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Generation expansion planning (GEP) problems

Optimization Problems in Energy Systems [H0P08a] – [H0P09a]

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0 Objectives of today's lecture

- You know how to formulate a simple generation expansion planning problem;
- You understand the basics of how one may solve such problems;
- You can interpret the solution to these problems based on their optimality conditions;
- You are familiar with some extensions of our basic generation expansion planning problem and challenges in generation expansion planning modeling.

0 Outline

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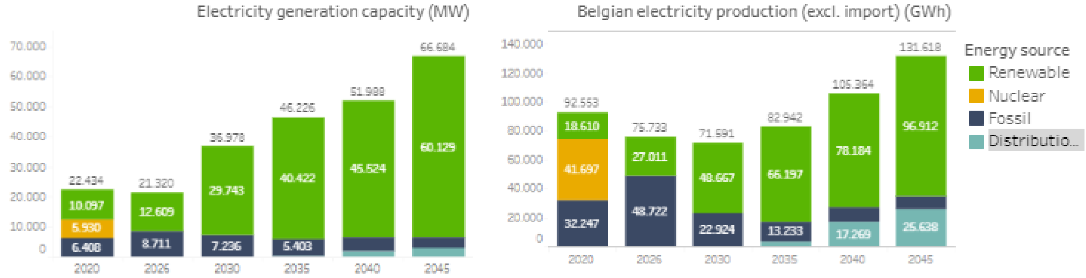
1 Outline

1 Generation expansion planning (GEP) problem?

Recall: **UC/ED** deals with operational decisions:
When should each power plant be started, stopped and how much should it generate to meet the demand for electric power on, e.g., the next day at minimum cost?

Now: **GEP** focusses on operational & investment decisions:
Which power plant investments need to be made and when should each power plant be started, stopped and how much should it generate to meet the demand for electric power on, e.g., each day of the next 50 years at minimum cost?

1 Typical output of a GEP problem



EnergyVille, *Belgian Long Term Electricity System Scenarios*, 2020. Available online: https://www.energyville.be/belgian-long-term-electricity-system-scenarios

1 Generation expansion planning problem?

Scope:

- Integrated assessment models [POLES, GCAM],
- Energy-economy models [TIMES-MACRO],
- Energy-system planning models [TIMES, PRIMES],
- Power-system planning models [ReEDS, LIMES].

Methodology:

- Computable general equilibrum models
- Optimization models [TIMES, ReEDS]
- Equilibrium models
- System-dynamics models
- Agent-based models
- ...

Kris Poncelet, *Chapter 2: Long-term energy-system planning models* in *Long-term energy-system optimization models*, PhD dissertation, KU Leuven, Leuven, Belgium, 2018.

1 Generation expansion planning in this course

- Investments & operation of generation capacity at minimum cost:
  - scope: partial equilibrium (electricity sector only), multiple geographical regions (interconnected)
  - time frame: one to 50 years ahead, with a temporal resolution up to 1 hour, potentially on a limited number of days/year
  - modelling approach: bottom-up, based on technical operation of the electricity sector
- $\sim$ a monopoly, vertically integrated utility:
  - Conceptually simpler;
  - Comparison with "benevolent monopolist";
  - Allows incorporating policy constraints (RES targets or limits on emissions).
- $\sim$ to our assumptions on UC/ED!

1 Generation expansion planning (GEP) problem?

Which power plant investments need to be made and when should each power plant be started, stopped and how much should it generate to meet the demand for electric power on, e.g., each day of the next 50 years at minimum cost?

Taking into account

- the technical constraints of existing and candidate power plants and energy storage systems;
- the demand and its expected evolution over the considered model horizon;
- the availability of non-dispatchable units (e.g., RES), their expected evolution over the model horizon and potential resource constraints (e.g., land avaiable for new wind turbines);
- Policy and adequacy constraints.

1 Generation expansion planning problem challenges

- RES-dominated systems: temporal detail more important to capture flexiblity requirements and resource potential, technical detail in bottom-up models of flexiblity providers may need to increase;
- Storage: chronology in time series of load and resource availability needs to be accurately represented to capture arbitrage opportunities;
- Interconnected systems: increasing interconnection with neighbouring systems $\leftrightarrow$ country-specific analysis?
- Short-term (operating reserves) and long-term uncertainty (e.g., fuel prices);
- ...

UC problem + capacity decisions $\leftrightarrow$ 50 years, 365 days/year, 24 hours/day $\rightarrow$ 438,000 time steps $\times$ thousands of constraints/time step $\times$ number of countries considered $\times$ number of scenarios

1 Generation expansion planning problems in ”real life”

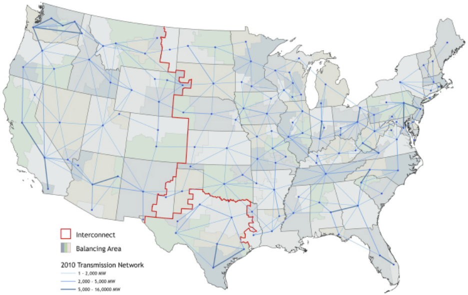
A trade-off between computational effort and accuracy, taking into account limited knowledge of evolution of system parameters in (far) future:

- Temporal structure: limited set of representative time steps per milestone year;
- Operational detail: technical detail similar to economic dispatch model (often LP), often on technology instead of power plant basis;
- Geographical structure: zonal aggregation, transmission network accounted for via trade-based or DC load flow approximation.

1 Generation expansion planning problems in ”real life” – ReEDS

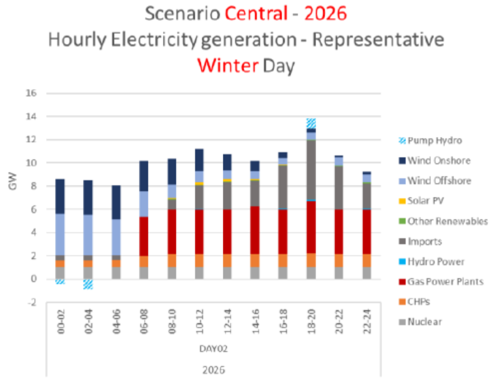
Table 1. Definition of ReEDS Time-Slice

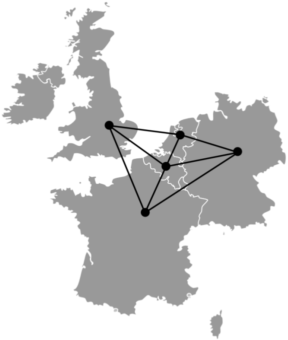
Time-Slice	Hours/Year	Season	Time of Day	Period
H1	736	Summer	Overnight	10 p.m. to 6 a.m.
H2	644	Summer	Morning	6 a.m. to 1 p.m.
H3	328	Summer	Afternoon	1 p.m. to 5 p.m.
H4	460	Summer	Evening	5 p.m. to 10 p.m.
H5	488	Fall	Overnight	10 p.m. to 6 a.m.
H6	427	Fall	Morning	6 a.m. to 1 p.m.
H7	244	Fall	Afternoon	1 p.m. to 5 p.m.
H8	305	Fall	Evening	5 p.m. to 10 p.m.
H9	960	Winter	Overnight	10 p.m. to 6 a.m.
H10	840	Winter	Morning	6 a.m. to 1 p.m.
H11	480	Winter	Afternoon	1 p.m. to 5 p.m.
H12	600	Winter	Evening	5 p.m. to 10 p.m.
H13	736	Spring	Overnight	10 p.m. to 6 a.m.
H14	644	Spring	Morning	6 a.m. to 1 p.m.
H15	368	Spring	Afternoon	1 p.m. to 5 p.m.
H16	460	Spring	Evening	5 p.m. to 10 p.m.
H17	40	Summer	Peak	40 highest demand hours of H3



Stuart Cohen et al., *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018*, Tech. report, Boulder, CO, USA, 2019.

1 Generation expansion planning problems in "real life" – TIMES





Tim Mertens et al., *Representing cross-border trade of electricity in long-term energy-system optimization models with a limited geographical scope*, Applied Energy, Volume 261, 2020.
EnergyVille, *Belgian Long Term Electricity System Scenarios*, 2020. Available online:
https://www.energyville.be/belgian-long-term-electricity-system-scenarios

1 Why should you care?

- Energy/power system optimization models are key tools to support policy making (e.g., explore transition pathways - both prescriptive/normative & descriptive);
- GenCo's may use variants to support investment decisions;
- Facilitate understanding how market designs may provide incentives for investments in new power plant capacity (e.g., the missing money problem, scarcity rents in energy-only markets).

Outline

2 A basic generation expansion planning problem – Assumptions

- Greenfield approach: we don't account for existing capacity;
- Single country perspective, no interconnections;
- Temporal scope: one year, hourly time step;
- No uncertainty considered, no operating reserve requirements or planning reserve margin;
- No resource constraints;
- Only investments in reference technologies, not on a power plant level;
- No intertemporal constraints (e.g., ramping limitations) $\rightarrow$ all time periods are decoupled;
- No policy constraints.

2 A basic generation expansion planning problem – Overview

Minimize	Total investment & operating cost	(1a)
Subject to	Fuel cost definition	(1b)
	CO_2 emission cost definition	(1c)
	Market clearing condition (supply equals demand)	(2a)
	Loss of load constraint	(2c)
	Investment & generation limits	(3a)

2 Objective function: total investment & operating cost (1a) (1/2)

$$\text{Min.} \sum_{i \in \mathcal{I}} IC_i \cdot cap_i + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} (fcd_{i,j} + ccd_{i,j}) + \sum_{j \in \mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

- Annuity IC_i of overnight investment cost OC_i of each technology i;
- Fuel costs $fcd_{i,j}$ of technology i at every time step j;
- CO_2 emission costs $ccd_{i,j}$ of technology i at every time step j;
- Penalty $VOLL$ for not serving a part of the load ens_j in time step j.

2 Objective function: total investment & operating cost (1a) (2/2)

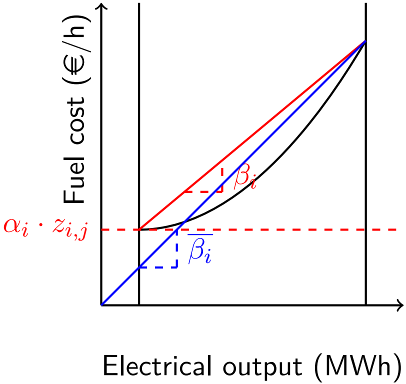
Annuity of "overnight investment cost" IC_i (€/MWy) is calculated as

$$IC_i = \frac{r \cdot OC_i}{1 - \frac{1}{(1+r)^T}}$$

with r the discount rate, T the lifetime of the asset and OC_i the overnight investment cost (€/MW).

2 Fuel cost definition (1b)

Fuel cost curve of reference power plant for technology i



- Thermal or conventional power plants: primary fuel in, electricity out.
- Fuel cost curve (€/h): primary fuel input (MWh primal energy/h) x primary fuel cost (€/MWh primal energy) as a function of the electricity output (MWh)
- Approximation in UC formulation:

$$fcd_{i,j} = \alpha_i \cdot z_{i,j} + \beta_i \cdot (g_{i,j} - z_{i,j} \cdot \underline{G_{i,j}})$$

- Approximation in GEP formulation:

$$\forall i \in \mathcal{I}, j \in \mathcal{J} : \quad fcd_{i,j} = \overline{\beta_i} \cdot g_{i,j} \tag{1b}$$

2 CO_2 emission cost definition (1c)

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad ccd_{i,j} = \alpha^{CO_2} \cdot \overline{\delta_i} \cdot g_{i,j} \tag{1c}$$

- CO_2 emission costs is determined by the primary fuel use and its CO_2 intensity ($\overline{\delta_i} \cdot g_{i,j}$) multiplied by the CO_2 emission price (α^{CO_2}, e.g., EAU price in EU ETS);
- Primary fuel use is driven by power output, hence, fully analogous to fuel costs.

2 Market clearing condition or power balance (2a)

$$\forall j \in \mathcal{J} : \quad \sum_{i \in \mathcal{I}} g_{i,j} = D_j - ens_j \tag{2a}$$

- At all time steps j, the demand D_j needs to be equal to the generation $g_{i,j}$;
- If this condition can not be met, load must be shed (ens_j);
- Electricity may be generated $g_{i,j}$ from conventional resources ($\mathcal{I}^D \subset \mathcal{I}$) or renewables ($\mathcal{I}^R \subset \mathcal{I}$).

2 Loss of load or energy-not-served constraint (2c)

$$\forall j \in \mathcal{J} : \quad 0 \leq ens_j \leq D_j \tag{2c}$$

- Amount of lost load is constrained by electricity demand.

Extensions:

- Differentiation of tiers of the electricity demand according to willingness to pay or $VOLL$;
- Emergency measures $\leftrightarrow$ demand response, voluntary load shedding or price-elastic demand.

2 Investment & generation limits (3a)

$$\forall i \in \mathcal{I}, j \in \mathcal{J} : 0 \leq g_{i,j} \leq AF_{i,j} \cdot cap_i \tag{3a1}$$

$$\forall i \in \mathcal{I} : 0 \leq cap_i \tag{3a2}$$

- The generation of each technology i is limited to the installed capacity cap_i, corrected for an availability factor $AF_{i,j} \leq 1$.
- For conventional technologies $i \in \mathcal{I}^D$, this may reflect an average availability (forced and unforced outages), a derating to reflect its availability during moments of peak demand or a fixed maintenance schedule;
- For renewable technologies $i \in \mathcal{I}^R$, this is a normalized output profile, i.e., how much output (MWh/h) can one expect at time step j per unit of installed capacity (MW).
- Note that the inequality sign implies the possibility of curtailment!

2 A basic generation expansion planning problem – Overview

$$\textit{Minimize} \quad \sum_{i \in \mathcal{I}} IC_i \cdot cap_i + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} (fcd_{i,j} + ccd_{i,j}) + \sum_{j \in \mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\textit{Subject to} \quad \forall i \in \mathcal{I}, j \in \mathcal{J} : \quad fcd_{i,j} = \overline{\beta_i} \cdot g_{i,j} \tag{1b}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J} : \quad ccd_{i,j} = \alpha^{CO_2} \cdot \overline{\delta_i} \cdot g_{i,j} \tag{1c}$$

$$\forall j \in \mathcal{J} : \quad \sum_{i \in \mathcal{I}} g_{i,j} = D_j - ens_j \tag{2a}$$

$$\forall j \in \mathcal{J} : \quad 0 \leq ens_j \leq D_j \tag{2c}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J} : 0 \leq g_{i,j} \leq AF_{i,j} \cdot cap_i \tag{3a1}$$

$$\forall i \in \mathcal{I} : 0 \leq cap_i \tag{3a2}$$

2 A basic generation expansion planning problem – Condensed notation

$$\textit{Minimize} \quad \sum_{i \in \mathcal{I}} IC_i \cdot cap_i + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j \in \mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\textit{Subject to} \quad \forall j \in \mathcal{J}: \quad \sum_{i \in \mathcal{I}} g_{i,j} = D_j - ens_j \tag{2a}$$

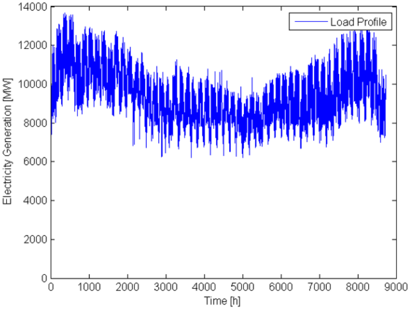
$$\forall j \in \mathcal{J}: \quad 0 \leq ens_j \leq D_j \tag{2c}$$

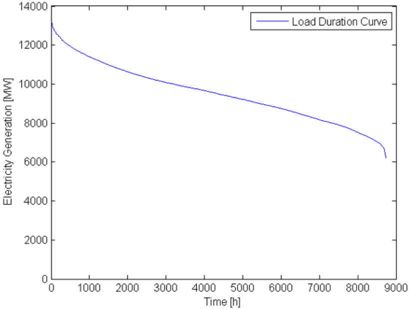
$$\forall i \in \mathcal{I}, j \in \mathcal{J}: 0 \leq g_{i,j} \leq AF_{i,j} \cdot cap_i \tag{3a1}$$

$$\forall i \in \mathcal{I}: 0 \leq cap_i \tag{3a2}$$

2 Graphical solution method - screening curves (1/5)

- Let's assume the installed RES capacity is given;
- Time periods are decoupled (no inter-temporal constraints), hence, we can rearrange our load time series in any way we want without affecting the solution;
- Let's introduce the (residual) load duration curve:





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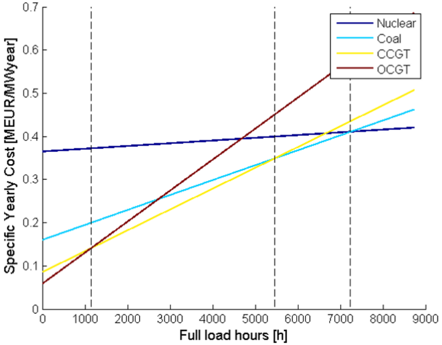
2 Graphical solution method - screening curves (2/5)

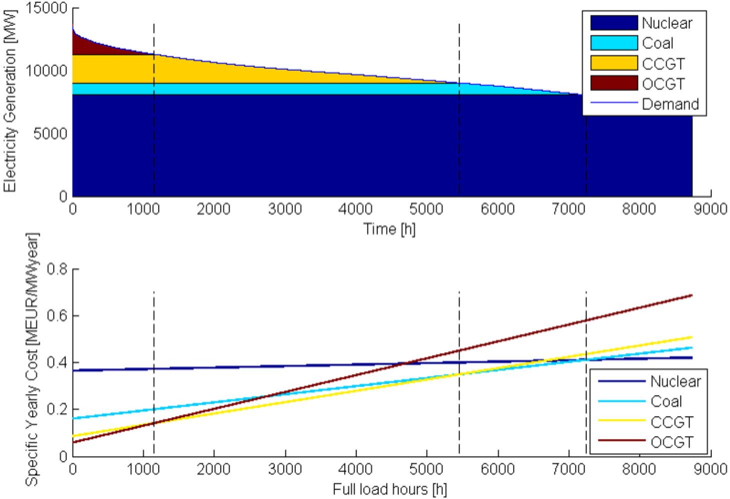
- With the defined cost structure and a time-invariant availability $AF_{i,j}$, it is straightforward to calculate a specific cost (i.e., € per MWyear) as a function of the number of full load hours for each technology:



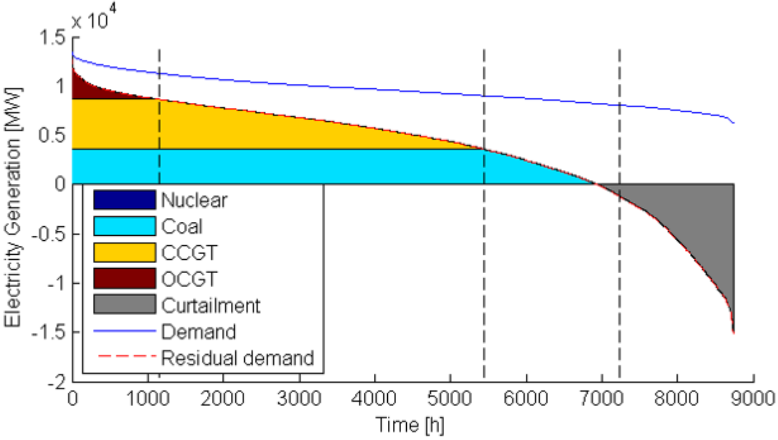
Cheapest technology?

- Nuclear if CF $\in$ [7239, 8760] h/year
- Coal if CF $\in$ [5451, 7239] h/year
- CCGT if CF $\in$ [1151, 5451] h/year
- OCGT if CF $\in$ [0, 1151] h/year

2 Graphical solution method - results no RES case (3/5)



2 Graphical solution method - results high RES case (4/5)



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2 Graphical solution method - screening curves (5/5)

- Implicit assumption: $VOLL \geq IC_i^{peak} + VC_i^{peak}$, hence, no load shedding.
- Storage?
- No inter-temporal constraints: realistic in high RES setting?
- RES investments?

2 Solution based on optimality conditions (1/6)

Step 1: Standard form of GEP in condensed notation

$$\textit{Minimize} \quad \sum_{i\in\mathcal{I}} IC_i \cdot cap_i + \sum_{i\in\mathcal{I},j\in\mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j\in\mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\textit{Subject to} \quad \forall j \in \mathcal{J}: \quad -\sum_{i\in\mathcal{I}} g_{i,j} + D_j - ens_j = 0 \qquad (\lambda_j) \tag{2a}$$

$$\forall j \in \mathcal{J}: \quad -ens_j \leq 0 \qquad (\underline{\mu_j}) \tag{2c1}$$

$$\forall j \in \mathcal{J}: \quad ens_j - D_j \leq 0 \qquad (\overline{\mu_j}) \tag{2c2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -g_{i,j} \leq 0 \qquad (\underline{\nu_{i,j}}) \tag{3a1}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad g_{i,j} - AF_{i,j} \cdot cap_i \leq 0 \qquad (\overline{\nu_{i,j}}) \tag{3a2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -cap_i \leq 0 \qquad (\underline{\xi_i}) \tag{3a3}$$

2 Solution based on optimality conditions (2/6)

Step 2: Lagrangian

$$
\begin{aligned}
\mathcal{L} = & \sum_{i \in \mathcal{I}} IC_i \cdot cap_i + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j \in \mathcal{J}} VOLL \cdot ens_j \\
& + \sum_{j \in \mathcal{J}} \lambda_j \cdot (\quad - \sum_{i \in \mathcal{I}} g_{i,j} + D_j - ens_j) \\
& + \sum_{j \in \mathcal{J}} \underline{\mu_j} \cdot (-ens_j) + \sum_{j \in \mathcal{J}} \overline{\mu_j} \cdot (ens_j - D_j) \\
& + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} \underline{\nu_{i,j}} \cdot (-g_{i,j}) + \sum_{i \in \mathcal{I}, j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot (g_{i,j} - AF_{i,j} \cdot cap_i) \\
& + \sum_{i \in \mathcal{I}} \underline{\xi_i} \cdot (-cap_i)
\end{aligned} \tag{1a}
$$

2 Solution based on optimality conditions (3/6)

Step 3: Optimality conditions

$$\frac{\partial \mathcal{L}}{\partial g_{i,j}} = VC_i - \lambda_j - \underline{\nu_{i,j}} + \overline{\nu_{i,j}} = 0$$

$$\frac{\partial \mathcal{L}}{\partial cap_i} = IC_i - \sum_{j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot AF_{i,j} - \underline{\xi_i} = 0$$

$$\frac{\partial \mathcal{L}}{\partial ens_j} = VOLL - \lambda_j - \underline{\mu_j} + \overline{\mu_j} = 0$$

$$-\sum_{i \in \mathcal{I}} g_{i,j} + D_j - ens_j = 0$$

$$-ens_j \leq 0$$

$$ens_j - D_j \leq 0$$

$$-g_{i,j} \leq 0$$

$$g_{i,j} - AF_{i,j} \cdot cap_i \leq 0$$

$$-cap_i \leq 0$$

$$\underline{\mu_j} \cdot (-ens_j) = 0$$

$$\overline{\mu_j} \cdot (ens_j - D_j) = 0$$

$$\underline{\nu_{i,j}} \cdot (-g_{i,j}) = 0$$

$$\overline{\nu_{i,j}} \cdot (g_{i,j} - AF_{i,j} \cdot cap_i) = 0$$

$$\underline{\xi_i} \cdot (-cap_i) = 0$$

$$\underline{\mu_j}, \overline{\mu_j}, \underline{\nu_{i,j}}, \overline{\nu_{i,j}}, \underline{\xi_i} \geq 0$$

2 Solution based on optimality conditions (4/6)

Step 4: Interpretation

When will one invest in a technology i? Let's assume $cap_i > 0$, then $\underline{\xi_i} = 0$

$$\frac{\partial \mathcal{L}}{\partial cap_i} = IC_i - \sum_{j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot AF_{i,j} = 0 \tag{1}$$

Hence, investment condition: $IC_i = \sum_{j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot AF_{i,j}$.

2 Solution based on optimality conditions (5/6)

Step 4: Interpretation

How does $\overline{\nu_{i,j}}$ get a non-zero value?

$$\frac{\partial \mathcal{L}}{\partial g_{i,j}} = VC_i - \lambda_j - \underline{\nu_{i,j}} + \overline{\nu_{i,j}} = 0$$
$$\overline{\nu_{i,j}} \cdot (g_{i,j} - AF_{i,j} \cdot cap_i) = 0$$
$$\underline{\nu_{i,j}} \cdot (-g_{i,j}) = 0$$

If $\overline{\nu_{i,j}} > 0 \rightarrow g_{i,j} = AF_{i,j} \cdot cap_i$ (technology used at capacity) and $\underline{\nu_{i,j}} = 0$. Hence,

$$\lambda_j = VC_i + \overline{\nu_{i,j}} \qquad (2)$$

In other words, $\overline{\nu_{i,j}}$ may be interpreted as the inframarginal + scarcity rent.

2 Solution based on optimality conditions (6/6)

Step 4: Interpretation

What if load shedding occurs? Let's assume $0 < ens_j < D_j$, hence $\overline{\mu_j} = \underline{\mu_j} = 0$:

$$\frac{\partial \mathcal{L}}{\partial ens_j} = VOLL - \lambda_j = 0$$

or $\lambda_j = VOLL$.

Combined with $VC_i - \lambda_j - \underline{\nu_{i,j}} + \overline{\nu_{i,j}} = 0$, this means that λ_j is either equal to the variable cost of the marginal technology or in the interval $[\max(VC_i), VOLL]$.

As load shedding occurs in few time steps, some technologies need to recover investments on few hours $\rightarrow$ risky if, e.g., peak demand is uncertain!

Note $\lambda_j \sim$ price on a perfectly competitive energy-only market with price cap at $VOLL$.

2 Discussion

- Absence of any technical constraints on flexibility of conventional technologies $\rightarrow$ high RES systems?
  - intertemporal constraints are possible (e.g., ramping), but at technology level;
  - some technological constraints that require binary decisions or power plant-specific decisions may be approximated (e.g., "Clustered Unit Commitment")
- Other flexibility providers (storage, demand response, . . .) not included but may be added (not covered in this lecture);
- Focus on single year, neglecting legacy capacity, does not allow for real-world applications;
- Long-term planning assuming perfect foresight?
- . . .

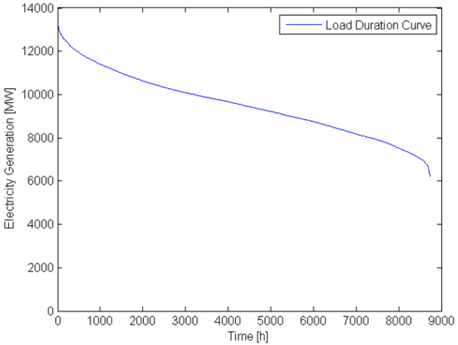
Addressing these challenges will lead to more complex, more difficult to solve models . . .

3 Outline

3 Overview of discussed extensions

- Ensuring adequacy: planning reserve margin constraints
- Policy constraints: RES targets and emission caps
- Temporal representation: Multiple years, represented via a selected number of representative periods/year
- Technical representation: to MILP or not to MILP

3 Ensuring adequacy: planning reserve margin constraints (1/5)



- So far: peak demand is known;
- In absence of load shedding, the peak demand determines the installed capacity;
- What if the considered demand profile or LDC is merely an estimate of the true load?
- Most straightforward solution: encoporate explicit capacity targets in the problem!
- Often referred to as ”planning reserve margin”

3 Ensuring adequacy: planning reserve margin constraints (2/5)

Minimize	Total investment & operating cost	(1a)
Subject to	Market clearing condition (supply equals demand)	(2a)
	Planning reserve margin constraint	(2b)
	Loss of load constraint	(2c)
	Investment & generation limits	(3a)

3 Ensuring adequacy: planning reserve margin constraints (3/5)

The planning reserve margin PRM is enforced as

$$\sum_{i \in \mathcal{I}} \overline{AF_i} \cdot cap_i \geq (1 + PRM) \cdot \overline{D_j} \tag{2b}$$

with $\overline{AF_i}$ the availability of technology i during moments of (residual) peak demand (also known as capacity credit), $\overline{D_j}$ the peak demand and PRM "margin" in terms of capacity.

- With a $PRM > 1$ and $\overline{D_j} = \max(D_j)$, this will typically result in installed capacity that is <u>not</u> dispatched!
- Ex-ante estimation PRM: how to make trade-off between cost of additional capacity and benefit of avoided load shedding? Case-specific!
- Ex-ante estimation $\overline{AF_i}$: capacity credit depends on power system (e.g., residual demand). Capacity credit of RES? What if multiple time steps with scarcity?

3 Ensuring adequacy: planning reserve margin constraints (4/5)

$$\text{Minimize} \sum_{i\in\mathcal{I}} IC_i \cdot cap_i + \sum_{i\in\mathcal{I},j\in\mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j\in\mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\text{Subject to } \forall j \in \mathcal{J}: \quad -\sum_{i\in\mathcal{I}} g_{i,j} + D_j - ens_j = 0 \qquad (\lambda_j) \tag{2a}$$

$$(1+PRM)\cdot \overline{D_j} - \sum_{i\in\mathcal{I}} \overline{AF_i}\cdot cap_i \leq 0 \qquad (\pi) \tag{2b}$$

$$\forall j \in \mathcal{J}: \quad -ens_j \leq 0 \qquad (\underline{\mu_j}) \tag{2c1}$$

$$\forall j \in \mathcal{J}: \quad ens_j - D_j \leq 0 \qquad (\overline{\mu_j}) \tag{2c2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -g_{i,j} \leq 0 \qquad (\underline{\nu_{i,j}}) \tag{3a1}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad g_{i,j} - AF_{i,j}\cdot cap_i \leq 0 \qquad (\overline{\nu_{i,j}}) \tag{3a2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -cap_i \leq 0 \qquad (\underline{\xi_i}) \tag{3a3}$$

3 Ensuring adequacy: planning reserve margin constraints (5/5)

Based on the optimality conditions of Problem (1a)-(3a3), you can obtain:

$$\frac{\partial \mathcal{L}}{\partial cap_i} = IC_i - \sum_{j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot AF_{i,j} - \underline{\xi_i} - \pi \cdot \overline{AF_i} = 0$$

Recall investment condition without planning reserve margin, with $\overline{\nu_{i,j}}$ the inframarginal + scarcity rents:

$$IC_i = \sum_{j \in \mathcal{J}} \overline{\nu_{i,j}} \cdot AF_{i,j}$$

New investment condition with planning reserve margin, with π the payment of a centralized capacity market (€/MW), corrected for the capacity contribution $\overline{AF_i}$:

$$IC_i = \sum \overline{\nu_{i,j}} \cdot AF_{i,j} + \pi \cdot \overline{AF_i}$$

3 Policy constraints: RES targets and emission caps (1/4)

Minimize	Total investment & operating cost	(1a)
Subject to	Market clearing condition (supply equals demand)	(2a)
	RES target	(2d)
	Loss of load constraint	(2c)
	Investment & generation limits	(3a)

3 Policy constraints: RES targets and emission caps (2/4)

A target for RES-based generation at technology level:

$$\forall i \in \mathcal{I}^R : \quad \sum_{j \in \mathcal{J}} g_{i,j} \geq RT_i \cdot \sum_{j \in \mathcal{J}} D_j \tag{2d1}$$

A target for RES-based generation at system level:

$$\sum_{i \in \mathcal{I}^R, j \in \mathcal{J}} g_{i,j} \geq RT \cdot \sum_{j \in \mathcal{J}} D_j \tag{2d2}$$

Note that these targets account for scheduled RES-based generation, i.e., avaiable generation corrected for curtailment.

3 Policy constraints: RES targets and emission caps (3/4)

$$\textit{Minimize} \quad \sum_{i\in\mathcal{I}} IC_i \cdot cap_i + \sum_{i\in\mathcal{I}, j\in\mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j\in\mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\textit{Subject to} \quad \forall j \in \mathcal{J}: \quad -\sum_{i\in\mathcal{I}} g_{i,j} + D_j - ens_j = 0 \qquad (\lambda_j) \tag{2a}$$

$$RT \cdot \sum_{j\in\mathcal{J}} D_j - \sum_{i\in\mathcal{I}^R, j\in\mathcal{J}} g_{i,j} \leq 0 \qquad (\rho) \tag{2d2}$$

$$\forall j \in \mathcal{J}: \quad -ens_j \leq 0 \qquad (\underline{\mu_j}) \tag{2c1}$$

$$\forall j \in \mathcal{J}: \quad ens_j - D_j \leq 0 \qquad (\overline{\mu_j}) \tag{2c2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -g_{i,j} \leq 0 \qquad (\underline{\nu_{i,j}}) \tag{3a1}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad g_{i,j} - AF_{i,j} \cdot cap_i \leq 0 \qquad (\overline{\nu_{i,j}}) \tag{3a2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -cap_i \leq 0 \qquad (\underline{\xi_i}) \tag{3a3}$$

3 Policy constraints: RES targets and emission caps (4/4)

Based on the optimality conditions of Problem (1a)-(3a3), you can obtain:

$$\forall i \in \mathcal{I}^R : \quad \frac{\partial \mathcal{L}}{\partial g_{i,j}} = VC_i - \lambda_j - \underline{\nu_{i,j}} + \overline{\nu_{i,j}} - \rho = 0$$

Hence, each MWh generated from RES perceives an energy price λ_j corrected for the value of RES-based generation ρ (€/MWh).

This can be seen as a "subsidy" ($\sim$ Renewable Energy Certificate or REC auction) $\rightarrow$ correction on variable costs VC_i.

3 Policy constraints: RES targets and emission caps (1/4)

Minimize	Total investment & operating cost	(1a)
Subject to	Market clearing condition (supply equals demand)	(2a)
	Emissions cap	(2e)
	Loss of load constraint	(2c)
	Investment & generation limits	(3a)

3 Policy constraints: RES targets and emission caps (2/4)

Limiting emissions to a predefined threshold may be enforced as

$$\sum_{i \in \mathcal{I}, j \in \mathcal{J}} \overline{\delta_i} \cdot g_{i,j} \leq \overline{CO_2} \tag{2e}$$

with $\overline{\delta_i}$ the average emission intensity of technology i ($\mathrm{tCO_2/MWh}$).

3 Policy constraints: RES targets and emission caps (3/4)

$$\text{Minimize} \quad \sum_{i\in\mathcal{I}} IC_i \cdot cap_i + \sum_{i\in\mathcal{I},j\in\mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j\in\mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\text{Subject to} \quad \forall j \in \mathcal{J}: \quad -\sum_{i\in\mathcal{I}} g_{i,j} + D_j - ens_j = 0 \qquad (\lambda_j) \tag{2a}$$

$$\forall j \in \mathcal{J}: \quad -ens_j \leq 0 \qquad (\underline{\mu_j}) \tag{2c1}$$

$$\forall j \in \mathcal{J}: \quad ens_j - D_j \leq 0 \qquad (\overline{\mu_j}) \tag{2c2}$$

$$\sum_{i\in\mathcal{I},j\in\mathcal{J}} \overline{\delta_i} \cdot g_{i,j} - \overline{CO_2} \leq 0 \qquad (\sigma) \tag{2e}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -g_{i,j} \leq 0 \qquad (\underline{\nu_{i,j}}) \tag{3a1}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad g_{i,j} - AF_{i,j} \cdot cap_i \leq 0 \qquad (\overline{\nu_{i,j}}) \tag{3a2}$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}: \quad -cap_i \leq 0 \qquad (\underline{\xi_i}) \tag{3a3}$$

3 Policy constraints: RES targets and emission caps (4/4)

Based on the optimality conditions of Problem (1a)-(3a3), you can obtain:

$$\forall i \in \mathcal{I}^D : \quad \frac{\partial \mathcal{L}}{\partial g_{i,j}} = VC_i - \lambda_j - \underline{\nu_{i,j}} + \overline{\nu_{i,j}} + \overline{\delta_i} \cdot \sigma = 0$$

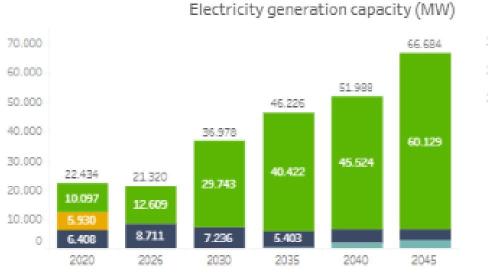
Hence, each MWh generated from CO_2-emitting technologies is valued at an energy price λ_j corrected for the cost of reducing emissions by one additional ton of CO_2, corrected for its average emission intensity: $\overline{\delta_i} \cdot \sigma$.

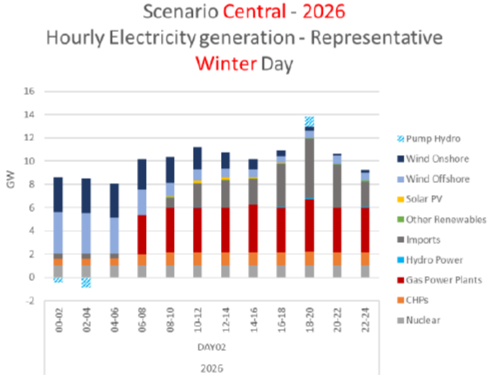
This can be seen as a "CO_2 tax" or the emission allowance price in a cap-and-trade system $\rightarrow$ penalty on top of variable costs VC_i

Note that VC_i may contain component related to exogenous "CO_2 tax"/emission allowance price. May be combined with endogenous emissions cap (e.g., emission reduction target for power sector, covered under EU ETS), but requires careful interpretation.

3 Temporal representation (1/9)

Investment decisions take place in a number of milestone years. The dispatch in each year is reduced to a number of representative periods.





EnergyVille, *Belgian Long Term Electricity System Scenarios*, 2020. Available online: https://www.energyville.be/belgian-long-term-electricity-system-scenarios

3 Temporal representation (2/9)

Let's define

- Set $\mathcal{P}$, index p, as the set of periods or milestone years represented in the GEP (e.g., 2020, 2025, 2030, ...);
- Set $\mathcal{J}$, index j, the set of time steps considered in each milestone year, $|\mathcal{J}| <<< 8760$.
- W_j as the relative weight of a time step j, $\sum_{j \in \mathcal{J}} W_j = 8760$;
- A_p the discount factor to convert expenses in year p to their net present value, i.e., $A_p = 1/(1+r)^{p-1}$ with r the discount rate.

In other words, each milestone year p is represented by $|\mathcal{J}|$ timesteps, with a weight W_j.

3 Temporal representation (3/9)

Minimize	Net present value of total investment & operating cost	(1a)
Subject to	Market clearing condition (supply equals demand)	(2a)
	Loss of load constraint	(2c)
	Investment & generation limits	(3a)

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3 Temporal representation (4/9)

$$\textit{Minimize} \sum_{p\in\mathcal{P}} A_p \cdot \left[\sum_{i\in\mathcal{I}} OC_i \cdot cap_{i,p} + \sum_{i\in\mathcal{I},j\in\mathcal{J}} W_j \cdot VC_i \cdot g_{i,j,p} + \sum_{j\in\mathcal{J}} W_j \cdot VOLL \cdot ens_{j,p} \right] \quad (1a)$$

$$\textit{Subject to } \forall j \in \mathcal{J}, p \in \mathcal{P} : - \sum_{i\in\mathcal{I}} g_{i,j,p} + D_j - ens_{j,p} = 0 \quad (2a)$$

$$\forall j \in \mathcal{J}, p \in \mathcal{P} : \quad -ens_{j,p} \leq 0 \quad (2c1)$$

$$\forall j \in \mathcal{J}, p \in \mathcal{P} : \quad ens_{j,p} - D_j \leq 0 \quad (2c2)$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}, p \in \mathcal{P} : \quad -g_{i,j,p} \leq 0 \quad (3a1)$$

$$\forall i \in \mathcal{I}, j \in \mathcal{J}, p \in \mathcal{P} : \quad g_{i,j,p} - AF_{i,j} \cdot cap_{i,p} \leq 0 \quad (3a2)$$

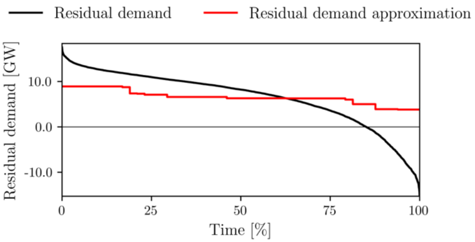
$$\forall i \in \mathcal{I}, j \in \mathcal{J}, p \in \mathcal{P} : \quad -cap_{i,p} \leq 0 \quad (3a3)$$

3 Temporal representation (5/9)

- This structure allows incorporating legacy capacity and accounting for life time of assets. Note this is not included in formulation on previous slide: once new investment is made, it is available until the end of the model horizon;
- Policy constraints may be imposed and may become increasingly stricter from one period to the next;
- Note that VC_i and OC_i may also become time dependent (e.g., changing fuel prices or decreasing investment cost RES-based generation) (not included in formulation on previous slide);
- This allows studying transition pathways (cf. EnergyVille study);

3 Temporal representation (6/9)

Critical question we've ignored so far: how should we obtain representative time steps? How many time steps should we consider?

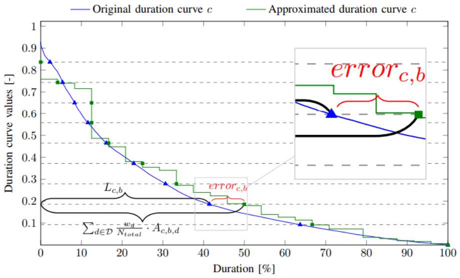


Representation of the residual load based on 12 time steps, selected via a heuristic

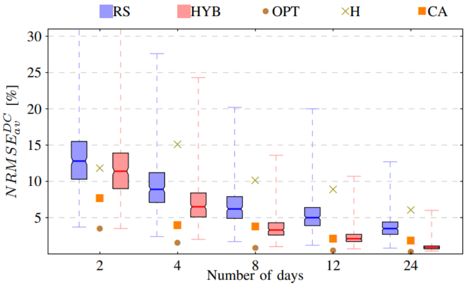
- Underestimation of need for firm capacity
- Overestimates use of baseload capacity
- Curtailment overlooked

3 Temporal representation (7/9)

Can we do better?



Error on (residual) load duration curve as objective

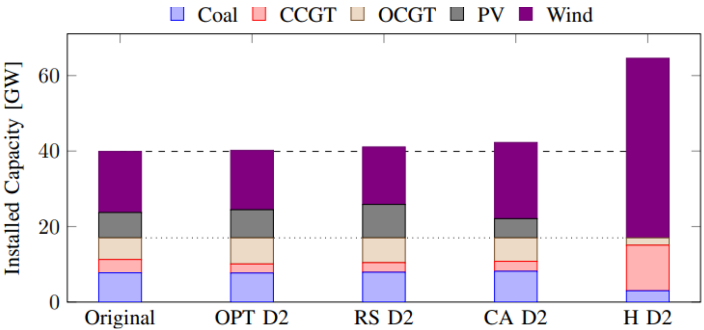


RSME of 5 different methods to select representative days

Source: K. Poncelet et al., "Selecting Representative Days for Capturing the Implications of Integrating Intermittent Renewables in Generation Expansion Planning Problems," in IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 1936-1948, 2017.

3 Temporal representation (8/9)

Does this matter?



Source: K. Poncelet et al., "Selecting Representative Days for Capturing the Implications of Integrating Intermittent Renewables in Generation Expansion Planning Problems," in IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 1936-1948, 2017.

3 Temporal representation (9/9)

Does this matter?

- State-of-the-art tools to find representative time steps/days may drastically improve the outcome of your planning model;
- Caveat: storage!

3 Technical representation (1/7)

So far, we neglected all technical constraints, which may have a significant impact:

- Underestimation of costs;
- Bias towards baseload and intermittent RES;
- Impact is strongly system/case dependent.

Ideally, we invest in "candidate power plants" and ensure that their operating schedules satisfy all technical constraints $\rightarrow$ GEP+UC.

3 Technical representation (2/7)

Let's define

- set $\mathcal{I}$, index i, as the set of candidate power plants with capacity $\overline{cap_i}$;
- Ψ as the feasible set formed by all UC-constraints, i.e., $g_{i,j} \in \Psi$.
- Binary variable $x_i \in \{0, 1\}$ which equals 1 if one invests in candidate power plant i.

3 Technical representation (3/7)

Then we can formulate this problem as

$$\textit{Minimize} \quad \sum_{i\in\mathcal{I}} IC_i \cdot cap_i + \sum_{i\in\mathcal{I},j\in\mathcal{J}} VC_i \cdot g_{i,j} + \sum_{j\in\mathcal{J}} VOLL \cdot ens_j \tag{1a}$$

$$\begin{aligned}
\textit{Subject to} \quad & \forall j \in \mathcal{J} : \quad -\sum_{i\in\mathcal{I}} g_{i,j} + D_j - ens_j = 0 \\
& \forall j \in \mathcal{J} : 0 \leq ens_j \leq D_j \\
& \forall i \in \mathcal{I} : 0 \leq cap_i \leq \overline{cap_i} \cdot x_i \\
& \forall i \in \mathcal{I} : x_i \in \{0,1\} \\
& \forall i \in \mathcal{I}, j \in \mathcal{J} : g_{i,j} \in \Psi
\end{aligned}$$

In "real-life" applications, this problem quickly becomes untractable, but approximations exist.

3 Technical representation (4/7)

Does it matter?

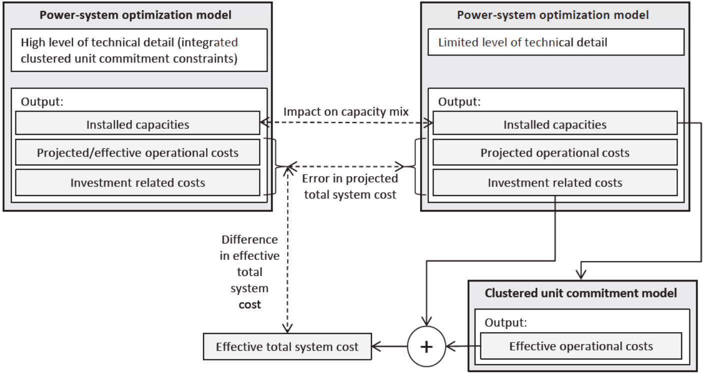
In a case study based on the German power system, we'll look at

- Four target capacity mixes: low RES - high RES target $\times$ with and without nuclear (A $\rightarrow$ D);
- Technical constraints power plants: very flexible (high flex), inflexible (low flex) or no constraints (merit order-based activation, MO) $\times$ with and without storage (S).

Kris Poncelet, *Chapter 5: Improved Technical Representation in Planning Models*, in *Long-term energy-system optimization models*, PhD dissertation, KU Leuven, Leuven, Belgium, 2018.

3 Technical representation (4/7)

Does it matter?



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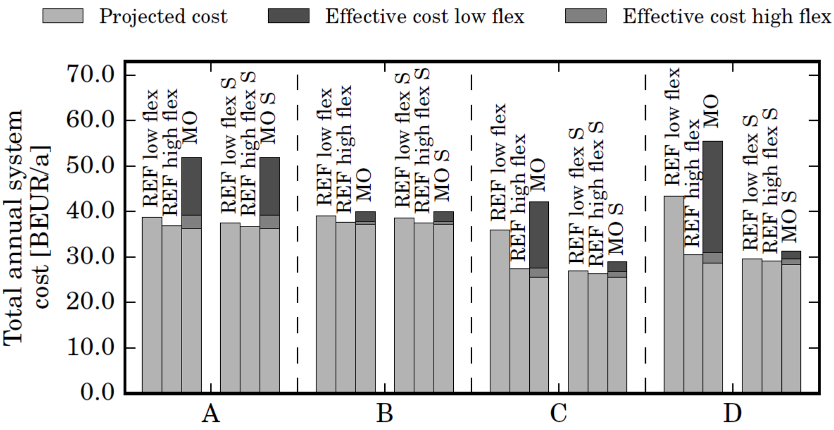
3 Technical representation (5/7)

Does it matter?



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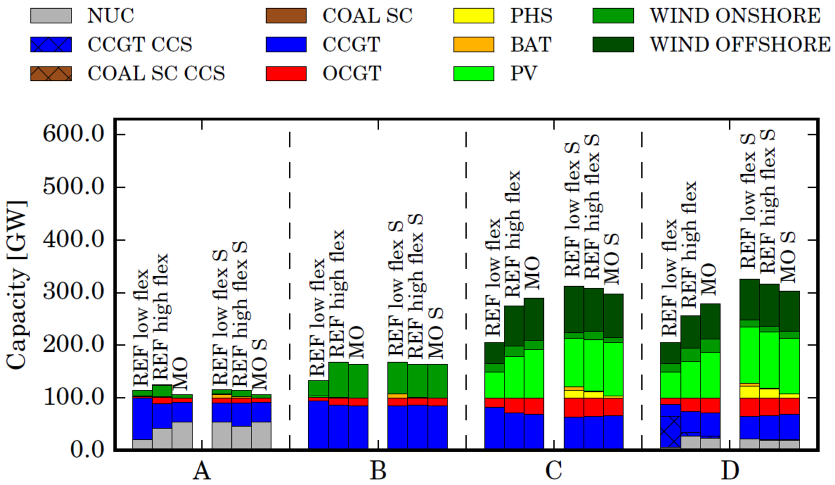
3 Technical representation (6/7)

Does it matter?



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3 Technical representation (7/7)

Does it matter?

- Technical constraints may have a limited impact. Two exceptions:
  - Without storage, baseload + RES in high RES scenarios. Realistic?
  - Investment in storage is driven by technical constraints.
- Caution required when integrating technical constraints without considering sufficient flexibility options: may lead to overly conservative results.

4 Outline

4 Summary

In this lecture, we have

- formulated a simple generation expansion planning problem;
- discussed the basics of how one may solve such problems;
- discussed how optimality conditions facilitate the interpretation of the solutions of these problems;
- extended our basic GEP with policy and adequacy constraints;
- discussed the importance (or absence thereof) of technical constraints and high temporal detail.

Thank you for your attention!
Questions?

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5 References & Background reading material

- Daniel Kirschen and Goran Strbac, *Fundamentals of Power System Economics*, Wiley, 2018.
- Ross Baldick, *Lecture Notes for the course: Restructured Electricity Markets: Locational Marginal Pricing*, 2018.
- Kris Poncelet, *Long-term energy-system optimization models*, PhD dissertation, KU Leuven, Leuven, Belgium, 2018.