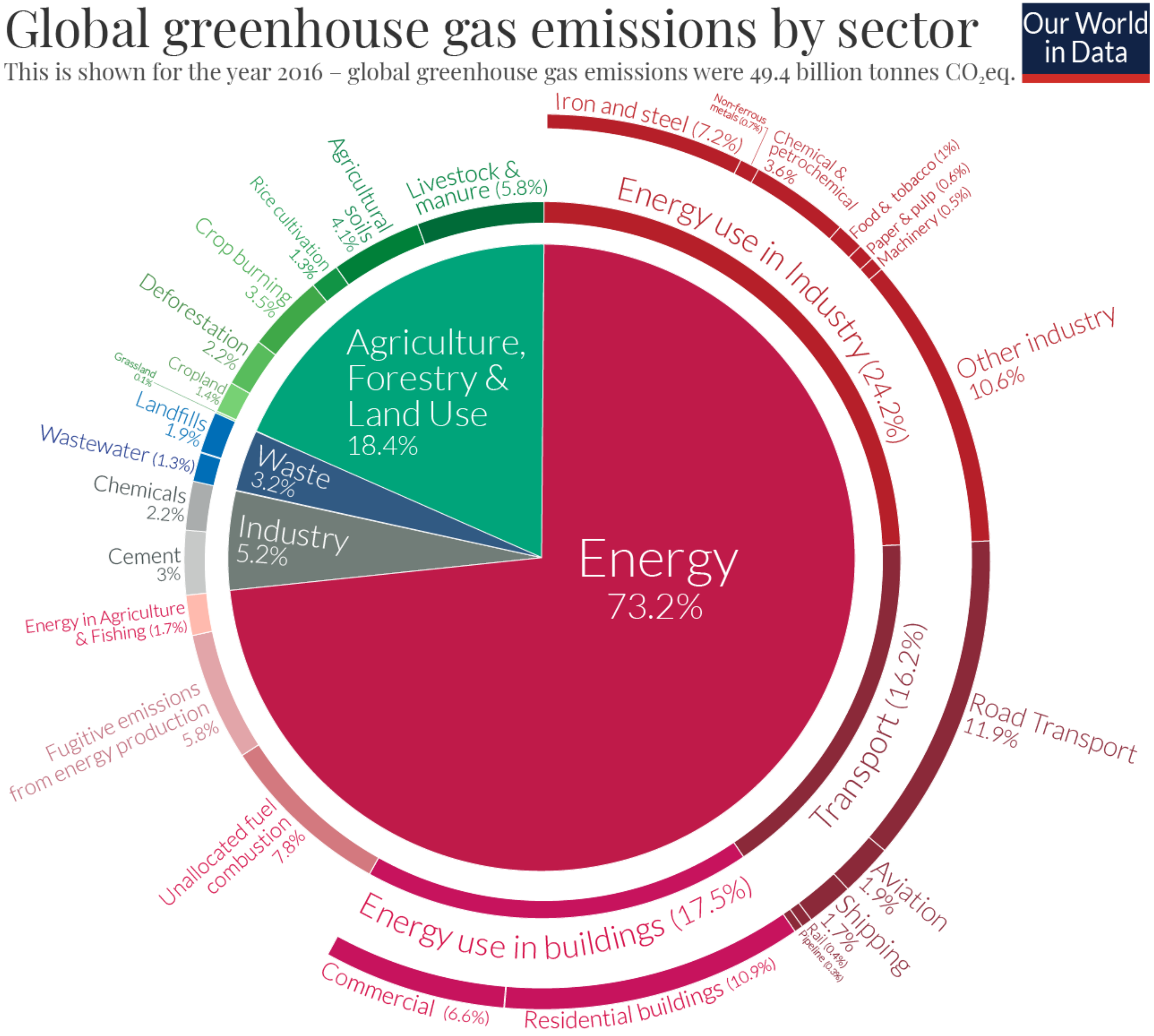
DTU

46770 Integrated energy grids

Marta Victoria

Lecture 11 – Multi-carrier energy systems I (heating and land transport)

The energy system comprises other sectors besides electricity, and they imply significant emissions



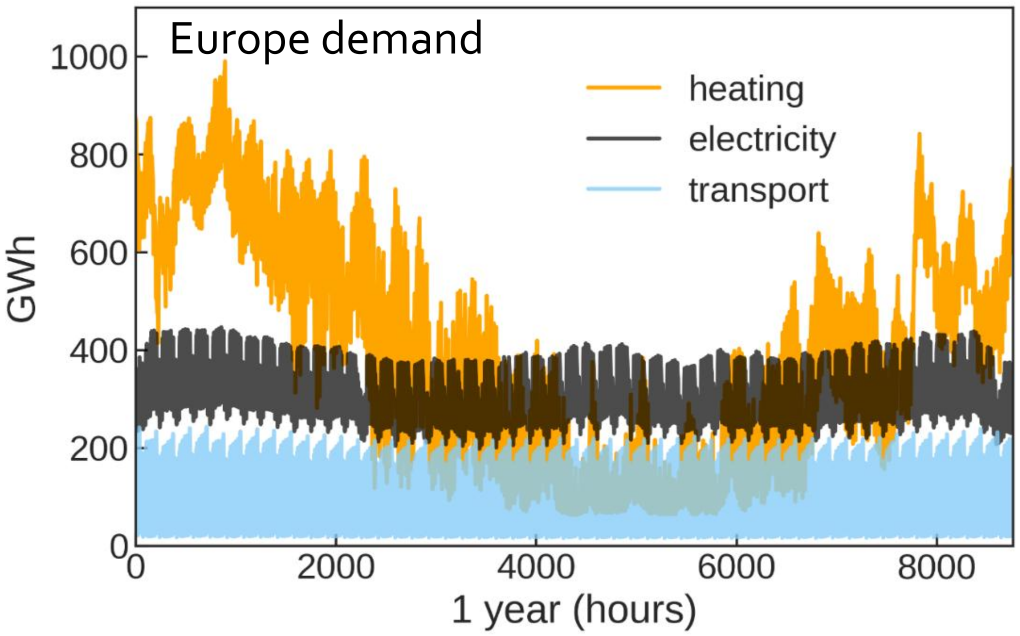
Learning goals

- Identify the main challenges and opportunities introduced by muti-carrier energy systems comprising power, heating and land transport
- Describe modelling approaches that can be used to represent heating/cooling demand and heating generation and storage technologies
- Describe modelling approaches that can be used to represent the electrification of land transport
- Calculate representative time series for heating, cooling and land transport demand
- Formulate optimization problems comprising power, heating and land transport sectors in the computer

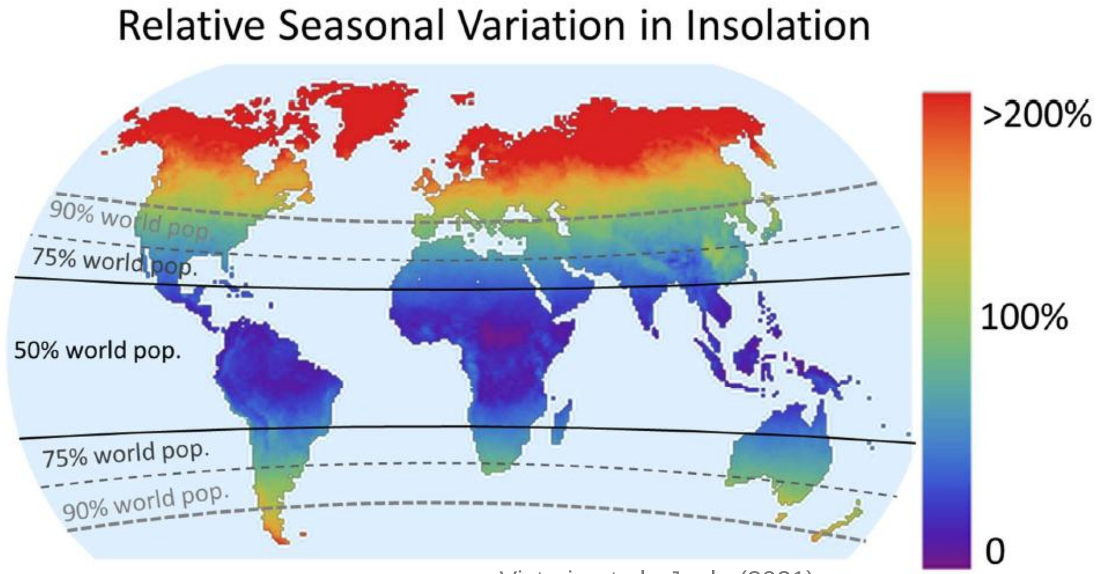
Modelling heating/cooling demand and flexibility

Heating and cooling

Challenge: In Northern latitudes, heating demand shows much higher seasonal variation than electricity or transport demand.



Opportunity: Most of the world's population lives in the Sun Belt close to the equator where the solar resource is abundant and seasonal variation is low



Victoria et al., Joule (2021)

Solar PV generation is synchronized with cooling demand ! Laine et al., Energy Environ. Sci.,2019

Zhu et al., Applied Energy, 2020.

How can we model heating demand?

Conversely to electricity, we don't have historical data on heating demand with hourly resolution.

The profile of heating/cooling demand can be estimated using population-weighted ambient temperature.

Heating Degree Days or

Heating Degree Hours (HDH)

$$HDH \begin{cases} 0 & if\ \ T_{amb} > T_{threshold} \\ (T_{threshold} - T_{amb}) & if\ \ T_{amb} < T_{threshold} \end{cases}$$

$T_{threshold}$ ≈17ºC

Cooling Degree Days or

Cooling Degree Hours (CDH)

$$CDH \begin{cases} (T_{amb} - T_{threshold}) & if\ T_{amb} > T_{threshold} \\ 0 & if\ T_{amb} < T_{threshold} \end{cases}$$

$T_{threshold}$ ≈ 25ºC

The time series is then scaled based on the annual heating demand (for which we have historical data)

$$heating\ demand(t) = scale\ factor \cdot HDH(t) + hot\ water\ demand$$

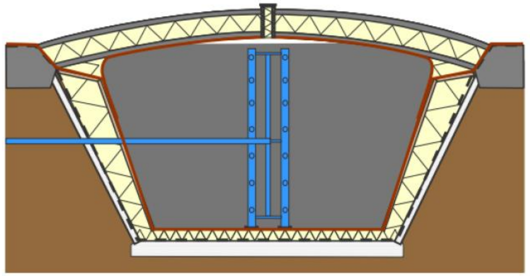
$$cooling\ demand(t) = scale\ factor \cdot CDH(t)$$

Central vs individual solutions

Centralized systems

- Feasible for regions with high population density
- We need to model heat networks
- Technologies:

Combined Heat and Power



Central thermal energy storage
(self-discharge rate=0.02%/h)

Heat pumps

Electric heating

Individual systems

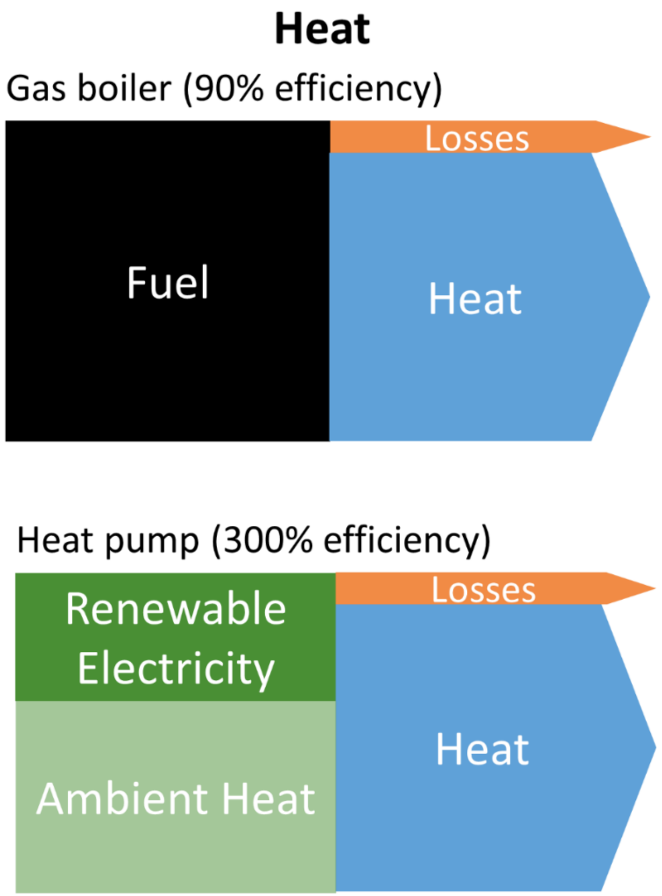
- Typical in locations without district heating
- Technologies:

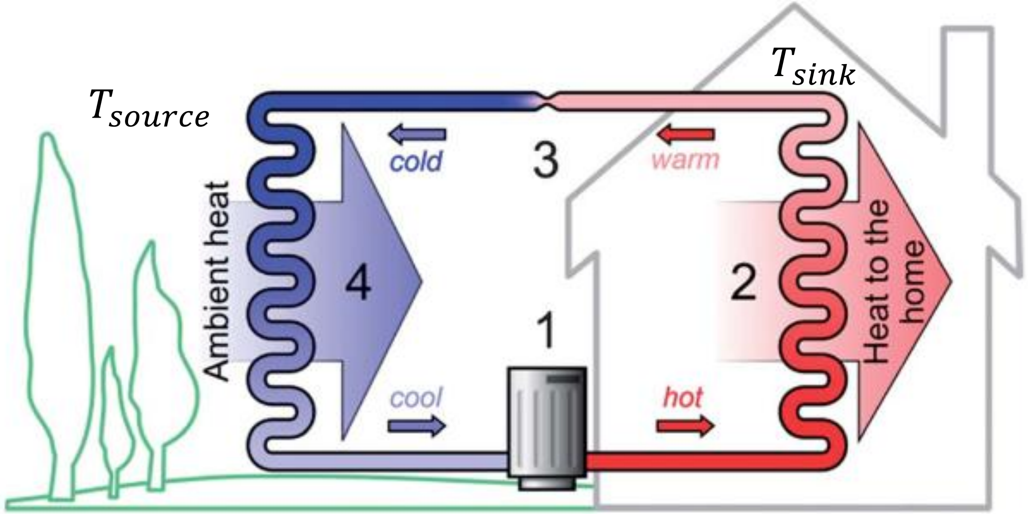
Gas/biomass boilers

Individual thermal energy storage
(self-discharge rate=1.5%/h)

Heat pumps

Opportunities: Efficiency (Coefficient of Performance, COP) increases when using heat pumps, relative to fossil-based heating





Stafell, Energy Con. & Manag. 2012

But it is important to model that COP is lower when ambient temperature (T_{source}) is low

$$COP(\Delta T) = 6.81 - 0.121\Delta T + 0.00063\Delta T^2$$
$$\Delta T = T_{sink} - T_{source}$$
$$T_{sink} = 55^0 C$$

We can also use ground-sourced or sea water-sourced heat pumps

Learnings from modeling the European energy systems

Optimization problem

Most energy system models are just optimization problems… with millions of variables and constraints.

We can start by calculating the optimal capacities for different technologies and how they need to be operated.
This is called **join capacity and dispatch optimization**.

$$\min \left(\sum_{n,s} \begin{matrix} generation \\ costs \end{matrix} + \begin{matrix} storage \\ costs \end{matrix} + \begin{matrix} transmission \\ costs \end{matrix} + \sum_{n,s,t} \begin{matrix} variable \\ costs \end{matrix} \right)$$

$subject\ to:$

$$\sum_{s,t} CO_2\ emissions \leq CO_2\ limit \quad \leftrightarrow \quad \mu_{CO2}$$

$$\sum_{s} generation_{s,t,n} + balance_{t,n} = demand_{t,n} \quad \leftrightarrow \quad \lambda_{t,n} \qquad \forall t, n$$

$$generation_{s,t} \leq Capacity\ Factor_{s,t} \cdot Capacity_s$$

$$Capacity_{n,s} \leq Potential\ Capacity_{n,s}$$

$$Storage_t = f(Storage_{t-1}, charge_t, discharge_t)$$

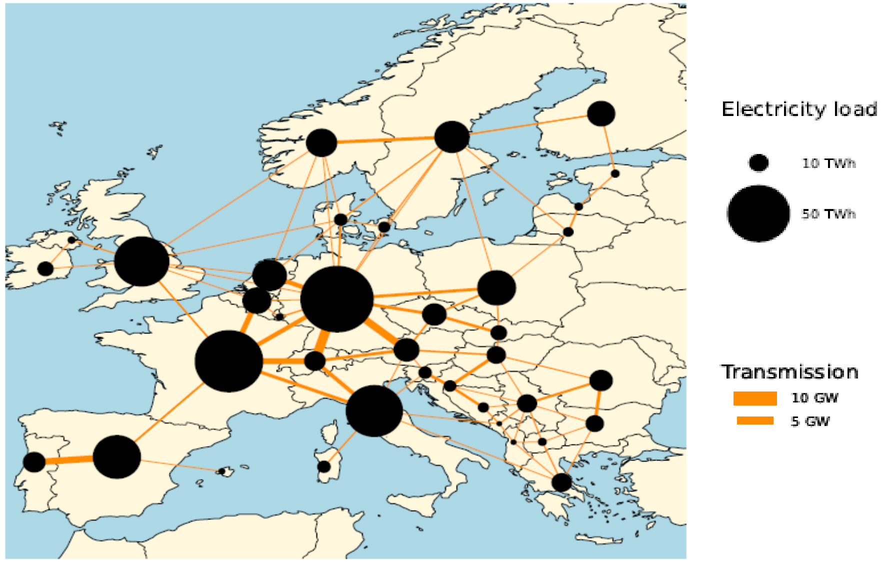
$$power\ flow_l \leq Capacity_l$$

$$power\ injection_n = \sum_l K_{nl}\ power\ flow_l$$

$$\sum_l C_{lc}\ x_l\ power\ flow_l = 0$$

The objective is to minimize annualized total system costs

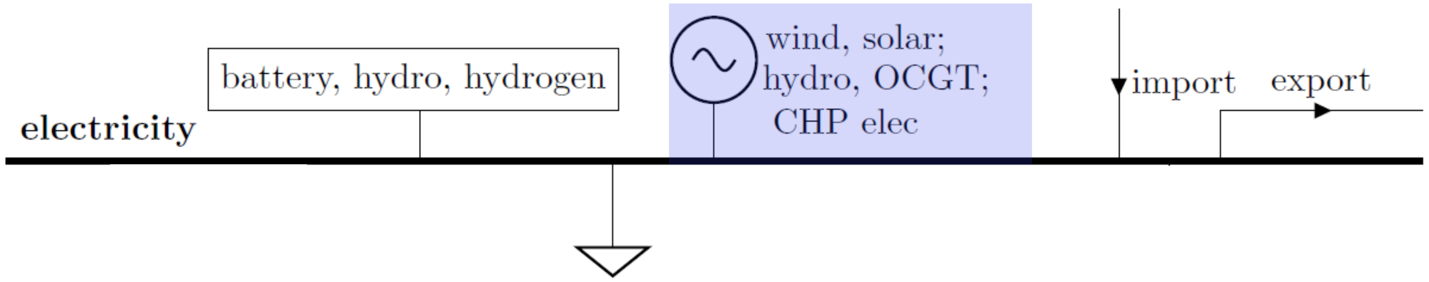
n=nodes in the network
s=technologies
t=timesteps
l=links



* The model assumes long-term market equilibrium, perfect competition and foresight

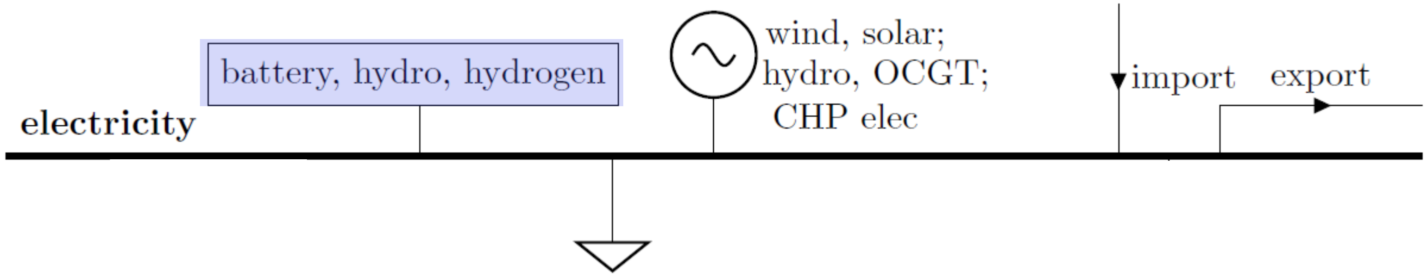
Optimal power system (95% CO_2 reduction)

Let's start by obtaining insights from a simplified European power system.



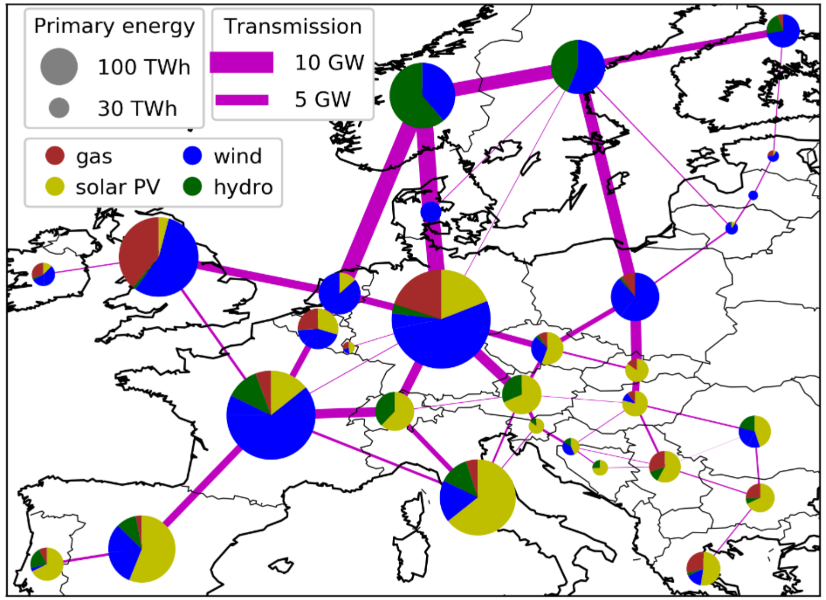
Optimal power system (95% CO_2 reduction)

Let's start by obtaining insights from a simplified European power system



Optimal power system (95% CO_2 reduction)

Primary energy

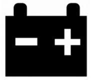


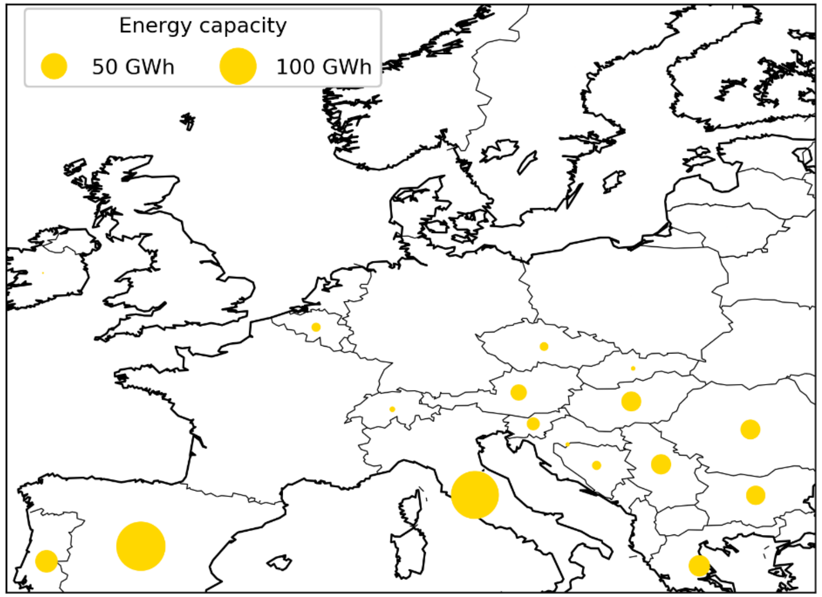
Wind generation represents in average 55% of the electricity demand, solar PV represents 33%

(570 GW onshore wind capacity,

60 GW offshore wind capacity)

Electric Batteries

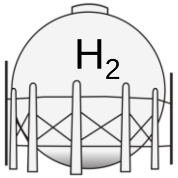


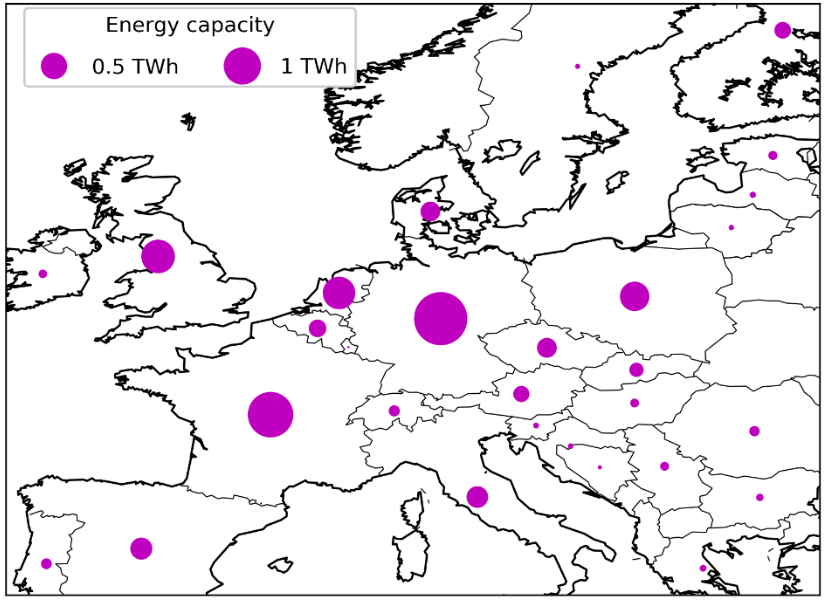


Southern countries: PV + batteries

$$\frac{energy\ capacity}{power\ capacity} \sim 6\ hours$$

Hydrogen storage



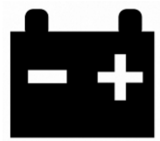


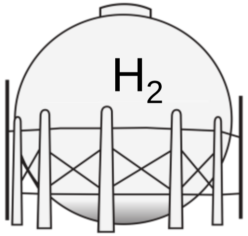
Northern countries: wind + hydrogen storage + interconnections

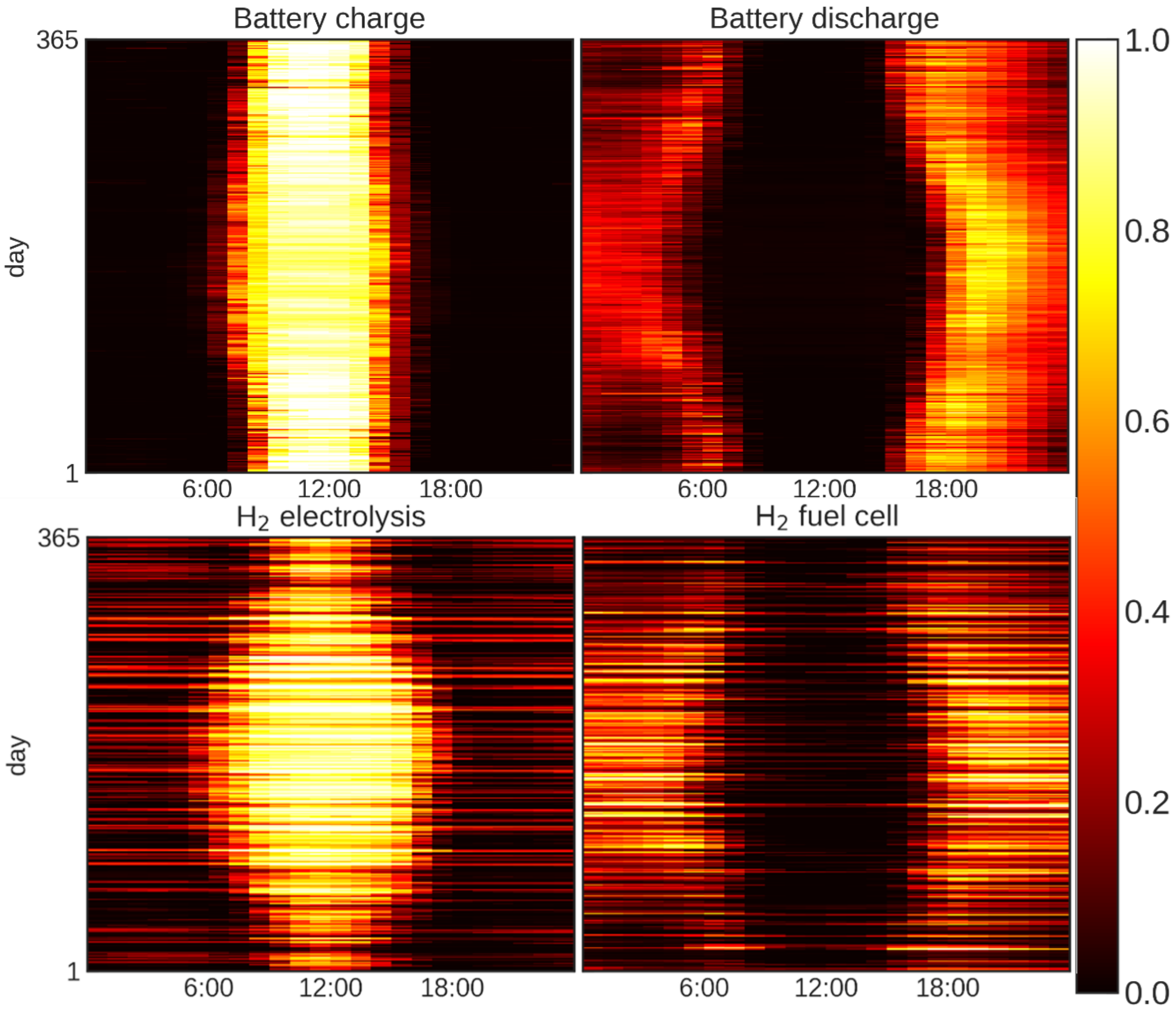
$$\frac{energy\ capacity}{power\ capacity} \sim 2\ days$$

Victoria et al., Energy Conversion and Management (2019)

Optimal power system (95% CO_2 reduction)





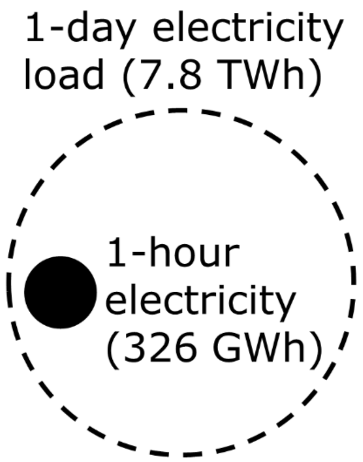


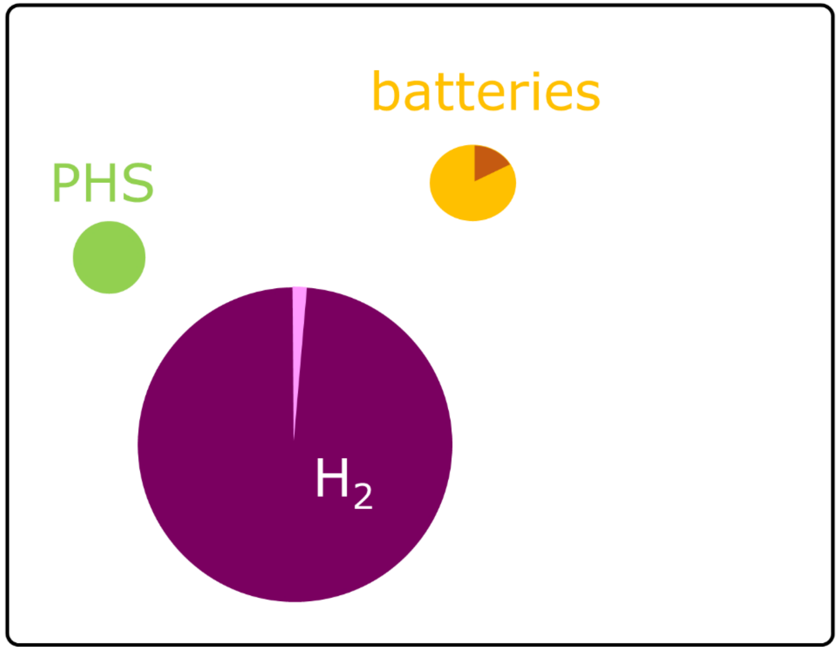
Victoria et al., Energy Conversion and Management (2019)

As expected, batteries charge during the day and discharge during the night.

Hydrogen storage operation is impacted by wind generation fluctuations with weekly frequency.

How much storage capacity is needed?





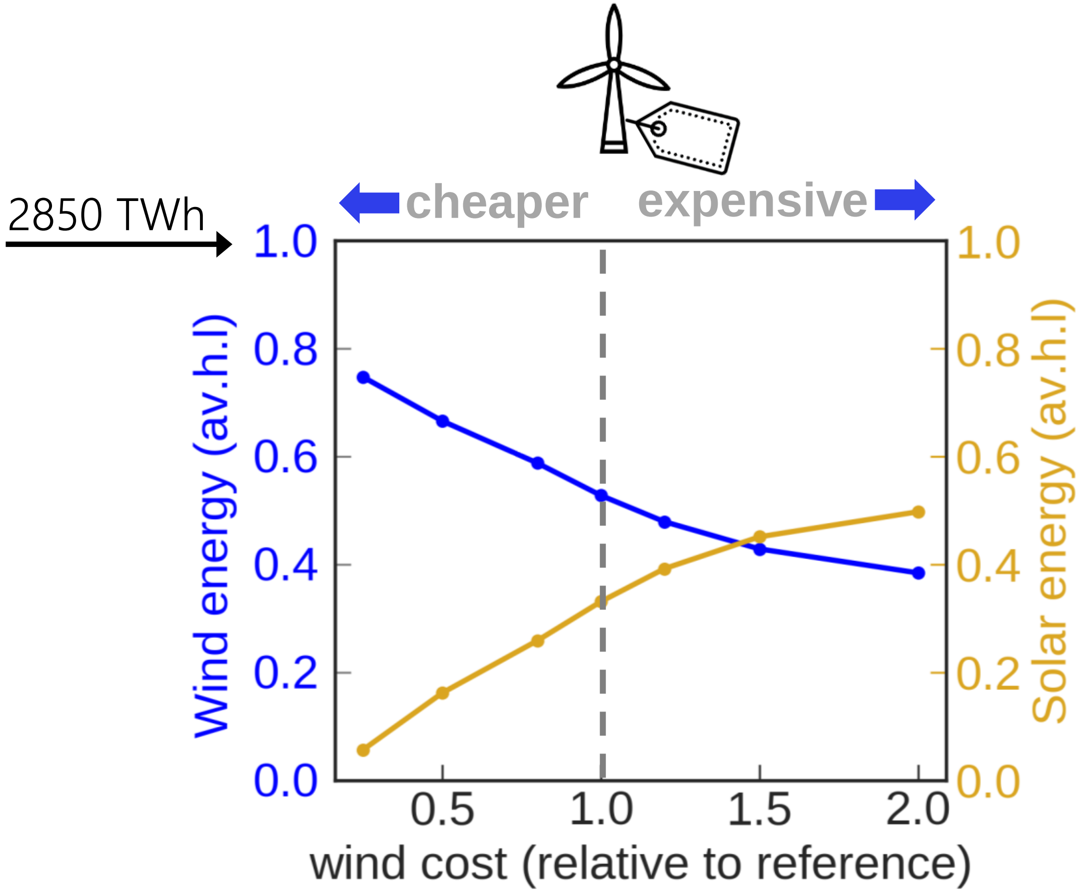
Victoria et al., Energy Conversion and Management (2019)

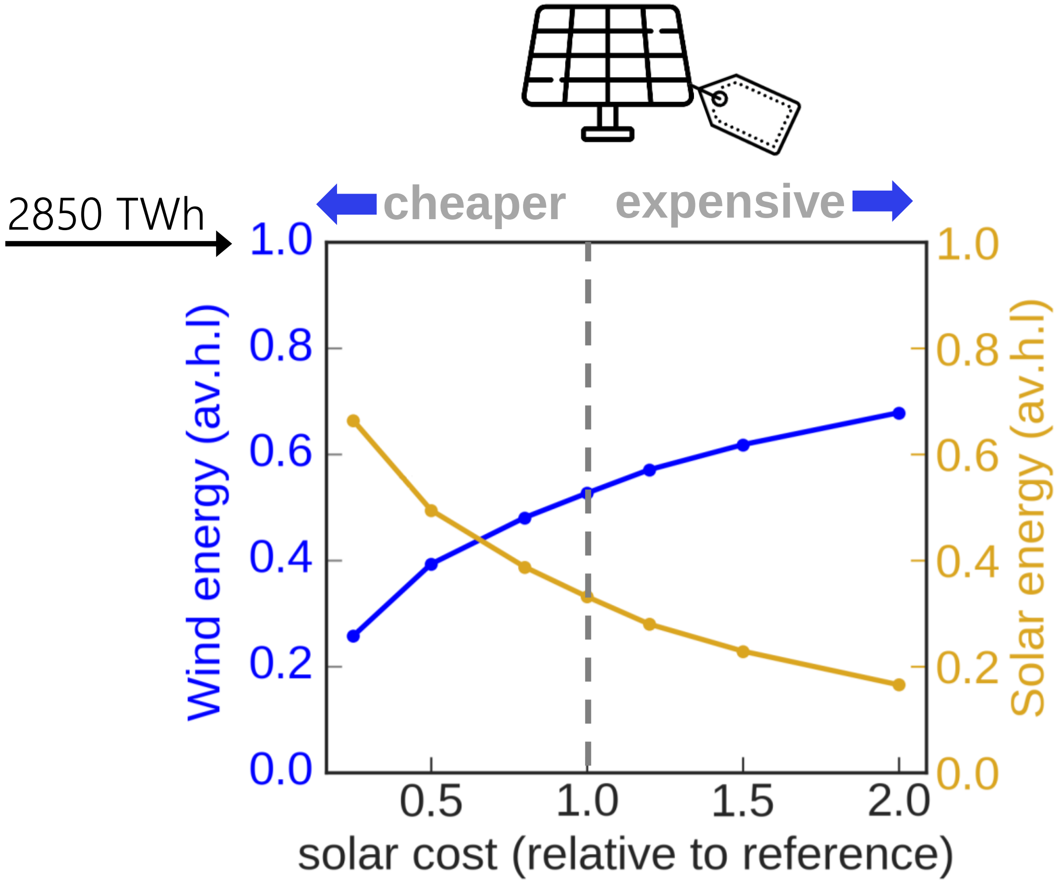
Optimal power system (95% CO_2 reduction)

- Pumped Hydro Storage ~ 0.9 average hourly electricity demand (exogenously fixed)
- Battery ~ 1.4 hourly electricity demand
- H_2 storage ~ 20 average hourly electricity demand

Brown et al., Energy 2018

Sensitivity to wind and PV costs

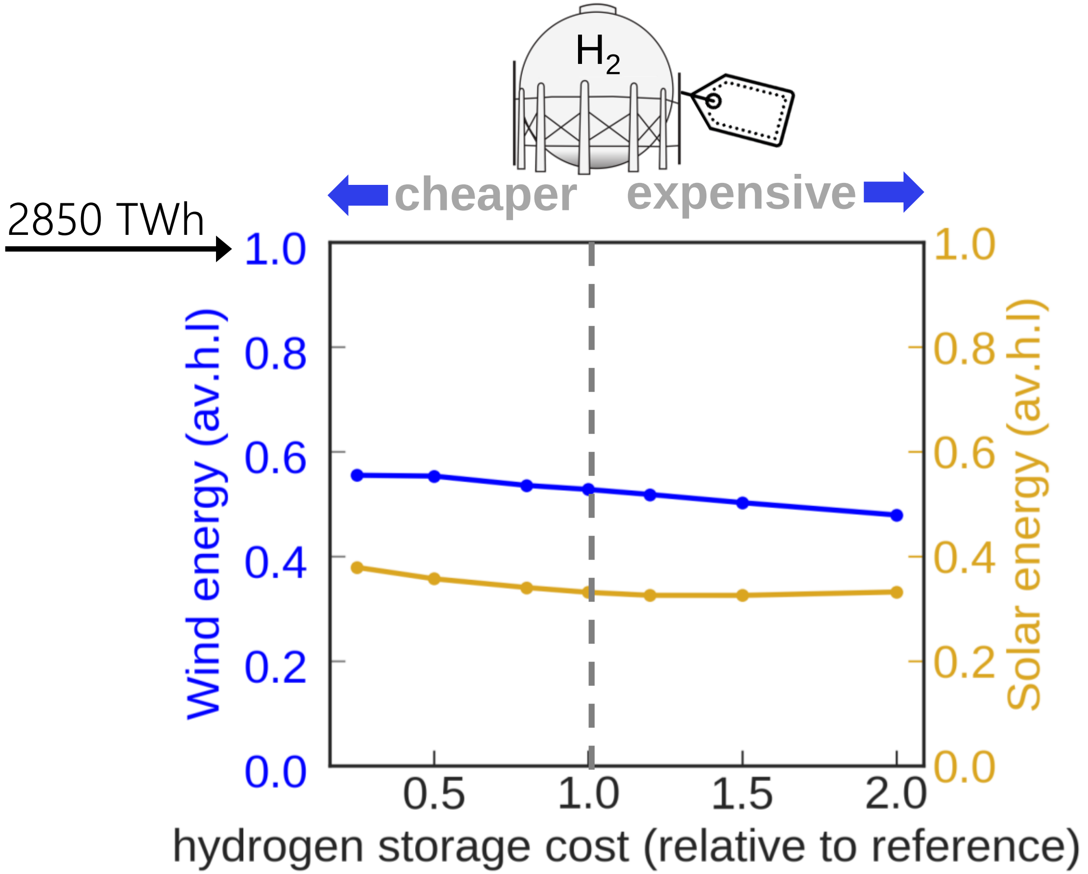


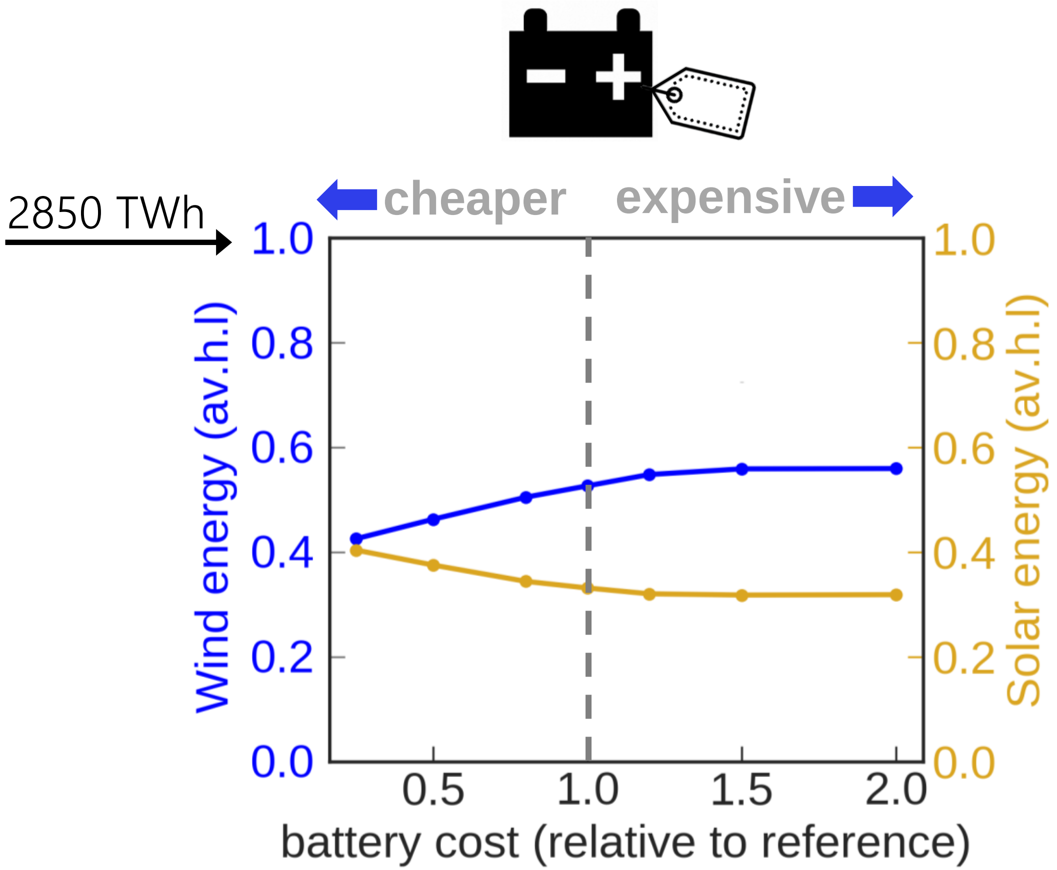


Even for very cheap PV, no 100% solar system is optimum as it would requires large (expensive) battery capacity.

Victoria et al., Progress in Photovoltaics EUPVSEC Special Issue (2019)

Sensitivity to battery and hydrogen storage costs

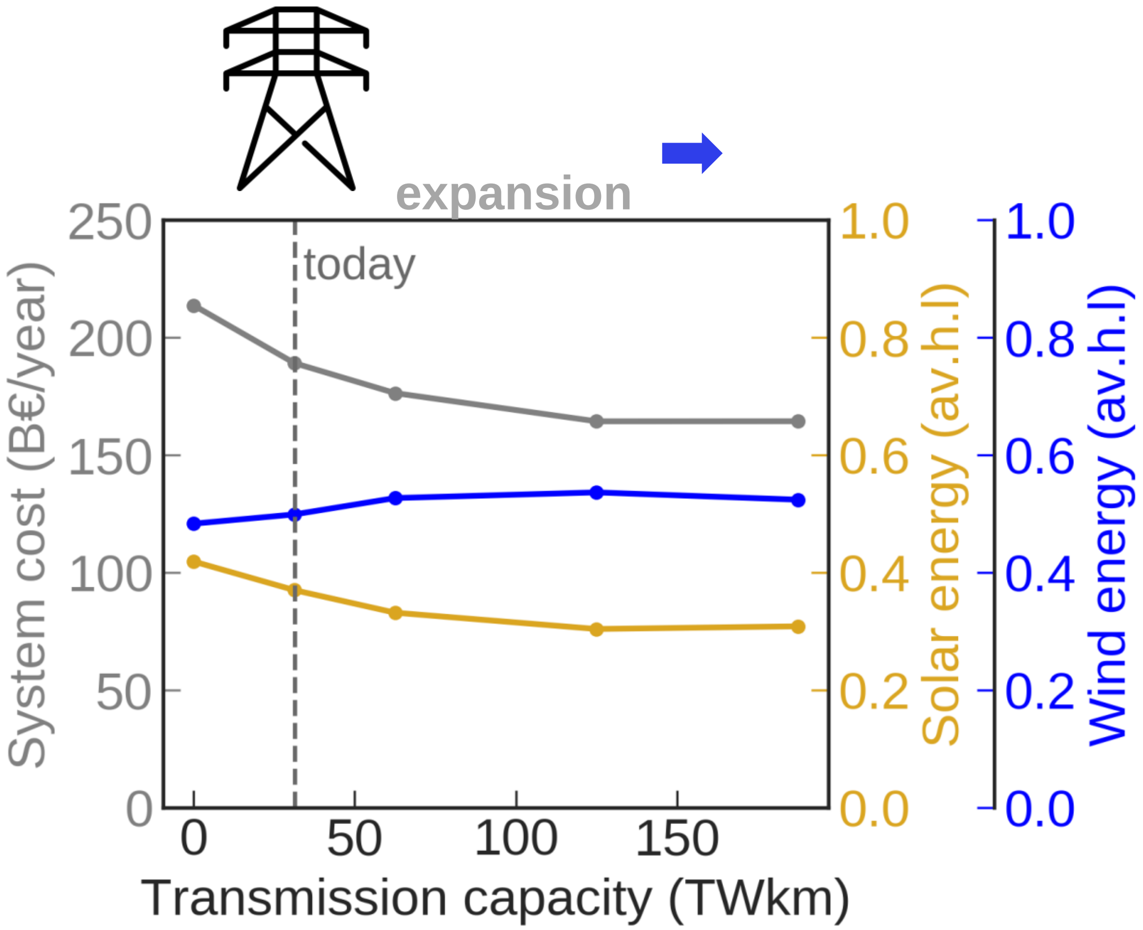




Cheap batteries increase optimal PV penetration.

Victoria et al., Progress in Photovoltaics EUPVSEC Special Issue (2019)

Impact of transmission capacity expansion

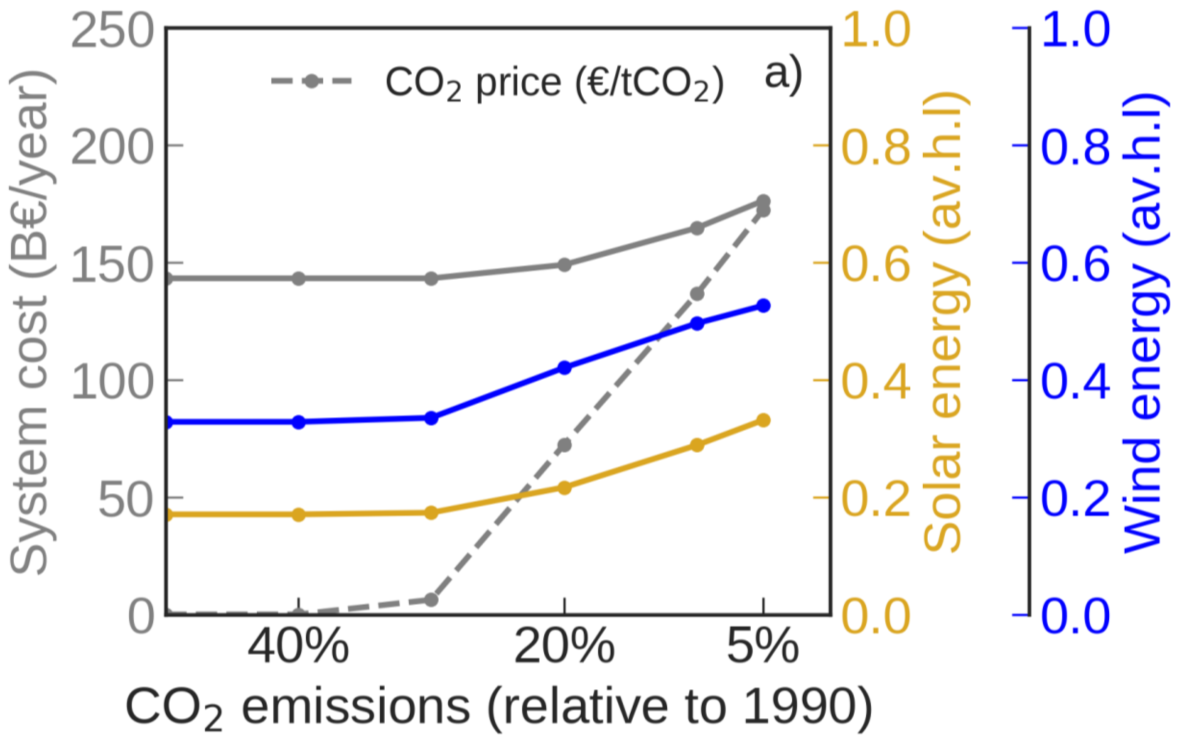


Increasing transmission capacity reduces PV optimal penetration.

Increasing transmission capacity reduces system costs but most of the benefits are captured by the initial 25% grid expansion.

Victoria et al., Progress in Photovoltaics EUPVSEC Special Issue (2019)

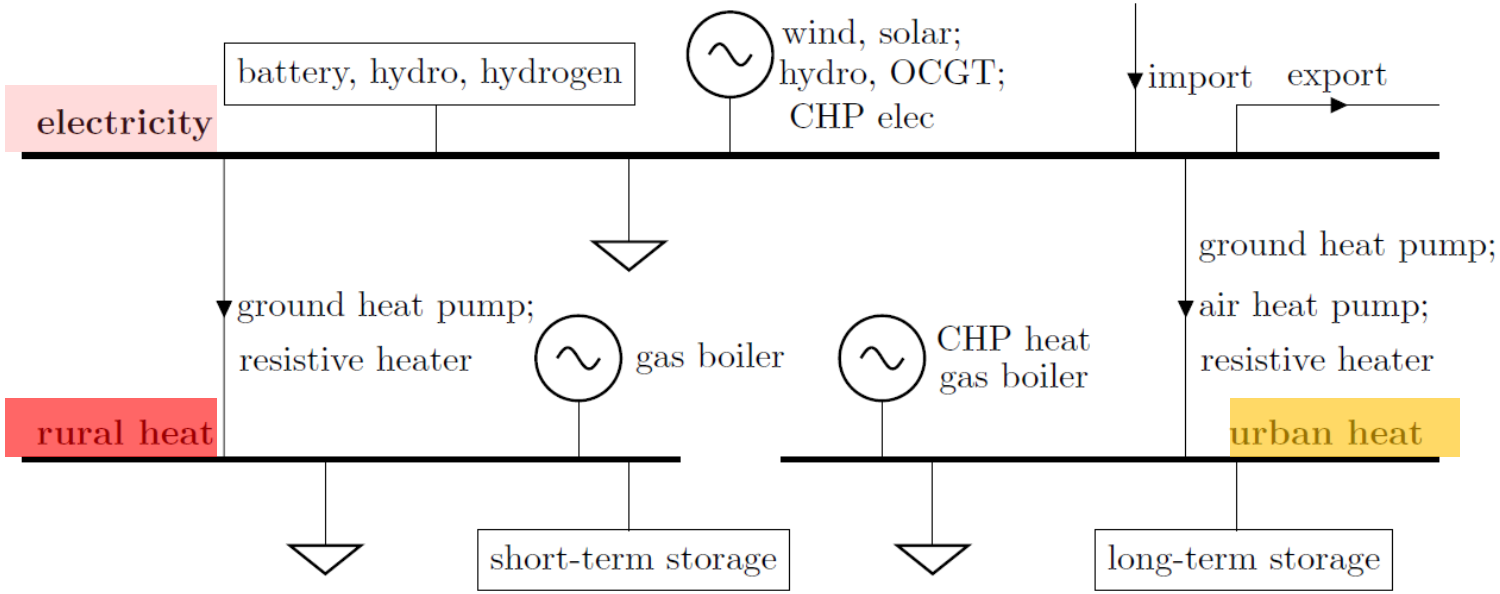
Sensitivity to CO_2 emissions allowance



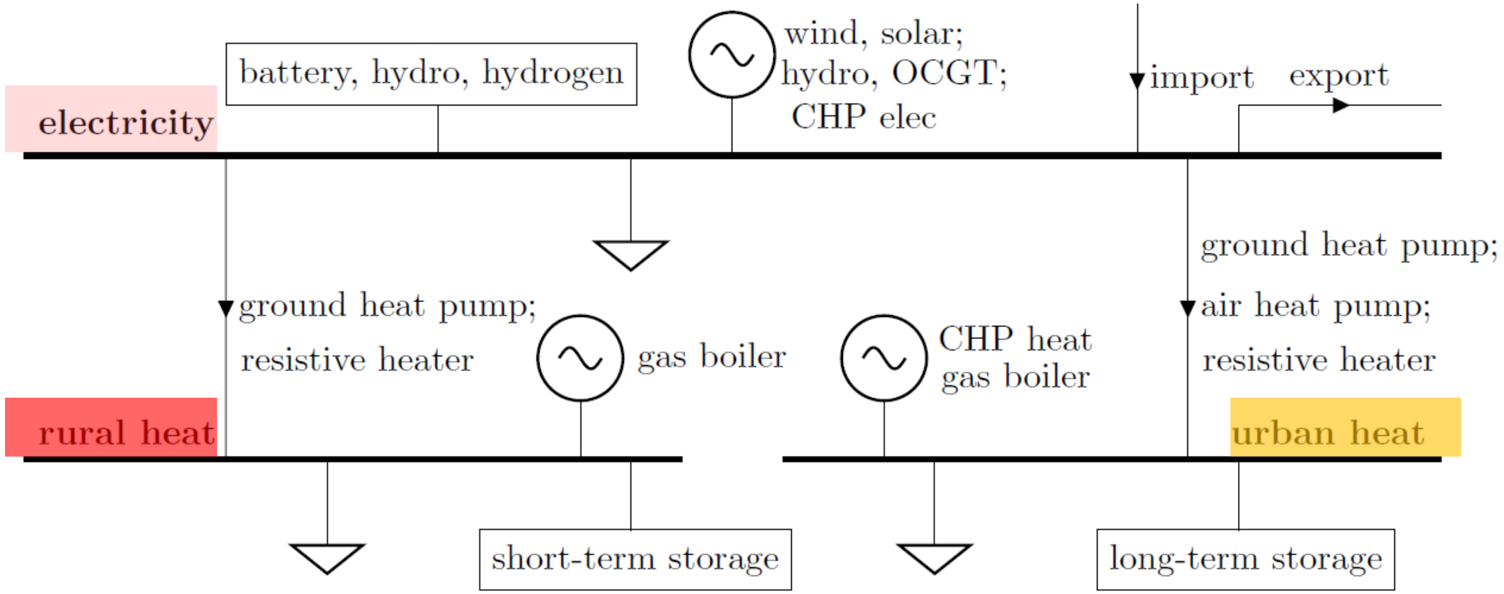
When CO_2 emissions are restricted, higher solar and wind capacities are needed. Higher CO_2 prices are also necessary.

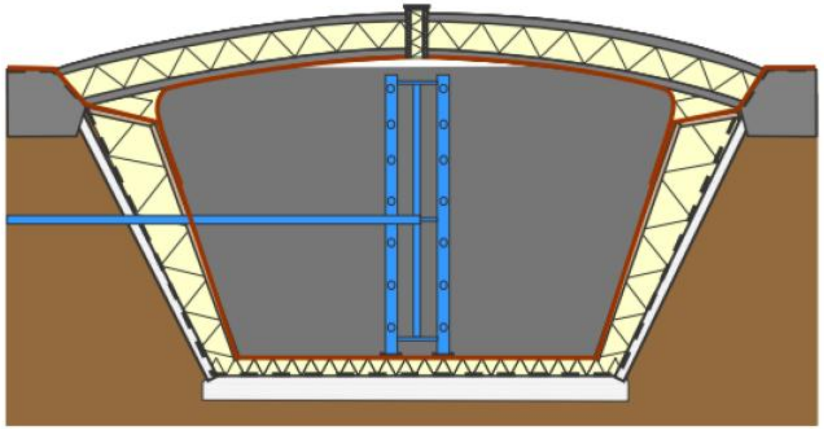
Victoria et al., Progress in Photovoltaics EUPVSEC Special Issue (2019)

Sector-coupled network model



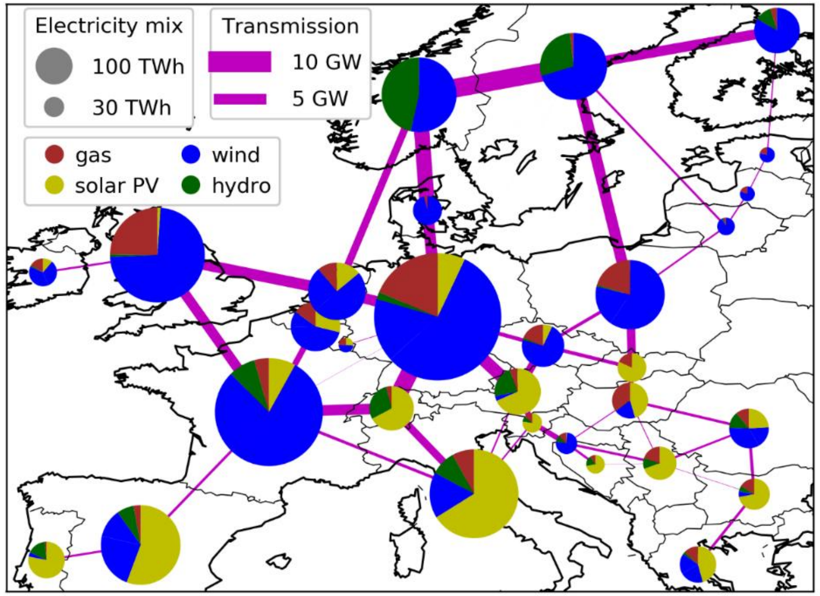
Sector-coupled network model

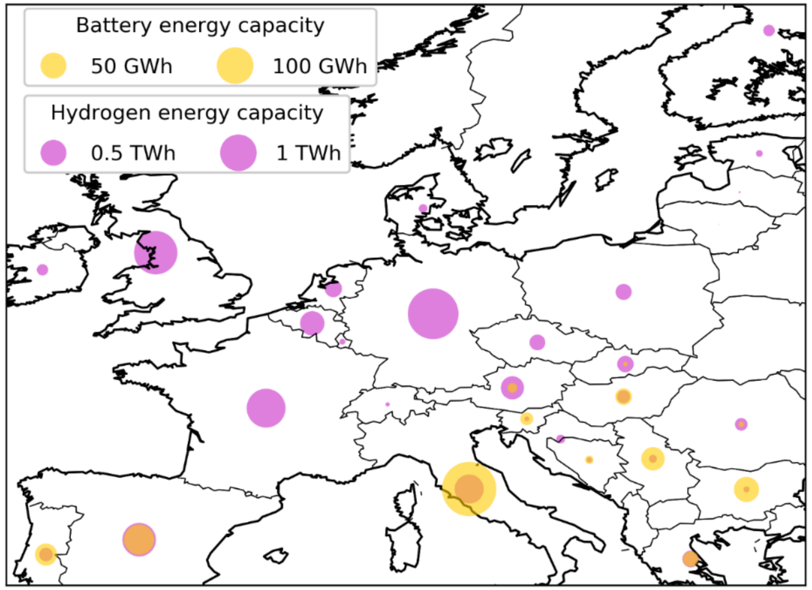


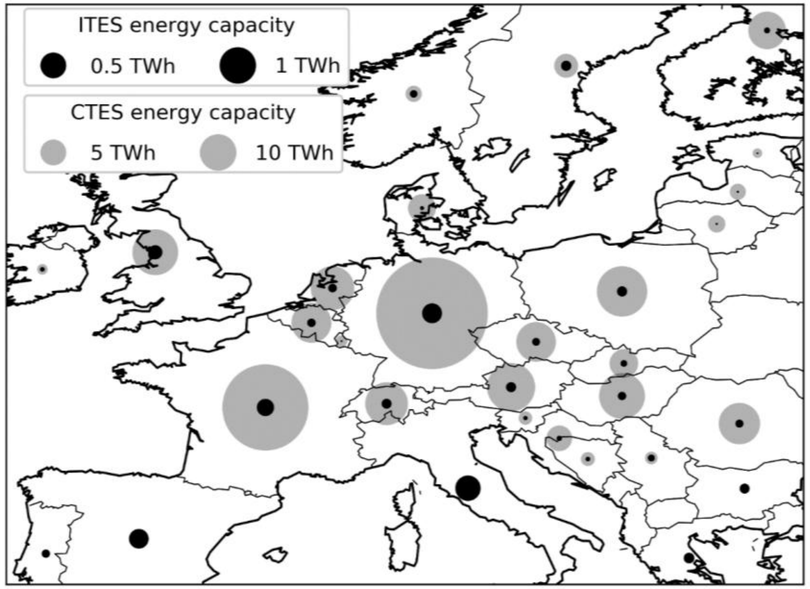


Primary energy and storage

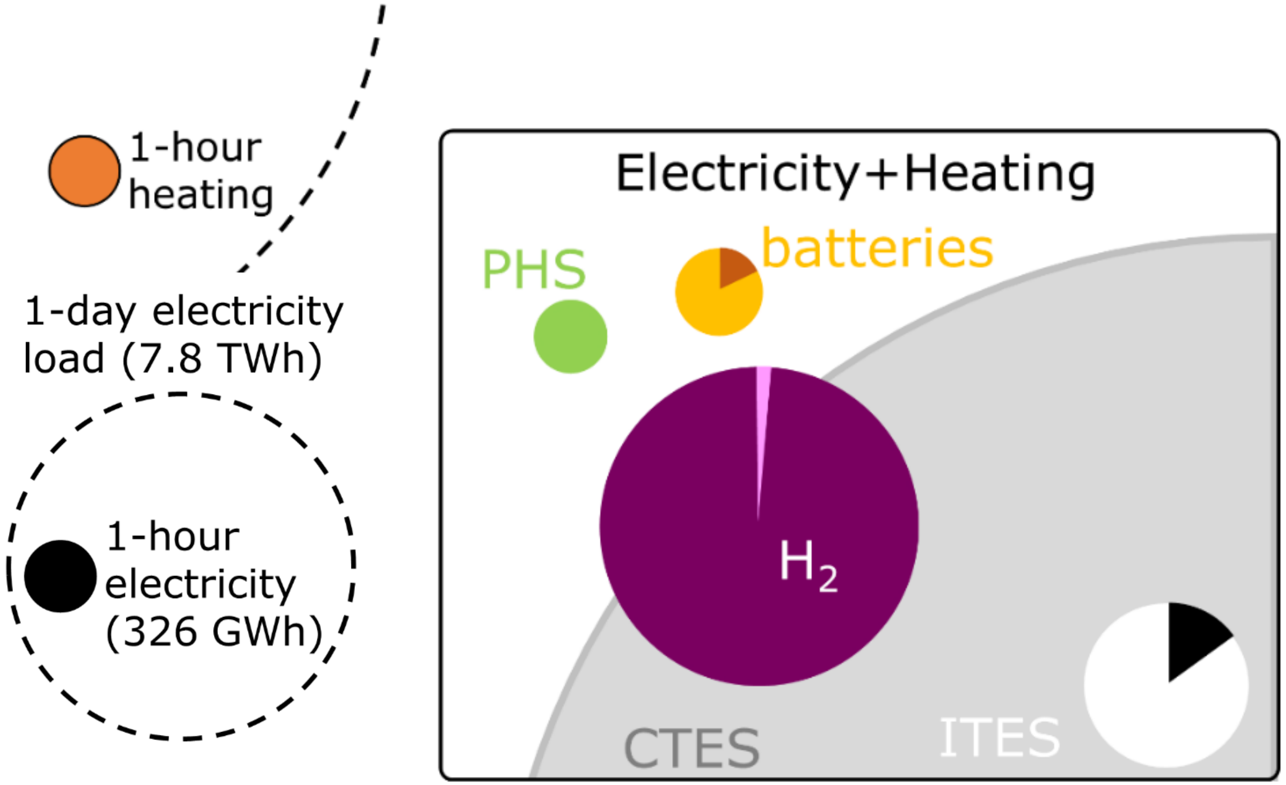
Electricity + heating scenario (5% CO_2 emissions, relative to 1990)







How much storage capacity is needed?



Individual thermal energy storage (ITES) sized to store heat demand for a few hours

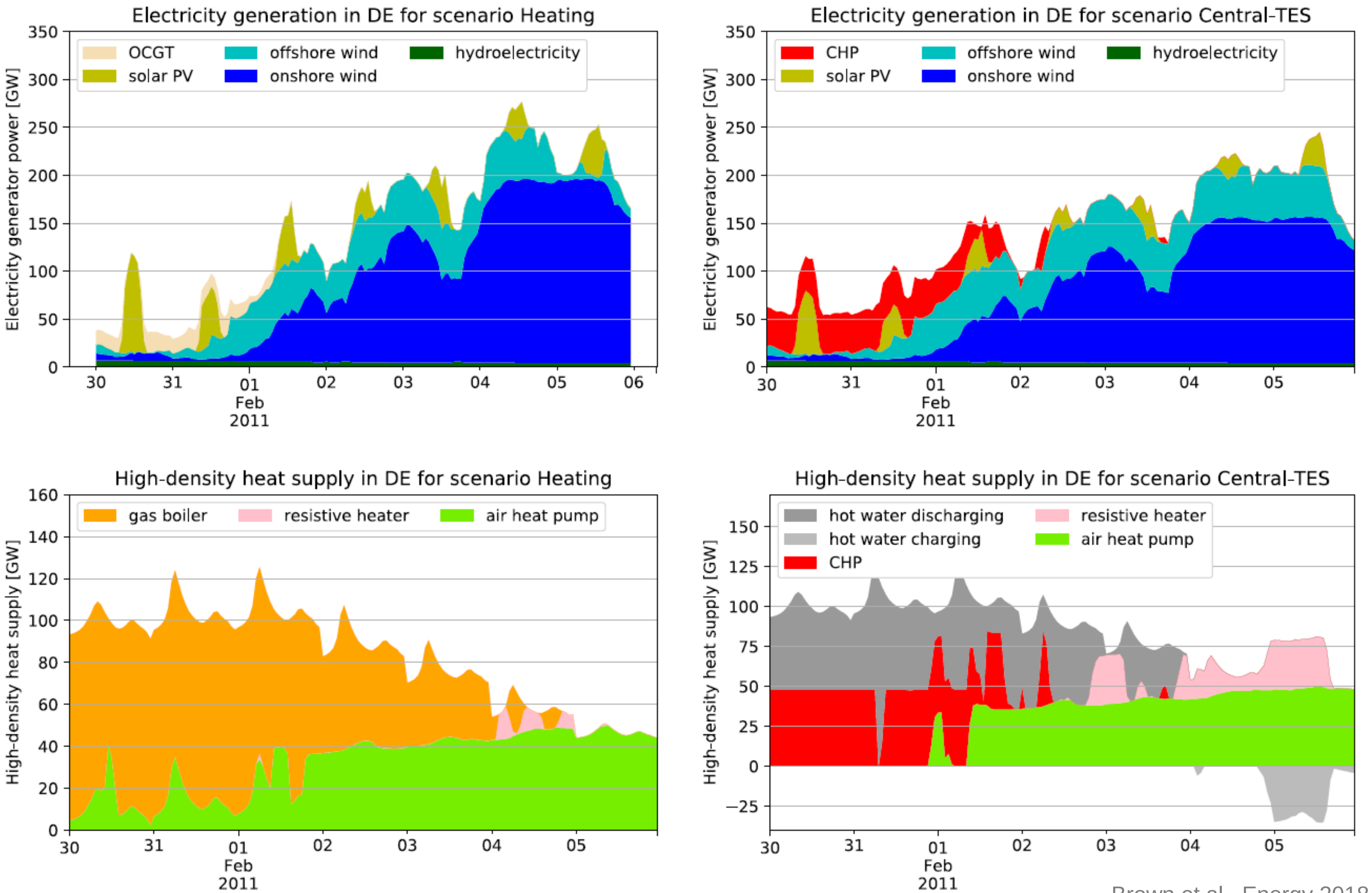
Centralized thermal energy storage (CTES) sized to store heating demand for months

Victoria et al., Energy Conversion and Management (2019)

Storage dispatch

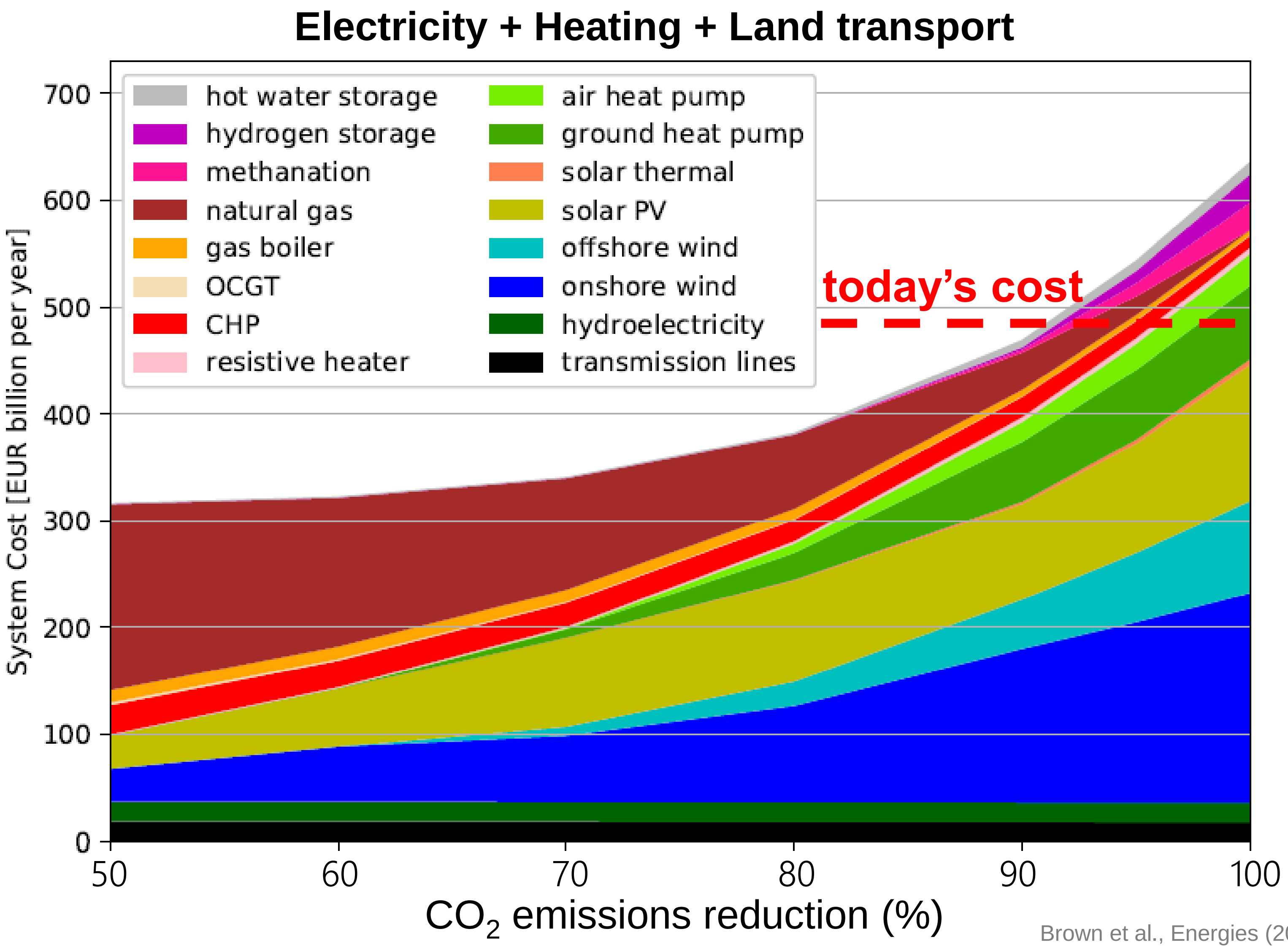
Centralized thermal energy storage (hot water tanks) supplies heat during cold spell (cold week with low solar and wind generation) avoiding the need of gas.

Without central TES | **With central TES**



Brown et al., Energy 2018

Impact of CO_2 reduction target



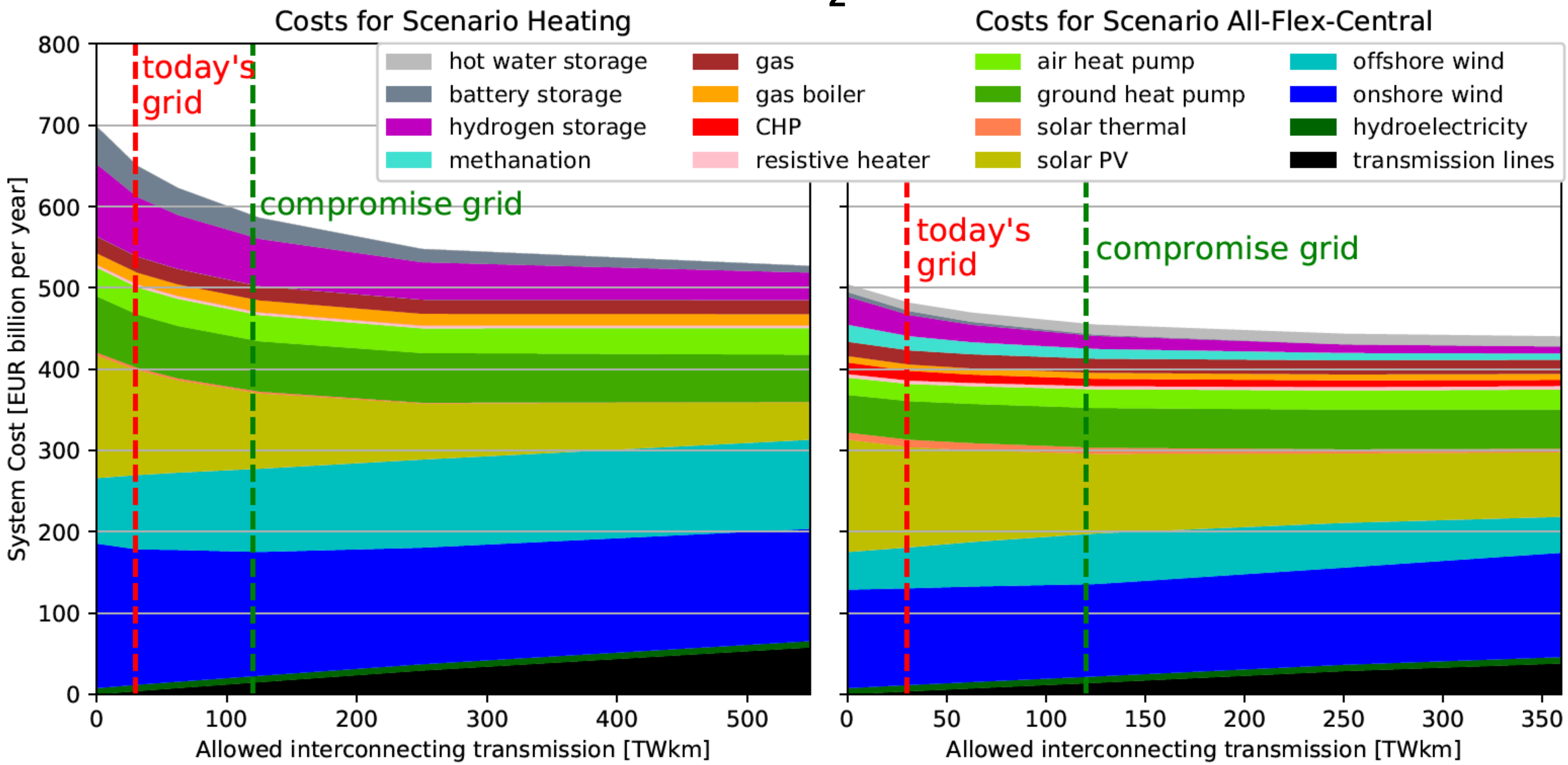
Brown et al., Energies (2019)

As CO_2 emissions are restricted the system becomes more expensive …

… but not linearly, the last 20% is the hardest!

Impact of transmission grid expansion get reduced

5% CO_2 limit



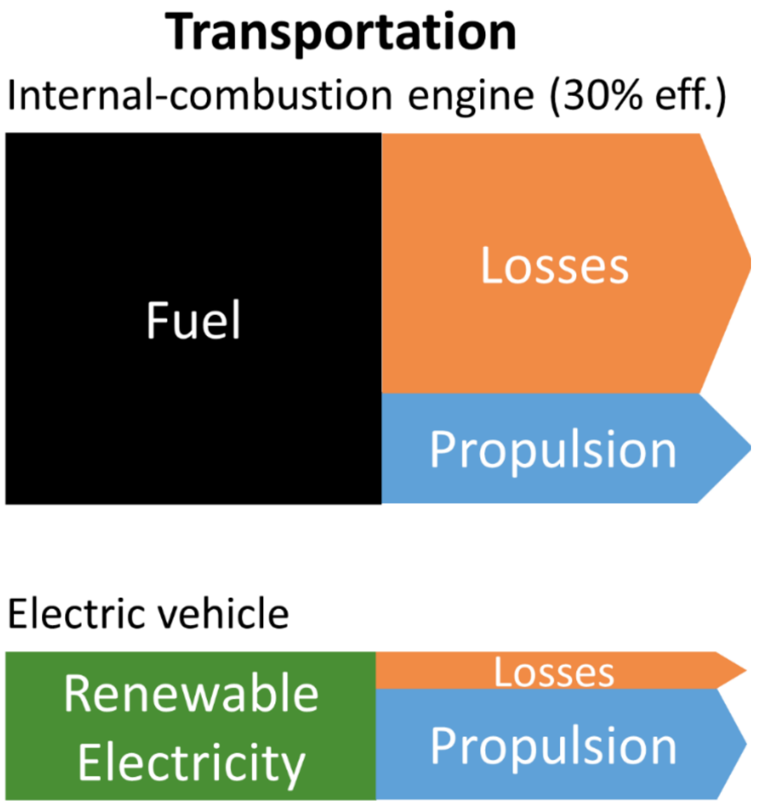
Brown et al., Energy 2018

Modelling land transport demand and flexibility

Land transport

Challenge: Full electrification of land transport demand will add around 1000 TWh/a to current electricity demand in Europe (3000 TWh/a)

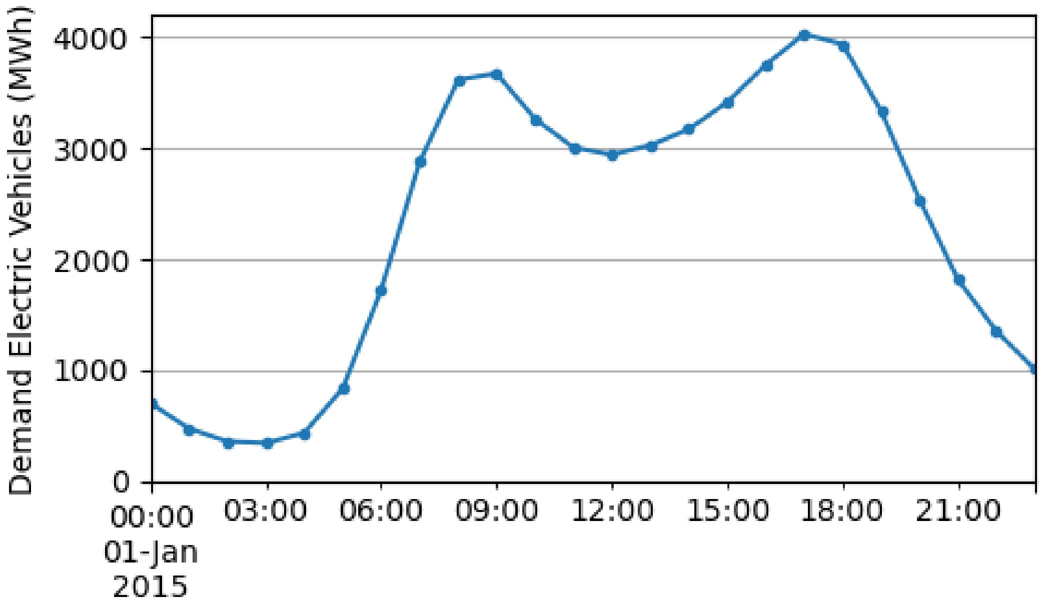
Opportunities: Efficiency increase, EV batteries bring large flexibility to the system, strong synergy with rooftop solar PV



How can we model land transport demand?

Let’s assume we want to estimate hourly-resolved demand for a fleet of Electric Vehicles (EVs)

1. Annual demand data for current cars fleet exists and can be transformed into electrified demand taking into account the different efficiency of Internal Combustion Engine (ICE) cars and EVs
2. Hourly-resolved data on cars usage can be used to create time series, e.g. assuming that EVs are charged right after they are used
3. We can model all the cars in a country/region lumped assuming average values (e.g. for every home-charger a capacity of 11 kW and 90% efficiency).



This represents unflexible demand from EVs.

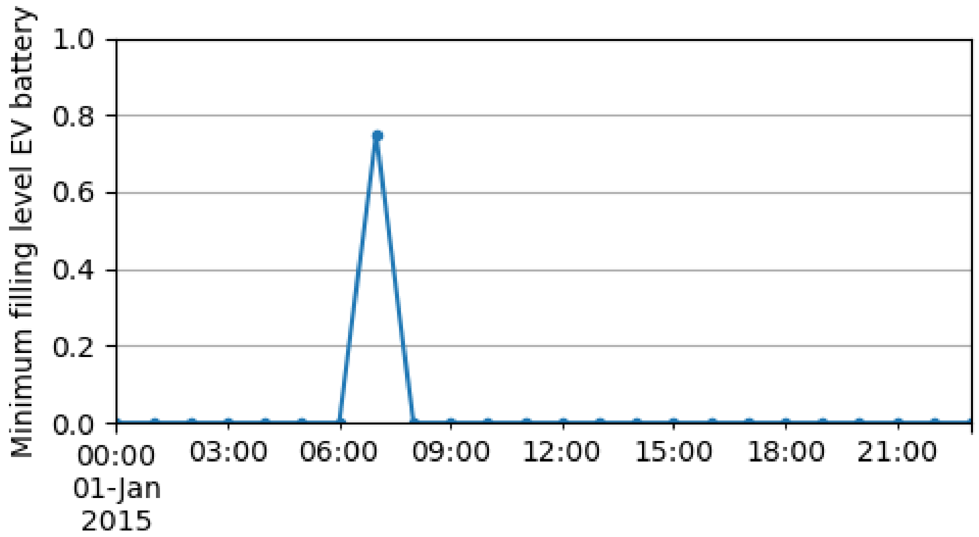
How can we model land transport flexibility?

- **Smart-charging or Demand-Side Management (DSM)**

An EV battery can be added so that it is charged when is optimal for the system.

We can model all the cars in a country/region lumped assuming for every EV an average capacity (e.g. 50 kWh)

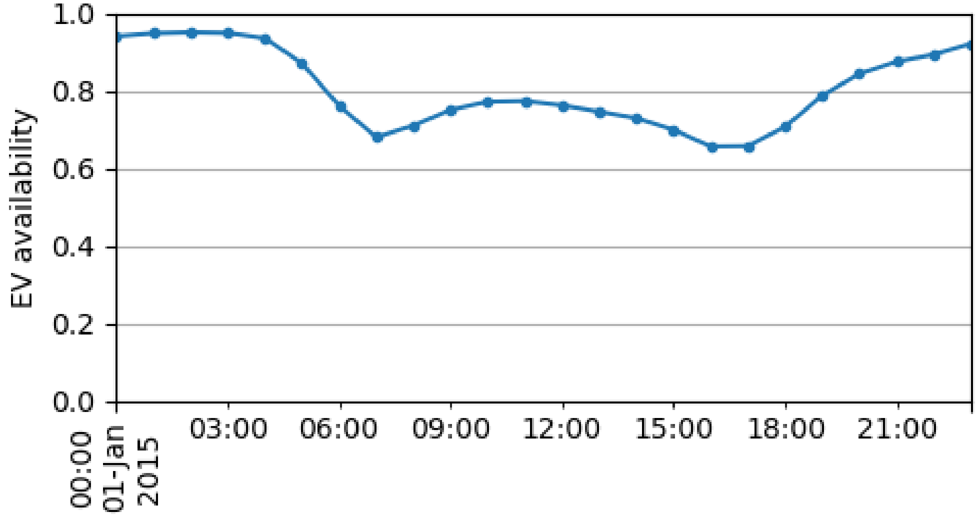
To make the operation of the EV batteries more realistic, we can also impose that their state of charge > 75% at 7 a.m. every day



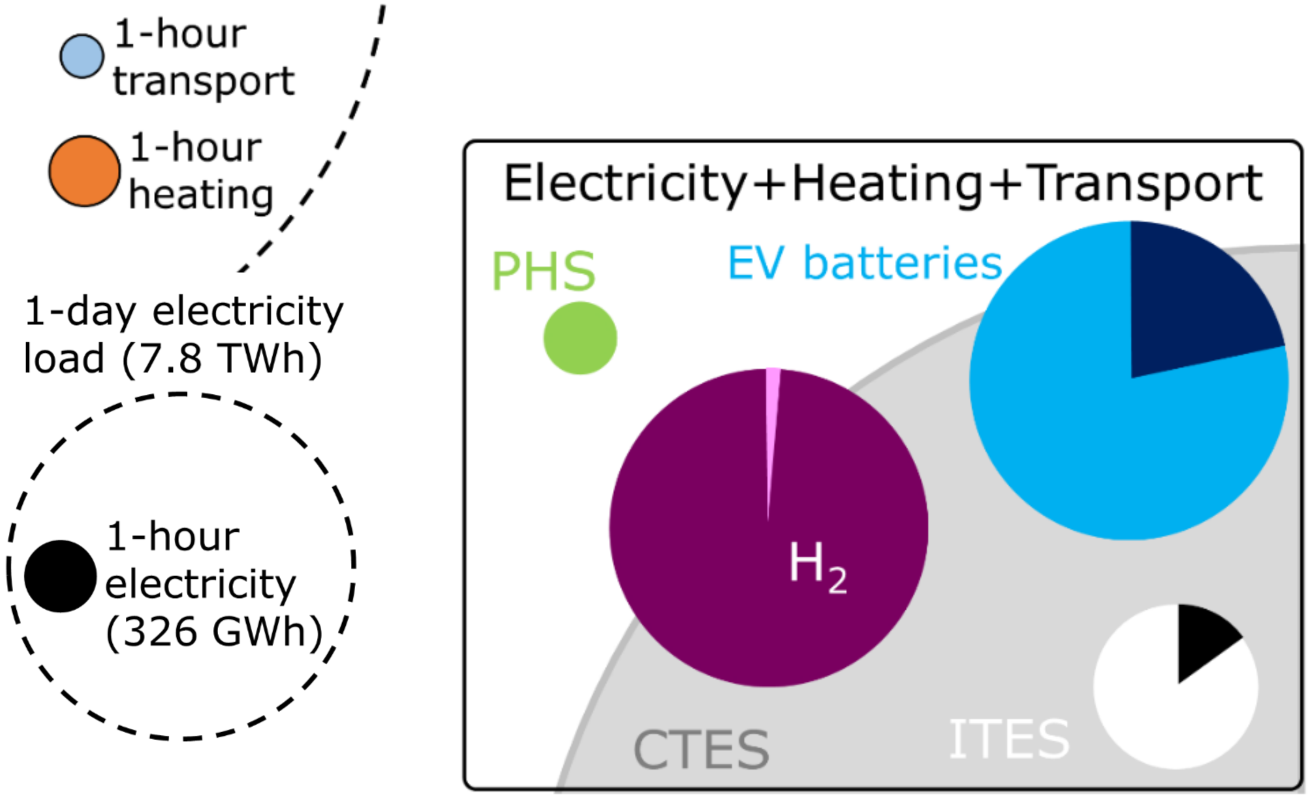
- **Vehicle-to-Grid (V2G)**

We can also include the hypothesis that a percentage of cars allow vehicle-to-grid services.

We can calculate some availability profile (based on when cars are not been used).



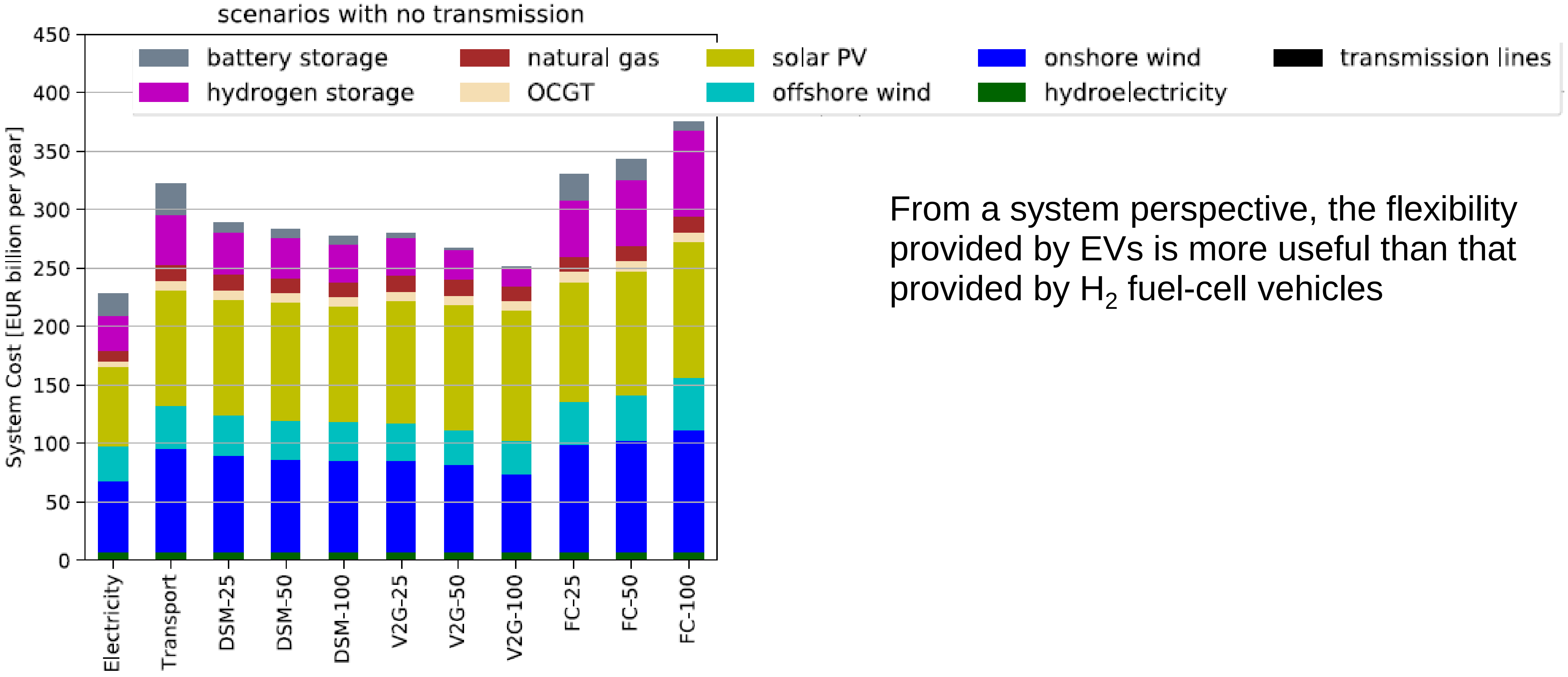
How much storage capacity is needed?



EV battery capacity could be enough to remove the need for static batteries

Victoria et al., Energy Conversion and Management (2019)

Electric Vehicles vs Hydrogen Vehicles



Brown et al., Energy 2018

From a system perspective, the flexibility provided by EVs is more useful than that provided by H_2 fuel-cell vehicles

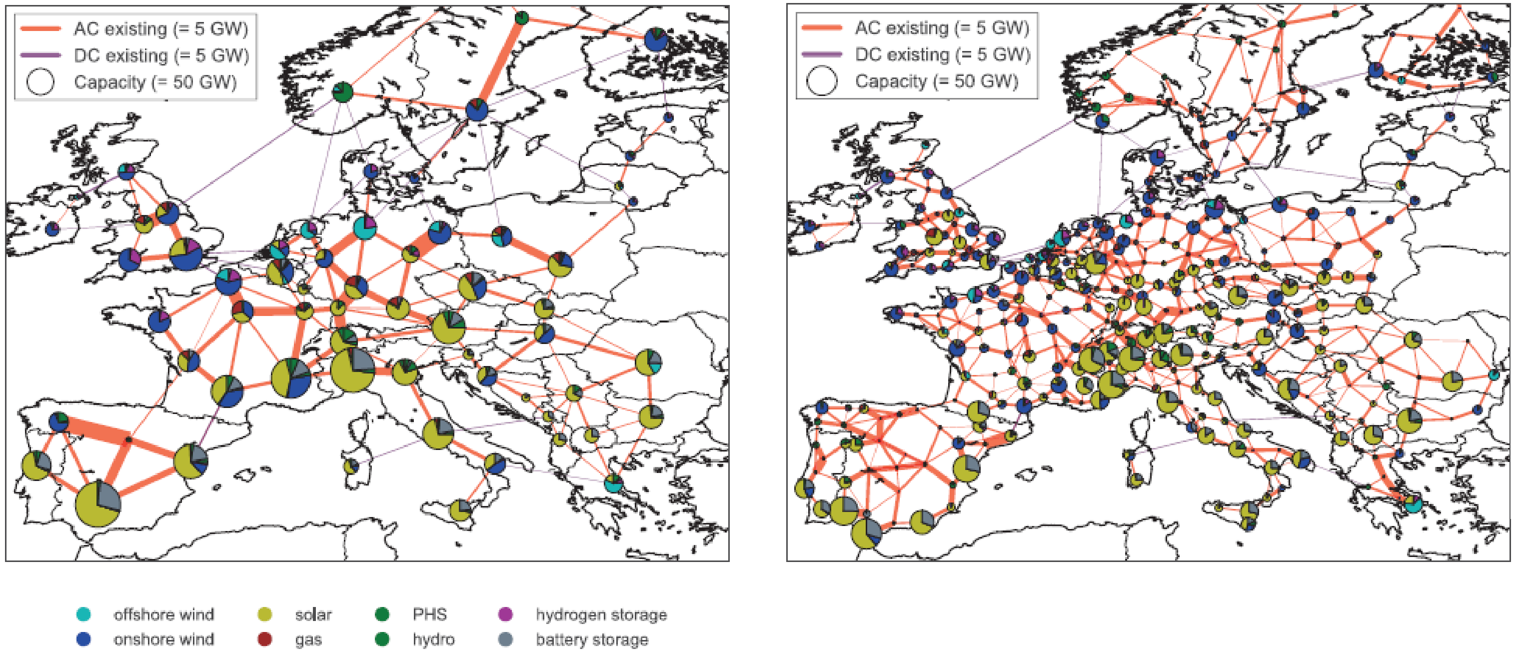
Which temporal and spatial resolution is good enough?

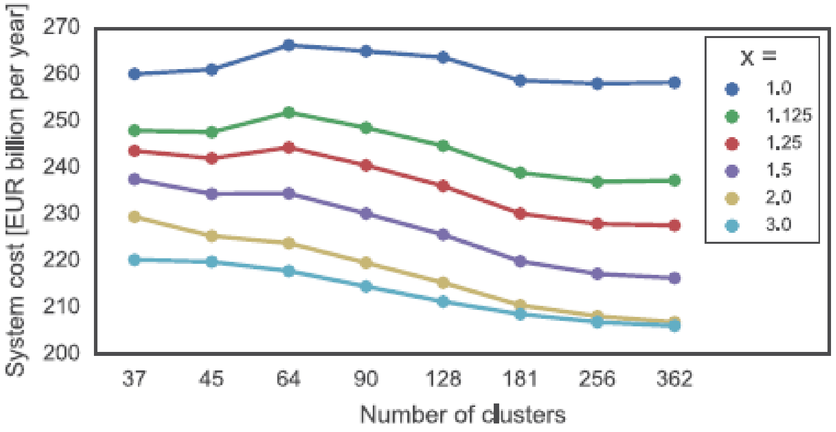
Which spatial resolution is good enough?

When increasing the number of nodes, the system cost remains roughly constant due to the counterbalancing of two effects:

(a) sites with high capacity factors for wind and solar are available for a more finely resolved network,

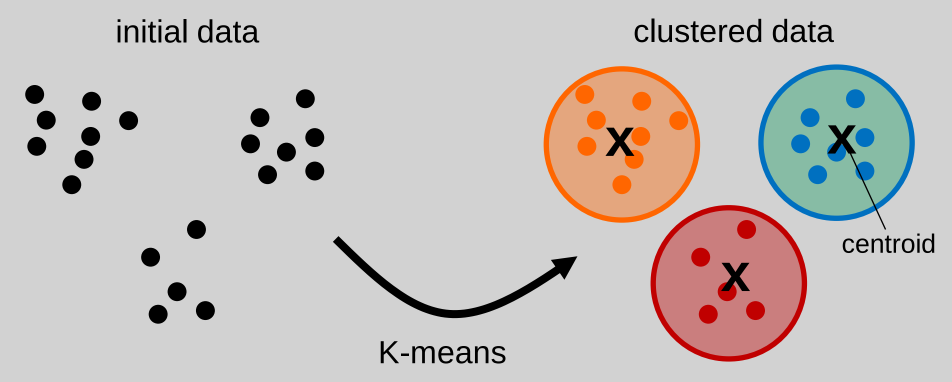
(b) but the emergence of bottlenecks inside countries prevents the use wind energy generated at exterior nodes



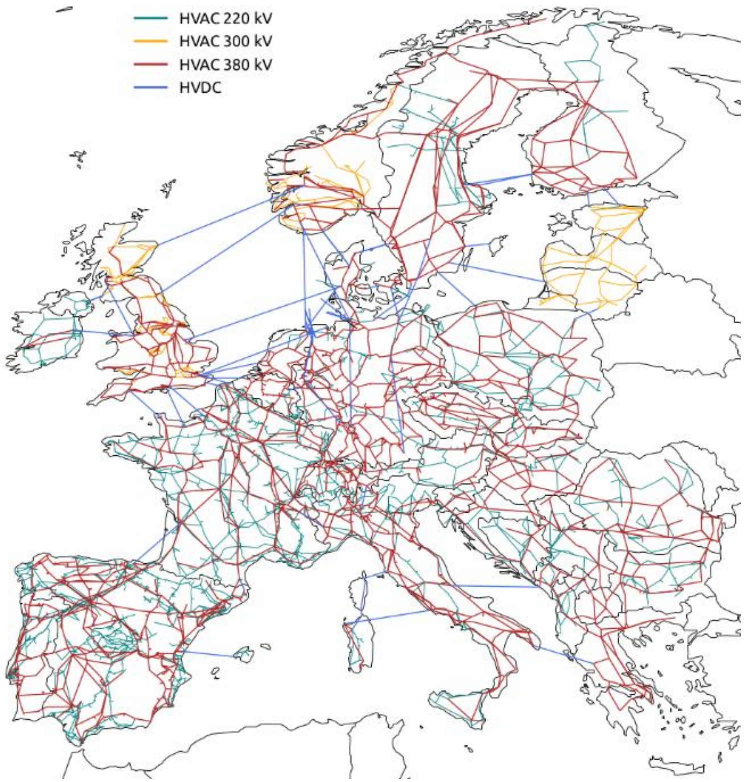


Hörsch and Brown, IEEE (2017)

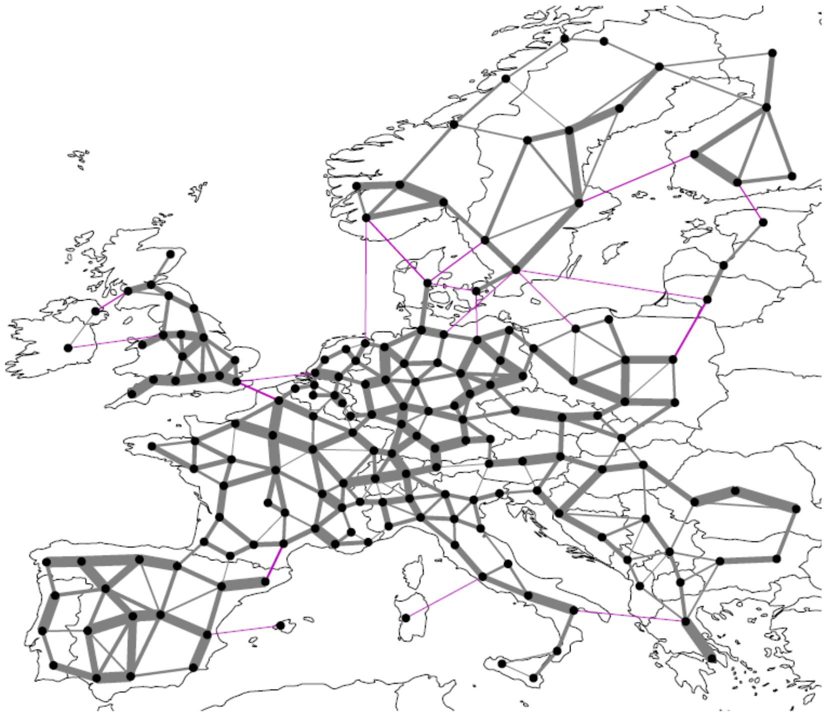
How can we cluster power networks?



We cluster the network using k-means algorithms.



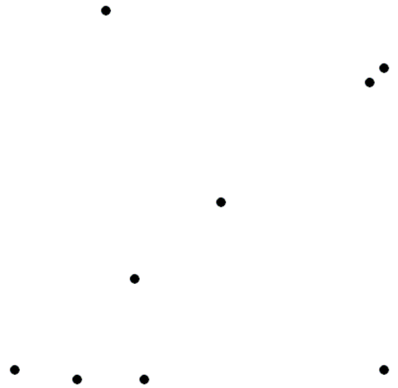
Existing HVAC and HVDC network in Europe



Network clustered to 181 nodes

The area is split using Voronoi cells

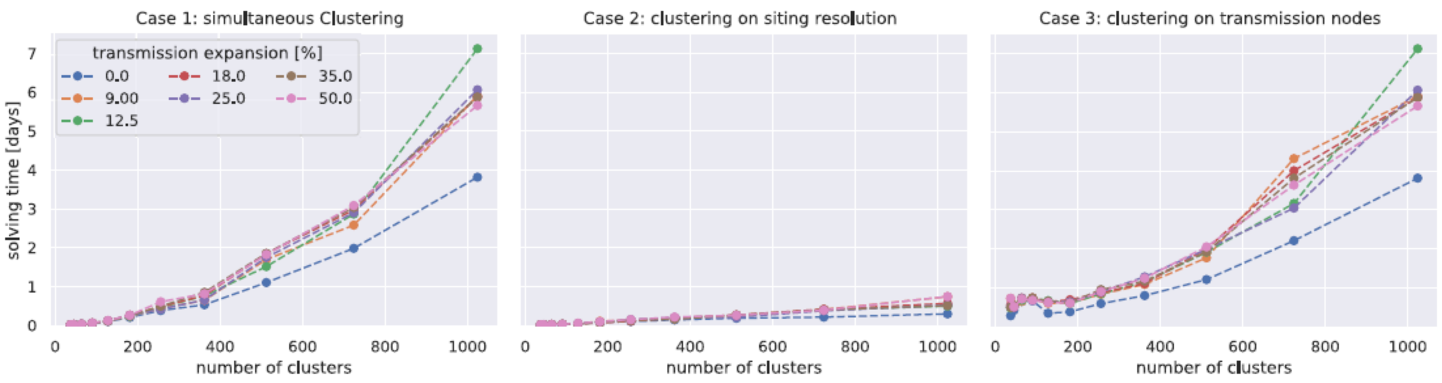
(each point assigned to the closest node)



Source: wikipedia

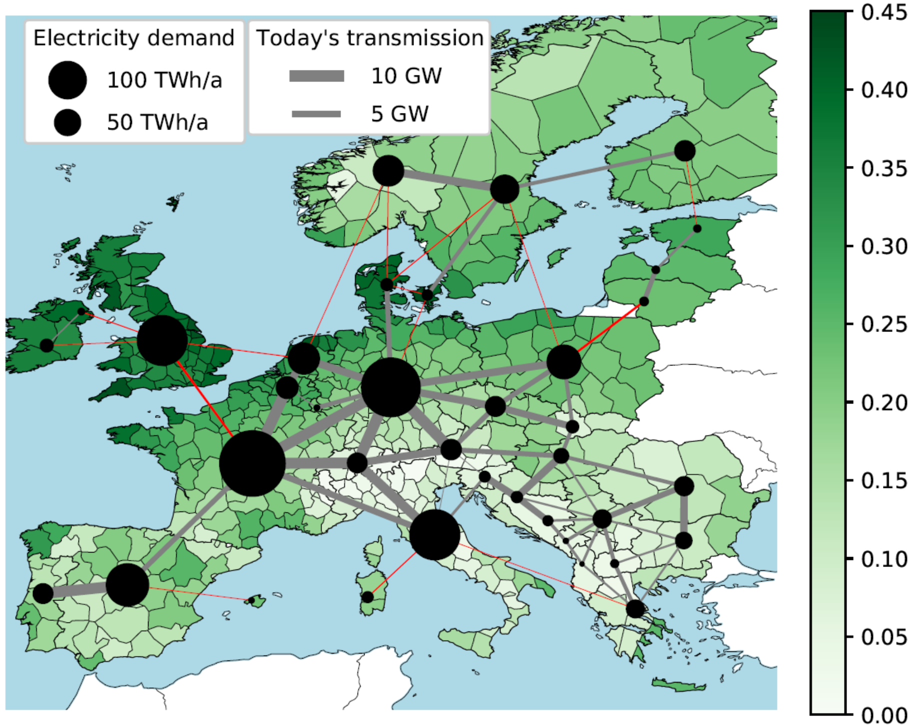
Which spatial resolution is good enough?

Attaining high resolution on transmission nodes increases solving time, but increasing (only) resolution on sites for renewable has negligible impact.



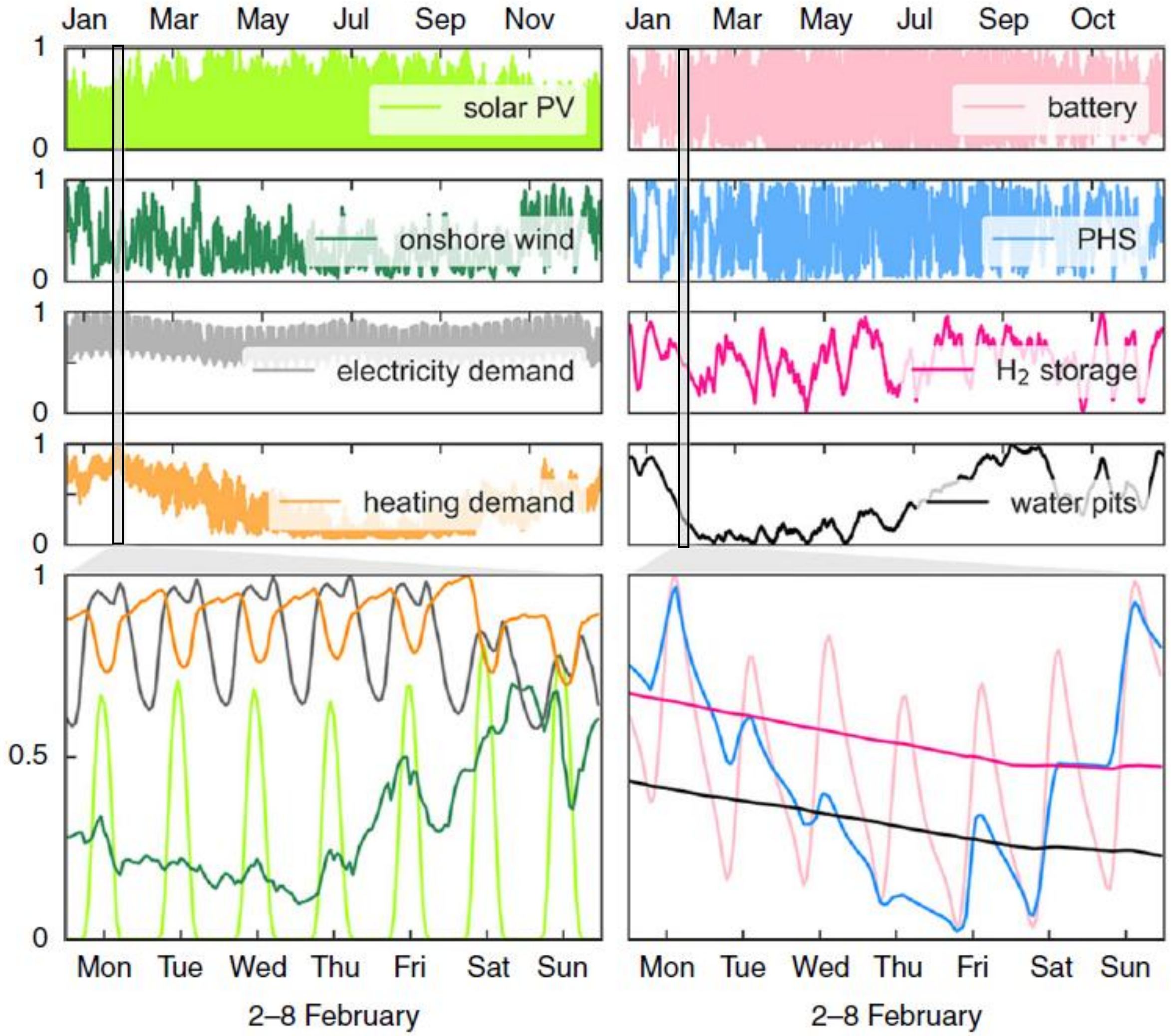
Frysztacki et al., Applied Energy (2021)

In our recent works, we keep a 37-node network and 370 nodes to resolve solar and wind resource.



Victoria et al., Joule (2022)

Which time resolution is good enough?



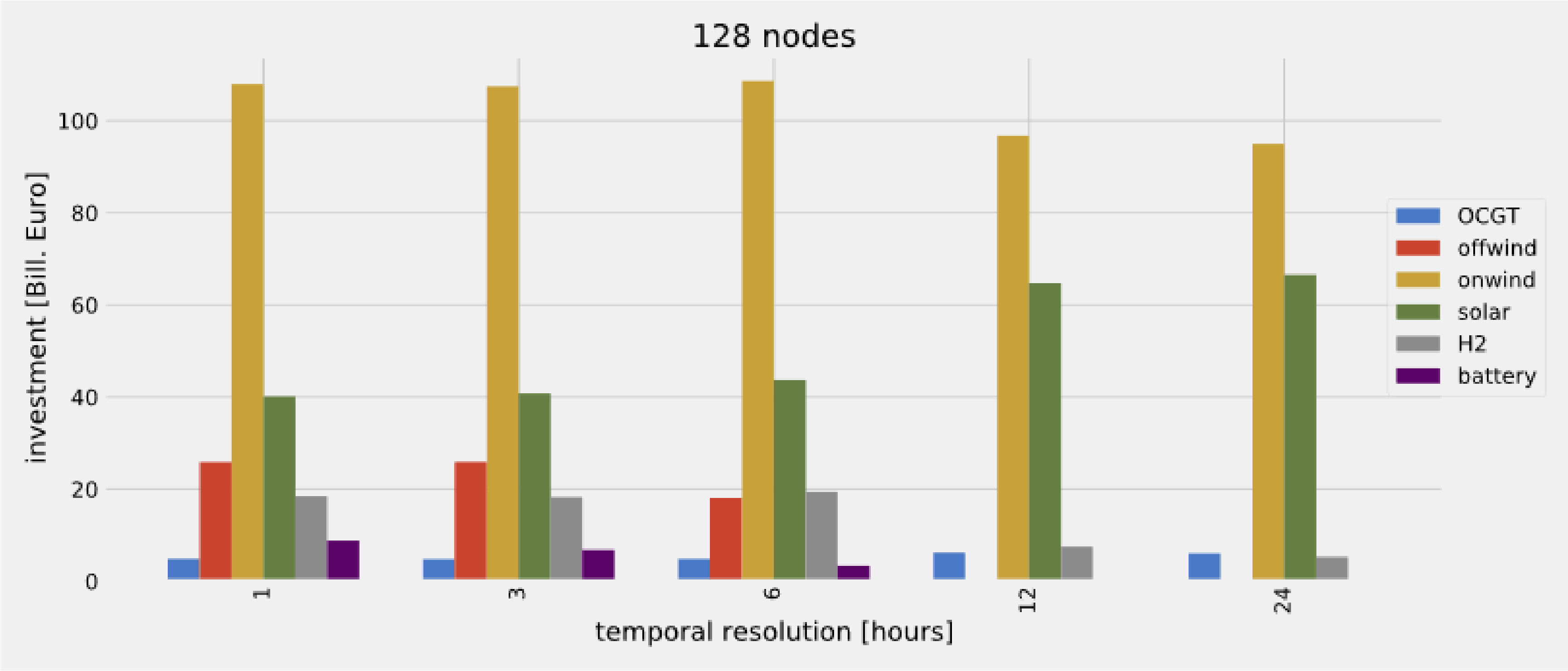
Victoria et al., Nature Commun. (2020)

We need **uninterrupted hourly time stepping for a full year** to capture the main fluctuations:

- solar and wind power generation smoothed by the grid and storage
- the role of long-term storage
- system operation during dark doldrums (i.e., periods with low wind and solar generation)

Which time resolution is good enough?

Resolution coarser than 3 hours get a solar balance “for free” and does not need batteries



Schyska et al., Joule. (2021)

Problems for this lecture

Problems 11.1 (**Group 22**)

Problems 11.2 (**Group 23**)