Resource adequacy in carbon-neutral power systems

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Background

- **PhD in Power Systems (2013)**
  Comillas Pontifical University, Spain
- **MSc in Computation for Design and Optimization (2008)**
  Massachusetts Institute of Technology, USA
- **Dipl.-Ing. Technical Mathematics (2008)**
  Graz University of Technology, Austria

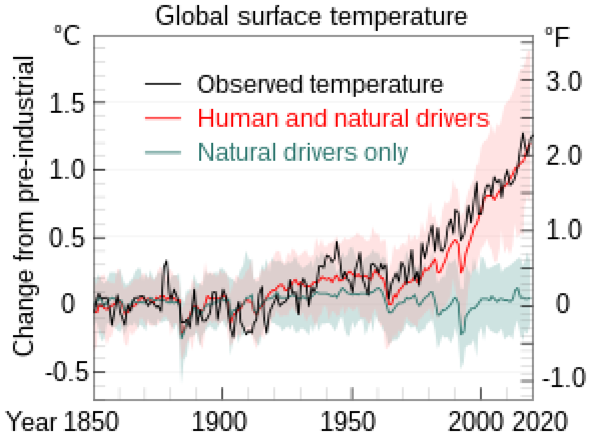
Outlook

Source: https://www.instagram.com/p/CGtFYBOBl8l/

- Motivation. Why do we care about energy system planning?
- Mathematical modeling and optimization as decision support tools
- Illustrative case study
- Conclusions

Why do we care about energy system planning?

There is this thing called **climate change**.



Source: https://en.wikipedia.org/wiki/Climate_change#/media/File:Global_Temperature_And_Forces_With_Fahrenheit.svg

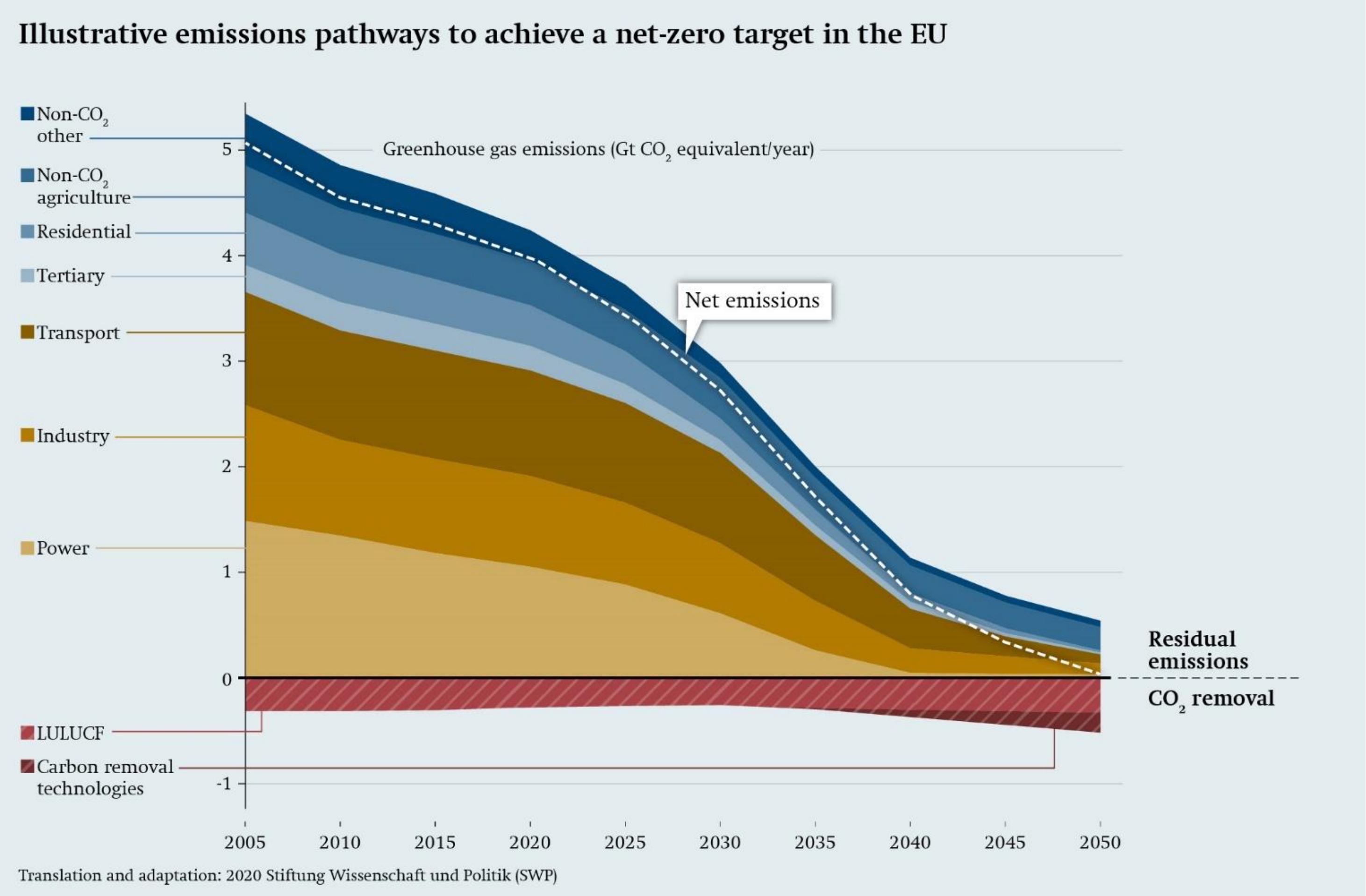
Source: https://www.dw.com/en/greece-wildfiresthousands-flee-island-of-evia-as-blazes-continue-to-ravage-lands/a-58794368

Source:https://www.premiumtimesng.com/news/top-news/473966-over-80-dead-dozens-missing-as-floods-hit-germany.html

Source: https://www.greenpeace.org/usa/warsaw-climate-talks-so-bad-us-looked-good/melting-ice-polar-bear-on-20631-jpg/

Decarbonization in Europe (and Austria)

- How do we define **climate neutrality** in Europe.
- We want to achieve it **until 2050** (European Commission).
- **Austria** (EAG): In 2030 total system demand has to be 100% **net national** produced by renewables.



Source: https://www.swp-berlin.org/en/publication/eu-climate-policy-unconventional-mitigation

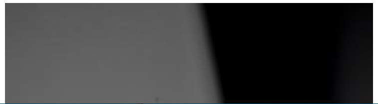
What is resource adequacy?

- Resource adequacy ensures there is **enough capacity** and reserves to maintain a **balanced supply** and **demand** across the electric grid.
- In the past, resource adequacy provided by dispatchable (e.g. thermal) generation.
- Decarbonization causes our **power systems** to **change**:
  - Capacity of variable renewable energy sources, and storage technologies must increase
  - Electrification of other sectors (transport, industry, H2, etc.) because of decarbonization
  - Demand itself is shifting (prosumers, electric vehicles, demand-side management, energy communities, etc.)
  - Climate change (extreme weather conditions)

- The **goal** is to maintain **reliable, safe** and **affordable** provision of electric energy on the path towards decarbonization.

Source: https://unsplash.com/photos/N2Td7KplvYc
https://unsplash.com/photos/kufsOr1-F-s
https://img.fuelcellsworks.com/wp-content/uploads/2021/05/Hydrogen-Storage-2.jpg
https://unsplash.com/photos/uBKg9f0aUrY, Source (EPRI): https://www.youtube.com/watch?v=YbYHignnRR4

Challenges of decarbonization



- **Soc** … (e.g. profitability)
  my

Modeling and optimization can serve as **decision support tool** to achieve **resource adequacy** in future power systems.

Modeling and optimization as decision support tools to achieve resource adequacy

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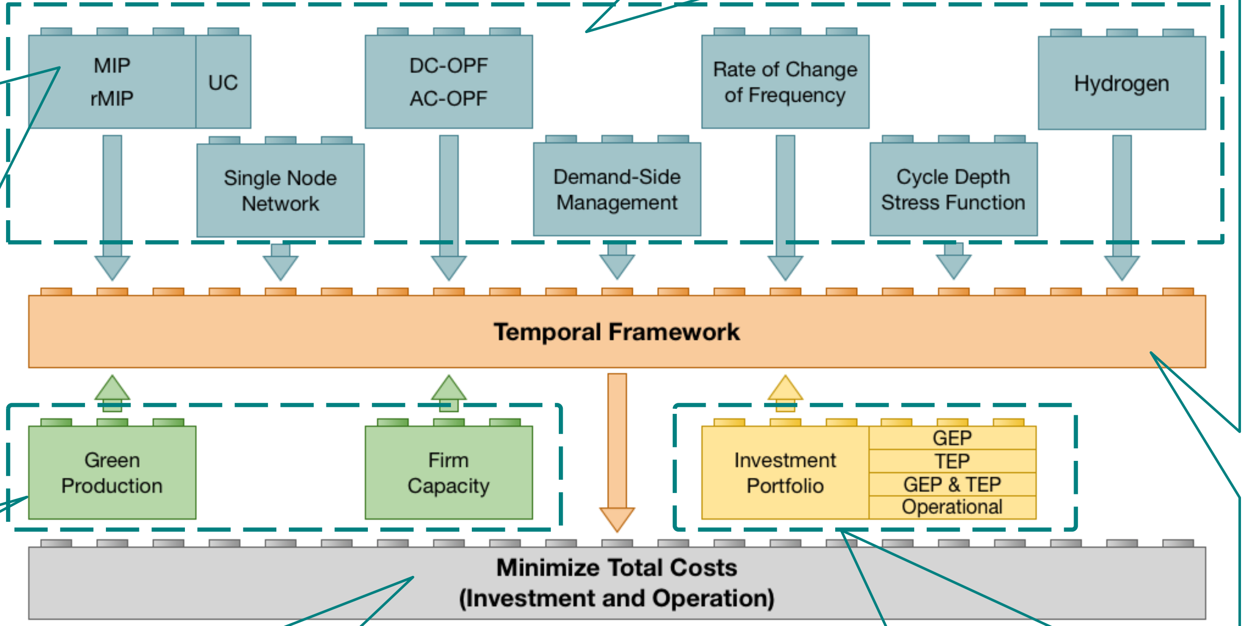
Open-source tool for Low-carbon Expansion and Generation Optimization (LEGO)

Source: Wogrin, S., Tejada-Arango, D., Delikaraoglou, S. and Botterud, A., 2020. Assessing the impact of inertia and reactive power constraints in generation expansion planning. Applied Energy, 280, p.115925.

GitHub https://github.com/wogrin/LEGO

Model options: yes/no?



Mixed-integer quadratically constrained program (MIQCP)

- deterministic
- single-year
- modular & flexible
- GAMS & Excel

Relaxed MIP (rMIP)

- relax UC
- economic results (prices & profits)

Policy constraints

- technical
- **environmental**
- **political**

Objective function

Generation units *g*:

- thermal *t* (CCGT, OCGT, …)
- renewable *r* (wind, solar)
- storage *s* (hydro, batteries)

Highly flexible temporal structure

- hours *p*
- representative periods *rp*
- hours within rp *k*

mapping

hindex(p,rp,k)
relation among p, rp and k
/
h0001.rp07 .k0001
h0002.rp07 .k0002
h0003.rp07 .k0003
… .… .…

weights

pWeight_rp(rp)
representatives periods weight [h]
/

rp01	20
rp02	135
rp03	46

pWeight_k(k)
hourly weight for each rp [h]
/

k0001	1
k0002	1
k0003	1

Mathematical Formulation …

Objective function

$$
\begin{aligned}
min \sum_{rp,k} W^{RP}_{rp} W^K_k \Big(\sum_t (C^{SU}_t y_{rp,k,t} + C^{UP}_t u_{rp,k,t} + C^{VAR}_t p_{rp,k,t}) \\
+ \sum_r C^{OM}_r p_{rp,k,r} + \sum_s C^{OM}_s p_{rp,k,s} + \sum_i C^{ENS} pns_{rp,k,i} \Big) \\
+ \sum_{rp,k} W^{RP}_{rp} W^K_k \Big(\sum_t (C^{VAR}_t C^{RES+} res^+_{rp,k,t} + C^{VAR}_t C^{RES-} res^-_{rp,k,t}) \\
+ \sum_s (C^{OM}_s C^{RES+} res^+_{rp,k,s} + C^{OM}_s C^{RES-} res^-_{rp,k,s}) \Big) \\
+ \sum_g C^{INV}_g x_g
\end{aligned}
$$

Hydrogen production

$$0 \leq p^{H2}_{rp,k,h2g} \leq \overline{P}^E_{h2g} W^K_k HPE_{h2g} (x^{H2}_{h2g} + EU^{H2}_{h2g}) \quad \forall rp,k,h2g$$

$$cs^E_{rp,k,h2g} W^K_k HPE_{h2g} = p^{H2}_{rp,k,h2g} \quad \forall rp,k,h2g$$

$$\sum_{h2gh2i(h2g,h2i)} p^{H2}_{rp,k,h2g} + h2ns_{rp,k,h2i} = \sum_{h2sec} D^{H2}_{rp,k,h2i,h2sec} \quad \forall rp,k,h2i$$

$$0 \leq h2ns_{rp,k,h2i} \leq \sum_{h2sec} D^{H2}_{rp,k,h2i,h2sec} \quad \forall rp,k,hi$$

$$x^{H2}_{h2g} \in \mathbb{Z}^{+,0}, x^{H2}_{h2g} \leq \overline{X}^{H2}_{h2g} \quad \forall h2g$$

Unit commitment

$$\sum_t res^+_{rp,k,t} + \sum_s res^+_{rp,k,s} \geq RES^+ \sum_i D^P_{rp,k,i} \quad \forall rp,k$$

$$\sum_t res^-_{rp,k,t} + \sum_s res^-_{rp,k,s} \geq RES^- \sum_i D^P_{rp,k,i} \quad \forall rp,k$$

$$p_{rp,k,t} = u_{rp,k,t} \underline{P}_t + \hat{p}_{rp,k,t} \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} + res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - y_{rp,k,t}) \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} + res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(u_{rp,k,t} - z_{rp,k++1,t}) \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} \geq res^-_{rp,k,t} \quad \forall rp,k,t$$

$$u_{rp,k,t} - u_{rp,k--1,t} = y_{rp,k,t} - z_{rp,k,t} \quad \forall rp,k,t$$

$$u_{rp,k,t} \leq x_t + EU_t \quad \forall rp,k,t$$

$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} + res^+_{rp,k,t} \leq u_{rp,k,t} RU_t \quad \forall rp,k,t$$

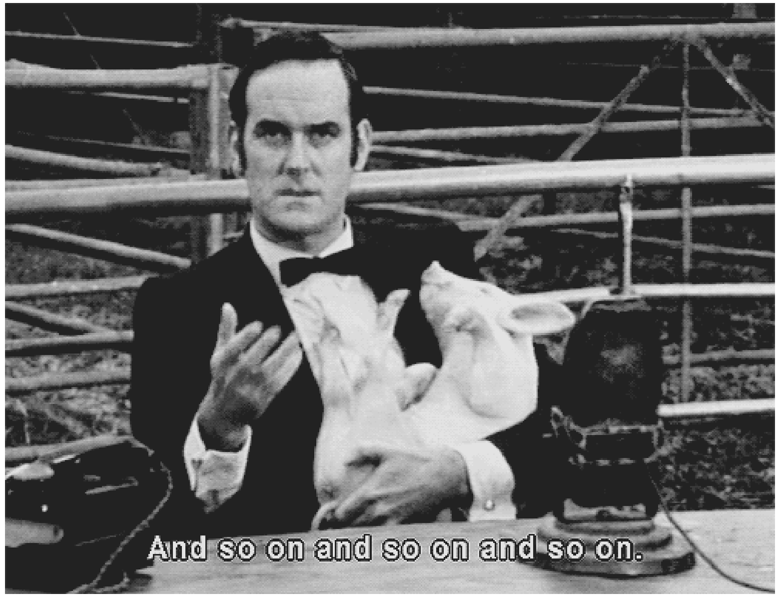
$$\hat{p}_{rp,k,t} - \hat{p}_{rp,k--1,t} - res^-_{rp,k,t} \geq -u_{rp,k--1,t} RD_t \quad \forall rp,k,t$$

$$0 \leq p_{rp,k,t} \leq \overline{P}_t (x_t + EU_t) \quad \forall rp,k,t$$

$$0 \leq \hat{p}_{rp,k,t}, res^-_{rp,k,t}, res^+_{rp,k,t} \leq (\overline{P}_t - \underline{P}_t)(x_t + EU_t) \quad \forall rp,k,t$$

$$u_{rp,k,t}, y_{rp,k,t}, z_{rp,k,t} \in \{0,1\} \quad \forall rp,k,t$$

Power flow



Source: Wogrin, S., Tejada-Arango, D., Delikaraoglou, S. and Botterud, A., 2020. Assessing the impact of inertia and reactive power constraints in generation expansion planning. Applied Energy, 280, p.115925.

Capacity Mechanisms: Firm capacity

- **Firm capacity** is the uninterruptible guaranteed maximum power output available immediately over time.
- As an example capacity mechanism we analyze a type of "**firm capacity constraint**"

$$\sum_g FC_g \overline{P}_g (x_g + EU_g) \geq D^{peak} FP \quad : (\nu)$$

Capacity payment

Total firm capacity installed ≥110% of hourly peak demand

Technology	Firm Capacity Coefficient (pu)
Thermal	0,95-0,97
Wind power	0,07
Solar PV	0,14
Hydro (ROR)	0,77
Hydro (Reservoir)	0,25
Batteries	0,96

Source: Gerres, Timo, et al. "Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study." Energy Policy 129 (2019): 1320-1330.

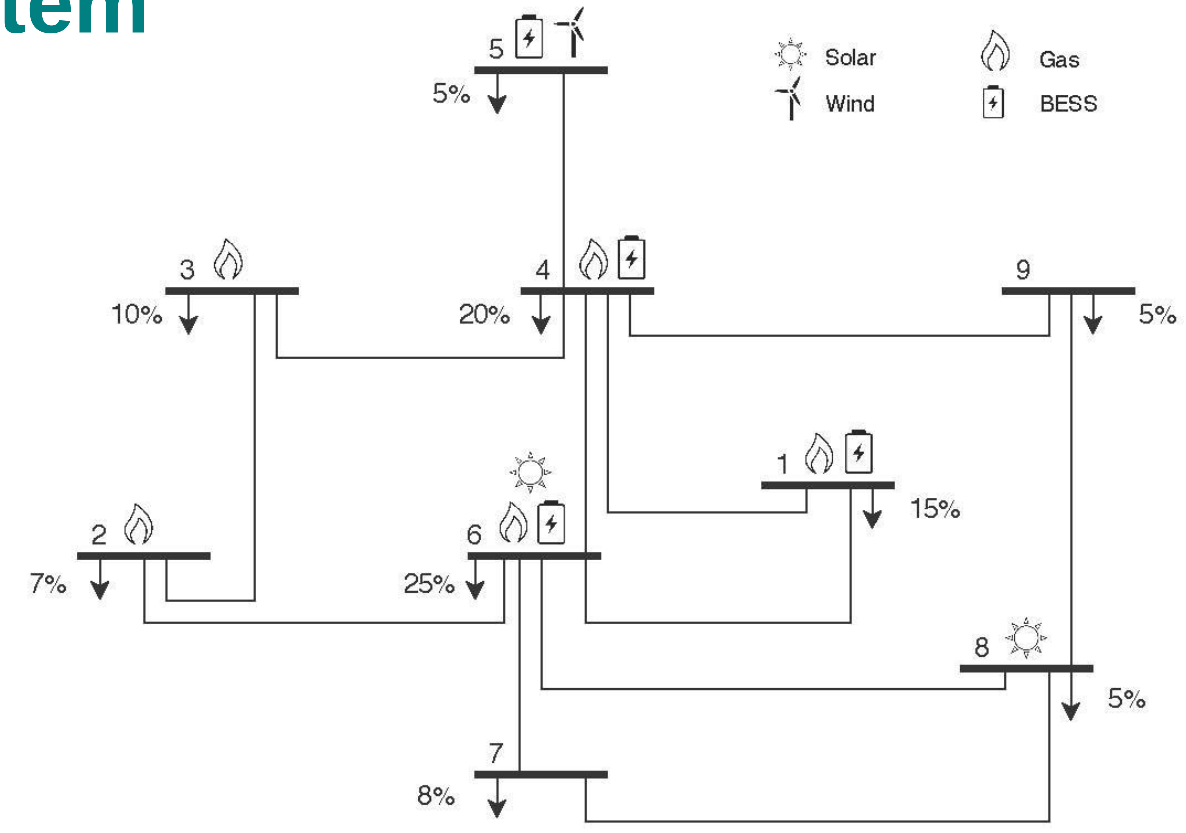
Source: https://unsplash.com/photos/qBrF1yu5Wys

Illustrative Case Study

Stylized electric power system

(Not Austria)

- 9 node system, 13 transmission lines
- Candidate units:
  - Thermal, Wind, Solar, BESS
- Time horizon 1 year
- Demand (in %)
- Study **future** versus **current** system



Current system: greenfield planning

We assume a 110% firm capacity factor.

Technology	Investments (MW)
BESS	383
WIND	2020
SOLAR	1418
CCGT	3216
OCGT	1185
TOTAL	8222

Investments in generation capacity

Profits (M€)

Firm capacity constraint active

	CCGT	OCGT	BESS	Wind	Solar
Spot market revenues	1177.45	11.87	31.71	152.65	114.62
Spot market purchases	0	0	-17.46	0	0
Reserve market revenues	0.59	0.14	4.39	0	0
Reserve market costs	-0.59	-0.08	-1.43	0	0
O&M costs	-1122.66	-11.93	-1.85	-9.54	0
Investment costs	-134.50	-29.37	-24.85	-146.75	-119.74
Firm capacity payments	79.70	29.37	9.48	3.65	5.12
Total profits	0	0	0	0	0

Future system: greenfield planning

Technology	Investments (MW)
BESS	8871
WIND	7045
SOLAR	17118
TOTAL	**33034**

	BESS	Wind	Solar
Spot market revenues	1532.92	528.01	1445.92
Spot market purchases	-920.75	0	0
Reserve market revenues	5.37	0	0
Reserve market costs	-1.52	0	0
O&M costs	-39.76	-16.25	0
Investment costs	-576.26	-511.76	-1445.92
Firm capacity payments	0	0	0
Total profits	0	0	0

- Firm capacity constraint is **not binding**.
- Hence, firm **capacity payment** is **zero**.
- We no longer have a capacity but an **ENERGY problem**.

Future stylized system: repercussions

- When increasing power demand (in one hour only for 1% – within the 110% firm capacity limit), we still get 4 GWh non-supplied energy (NSE) and total system cost increase of 1.5%.
- The firm capacity constraint is **ill-defined** in low-carbon power systems.
- We HAVE the capacity, but we lack the ENERGY.
- Define a **firm energy constraint** instead (a la Cramton & Stoft).

$$\sum_{r} fe_r^{VRE} + \sum_{s=BESS} fe_s^{BESS} + \sum_{s=hydro} fe_s^{HYD} + \sum_{tfast} fe_t^{THRM} \geq D_{rp,k,i}^{P} \quad \forall rp$$

- But how much firm energy can each technology provide?

Source: Cramton, Peter, and Steven Stoft. "Colombia firm energy market." 2007 40th Annual Hawaii International Conference on System Sciences (HICSS'07). IEEE, 2007.

Future system & firm energy

- **Renewables**: energy provided during the worst historic day.
- **Thermal**: maximum capacity (minus EFOR).
- **Storage**: this is not entirely clear.
  - Hydro: based on inflows.
  - Batteries: not discussed in Cramton & Stoft.
- Firm energy of sector coupling, import/export?
- Case (Batteries do not provide firm energy):

Technology	Investments 110% Firm capacity (MW)	Investments 100% Firm energy (MW)
BESS	8871	8962
WIND	7045	3629
SOLAR	17118	74979
TOTAL	33034	87570

- For +1% of demand, no NSE.
- Total system cost more than doubles.

Can batteries provide firm energy?

- **How to define firm energy of batteries**: related to its capacity? to renewable curtailment? to actual daily production?
- Accounting for batteries would yield more reasonable investments and system costs.
- But the **daily firm energy constraint can still fail** during certain hours (night versus day).
- What would be an appropriate **remuneration scheme**?

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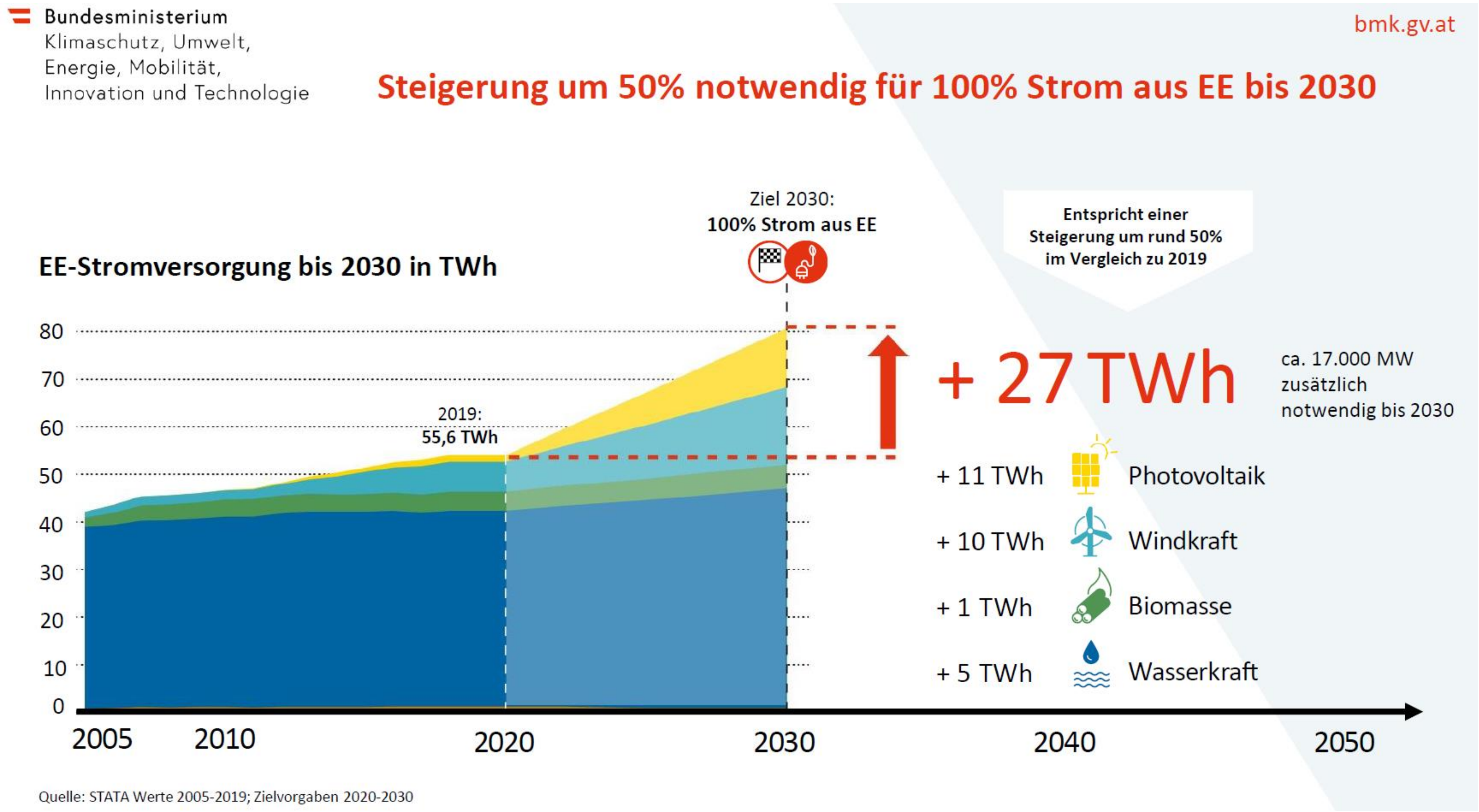
Source: https://unsplash.com/photos/RVyc3Zzhpt8

How does this extend to Austria?

Status Quo and EAG Goals



+5 TWh Hydro: What does that mean?

Murkraftwerk Graz

Annual production: 82 GWh

$\frac{5\ TWh}{82\ GWh} \approx$ **60 times** the Murkraftwerk until 2030

From planning to operation: 10 years!

Donaukraftwerk Aschach

Annual production: 1.662 GWh

$\frac{5\ TWh}{1.662\ GWh} \approx$ **3 times** the Donaukraftwerk Aschach until 2030

But the Danube is practically maxed out!

Images: Energie Steiermark (left), Verbund (right)

+11 TWh PV: What does that mean?

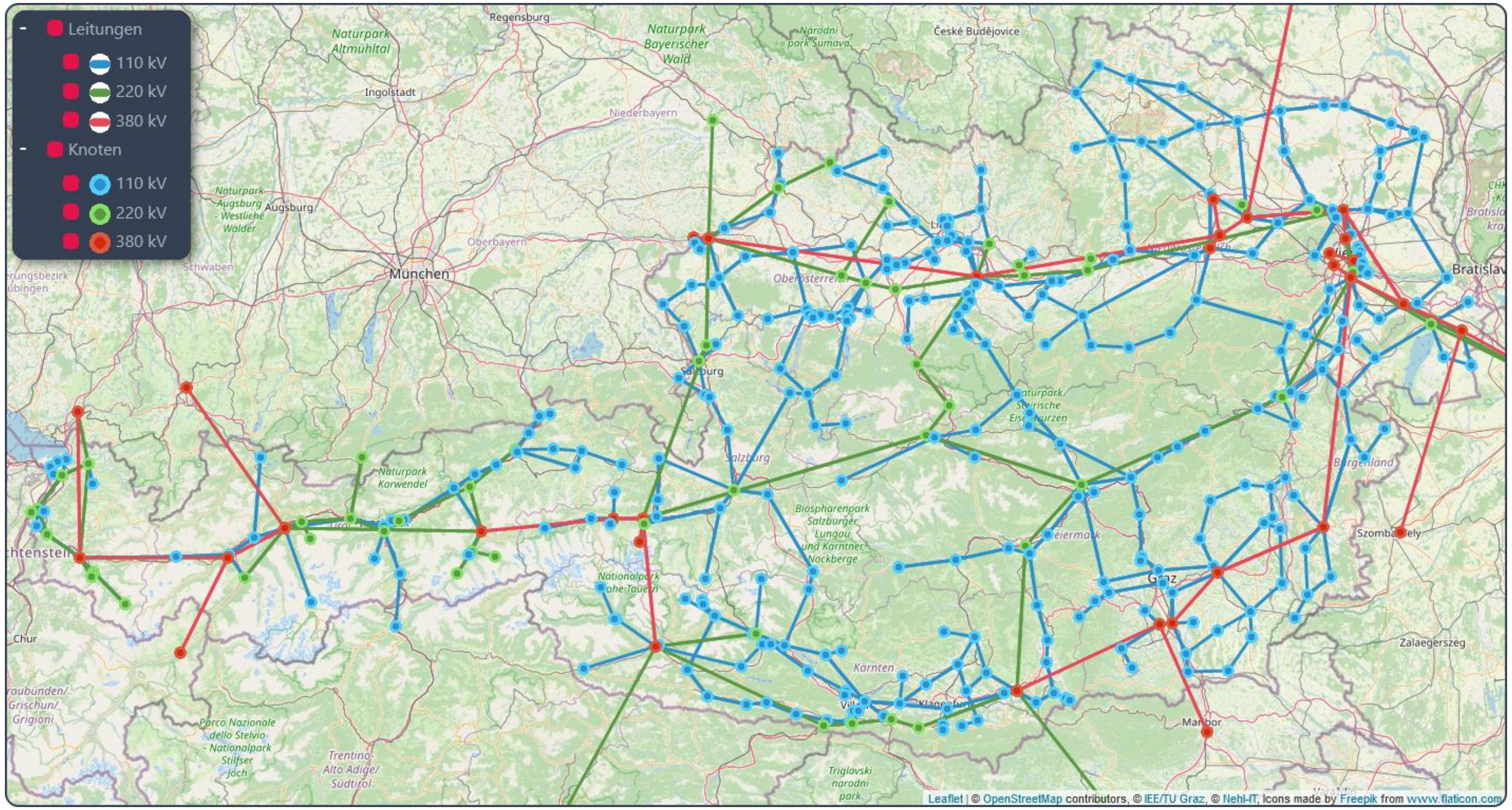
- Required area of approx.
  10.270 Soccer fields
  (if panels are flat)

Image: mcg.at

We study the Austrian System: LEGO/Atlantis

- Austria‘s electricity infrastructure:
  - 1,304 generators
  - 468 nodes
  - 1,097 power lines (110, 220, 380 kV)

- Model summary
  - 900,000 variables
  - 800,000 equations



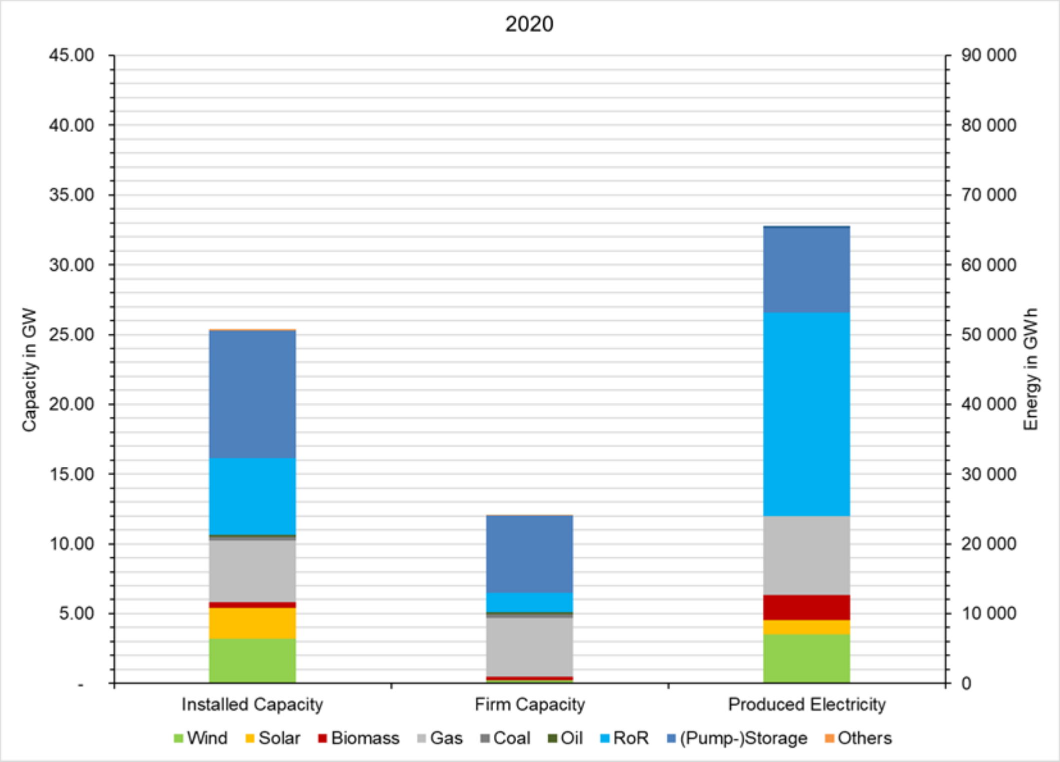
InfraTrans 2040

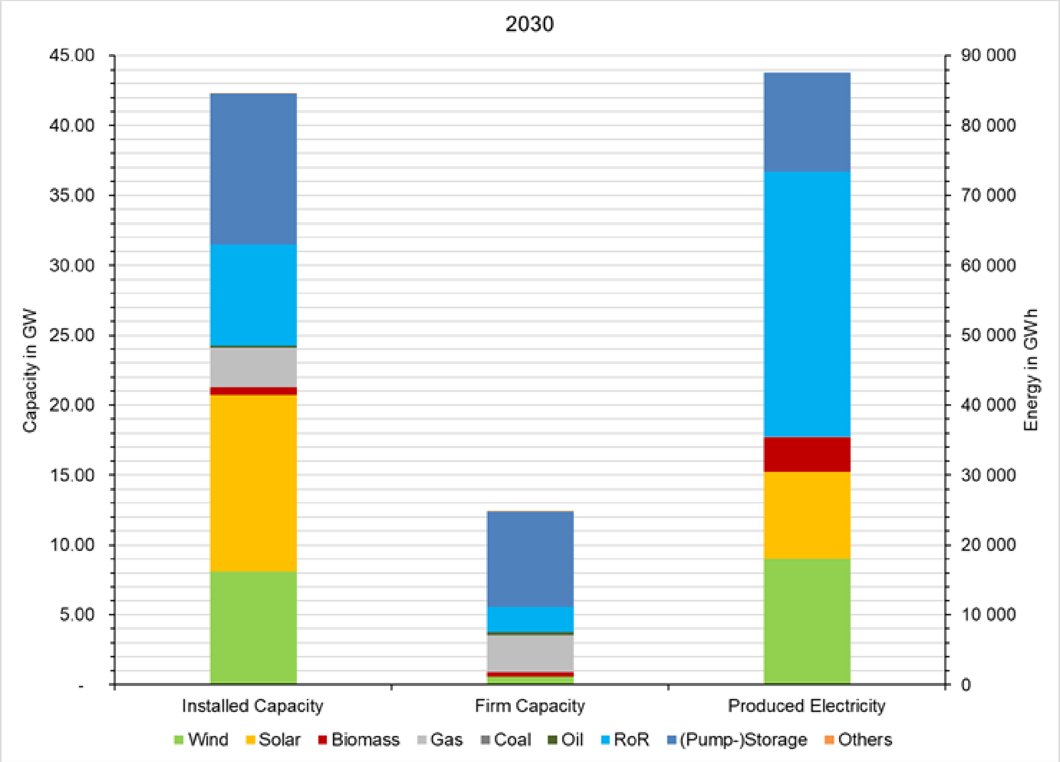
START2030

powered by klima+ energie fonds

Comparison: firm capacity now & future

- In the current Austrian power system, we have 124%* of firm capacity installed.
- In the future Austrian power system (a la EAG goals) firm capacity amounts to 99%**





* Calculated as firm capacity installed divided by hourly peak demand.

** Subject to several underlying hypotheses: evolution of peak demand, firm capacity factors, existing generators.

Final Takeaways

- **Climate neutrality** poses a complex challenge
- **Mathematical models** are a useful tool for power system analysis
- **Resource adequacy** of future low-carbon power systems needs to be assessed carefully
- **Young people in/for science!**

Source: https://unsplash.com/photos/DwgPkR02Wpc

Thank you. Questions?

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