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Lecture 6: Storage and Demand-Side Management

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Principles of electricity storage

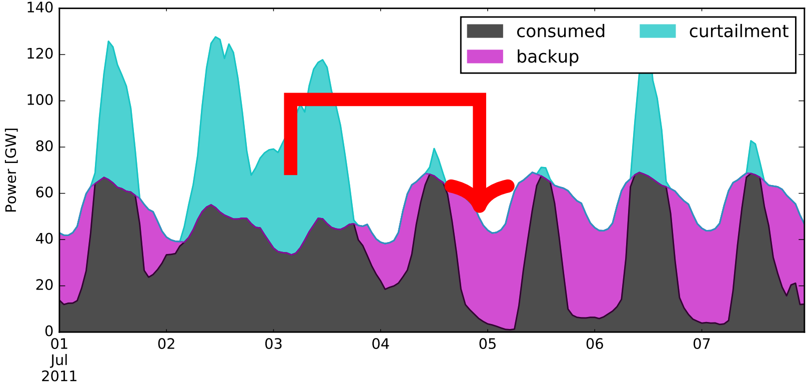
Recall from Previous Lectures

Conceptual options to balance wind and solar (avoiding need for backup and curtailment):

- Transmission grid (last lecture)
- **Storage**
- Demand-side management
- Sector coupling

Basic idea of storage

Networks were used to shift power imbalances between different places, i.e. in **space**.
Electricity storage can shift power in **time**.



Storage: Power Versus Energy Capacity

For a storage unit, we have to distinguish between the **power capacity** (MW) at which we can discharge (dispatch) or charge the storage, and the **energy capacity** (MWh) it can store.

Examples:

- A Tesla battery electric vehicle can charge with a power of 11 kW at home or 100-150 kW at a supercharger. The Model S has an energy capacity of 100 kWh.
- The Hornsdale utility-scale battery in South Australia has a power capacity of 100 MW and an energy capacity of 185 MWh.

Storage consistency

Storage units, such as batteries or hydrogen storage, labelled by r, can both dispatch/discharge power within its discharging capacity (in MW):

$$0 \leq g_{i,r,t,\text{discharge}} \leq G_{i,r,\text{discharge}}$$

and consume power to charge the storage within its charging capacity (in MW):

$$0 \leq g_{i,r,t,\text{charge}} \leq G_{i,r,\text{charge}}$$

The total power (positive when discharging, negative when charging) can then be written:

$$g_{i,r,t} = g_{i,r,t,\text{discharge}} - g_{i,r,t,\text{charge}}$$

There is also a limit on the total energy $e_{i,r,t}$ at each time:

$$0 \leq e_{i,r,t} = e_{i,r,0} - \sum_{t'=1}^{t} g_{i,r,t'} \leq E_{i,r}$$

where $E_{i,r}$ is the energy capacity (in MWh). Or in iterative form

$$0 \leq e_{i,r,t} = e_{i,r,t-1} + g_{i,r,t,\text{charge}} - g_{i,r,t,\text{discharge}} \leq E_{i,r}$$

Incorporation in power balance with generation, demand and network

We can then incorporate the storage power $g_{i,r,t}$ in our power imbalance for each node i and each time t from last lecture:

$$p_{i,t} = \sum_s g_{i,s,t} + \sum_r g_{i,r,t} - d_{i,t} = \sum_\ell K_{i\ell} f_{\ell,t}$$

(s runs over generation technologies, r over storage technologies, ℓ over network lines)

The nodes are linked in space by the network and in time by the consistency for the storage energy.

If we expand the storage power $g_{i,r,t}$ into its charging and discharging parts:

$$p_{i,t} = \sum_s g_{i,s,t} + \sum_r (g_{i,r,t,\text{discharge}} - g_{i,r,t,\text{charge}}) - d_{i,t} = \sum_\ell K_{i\ell} f_{\ell,t}$$

we see that the discharging part has the sign of a generator putting power into the system, while the charging part acts like a demand extracting power from the system.

Storage consistency: continuous version

In the previous slide we had discrete time points $t \in \{0, 1, 2, \ldots\}$.

The discrete equation for the total energy (sometimes called the **state of charge**):

$$0 \leq e_{i,r,t} = e_{i,r,0} - \sum_{t'=1}^{t} g_{i,r,t'} \leq E_{i,r}$$

is nothing other than an integration over time t.

So if we write $g_{i,r,t}$ and $e_{i,r,t}$ as continuous functions of t, $g_{i,r}(t)$ and $e_{i,r}(t)$, we get an integration:

$$0 \leq e_{i,r}(t) = e_{i,r}(0) - \int_0^t g_{i,r}(t')dt' \leq E_{i,r}$$

Continuous example

Consider a single node (i.e. no network) with a constant demand

$$d(t) = D$$

and a renewable wind generator with a capacity $G = 2D$ and an availability time series

$$G(t) = \frac{1}{2}\left(1 + \sin\left(\frac{2\pi}{T}t\right)\right)$$

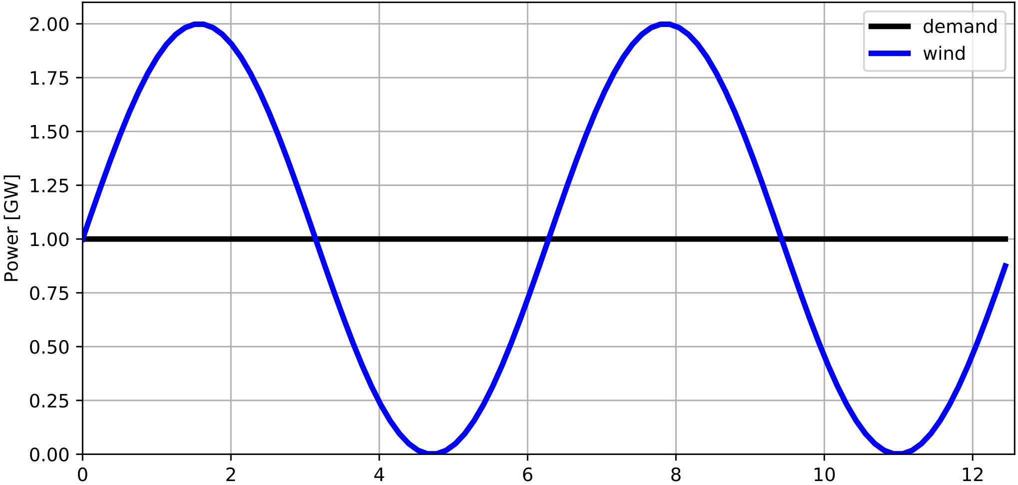
so that it oscillates with period T and on average produces enough energy for the demand

$$\langle G(t) G \rangle = D$$

Question: What are the power and energy capacities of the ideal storage unit to balance this system?

Continuous example

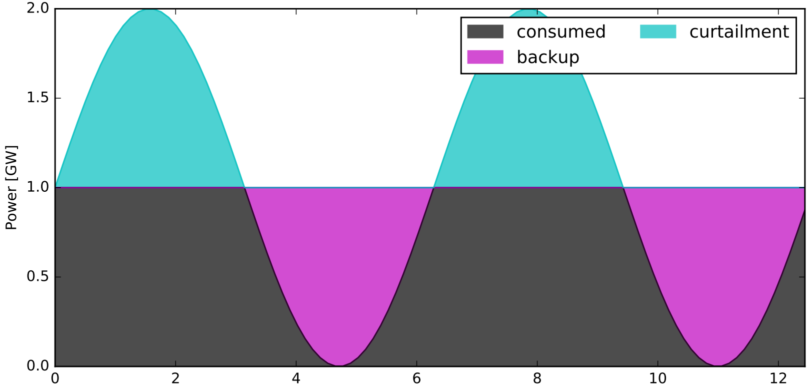
For $D = 1$, $T = 2\pi$:



Our residual demand or mismatch is now

$$m(t) = d(t) - GG(t) = D - D\left(1 + \sin\left(\frac{2\pi}{T}t\right)\right) = -D\sin\left(\frac{2\pi}{T}t\right)$$

For $D = 1$, $T = 2\pi$:



Storage Power

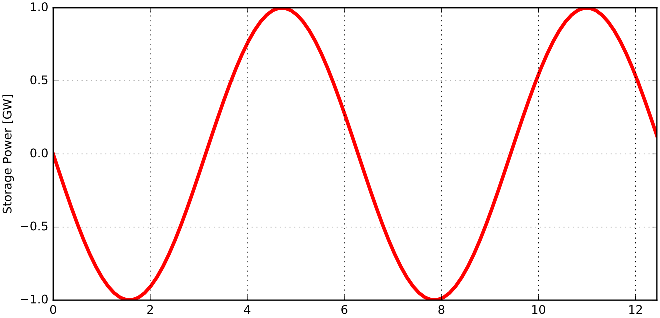
To balance this, we need a storage unit with power profile $g_r(t)$ such that the node balances:

$$0 = p(t) = GG(t) + g_r(t) - d(t) = g_r(t) - m(t)$$

i.e.

$$g_r(t) = d(t) - GG(t) = m(t) = -D\sin\left(\frac{2\pi}{T}t\right)$$

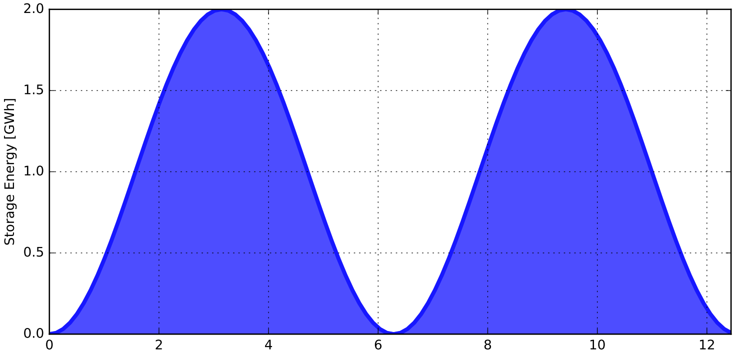
This will have power capacities $G_{r,\mathrm{discharge}} = G_{r,\mathrm{charge}} = D$. For $D = 1$, $T = 2\pi$:



How much energy capacity E_r do we need? The energy profile is:

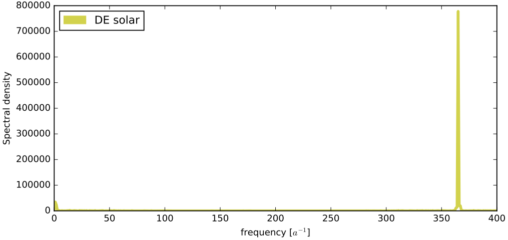
$$e_r(t) = \int_0^t (-g_r(t'))dt' = D \int_0^t \sin\left(\frac{2\pi}{T}t'\right) dt' = \frac{TD}{2\pi}\left[1 - \cos\left(\frac{2\pi}{T}t\right)\right]$$

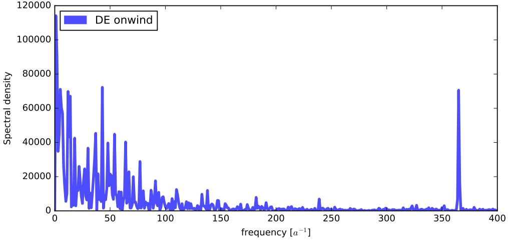
This peaks at $t = \frac{T}{2}$ so $E_r = \max_t\{e_r(t)\} = \frac{TD}{\pi}$. Faster oscillations, i.e. shorter periods, $\Rightarrow$ less energy capacity. So for $D = 1$, $T = 2\pi$, maximum is $E_r = 2$:



Fourier coefficients of wind and solar in Germany

Although wind and solar are not perfect sine waves, if we decompose the time series in Fourier components, we do see **dominant frequencies** which can help us understand how to dimension storage.





Storage Energy: concrete examples

How does our formula $E_r = \frac{TD}{\pi}$ look for different generation technologies with simplified sinusoidal profiles?

Consider a simplified demand of $D = 1$ MW.

quantity	symbol	units	solar	wind
generation capacity	G	MW	2	2
storage power capacity	G_r	MW	1	1
period	T	h	24	$7 \cdot 24 = 168$
storage energy capacity	E_r	MWh	7.6	53

Faster daily oscillations of solar need smaller storage capacity than weekly oscillations of wind.

NB: In reality of course solar and wind are not perfect sine waves...

There are a few extra details to add now. First, no renewable has a perfectly regular sinusoidal profile.

Second, the iterative integration equation for the storage energy

$$e_{i,r,t} = e_{i,r,t-1} + g_{i,r,t,\text{charge}} - g_{i,r,t,\text{discharge}}$$

needs to be amended for **efficiencies** $\eta \in [0,1]$ (corresponding to **losses** $1-\eta$)

$$e_{i,r,t} = \eta_0 e_{i,r,t-1} + \eta_1 g_{i,r,t,\text{charge}} - \eta_2^{-1} g_{i,r,t,\text{discharge}}$$

$1-\eta_0$ corresponds to **standing losses** or **self-discharge**, η_1 to the **charging efficiency** and η_2 to the **discharging efficiency**.

Different storage units have different parameters

We can relate the power capacity G_r to the energy capacity E_r with the maximum number of hours the storage unit can be charged at full power before the energy capacity is full, $E_r = \text{max-hours} * G_r$.

	Battery	Hydrogen	Pumped-Hydro	Water Tank
η_0	$1-\varepsilon$	$1-\varepsilon$	$1-\varepsilon$	depends on size
η_1	0.9	0.75	0.9	0.9
η_2	0.9	0.58	0.9	0.9
max-hours	2-10	weeks	4-10	depends on size
euro per kW [G_r]	300	500+450	depends	low
euro per kWh [E_r]	200	10	depends	low

Parameters are roughly based on **Budischak et al, 2012** with projections for 2030.

Different storage units have different use cases

Consider the cost of a storage unit with 1 kW of power capacity, and different energy capacities.

The total losses are given by the **round-trip losses** in and out of the storage $1 - \eta_1 \cdot \eta_2$.

	Battery	Hydrogen
losses	$1 - 0.9^2 = 0.19$	$1 - 0.58*0.75 = 0.57$
€ for 2 kWh	$300 + 2x200 = 700$	$950 + 2x10 = 970$
€ for 100 kWh	$300 + 100x200 = 20300$	$950 + 100x10 = 1950$

Battery has lower losses and is cheaper for short storage periods.

Hydrogen has higher losses but is much cheaper for long storage periods (e.g. several days).

You try: Explore use cases using **https://model.energy** for Mexico (solar+battery) and Ireland (wind+hydrogen).

Advanced: Levelised Cost of Storage (LCOS)

Analogous to the levelised cost of electricity (LCOE) for generators, you can also defined a **Levelised Cost of Storage (LCOS)** for the costs of sending a MWh through a roundtrip cycle of the storage. To simplify the calculations we assume that the annual fixed costs (annuity of investment as well as maintenance) are 10%/a of the investment costs.

For the battery we assume 200 full battery cycles per year (200 cycle/a) and an energy/power ratio of 2 kWh/kW. Then the costs per cycle are

$$\frac{20\ €/\mathrm{kWh/a} + 30\ €/\mathrm{kW/a} \div 2\ \mathrm{kWh/kW}}{200\ \mathrm{cycle/a}} = 22.5 €/\mathrm{MWh/cycle}$$

This is cost added to e.g. solar energy going through a battery.

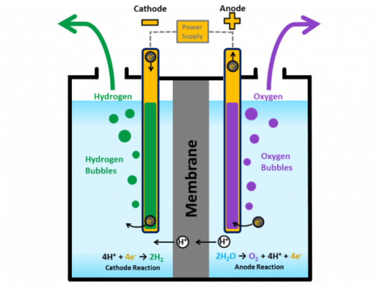
For the hydrogen storage we assume 10 cycle/a and an energy/power ratio of 100 kWh/kW.

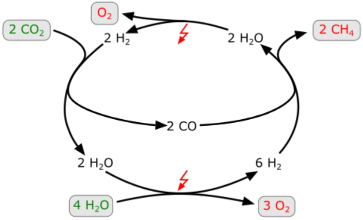
$$\frac{1\ €/\mathrm{kWh/a} + 95\ €/\mathrm{kW/a} \div 100\ \mathrm{kWh/kW}}{10\ \mathrm{cycle/a}} = 195 €/\mathrm{MWh/cycle}$$

Better make sure as little power goes through hydrogen conversion as possible...

Power-to-Gas

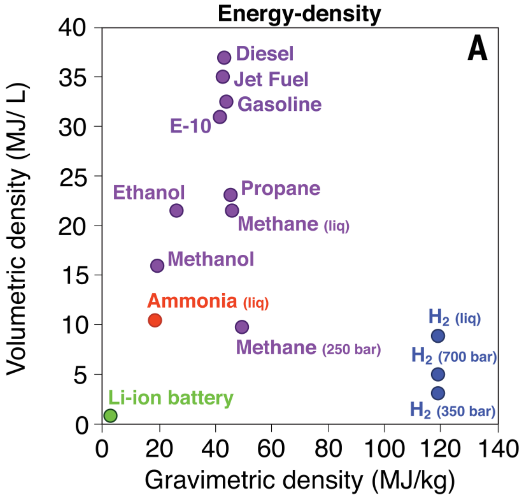
Power-to-Gas (P2G)





Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to **hydrogen** H_2 (and oxygen O_2). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH_4 (main component of natural gas) or liquid fuels C_nH_m. Used for **hard-to-defossilise sectors**:

- **dense fuels** for transport (planes, ships)
- **steel-making** & **chemicals industry**
- **high-temperature heat** or **heat for buildings**
- **backup energy** for cold low-wind winter periods, i.e. as storage



- Hydrogen has a very good gravimetric density (MJ/kg) but poor volumetric density (MJ/L).
- Liquid hydrocarbons provide much better volumetric density for e.g. aviation.
- WARNING: This graphic shows the thermal content of the fuel, but the **conversion efficiency** of e.g. an electric motor for battery electric or fuel cell vehicle is much better than an internal combustion engine.

Source: Davis et al, 2018

Power to Gas Concept as Storage

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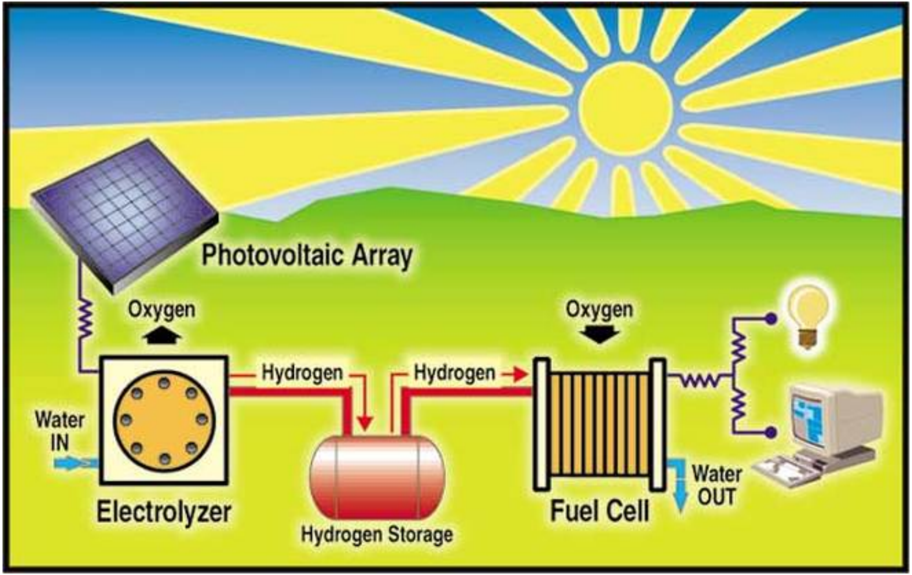
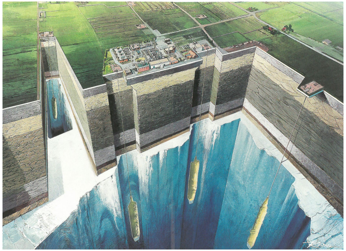


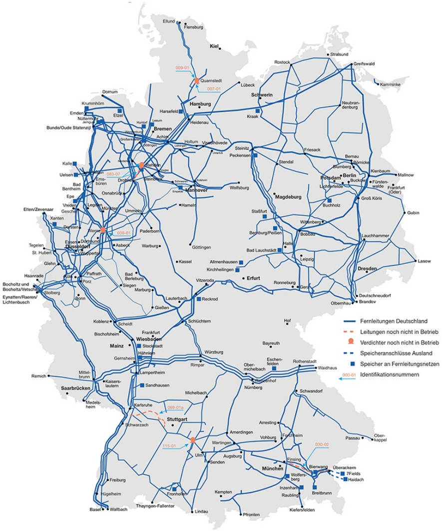
Source: Buildipedia

Power-to-Gas (P2G)

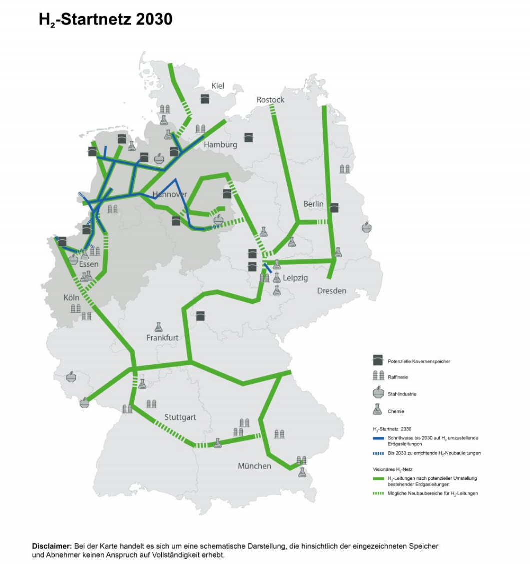


- Gases and liquids are easy to **store** and **transport** than electricity.
- Storage capacity of the German natural gas network in terms of energy: ca 230 TWh. Europe wide it is 1100 TWh (see online table). In addition, losses in the gas network are small.
- (NB: Volumetric energy density of hydrogen, i.e. MWh/m^3, is around three times lower than natural gas.)
- Pipelines can carry many GW underground, out of sight.

German Natural Gas Grid



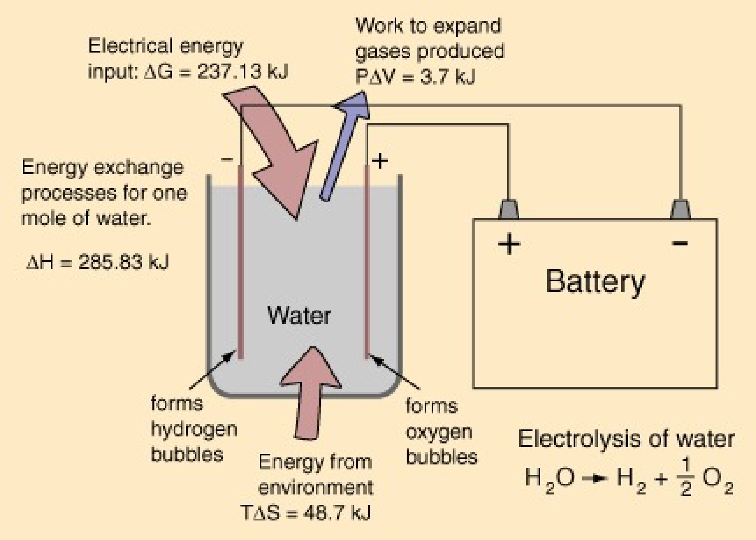
German Gas Transmission Network Operators Plan a Hydrogen Network



- German Gas Transmission Network Operators have published a plan for a new nationwide hydrogen network to take hydrogen between sites of production (e.g. electrolysis near the coast where offshore wind is connected), sites of storage (underground caverns) and consumers of hydrogen (industry, etc.).
- 90% of planned 2050 hydrogen network converts old natural gas pipelines; only 10% needs to be built new.

Source: **Fernleitungsnetzbetreiber**

Electrolysis



Source: Hyperphysics, Georgia State University

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

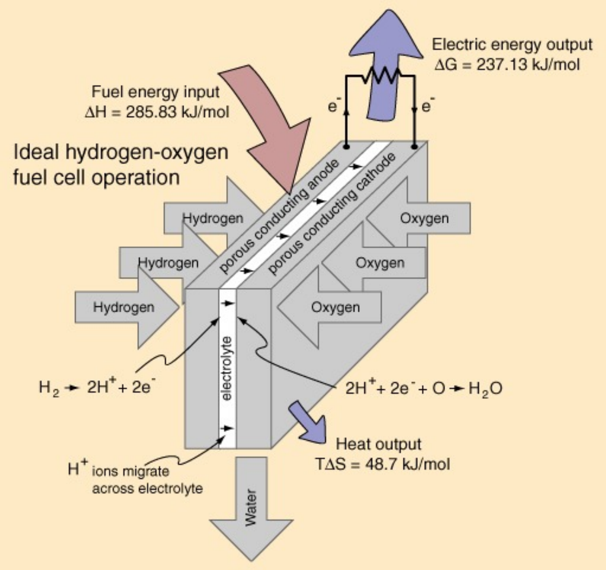
For one mole at conditions 298 K and one atmosspheric pressure

x	H_2	O_2	H_2O
Entropy [J/K]	130.7	205.1	69.9
Enthalpy [kJ]	0	0	-285.8

Gibbs free energy $dG = dH - TdS$,

$$\Delta G = 285.8kJ - 48.7kJ = 237.1kJ$$

Fuel Cell



Source: Hyperphysics, Georgia State University

Again: one mole at conditions 298 K and one atmosspheric pressure

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

Gibbs free energy $dG = dH - TdS$,

$$\Delta G = 285.8kJ - 48.7kJ = 237.1kJ$$

max theoretical efficiency

$$\frac{\Delta G}{\Delta U} = 0.83$$

Demand-Side Management (DSM)

Recall from Previous Lectures

Conceptual options to balance the power system:

- Transmission grid
- Storage
- **Demand-side management**
- Sector coupling

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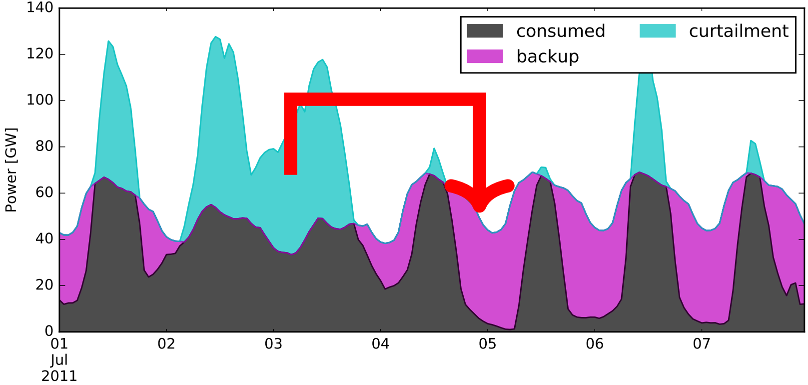
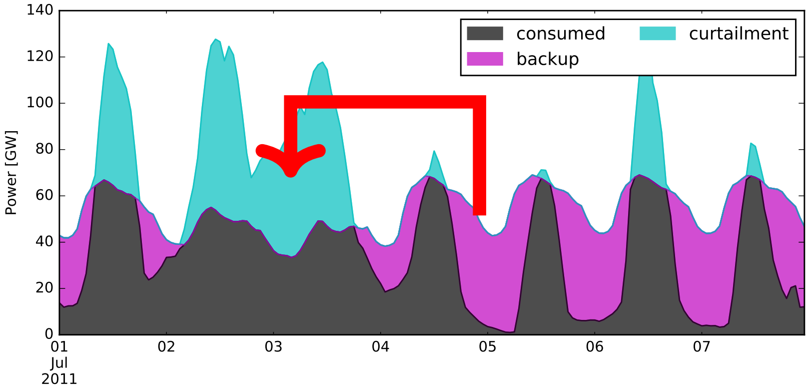
Basic idea of storage: move supply:



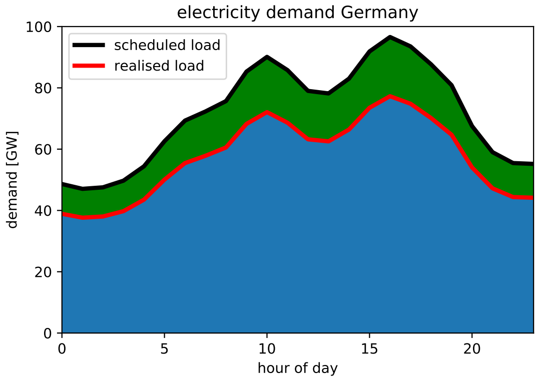
Basic Idea of Demand-Side Management

Modify demand instead of generation!



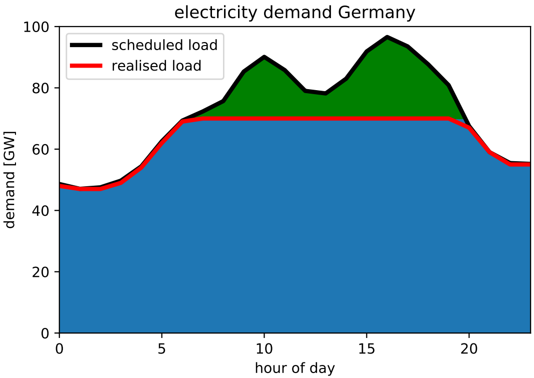
Demand-Side Management / Demand-Side Response

- Modification of the demand for energy through various means such as price incentives
- Charge consumers based on the true price of utilities at the time of consumption
- Alternative motivation may be grid bottlenecks from local distribution grid
- Issues: higher utility cost for consumers, communication infrastructure, synchronisation, cost, privacy, hacking



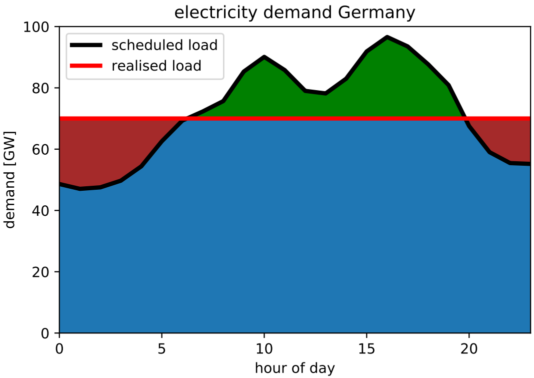
- Permanent reduction of the demand by use of more efficient appliances
  - washing machines
  - refrigerators
  - water heaters
- Germany: Reduction of 25% of gross electrical energy by 2050 compared to 2008

Cases of DSM: Peak Shaving



- Infrastructure designed for peak demand situations
- Commercial consumers often charged based on their peak demand

Cases of DSM: Load Shifting



- Shift electrical demand from times of deficits to times of surpluses
- provide price incentives to cause load shifting via smart meters
- different price incentive schemes possible, e.g., time of use prices, seasonal prices, etc.

Modelling Approach for DSM

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- loads sorted into different categories with assumed max. shifting periods (e.g. 8 hours for household applications)
- shifting charges a virtual storage buffer, where L_n is the original demand and R_n is what is actually realised

$$P_n[R_n(t)](t) = R_n(t) - L_n(t). \tag{1}$$

$P_n < 0$ means load is reduced by DSM, $P_n > 0$ means load is increased.

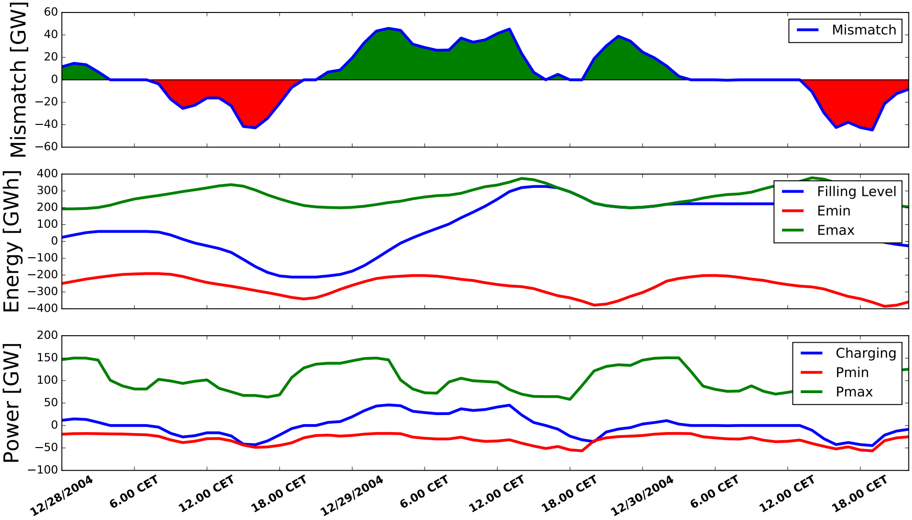
- filling level is consequently given by

$$E_n[R_n(t)](t) = \int_0^t P_n[R_n(t')](t')dt' \tag{2}$$

- constraints by shifting periods, e.g.

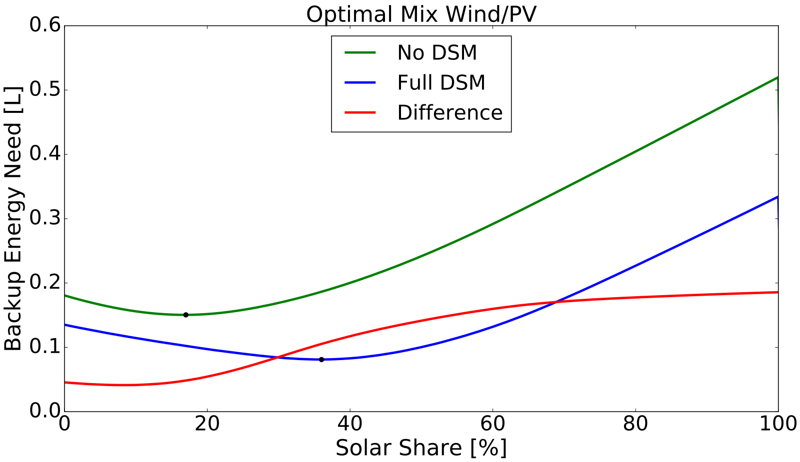
$$E_n^+(t) = \int_t^{t+\Delta t} L_n(t')dt' \tag{3}$$

Modelling Approach for DSM



Modelling Approach for DSM

Load shifting supports system integration of variable renewables, especially PV



Source: **Kies et al., Energies, 2016**

Demand-Side Management (DSM) Summary

- Demand-side management can contribute to successful power system operation
- Efficiency first!
- "Daily" scale supports PV integration
- Building infrastructure for DSM can be cost-intensive and cause minor additional energy consumption
- Needs a careful consideration of constraints from consumer side
- Synchronisation via pricing can amplify fluctuations
- Other concerns: hacking and privacy