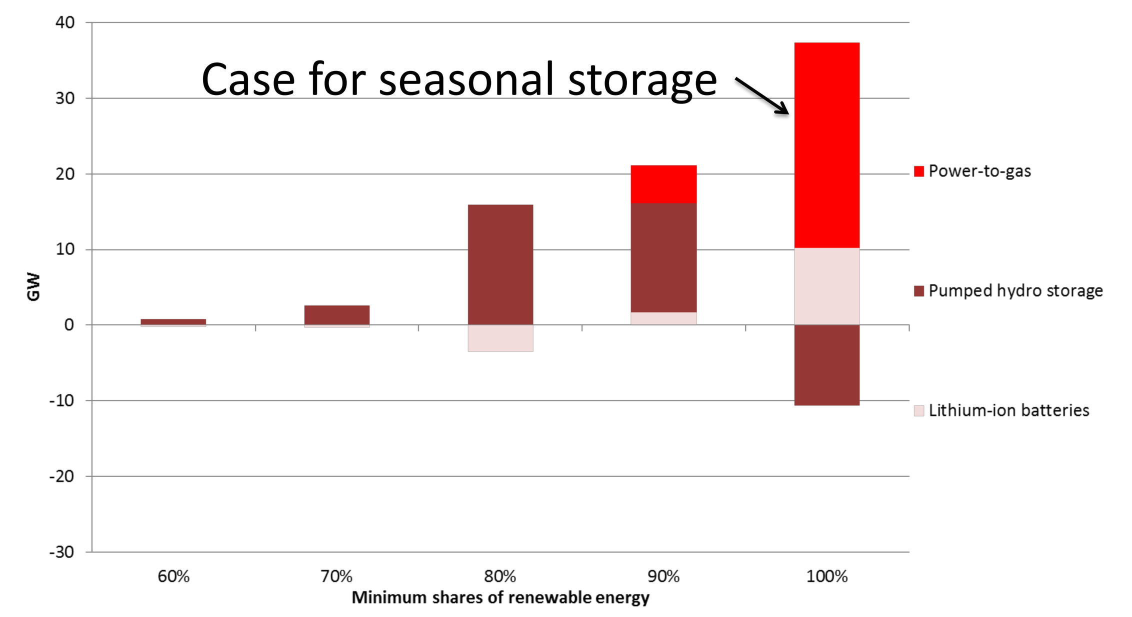

**Changes in power storage capacities: technology portfolio of "Roadmap Storage"**




**Installed capacities in the baseline**




**Changes in power storage capacities: half specific investments for Li-ion**




**Changes in power storage capacities: no availability of biomass**

## CONCLUSIONS

- **It is important to capture the full system value of power storage in the context of other flexibility options:**
  - Arbitrage value, capacity value, reserve value
- **Findings under baseline assumptions:**
  - Moderate power storage requirement up to 80% renewables
  - Other low-cost flexibility options on both the supply side and demand side
  - Storage requirement increases strongly towards 100% renewables
- **Sensitivities:**
  - Costs and availabilities of other options are important, particularly biomass and offshore wind power
  - Substantial effects of lower battery storage costs
  - Long-term storage only relevant in case of biomass restrictions and/or "dark doldrums"
- **Case for continued research, development and demonstration to safeguard the energy transition**

## SELECTED REFERENCES

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**All publications of the StoRES project: http://tinyurl.com/stores-publications**