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Probabilistic welfare analysis for system adequacy – analytical and numerical insights

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Motivation

European Single Market for Electricity → requires integration of infrastructure

Growing share of renewable contribution to generation → growing need for infrastructure expansion and backup capacity

Increasing cross-border flows → Need for Transmission expansion

Derive the **value of transmission and generation capacity** as components of system adequacy

Agenda

1. Introduction

2. Methodology
   - Single-node system
     generation adequacy accounting for generation outages
   - 2-node system
     generation and transmission adequacy accounting for generation and transmission outages

3. Application
   - Single-node system
   - 2-node system

4. Conclusions and outlook

Introduction

- Probabilistic approach to system adequacy
  - Generation adequacy
  - Generation and transmission adequacy
- Value of transmission capacity
  - **Increasing reliability by replacing backup capacity/ pooling generation capacity**
  - More efficient use of resources/ generation potential
  - Smoothening of demand asynchronies
- Concept: Social welfare analysis
  - Perspective of a central social planner
  - As two stage decision problem
    - 1st: investment into generation (and transmission) capacity
    - 2nd: operation of existing system

Methodology

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- Objective function

$$\max_{K_i, L_{i,j}, y_i(t,s(t)), f_{i,j}(,t,s(t))} W = \int_0^T \sum_{s \in S} \pi_{s(t)} \left[v \cdot (D_i(s,t) - u_i(s,t)) - c_{var,i} \cdot y_i(s,t) \right] dt - C_{inv}$$

- Subject to several constraints:
  - $y_i(s,t) \le \psi_i(s,t) \cdot K_i$
  - $D_i(s,t) = y_i(s,t) + \sum_{j=1}^{J} f_{j,i}(s,t) - \sum_{j=1}^{J} f_{i,j}(s,t) + u_i(s,t)$
  - $f_{i,j} \le \psi_{i,j}(s,t) \cdot L_{i,j}$

Methodology: single-node system

- Setting
  - Generation capacity: single controllable conventional technology subject to outages
  - Inelastic demand function: load duration curve approximated by linear function
- Lagrangian function

$$L(K, y, u, \lambda_E, \lambda_K) = \int_0^T \sum_{s \in S} \pi_{s(t)} [v \cdot (D - u) - c_{var} \cdot y]\, dt - \lambda_E \cdot [D - y - u] - \lambda_K \cdot [y - \psi K] - c_{inv} \cdot K$$

- Necessary conditions for optimal decisions
  - $\frac{\partial L}{\partial y(t,s(t))} = \pi_{s(t)} \cdot (-c_m + \lambda_E - \lambda_K) \leq 0 \qquad \perp y(t, s(t)) \geq 0 \qquad (1)$
  - $\frac{\partial L}{\partial u(t,s(t))} = \pi_{s(t)} \cdot \left(-v + \lambda_E\big(t, s(t)\big)\right) \leq 0 \qquad \perp u(t, s(t)) \geq 0 \qquad (2)$
  - $\frac{\partial L}{\partial \lambda_E(t,s(t))} = D(t, s(t)) - y\big(t, s(t)\big) - u(t, s(t)) \stackrel{!}{=} 0 \qquad (3)$
  - $\frac{\partial L}{\partial \lambda_K(t,s(t))} = y(t, s(t)) - \psi\big(t, s(t)\big)K \leq 0 \qquad \perp \lambda_K \geq 0 \qquad (4)$
  - $\frac{\partial L}{\partial K} = -c_{inv} + \int_0^T \sum_{s \in S} \pi_{s(t)} \cdot \lambda_K\big(t, s(t)\big)\, dt \leq 0 \qquad \perp K \geq 0 \qquad (5)$
- Results
  - Non-binding capacity constraint: $\lambda_K = 0, \quad \lambda_E = c_m$
  - Binding capacity constraint: $\lambda_K > 0, \quad \lambda_E = v$

→ $c_{inv} = \int_0^T \sum_{s \in S} \pi_{s(t)} \cdot \lambda_K\big(t, s(t)\big)\, dt$

Methodology: 2-node system

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- Setting
  - Generation capacity: one controllable conventional technology in each country
  - Assumption: $c_{m1} < c_{m2}$
  - Transmission investment

- Objective function

$$W = \int_0^T \sum_{s \in S} \pi(s,t)[v \cdot (D_1(t,s) + D_2(t,s) - u_1(t,s) - u_2(t,s)) - c_{m1}y_1(t,s) - c_{m2}y_2(t,s)]\, dt - c_{inv1} \cdot K_1 - c_{inv2} \cdot K_2 - c_{invl} \cdot L_{12}$$

- Necessary conditions for optimal decisions
  - 6 FOCs for shadow prices
  - 5 FOCs for 2nd stage decision variables
  - 3 FOCs for 1st stage decision variable

  → Distinguish different situations according to relevance of capacity constraints

Methodology: 2-node system

Different situations according to the relevance of capacity constraints

Binding transmission constraint

- Excess local generation capacity

  ① $\lambda_{L1} = c_{m2} - c_{m1}$

- Binding generation capacity constraint in country 2

  ② $\lambda_{L1} = v - c_{m1}$

- Binding generation capacity constraint in country 1

  ③ $\lambda_{L2} = v - c_{m2}$

Excess transmission capacity ④ ⑤ ⑥

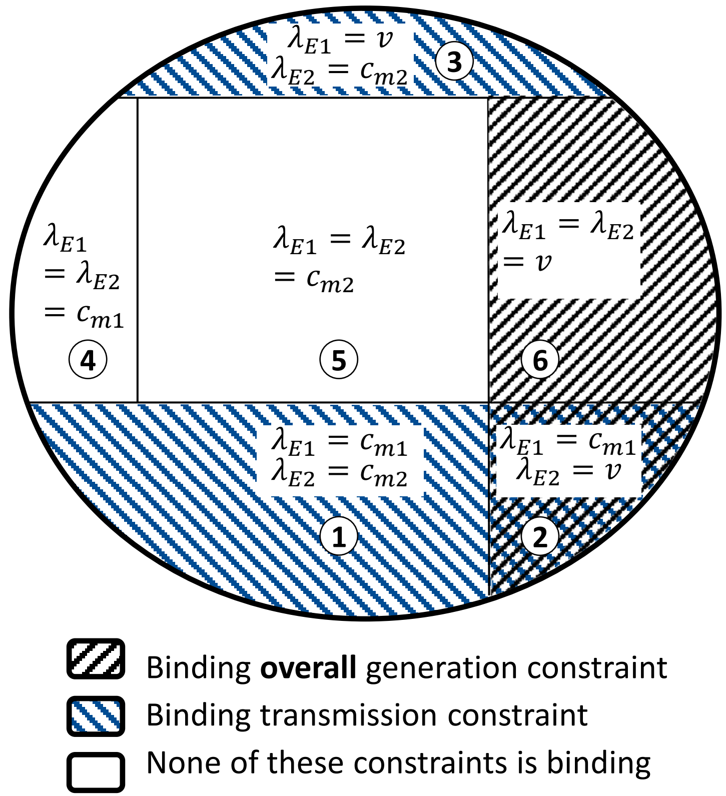
→ No price differences although possibility of transmission increases overall surplus

→ Zero value added by marginal transmission line

$$\lambda_{L1} = \lambda_{L2} = 0$$

→ Refinancing of investment costs

$$c_{inv,L} = \int_0^T \sum_{s \in S} \pi_{s(t)} \psi_L (\lambda_{L1} - \lambda_{L2})\, dt$$



Application: single-node system

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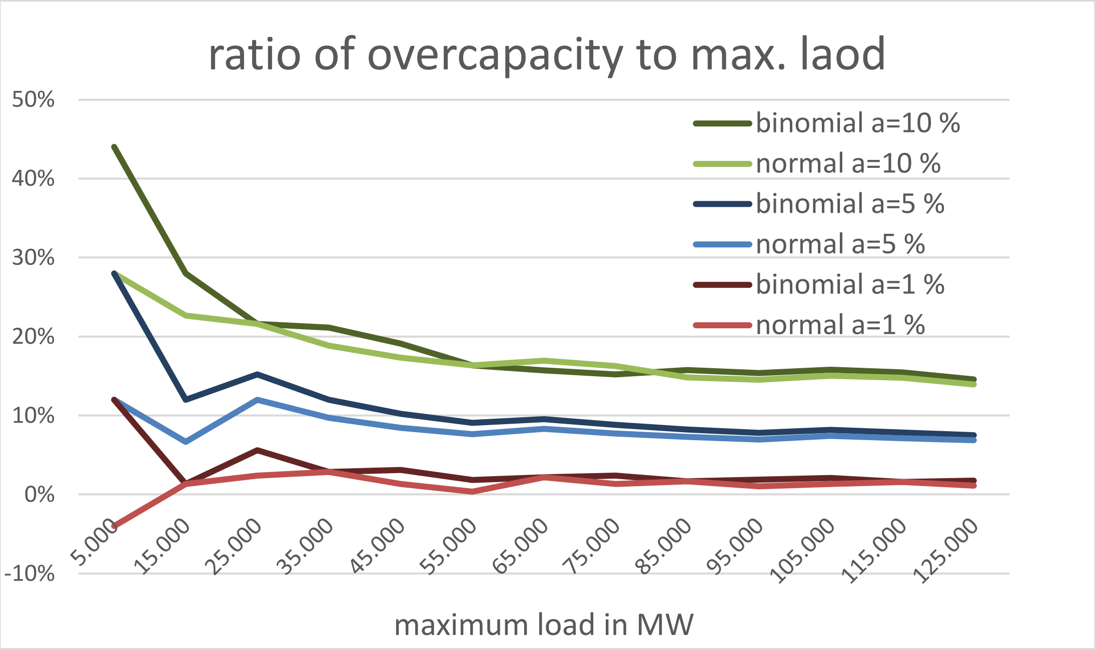
- Germany
  - Simplified linearized load duration curve: max. load 86,000 MW, min. 43,000 MW
  - Assumption: lumpy investment in equally sized generation units (800 MW)
  - Optimal generation capacity: 117 generation units, i.e. 93,600 MW generation capacity (108 without outages)

- Dependence on system size
  - Comparison: binomial vs normal distribution of outages
  - Small differences for large systems
  - Normal distribution underestimates optimal overcapacity for small systems



Application: 2-node system

- Parameterization calibrated on Germany and the Netherlands
  - Lumpy generation (800 MW) and transmission (500 MW) investment

- Assumptions
  - Demand in both countries is perfectly correlated

  → Transmission value arising from balancing of asynchronous demand pattern is not accounted for
  - Single generation technology and unit size in both countries

  → Transmission value arising from more efficient use of generation capacity is not accounted for

- Examined cases
  - Abundant transmission capacity
  - No transmission capacity
  - Optimal transmission capacity

Application: 2-node system

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Case	Region	Max. Load (MW)	n*	Generation cap (MW)	L*	Transmission cap (MW)	System costs (bn €)	Decision variable(s)
Copper plate	Total	95,000	**128**	102,400	∞	abundant*	35.362	n (# generation units)
Separate systems	Total	95,000	131	104,800	0	0	35.451	
	DE	71,250	**97**	77,600				n_i (# national generation units)
	NL	23,750	**34**	27,200				n_i
Optimal Tcap	Total	95,000	128	102,400	**6**	3,000	35.365	n_i, transmission capacity
	DE	71,250	**95**	76,000				
	NL	23,750	**33**	26,400				

* in copper plate case, transmission network is assumed to be existent at no costs
bold numbers highlight decision variables in the respective optimization problem

- Derive value of transmission by comparing extreme cases: abundant and no transmission capacity
- Difference in social welfare or respectively system costs btw. these (89 million €) is the max. WTP for the transmission infrastructure

Conclusions and outlook

Probabilistic welfare analysis for system adequacy – analytical and numerical insights

- Conclusions
  - Analytical approach to derive value of transmission capacity is feasible
  - Complexity already arises in simple 2-node settings
  - Analytical approach confirms expectations on synergies and allows simple quantification
  - Analytical approach may be used to get lower and/or upper bounds on benefits in more complex settings

- Further steps
  - Account for further differences btw. countries and corresponding value components of transmission
    - Different technologies → derive value of transmission originating from a more efficient use of resources
    - Different load patterns → derive value of transmission originating from smoothening of demand
  - Relation between components
  - Transfer to more complex setting

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Many thanks!

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