Capacity Expansion with Reliability Criteria

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Source: section 11.5, Papavasiliou [1]

Outline

- EENS constraints
- LOLE constraints

Capacity expansion model without LOLE or EENS constraint

$$(SCE): \max_{p,d,x} \sum_{\omega \in \Omega} P_\omega \cdot \sum_{j=1}^{m} \Delta T_j \cdot (V \cdot d_j(\omega) - \sum_{i=1}^{n} MC_i \cdot p_{ij}(\omega)) - \sum_{i=1}^{n} I_i \cdot x_i$$

$$\sum_{i=1}^{n} p_{ij}(\omega) = d_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$p_{ij}(\omega) \leq x_i, i = 1, \dots, n, j = 1, \dots, m, \omega \in \Omega$$

$$d_j(\omega) \leq D_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$p, d, x \geq 0$$

Reliability

- System **reliability**: system *adequacy* and *security*
- Distinction between adequacy and security: relates to distinction between static and dynamic system conditions

Adequacy

- **Adequacy**: the ability of the system to satisfy all operating constraints (such as serving load, not violating transmission line and transformer limits, or violating voltage limits) under *static* operating conditions
- Sometimes refers to the ability of the system to continue operating within its technical constraints even in case of outage of individual components
- When the system is not adequate some corrective action is required, such as the redispatch of generation units, load shedding, or other corrective actions

Security

- **Security**: ability of the system to transition from one operating state to another in the case of unanticipated disruptions
- Security therefore refers to dynamic system response
- In these notes we focus on adequacy, not security

Usual reliability criteria

- Certain reliability criteria are recently integrated in long-term system planning through adequacy studies
- Two usual criteria: EENS and LOLP
- **Expected energy not served** (EENS): expected value of involuntary interruption of energy supplied to loads
- **Loss of load probability** (LOLP): expected number of hours when involuntary load shedding occurs

Economic viability assessment

- Adequacy studies use the notion of **economic viability assessment** (EVA)
- Idea: use short-term system operating model with *given* technology mix as a guide for expanding/retiring technologies, based on a profitability criterion
  - Profitable technologies expand
  - Technologies suffering losses are retired
- The EVA method corresponds to an exact Lagrange decomposition algorithm for solving long-term capacity expansion problems
- Thus, the reasoning of the methodology is questionable because it reproduces the optimal long-term mix with predictable results:
  1. Technologies that are not lower or upper bounded in level of investment exactly recover investment costs $\Rightarrow$ no adequacy mechanism is required
  2. Technologies that are upper bounded in level of investment are profitable $\Rightarrow$ no adequacy mechanism required
  3. Technologies that are lower bounded in level of investment are suffering damages $\Rightarrow$ adequacy mechanism required

EVA and RAA

- The economic viability assessment is part of a broader analysis which is used as a quantitative basis for establishing the need of implementing capacity remuneration mechanisms beyond the energy-only market
- Interleaving of EVA with a **resource adequacy assessment** (RAA)
- Resource adequacy assessment: evaluation of reliability metrics (such as EENS or LOLE) for a *given* technology mix
- Methodological weaknesses:
  - The role of aversion towards investment risk is not clearly represented
  - The role of market incompleteness due to poor market design is not clearly represented
  - The lack of active consumer engagement in the market is not clearly represented
- Indication of lack of methodological clarity:
  - Some system operators first conduct an EVA *followed* by a RAA (ENTSOE methodology until 2023)
  - Other operators follow the opposite order, with the EVA *following* the RAA (ENTSOE methodology after 2023)

EENS constraints

Capacity expansion model with EENS constraint

$$(EENS): \min_{p,ls,x} \sum_{\omega \in \Omega} P_\omega \cdot \sum_{j=1}^{m} \Delta T_j \cdot (\sum_{i=1}^{n} MC_i \cdot p_{ij}(\omega)) + \sum_{i=1}^{n} I_i \cdot x_i$$

$$\sum_{i=1}^{n} p_{ij}(\omega) + ls_j(\omega) = D_j(\omega), j = 1, \ldots, m, \omega \in \Omega$$

$$p_{ij}(\omega) \leq x_i, i = 1, \ldots, n, j = 1, \ldots, m, \omega \in \Omega$$

$$ls_j(\omega) \leq D_j(\omega), j = 1, \ldots, m, \omega \in \Omega$$

$$(\lambda): EENS - \sum_{\omega \in \Omega} P_\omega \cdot \sum_{j=1}^{m} \Delta T_j \cdot ls_j(\omega) \geq 0$$

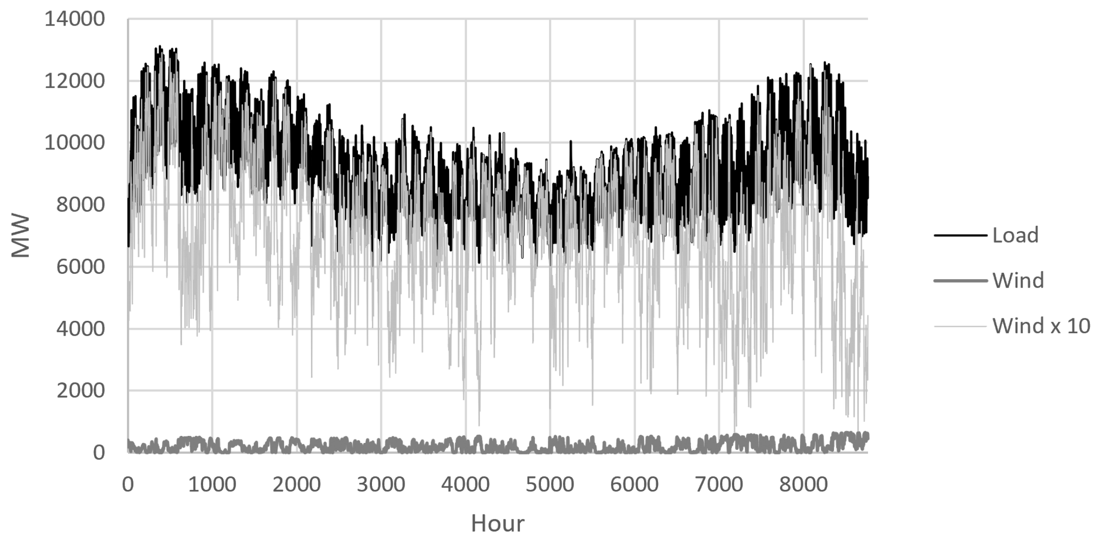
$$p, ls, x \geq 0$$

Observations

- Inelastic demand
- ls variable: load that is not satisfied
- Distinction between time periods and scenarios is not essential
  - We can replace the tuple (t, ω) with a "state of the world" index $s = (t, \omega)$
  - We can replace the product of probability and duration $P_\omega \cdot \Delta T_t$ with a probability of the state of the world $\Pi_s = P_\omega \cdot \Delta T_t$

Example: stochastic capacity expansion with EENS constraint

- We return to the model of figure 1 [1]
- Two load scenarios:
  - Reference (10% probability)
  - 10x wind (90% probability)
- We enforce an EENS constraint of 0.522437 MWh per hour
- Optimal investment
  - Coal: 4457.43 MW
  - Natural gas: 1803.24 MW
  - Nuclear: 4792.34 MW
  - Oil: 1285.63 MW
- Dual multiplier of EENS constraint: 1002.31 $/MWh



Technology	Fuel cost ($/MWh)	Investment cost ($/MWh)
Coal	25	16
Natural gas	80	5
Nuclear	6.5	32
Oil	160	2

Equivalence of elastic demand and EENS constraint

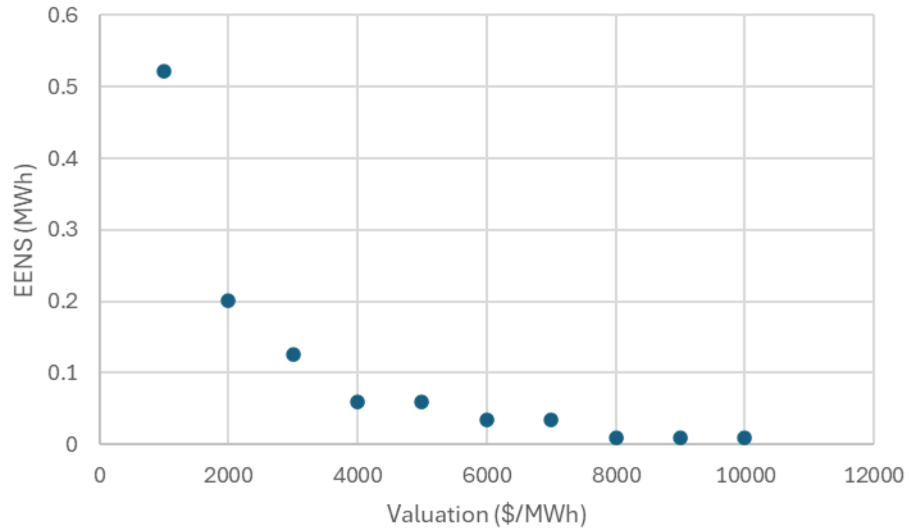
- Due to strong duality, the following are equivalent:
  - Model with EENS constraint
  - Model without EENS constraint, where load valuation is equal to the dual multiplier λ of the EENS requirement constraint

Example: equivalence of EENS constraint and elastic demand

- We return to the example of slide 9 and replace the EENS constraint with elastic demand with a valuation of 1000 $/MWh
  - Interpretation: energy-only market with elastic consumers with a valuation of 1000 $/MWh
- Optimal technology mix: identical to slide 9
- Deviation between consumer valuation (1000 $/MWh) and value of dual multiplier λ in slide 9 (1002.31 $/MWh) due to numerical precision of solver

Example: equivalence between EENS constraint and elastic demand

- There is a correspondence between consumer valuation and EENS level
- Higher valuation implies lower EENS
- Beyond 176000 $/MWh, optimal EENS level becomes zero for this specific example



Critical assessment of EENS constraints

- What is the role of EENS constraints in adequacy studies?
- By enforcing an EENS constraint in adequacy studies, there are two possible outcomes:
  1. The constraint is binding, in which case the system is expanded beyond what is economically efficient
  2. The constraint is not binding, in which case it is redundant

Example: active and inactive EENS constraint

- We return to the example of slide 13
- We introduce, in addition to the elastic demand with a valuation of 1000 $/MWh, an EENS constraint
- For an EENS value greater than 0.522437 MWh the constraint is not binding (so it is as if it does not exist)
- For an EENS value lower than 0.522437 MWh (e.g. 0.4 MWh) the constraint is binding but the technology mix is *suboptimal*
  - Coal: 4457.43 MW (same as model without EENS requirement)
  - Natural gas: 1803.24 MW (same as model without EENS requirement)
  - Nuclear: 4792.34 MW (same as model without EENS requirement)
  - Oil: 1340.65 MW (more than 1285.63 MW in model without EENS constraint) $\Rightarrow$ overdimensioning in peak technology (similar side-effect to CRMs and ORDCs)

Interpretation of dual multiplier of EENS constraint

- The EENS constrained model has an equivalent model with appropriate consumer valuations (which should equal λ)
- But the λ multipliers are ***not*** equivalent to consumer valuation
- Concretely: λ can depend on the topology of a system or the cost of the technological options
- Consumer valuation does not depend on these factors

Example: changing model parameters

	Energy-only market with consumer valuation 1000 $/MWh Oil inv. cost: 160 $/MWh	Energy-only market with consumer valuation 1000 $/MWh Oil inv. cost: 200 $/MWh
Nuclear (MW)	4792.34 MW	4792.34 MW
Coal	4457.43 MW	4457.43 MW
Nat. gas (MW)	1803.24 MW	2078.23 MW
Oil (MW)	1285.63 MW	1000.64 MW

Increase in investment cost of oil ⇒ natural gas displaces oil

Example: changing the model parameters

	Energy-only market with consumer valuation 1000 $/MWh Oil inv. cost: 200 $/MWh	Central planning with EENS 0.522437 MWh per hour Oil inv. cost: 200 $/MWh
Nuclear (MW)	4792.34 MW	4792.34 MW
Coal	4457.43 MW	4457.43 MW
Nat. gas (MW)	2078.23 MW	2078.23 MW
Oil (MW)	1000.64 MW	1010.64 MW

Increase in investment cost of oil $\Rightarrow$ natural gas displaces oil

New λ multiplier: 1042.31 $/MWh (but consumer valuation has not changed)

Central planning with pre-oil-price-increase EENS requirement distorts the optimal mix

Example: changing the model parameters

	Energy-only market with consumer valuation 1000 $/MWh Oil inv. cost: 200 $/MWh	Energy market with consumer valuation 1000 $/MWh Market distortion: EENS requirement of 0.522437 MWh per hour Oil inv. cost: 200 $/MWh
Nuclear (MW)	4792.34 MW	4792.34 MW
Coal	4457.43 MW	4457.43 MW
Nat. gas (MW)	2078.23 MW	2078.23 MW
Oil (MW)	1000.64 MW	1010.64 MW

Interfering in the energy only market with an EENS requirement distorts the optimal mix

Institutional implications

- A market corresponds to a system with a constant valuation **without** EENS constraints
- If the system conditions change then the long-term equilibrium will adapt to a new long-term mix
- If we introduce an additional EENS constraint to this system (as is the case, for example, in adequacy studies with EENS constraints), then the mix will be disrupted, and whenever the EENS constraint is binding the system will feature excess investment beyond the optimal level
- In other words, even though adequacy assessment models with EENS constraints have equivalent economic institutions, i.e. energy-only markets, that can reproduce the same outcome in a decentralized way in a static environment, this is no longer the case in a dynamic environment where the parameters of the economy change
- In such a dynamic environment a free economy will adjust towards a new long-term equilibrium with an optimal mix, whereas a central planning system with EENS constraints will result in a different mix (which will typically feature excess investments)

LOLE constraints

Behavior of LOLP in classical expansion planning models

- Relationship between LOLP and peak technology investment cost:

$$I_n \simeq VOLL \cdot LOLP$$

- Proof: next slide
- Intuition: the marginal benefit of constructing an additional MW of the peak technology ($VOLL \cdot LOLP$) must equal the marginal cost of investing in this peak technology (I_n)

Proof that $I_n \simeq VOLL \cdot LOLP$

- We isolate the following KKT condition which concerns the peak technology:

$$0 \leq x_n \perp I_n - \sum_{j=1}^{m} \Delta T_j \cdot \mu_{nj} \geq 0$$

- If the peak technology is invested in, then when $ls_j > 0$ we have that $0 < p_{nj} = x_n$ thus $\rho_j = VOLL$ and therefore $\mu_{nj} = VOLL - MC_n$
- Thus:

$$\begin{aligned} I_n &\simeq \sum_{j=1}^{m} \mathbb{I}(ls_j > 0) \cdot \Delta T_j \cdot \mu_{nj} \\ &= \sum_{j=1}^{m} \mathbb{I}(ls_j > 0) \cdot \Delta T_j \cdot (VOLL - MC_n) \\ &= (VOLL - MC_n) \cdot \sum_{j=1}^{m} \mathbb{I}(ls_j > 0) \cdot \Delta T_j \\ &\simeq VOLL \cdot LOLP \end{aligned}$$

Proof that $I_n \simeq VOLL \cdot LOLP$

- The $\simeq$ in the first equality is due to the fact that we may have $\mu_{nj} > 0$ even if $ls_j = 0$ (e.g. if inelastic demand intersects the supply curve at the level of total installed capacity)
- The precise relation is the following:

$$\sum_{j=1}^{m} \mathbb{I}\left(ls_j > 0\right) \cdot \Delta T_j \cdot \mu_{nj} \leq I_n \leq (\sum_{j=1}^{m} \mathbb{I}\left(ls_j > 0\right) + 1) \cdot \Delta T_j \cdot \mu_{nj}$$

- The $\simeq$ in the last equality of the proof is due to the fact that $VOLL \gg MC_n$

LOLP and LOLE

- LOLE: weighting of the LOLP reliability index
- LOLE converts LOLP to a certain time horizon
- Example: LOLP of 0.1% corresponds to 0.365 days of faiulure to meet load per year
- We refer to both indices as being *equivalent*, and correspond to a unitless quantity (thus an expected probability of failing to meet load)

Capacity expansion model with LOLE constraint

$$(LOLE): \max_{p,d,ls,x,u} \sum_{\omega \in \Omega} P_\omega \cdot \sum_{j=1}^{m} \Delta T_j \cdot (V \cdot d_j(\omega) - \sum_{i=1}^{n} MC_i \cdot p_{ij}(\omega)) - \sum_{i=1}^{n} I_i \cdot x_i$$

$$\sum_{i=1}^{n} p_{ij}(\omega) = d_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$\sum_{i=1}^{n} p_{ij}(\omega) + ls_j(\omega) = D_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$p_{ij}(\omega) \leq x_i, i = 1, \dots, n, j = 1, \dots, m, \omega \in \Omega$$

$$ls_j(\omega) \leq D_j(\omega) \cdot u_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$d_j(\omega) \leq D_j(\omega), j = 1, \dots, m, \omega \in \Omega$$

$$\sum_{\omega \in \Omega} P_\omega \cdot \sum_{j=1}^{m} \Delta T_j \cdot u_j(\omega) \leq LOLE$$

$$p, d, ls, x \geq 0, u \in \{0,1\}$$

Comments on (LOLE) model

- Mixed integer two-stage stochastic program
- First-stage decisions: investments x
- Binary variables $u_j(\omega)$: indicate if we are able to ($u_j(\omega) = 0$) or fail to ($u_j(\omega) = 1$) satisfy load in period j of scenario ω
- Fourth constraint: allows us to activate loss of load variable ($ls_j(\omega) > 0$) under the condition that we decide not to serve load in the given period of the given scenario ($u_j(\omega) = 1$)
- Sixth constraint: LOLE constraint

Comments on (LOLE) model

- Introducing elastic consumers in the model is important for getting reasonable results
- If the model is restated with an objective of minimizing cost, the model ***fully*** **sheds** load in those periods where installed capacity cannot fully cover load

Relation to classic expansion planning model

- Identical to stochastic capacity expansion model (SCE) of slide 3, with the exception of the second, fourth and sixth constraint (blue parts of slide 25) which are added to the model
- Thus, the model is suboptimal with respect to the outcome of perfect competition of (SCE): since we introduce new constraints to the model, the outcome cannot be better than that of the original capacity expansion model

Computational challenges of (LOLE) model

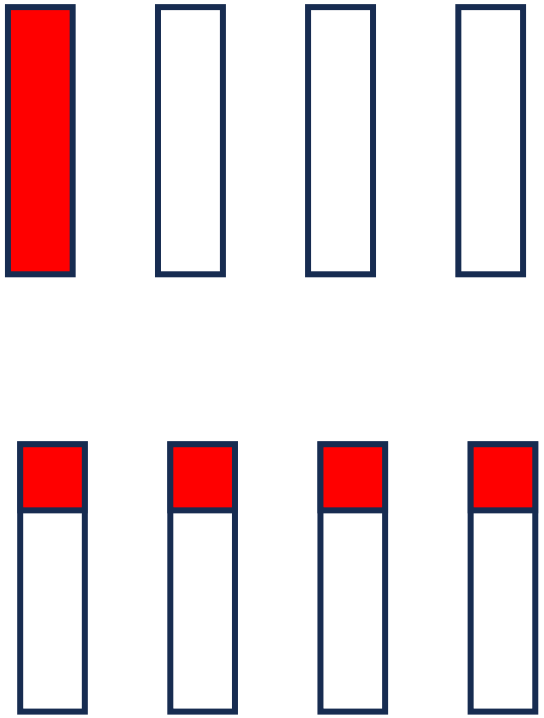
- The (LOLE) model is computationally problematic
- It inherits the large dimensionality of capacity expansion models
- And consists of a very large number of binary variables: $m \times |\Omega|$
- In practical applications this can lead to an order of magnitude of tens or hundreds of thousands of binary variables $\Rightarrow$ prohibitive size

Difference between (LOLE) and (EENS) models

When there are load curtailments, the (LOLE) model attempts to limit them to a few hours, even if in these periods the curtailments are "deeper"

Example: deep curtailments versus long curtailments

- Consider a system that is forced to curtail 400 MWh of load
- The curtailment of 400 MWh in 1 hour versus 100 MW in 4 hours results in
  - The same contribution towards violating an EENS constraint
  - A quarter of the contribution towards violating a LOLE constraint



Curtailment of 400 MWh in 1 hour (top) versus 100 MWh in 4 hours (bottom)

Investments subject to LOLE versus EENS criteria

- We return to the system of slide 13
- The LOLE of the system at the optimal solution is 0.237442%
- Suppose that we increase load at the peak period of the reference scenario
  - Peak period: hour 379
  - Peak load: 13079.62 MW
- *No* effect on the (LOLE) model with a LOLE constraint of 0.237442%
- Effect on (EENS) model with an EENS constraint of 0.522437 MWh per hour: oil investments increase from 1285.63 MW to 1290.47 MW

References

[1] A. Papavasiliou, Optimization models in electricity markets, Cambridge University Press

https://www.cambridge.org/highereducation/books/optimization-models-in-electricity-markets/0D2D36891FB5EB6AAC3A4EFC78A8F1D3#overview