Energy transmission networks at different scales

Method, results and limits

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Section 1

Introduction

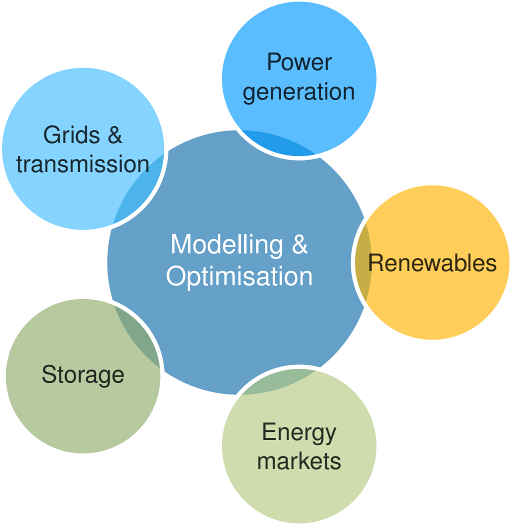
Institute for Renewable and Sustainable Energy Systems

Chair at TUM Department of Electrical and Computer Engineering

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**



This talk

Outline

Method

Optimal planning and operation of technical energy infrastructure

Results

Energy systems from buildings over countries to continents

Limits

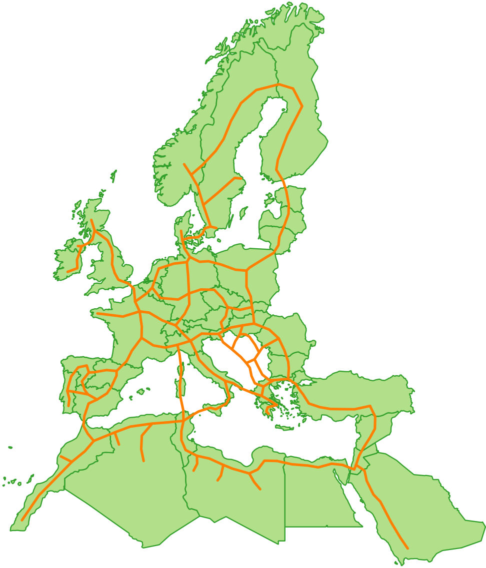
Multiple objectives, unquantifiable constraints, trade-off decisions

Section 2

Method

High-level model overview: space

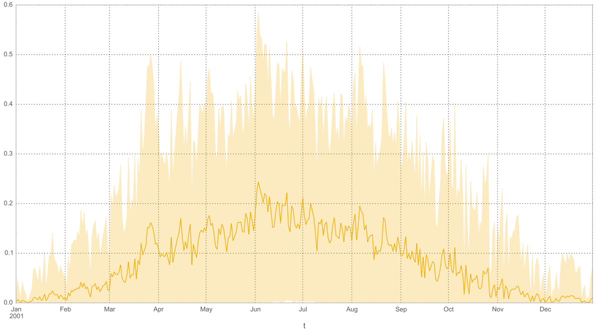
Main use: distance relationships for energy transmission cost and losses

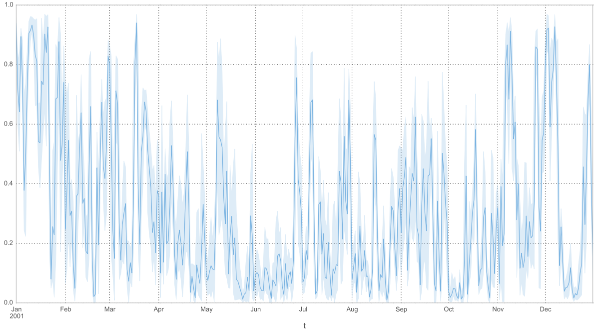


High-level overview: time

Main use: Storage technologies and intermittent renewable energy feed-in

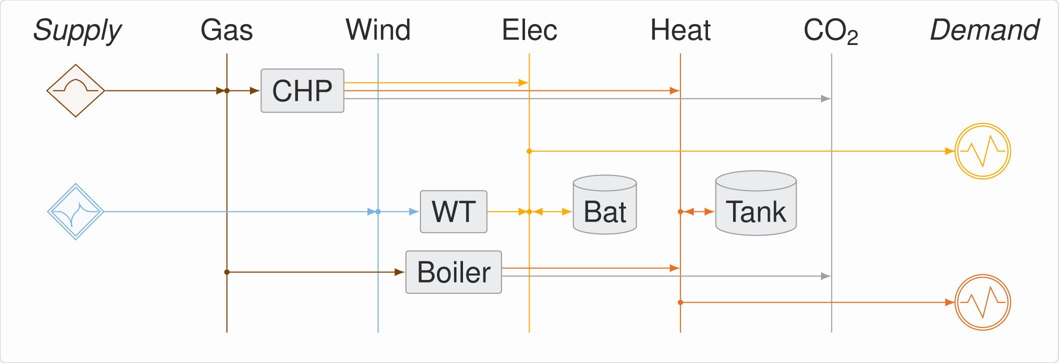
Annual time series of power generation from solar (PV) and wind (turbine) for a location in Southern Bavaria, Germany. Curve = daily mean; area = daily min/max





Technology

Reference energy representation for arbitrary process chains



Each node in an energy system graph can contain a similar, but independently planned/operated process chain

Mathematical modelling I

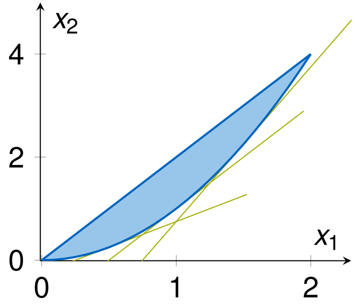
Linear programming for scalable problem formulations

With vector $\boldsymbol{x} \in \mathbb{R}^n$ of decision variables, cost vector $\boldsymbol{c} \in \mathbb{R}^n$ and constraint matrix/vector $\boldsymbol{A} \in \mathbb{R}^{m \times n}$, $\boldsymbol{b} \in \mathbb{R}^m$ most of our models fall into the family of linear programs (LPs):

$$\min \boldsymbol{c}^\mathrm{T}\boldsymbol{x} \tag{1}$$

$$\text{s.t. } \boldsymbol{Ax} \leq \boldsymbol{b} \tag{2}$$

Optimal solution attainable even for large ($m, n \rightarrow 10^7$) 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.



Example of a convex region approximated by sequence of three linear constraints

Mathematical modelling II

Linear and mixed-integer linear programming

Binary decision variables $x \in \{0, 1\}$ allow to approximate **economics of scale**: Higher capacities P (kW) lead to lower specific costs z (€/a).

LP

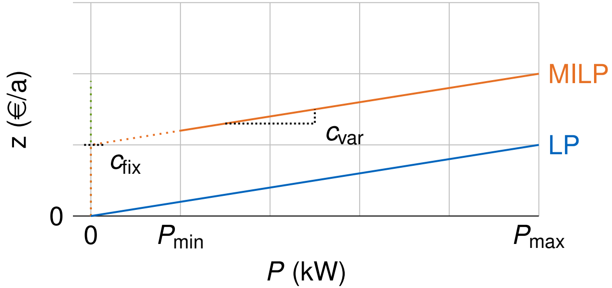
$$z = c_{\text{var}} P \qquad (3)$$

MILP

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

$$P \leq x \, P_{\max} \qquad (5)$$

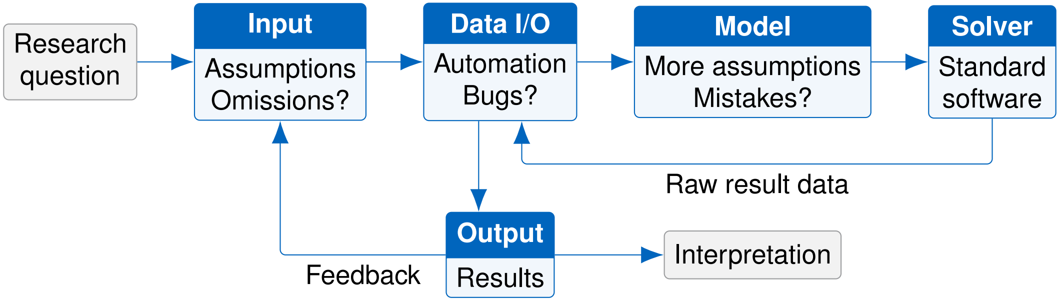
$$P \geq x \, P_{\min} \qquad (6)$$



Optimisation framework

Conceptual overview on the full

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.



Background for the following results

Common assumption

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.

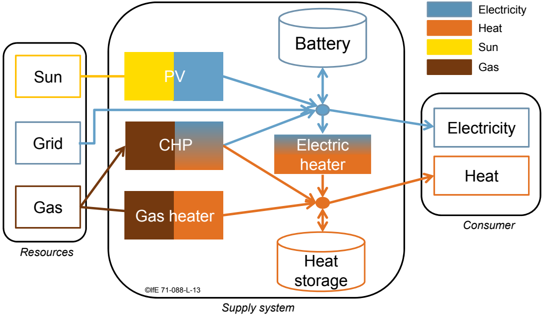
Long-term goal therefore: decarbonised power sector with large share of fluctuating renewable energy sources.

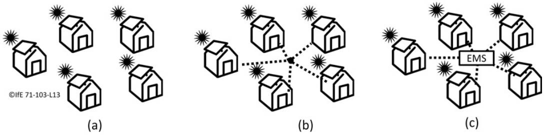
Main challenge: how to cover must energy demand from intermittent sources without sacrificing full demand coverage?

Section 3

Results

Local scale: neighboorhoods & cities





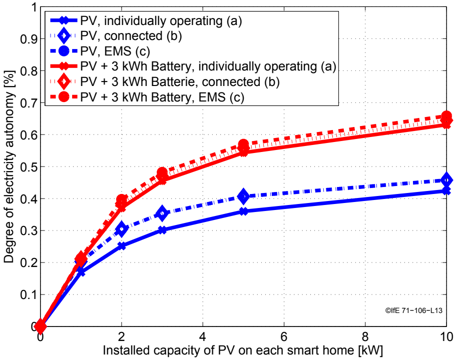
(a) individually operating
(b) connected (independent operation)
(c) EMS (central operation)

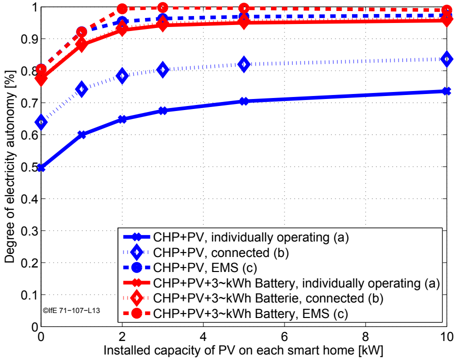
Assumption: flexibility (power conversion & storage) within each single building
Question: what is the benefit of coordination & cooperation for a group of homes?

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

Degree of autonomy for smart homes

(No) storage, either with PV only (left) or with PV and CHP combined (right)

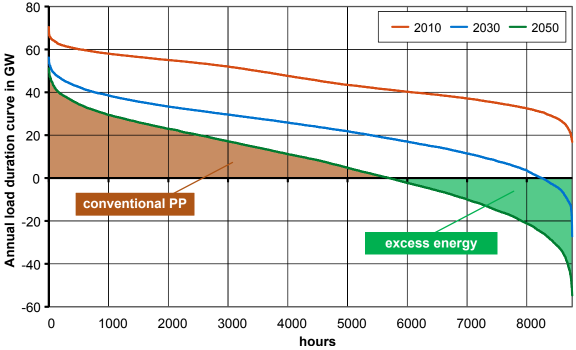


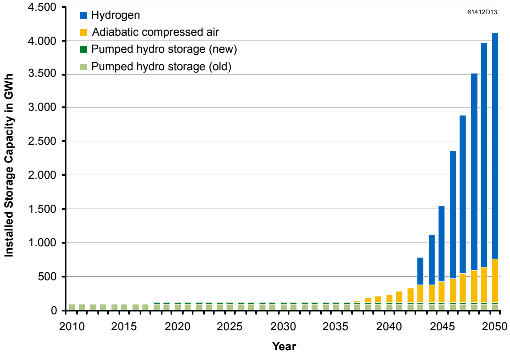


Effect of local storage with PV caps out early. If more collaboration (shared storage) is allowed, maximum attainable local supply is increased.

Medium scale: regions & countries

Residual load curve and storage for a national power system



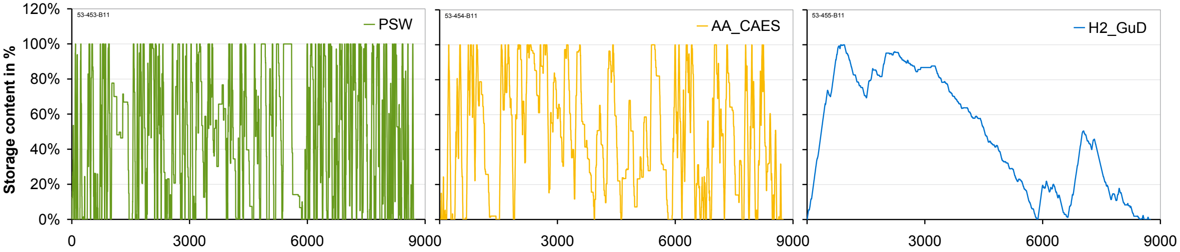


Question: how to integrate fluctuating renewables on a national (Germany) scale? High degree of autonomy (to lower carbon emissions) is needed.

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

Large scale: EU-MENA study

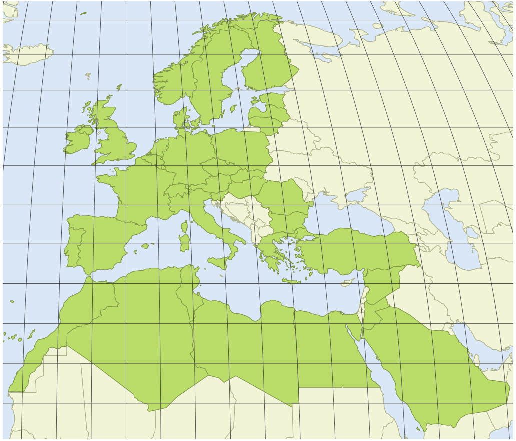
Approach (1/2)

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, CO_2 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

Large scale: EU-MENA study

Approach (2/2)

Result

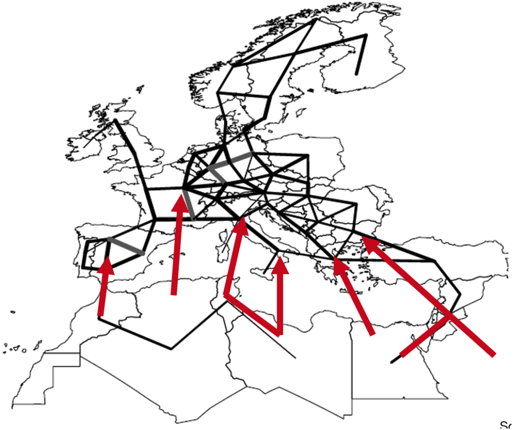
Cost-minimal power generation and transmission capacities

Main constraint

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

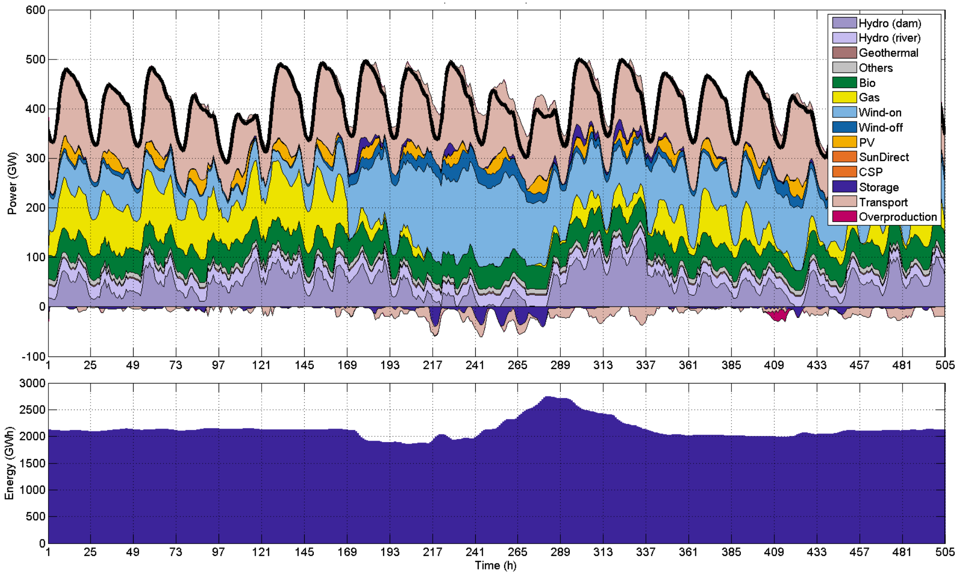
Power exchange

is *not* required, but possible (after investing in transmission)



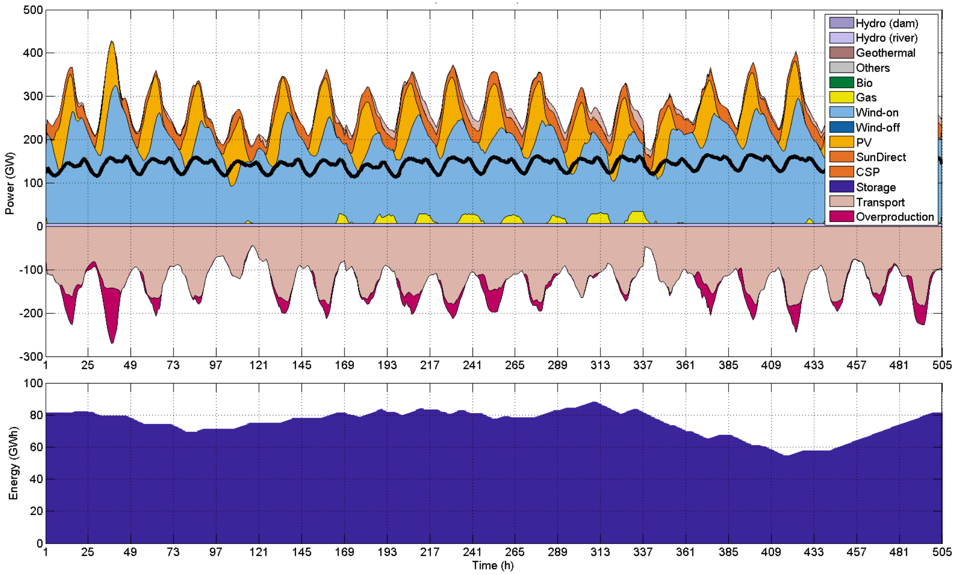
Large scale: EU-MENA study

Result base scenario: 3 weeks in EU



Large scale: EU-MENA study

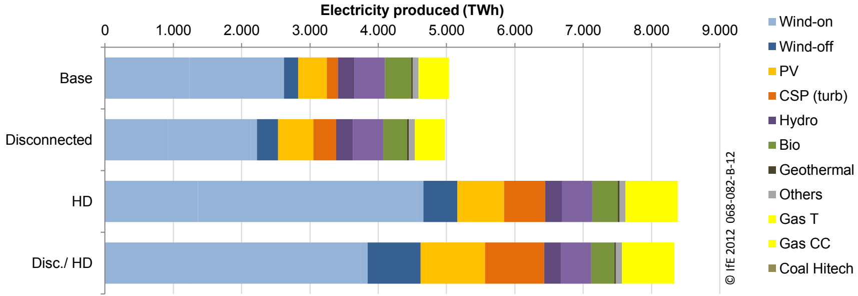
Result base scenario II: 3 weeks in MENA



Large scale: EU-MENA study

Result comparison of four main scenarios

- 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



Obersvations

Drawn from research on all scales

- 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 achieved
- On a medium (country) scale, autarky in power production is within reach if supply chains and fuel sources are not part of the
- Sector coupling (electricity, heating & cooling, transport) to the common energy carrier electricity unlocks synergies, but increases technical complexity

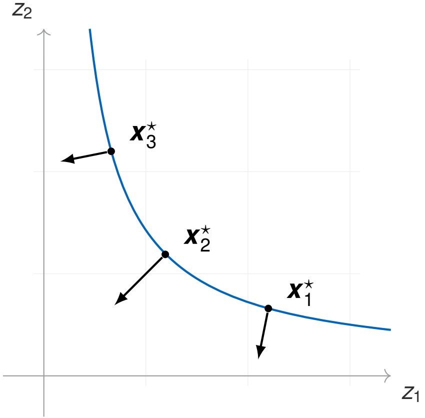
Challenges and opportunities of power systems from smart homes to super-grids, P. Kuhn, M. Huber, J. Dorfner, T. Hamacher; Ambio 45(1):50–62; 2016; DOI: 10.1007/s13280-015-0733-x

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