Energy System Modelling
Summer Semester 2020, Lecture 2

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

Unless otherwise stated, graphics and text are Copyright ©Tom Brown, 2020. Graphics and text for which no other attribution are given are licensed under a Creative Commons Attribution 4.0 International Licence.
Table of Contents

1. Electricity Consumption
2. Electricity Generation
3. Variable Renewable Energy (VRE)
4. Balancing a Single Country
Electricity Consumption
Why is electricity useful?

Electricity is a versatile form of energy carried by electrical charge which can be consumed in a wide variety of ways (with selected examples):

- Lighting (lightbulbs, halogen lamps, televisions)
- Mechanical work (hoovers, washing machines, electric vehicles)
- Heating (cooking, resistive room heating, heat pumps)
- Cooling (refrigerators, air conditioning)
- Electronics (computation, data storage, control systems)
- Industry (electrochemical processes)

Compare the convenience and versatility of electricity with another energy carrier: the chemical energy stored in natural gas (mostly methane), which can only be accessed by burning it.
**Power** is the rate of consumption of energy.

It is measured in **Watts**:

\[
1 \text{ Watt} = 1 \text{ Joule per second}
\]

The symbol for Watt is W, 1 W = 1 J/s.

1 kilo-Watt = 1 kW = 1,000 W

1 mega-Watt = 1 MW = 1,000,000 W

1 giga-Watt = 1 GW = 1,000,000,000 W

1 tera-Watt = 1 TW = 1,000,000,000,000 W
At full power, the following items consume:

<table>
<thead>
<tr>
<th>Item</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>New efficient lightbulb</td>
<td>10 W</td>
</tr>
<tr>
<td>Old-fashioned lightbulb</td>
<td>70 W</td>
</tr>
<tr>
<td>Single room air-conditioning</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>Kettle</td>
<td>2 kW</td>
</tr>
<tr>
<td>Factory</td>
<td>~1-500 MW</td>
</tr>
<tr>
<td>CERN</td>
<td>200 MW</td>
</tr>
<tr>
<td>Germany total demand</td>
<td>35-80 GW</td>
</tr>
</tbody>
</table>
In the electricity sector, energy is usually measured in ‘Watt-hours’, Wh.

1 kWh = power consumption of 1 kW for one hour

E.g. a 10 W lightbulb left on for two hours will consume

10 W * 2 h = 20 Wh

It is easy to convert this back to the SI unit for energy, Joules:

1 kWh = (1000 W) * (1 h) = (1000 J/s)*(3600 s) = 3.6 MJ
Electricity spot market: trading of energy

Energy is traded in MWh; current price around 40-50 €/MWh. Was sinking until 2016 thanks to renewables and the **merit order effect**, but rising since 2016 due to rising **CO₂ price**:

Source: Agora Energiewende Jahresauswertung 2019
Consumption metering

• Look for your electricity meter at home

• Mine here shows 42470.3 kWh

• Check what the value is a week later
Electricity bill

My bill for 2014-5: 1900 kWh for a year, at a cost of €570, which corresponds to 0.3 €/kWh or 300 €/MWh. But the spot market price is 30 €/MWh, so what's going on??
Although the wholesale price is going down, other taxes, grid charges and renewables subsidy (EEG surcharge) have kept the price high.

HOWEVER the EEG is only high because it is paying for solar panels bought at a time when they were still comparatively expensive; but through the German subsidy, production volumes were high and the learning curve has brought the costs down exponentially.

Source: Agora Energiewende, 2019
Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the average power consumption?

\[
600 \text{ TWh/a} = \frac{(600 \text{ TW}) \times (1 \text{ h})}{(365 \times 24 \text{ h})} = \frac{600}{8760} \text{ TW} = 68.5 \text{ GW}
\]
The discrete actions of individual consumers smooth out statistically if we aggregate over many consumers.
The Germany load curve (around 500 TWh/a) shows **daily**, **weekly** and **seasonal** patterns; religious festivals are also visible.
Load duration curve

For some analysis it is useful to construct a duration curve by stacking the hourly values from highest to lowest.
Similarly we can also build the **probability density function** $pdf(x)$, $\int dx \, pdf(x) = 1$: 
Fourier transform to see spectrum

For a periodic, continuous, complex signal \( f(t) \), we can decompose it in frequency space to see which frequencies dominate the signal. This is called a **Fourier transform/series**.

For period \( T \) (in our case a year) the function \( f : [0, T] \rightarrow \mathbb{C} \) can be decomposed

\[
f(t) = \sum_{n=-\infty}^{n=\infty} a_n e^{-i2\pi nt/T}
\]

To recover the values of the **frequency amplitudes** \( a_n \), integrate over \( T \)

\[
a_n = \frac{1}{T} \int_0^T dt \left[ f(t) e^{i2\pi nt/T} \right]
\]

For a real-valued function \( f : [0, T] \rightarrow \mathbb{R} \), \( a_{-n} = a_n^* \).

For a periodic, **discrete** signal \( f_n \), the **Fast Fourier Transform** (FFT) is a computationally advantageous algorithm and is implemented in many programming libraries (see tutorial).
To remind yourself of how Fourier transforms work, check the formula for $a_n$ by inserting the expansion of $f(t)$ into the formula for $a_n$.

First hint: remember Euler’s formula:

$$e^{i\theta} = \cos \theta + i \sin \theta$$

Second hint: think about integrating a periodic signal over its period:

$$\frac{1}{T} \int_{0}^{T} dt \cos \frac{2\pi nt}{T} = \begin{cases} 1, & \text{if } n = 0 \\ 0, & \text{otherwise} \end{cases}$$
If we Fourier transform, the **seasonal**, **weekly** and **daily** frequencies are clearly visible.
Electricity Generation
Conservation of Energy: Energy cannot be created or destroyed: it can only be converted from one form to another.

There are several ‘primary’ sources of energy which are converted into electrical energy in modern power systems:

- Chemical energy, accessed by combustion (coal, gas, oil, biomass)
- Nuclear energy, accessed by fission reactions, perhaps one day by fusion too
- Hydroelectric energy, allowing water to flow downhill (gravitational potential energy)
- Wind energy (kinetic energy of air)
- Solar energy (accessed with photovoltaic (PV) panels or concentrating solar thermal power (CSP))
- Geothermal energy

NB: The definition of ‘primary’ is somewhat arbitrary.
At full power, the following items generate:

<table>
<thead>
<tr>
<th>Item</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panel on house roof</td>
<td>15 kW</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>3 MW</td>
</tr>
<tr>
<td>Coal power station</td>
<td>1 GW</td>
</tr>
</tbody>
</table>
Generators

With the exception of solar photovoltaic panels (and electrochemical energy and a few other minor exceptions), all generators convert to electrical energy via rotational kinetic energy and electromagnetic induction in an *alternating current generator*.
Example of electricity generation across major EU countries in 2013

Electricity Generation in 2013 [TWh/a]

- Solar
- Hydro
- Hard Coal
- Wind
- Oil
- Lignite
- Biomass
- Gas
- Nuclear
Renewables reached 40% of gross electricity generation in Germany in 2019.
Efficiency

When fuel is consumed, much/most of the energy of the fuel is lost as waste heat rather than being converted to electricity.

The thermal energy, or calorific value, of the fuel is given in terms of \( \text{MWh}_{\text{th}} \), to distinguish it from the electrical energy \( \text{MWh}_{\text{el}} \).

The ratio of input thermal energy to output electrical energy is the **efficiency**.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Calorific energy MWh(_{\text{th}})/tonne</th>
<th>Per unit efficiency MWh(<em>{\text{el}})/MWh(</em>{\text{th}})</th>
<th>Electrical energy MWh(_{\text{el}})/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>2.5</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>6.7</td>
<td>0.45</td>
<td>2.7</td>
</tr>
<tr>
<td>Gas (CCGT)</td>
<td>15.4</td>
<td>0.58</td>
<td>8.9</td>
</tr>
<tr>
<td>Uranium (unenriched)</td>
<td>150000</td>
<td>0.33</td>
<td>50000</td>
</tr>
</tbody>
</table>
The cost of a fuel is often given in €/kg or €/MWh\textsubscript{th}.

Using the efficiency, we can convert this to €/MWh\textsubscript{el}.

For the full marginal cost, we have to also add the CO\textsubscript{2} price and the variable operation and maintenance (VOM) costs.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Per unit efficiency</th>
<th>Cost per thermal</th>
<th>Cost per elec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>0.4</td>
<td>4.5</td>
<td>11</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>0.45</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>Gas (CCGT)</td>
<td>0.58</td>
<td>19</td>
<td>33</td>
</tr>
<tr>
<td>Uranium</td>
<td>0.33</td>
<td>3.3</td>
<td>10</td>
</tr>
</tbody>
</table>
The CO₂ emissions of the fuel.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>$t_{\text{CO₂}}/t$</th>
<th>$t_{\text{CO₂}}/\text{MWh}_{\text{th}}$</th>
<th>$t_{\text{CO₂}}/\text{MWh}_{\text{el}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>0.9</td>
<td>0.36</td>
<td>0.9</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>2.4</td>
<td>0.36</td>
<td>0.8</td>
</tr>
<tr>
<td>Gas (CCGT)</td>
<td>3.1</td>
<td>0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Uranium</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Current CO₂ price in EU Emissions Trading Scheme (ETS) is around €25/t_{\text{CO₂}}.
What CO$_2$ price, i.e. $x\text{ }\text{€/tCO}_2$, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.
You calculate: What CO$_2$ price to switch gas and lignite?

What CO$_2$ price, i.e. $x\, €/t\text{CO}_2$, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.

We need to solve for the switch point by adding the CO$_2$ price to the fuel cost. Left is lignite, right is gas:

\[11\, €/\text{MWh}_\text{el} + (0.9 \, \text{tCO}_2/\text{MWh}_\text{el}) \cdot (x\, €/\text{tCO}_2) = 33\, €/\text{MWh}_\text{el} + (0.35 \, \text{tCO}_2/\text{MWh}_\text{el}) \cdot (x\, €/\text{tCO}_2)\]

Solve:

\[x = \frac{33 - 11}{0.9 - 0.35} = 40\]
CO2 and import costs change over time...

Import prices for natural gas, hard coal, and oil, as well as CO₂ certificate prices

Source: Agora Energiewende, 2019
...which affects the marginal costs of generation

![Graph showing marginal costs for new natural-gas power plants and old power plants fired with lignite and hard coal]

Source: Agora Energiewende, 2019
CO₂ emissions in electricity generation stagnated for years because of coal, which is slowly being pushed out by the CO₂ price and in the longer term by the Kohleausstieg.

Source: Agora Energiewende Jahresauswertung 2019
A generator’s **capacity factor** is the average power generation divided by the power capacity.

For variable renewable generators it depends on weather, generator model and curtailment; for dispatchable generators it depends on market conditions and maintenance schedules.

A generator’s **full load hours** are the equivalent number of hours at full capacity the generator required to produce its yearly energy yield. The two quantities are related:

\[
\text{full load hours} = \text{per unit capacity factor} \cdot 365 \cdot 24 = \text{per unit capacity factor} \cdot 8760
\]

Typical values for Germany:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>capacity factor [%]</th>
<th>full load hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>wind</td>
<td>20-35</td>
<td>1600-3000</td>
</tr>
<tr>
<td>solar</td>
<td>10-12</td>
<td>800-1000</td>
</tr>
<tr>
<td>nuclear</td>
<td>70-90</td>
<td>6000-8000</td>
</tr>
<tr>
<td>open-cycle gas</td>
<td>20</td>
<td>1500</td>
</tr>
</tbody>
</table>
Variable Renewable Energy (VRE)
Unlike the load, the solar feed-in is much more variable, dropping to zero and not reaching full output (when aggregated over all of Germany).
How do we derive solar time series?

We take times series weather data for the solar radiation (also called irradiation or insolation) at each location in W/m². This is often provided for a horizontal surface, so we need to convert for the angles of the solar panel to the horizontal, and account for factors that affect the energy conversion (losses, outside temperature). We have a software library atlite that takes care of this. See https://model.energy or https://renewables.ninja for live examples.

Source: Volker Quaschning
Solar time series: weekly

If we take a weekly average we see higher solar in the summer.
Solar density function

![Graph showing the probability density of DE solar per unit]
If we Fourier transform, the **seasonal** and **daily** patterns become visible.
Wind time series

Wind is variable, like solar, but the variations are on different time scales. It drops close to zero and rarely reaches full output (when aggregated over all of Germany).
How do we derive wind time series?

We take times series weather data for the wind speeds at hub height (e.g. 60-100m) at each location in ms\(^{-1}\). In theory the power in the wind goes like \(v^3\), but in practice high wind speeds are rare and it is not economic to build the generator so large.

![Power production of a typical wind turbine](image_url)
How do we derive wind time series?

Wind speeds are typically distributed according to a Weibull probability distribution. Although the wind speeds are clustered at the lower end, most of the energy is generated between 5 and 15 ms$^{-1}$. 

Wind time series: weekly

If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (synoptic scale).
Wind duration curve

Percentage of time during year

DE onwind [per unit]
Wind density function
If we Fourier transform, the seasonal, synoptic (2-3 weeks) and daily patterns become visible.
Balancing a Single Country
Suppose we now try and cover the electrical demand with the generation from wind and solar. How much wind and solar do we need? We have three time series:

- \( \{d_t\}, d_t \in \mathbb{R} \) the load (varying between 35 GW and 80 GW)
- \( \{w_t\}, w_t \in [0, 1] \) the wind availability (how much a 1 MW wind turbine produces)
- \( \{s_t\}, s_t \in [0, 1] \) the solar availability (how much a 1 MW solar turbine produces)

We try \( W \) MW of wind and \( S \) MW of solar. Now the effective residual load or mismatch is

\[
m_t = d_t - Ww_t - Ss_t
\]

We choose \( W \) and \( S \) such that on average we cover all the load

\[
\langle m_t \rangle = 0
\]

and so that the 70% of the energy comes from wind and 30% from solar (\( W = 147 \) GW and \( S = 135 \) GW).
Mismatch time series

DE mismatch [GW]

Jan 2011
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Mismatch time series
Mismatch duration curve

![Mismatch duration curve graph](image)

**Mismatch duration curve**

- Percentage of time during year
- DE mismatch [GW]
Mismatch density function

![Mismatch density function graph](image)

- Probability density on the y-axis.
- DE mismatch [GW] on the x-axis.
If we Fourier transform, the synoptic (from wind) and daily patterns (from demand and solar) become visible. Seasonal variations appear to cancel out.
How to deal with the mismatch?

The problem is that \( \langle m_t \rangle = 0 \) is not good enough! We need to meet the demand in every single hour.

This means:

- If \( m_t > 0 \), i.e. we have unmet demand, then we need backup generation from dispatchable sources e.g. hydroelectricity reservoirs, fossil/biomass fuels.

- If \( m_t < 0 \), i.e. we have over-supply, then we have to shed / spill / curtail the renewable energy.
Mismatch

Dec 2011

Power [GW]

consumed
curtailment
backup

Dec
2011

05 12 19 26
Mismatch duration curve

Mismatch [GW]

Percentage of time during year

backup
curtailment
What to do?

Backup energy costs money and may also cause CO₂ emissions.

Curtailing renewable energy is also a waste.

We’ll look in the next lectures at **four other solutions**:

1. **Smoothing** stochastic variations of renewable feed-in over continental areas, e.g. the whole of Europe.

2. Using **electricity storage** to shift energy from times of surplus to times of deficit.

3. Shifting demand to different times, when renewables are abundant, i.e. **demand-side management** (DSM).

4. Consuming the electricity in **other sectors**, e.g. transport or heating, where there are further possibilities for DSM (battery electric vehicles, heat pumps) and cheap storage possibilities (e.g. thermal storage or power-to-gas as hydrogen or methane).