Energy System Modelling
Summer Semester 2020, Lecture 5

Dr. Tom Brown, tom.brown@kit.edu, https://nworbmot.org/
Karlsruhe Institute of Technology (KIT), Institute for Automation and Applied Informatics (IAI)

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Table of Contents

1. Principles of electricity storage
2. Power-to-Gas
3. Demand-Side Management (DSM)
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 \textit{space}. Electricity storage can shift power in \textit{time}.

![Graph showing power consumption, backup, and curtailment over time.](image-url)
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 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, \( \ell \) 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.
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 \( D = 1, \ T = 2\pi \):
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 \( G_{r,\text{discharge}} = G_{r,\text{charge}} = D \). For \( D = 1 \), \( T = 2\pi \):
Storage Energy

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, ⇒ less energy capacity. So for $D = 1$, $T = 2\pi$, maximum is $E_r = 2$: 

![Graph showing storage energy profile](image-url)
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.

<table>
<thead>
<tr>
<th>quantity</th>
<th>symbol</th>
<th>units</th>
<th>solar</th>
<th>wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>generation capacity</td>
<td>$G$</td>
<td>MW</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>storage power capacity</td>
<td>$G_r$</td>
<td>MW</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>period</td>
<td>$T$</td>
<td>h</td>
<td>24</td>
<td>$7 \cdot 24 = 168$</td>
</tr>
<tr>
<td>storage energy capacity</td>
<td>$E_r$</td>
<td>MWh</td>
<td>7.6</td>
<td>53</td>
</tr>
</tbody>
</table>

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...
Efficiency and losses

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, \( \eta_1 \) to the charging efficiency and \( \eta_2 \) 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, $E_r = \text{max-hours} \times G_r$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Battery</th>
<th>Hydrogen</th>
<th>Pumped-Hydro</th>
<th>Water Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_0$</td>
<td>$1 - \varepsilon$</td>
<td>$1 - \varepsilon$</td>
<td>$1 - \varepsilon$</td>
<td>depends on size</td>
</tr>
<tr>
<td>$\eta_1$</td>
<td>0.9</td>
<td>0.75</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>0.9</td>
<td>0.58</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>max-hours</td>
<td>2-10</td>
<td>weeks</td>
<td>4-10</td>
<td>depends on size</td>
</tr>
<tr>
<td>euro per kW [$G_r$]</td>
<td>300</td>
<td>500+450</td>
<td>depends</td>
<td>low</td>
</tr>
<tr>
<td>euro per kWh [$E_r$]</td>
<td>200</td>
<td>10</td>
<td>depends</td>
<td>low</td>
</tr>
</tbody>
</table>

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 $1 - \eta_1 \cdot \eta_2$.

<table>
<thead>
<tr>
<th></th>
<th>Battery</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>losses</td>
<td>$1 - 0.9^2 = 0.19$</td>
<td>$1 - 0.58 \times 0.75 = 0.57$</td>
</tr>
<tr>
<td>€ for 2 kWh</td>
<td>$300 + 2 \times 200 = 700$</td>
<td>$950 + 2 \times 10 = 970$</td>
</tr>
<tr>
<td>€ for 100 kWh</td>
<td>$300 + 100 \times 200 = 20300$</td>
<td>$950 + 100 \times 10 = 1950$</td>
</tr>
</tbody>
</table>

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](https://model.energy) for Mexico (solar+battery) and Ireland (wind+hydrogen).
Power-to-Gas
Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to \textbf{hydrogen} H\(_2\) (and oxygen O\(_2\)). We can combine hydrogen with carbon oxides to get \textbf{hydrocarbons} such as methane CH\(_4\) (main component of natural gas) or liquid fuels C\(_n\)H\(_m\). Used for \textbf{hard-to-defossilise sectors}:

- \textbf{dense fuels} for transport (planes, ships)
- \textbf{steel-making} & \textbf{chemicals industry}
- \textbf{high-temperature heat} or \textbf{heat for buildings}
- \textbf{backup energy} for cold low-wind winter periods, i.e. as storage
Power to Transport Fuels

- 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

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

Electrical energy input: $\Delta G = 237.13 \text{ kJ}$

Work to expand gases produced
$P\Delta V = 3.7 \text{ kJ}$

Energy exchange processes for one mole of water.
$\Delta H = 285.83 \text{ kJ}$

Energy from environment
$T\Delta S = 48.7 \text{ kJ}$

Forms hydrogen bubbles

Forms oxygen bubbles

Water

Battery

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

Source: Hyperphysics, Georgia State University
Thermodynamic Calculation Electrolysis

\[ H_2O \rightarrow H_2 + \frac{1}{2}O_2 \]

For one mole at conditions 298 K and one atmospheric pressure

<table>
<thead>
<tr>
<th></th>
<th>( H_2 )</th>
<th>( O_2 )</th>
<th>( H_2O )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entropy [J/K]</td>
<td>130.7</td>
<td>205.1</td>
<td>69.9</td>
</tr>
<tr>
<td>Enthalpy [kJ]</td>
<td>0</td>
<td>0</td>
<td>-285.8</td>
</tr>
</tbody>
</table>

Gibbs free energy \( dG = dH - TdS \),

\[ \Delta G = 285.8 kJ - 48.7 kJ = 237.1 kJ \]
Fuel Cell

Ideal hydrogen-oxygen fuel cell operation

Fuel energy input
\[ \Delta H = 285.83 \text{ kJ/mol} \]

Electric energy output
\[ \Delta G = 237.13 \text{ kJ/mol} \]

\[ \text{H}_2 \rightarrow 2\text{H}^+ + 2e^- \]

\[ 2\text{H}^+ + 2e^- + \text{O} \rightarrow \text{H}_2\text{O} \]

Heat output
\[ T\Delta S = 48.7 \text{ kJ/mol} \]

Source: Hyperphysics, Georgia State University
Thermodynamics of Fuel Cell

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

\[ H_2O \rightarrow H_2 + \frac{1}{2}O_2 \]

Gibbs free energy \( dG = dH - TdS \),

\[ \Delta G = 285.8\,kJ - 48.7\,kJ = 237.1\,kJ \]

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
Basic idea of storage: move supply:
Basic Idea of Demand-Side Management

Modify demand instead of generation!
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

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

- loads into different categories with assumed max. shifting periods (e.g., 8 hours for household applications)
- shifting charges a virtual storage buffer

\[ P_n[R_n(t)](t) = R_n(t) - L_n(t). \]  (1)

- filling level is consequently given by

\[ E_n[R_n(t)](t) = \int_0^t P_n[R_n(t')](t')dt' \]  (2)

- constraints by shifting periods, e.g.,

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