Capacity Expansion Games

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Agenda

1. Investment in electricity generation
2. Capacity Expansion Games
3. Conclusion & Perspectives

Investment in electricity generation

Optimal investment in electricity generation

- Even for a regulated monopoly, leads to difficult large scale stochastique control problems:
  - Large number of possible technologies with different cost structures, construction delays, and operational constraints.
  - Many risk factors: demand, fuel prices, outages, inflows.
  - Long lifetime of generation plants (40-50 years).
  - Capital intensive industry (EPR investment at Hinkley Point $\approx$ 18 billions GBP).
- Deregulation made the problem even more difficult
  - Incomes depends on wholesale electricity prices leading to important financial risks (500 billions € of stranded assets in EU in the last years)
  - Competition on generation. Limited space on the stack curve.
  - Regulation uncertainty.

Large set of technologies

Main generation technologies

- Gas: Combined Cycle, gas turbine
- Coal: Conventional, Advanced, Gasification
- Nuclear: Light Water, Pressurised Water, Boiling Water, Gen3+ (EPR)
- Hydroelectricity: run of the river, or gravitational
- Diesel
- Wind: onshore or offshore
- Photovoltaic: distributed or centralized, solar to electricity or heat concentration
- Biomass
- Marine (getting energy from the tides or the waves)

Cost structure

International Energy Agency, Projected Costs of Generating Electricity – 2005 Edition.

	Investment	O&M	TTB	Lifetime	Load Factor	Efficiency
Gas	400-800	20-40	1-2	20-30	-	0.5
Coal	1000-1500	30-60	4-6	40	-	0.3
Nuclear	1000-2500	45-100	5-9	40	85	0.3
Wind onshore	1000-2000	15-30	1	20-40	15-35	0.3
Wind offshore	1500-2500	40-60	1-2	20-40	35-45	-
Solar PV	2700-10000	10-50	1-3	20-40	9-25	-

Investment cost in USD05/KWe; O&M, operation and maintenance cost in USD05/KWe/year; Contruction time in years; Load factor in percentage.

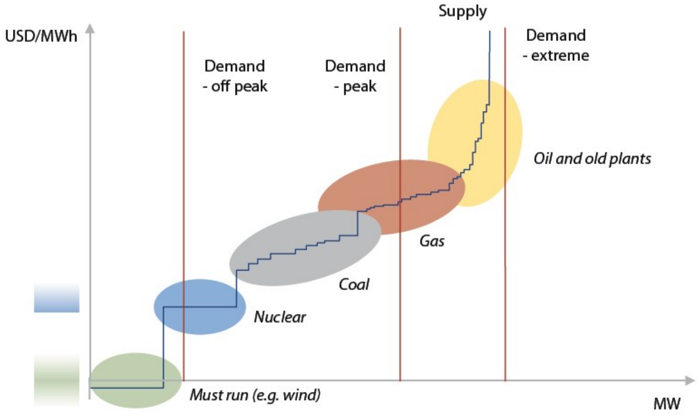
Technical constraints

Order of magnitude for dynamical constraints of thermal generation plant - source: author

	Startup cost kUSD	Pmin MWe	MST hour	MRT hour	RC MWe/h	MNS
Gas	0		38		∞	-
Coal	50	500	4-8	8	200	-
Oil	50	300	2-6	6-8	200	-
Nuclear	-	300	24	72	∞	30-40

Pmin: minimun technical power for a 1000 MW installed capacity plant; MST: minimum stoping time; MRT: minimun running time; RC: ramping capacity; MNS: maximum number of start-up and shut-down per year.

Generation technologies merit order



Running time of a power plant depends on its relative competitiveness

How to solve it?

- Significant gap between industry practice and mathematical economic and financial literature
- Main decision tool used by utilities: the Net Present Value (NPV) (far before real options)
- Main models: Generation Expansion Planning (IAEA, [1984]).
- Computes the optimal generation portfolio to satisfy the demand with a certain level of reliability.
- GEP models provide a policy.
- Legion of GEP models. See Foley et al (2010) for a complete survey.
- Detail modeling of the electric system and of generation assets.
- Same methodology is still applied in deregulated market.

Methods during monopoly

Le Plan ou l'Anti-Hasard, P. Massé, Hermann, 1991

En 1954, une controverse s'était élevée sur l'intérêt des réservoirs hydroélectriques. [...] J'ai été conduit, pour surmonter la difficulté, à formuler un programme linéaire à 4 contraintes et à 4 variables en vue de minimiser la somme des coûts de production actualisés correspondant à la desserte des objectifs. [...]

En 1957, [...] à un colloque à Los Angeles, ce fut l'occasion pour moi de rencontrer G. B. Dantzig et, sur ses conseils, de passer de programmes modestes à quelques inconnues et quelques contraintes, justiciables du calcul manuel, à un programme comprenant 69 inconnues et 57 contraintes et relevant de machines électroniques. [...]

Cependant, ce programme fut jugé insuffisant, [...] et l'Electricité de France entreprit ultérieurement une nouvelle étape représentée par un modèle à 255 inconnues et 225 contraintes qui fut résolu en 1961.

The case of real options method

Real options principle

- Investments are options (McDonald & Siegel [1986]'s seminal paper)
- Don't invest when the NPV is positive, but when it is maximum.
- Financial framework: American options.
- Mathematical framework: Optimal Stopping Time Problems.

Remarks

- Does not limit to irreversible investment in monopoly.
- Applications with reversible investment, delays and competition.
- Important economic literature on real options (Dixit & Pindyck, **Investment Under Uncertainty**, 1994).
- $\Rightarrow$ They should have emerged as the alternative method.

A short suvey of two thousand paper literature

- McDonald and Siegel (1986): Analytical. shows the significant difference threshold investment between NPV and real option.
- Smets 1993 Yale PhD thesis: Analytical. first model mixing competition to invest between two player with one-single investment each.
- Bar-Ilan, Sulem & Zanello (2002): Quasi-analytical. dimension 2, demand (ABM) and capacity, impulse control model with numerical solution for the thresholds.
- Grenadier (2002): Analytical. dimension 2, demand (Ito process) and capacity, time to build, oligopoly, analytical solution.
- Mo, Hegge & Wangensteen (1991): numerics. Dimension 3.
- Botterud, Ilic & Wangensteen (2005) : numerics. Dimension 3
- A. Campi, Langrené & Pham 2014: numerics. Dimension 9.

Are real options methods applied in industry?

- It remains marginal in the industry (many surveys on capital budgeting methods, see Baker [2012]).
- Economic literature develops low dimension model with analytical solutions for comparative static applications.
- Whereas industry would require high dimension model for which no analytical solution is to be hoped.
- But, those models can be used to tackle specific, precise question with large economic impact.

Competition on electricity capacity expansion

Simple (yet not trivial) model aiming to capture

- competition between two industries
- irreversibility
- capital intensive investment
- limited market size
- asymetric effect of carbon price

Capacity Expansion Game An optimal switching duopoly model

The problem

- Value of nuclear power plants strongly depends on a significative carbon price.
- A 30 USD carbon price would make nuclear technology more economical than coal-fired plants for baseload electricity generation (IEA, Projected Costs of Electricity Generation, 2010).
- Carbon price is now ≈ 5 €.

- Nuclear industry dilemna:
    - wait for a rise of carbon price while bearing the risks of seeing coal technology take all the space for baseload generation or...
    - ... preempt the space right now.
- Significative dependence of the carbon price to political will.

The model

- Two firms can increase their generation capacity $Q^i(t)$ by paying a lump-sum capital K^i to produce the same good (baseload electricity).
- Both firms know how much capacity is available in baseload generation.
- N_t^i is number of expansion options remaining for firm $i = 1, 2$.
- Instantaneous profit rates are asymetrically affected by the carbon price X_t:
  - $\pi^1_{n_1,n_2}(X_t) = (P_{n_1,n_2} - C^1 + \rho^1 X_t) Q^1_{n_1,n_2}$
  - $\pi^2_{n_1,n_2}(X_t) = (P_{n_1,n_2} - C^2 - \rho^2 X_t) Q^2_{n_1,n_2}$.
- Electricity price P_{n_1,n_2} is deterministic. It decreases as capacity/supply rises.
- The carbon price is supposed to follow an OU process

$$dX_t = \mu(\theta - X_t)\,dt + \sigma dW_t,$$

with $X_0 \ll \theta$ and where μ represents the strength of the political will to enforce a carbon price of θ.

Firms' objective function

- Assume actions of firms to be of Markovian type

$$\mathcal{A}^i = \left\{ \boldsymbol{\alpha}^i := \alpha^i \left(X_t,\ \vec{N}_t \right) \right\}$$

- The set of actions of firm 1 (resp. 2) consists of stopping times:

$$\mathcal{A}^1 = \left\{ \boldsymbol{\alpha}^1 := \left(\tau^1_{n_1,n_2} \right) \middle| \, n_1 > 0, \forall n_2 \right\},$$
$$\mathcal{A}^2 = \left\{ \boldsymbol{\alpha}^2 := \left(\tau^2_{n_1,n_2} \right) \middle| \, n_2 > 0, \forall n_1 \right\}.$$

- Objective function

$$J^i_{n_1,n_2}(x; \boldsymbol{\alpha}^1, \boldsymbol{\alpha}^2) := \mathbb{E}^{x;n_1,n_2} \Big\{ \underbrace{\int_0^{+\infty} e^{-rs} \pi^i_{N^1_s, N^2_s}(X_s) ds}_{\text{Future Cashflows}} - \underbrace{K^i \times \sum_{j=1}^{n_1} e^{-r\mathcal{I}^i_j}}_{\text{Investment Costs}} \Big\}.$$

with $\mathcal{I}^i_j$: j-th capacity investment time ($\mathcal{I}^i_j = \inf\{s > \mathcal{I}^i_{j-1} : N^i_{s-} > N^i_s\}$).

- Decisions of one firm affect the other through the joint dependence on $\vec{N}_t$
  - Capacity expansion becomes a nonzero-sum stochastic game.
  - Solve by constructing a *Nash equilibrium*.

Definition (*Nash Equilibrium*)

Let $J^i(x,\cdot)$ *denote the NPV received by firm* i *with* $X_0 = x$. *A set of actions* $\boldsymbol{\alpha}^* = (\boldsymbol{\alpha}^{\mathbf{1},*},\, \boldsymbol{\alpha}^{\mathbf{2},*})$ *is said to be a Nash equilibrium of the game, if for* $i \in \{1,\, 2\},\ \forall \boldsymbol{\beta}^{\mathbf{i}} \in \mathcal{A}^i$:

$$J^i(x,\, \boldsymbol{\alpha}^{*-\mathbf{i}}, \boldsymbol{\beta}^{\mathbf{i}}) \le J^i(x, \boldsymbol{\alpha}^*) =: V^i(x).$$

Denote $V^i_{n_1,n_2}(x) := J^i_{n_1,n_2}(x, \boldsymbol{\alpha}^*)$.

Reduction of the problem

- Denote $D^i_{n_1,n_2}(x) := \mathbb{E}_x\left[\int_0^\infty e^{-rs}\pi^i_{n_1,n_2}(X_s)\,ds\right]$.
- Fixing $\tau^2_{n_1,n_2}$ and firm 1 solves

$$\widetilde{V}^1_{n_1,n_2}(x,\tau^2_{n_1,n_2}) - D^1_{n_1,n_2}(x) =$$

$$\sup_{\tau\in\mathcal{T}} \mathbb{E}_x\Bigg[\underbrace{e^{-r\tau}\mathbb{1}_{\{\tau<\tau^2_{n_1,n_2}\}}\left(V^1_{n_1-1,n_2}(X_\tau) - D^1_{n,n_2}(X_\tau) - K^1\right)}_{\text{firm 1 invests first: first-mover}}$$

$$+\underbrace{e^{-r\tau^2_{n_1,n_2}}\mathbb{1}_{\{\tau>\tau^2_{n_1,n_2}\}}V^1_{n_1,n_2-1}\left(X_{\tau^2_{n_1,n_2}} - D^1_{n_1,n_2}(X_{\tau^2_{n_1,n_2}})\right)}_{\text{firm 2 invests first: second-mover}}\Bigg].$$

Threshold-type best-response

- Abstract optimal stopping problem:

$$V_R(x) = \sup_{\tau \in \mathcal{T}} \mathbb{E}_x \left\{ \mathbb{1}_{\{\tau < \tau_R\}} e^{-r\tau} h(X_\tau) + \mathbb{1}_{\{\tau > \tau_R\}} e^{-r\tau_R} \ell(X_{\tau_R}) \right\}.$$

- $h(\cdot)$: first-mover payoff; $\ell(\cdot)$: second-mover payoff.
- Assume best-response strategies are of threshold type, i.e.

$$\tau^1_{n_1,n_2}(s_2) = \inf\{t \geq 0 : \ X_t \geq S^1_{n_1,n_2}(s_2)\}$$
$$\tau^2_{n_1,n_2}(s_1) = \inf\{t \geq 0 : \ X_t \leq S^2_{n_1,n_2}(s_1)\}$$

- Equilibrium policies correspond to crossing points of the best-response curves $S^1_{n_1,n_2}(s_2)$ and $S^2_{n_1,n_2}(s_1)$
- Best-response function $S^i_{n_1,n_2}$ are computed recursively with boundary stages $n_2 = 0$ ($n_1 = 0$) reducing to single-agent optimization problem.

Preemptive best-response & equilibrium

- Threshold-type equilibrium may not exist (best-response curve may not cross)
- Consider $L^1 := \inf\{x, \quad h^1(x) > \ell^1(x)\}$, i.e. the threshold where Firm 1 is indifferent between waiting and investing.
- If $s_2 < L^1$, Firm 1 benefits from Firm 2 investment and thus, waits.
- If $L^1 < s_2$, Firm 1 has an incentive to preempt when $L^1 < x \le s_2$.
- Preemptive best-response:

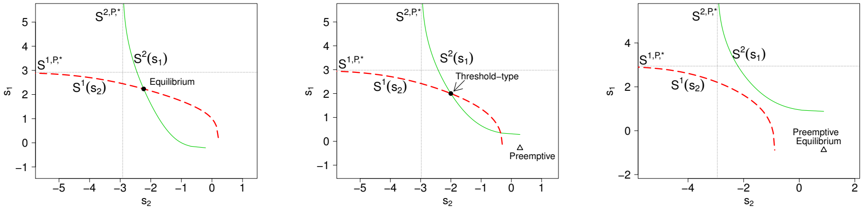
$$\tau^{1,e}_{1,1}(s_2) = \inf\{t \ge 0 : \ L^1_{1,1} < X_t \le (s_2+) \text{ or } X_t \ge S^1(s_2)\}$$

- Leads to a (unique) preemptive equilibrium:

$$\tau^{1,e,*} = \inf\{t \ge 0 : \ L^1 < X_t \le L^2 \text{ or } X_t \ge S^{1,e,*}\}$$

- Under that equilibrium, firms invest immediatly when $L^1 < x < L^2$.

Equilibrium Policies



- Crossing points: threshold-type equilibrium strategies.
- "Δ" marks the unique preemptive equilibrium.
- No threshold-type $\Longrightarrow$ a unique preemptive equilibrium.
- No preemptive $\Longrightarrow$ existence of threshold-type equilibria.

Back to our problem

Setting the parameters

- Investment in nuclear is more expensive than in coal: $K_2 < K_1$.
- First, consider an initial state with only one option to invest per firm.
- Denote p_1 and p_2 the LCOE of both technologies.
- Electricity prices P_{n_1,n_2} are fixed in a way such that $P_{1,1} = \max(p_1, p_2)$ but $P_{0,0} < \min(p_1, p_2)$.
- $P_{1,0}$ and $P_{0,1}$ are set such that investment is worth conditionned on a high or low enough value of carbon.

Parameters value in the large scale investment

Parameter	Value	Unit
Private discount rate r	10%	
Nuclear expansion cost K^1	1400	USD/MWe
Coal expansion cost K^2	850	USD/MWe
Revenue rate $P_{1,1}$	24	USD/MWh
Revenue rate $P_{1,0}$	22	USD/MWh
Revenue rate $P_{0,1}$	22	USD/MWh
Revenue rate $P_{0,0}$	10	USD/MWh
Cost Sensitivity ρ	0.25	
Long-run carbon price θ	30	USD/tCO2
Political will μ	$[0.1, 0.25]$	
Initial carbon price X_0	5	USD/tCO2

Table: Parameter values.

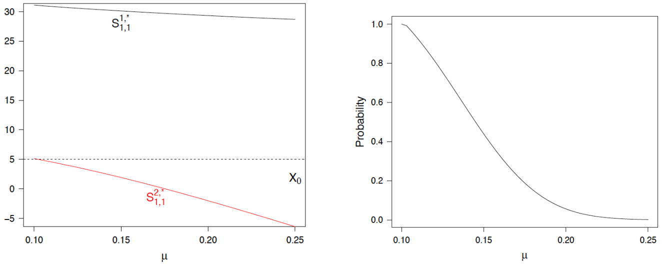


Figure: (Left) Investment thresholds $S^{1,*}_{1,1}, S^{2,*}_{1,1}$. (Right) Probability that the coal-fired investor invests first $Prob_{1,0}$.

- Result matches intuition: higher political will deter investment in coal technology.
- Less predictable result: the insensitivity of the investment threshold in nuclear technology.
- Carbon price is less an opportunity for nuclear technology than a threat for coal technology.

Multi-stage investment case $(2, 2)$

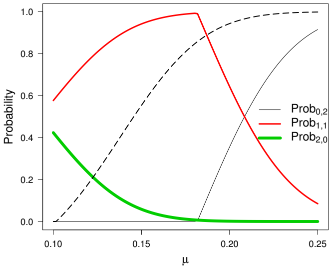
- Still investment in nuclear is more expensive than in coal: $K_2 < K_1$.
- Still just enough space for 2 units.
- Price decline to 23 with 1 investment and to 22 with 2 investments.
- More investment makes the price not worth investing anymore.
- Denote p_1 and p_2 the LCOE of both technologies.
- Electricity prices P_{n_1,n_2} are fixed in a way such that $P_{1,1} = \max(p_1, p_2)$ but $P_{0,0} < \min(p_1, p_2)$.
- $P_{1,0}$ and $P_{0,1}$ are set such that investment is worth conditionned on a high or low enough value of carbon.

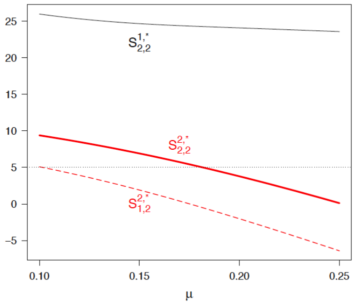
Parameters value in the multi-stage investment case

Parameter	Value	Unit
Discount rate r	10%	
Nuclear Inv. cost K_1	1.400	USD/MWh
Coal Inv. cost K_2	0.850	USD/MWh
$P_{2,2}$	24	USD/MWh
$P_{1,0}$	10	USD/MWh
$P_{0,1}$	10	USD/MWh
$P_{0,0}$	8	USD/MWh
CO2 profit sensitivity ρ	0.25	
Long-run carbon price θ	30	USD/MWh
Political will μ	$[0.1, 0.25]$	
Initial carbon price	5	USD/tCO2

Table: Parameter values

Effect of Political Will μ





- Low $\mu \Rightarrow$ one small coal-fired plant is built instantly.
- Strong political will μ guides the market to exclusively nuclear power plants.
- Dashed line: probability that two nuclear plants are built if a small nuclear plant is built at $X_0 = 5$ preemptively.

Conclusion

- Possible to analyse the interaction at the industries level with a compact model
- Model's results fit intuition
- But it alse provides more insights

Perspective

- Numerics for optimal switching games