Building renewable electricity systems: opportunities and challenges

Stefan Pfenninger

Associate Professor of Energy System Modelling

Faculty of Technology, Policy and Management

s.pfenninger@tudelft.nl

www.pfenninger.org

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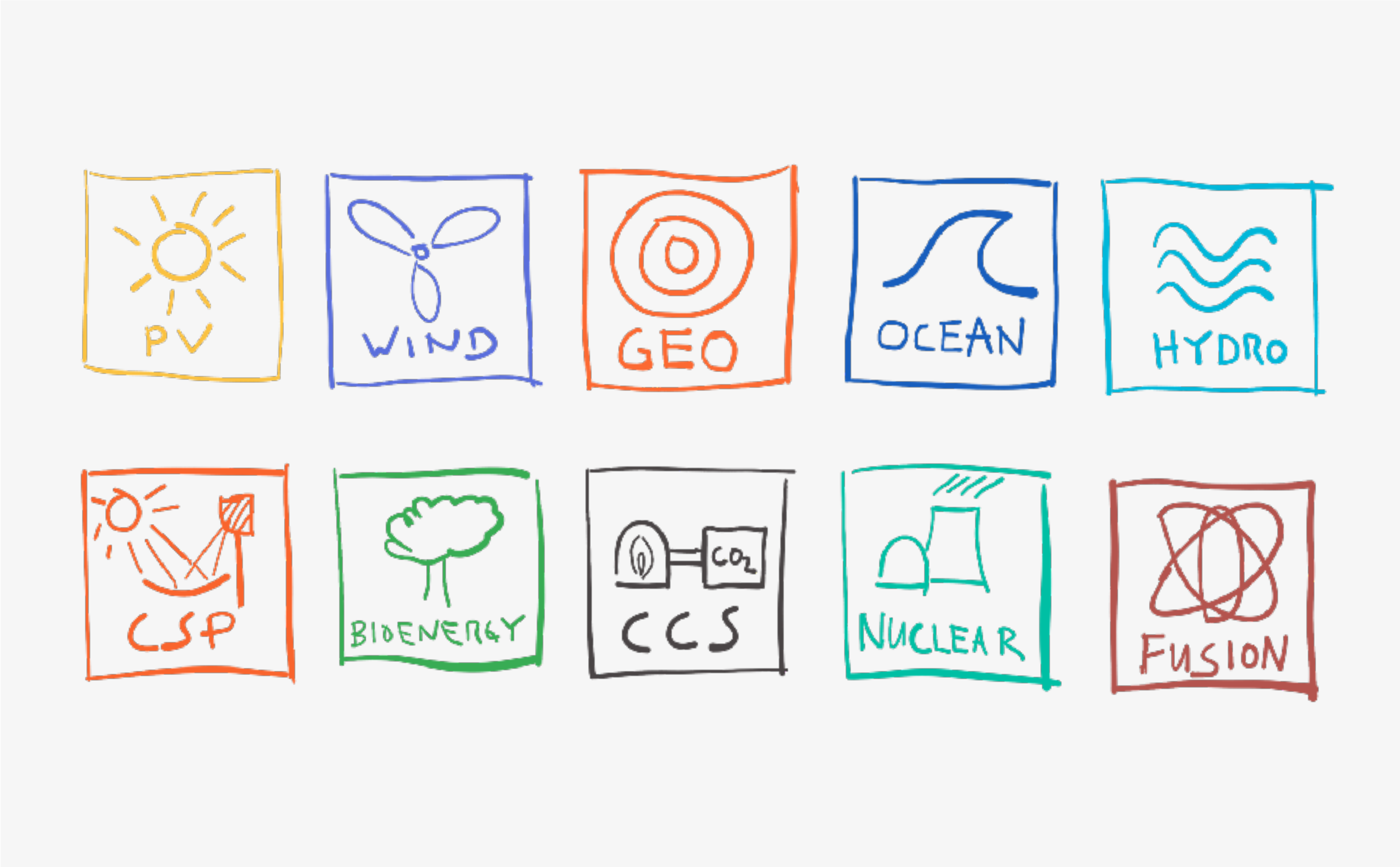
TU Delft



1 Setting the stage:
Climate-neutral electricity

2 The problem of dealing with
variability, and possible solutions

3 Combinations that work, and
how to make informed decisions

1

Setting the stage:
Climate-neutral electricity

2

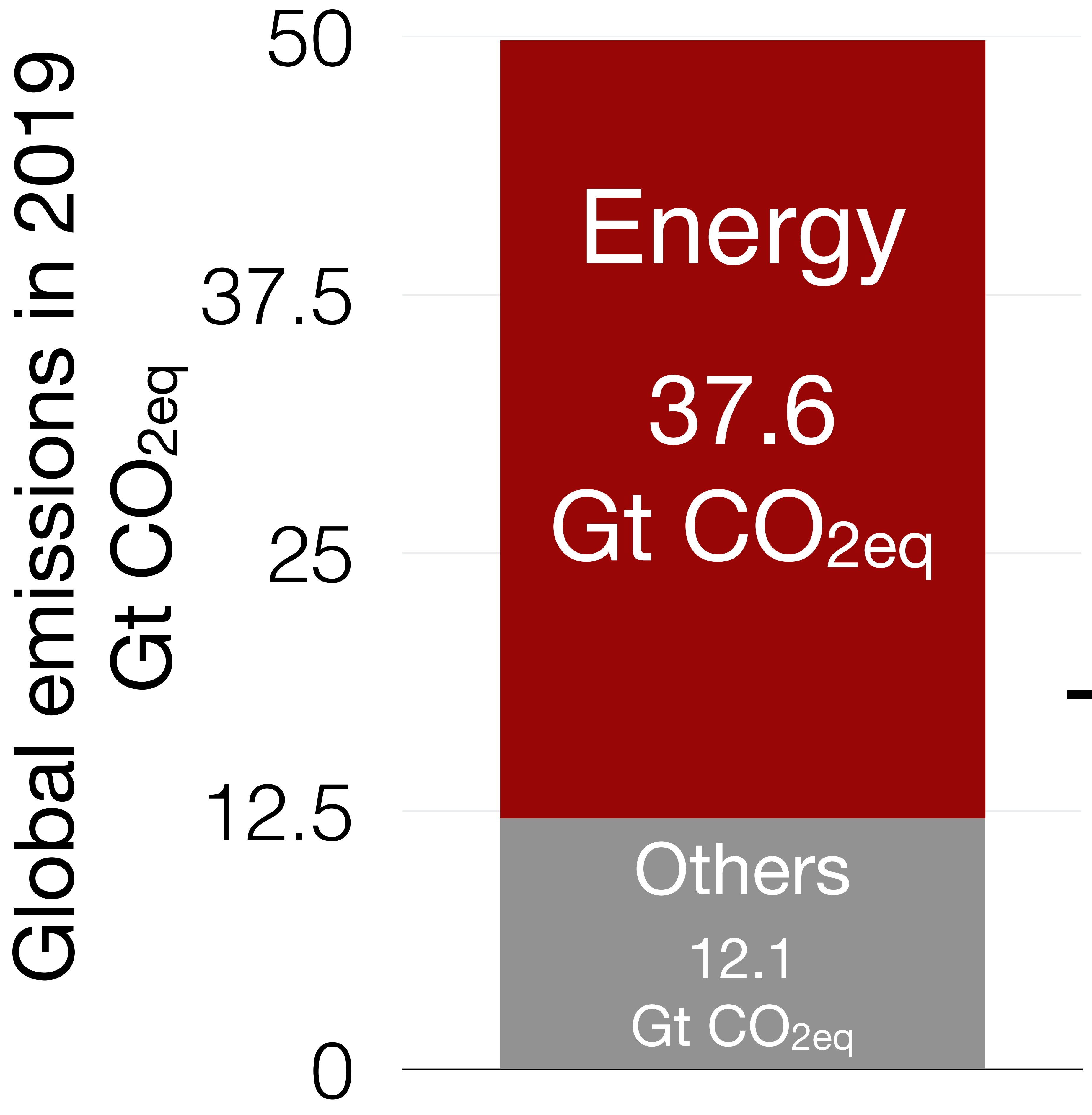
The problem of dealing with variability, and possible solutions

3

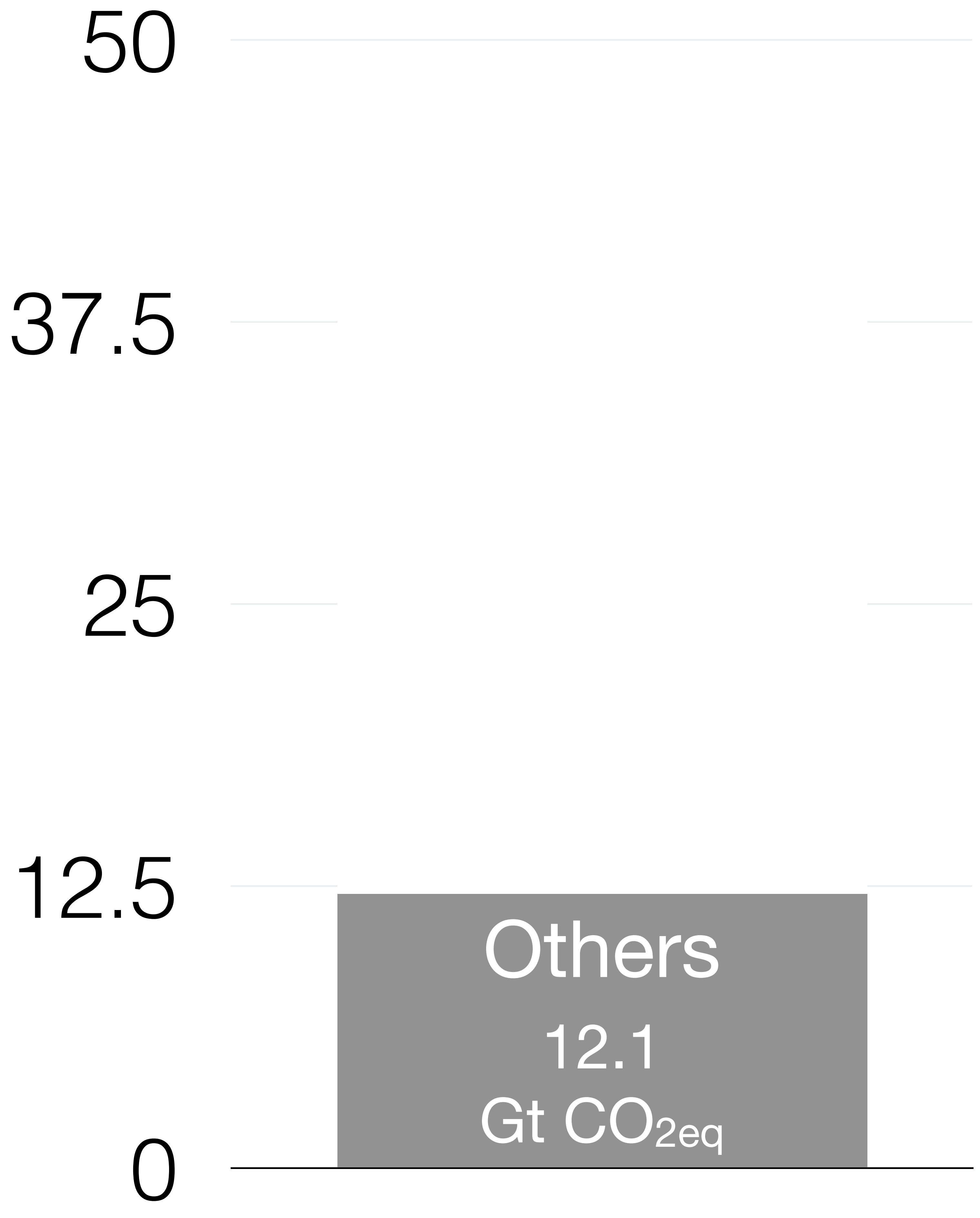
Combinations that work, and how to make informed decisions

The pivotal role of electricity

Two simple steps to eliminate energy emissions



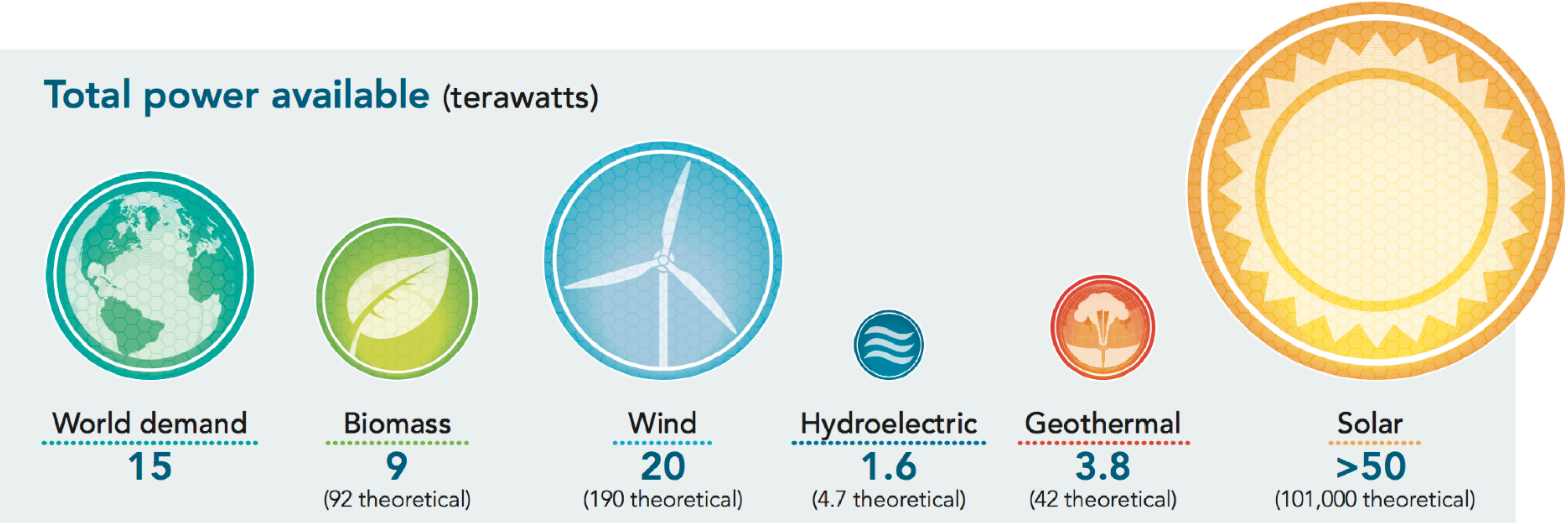
1. Electrify everything
2. Generate emissions-free electricity



Emissions data: Climate Watch (2023), https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&end_year=2019&start_year=1990

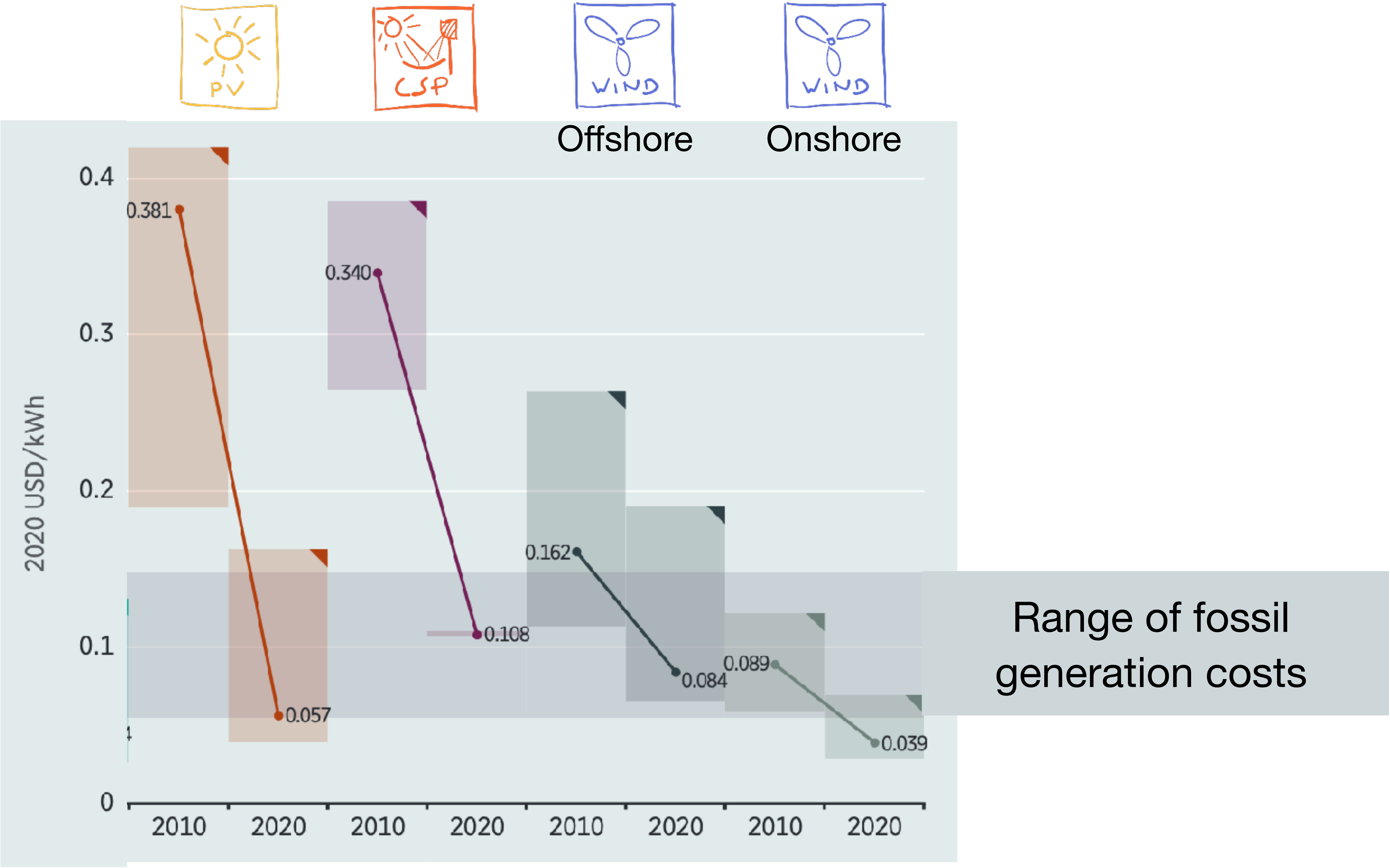
Why electrification?
The triumph of solar and wind power

Globally massive resource of solar and wind power



Cho (2010). Science

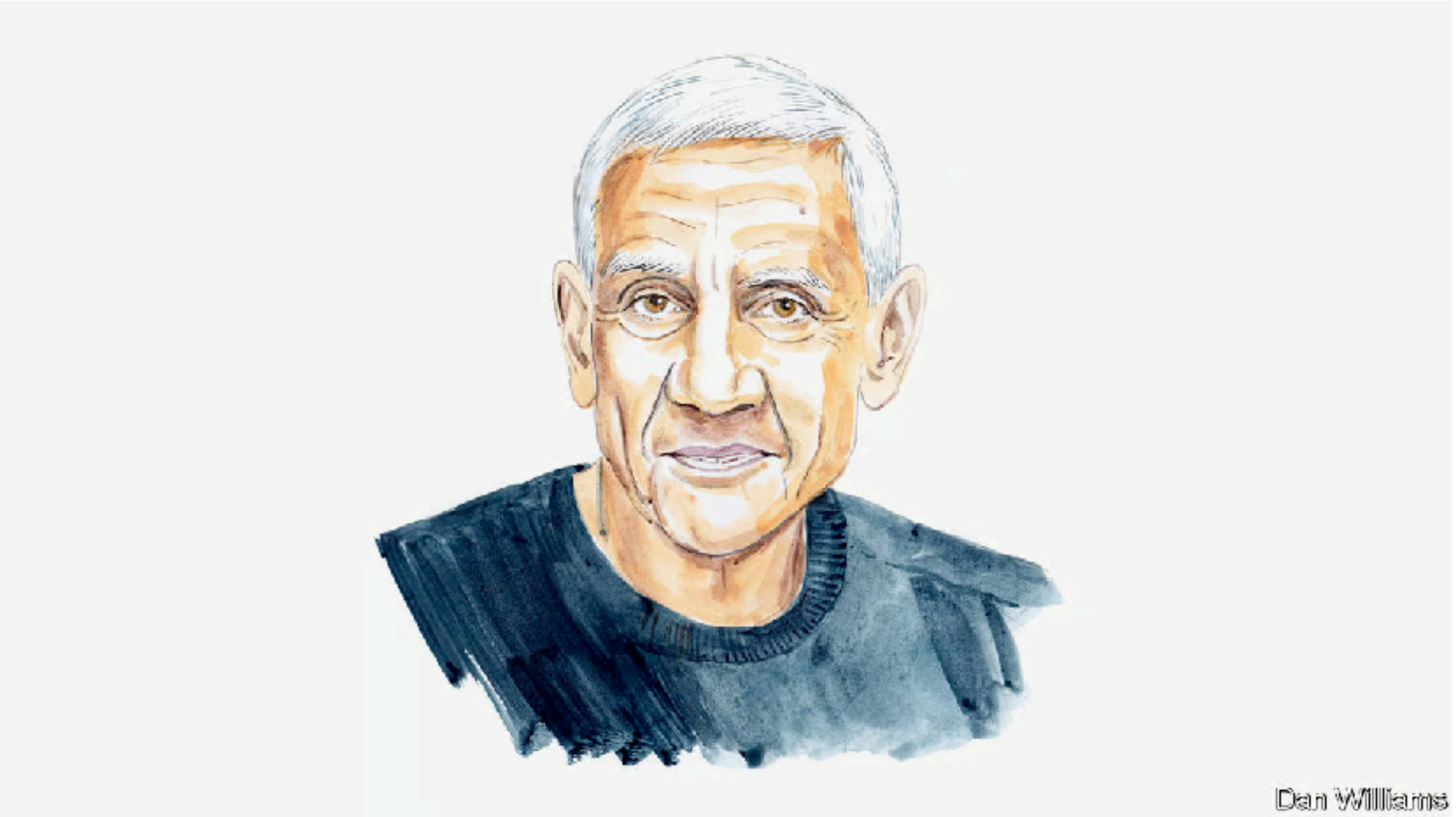
Rapidly falling costs of solar and wind power



https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

The Economist **By Invitation**

Michael Liebreich: It takes time to scale new techs. We have no choice but to deploy the techs we have today. Of course, R&D in next-gen techs should continue at the same time.



Vinod Khosla: Hoping to deploy today's techs globally is unrealistic. Wind and solar are not reliable enough; we need things like next-gen nuclear fission and fusion.

https://www.economist.com/by-invitation/2023/02/07/michael-liebreich-wants-existing-low-carbon-technologies-to-be-scaled-up-much-faster
https://www.economist.com/by-invitation/2022/11/08/vinod-khosla-says-rushing-to-meet-carbon-reduction-targets-by-2030-may-hinder-what-can-be-achieved-by-2050

LCOE: Levelised cost of electricity (or energy)

Depreciation rate $d = \frac{i(1+i)^n}{(1+i)^n - 1}$

n: lifetime in years
i: discount rate

overnight investment cost ($) * depreciation rate

$$\text{LCOE} = \frac{\text{annualised investment cost (\$)}}{\text{average annual generation (kWh)}} + \text{operational cost (\$/kWh)}$$

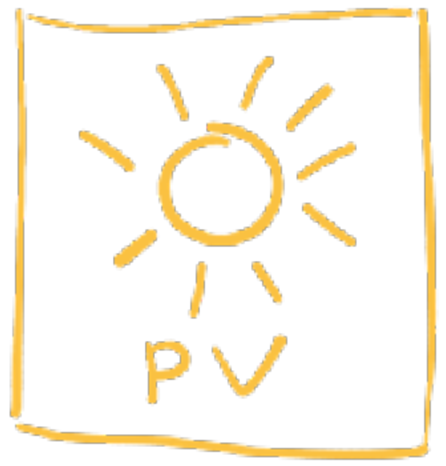
Example: rooftop PV system with 1 kW capacity

Discount rate: 0.05
Lifetime: 20 years
Investment cost: 375 $/kW
Size: 1 kW
Annual generation: 1000 kWh

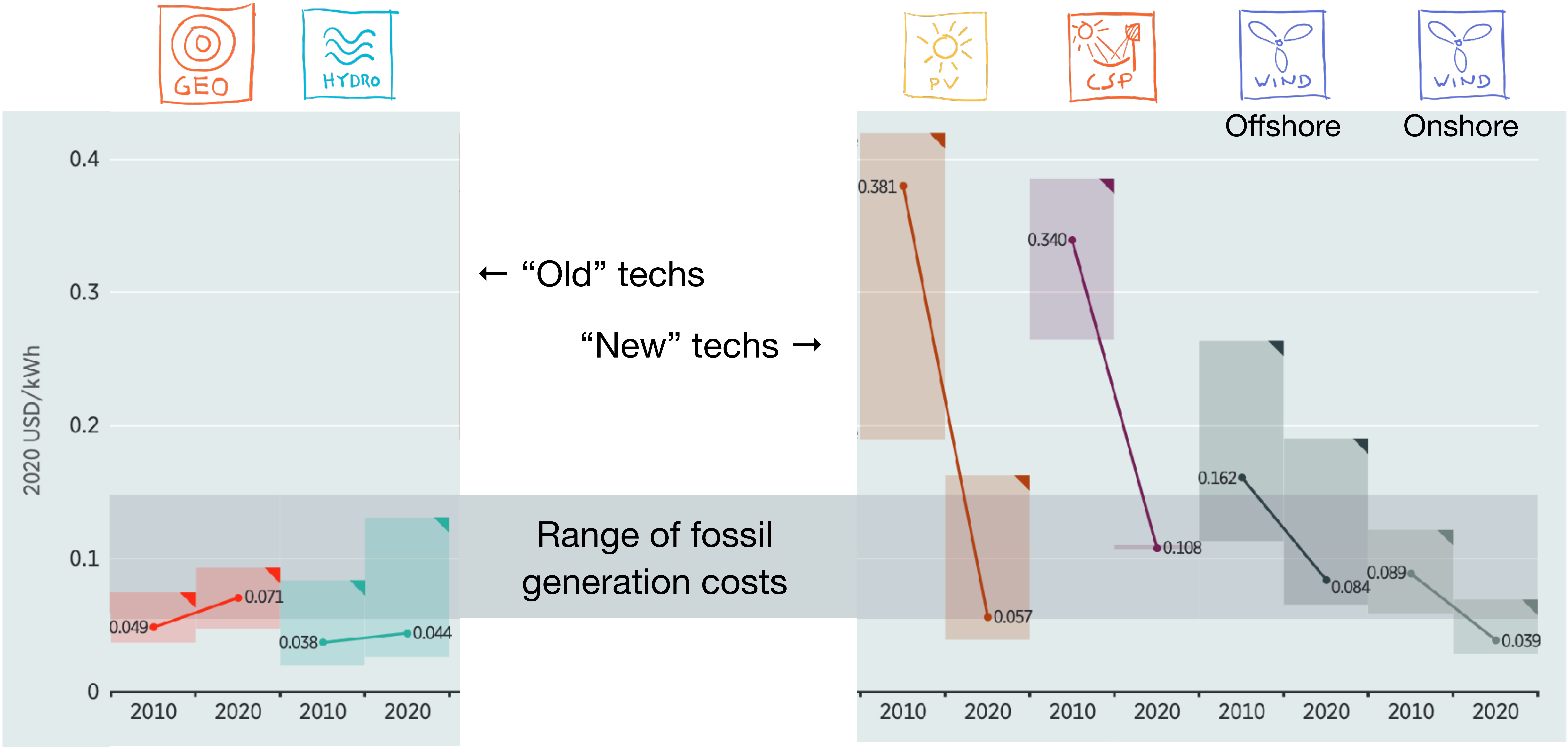
i=0.05, n=20 → d=0.08

$$\text{LCOE} = \frac{375 \text{ \$/kW} * 1 \text{ kW} * 0.08}{1000 \text{ kWh}} + 0.01 \text{ \$/kWh} = 0.04 \text{ \$/kWh}$$

Old and new renewables



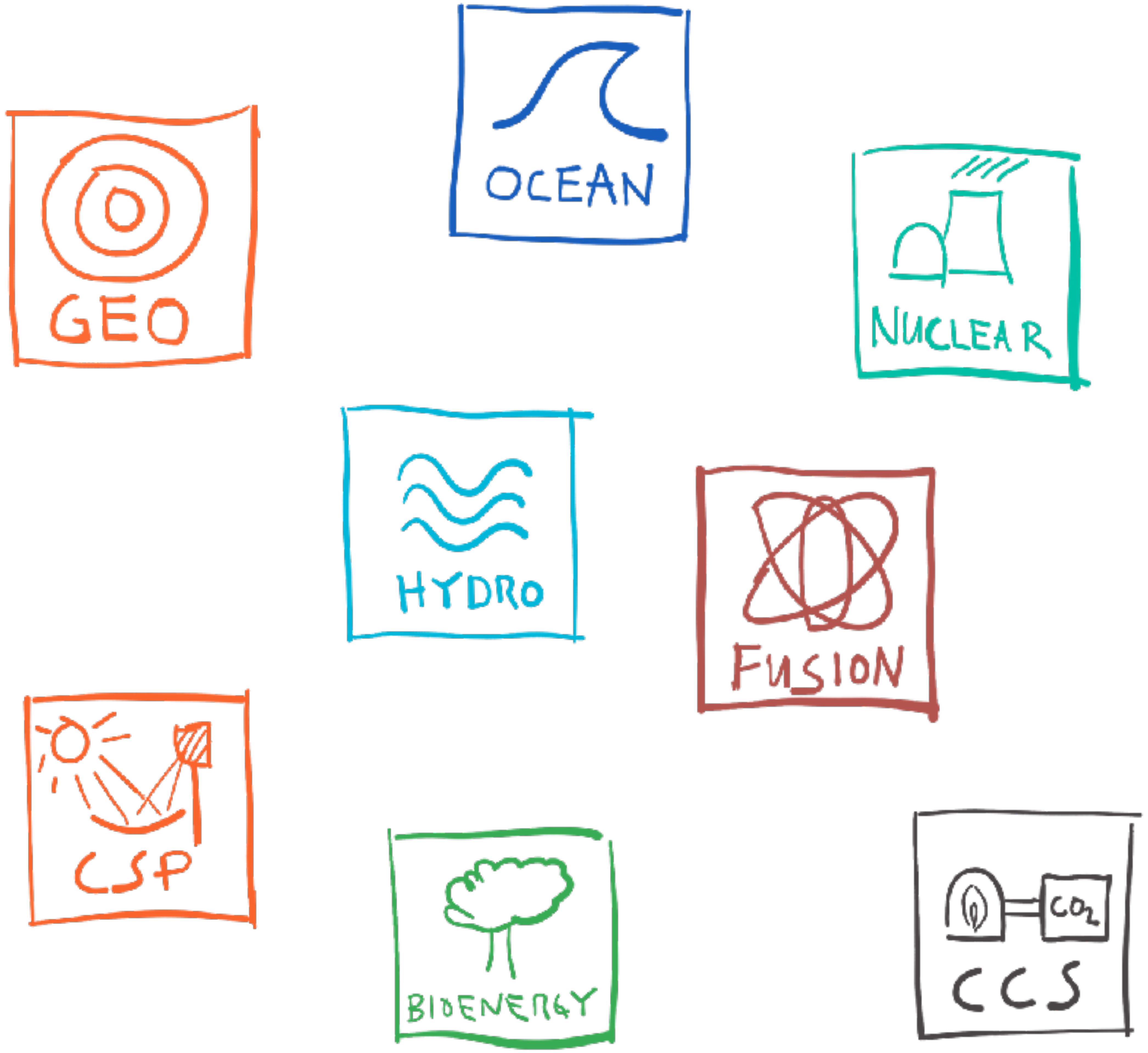
Levelised costs of electricity (LCOE)



https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

Wind and solar power are the most credible sources of large amounts of climate-neutral electricity

	PV	WIND
Key feature	✓ highly scalable	✓ can be built offshore (far from people)
Cost	✓ very low	✓ very low
Variability	✗ very high	✗ high
Resource	✓ large, available globally	✓ large, available globally
Controversial?	✓ no	✓ no
Commercially available right now?	✓ yes	✓ yes



Summary

- Costs of "new" renewables have come down so much that they are the most credible technologies now to provide large amounts of clean electricity (on the timescale to address climate change)
- Partly because of this, electrification of as much energy use as possible must be a cornerstone of climate change mitigation
- But wind+solar power are only a real solution if their variability can be managed - can it?

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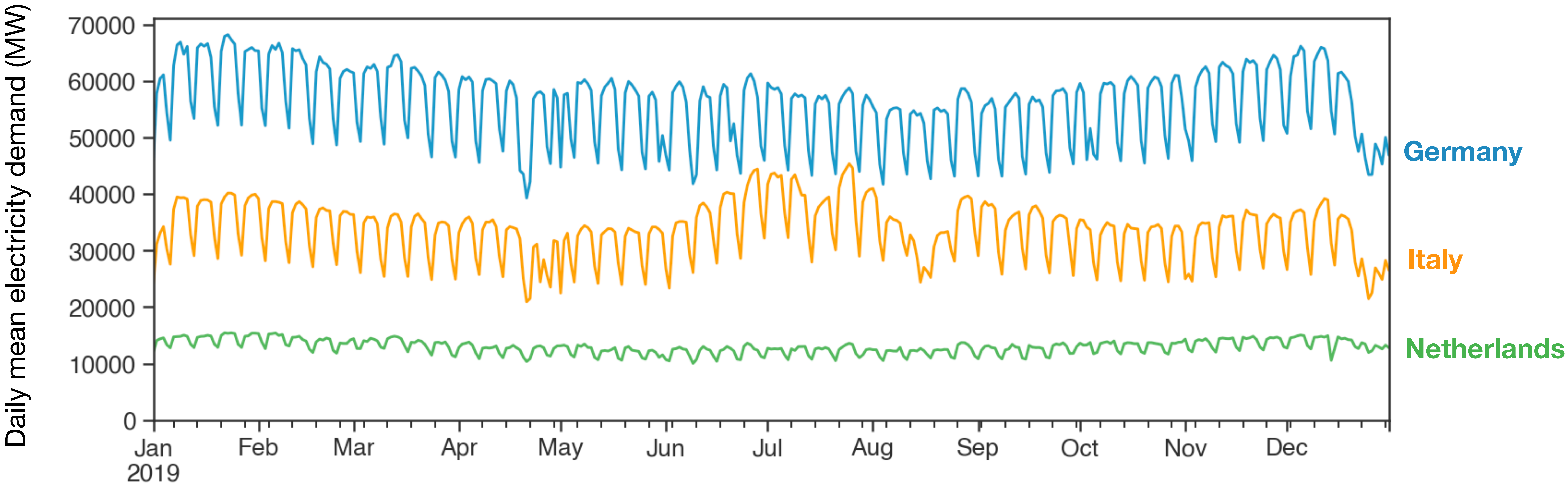
Variability: the problem

Electricity demand varies through time

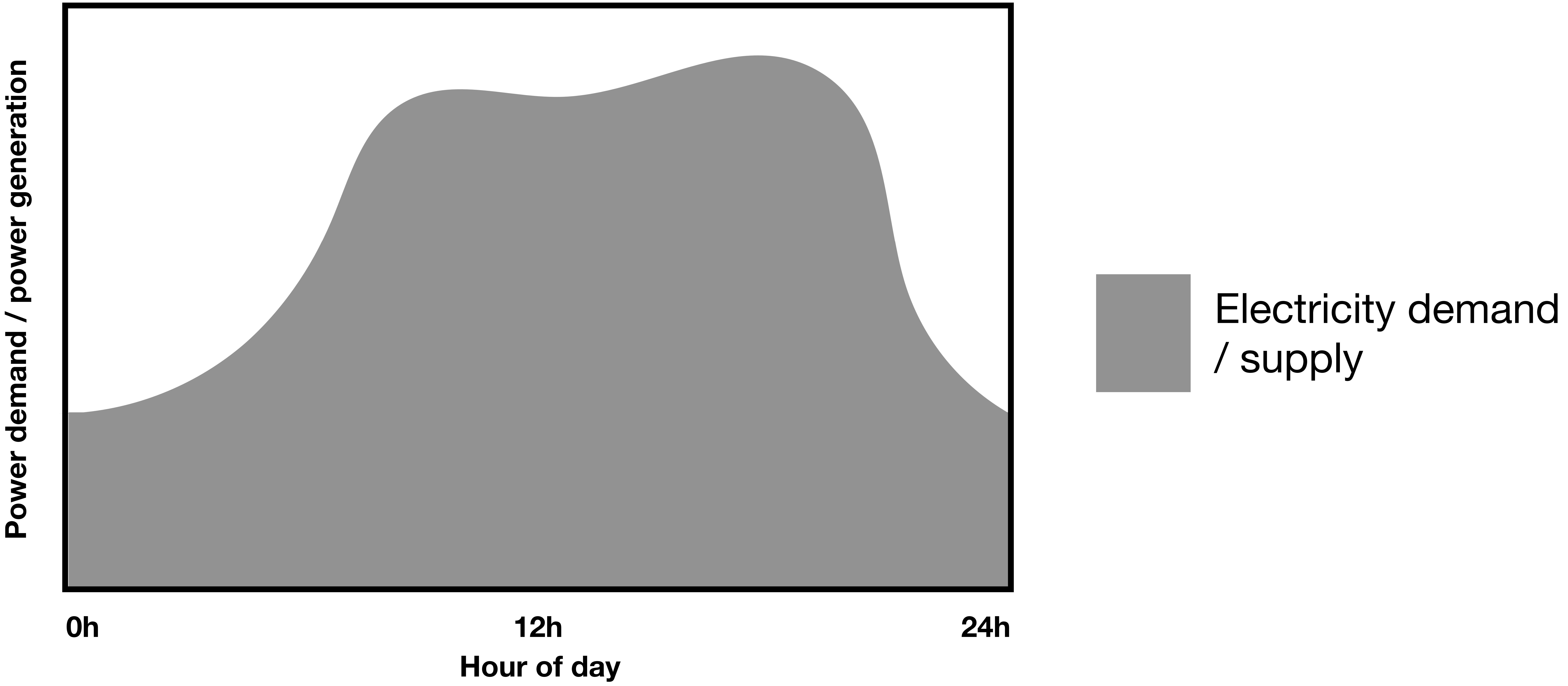


Some of the factors that influence demand:

- Time of day
- Weekday vs weekend
- Weather (so, seasons)
- Special days like Christmas
- Special periods like vacations

Data: ENTSO-E transparency platform via open-power-system-data.org

Generation and demand must always be perfectly matched



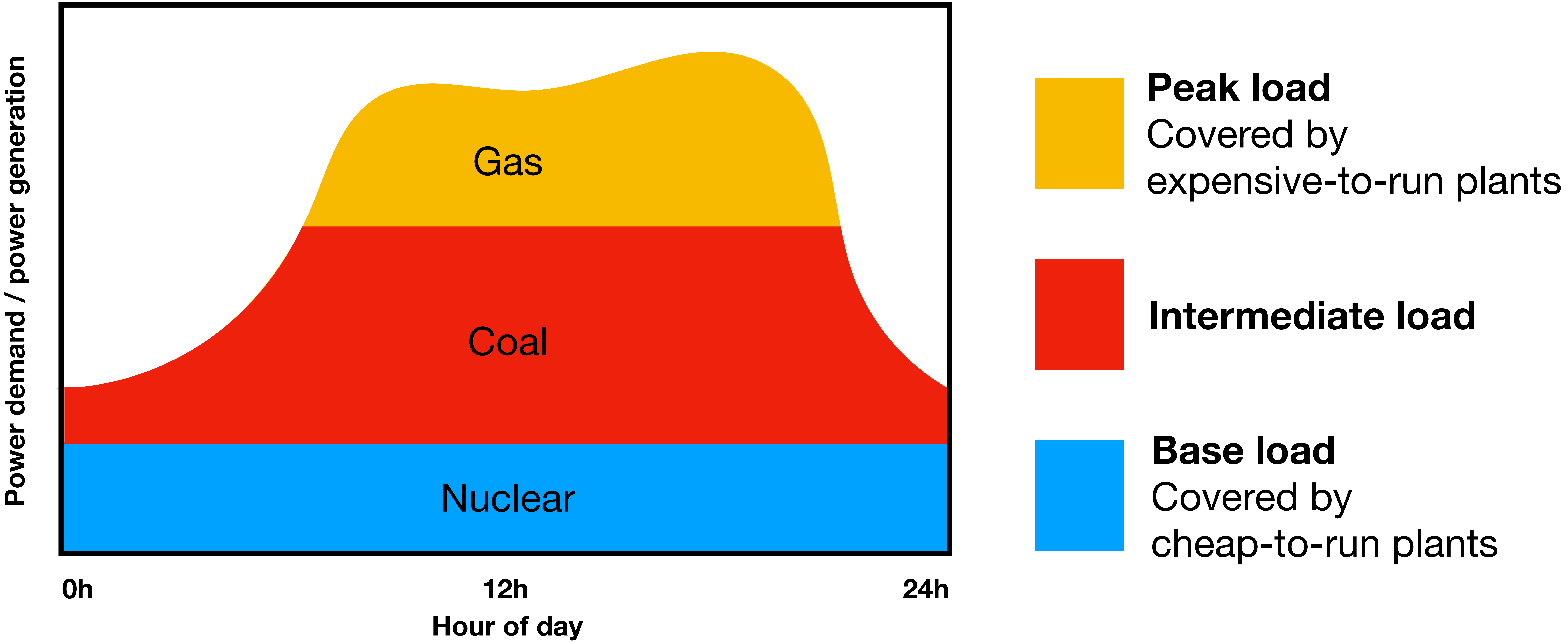
Adapted from Fig. 6.4 in Blok & Nieuwlaar (2016)

“Traditional” power plants

https://www.power-technology.com/projects/maasstroom-energie/

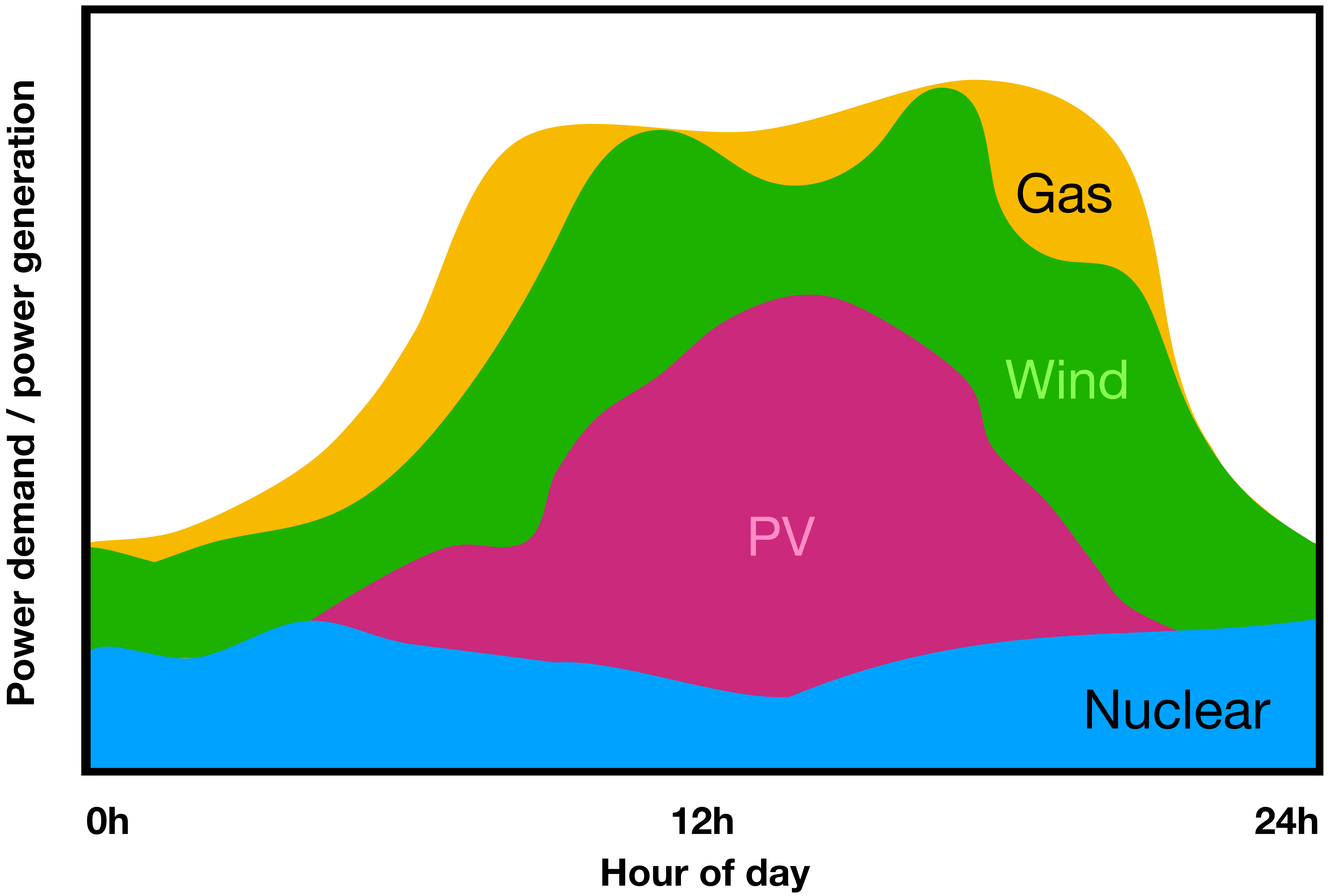
https://en.wikipedia.org/wiki/Electricity_generation#/media/File:Turbogenerator01.jpg

Traditional power system operation



Adapted from Fig. 6.4 in Blok & Nieuwlaar (2016)

Power system with PV and wind



Peak load
"Eaten into" by variable renewables

Variable wind and PV

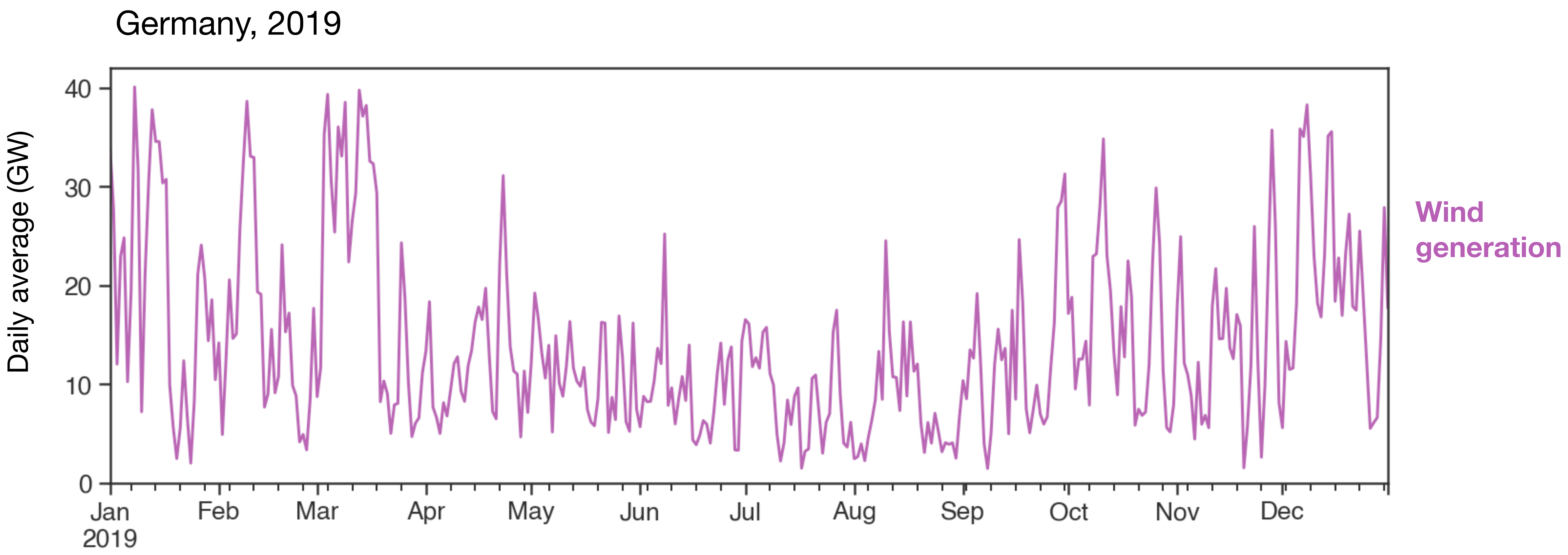
Base load
"Eaten into" by variable renewables

Data source: MERRA reanalysis, NASA

Scales of variability

Data source: MERRA reanalysis, NASA

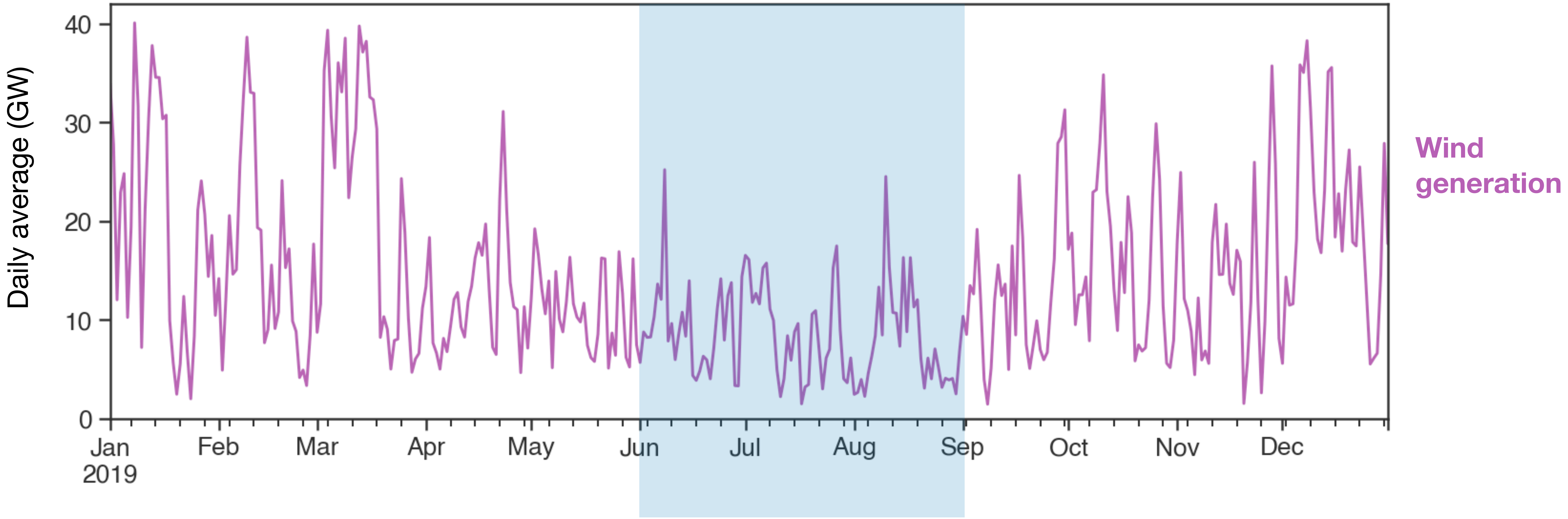
Time series of wind generation



Data: ENTSO-E transparency platform via open-power-system-data.org

CF: single number summarising a time period

$$\text{Capacity factor (CF, unitless quantity)} = \frac{\text{Generation (GW}\cdot\text{h)}}{\text{Duration (h)} \times \text{Capacity (GW)}}$$



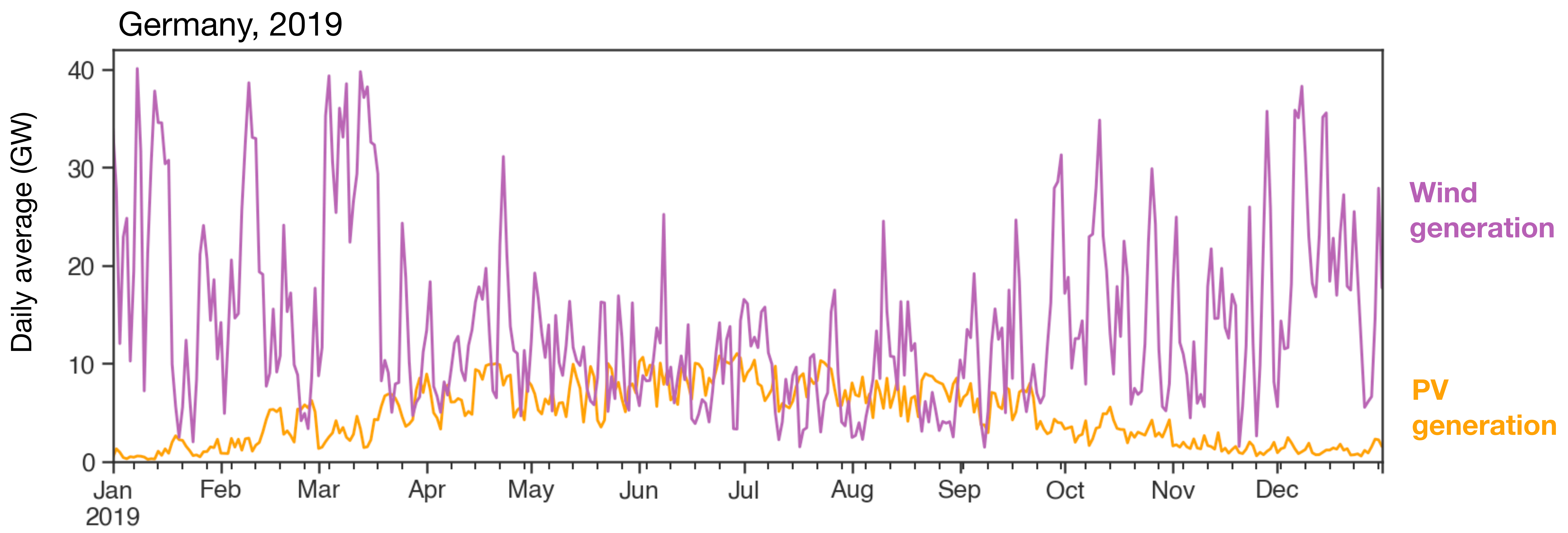
Assuming wind capacity = 60 GW

Summer CF = 14%

Annual CF = 24%

Data: ENTSO-E transparency platform via open-power-system-data.org

Time series of wind and PV generation



Assuming wind capacity = 60 GW	Wind annual CF = 24%

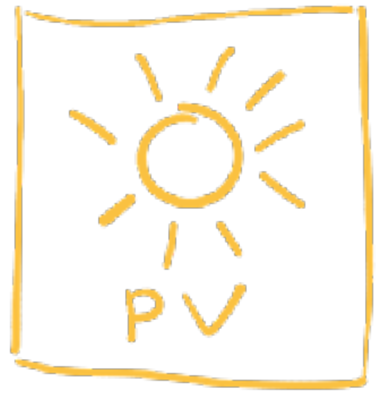
Assuming PV capacity = 45 GW	PV annual CF = 11%

Data: ENTSO-E transparency platform via open-power-system-data.org

Typical capacity factors

Typical annual averages

often written as % (0-100) rather than fraction (0-1)



Around 10% (in NL)

Around 20% (in a sunny place)

Around 30% (in NL)

40-60%

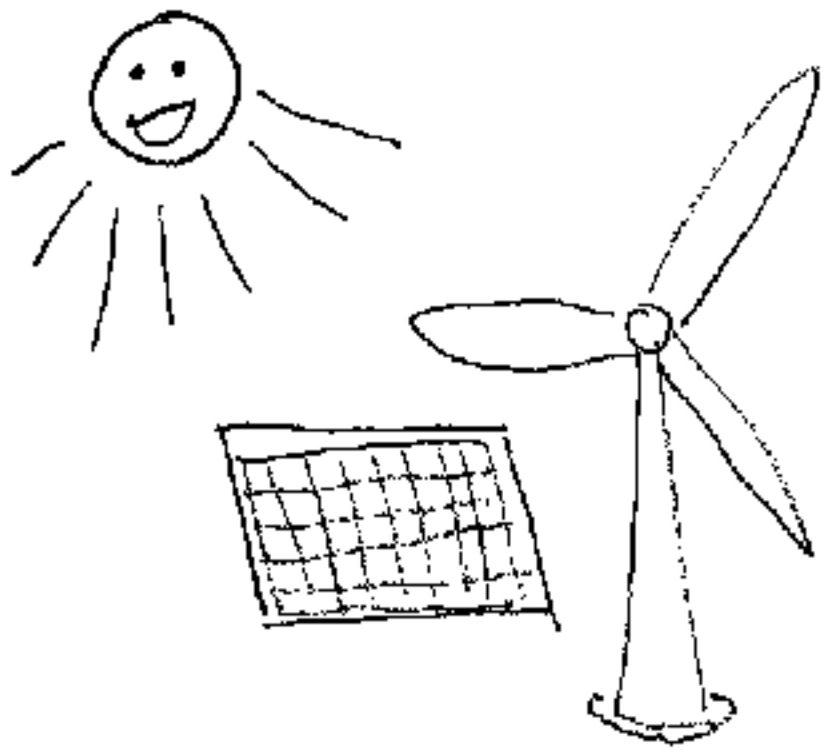
80% (with storage)

80%

Variability: the solutions

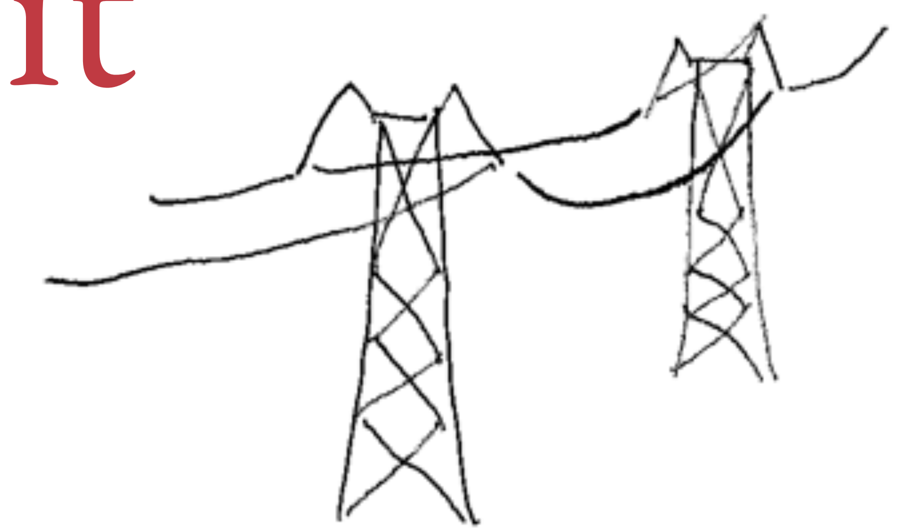
What we want and how to get it

We want:



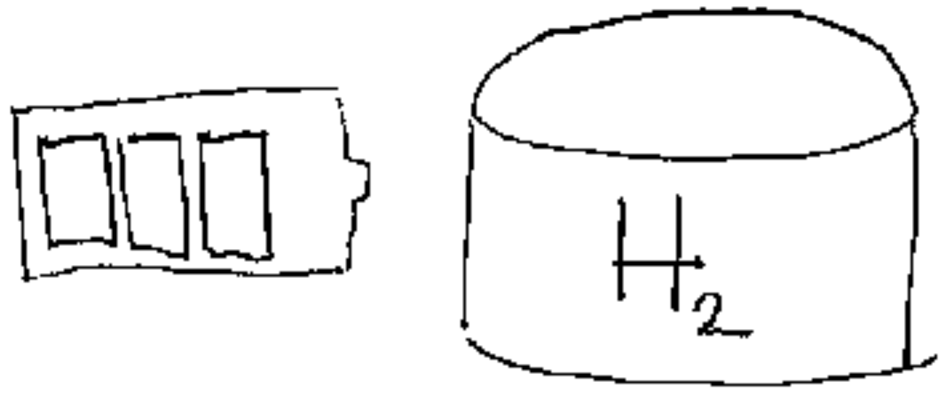
An electricity system with a high share of variable renewable generation (especially solar + wind)

Three ways to get it:



Grids

Balancing through space

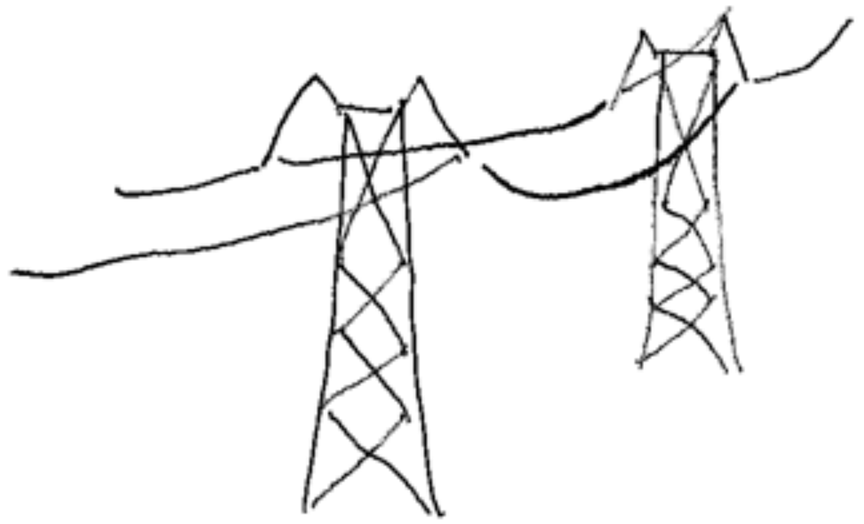


Storage

Balancing through time

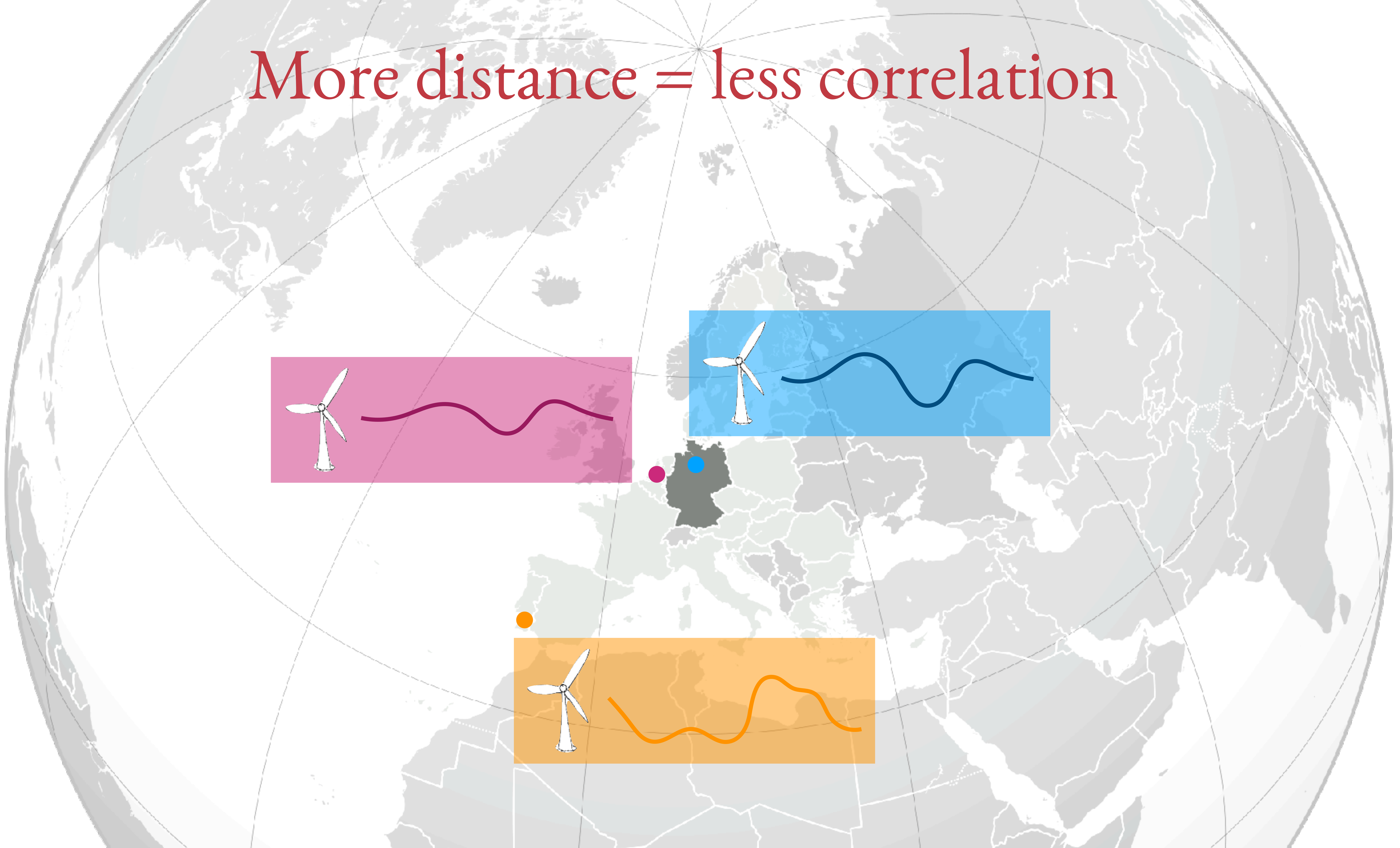
Flexibility

Balancing by adjusting demand



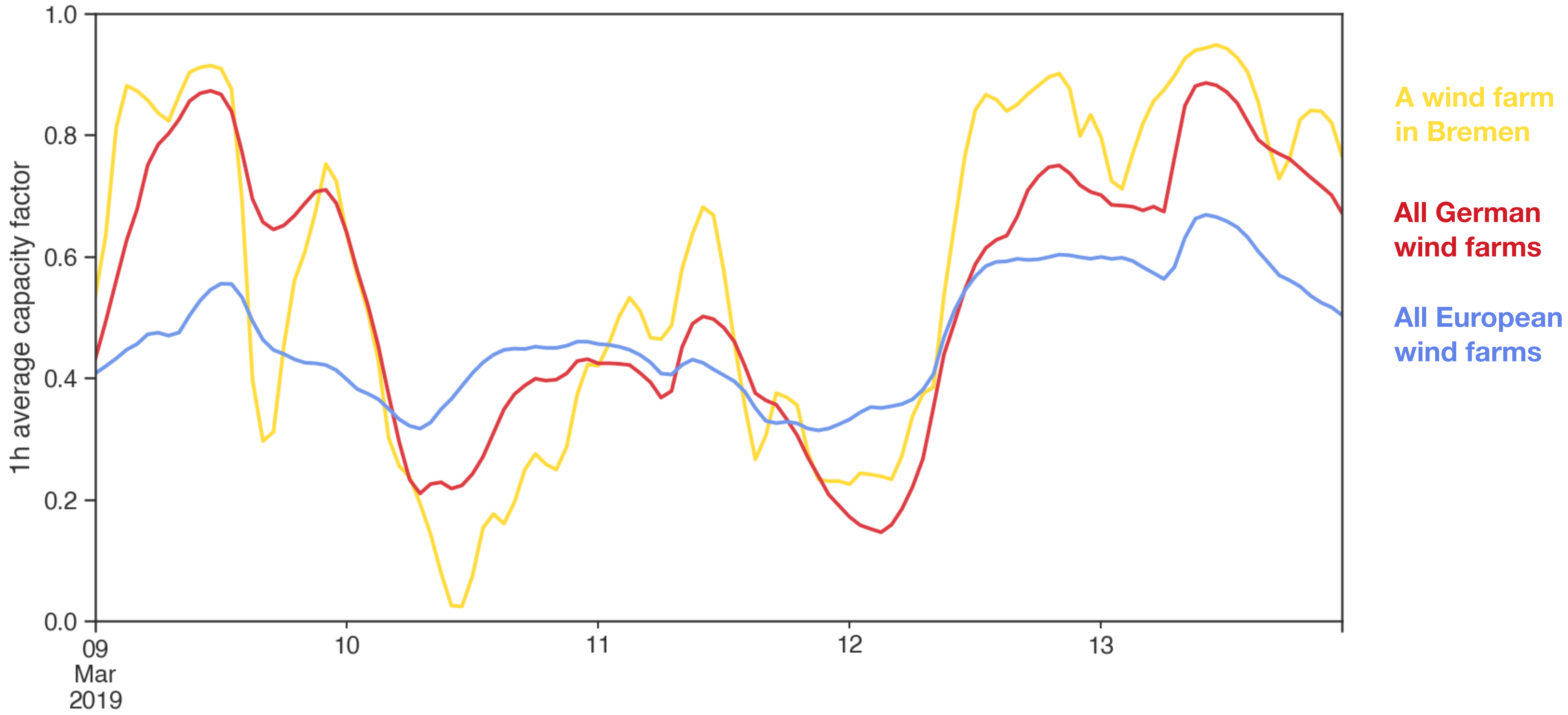
Grids: balancing through space

More distance = less correlation



Map: https://commons.wikimedia.org/wiki/File:EU-Germany_(orthographic_projection).svg, used under a CC-BY-SA license

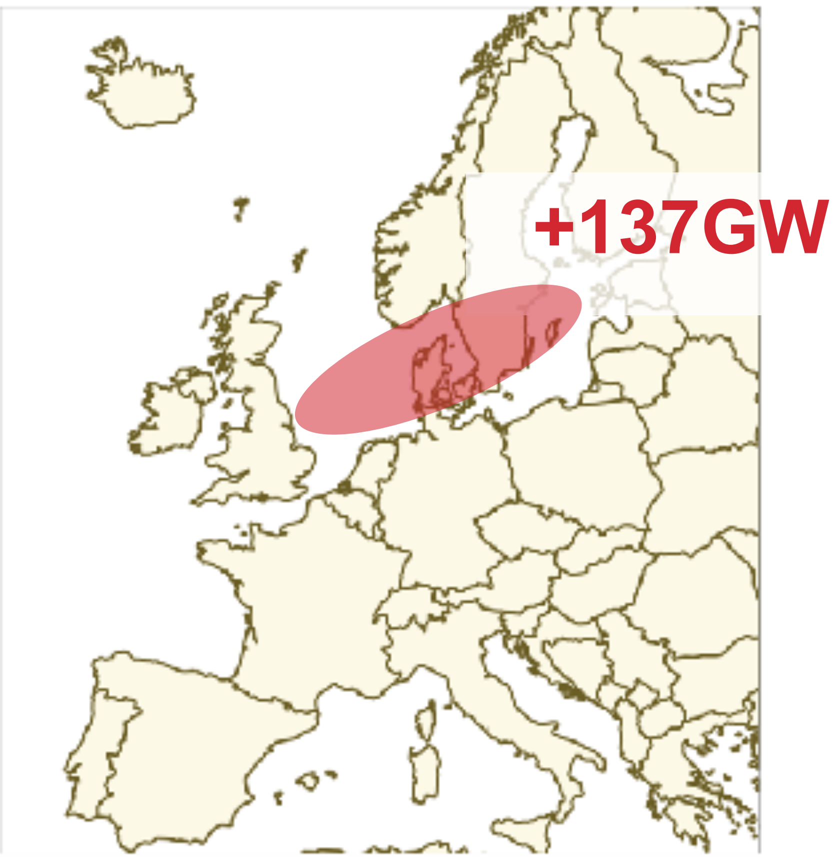
Bigger area = smoother output



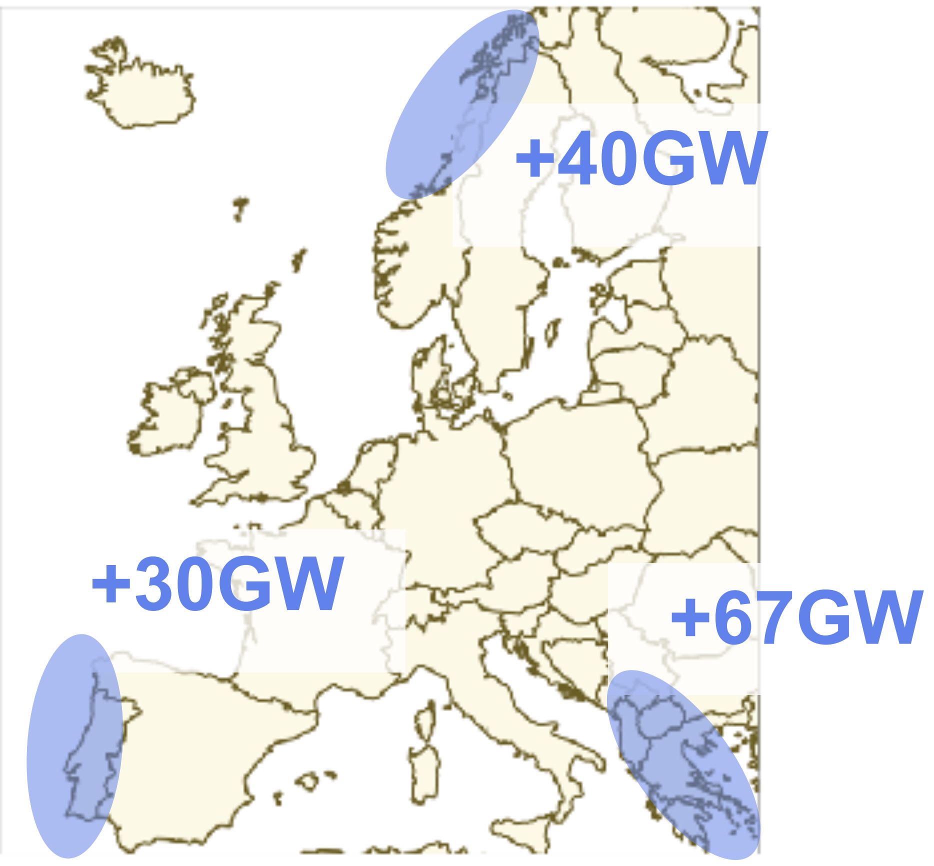
Data: Renewables.ninja

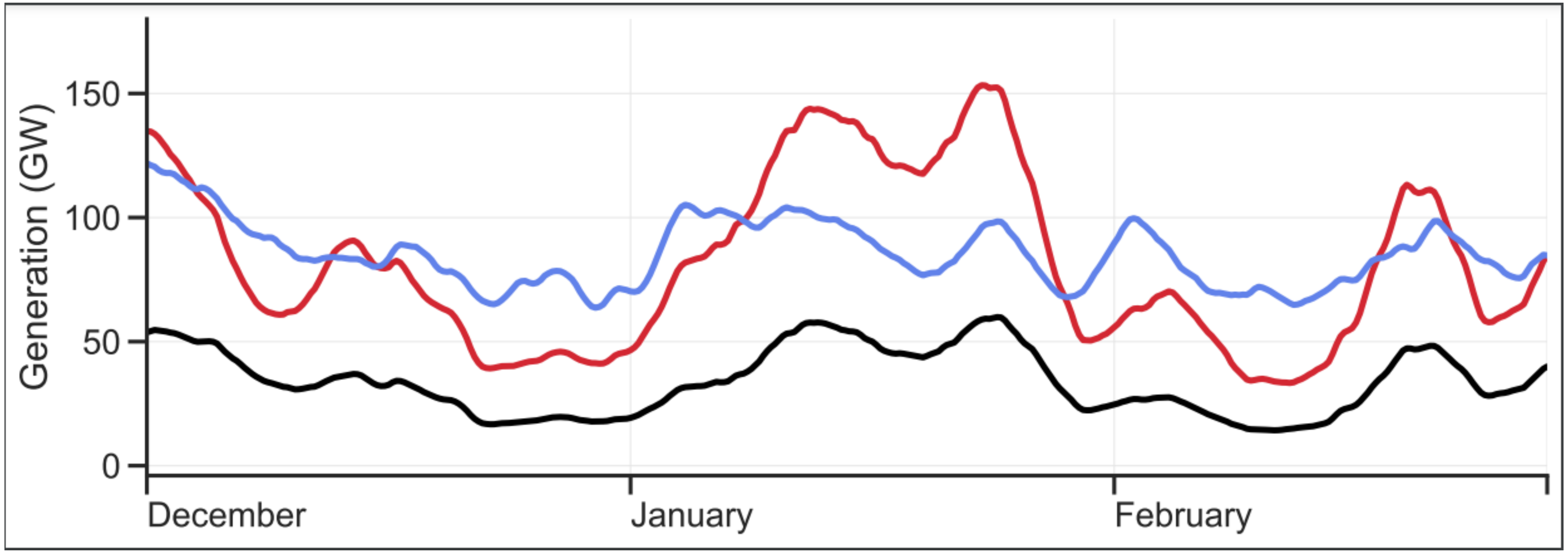
Meteorological understanding can improve planning

Concentrate new wind farms on the North Sea



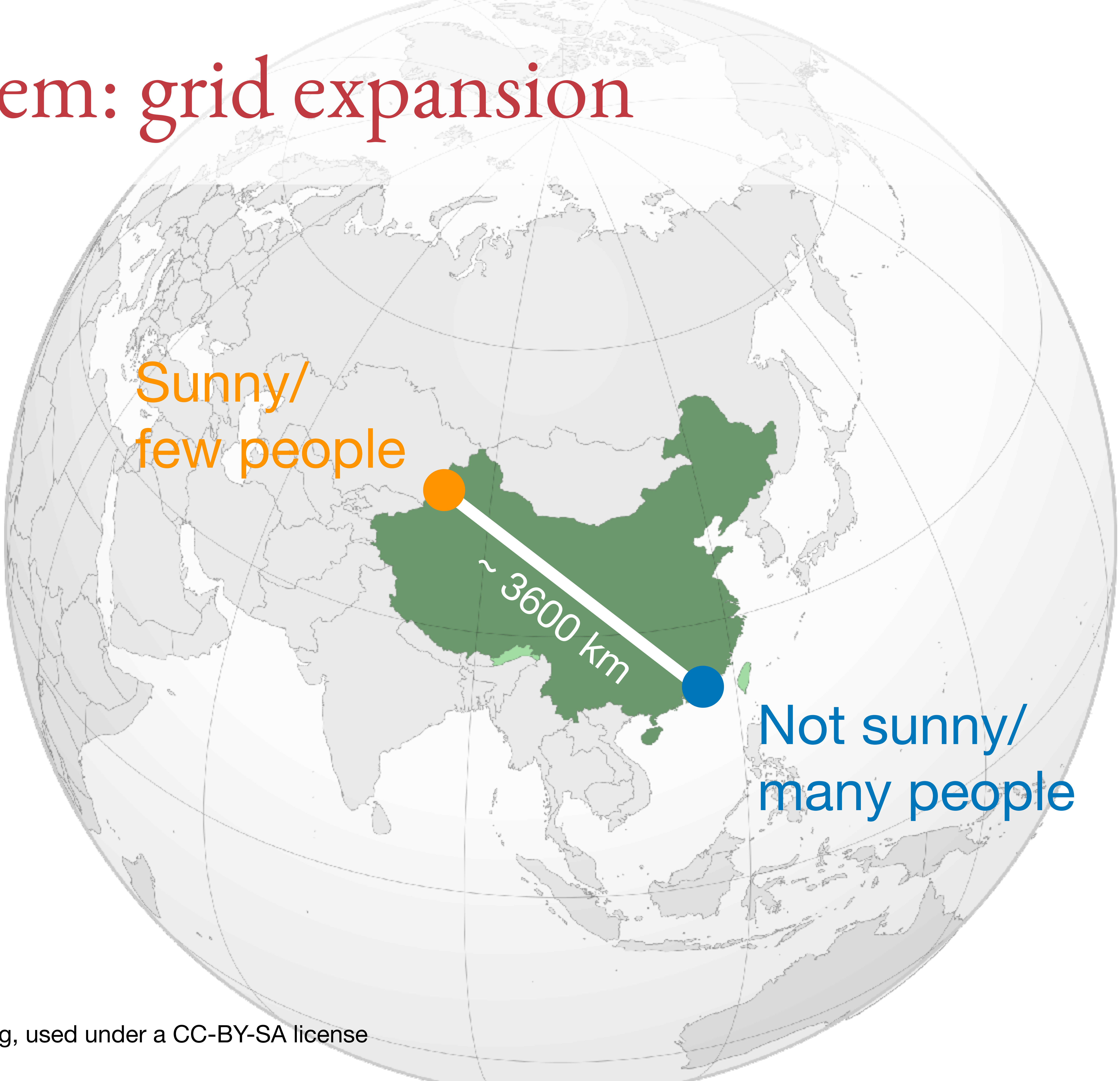
Distribute new wind farms





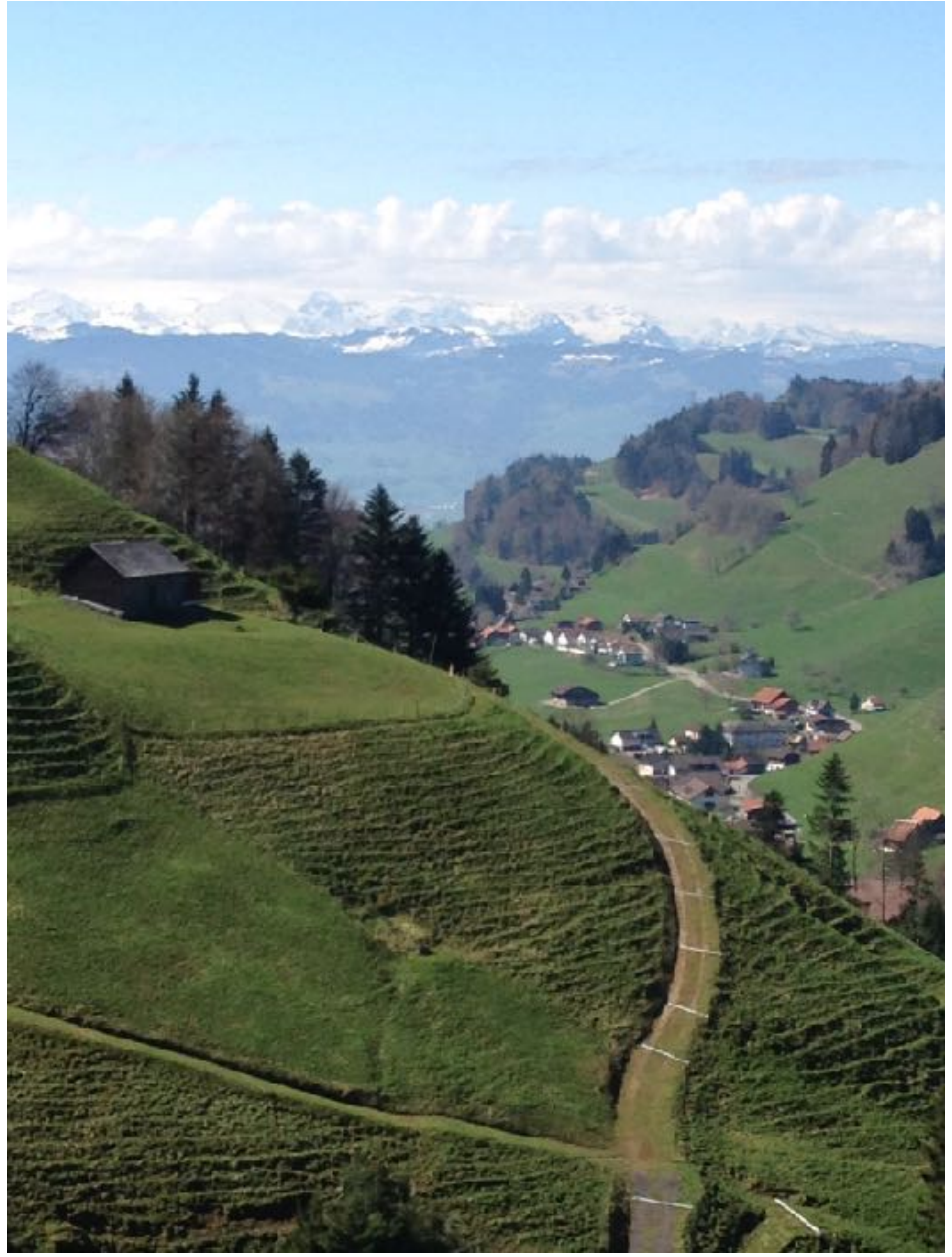
Results from the study Grams et al. (2017). *Nature Climate Change*. https://doi.org/10.1038/nclimate3338

Problem: grid expansion

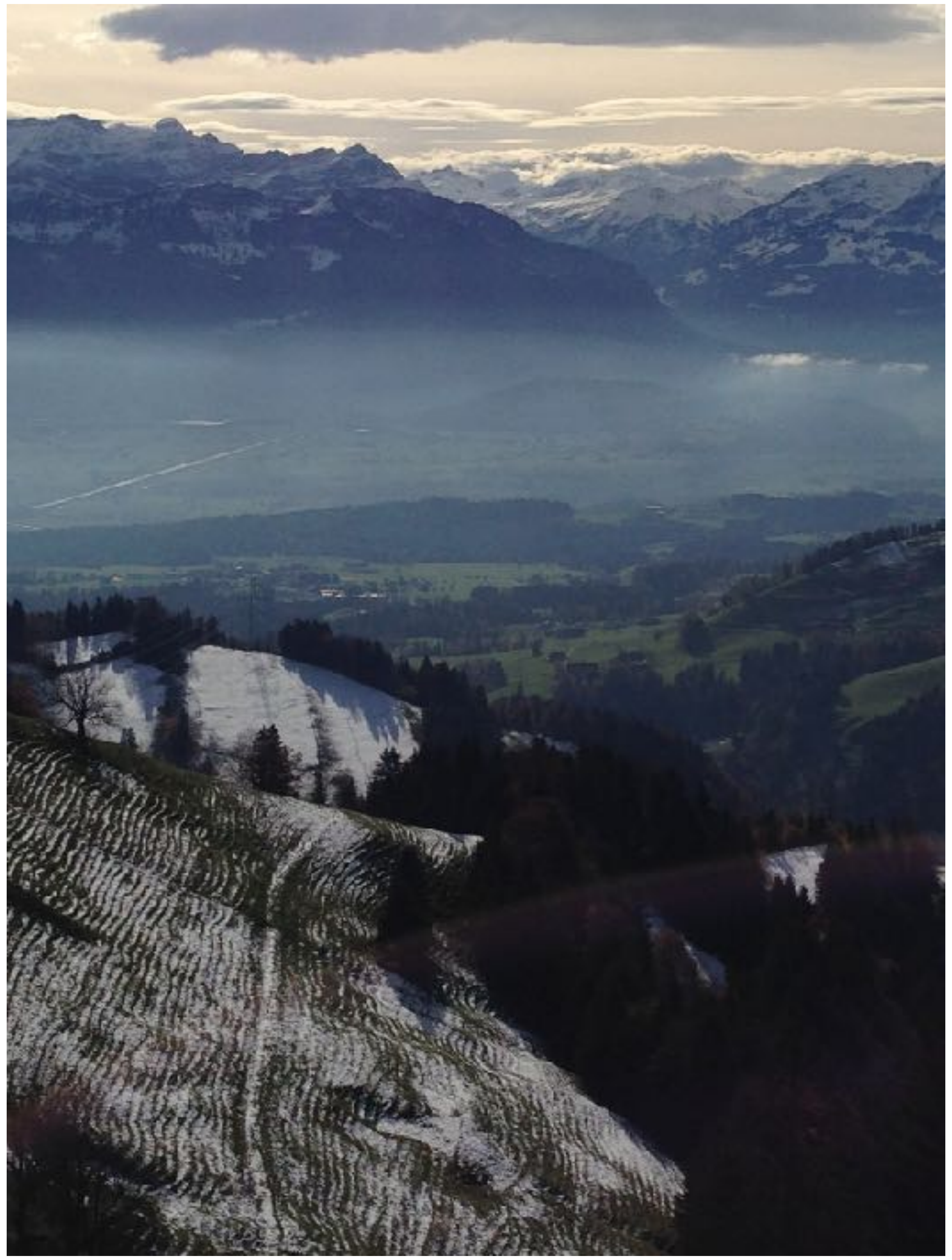


Map: https://commons.wikimedia.org/wiki/File:CHN_orthographic.svg, used under a CC-BY-SA license
Photo by Andrey Metelev on Unsplash

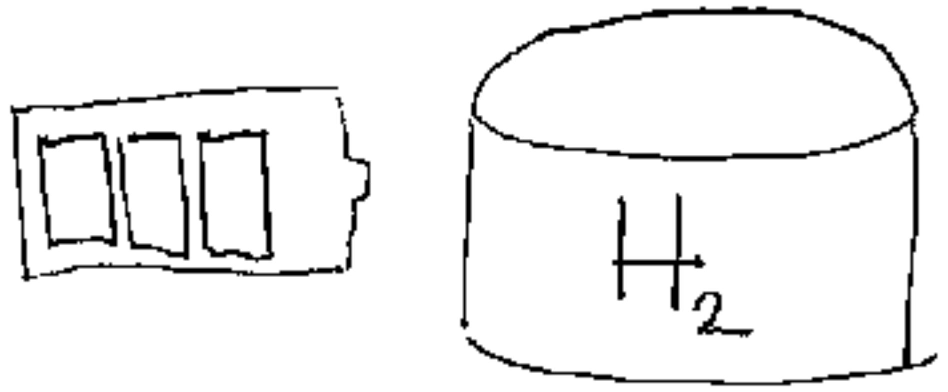
Problem: seasonal variability



Summer



Winter



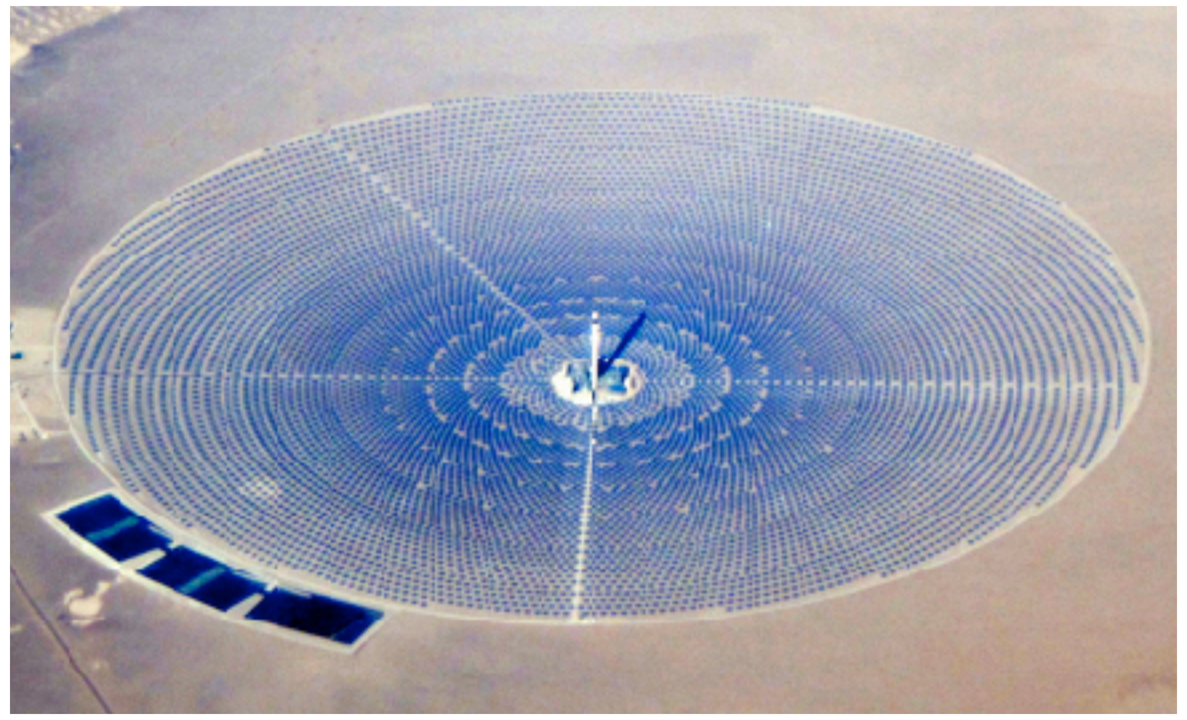
Storage: Balancing through time

How to “store” electricity

			Batteries						Options with non-electric uses	
	Capacitor	Flywheel	Li-ion	Sodium sulfur	Lead acid	Vanadium redox flow	Compressed air	Pumped hydro	Heat	Hydrogen
Time duration										
Large-scale use			✓					✓	✓	

Li-ion

Pumped hydro

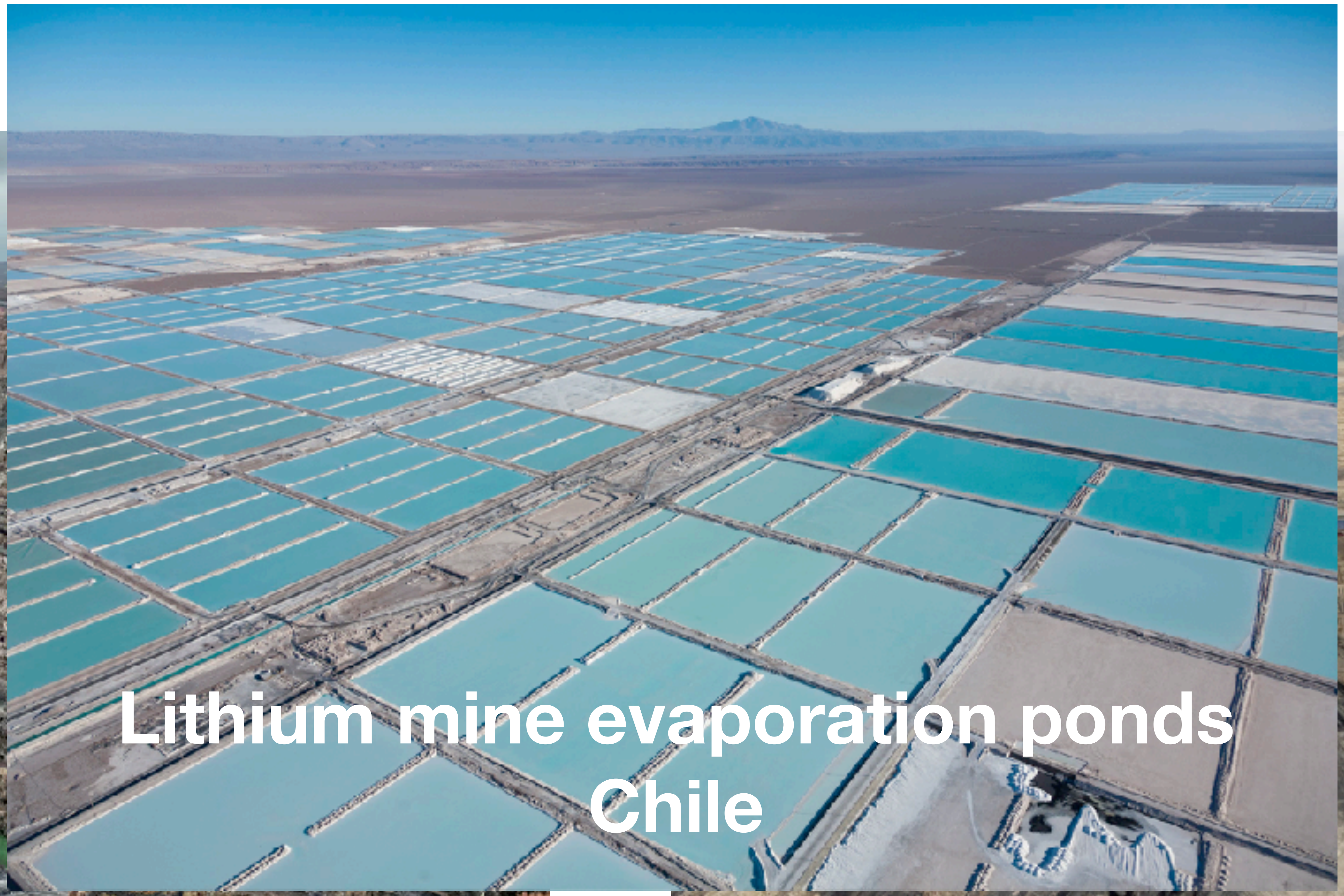


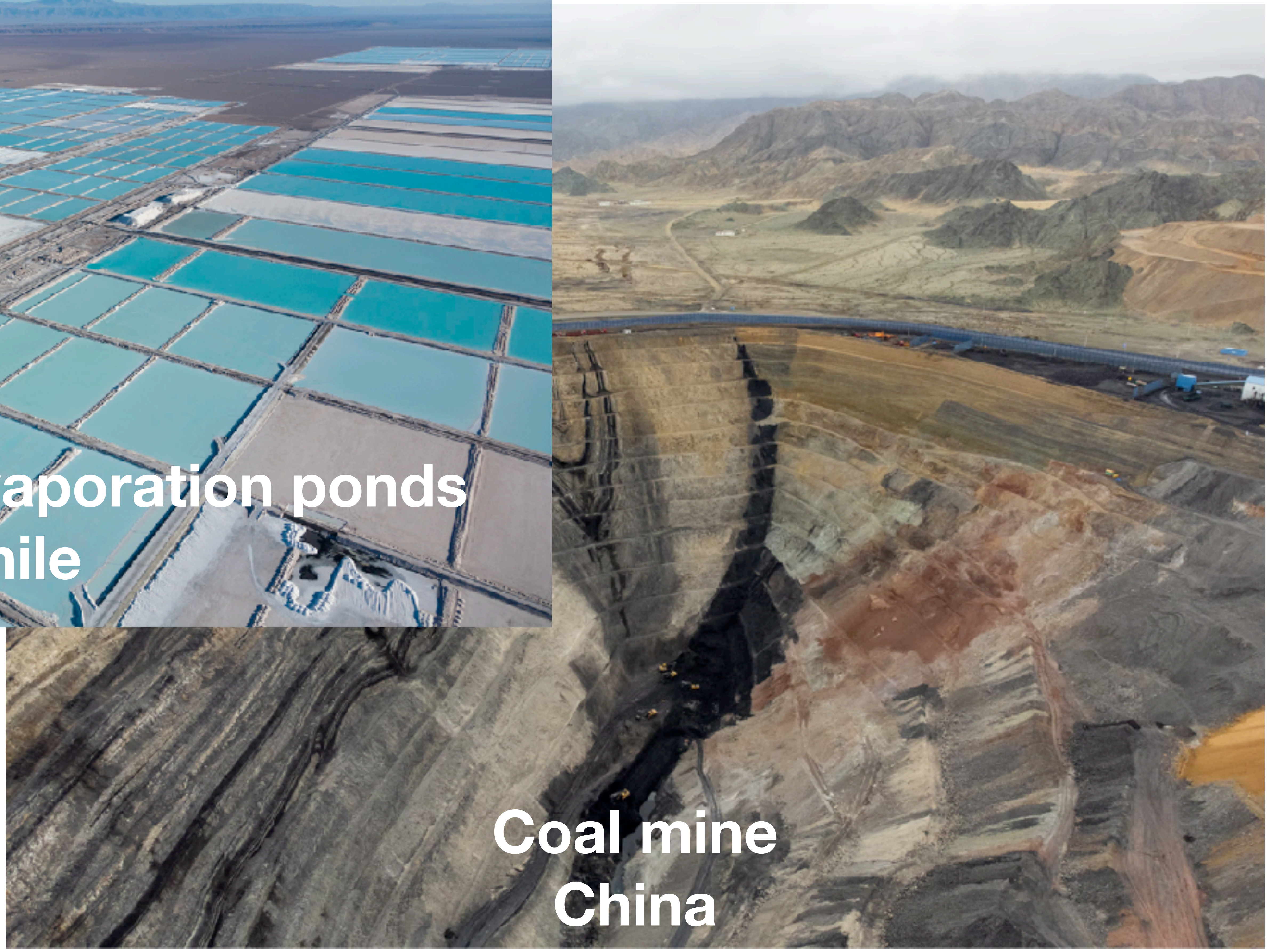
Heat

Batteries (currently Li-ion) are scalable like PV

iPhone 13 Pro battery: 0.012 kWh
Rooftop system photo: https://zpenergy.co.za/zpe_projects/15kva-hybrid-inverter-30kwhr-li-on-battery-10kw-solar-pv-sandton-gp/
Bulgana photo from https://neoen.com/en/what-we-do/

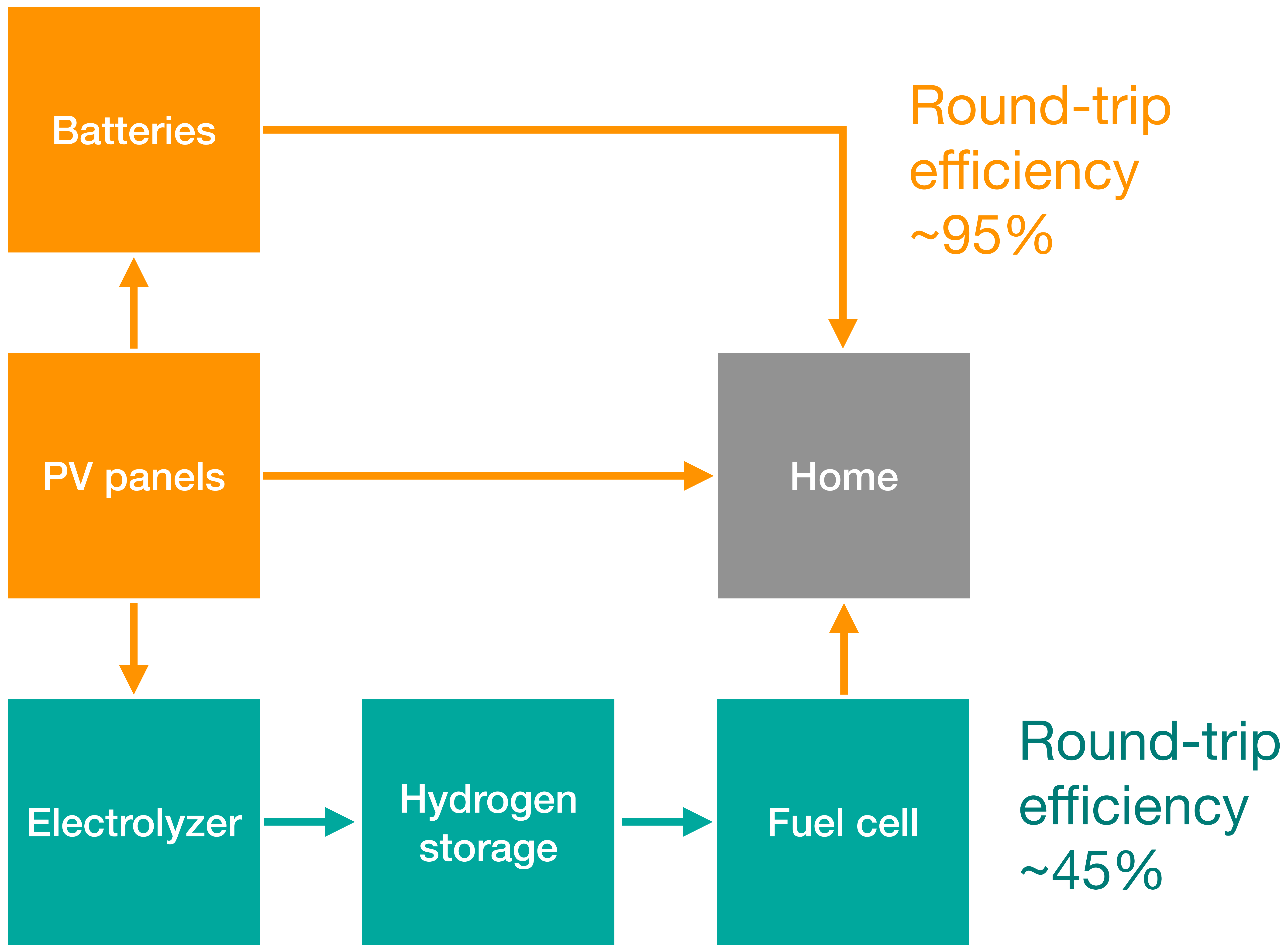
Raw materials like lithium for batteries





Gold and coal mine photos from Unsplash
Lithium mine photo: https://newmobility.news/2017/11/13/sale-worlds-largest-lithium-mine/

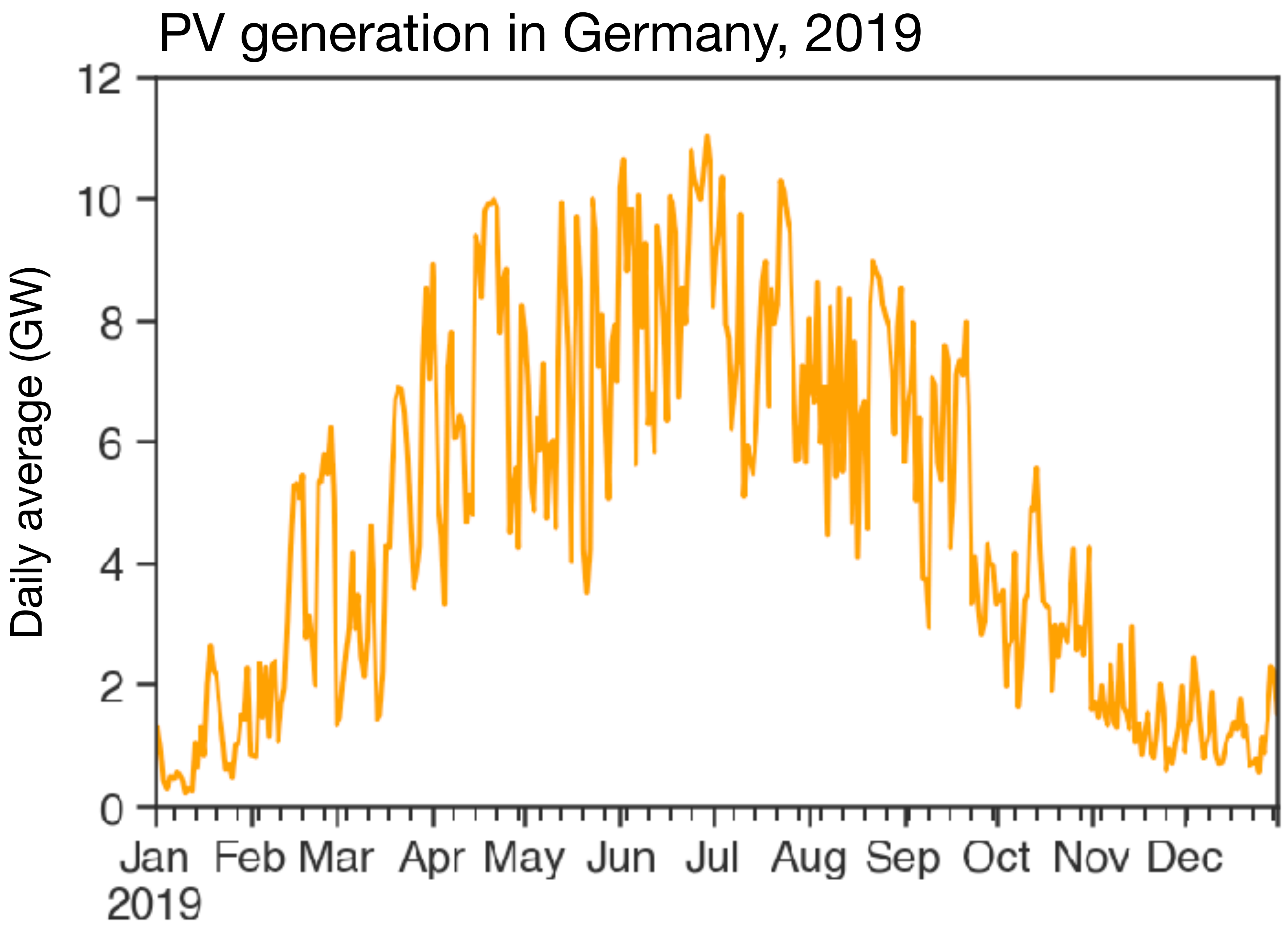
Hydrogen storage compared to battery storage



Hydrogen storage compared to battery storage

PV panels

Electrolyzer → Hydrogen storage → Fuel cell



Seasonal variability

Large tanks = relatively cheap

Most attractive storage technologies

All winter → Will most likely be hydrogen

Several days of bad weather → ?

One night →

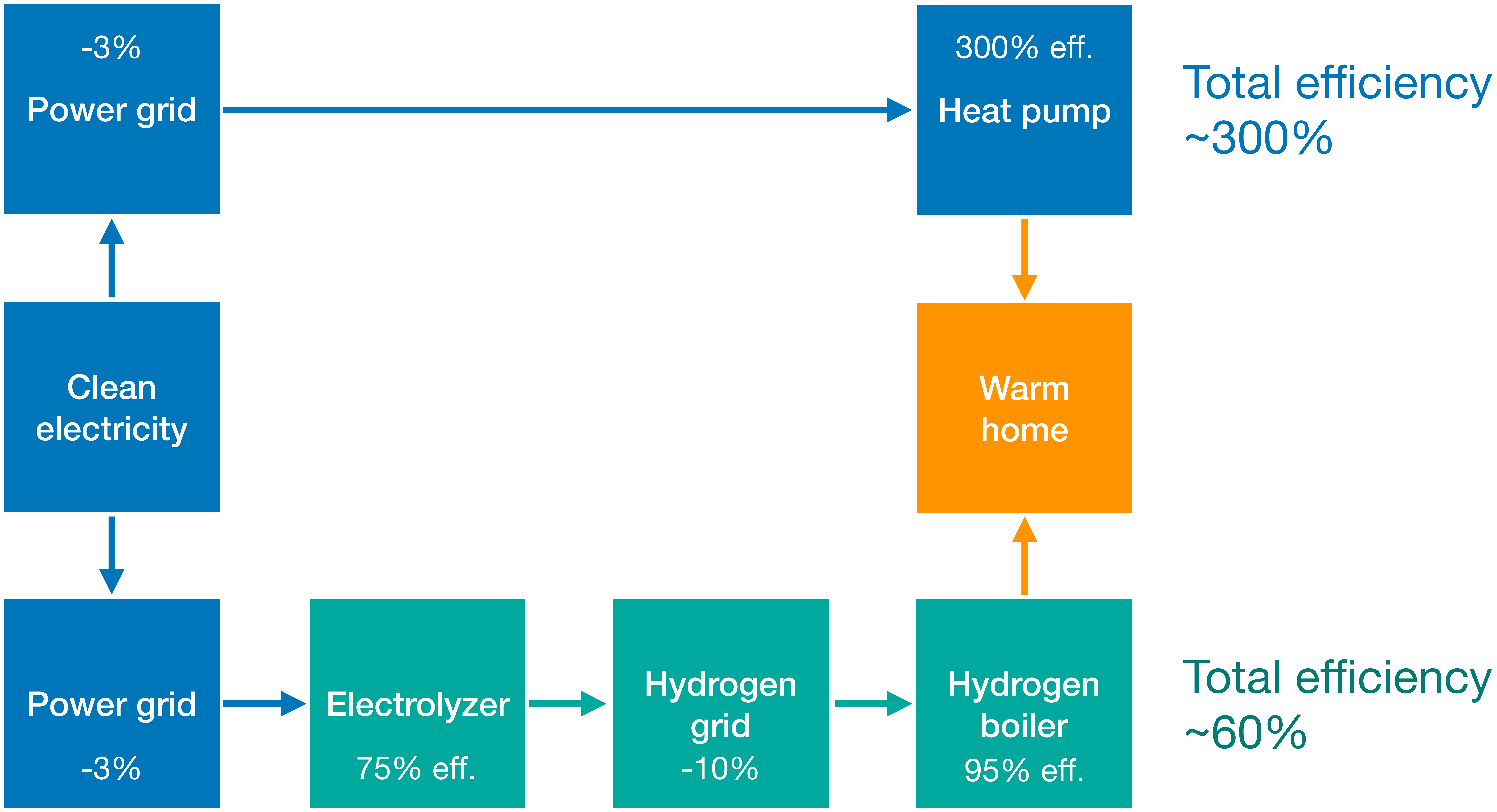
One hour → Will most likely remain batteries

Some possibilities:
Compressed air
Pumped hydro

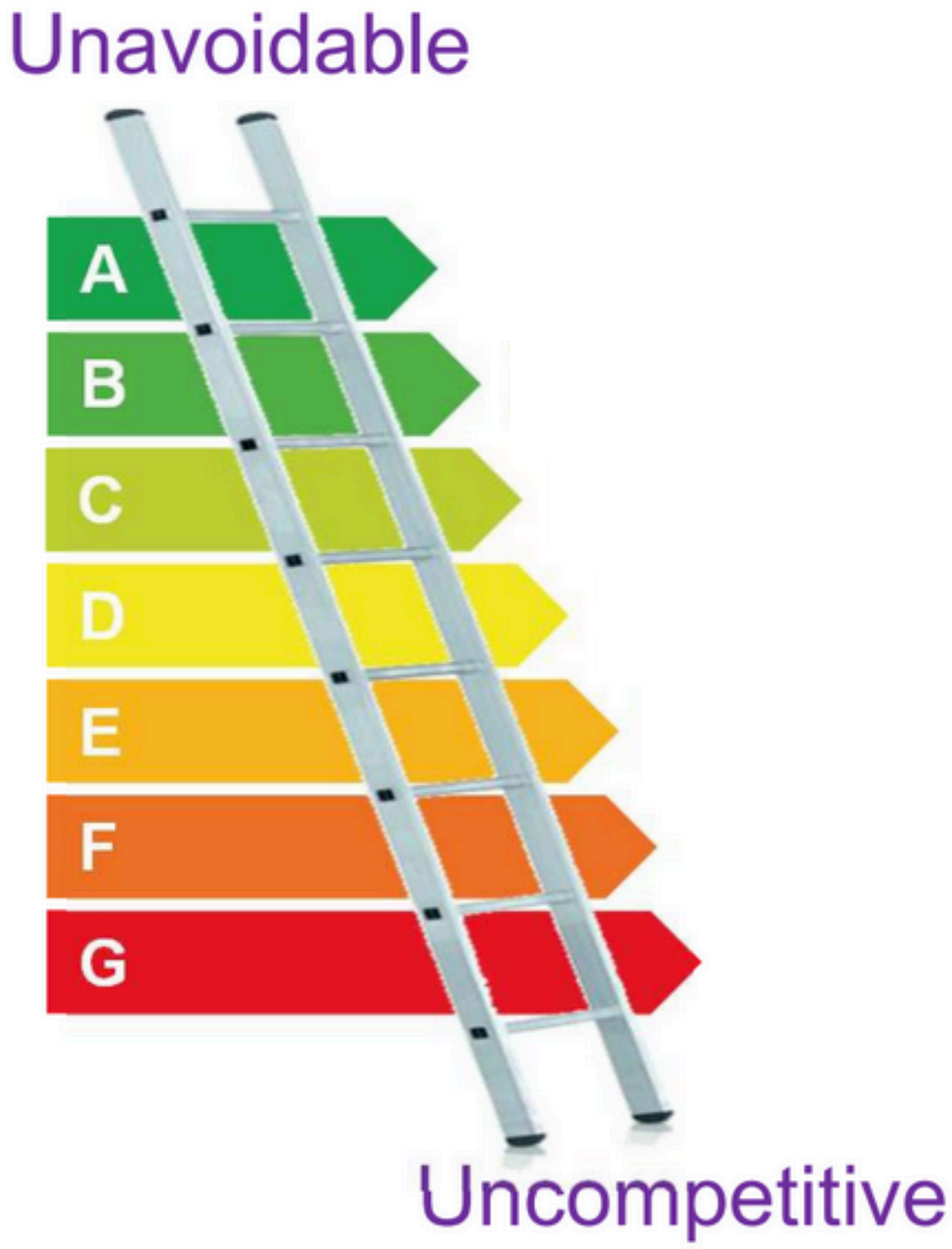
Estimation of cheapest storage technology in 2040

Data from Schmidt et al. (2019), https://doi.org/10.1016/j.joule.2018.12.008

The “hydrogen vs. electrification” debate

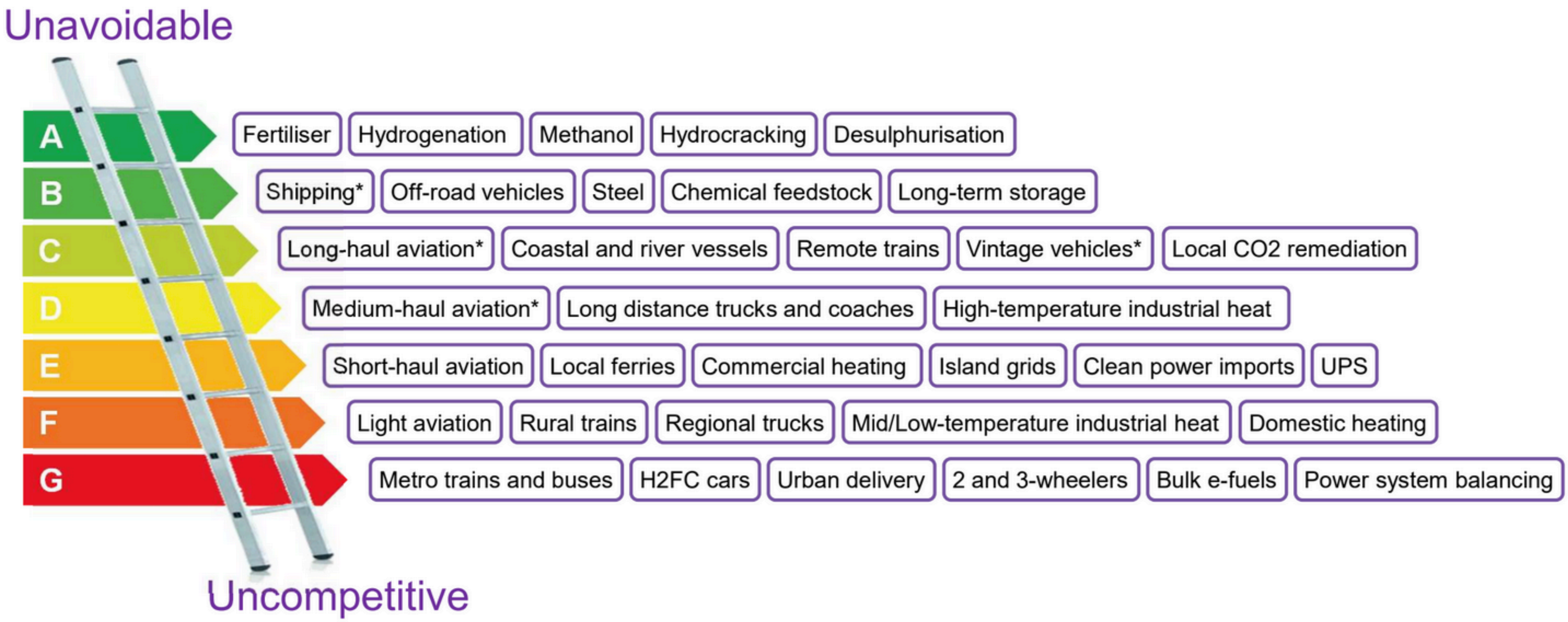


Liebreich's hydrogen ladder



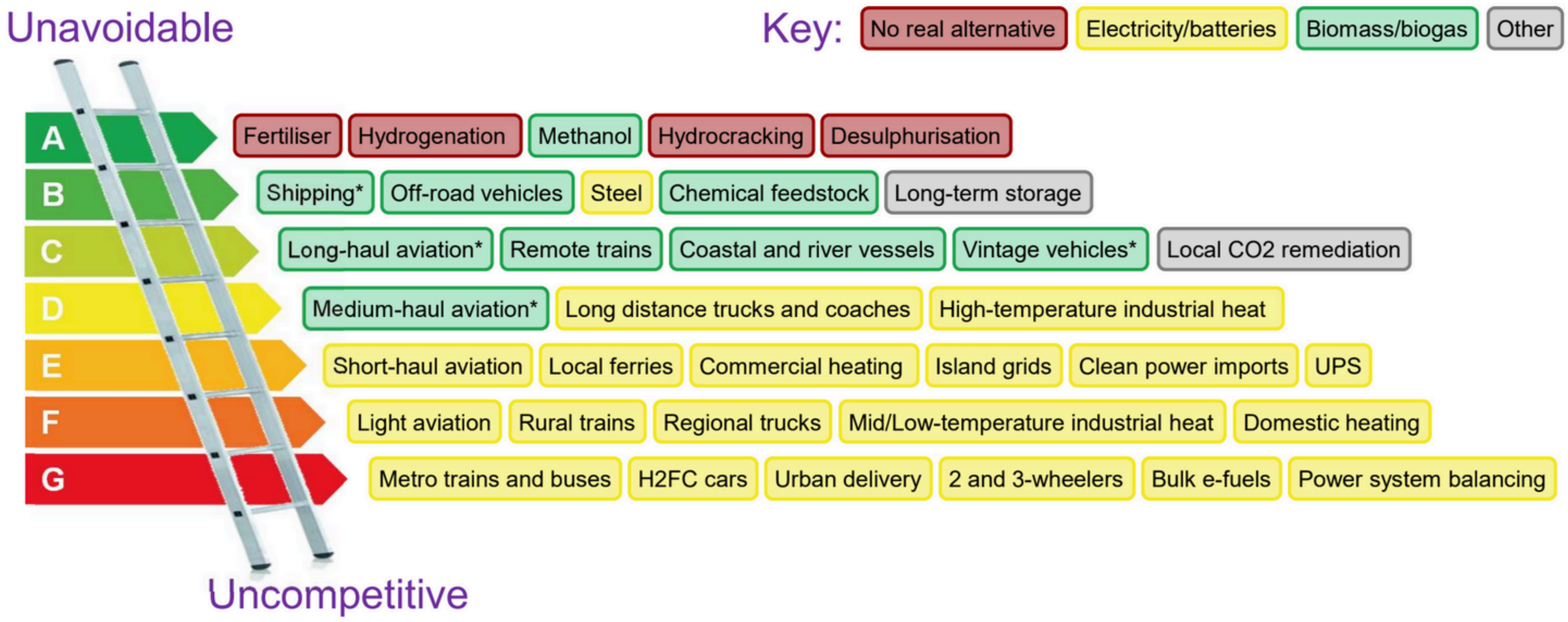
Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License
https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/

Liebreich’s hydrogen ladder



Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License
https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/

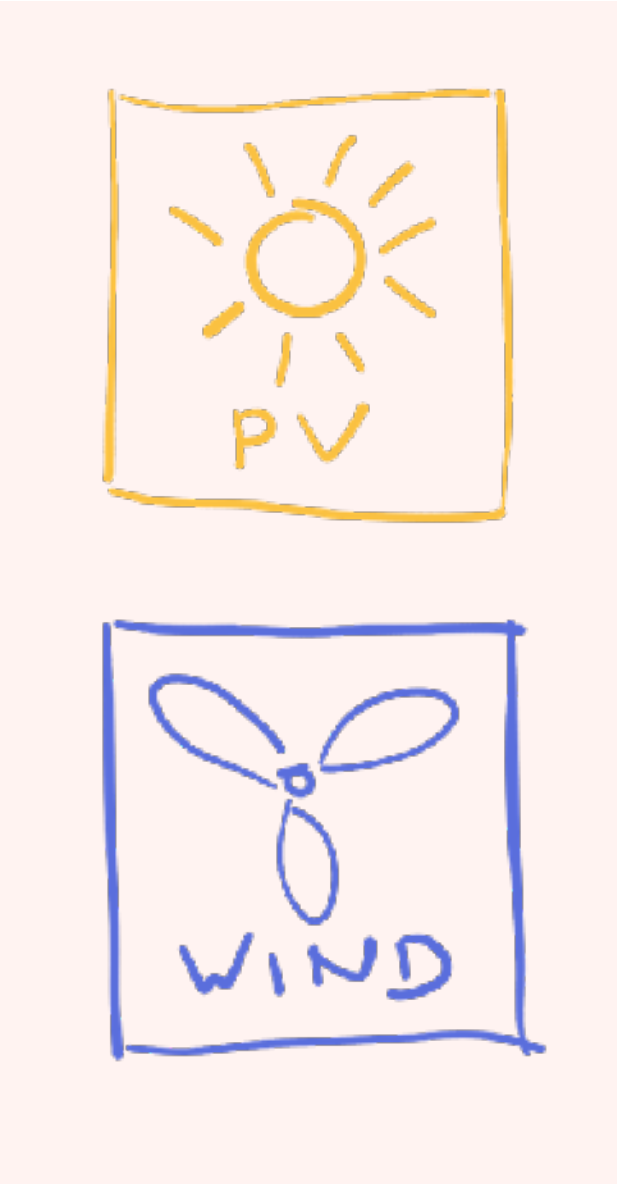
Most possible hydrogen applications have better alternatives



Source: Liebreich Associates; @mbliebreich; Re-used under Creative Commons Attribution 3.0 Unported License
https://www.liebreich.com/the-clean-hydrogen-ladder-now-updated-to-v4-1/

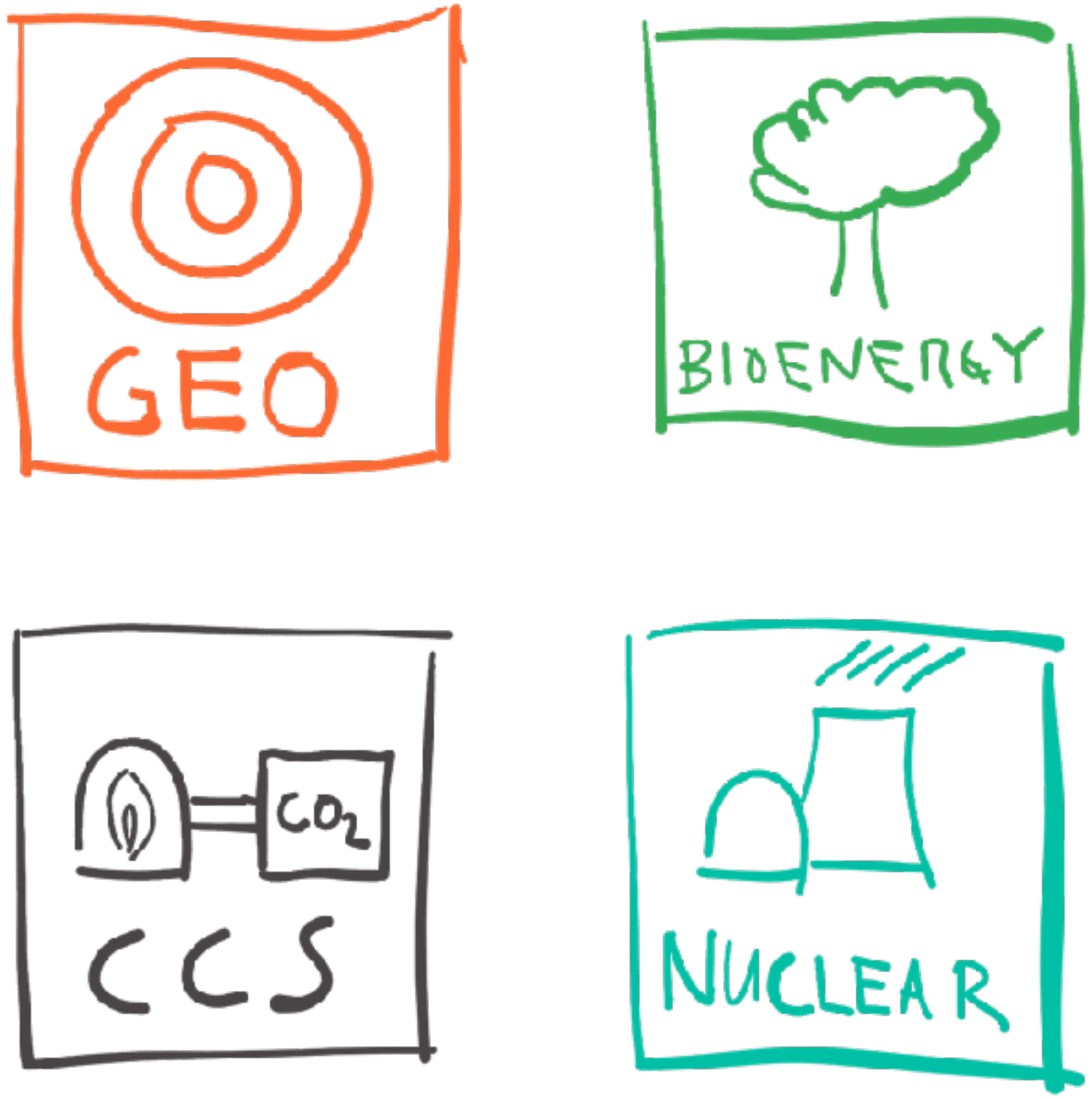
Flexibility: Balancing by adjusting demand

Flexible generators



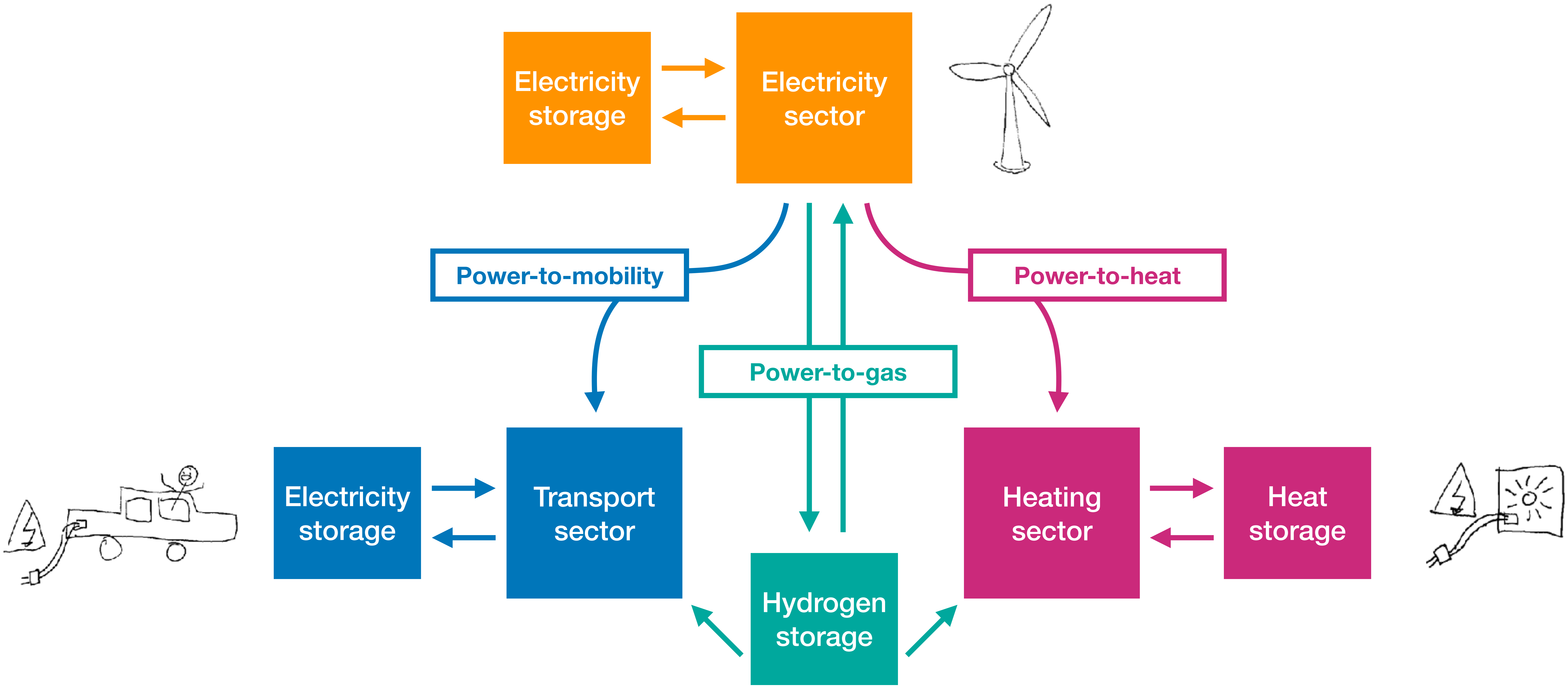
Very variable

Somewhat variable



Flexible

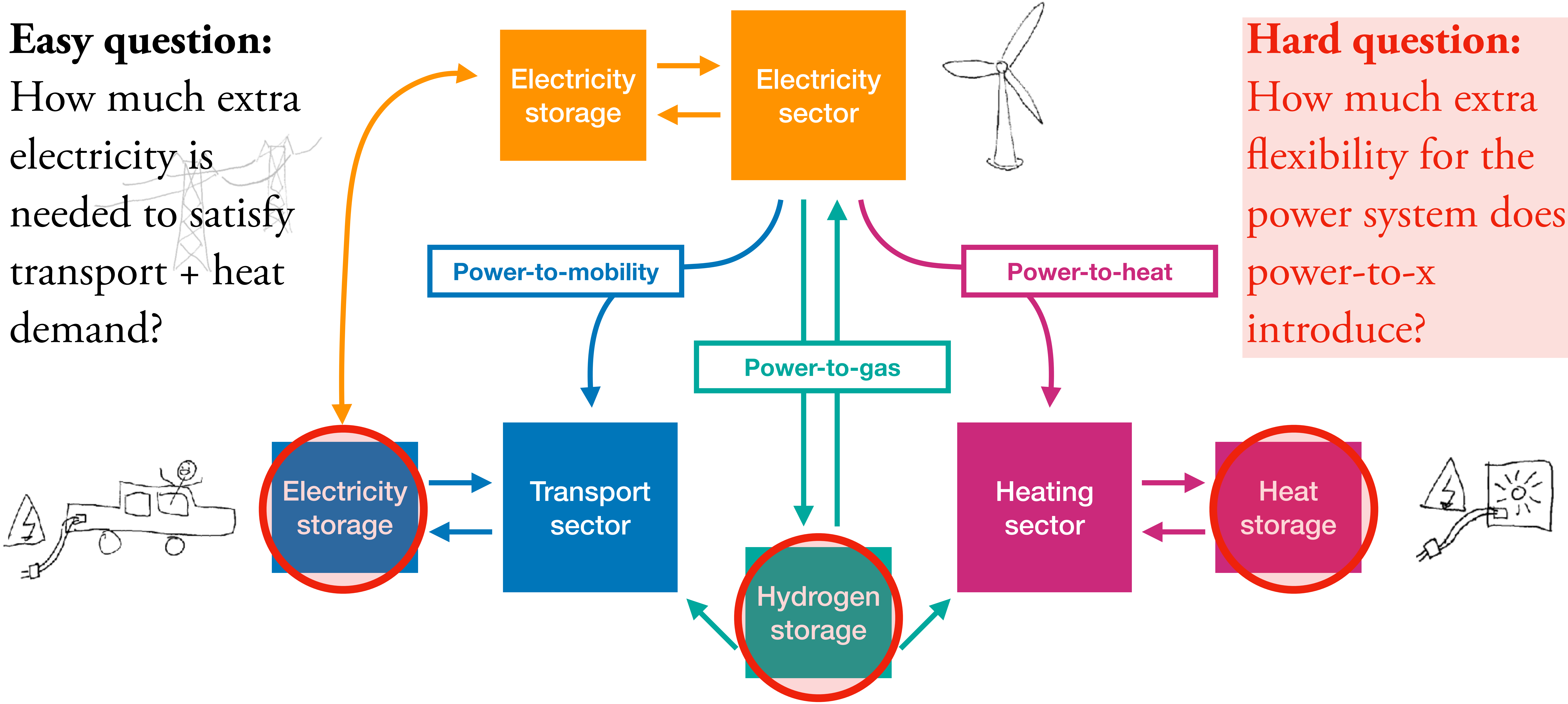
Sector coupling: transport + heat



Based on https://www.boell.de/en/2018/04/24/energy-atlas-graphics-and-license-terms?dimension1=ds_energyatlas, CC-BY licensed

More electricity demand — more flexibility?

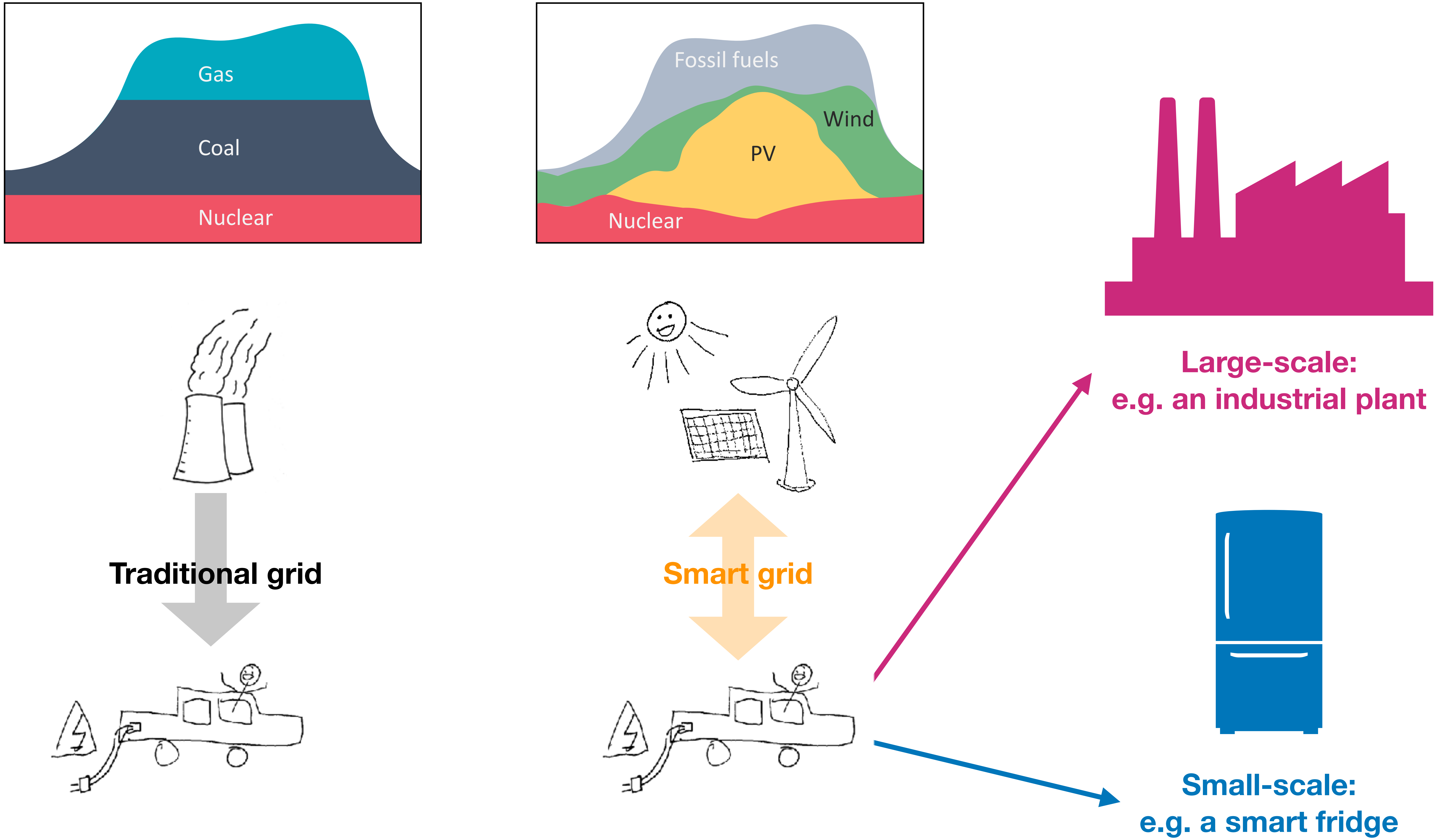
Easy question:
How much extra electricity is needed to satisfy transport + heat demand?



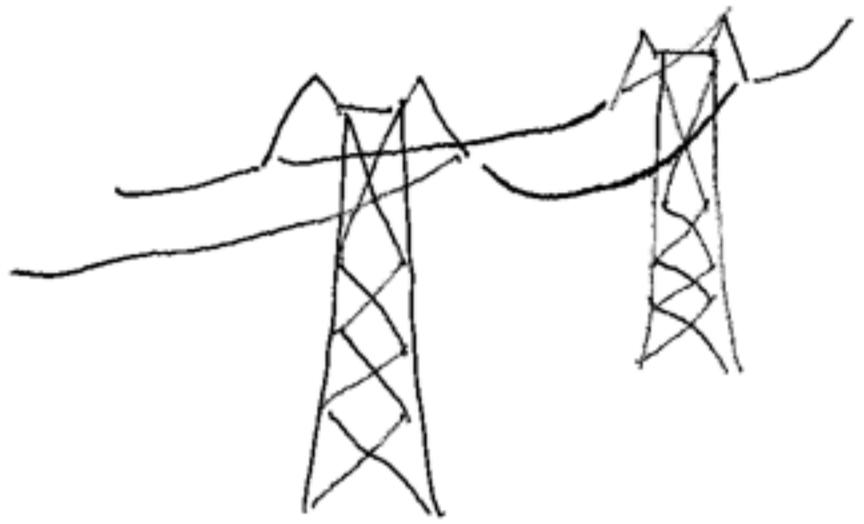
Hard question:
How much extra flexibility for the power system does power-to-x introduce?

Based on https://www.boell.de/en/2018/04/24/energy-atlas-graphics-and-license-terms?dimension1=ds_energyatlas, CC-BY licensed

Demand response: smart grid

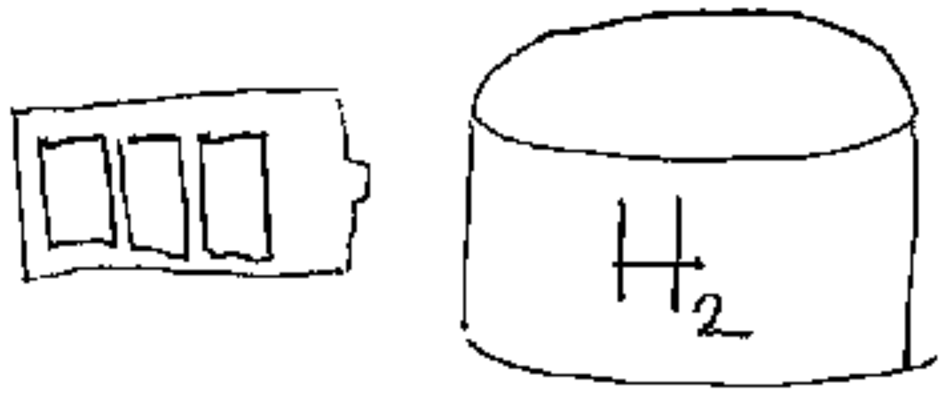


Summary



Grids

Balancing through space



Storage

Balancing through time

Flexibility

Balancing by adjusting demand

- No option alone can solve the challenge
- Short-term variability is basically solved (grids, batteries, flexibility) – long-term variability is harder: might be long-term storage with e.g. hydrogen?

1

Setting the stage:
Climate-neutral electricity

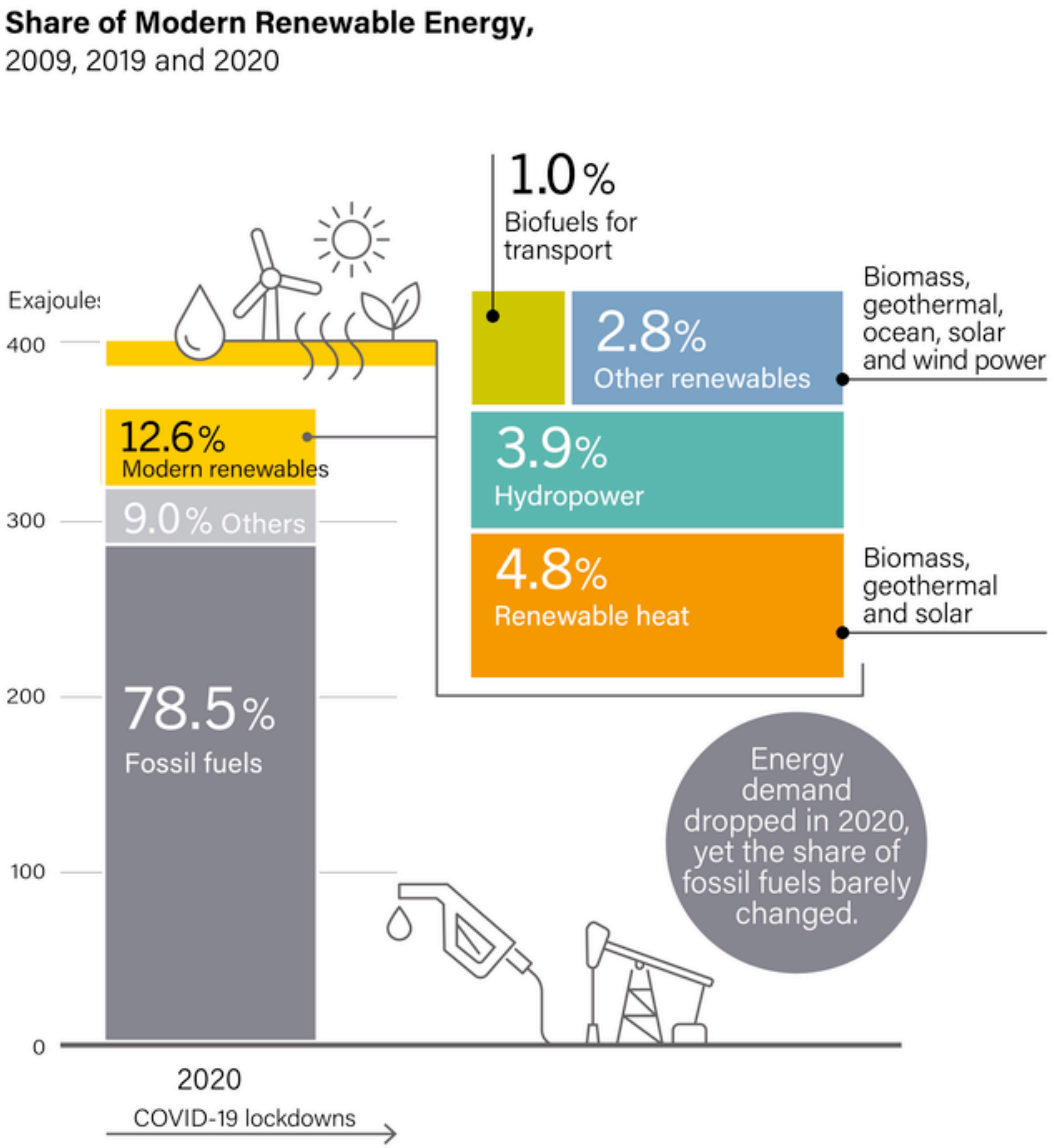
2

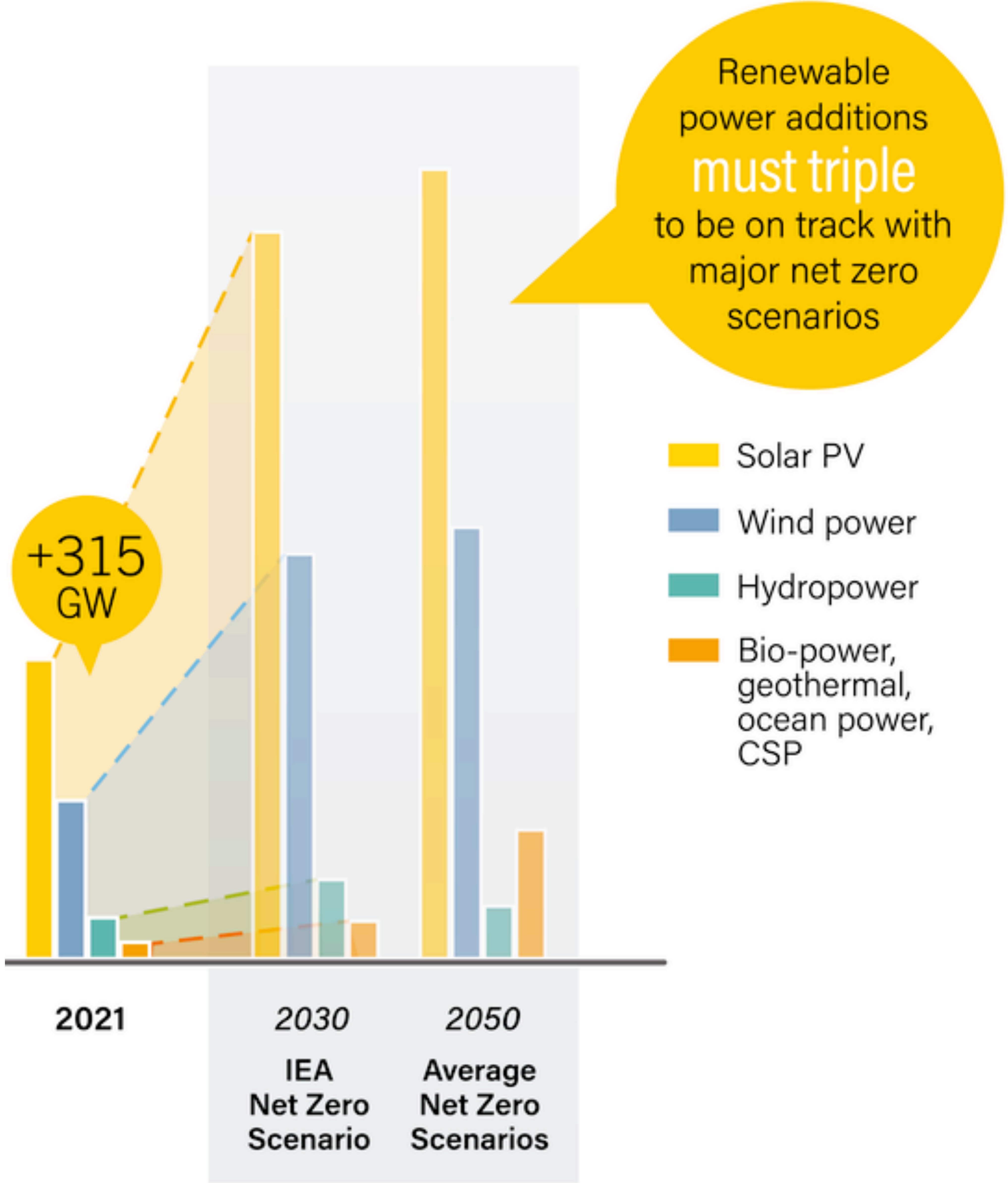
The problem of dealing with
variability, and possible solutions

3

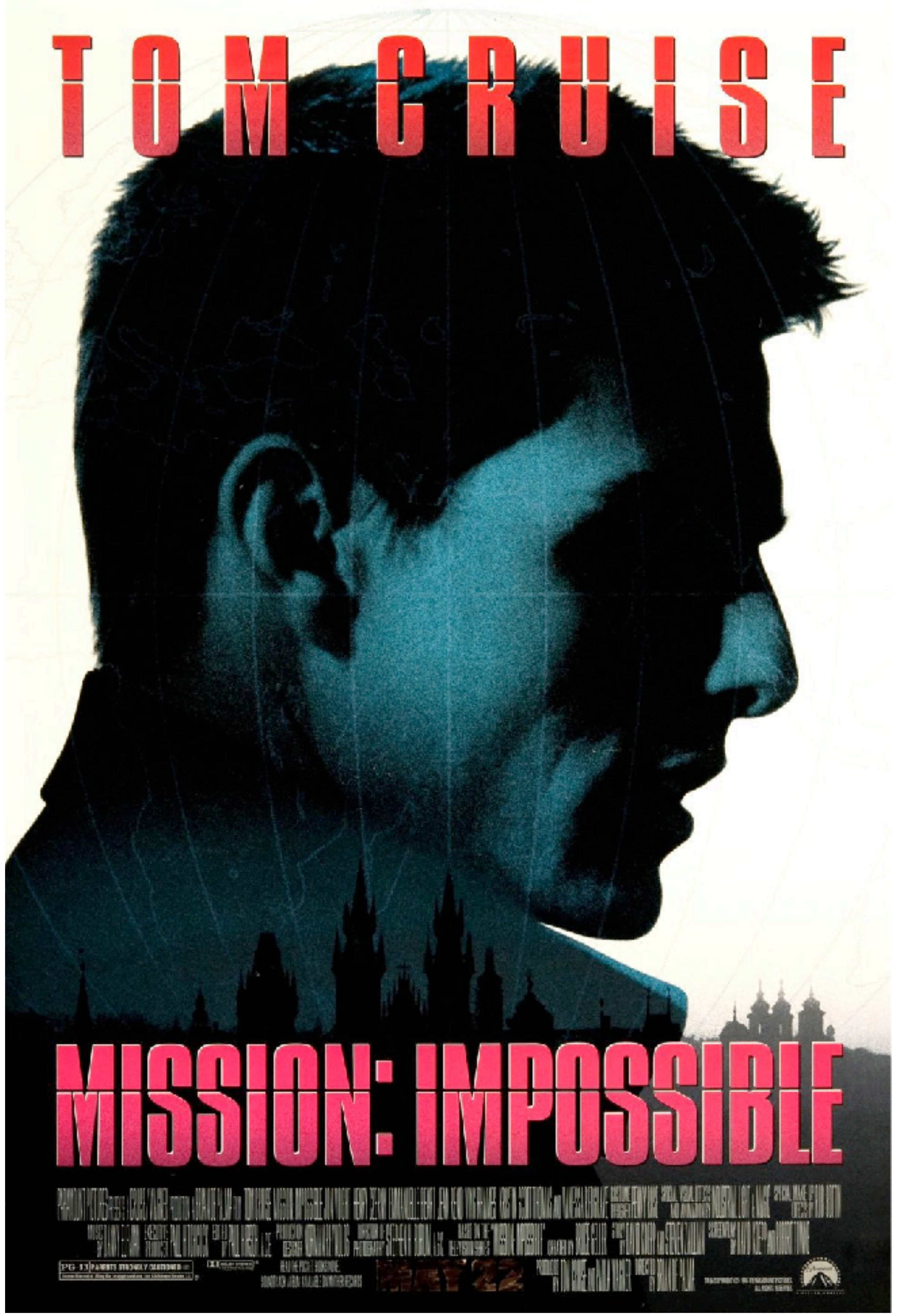
Combinations that work, and
how to make informed decisions

Massive capacity growth — but still far from being enough

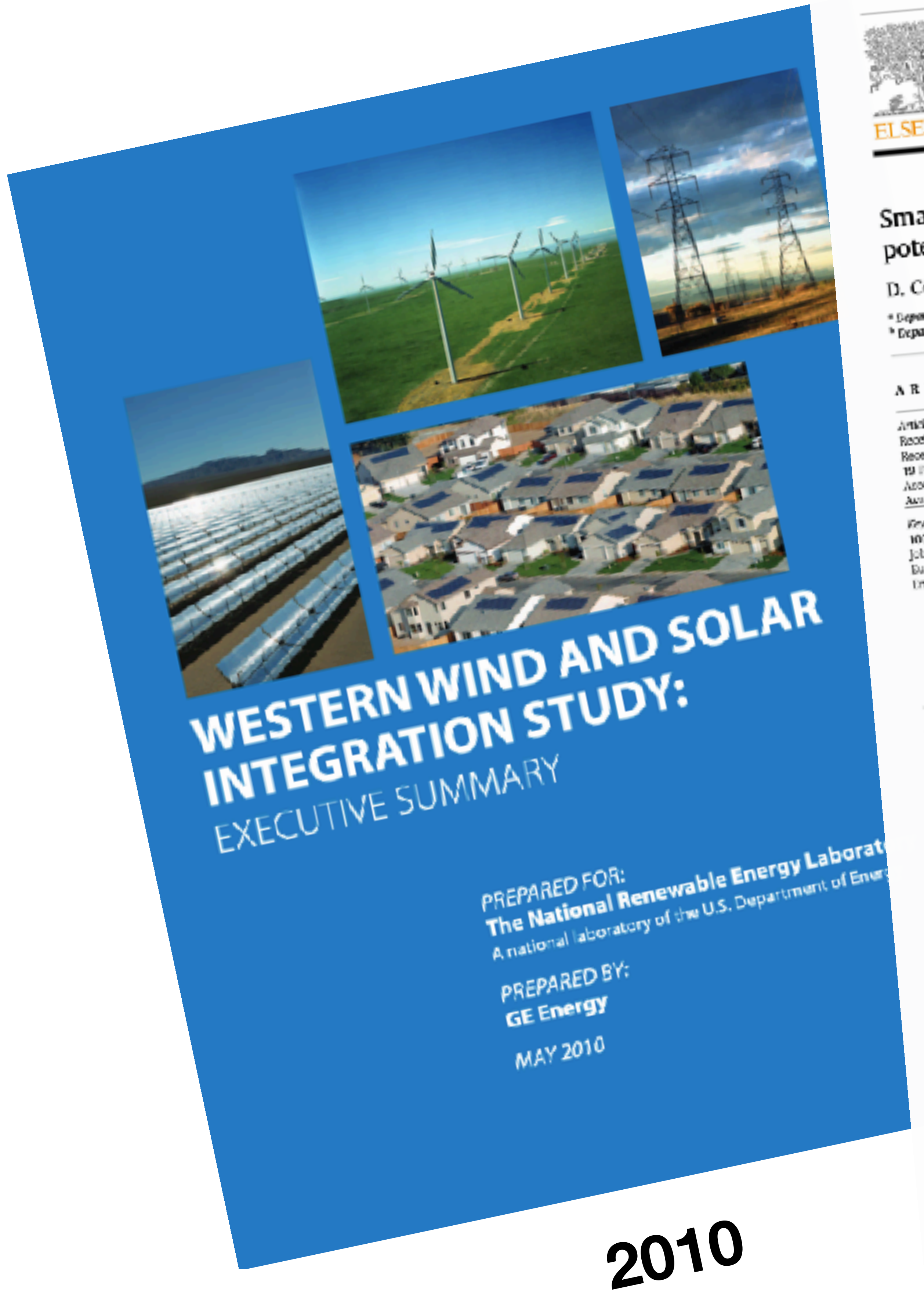




https://www.ren21.net/gsr-2022/chapters/chapter_01/chapter_01/


TOM CRUISE
MISSION: IMPOSSIBLE

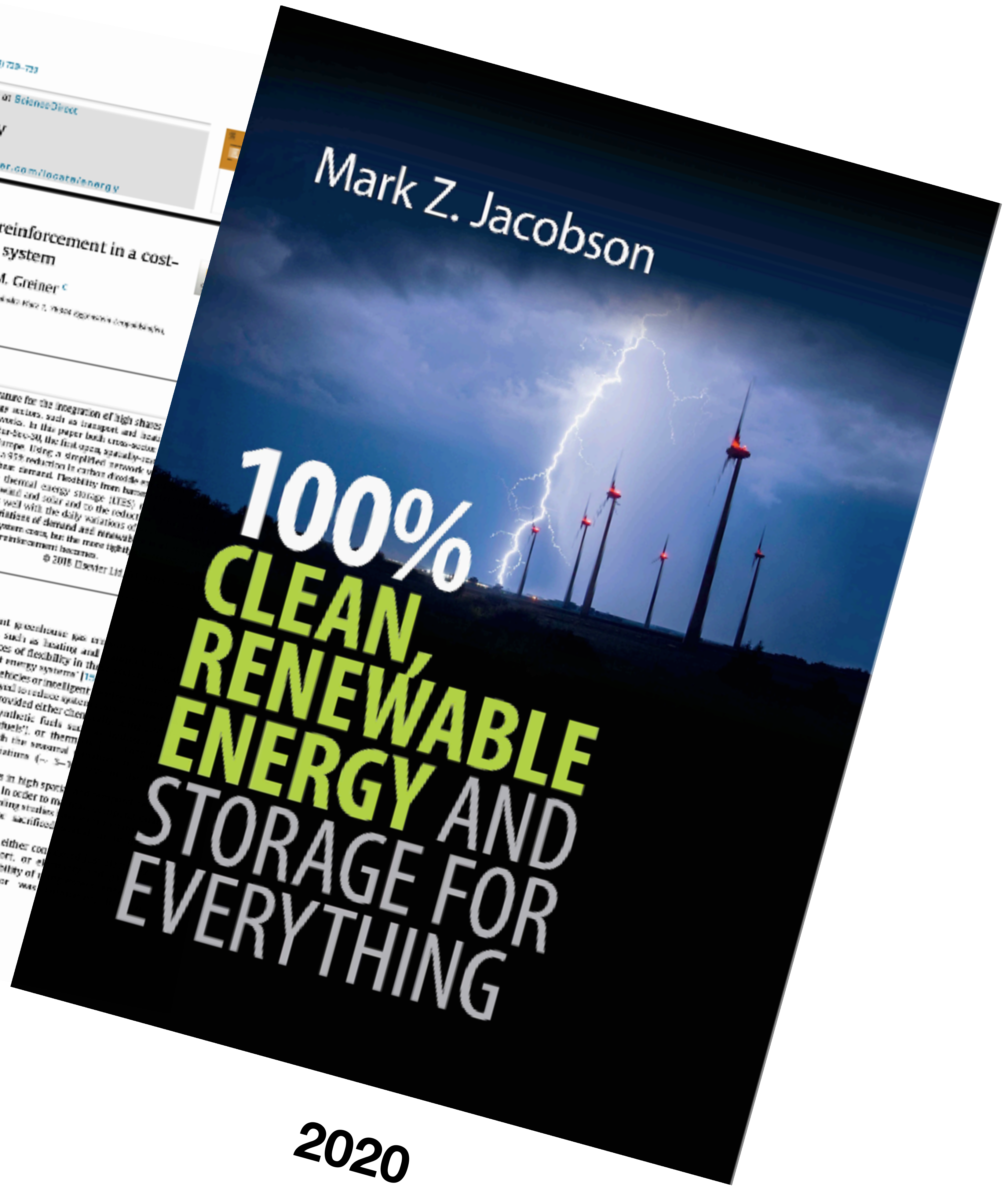
Is 100% renewable possible?



2010

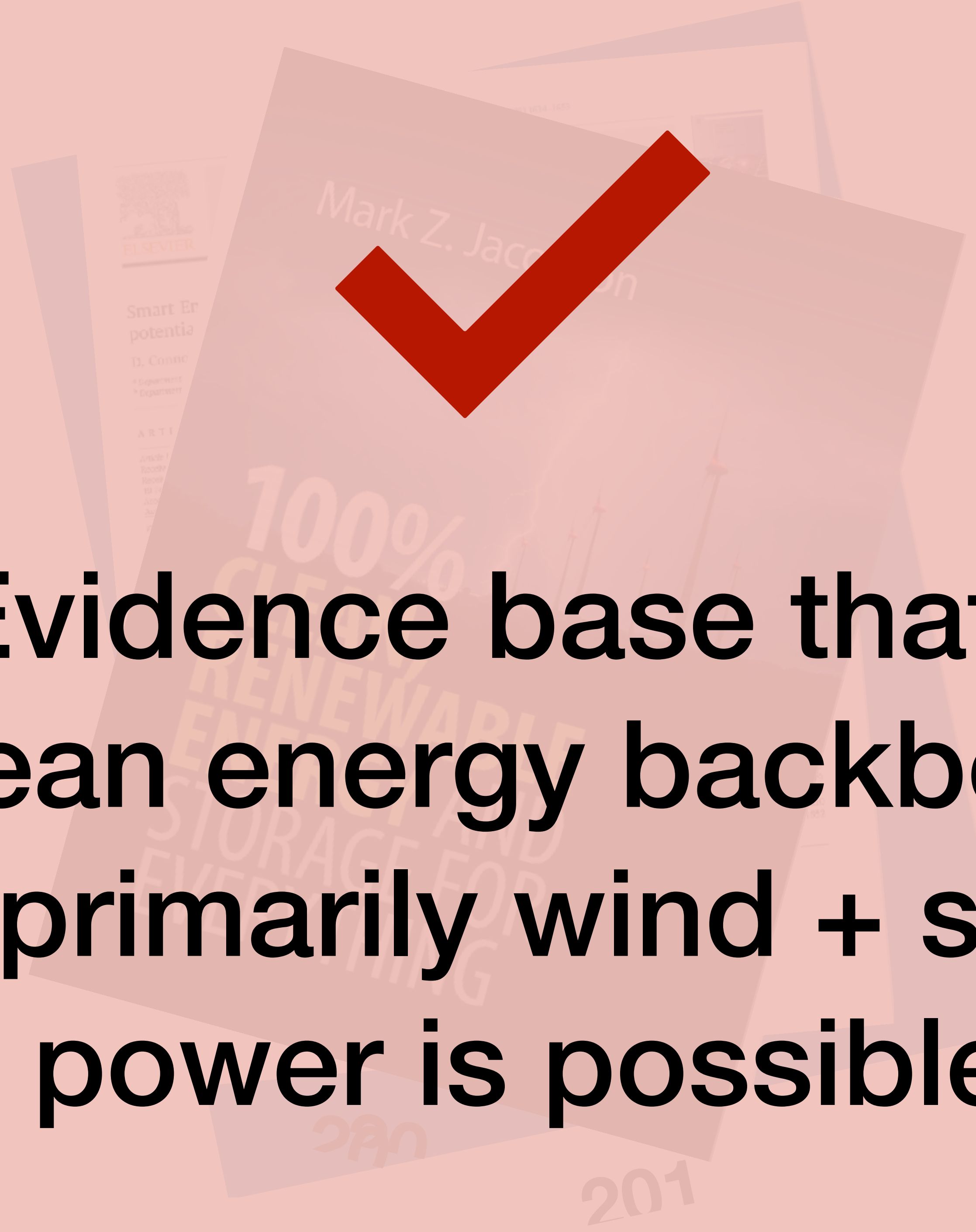
2016

2018



2020

Is 100% renewable possible?



Evidence base that a "clean energy backbone" of primarily wind + solar power is possible

?

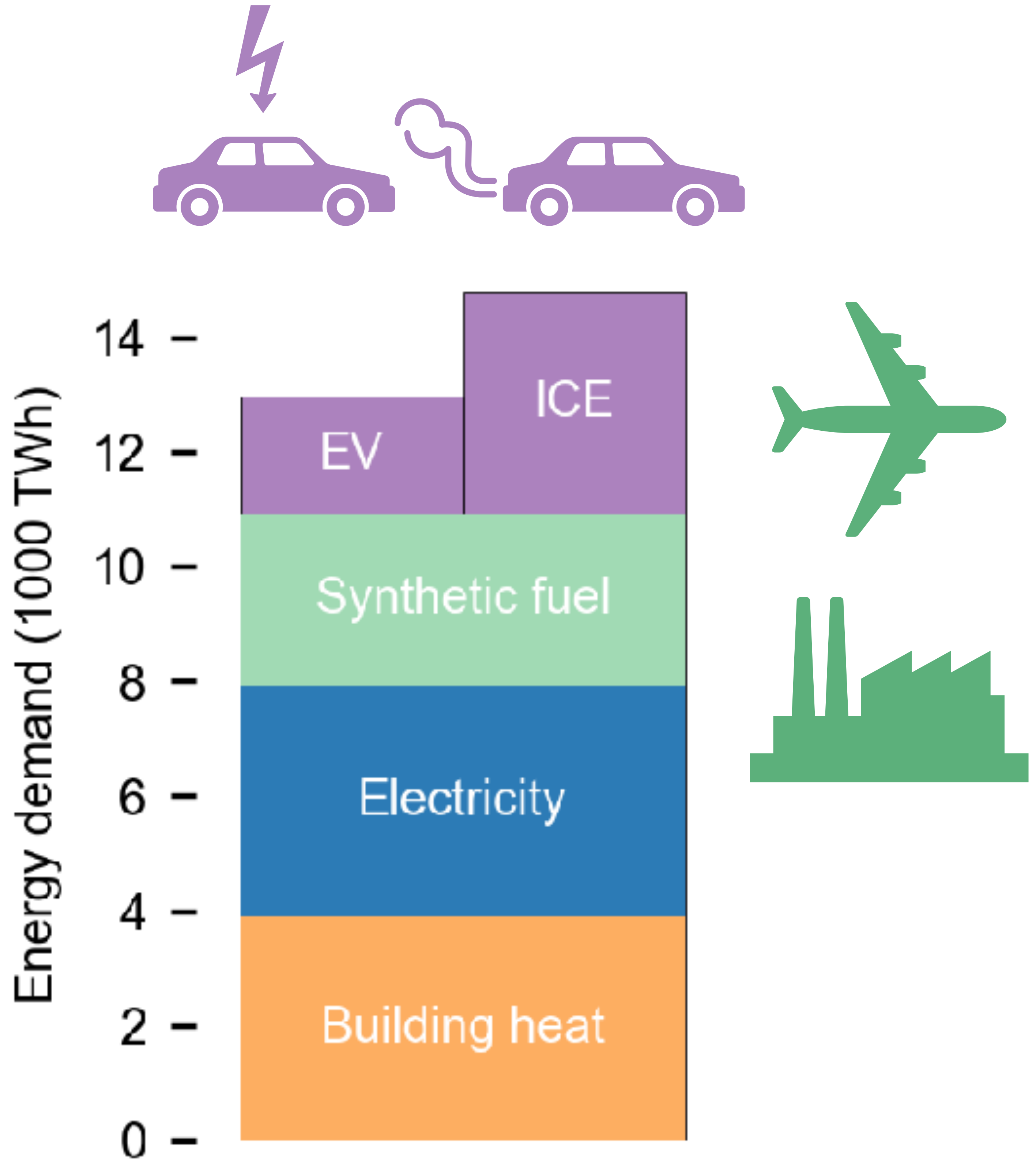
Pathways to implementing this while while navigating social, environmental, and other limits

Challenges: social, environmental, and other limits

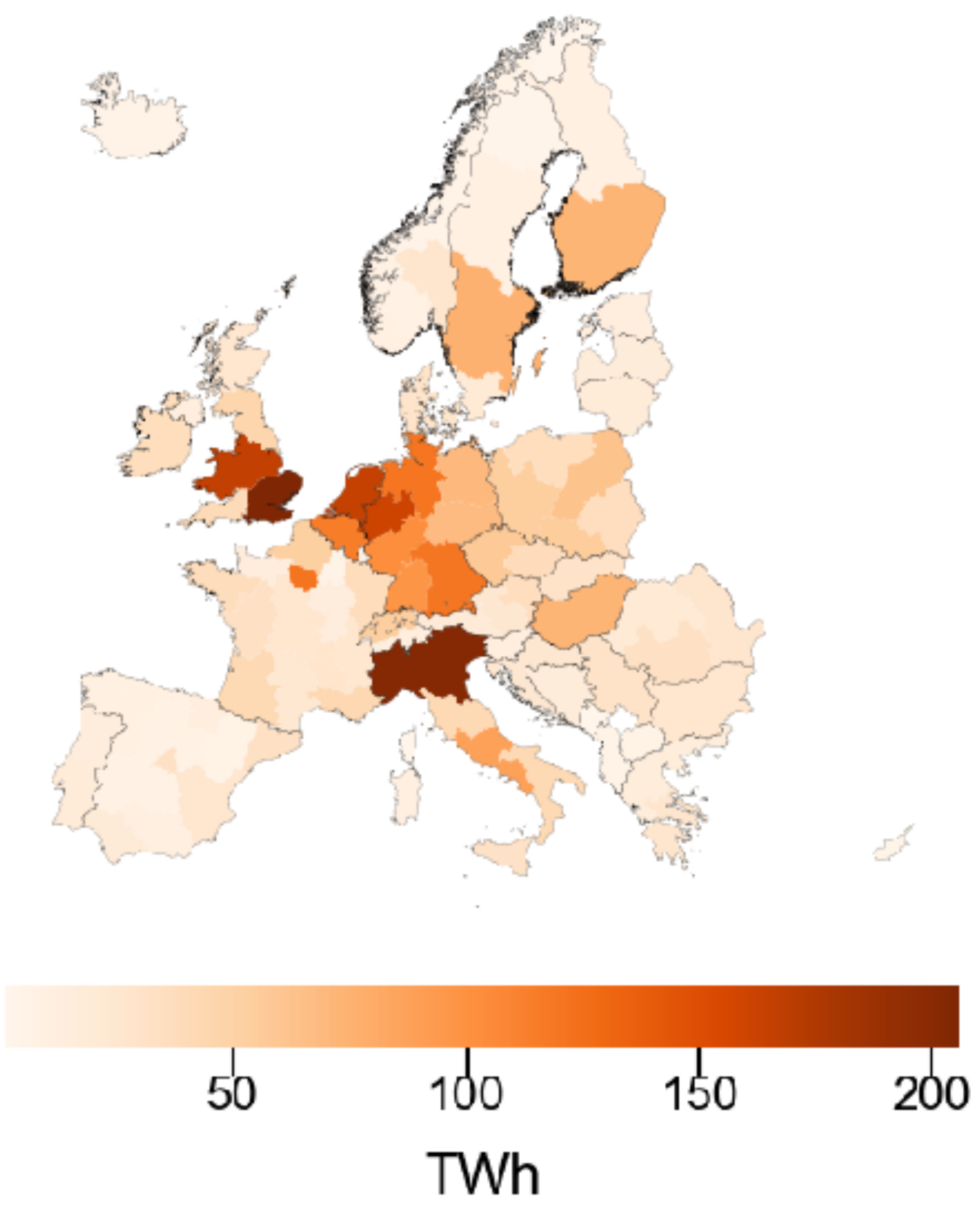
- Current EU-wide building renovation rate ~1% per year
- If 3% renovation rate from 2027, -77% to -100% EU space heating and cooling energy demand by 2060 possible

Chatterjee et al. (2022), https://doi.org/10.1007/978-3-030-99177-7_7

Example from my own research group

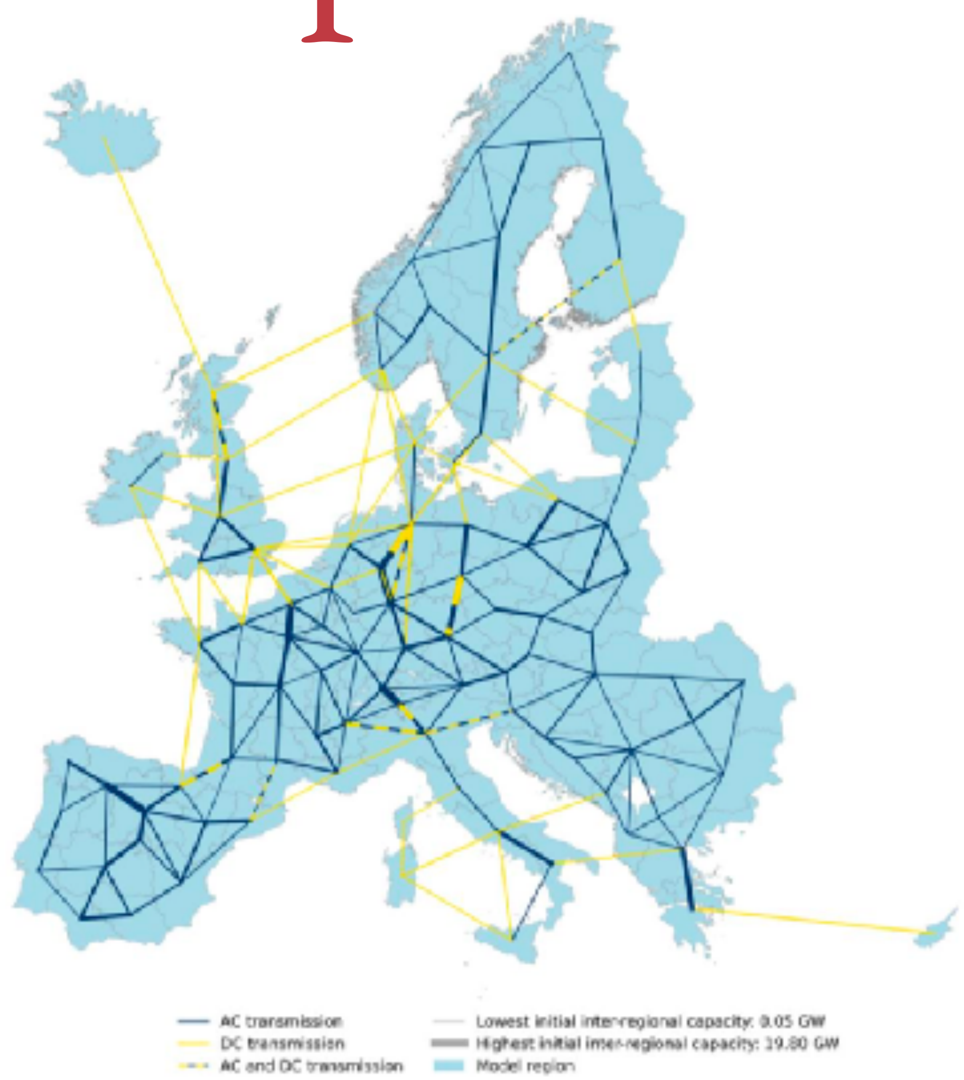


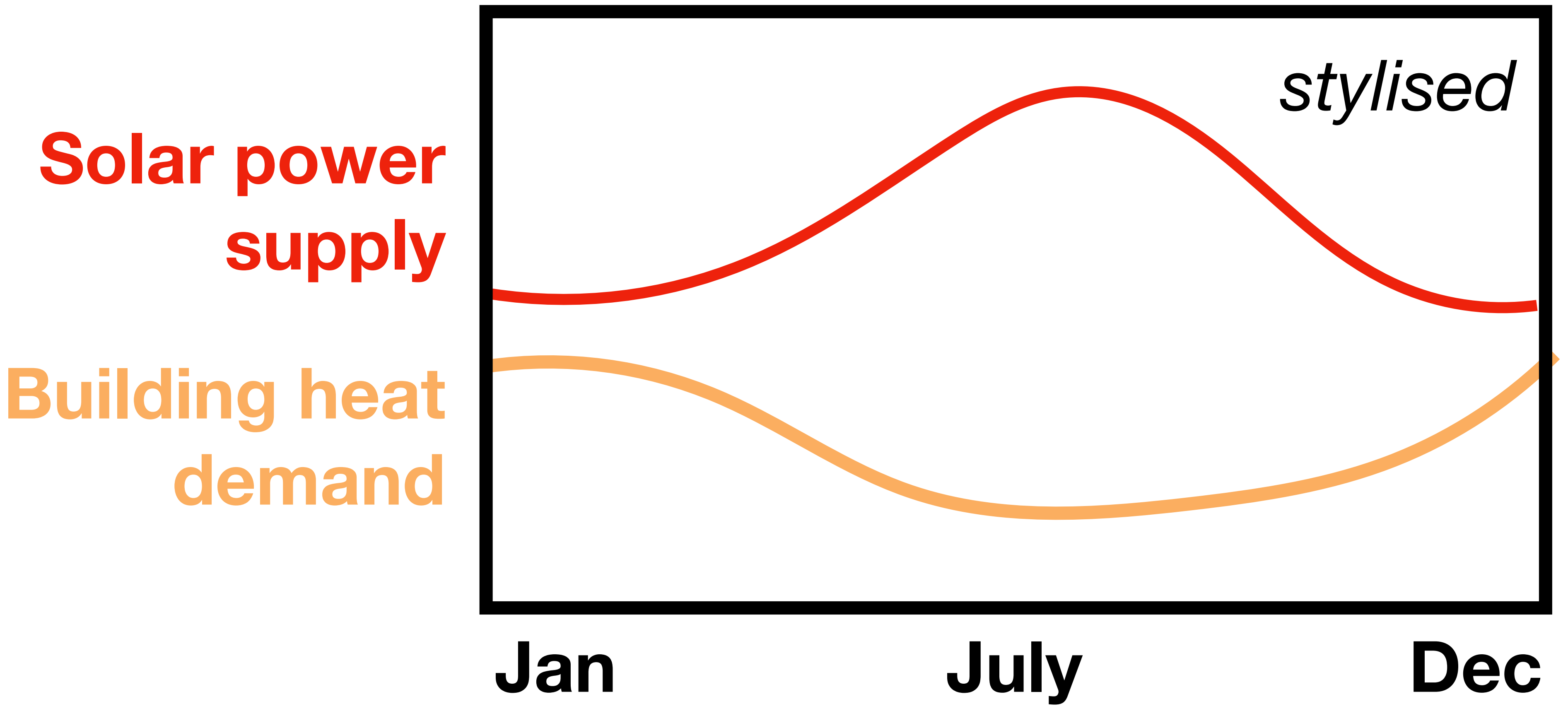
Demand for all energy in all sectors across Europe, + industrial feedstocks



Regional distribution of demand: e.g. building heat

Technologies for energy supply, conversion, transport, and their possible locations

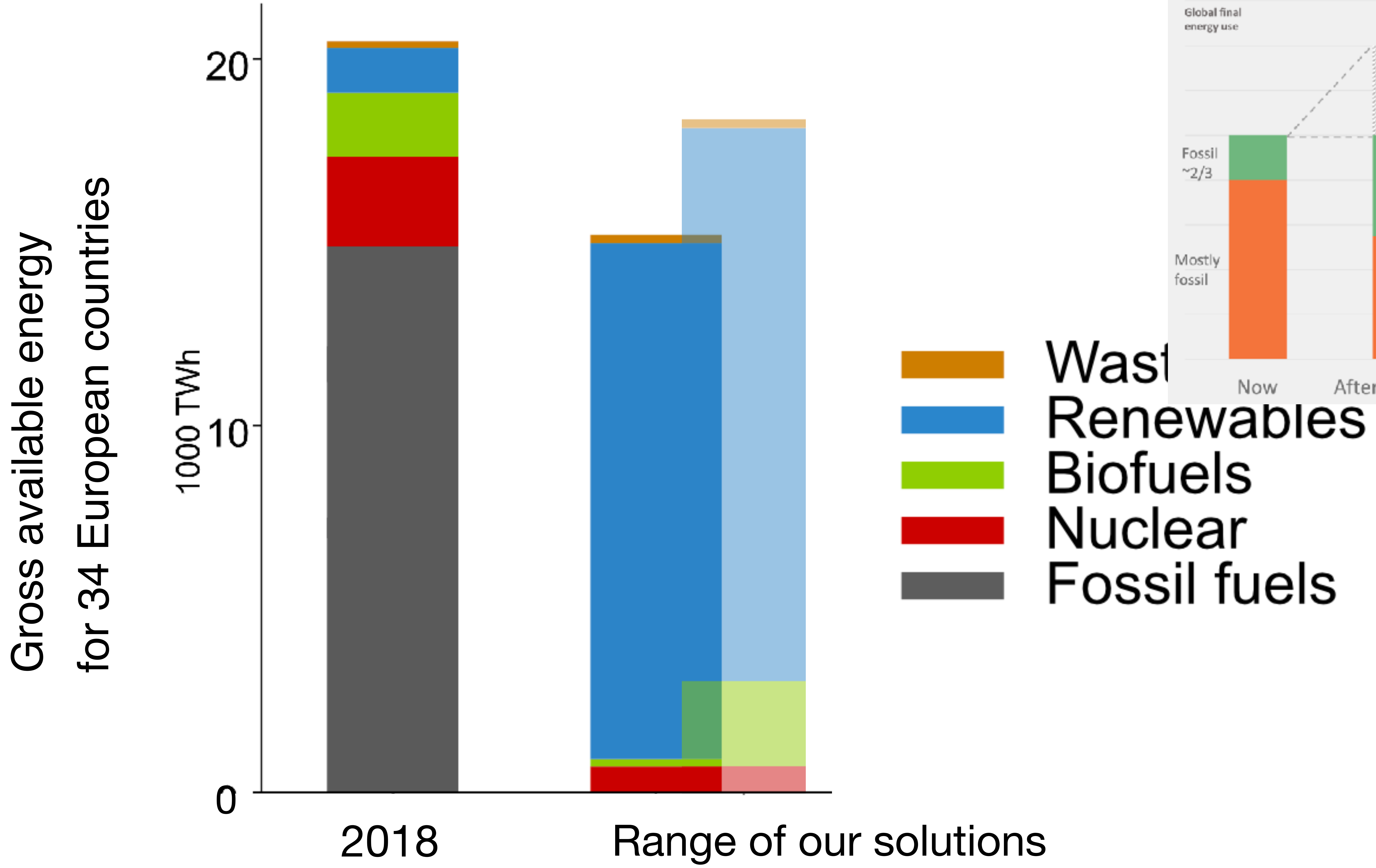




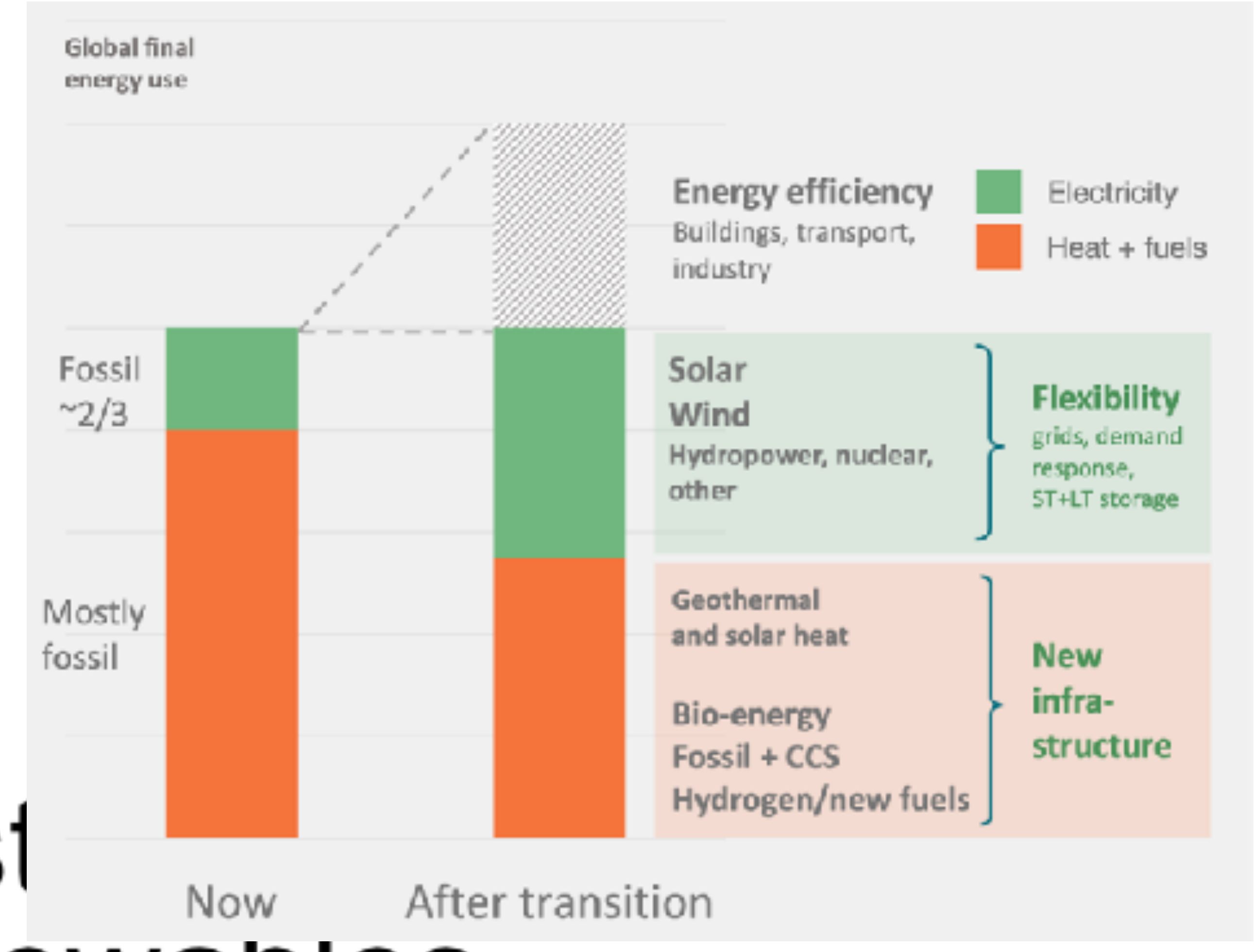
Time-varying (hourly) supply and demand

Pickering et al. (2022). *Joule*. https://doi.org/jbd7

European energy supply without imported fuels or electricity

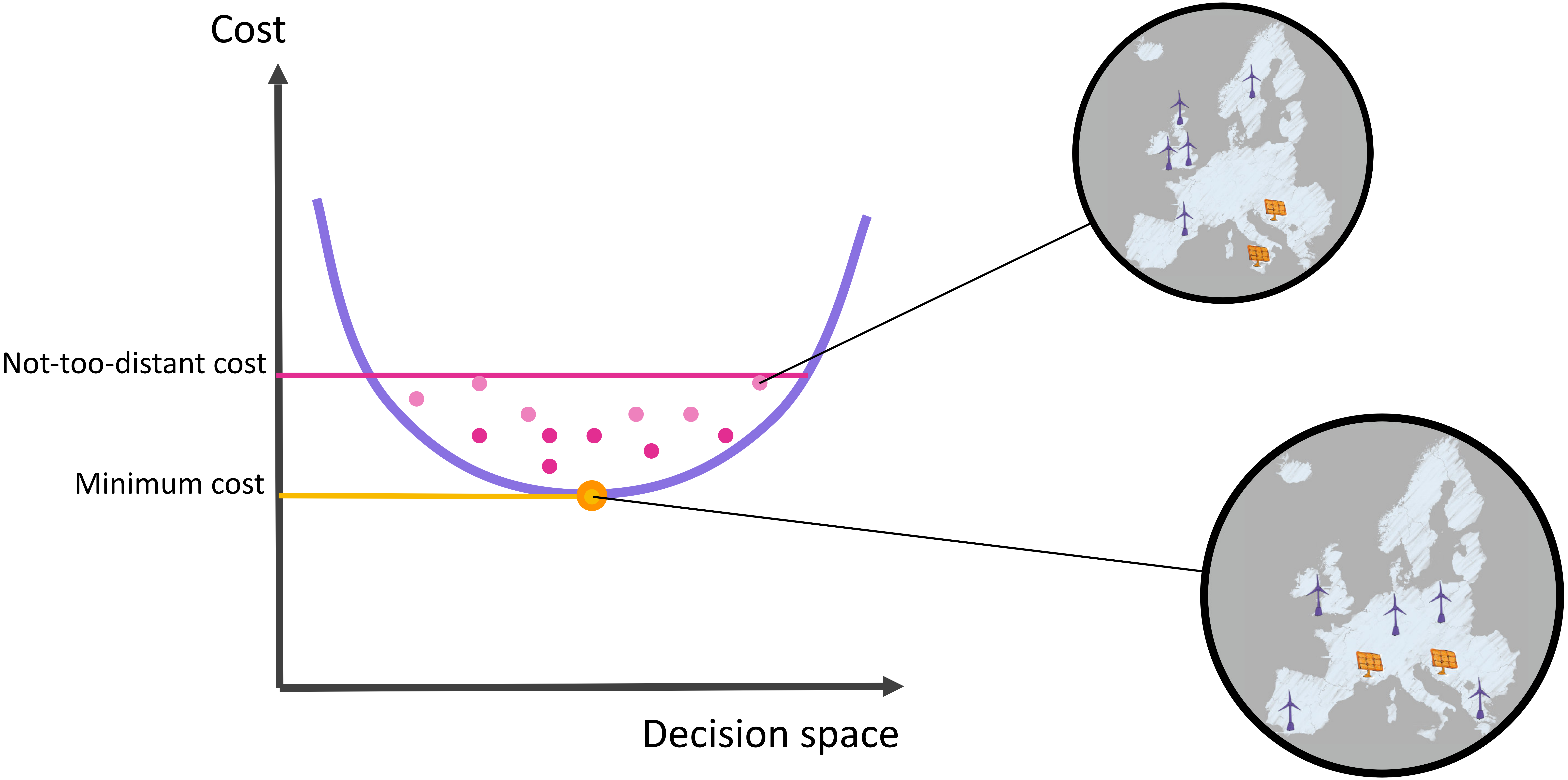


Not unlike Kornelis Blok's figure!



Pickering et al. (2022). *Joule*. https://doi.org/jbd7

SPORES: an algorithm for near-optimal results



Algorithm first published: Lombardi et al. (2020). *Joule*. https://doi.org/gg8z6v

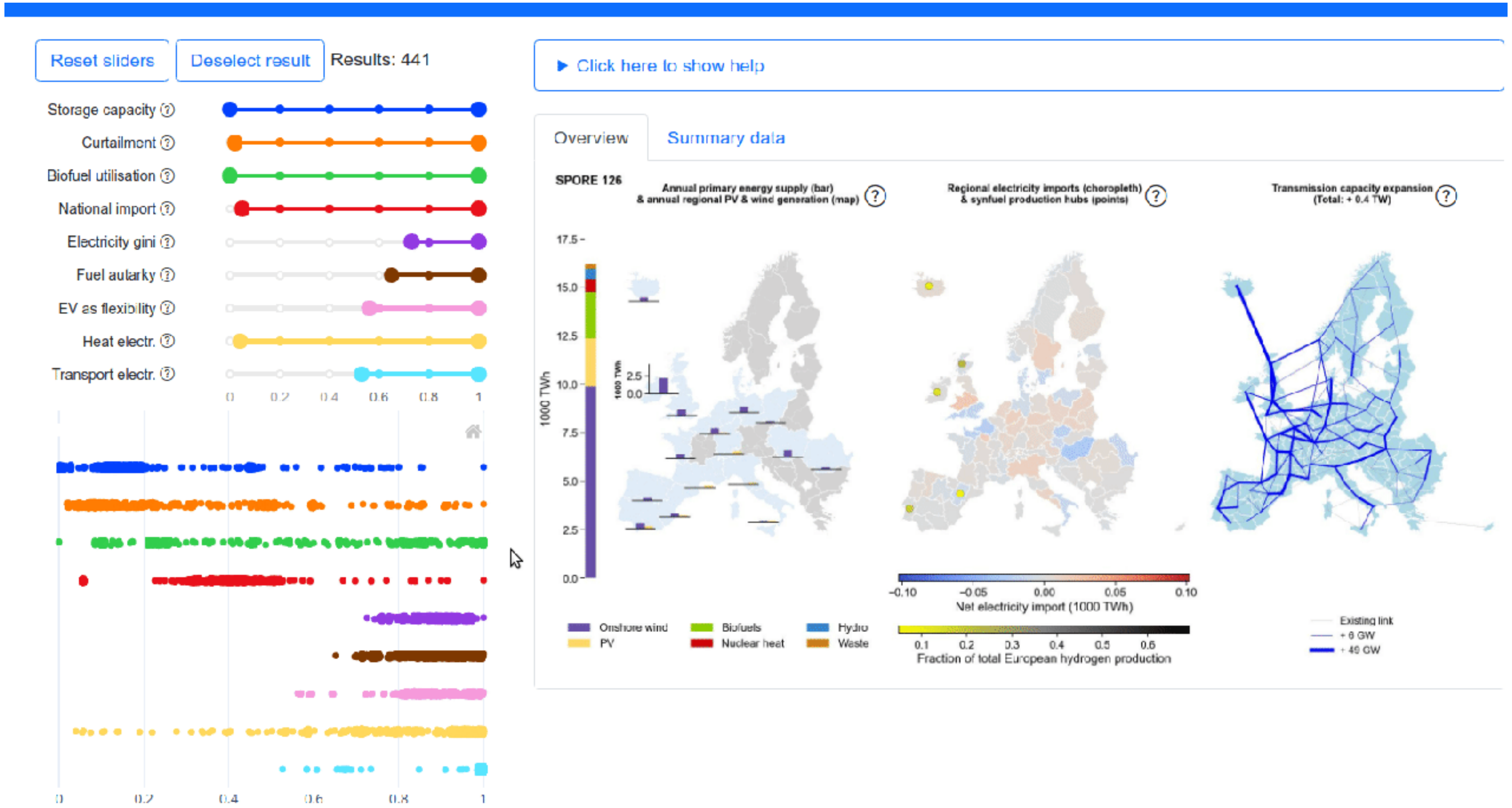
SPORE 376

https://explore.callio.pe/?spore-id::data=376

SPORE 341

Annual primary energy supply (bar)
& annual regional PV & wind generation (map)
Regional electricity imports (choropleth)
& synfuel production hubs (points)
Transmission capacity expansion
(Total: + 2.8 TW)
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
1000 TWh
2.5
0.0
1000 TWh
−0.10
−0.05
0.00
0.05
0.10
Net electricity import (1000 TWh)
0.1
0.2
0.3
0.4
0.5
0.6
Fraction of total European hydrogen production
Onshore wind
PV
Biofuels
Nuclear heat
Hydro
Waste
Offshore wind
Existing link
+ 6 GW
+ 49 GW

Almost anything is technically possible, but preferences restrict the spatial and technical maneouvering space



Explore the results: https://explore.callio.pe/

Summary

- Technically, almost anything is possible — but what is politically viable and how fast can the transition really be?
- Studies, reports, scenarios address such questions: often use least-cost optimisation models, and use assumptions that you might want to question.