Energy transmission networks at different scales
Method, results and limits

Johannes Dorfner
Institute for Renewable and Sustainable Energy Systems
Technical University of Munich

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Section 1

Introduction
Modelling of energy systems on different scales, e.g. smart micro grids, regional and global energy systems

Technology focused system models including socio-economic and environmental aspects

Development of future power systems including smart micro-grids and super-grids
### Method
Optimal planning and operation of technical energy infrastructure

### Results
Energy systems from buildings over countries to continents

### Limits
Multiple objectives, unquantifiable constraints, trade-off decisions
Section 2

Method
High-level model overview: space

Main use: distance relationships for energy transmission cost and losses
High-level overview: time
Main use: Storage technologies and intermittent renewable energy feed-in

Annual time series of power generation from solar (PV) and wind (turbine) for a location in Southern Bavaria, Germany. Curve = daily mean; area = daily min/max.
Each node in an energy system graph can contain a similar, but independently planned/operated process chain.
With vector $\mathbf{x} \in \mathbb{R}^n$ of decision variables, cost vector $\mathbf{c} \in \mathbb{R}^n$ and constraint matrix/vector $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{b} \in \mathbb{R}^m$ most of our models fall into the family of linear programs (LPs):

\begin{align}
\text{min } & \mathbf{c}^T \mathbf{x} \\
\text{s.t. } & \mathbf{A} \mathbf{x} \leq \mathbf{b}
\end{align}

Optimal solution attainable even for large $(m, n \to 10^7)$ problems. Through linearisation, also non-linear convex problems can be modelled with good precision. Main limitation: linearity of models does not allow modelling “concave” problems.
Binary decision variables $x \in \{0, 1\}$ allow to approximate \textbf{economics of scale}: Higher capacities $P$ (kW) lead to lower specific costs $z$ (€/a).

\textbf{LP}

$$z = c_{\text{var}}P \quad (3)$$

\textbf{MILP}

$$z = c_{\text{fix}}x + c_{\text{var}}P \quad (4)$$

$$P \leq x P_{\text{max}} \quad (5)$$

$$P \geq x P_{\text{min}} \quad (6)$$
General idea: rely on proven methods for modelling and solving optimisation problems. Concentrate on **controlling assumptions** and **interpreting results** rather than spending more time on adding (arbitrary) precision to models whose inputs necessarily have a high margin of error.
Energy transition is set. At least in Germany, nuclear fission is no longer an option. Long term reduction of greenhouse gas emissions in the power sector.

Long-term goal therefore: decarbonised power sector with large share of fluctuating renewable energy sources.

Main challenge: how to cover must energy demand from intermittent sources without sacrificing full demand coverage?
Section 3

Results
Local scale: neighborhoods & cities

Assumption: flexibility (power conversion & storage) within each single building
Question: what is the benefit of coordination & cooperation for a group of homes?

_Coordinating Smart Homes in Microgrids: A Quantification of Benefits_, M. Huber, F. Sänger, T. Hamacher; IEEE ISGT 2013; URL: [https://mediatum.ub.tum.de/node?id=1177232](https://mediatum.ub.tum.de/node?id=1177232)

(a) individually operating
(b) connected (independent operation)
(c) EMS (central operation)
Degree of autonomy for smart homes
(No) storage, either with PV only (left) or with PV and CHP combined (right)

Effect of local storage with PV caps out early. If more collaboration (shared storage) is allowed, maximum attainable local supply is increased.
Question: how to integrate fluctuating renewables on a national (Germany) scale? High degree of autonomy (to lower carbon emissions) is needed.

Iteratives Modell zur Optimierung von Speicherausbau und -betrieb in einem Stromsystem mit zunehmend fluktuierender Erzeugung, P. Kuhn; Dissertation, 2012; URL: https://mediatum.ub.tum.de/node?id=1271192
Use of different storage technologies

Pumped hydro for daily, hydrogen for seasonal use (year 2050)

- Exact form of results highly dependent on wind power time series
- Especially optimal size of hydrogen storage very sensitive (3 TWh to 22 TWh)
- Pumped hydro and compressed air mainly for peak demand satisfaction
- Full integration of renewable surplus not achievable/desirable
Main questions
(What are|Are there) benefits to linked electricity generation in EU und MENA (Middle East, North Africa)?

Method
Cost-minimal power generation system for over 30 scenarios (technology costs, CO₂ restrictions) with and without possible link from EU 27+2 (CH, NO) and MENA (9)

*Electricity system optimization in the EUMENA region*, M. Huber, J. Dorfner, T. Hamacher; technical report; 2012; DOI: 10.14459/2013md1171502
Result
Cost-minimal power generation and transmission capacities

Main constraint
Full power demand satisfaction through cheapest mix of fluctuating renewable energy sources

Power exchange is *not* required, but possible (after investing in transmission)
Large scale: EU-MENA study

Result base scenario: 3 weeks in EU
Large scale: EU-MENA study

Result base scenario II: 3 weeks in MENA

[Graph showing power generation and energy transmission over time]
Wind (onshore) dominating power source (reason: assumed cheapest)
- CSP, biogas and natural gas main *controllable* power source
- Transmission helps significantly in balancing of demand and supply
In a strict renewable (low GHG emissions) regime, the cheapest system designs tend to be solutions that favour **transmission over storage**.

On a **local scale**, only low degrees of independence from an overlaying infrastructure (power grid, ...) can reasonably be achieved.

On a medium (country) scale, autarky in power production is within reach if supply chains and fuel sources are not part of the system.

Sector coupling (electricity, heating & cooling, transport) to the common energy carrier electricity unlocks synergies, but increases technical complexity.

*Challenges and opportunities of power systems from smart homes to super-grids*, P. Kuhn, M. Huber, J. Dorfner, T. Hamacher; Ambio 45(1):50–62; 2016; DOI: 10.1007/s13280-015-0733-x
Interpretation limits of optimisation studies

What these results do not mean

These results only indicate a very stylised, technical feasibility of those systems. They ignore everything except costs, efficiencies, emissions, hard supply limits. Questions:

1. What is the “price” of mutual dependence?
2. Which optimisation criterion is the “best” to choose? Welfare? EROI?
3. How to determine the “optimal” trade-off between different goals?

Different weightings of objectives \((z_1, z_2)\) lead to different optima on the boundary of feasible solutions.
Section 4

Conclusion
**Conclusion**

**What to remember?**

- **Modelling** allows finding *cost*-minimal technical systems
- **Results** currently transmitting energy is cheaper than *storing*
- **Limits** of models stem from goals difficult (or impossible) to quantify
- **Trade-off** between goals must happen as a decision outside of modelling