Dresden | ENERDAY 2019 | 12. April 2019

Reliability constrained generation expansion planning:
Case study for different system sizes and characteristic renewable profiles

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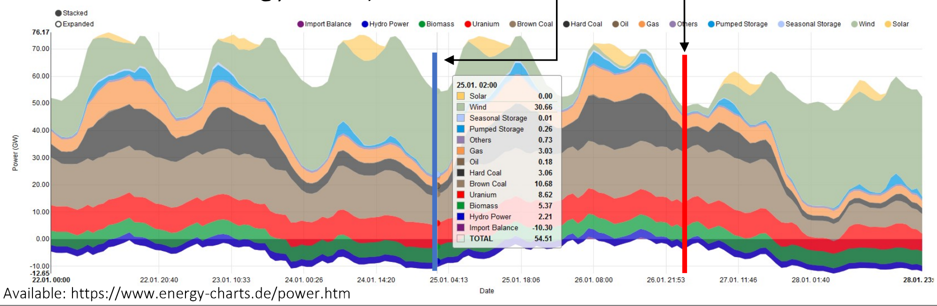
Agenda

- Motivation
- Research question
- Methodology
- Selected assumptions
- Preliminary results
- Summary & recommendations

Motivation

- Renewables (REN) are (getting) cheaper than fuel demand (LCOF $_{conventional}$ > LCOE $_{renewables}$)
- REN contribution fluctuates: (very) large, medium, (very) small
- Generation expansion planning (GEP): deterministic approaches (optimization frameworks assume e.g. reserve margin – RM, expected unserved energy - EUE)
- Verification of assumptions for optimization frameworks (e. g. RM)



Source: Electricity production in Germany, Week 4 (2018) [Online]. Available: https://www.energy-charts.de/power.htm

Research Question

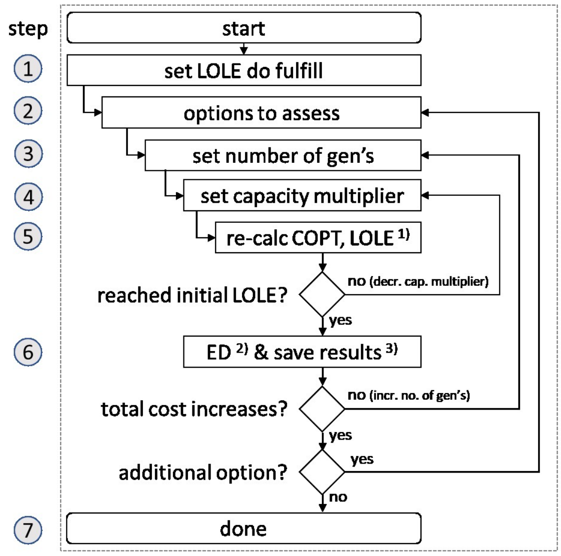
How much conventional (dispatchable) capacity is required with high penetration of renewables using probabilistic LOLE-constrained GEP?

Sensitivity assessment	Default	Sensitivities
▪ Characteristic REN resource quality (PV/Wind)	-/-, +/-, -/+, +/+	
▪ System size	1,000 MW	10, 100, 10,000, 100,000
▪ Fuel cost	20 EUR/MWh_{th}	10, 30
▪ Targeted Loss of Load Expectation (LOLE)	2.4 hours/year	1, 4.8
▪ Conventional power generation technology	CC	ST, GT, ICE
▪ Correction curves for ambient temperature	no	yes

Remark: -/+ .. low/high quality of REN resource
Abbreviations: CC: Combined Cycle Gas Turbine; ST: Steam Turbine; GT: Gas Turbine; ICE: Internal Combustion Engine; LOLE: Loss of Load Expectation;

Methodology

- Dynamic programming (DP) implemented in julia
- Objective function: minimize cost (annuity, fuel)
- Hourly multi-year time series at a time
- 'Normalized' demand
- Current model limitations:
  - Greenfield approach
  - One technology at a time, one size of units
  - Perfect foresight assumed
  - Single node, closed system (no T&D, no exchange)
  - No energy shift (e.g. storage, DR, DSM)

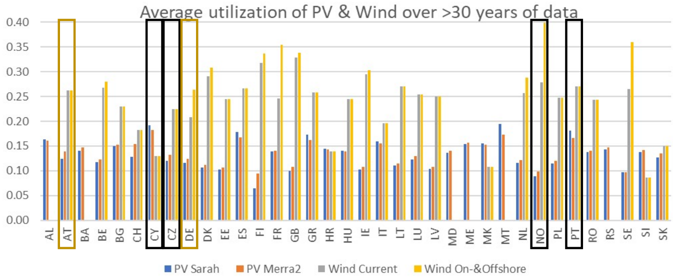


Remarks:
1) *binomial COPT (no. of units, size)*
   LOLP=prob(COPT, net load)
   LOLE = sum(LOLP) for each hour
2) *ED is based on hourly values (w/o detailed UC)*
3) *CapEx annuity, fuel cost;*

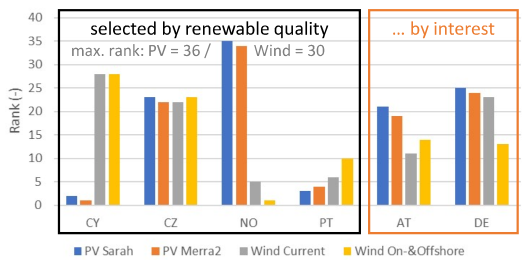
Abbreviations:
CapEx: Capital Expenditures
COPT: Capacity Outage Probability Table
ED: Economic Dispatch
LOLE: Loss of Load Expectation
LOLP: Loss of Load Probability
UC: Unit Commitment

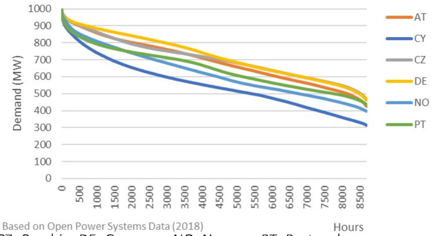
Remark: open data used in this work (open-power-system-data.org)
Abbreviations: DR: Demand Response; DSM: Demand Side Management;

Selected Assumptions 1/2 (Characteristic Profiles)



Data: www.renewables.ninja (2018)

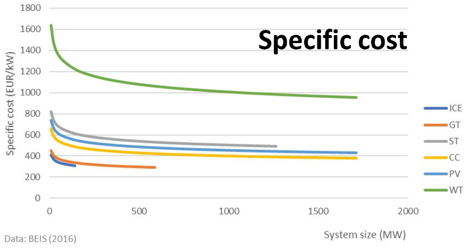




	Cap. Factor PV	Cap. Factor Wind
AT	12%	26%
CY	**19%**	13%
CZ	**13%**	**22%**
DE	12%	24%
NO	9%	**34%**
PT	**17%**	**27%**

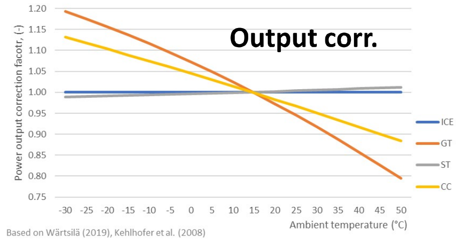
Abbreviations: AT: Austria, CY: Cyprus, CZ: Czechia, DE: Germany, NO: Norway, PT: Portugal

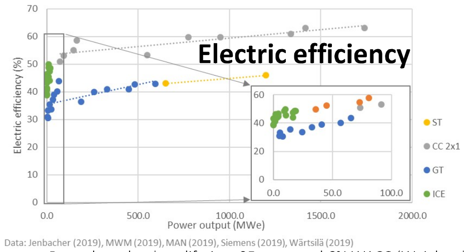
Selected Assumptions 2/2 (Economy of Scale, Correction Curves)



	ICE	GT	ST	CC	PV	WT
a	1000	1100	2000	1600	1800	4000
b	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
max. size (MW)	19	593	1200	1740		

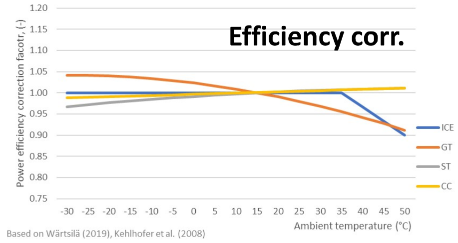
Capital expenditures (power curve):
\$/kW = a*{kW}^b





	GT	CC	ST	ICE
a	35.4	53.2	39.5	42.7
b	0.014	0.006	0.006	0.323

Efficiency curve (linear curve):
$\eta = a + b * \{MW\}$



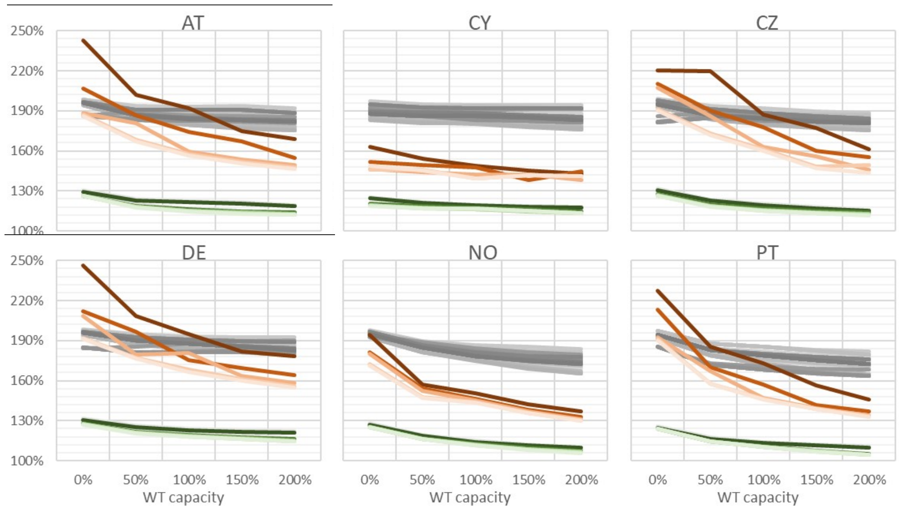
Ambient Temperatures:

	T_{max}	T_{min}	dT
AT	33	-22	**54**
CY	34	0	**34**
CZ	36	-26	**62**
DE	34	-16	**51**
NO	25	-17	**42**
PT	31	0	**31**

Data:
www.ncdc.noaa.gov (CY, NO, PT), open-power-system-data.org (AT, CZ, DE)

Remark: technology lifetime 25 years and 6% WACC (Weighted Average Cost of Capital) assumed for all technologies;

Preliminary Results 1/2 (Required Conventional Capacity)



Legend: grey: demand 1,000 MW; orange: 10,000 MW; green: 100,000 MW CC, ST, GT and 1,000 MW ICE
Abbreviations: AT: Austria; CY: Cyprus, CZ: Czechia, DE Germany, NO: Norway, PT: Portugal;

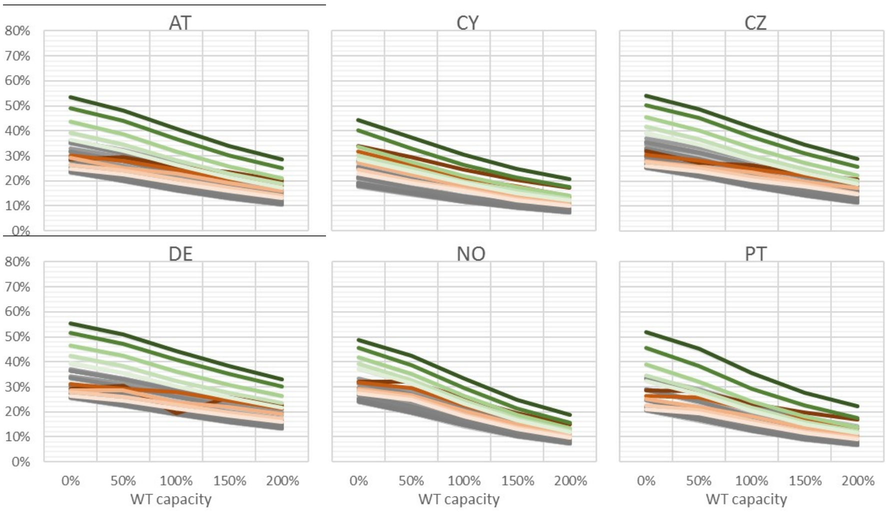
Summary:

System size (MW)	Number of units, Required cap.	Change unit size	Change required cap.
10	**2 units,** 180-195%, CC	-(6-12)%	-(14-18)%p
100	**2 units,** 180-195%, CC	-(6-12)%	-(14-18)%p
1,000	**50-55 units,** 130-105% , ICE **2 units,** 180-195%	-(1)% ICE -(6-12)%	-(10-17)%p
10,000	**8-10 units,** 245-130%, CC	-(20-25)%	-(90)%p
100,000	**54-58 units,** 130-105%, CC	-(2)% - +(1)%	-(15-20)%p

Findings:

- Peaky LDC (CY, NO)→ lower req. cap.
- Flatter LDC (DE, CZ) → highest req. cap.
- LOLE overrules fuel prices
- -/+ LOLE → 2-5% +/- of req. cap.
- Ambient temp. → small impact

Preliminary Results 2/2 (Average Capacity Factor)



Legend: grey: demand 1,000 MW; orange: 10,000 MW; green: 100,000 MW CC, ST, GT and 1,000 MW ICE
Abbreviations: AT: Austria; CY: Cyprus, CZ: Czechia, DE Germany, NO: Norway, PT: Portugal

Summary:

Remark: left box: 0-200% PV; right box 200%PV + 0-200% Wind

Findings:

- Need of conv. units for all cases
- Large decrease in all capacity factors

Summary & Recommendations

- No simple rule of thumb for Reserve Margin (RM)
  - Impact of LDC / net LDC shape (peaky LDC/net LDC → lower RM; flatter LDC /net LDC → highest RM)
  - Impact of technology size (economy of scale)
  - Impact of desired system reliability
  - Impact of fuel cost share
  - Diminishing impact of ambient temperature with growing REN penetration

System size (MW)	REN penetration [1)]	Reserve margin (RM)
≤1,000		100%
…		case by case (more towards 100%)
≥ 100,000	≤50% REN	2x FOR
	~ 100% REN	1x FOR
	~ 200% REN	0.33x FOR

- Next: add energy shift strategies (e.g. BES, TES)

Remark: 1) REN penetration is expressed as multiplier of peak demand

Q&A

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