# Economics of stationary electricity storage with various charge & discharge durations

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# In short

- Market-based analysis of heterogenous storage technologies and services
  - PHS, CAES, chemical batteries, flywheels,...
  - energy transfers, power transfers, real-time balancing, back-up to intermittent energies…

- Integration of storage technologies in the optimal mix and dispatch of electricity production.

- Recall that storage is not a production process. It turns electricity at one date into electricity at a later date. Then storage is competing against consumers at some dates and against producers at other dates.

# Outline

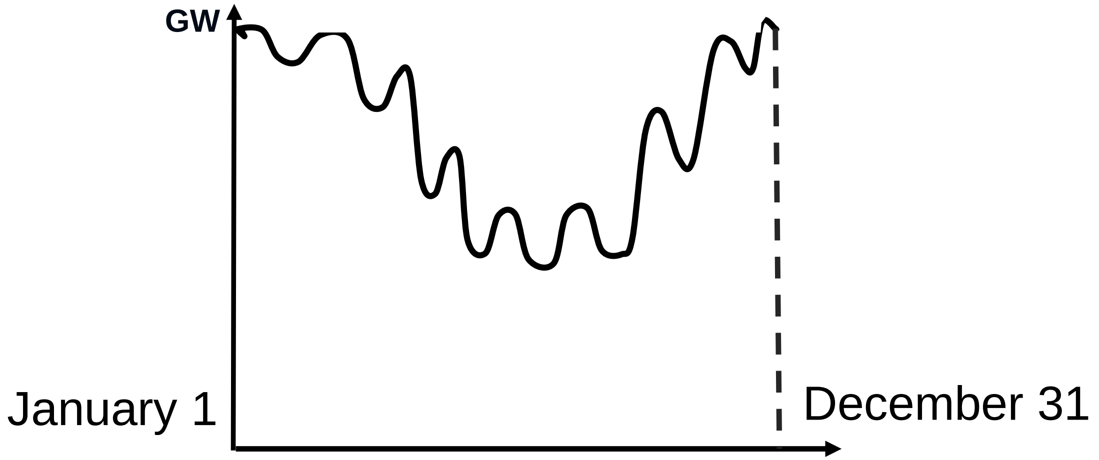
Reminder: optimal mix of reliable production plants without storage

1. Short run management of a storage installation
   - Optimal use
   - Comparative dynamics, in particular wrt discharge and charge durations
2. Investment in storage installations
   - Costs and profitability
   - Technologies ranking
3. Storage in the wholesale market
   - Feedback of storage investment on market prices

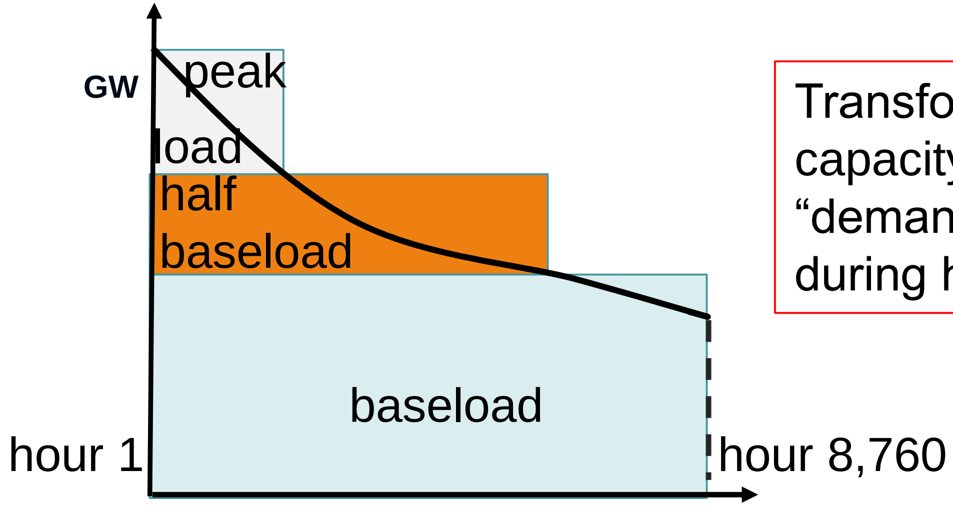
Conclusion

# Reminder: optimal electricity system without storage

1a. Evaluate expected demand



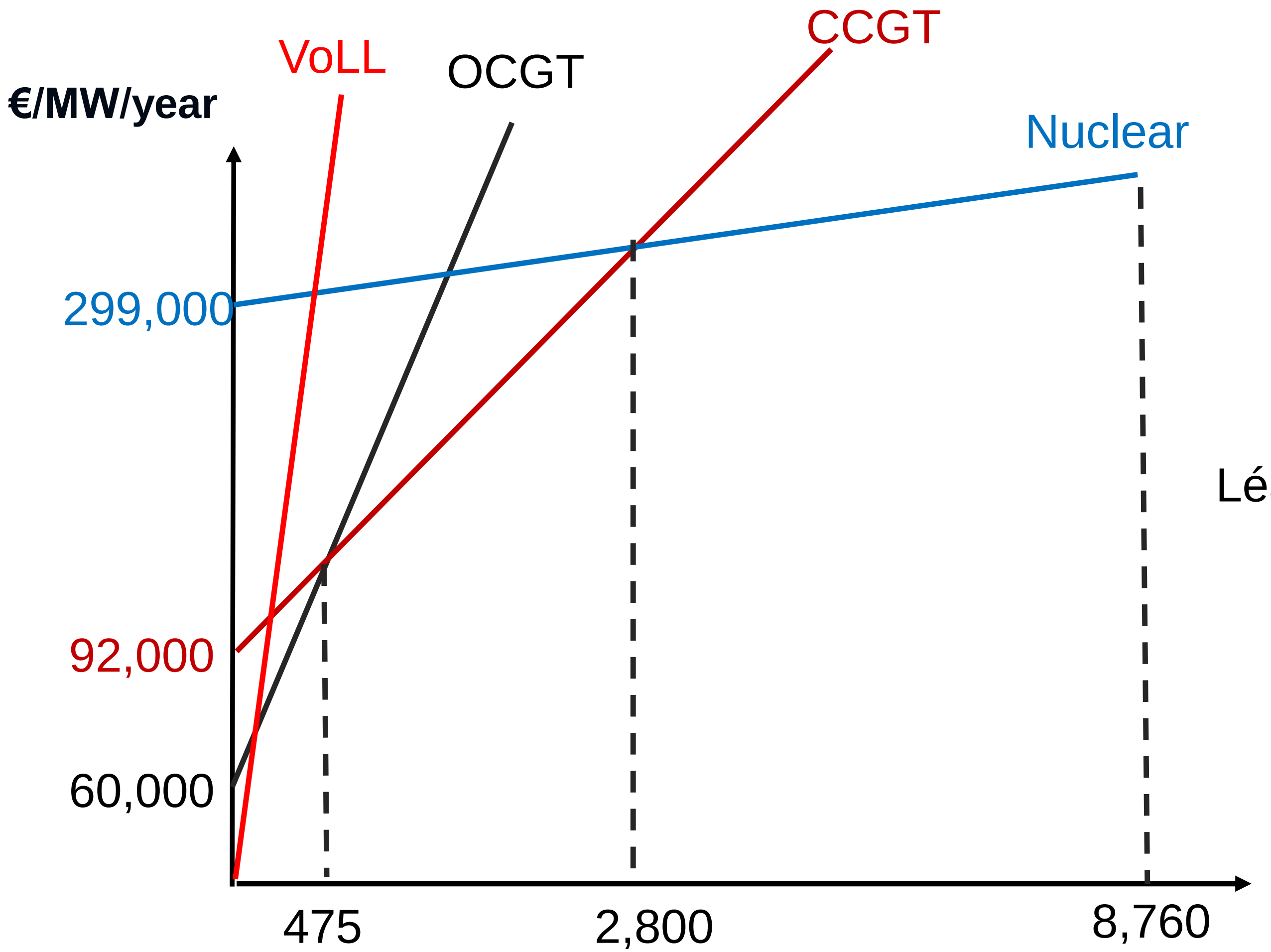

1b. Re-order demands from the highest to the lowest: → **load duration curve**




Transforms “demand for capacity $K_t$ at date t” into “demand for capacity $K_h$ during h hours”

# How much of each type of technology?

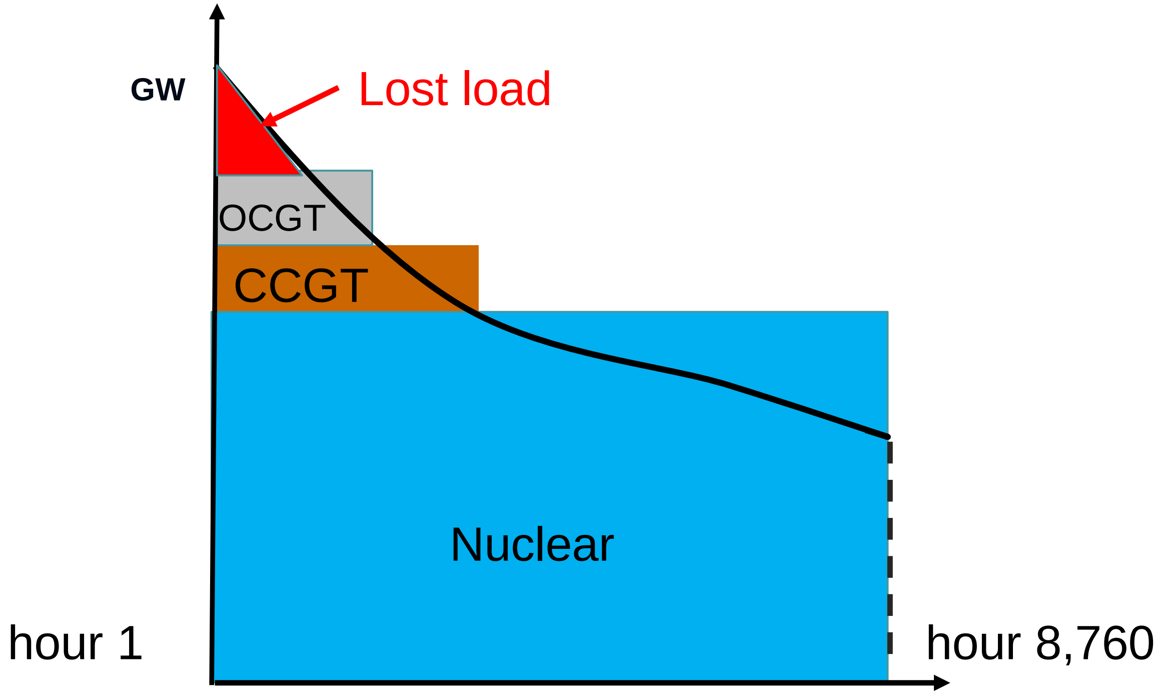
2. Classify technologies according to investment costs and operating costs




Source:
Léautier 2019

# Optimal mix

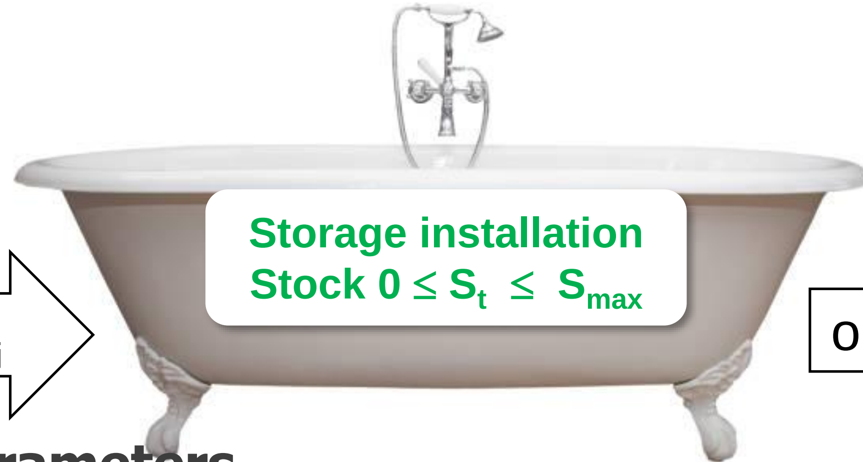
3. Adjusting capacity supply to capacity demand




⟶ **Duration is the key concept.**

⟶ **What is the equivalent of "operating costs" in the storage activity?**

# 1. Short run management of a storage installation



input $0 \le \mathbf{q}_{it} \le K_i$

**Storage installation**
**Stock $0 \le S_t \le S_{max}$**

output $0 \le \mathbf{q}_{ot} \le K_o$

**exogeneous parameters**

| | |
|---|---|
| $K_i$ | maximum capacity of filling, |
| $K_o$ | maximum capacity of discharging, |
| $S_{max}$ | maximum storage capacity of the equipment, |
| $r$ (<1) | proxy for energy losses in the storage system |
| $p_t$ | electricity price during period t |

**endogenous parameters**

| | |
|---|---|
| $q_{it}$ | input at period t, i.e. energy bought from the system and stored |
| $q_{ot}$ | output at period t, i.e. energy destored and sold to the system |
| $S_t$ | stock of energy contained in the installation at the beginning of t |
| $\Pi$ | profit to be maximized on the time span {1;T} |
| $\lambda_t$ | reserve value of energy |

# Short run optimization

$$\Pi = \max_{\{q_{ot}\},\{q_{it}\}} \sum_{t=1}^{T} p_t(q_{ot} - q_{it}) \quad \text{s.t.} \begin{cases} 0 \leq q_{ot} \\ q_{ot} \leq K_o \\ 0 \leq q_{it} \\ q_{it} \leq K_i \end{cases} \quad \text{and} \quad \begin{cases} S_{t+1} - S_t = r q_{it} - q_{ot} & (\lambda_t) \\ 0 \leq S_t \\ S_{final} \leq S_{T+1} \\ S_t \leq S_{\max} \\ S_1 \leq S_{initial} \end{cases}$$

- The shadow value of energy in stock at t ($\lambda_t$) is the key economic indicator of optimal management.
- This reserve value of energy is both
  - a measure of operating cost during discharging phases
  - a measure of utility during charging phases
- It is to be compared with the outside value $p_t$

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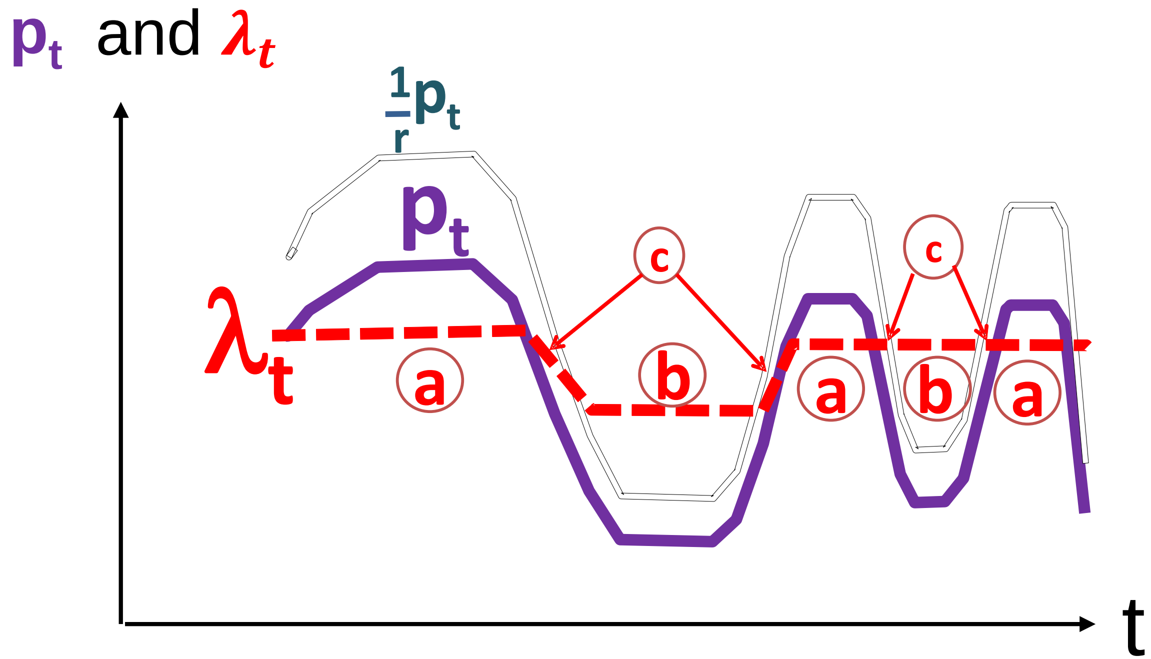
# Results

a) Destoring phases ($q_{ot}$=$K_o$, $q_{it}$=0) when $p_t \geq \lambda_t$

b) Storing phases ($q_{ot}$=0, $q_{it}$= $K_i$) when $p_t \leq r\lambda_t$.

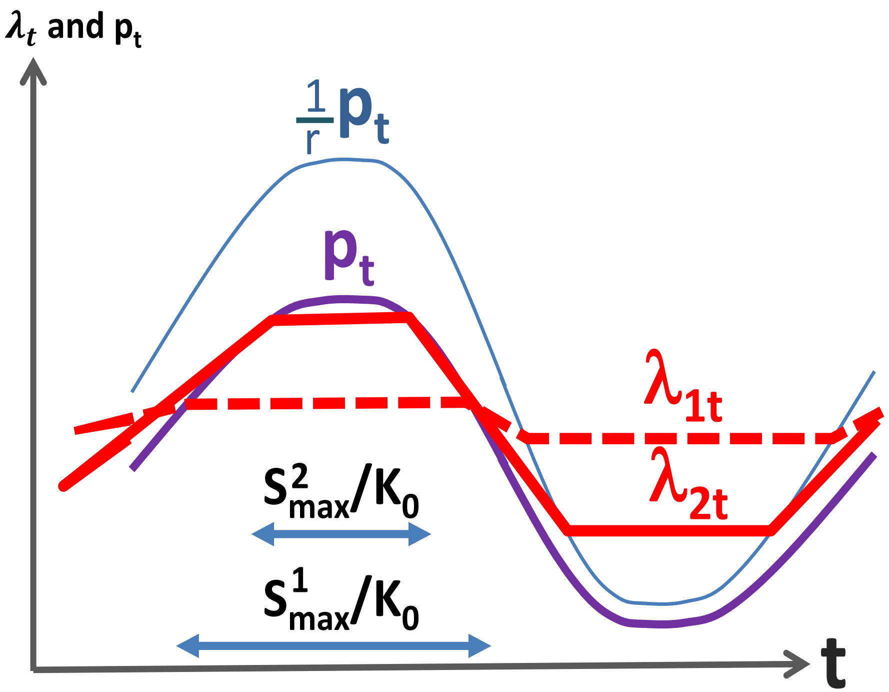
c) Idle phases ($q_{ot}$=0, $q_{it}$= 0) when $p_t < \lambda_t < p_t/r$




During phases (a) and (b), the Hotelling rule applies.

# Durations

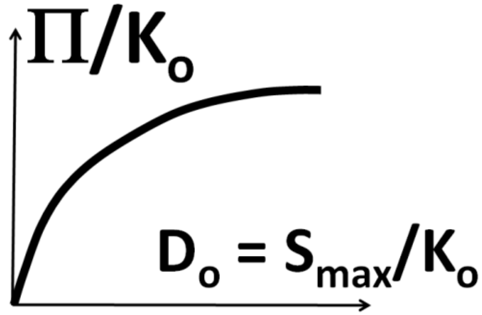
- Discharge duration $D_o = S_{max}/K_o$ is the minimum time needed to empty the reservoir initially full (i.e. discharging at maximal outflow capacity)
- Charge duration $D_i = S_{max}/(rK_i)$ is the minimum time needed to fill the reservoir initially empty (i.e. charging at maximal inflow capacity).




- Longer (dis-)charge durations contribute to lower differences in reserve values between destoring periods and storing periods, and to longer time of use of the installation across the whole period.

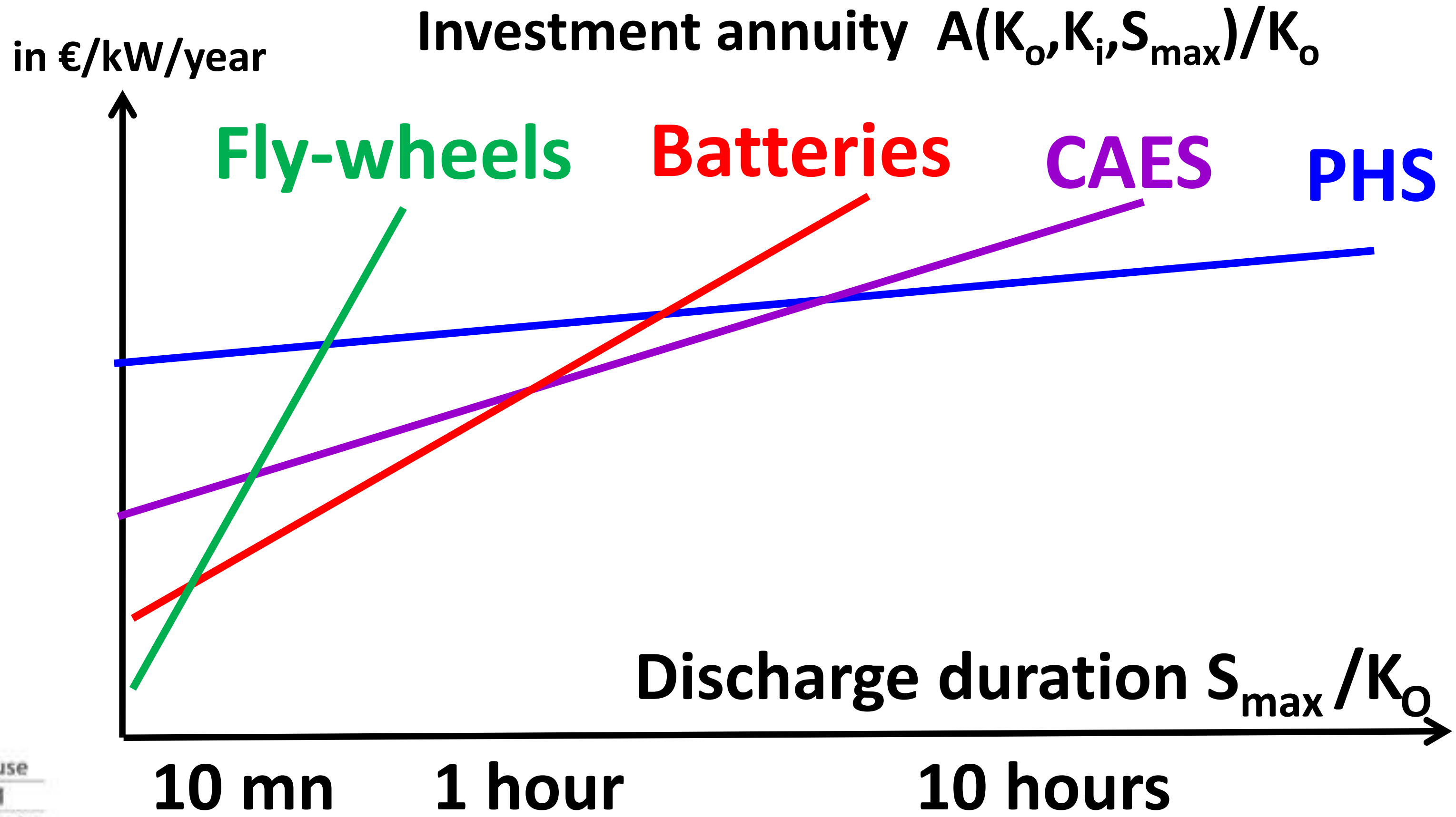
# Comparative dynamics

- The operating profit per year $\Pi$ is a multilinear function of $(K_o, K_i, S_{max}, S_{initial}, S_{final})$
- Keeping capacities $K_o$ and $K_i$ fixed, $\Pi$ is non-decreasing and concave wrt $S_{max}$, then wrt durations $D_o = S_{max}/K_o$ and $D_i = S_{max}/(rK_i)$



# 2. Investing in storage equipment

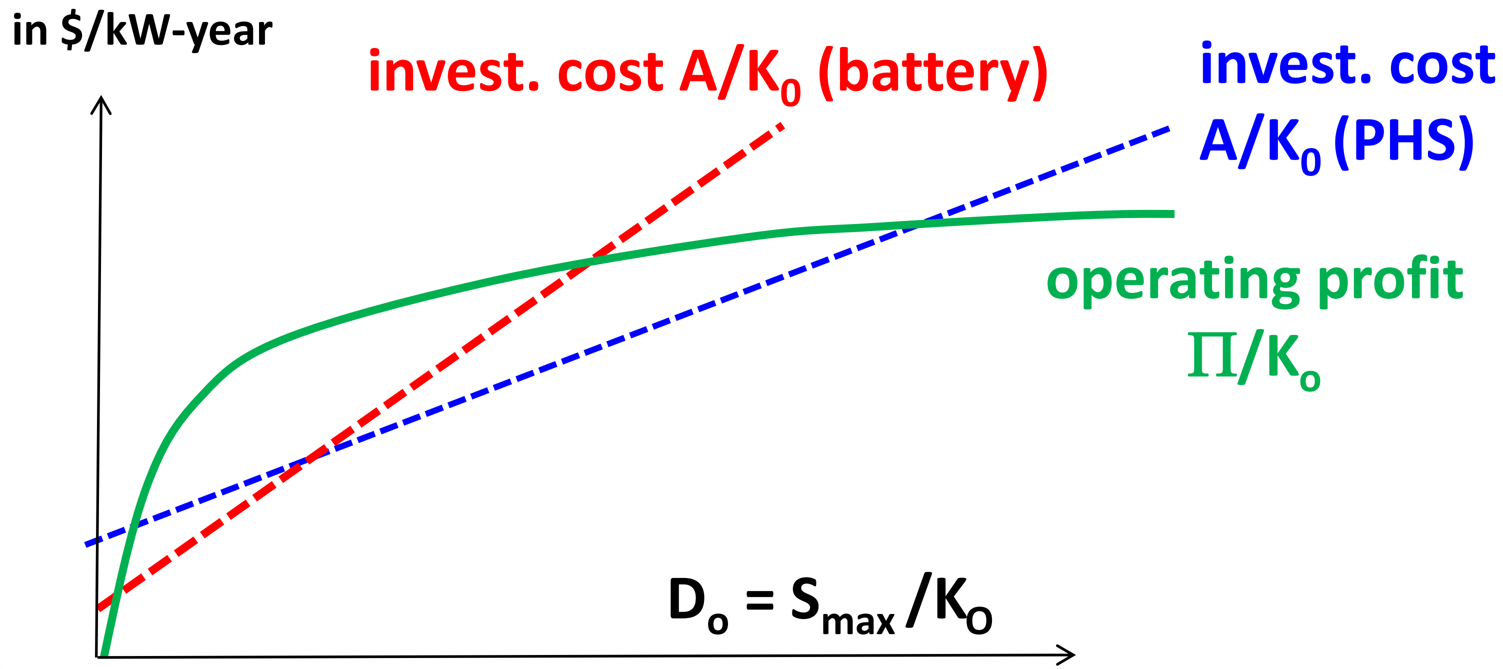
- On the equipment market, manufacturers propose heterogeneous types with different investment costs according to duration parameters.



# Matching the operating profit and the investment cost

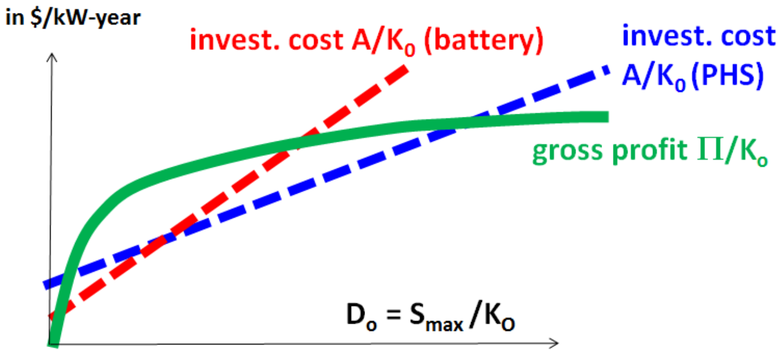
- Invest iff the Net Present Value is positive
- In terms of annuity:

operating profit $\Pi\,(K_o,K_i,S_{max}) \;\geq\;$ investment cost $A(K_o,K_i,S_{max})$



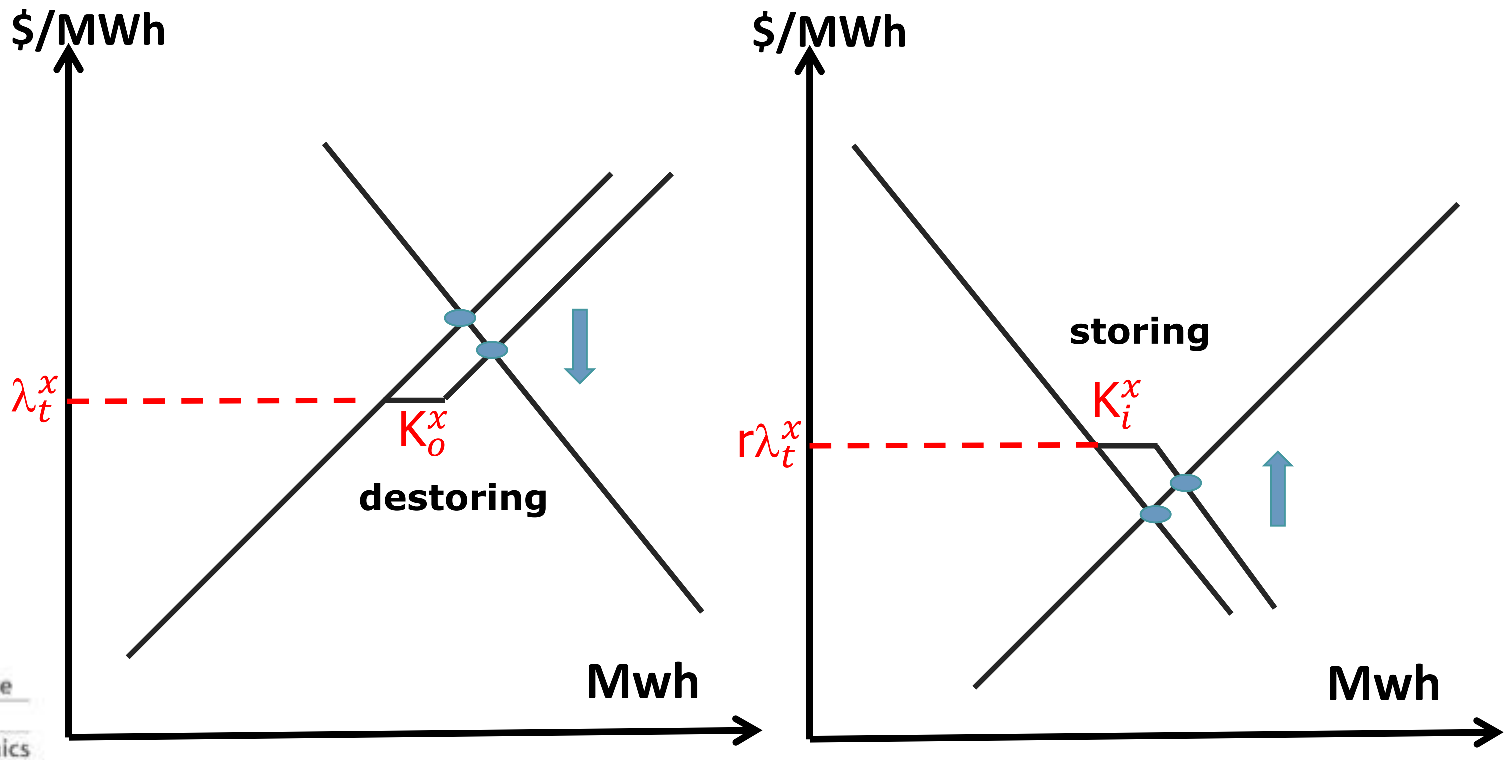
# Best choices

- For very short-duration services (less than 2-3 minutes), lead-acid batteries: for example, industrial consumers want enhanced quality of electricity (UPS)
- For short –duration services (less than 20-30 minutes), lithium and lead-acid batteries: for example for frequency control.
- For energy transfers between day and night (20-30 hours), batteries are much less competitive (except for out-of-grid load pockets) as compared with PHS.



# 3. Storage in the wholesale market

- Storage operator $x$ should bid $\lambda_t^x$ (and $r\lambda_t^x$) on the electricity market.
- If dispatched,
  - as a seller, it pushes the price down during high-price periods
  - as a buyer, it pulls the price up during low-price periods.

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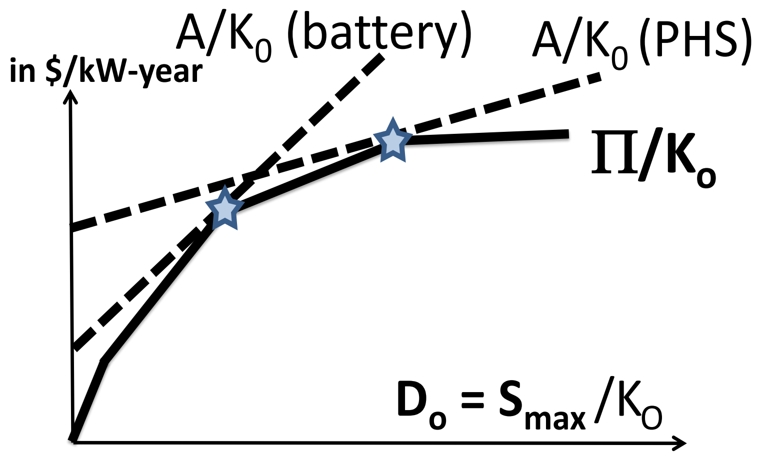
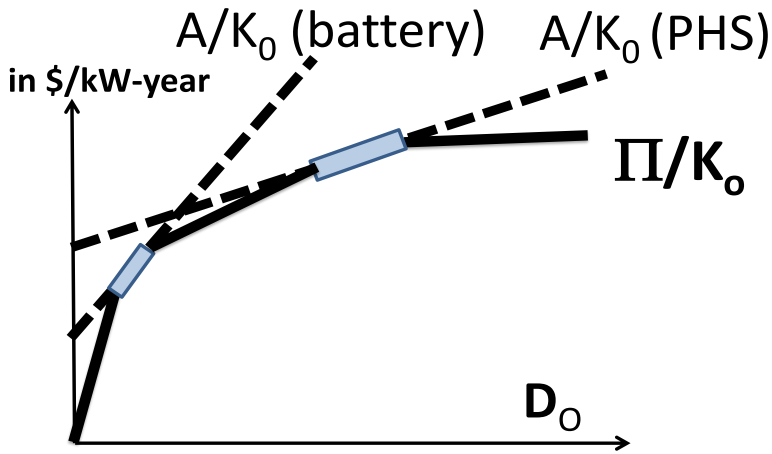
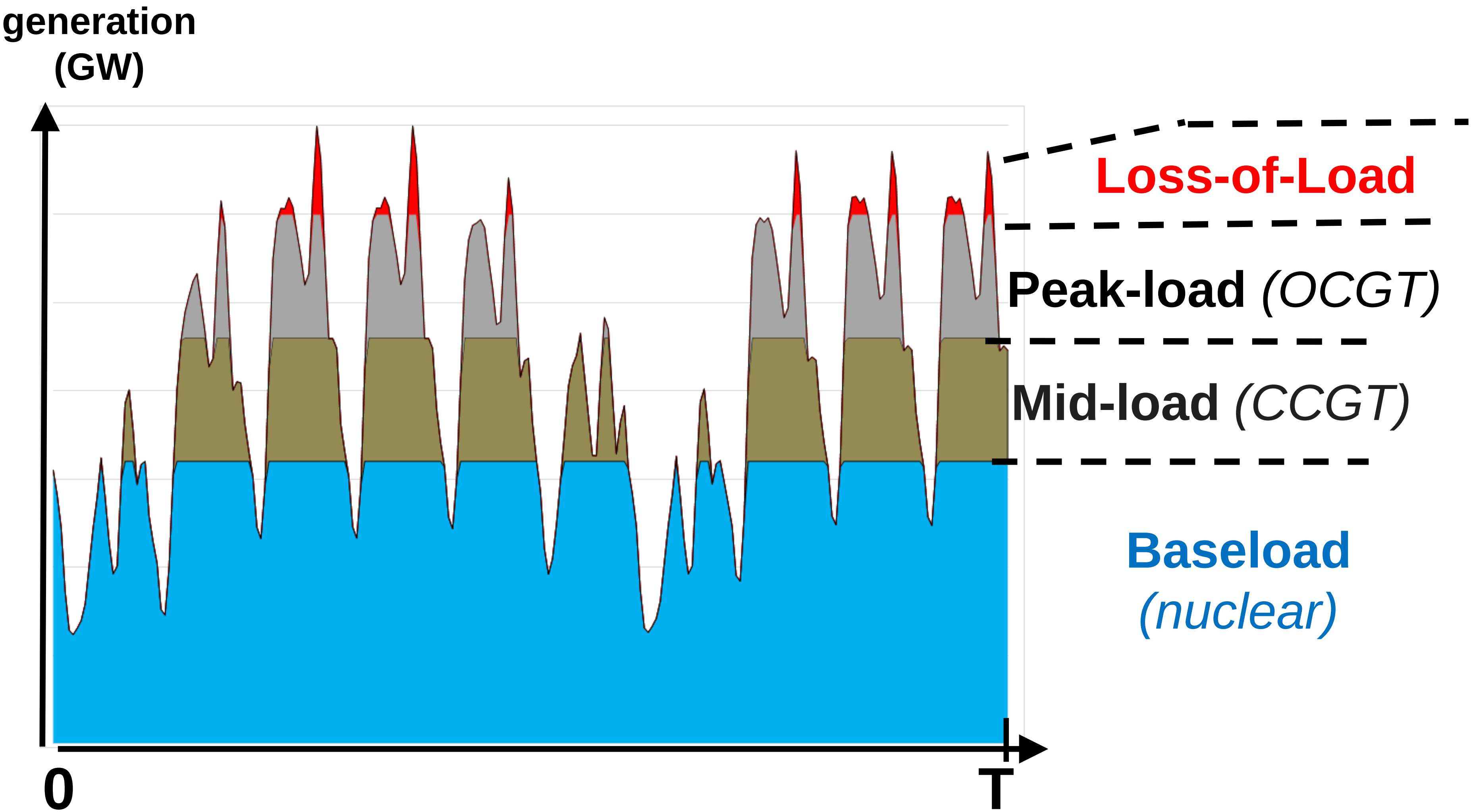
# Free entry

- Under competition with free entry, investors enter the storage activity to earn the operating profit. With prices going up during charging phases and down during discharging phases, **$\Pi$ is shifted downwards.**
- At the long-run equilibrium for storage investment it remains no marginal investment opportunity providing NPV > 0 with any technology: the operating profit function $\Pi$ has no segment above the equipment cost function A.



# Demand and production without storage equipment



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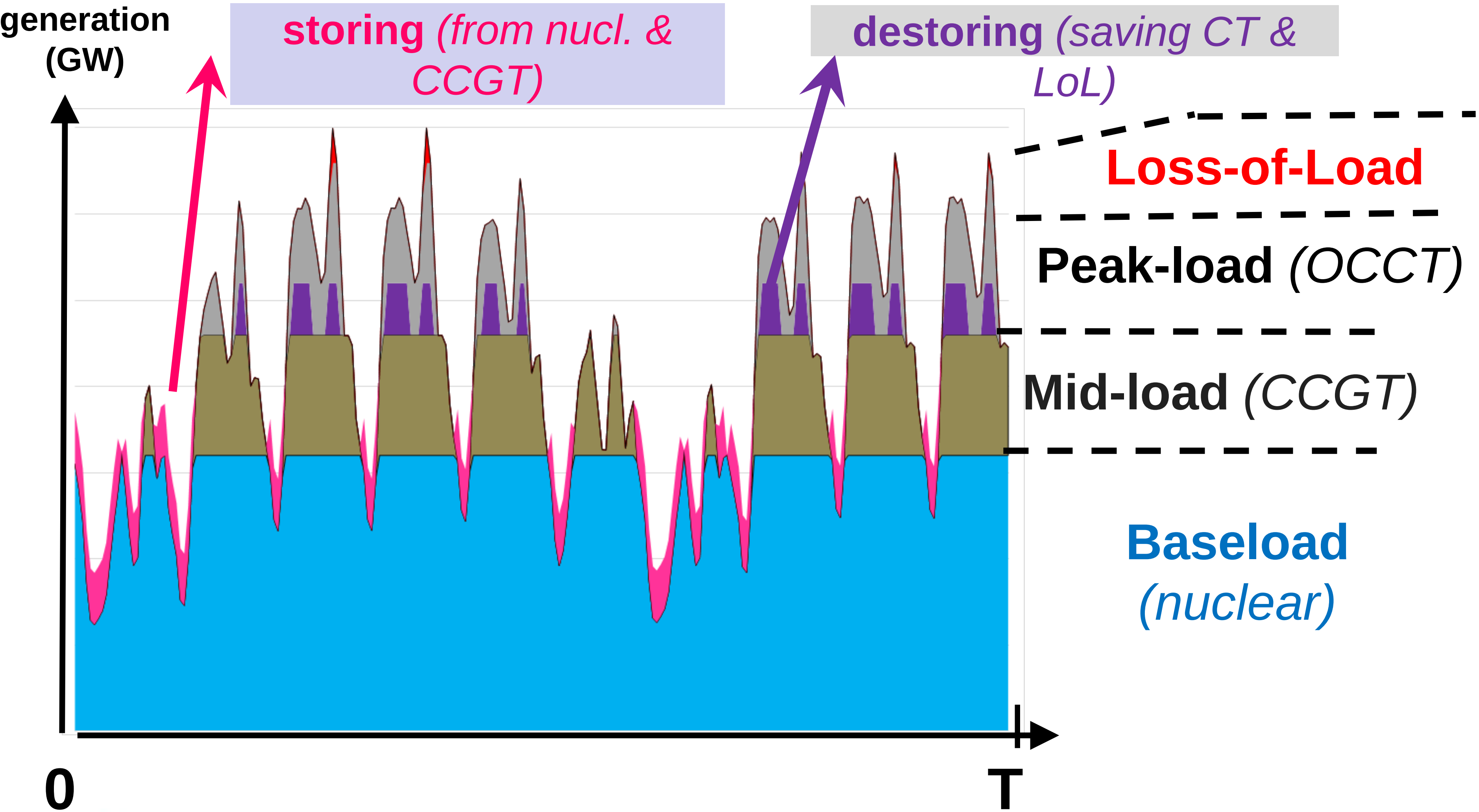


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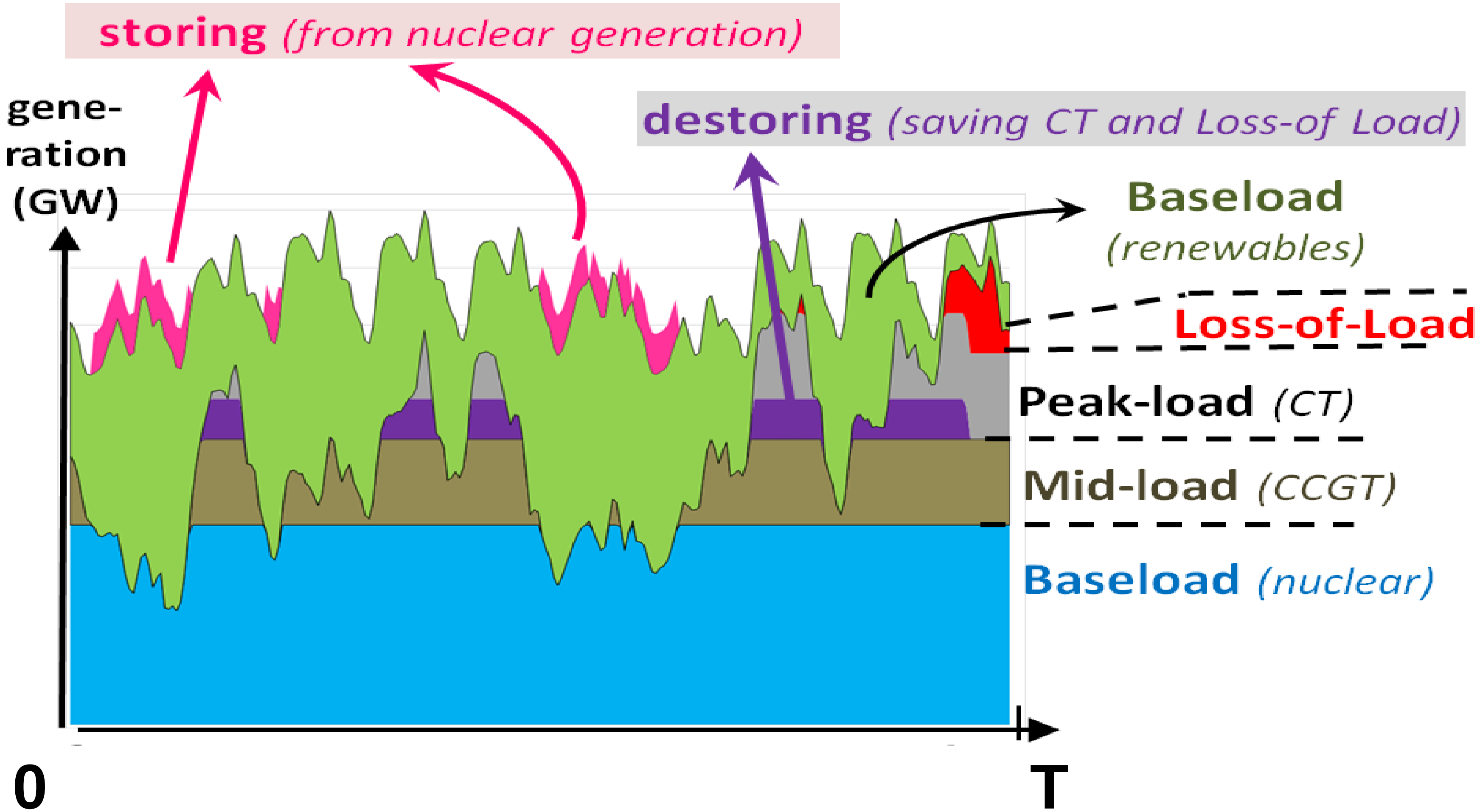
# Demand and production with storage equipment and renewables



# Conclusion

- A unified cost-benefit analysis that highlights the role of discharge-charge durations as a key metric for segmenting storage technologies and services.

- An electric system with efficient mix and size might integrate several types of storage installations to provide fossil fuel and capacity savings, but costs are too high to allow full substitutability.
- Further research
  - uncertainty on demand and/or renewables: storage equipment as an insurance device on top of a mere buffering function;
  - heterogenous r, $K_o$ and $K_i$
  - multi-service provision, economies of scope;