The Role of Spatial Scale in Joint Optimisations of Generation and Transmission for Highly Renewable Scenarios

T. Brown, J. Hörsch, S. Schramm

Frankfurt Institute for Advanced Studies (FIAS), University of Frankfurt

International Conference on Future Electric Power Systems and the Energy Transition, Champéry, Switzerland, 7th February 2017
1. The Challenges of Optimising Highly Renewable Energy Systems

2. Optimising Generation and Transmission Jointly

3. Spatial-Scale Dependence of Generation and Transmission Investment Optimisation

4. Conclusions
The Challenges of Optimising Highly Renewable Energy Systems
Three questions to answer

• How can we evaluate the two competing concepts for the ‘Energy Transition’: local, decentralised solar+storage versus large continental grids+wind?

• What are the consequences for the ‘Energy Transition’ if grid expansion is limited due to public acceptance problems?

• What is the consequence of modellers’ choice of spatial scale on optimisations of the energy system?
Examples from literature of energy system optimisation

<table>
<thead>
<tr>
<th>Study</th>
<th>Scope</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>What?</th>
<th>Flow physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Czisch (2005)</td>
<td>MENA</td>
<td>low</td>
<td>high</td>
<td>electricity (gen and grid)</td>
<td>transport</td>
</tr>
<tr>
<td>Hagspiel et al. (2014)</td>
<td>EU</td>
<td>medium</td>
<td>low</td>
<td>electricity (gen and grid)</td>
<td>linear</td>
</tr>
<tr>
<td>Egerer et al. (2014)</td>
<td>EU</td>
<td>high</td>
<td>low</td>
<td>electricity (grid only)</td>
<td>linear</td>
</tr>
<tr>
<td>Fraunhofers ISE, IWES DE</td>
<td>DE</td>
<td>none</td>
<td>high</td>
<td>electricity, heating, transport</td>
<td>none</td>
</tr>
</tbody>
</table>
Overarching goal

Find the “sweet spot” where:

- Computation time is finite (i.e. a week)
- Temporal resolution is “good enough”
- Spatial resolution is “good enough”
- Model detail is “good enough”

AND quantify the error we make by only being “good enough” (e.g. are important metrics ±10% or ±50% correct?)

AND be sure we’re got a handle on all sectoral interdependencies that might affect the results.
Optimising Generation and Transmission Jointly
Linear optimisation problem

Objective is the minimisation of total annual system costs, composed of capital costs \( c^* \) (investment costs) and operating costs \( o^* \) (fuel, etc.):

\[
\min f(\bar{P}_\ell, \bar{g}_{n,s}, g_{n,s,t}) = \sum_{\ell} c_\ell \bar{P}_\ell + \sum_{n,s} c_{n,s} \bar{g}_{n,s} + \sum_{n,s,t} w_t o_{n,s} g_{n,s,t}
\]

We optimise for \( n \) nodes, representative times \( t \) and transmission lines \( l \):

- the transmission capacity \( \bar{P}_\ell \) of all the lines \( \ell \)
- the generation and storage capacities \( \bar{g}_{n,s} \) of all technologies (wind/solar/gas etc.) \( s \) at each node \( n \)
- the dispatch \( g_{n,s,t} \) of each generator and storage unit at each point in time \( t \)

Representative time points are weighted \( w_t \) such that \( \sum_t w_t = 365 \times 24 \) and the capital costs \( c^* \) are annualised, so that the objective function represents the annual system cost.
Demand $d_{n,t}$ at each node $n$ and time $t$ is always met by generation/storage units $g_{n,s,t}$ at the node or from transmission flows $f_{\ell,t}$ on lines attached at the node (Kirchhoff’s Current Law):

$$d_{n,t} = \sum_s g_{n,s,t} + \sum_{\ell \in n} f_{\ell,t} \quad \leftrightarrow \quad \lambda_{n,t}$$

Nodes are shown as thick busbars connected by transmission lines (thin lines):

\[d_m = g_{m,w} + g_{m,s} + f_1 - f_2\]

\[d_n = g_{n,w} + g_{n,s} + f_2 + f_3\]
Generator/storage dispatch $g_{n,s,t}$ cannot exceed availability $\bar{g}_{n,s,t}$, which is bounded by capacity $\bar{g}_{n,s}$ and installable potential $\hat{g}_{n,s}$. Both the dispatch $g_{n,s,t}$ and the capacity $\bar{g}_{n,s}$ are subject to optimisation.

$$0 \leq g_{n,s,t} \leq \bar{g}_{n,s,t} \leq \bar{g}_{n,s} \leq \hat{g}_{n,s}$$
Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. They have a limited energy capacity (state of charge).

\[ \text{soc}_{n,t} = \eta_0 \text{soc}_{n,t-1} + \eta_1 g_{n,t,\text{store}} - \eta_2^{-1} g_{n,t,\text{dispatch}} \]

There are efficiency losses \( \eta \); hydroelectric dams can also have a river inflow.
The linearised power flows \( f_\ell \) for each line \( \ell \in \{1, \ldots, L\} \) in an AC network are determined by the reactances \( x_\ell \) of the transmission lines and the net power injection at each node \( p_n \) for \( n \in \{1, \ldots, N\} \).

The flows are related to the angles at the nodes:

\[ f_\ell = \frac{\theta_i - \theta_j}{x_\ell} \]  

(1)

In addition, the angle differences around each cycle must add to zero (Kirchoff’s Voltage Law).

Transmission flows cannot exceed the thermal capacities of the transmission lines (otherwise they sag and hit buildings/trees):

\[ |f_{\ell,t}| \leq \bar{P}_\ell \]

Since the impedances \( x_\ell \) change as capacity \( \bar{P}_\ell \) is added, we do multiple runs and iteratively update the \( x_\ell \) after each run, rather than risking a non-linear (or MILP) optimisation.
Constraints 5/5: Global constraints on CO\textsubscript{2} and transmission volumes

CO\textsubscript{2} limits are respected, given emissions $e_{n,s}$ for each fuel source $s$:

$$\sum_{n,s,t} g_{n,s,t} e_{n,s} \leq \text{CAP}_{\text{CO}_2} \quad \leftrightarrow \quad \mu_{\text{CO}_2}$$

We enforce a reduction of CO\textsubscript{2} emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

Transmission volume limits are respected, given length $d_\ell$ and capacity $\bar{P}_\ell$ of each line:

$$\sum_\ell d_\ell \bar{P}_\ell \leq \text{CAP}_{\text{trans}} \quad \leftrightarrow \quad \mu_{\text{trans}}$$

We successively change the transmission limit, to assess the costs of balancing power in time (i.e. storage) versus space (i.e. transmission networks).
Spatial-Scale Dependence of Generation and Transmission Investment Optimisation
We need spatial resolution to:

- capture the **geographical variation** of renewables resources and the load
- capture **spatio-temporal effects** (e.g. size of wind correlations across the continent)
- represent important **transmission constraints**

**BUT** we do not want to have to model all 5,000 network nodes of the European system.

**Source:** Own representation of Bart Wiegman’s GridKit extract of the online ENTSO-E map, https://doi.org/10.5281/zenodo.55853
There are lots of algorithms for clustering/aggregating networks, particularly in the engineering literature:

- $k$-means clustering on (electrical) distance
- $k$-means on load distribution
- Community clustering (e.g. Louvain)
- Spectral analysis of Laplacian matrix
- Clustering of Locational Marginal Prices with nodal pricing (sees congestion and RE generation)
- PTDF clustering
- Cluster nodes with correlated RE time series

The algorithms all serve different purposes (e.g. reducing part of the network on the boundary, to focus on another part).
Our goal: maintain main transmission corridors of today to investigate highly renewable scenarios with no grid expansion. Since generation fleet is totally rebuilt, do not want to rely on current generation dispatch (like e.g. LMP algorithm).

Today’s grid was laid out to connect big generators and load centres.

Solution: Cluster nodes based on load and conventional generation capacity using $k$-means.

I.e. find $k$ centroids and the corresponding $k$-partition of the original nodes that minimises the sum of squared distances from each centroid to its nodal members:

$$\min_{\{x_c\}} \sum_{c=1}^{k} \sum_{n \in N_c} w_n ||x_c - x_n||^2$$

(2)

where each node is weighted $w_n$ by the average load and the average conventional generation there.
Reconstitution of network

Once the partition of nodes is determined:

- A new node is created to represent each set of clustered nodes
- Hydro capacities and load is aggregated at the node; VRE (wind and solar) time series are aggregated, weighted by capacity factor; potentials for VRE aggregated
- Lines between clusters replaced by single line with length \(1.25 \times \text{crow-flies-distance}\), capacity and impedance according to replaced lines
- \(n - 1\) blanket safety margin factor grows from 0.3 with \(\geq 200\) nodes to 0.5 with 37 nodes (to account for aggregation)
**k-means clustering: Networks**

- Full Network
- Network with 362 clusters
- Network with 181 clusters
- Network with 128 clusters
- Network with 64 clusters
- Network with 37 clusters
Question of spatial resolution

How is the overall minimum of the cost objective (building and running the electricity system) affected by an increase of spatial resolution in each country?

We expect

- A better representation of existing internal bottlenecks will prevent the transport of e.g. offshore wind to the South of Germany.
- Localised areas of e.g. good wind can be better exploited by the optimisation.

Which effect will win?

First we only optimize the gas, wind and solar generation capacities, the long-term and short-term storage capacities and their economic dispatch including the available hydro facilities **without grid expansion**.
Steady total system cost at € 260 billion per year

This translates to € 82/MWh (compared to today of € 50/MWh to € 60/MWh)
If we break this down into technologies:

- 37 clusters captures around half of total network volume
- Redistribution of capacities from offshore wind to solar
- Increasing solar share is accompanied by an increase of battery storage
- Single countries do not stay so stable
Costs: Focus on Germany (w/o grid expansion)

- Offshore wind replaced by onshore wind at better sites and solar (plus batteries), since the represented transmission bottlenecks make it impossible to transport the wind energy away from the coast
- the effective onshore wind capacity factors increase from 26% to up to 42%
- Investments stable at 181 clusters and above

![Graph showing system cost vs number of clusters for different types of energy systems](image)
Nodal energy shares per technology (w/o grid expansion)
6 different scenarios of network expansion by constraining the overall transmission line volume in relation to today’s line volume \( \text{CAP}_{\text{trans}}^{\text{today}} \), given length \( d_l \) and capacity \( \bar{P}_l \) of each line \( l \):

\[
\bar{P}_l \geq \bar{P}_l^{\text{today}} \quad (3)
\]

\[
\sum_{l} d_l \bar{P}_l \leq \text{CAP}_{\text{trans}} \quad (4)
\]

where

\[
\text{CAP}_{\text{trans}} = x \text{CAP}_{\text{trans}}^{\text{today}} \quad (5)
\]

for \( x = 1 \) (today’s grid) \( x = 1.125, 1.25, 1.5, 2, x = 3 \) (optimal for overhead line at high number of cluster).
Costs: Total system cost

- Steady cost for No Expansion (1)
- For expansion scenarios, as clusters increase, the better exploitation of good sites decreases costs faster than transmission bottlenecks increase them.
- Decrease in cost is very non-linear as grid expanded (25% grid expansion gives 50% of optimal cost reduction).
- Only a moderate 20 – 25% increase in costs from the Optimal Expansion scenario (3) to the No Expansion scenario (1).
Costs: Break-down into technologies

- **System cost (EUR billion p.a.)**
- **Number of clusters**
- **Type**
  - onshore wind
  - offshore wind
  - solar
  - gas
  - gas (marginal)
  - battery storage
  - hydrogen storage
  - transmission lines

Branch limits for different types of systems:
- branch_limit = 1.0
- branch_limit = 1.5
- branch_limit = 3.0
Costs: Focus on Germany (CAP = 3)

- Investment reasonably stable at 128 clusters and above
- System consistently dominated by wind
- No solar or battery for any number of clusters
Behaviour as CAP is changed

- Same non-linear development with high number of nodes that we saw with one node per country
- Most of cost reduction happens with small expansion; cost rather flat once capacity has doubled, reaching minimum (for overhead lines) at 3 times today’s capacities
- Solar and batteries decrease significantly as grid expanded
- Reduction in storage losses too
256 clusters, branch limit of 1.5 of today's capacities

256 clusters, branch limit of 3 of today's capacities

AC expansion (= 10 GW)
DC expansion (= 10 GW)
Capacity (= 25 GW)
Locational Marginal Prices CAP=1 versus CAP=3

With today’s capacities:

With three times today’s grid:
With overhead lines the optimal system has around 3 times today’s transmission volume.

With underground cables (5-8 times more expensive) the optimal system has around 1.3 to 1.6 times today’s transmission volume.
CO2 prices versus line cap for 181 clusters

- CO2 price of between 150 and 250 €/tCO2 required to reach these solutions, depending on line volume cap
Idea of Open Energy Modelling

The whole chain from raw data to modelling results should be open:

Open data + free software ⇒ Transparency + Reproducibility

There’s an initiative for that! Next workshop in Frankfurt, 19-21 April 2017.

Source: openmod initiative
The FIAS software PyPSA is online at http://pypsa.org/ and on github. It can do:

- Static power flow
- Linear optimal power flow
- Security-constrained linear optimal power flow
- Total electricity system investment optimisation

It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables and sector coupling.
Conclusions
Conclusions

- This is no single solution for highly renewable systems, but a family of solutions with different costs and compromises.
- Generation costs always dominate grid costs, but the grid can cause higher generation costs if expansion is restricted.
- Systems with no grid extension beyond today are up to 25% more expensive, but small grid extensions (e.g. 25% more capacity than today) can lock in big savings.
- Need at least around 200 clusters for Europe to see grid bottlenecks if no expansion.
- Can get away with ~ 120 clusters for Europe if grid expansion is allowed.
- Much of the stationary storage needs can be eliminated by sector-coupling: DSM with electric vehicles, thermal storage; this makes grid expansion less beneficial.
- Understanding the need for flexibility at different temporal and spatial scales is key to mastering the complex interactions in the energy system.
Unless otherwise stated, the graphics and text are Copyright ©Tom Brown, 2017.

The source LaTeX, self-made graphics and Python code used to generate the self-made graphics are available here:

http://nworbmot.org/talks.html

The graphics and text for which no other attribution are given are licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.
### Cost and other assumptions

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Overnight Cost [€]</th>
<th>Unit</th>
<th>FOM [%/a]</th>
<th>Lifetime [a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind onshore</td>
<td>1182</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Wind offshore</td>
<td>2506</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Solar PV</td>
<td>600</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Gas</td>
<td>400</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>Battery storage</td>
<td>1275</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>2070</td>
<td>kW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>1.7</td>
<td>20</td>
</tr>
<tr>
<td>Transmission line</td>
<td>400</td>
<td>MWkm</td>
<td>2</td>
<td>40</td>
</tr>
</tbody>
</table>

Interest rate of $7\%$, storage efficiency losses, only gas has CO<sub>2</sub> emissions, gas marginal costs.
Shadow costs of line extension CAP for 3 times today’s volume

- For 200+ nodes the shadow price converges on the annual cost of a MWkm of overhead line (around € 30/a/MWkm)
- Value of lines is much higher with smaller number of clusters. Why?
- Possible reasons: inter-connectors in general weaker than country-internal connectors; more nodes means more flexibility to avoid network expansion