Generation capacity expansion under long-term uncertainties in the US electric market IAEE 2008

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EDF R&D

December 2008

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Agenda

Introduction

- High volatility in fuel markets and uncertainties on environmental policies
- Major uncertainties for the planning of generation capacity expansion
- This article discusses the optimal generation investment decisions under uncertainties surrounding coal, gas and CO_2 prices
- An optimization model for electric generation investments based on stochastic dynamic programming is presented
- The US electricity market seen as perfectly competitive is considered over the period 2010-2030 (data from the Annual Enegy Outlook 2008)

Related literature

- FH.Murphy and Y.Smeers, *Generation Capacity Expansion in Imperfectly Competitive Restructured Electricity Markets*, Operations Research, 53, 646-661, 2005
- SJ.Deng, B.Johnson and A.Sogomonian, *Exotic electricity options and the valuation of electricity generation and transmission assets*, Decis Support Syst, 30, 383-392, 2001
- PO.Pineau and P.Murto, *An Oligopolistic Investment Model of the Finnish Electricity Market*, Annals of Operations Research, 121, 123-148, 2003
- A.Botterud, M.D.Ilic and I.Wangensteen, *Optimal investments in power generation under centralized and decentralized decision making*, Power Systems IEEE Transactions on, 20, 254-163, 2005
- FH.Murphy and AL.Soyster, *Economic behavior of electric utilities*, Prentice-Hall Englewood Cliffs NJ, 1983

The global setting

- The objective of the model is to determine the optimal investment decisions on a perfectly competitive market (= social welfare maximisation)
- The investment decisions are taken on yearly time step
- The supply curve is a merit order stack on the variable costs for given installed capacities
- The demand curve is inelastic (hourly electric demand blocks)
- Within a yearly time step, the price of each hourly block is the crossing of the supply and demand curves
- Two types of generation capacities are considered :
  - *the initial capacities :* no investment / possible decommissionings
  - *the new capacities :* discrete capacity step/not decommissioned over the period

The model

In a perfectly competitive market where the demand is inelastic, the social welfare maximization is equivalent to a cost minimization :

$$\min_{(i_t)_{t \in T}} \mathbb{E}_S \sum_{t=1}^{T} g_t(l_t, i_t, x_t)(1+r)^{-t}$$

$$\text{s.t} \quad x_{t+1} = x_t + i_t - d_t$$

where :

- T planning horizon (years)
- t time step (year)
- S set of long-term scenarios
- i_t vector of invested capacities (MW) - *command variable*
- d_t vector of decommissioned capacities (MW)
- x_t vector of existing capacities (MW) - *state variable*
- l_t load duration curve (MW, hourly block)
- r risk-adjusted real discount rate
- g_t objective function-total cost function ($)
- g_T terminal cost function($), year T

The model

The total cost function at time t is :

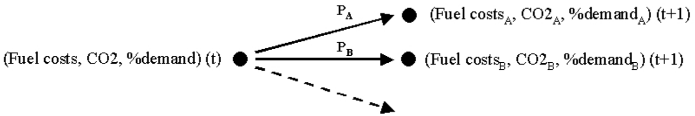
$$g_t(l_t, i_t, x_t) = C_t^{Gen}(l_t, x_t) + C_t^{O\&M}(x_t) + C_t^{Inv}(i_t)$$

where :

- $C_t^{Gen}(l_t, x_t)$ is the generation cost
- $C_t^{O\&M}(x_t)$ are Operation and Maintenance costs
- $C_t^{Inv}(i_t)$ is the investment cost

Uncertainty representation

We consider a possible uncertain future on fuel prices and CO_2 taxation modeled as a markovian event-tree :



The backward problem

- Bellman algorithm
- The objective is to calculate backwardly the investment decisions that minimize the objective function (here the total cost function)

The Bellman value at node n and for the installed capacity x_t is the minimum of the expected future objective function :

$$Vb_n(x_t) = \min^{n}_{(i_t)_{t \in T}} \left(g_t(I_t, i_t, x_t)(1+r)^{-t} + \sum_{n' \in F(n)} proba_{n'/n} Vb_{n'}(x_t + i_t) \right)$$

where :

- n' is a node son of n
- $F(n)$ is the set of all the nodes son of n
- $proba_{n'/n}$ is the probability to switch from node n to node n'

The general problem

- General objective : What are the optimal generation investment decisions in the US electricity market over the period 2010-2030 ?
- Investments are decided every five years and plants start producing immediately
- Fuel cost scenarios are taken from the Annual Energy Outlook 2008. The impact of different CO_2 price will be analyzed
- These scenarios are combined in an event tree centered around the Reference scenario

The questions

Question 1 Optimal investment decisions for the Reference scenario. Different CO_2 price scenarios are tested. Risk-neutral generators

Question 2 Testing the robustness of the investment decisions for the Reference scenario under uncertainties. Risk-neutral generators

Question 3 Optimal investment decisions for risk-averse generators

The technologies

- The generators can invest either in new coal plants, in new combined-cycle gas power plants (CCGTs) or in new oil peak plants
- Investments in new nuclear plants will be analyzed in a specific section

	Coal plant	CCGT	Nuclear plant	Peak unit
Heat rate *BTU/kWhr*	9200	7196	10400	10833
Investment cost *$/kW*	1534	717	2475	500
Fixed O&M *$/kW.year*	26.8	12.1	66.1	11.8
Variable O&M *$/MWhr*	4.5	2	0.5	3.5
CO_2 emissions *ton/MWhr*	0.74	0.35	0	0.83
Lifetime *years*	35	25	40	25
Size *MW*	600	250	1350	160

source : Annual Energy Outlook 2008

The 2005 US generation fleet

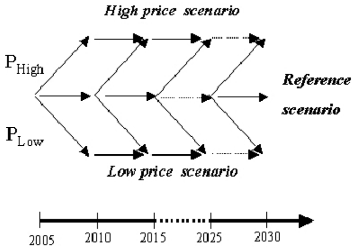
- 20% of all the initial technologies are decommissioned every five years
- Except for the Renewables/Hydro which are replaced not decommissioned/replaced identically
- The load factor are set to 90% for the thermal units and to 25% for the renewables

Coal plants	305 GW
Gas plants/CCGTs	258 GW
Peak units	127 GW
Nuclear plants	100 GW
Renewable energies	15 GW
Pumped storage	22 GW
Conventional Hydro power	77 GW
Total	**905 GW**

source : Annual Energy Outlook 2008

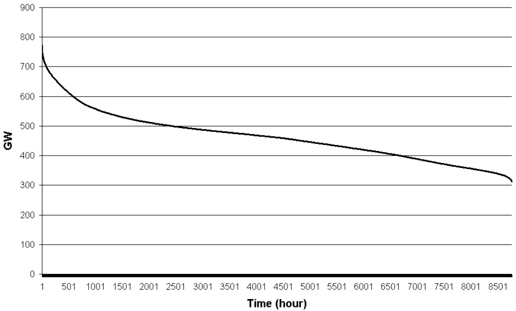
Uncertainty representation

- Three scenarios of the Annual Energy Outlook are considered : Reference case, High price case and Low price case
- The fuels are : coal (Average delivered price), gas (Henry Hub price) and oil (Distillate fuel oil)
- We make assumptions on the CO_2 emission price
- We combine these three scenarios as an event tree centered around the Reference case with constant probabilities P_{Low} and P_{High} to switch definitively to the Low or High price scenarios (every five years)



The demand

- The US electric grid is perfectly interconnected
- The US continuous load is made using FERC data by aggregating the regional electric grids load duration curves in 2005
- No demand growth is considered (the demand growth is supplied by new renewables)



Other data

- Discount rate equal to 8%
- Value of lost load equal to 20 000$/MWhr

Optimal investment planning for the Reference scenario - no nuclear investment

GW	2010	2015	2020	2025	2030	**Total**
Coal units	0	30	160	160	160	**510**
CCGTs	40	120	0	0	0	**160**
Peak units	80	0	0	0	0	**80**

TAB.: Reference scenario investment decisions - no nuclear and CO_2 price=0 $/ton

GW	CO_2 price ($/ton)				
	10	20	30	40	50
Coal units	480	450	400	160	0
CCGTs	190	220	270	510	670

TAB.: Sensitivity to CO_2 price

Impact of fuel price uncertainties on the investment decisions - no nuclear investment

- We set CO_2 price to 30 $/ton over the period
- We consider successively the possibility to switch to the Low and to the High scenario with different probabilities P_{Low} and P_{High} (if $P_{Low} > 0$ then $P_{High} = 0$ and inversely)
- We focus on the investment decisions if the Reference scenario occurs

GW	Low	P_{Low}				Reference	P_{High}				High
		40%	30%	20%	10%	(CO_2 **30$/ton**)	10%	20%	30%	40%	
Coal units	0	160	320	370	380	**400**	410	440	450	450	480
CCGTs	670	510	350	300	290	**270**	260	230	220	220	190

The Reference scenario is more robust to the risk to switch to the High price case (the technological mix is unchanged) than to the risk to switch to the Low price case (the technological mix is modified for high probabilities)

Impact of fuel price uncertainties on the investment decisions - with nuclear investment

- CO_2 price is still equal to 30 $/ton over the period
- The generators can invest in nuclear units in addition to CCGTs, coal and peak units
- We focus on the investment decisions if the Reference scenario occurs

GW	Low	P_{Low}				Reference	P_{High}				High
		40%	30%	20%	10%	(CO_2 **30$/ton**)	10%	20%	30%	40%	
Coal units	0	0	0	0	0	**0**	0	0	0	0	0
CCGTs	200	200	170	170	170	**170**	170	170	170	170	170
Nuclear units	470	470	500	500	500	**500**	500	500	500	500	500

Considering possible nuclear investments make the decisions not impacted by uncertainties regarding fuel prices if the Reference scenario occurs

A risk-averse objective function

- Previously, the generators took their investment decisions using mathematical expectation
- We assume here that the generators are risk-averse : "Min Max Regret" criterion
- The generators take their investment decisions with respect to the worst possible case

$$\min_{(i_t)_{t \in T}} \max_{S} \sum_{t=1}^{T} g_t(I_t, i_t, x_t)(1+r)^{-t}$$

$$\text{s.t} \quad x_{t+1} = x_t + i_t - d_t$$

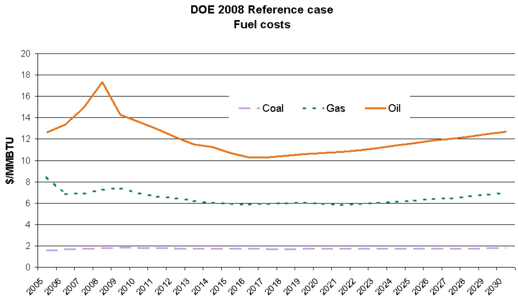
Impact of risk-aversion on the investment decisions - no nuclear investment

GW	2010	2015	2020	2025	2030
Coal units	0	0	160	160	160
CCGTs	40	150	0	0	0
Peak units	80	0	0	0	0

- We show that the investments are similar to the ones made in the deterministic High price scenario (with a CO_2 price equal to 30$/ton)
- Therefore, the worst case for generators corresponds to the scenario with relative high gas prices

Conclusions

- As far as the DOE Reference scenario is concerned, we show that, if the generators can invest only in fossil thermal units, the generation investment decisions cannot be seen as robust with respect to fuel and CO_2 price uncertainties (for some probabilities to switch)
- Conversely, if the generators can invest in nuclear units, then these uncertainties do not impact the robustness of the generation investment decisions
- Finally, we show that, with respect to fuel price uncertainties, the generators'risk-aversion can modify the investment decisions


DOE 2008 Reference case
Fuel costs
$/MMBTU
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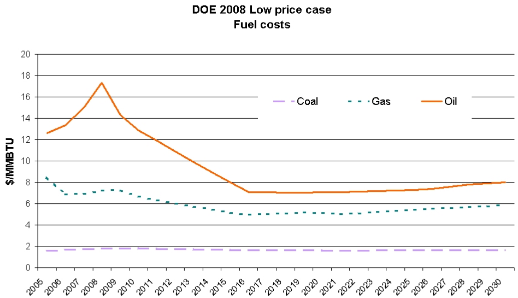
DOE 2008 Low price case
Fuel costs
$/MMBTU
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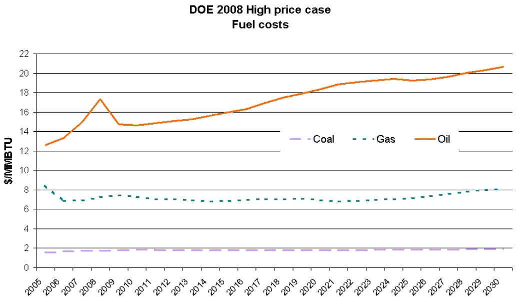
DOE 2008 High price case
Fuel costs
$/MMBTU
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