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Generation Capacity Expansion in a Risky Environment: A Stochastic Equilibrium Analysis

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Motivation

Private investors operate in a merchant world with different sources of uncertainty. These uncertainties have been increasing over time and are very hard to value.

Commodity Prices Risk

- Costs of fuels determine the marginal prices of the electrical system and the market prices; their relative behavior has an impact on the profitability of the different technologies

Residual Demand Risk

- Uncertainty in the total demand growth (or decline)
- Development of non competitive but CO_2 friendly technologies through various subsidies
- Decommissioning of nuclear and old conventional plants
- Demand behavior

Regulation risk

- Market architecture
- Carbon policy: uncertainty around the targets
- Sustainability of Subsidy Mechanisms

Summary

This presentation:

Very stylized two stage Investment model:

A two stage problem:

1. Decide investment today (2010–2011)
2. that will come on stream after 2016 (on which we know nothing)

Approach:

1. start from capacity expansion models because they allow for considerable details in the representation of the system
2. cast them in an economic equilibrium context because this better represents a competitive economy
3. and expand on the representation of risk because it can no longer be simply passed to the consumer

Questions:

1. Do results from a risk neutral case differ much from a risk averse case?
2. Do capacity markets change this finding?

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Model Typology

In this presentation: A simple two stage model and the corresponding equilibrium model with fixed price insensitive demand

Optimization	Equilibrium
Can be written as stochastic optimization model •Benefit: some features of power systems are amenable to optimization but not to equilibrium • e.g. unit commitment characteristics	A stochastic version of the equilibrium model Benefit: the equilibrium model can embed features that cannot be accommodated in optimization mode • price sensitive storage possibilities arising from smart grids • market imperfection such as average cost price

What we need is a margin by plant, indexed by scenario from an adequate short term model to make an investment decision

Introduction to the basic model (1/6)

1. The traditional capacity expansion model

- The simplest view: two periods
  - period 0: invest in a mix of technologies
  - period 1: operate the capacities
- Objective

  Satisfy a time segmented, price insensitive demand so as to minimize total (annual in this simple case) cost
- Early models go back to the sixties
- They expanded and progressively became quite sophisticated

Introduction to the basic model (2/6)

2. Some notation

- Capacities $x(k)$ in technology k operate at level $y(k,\ell)$ to satisfy demand level $d(\ell)$ of duration $\tau(\ell)$.
- Capacity cost is $I(k)$, operating cost is $c(k)$
- $e(k)$ are emission coefficients and NAP is the total allowed emission
- PC is interpreted as a shortage cost or as a price cap
- $z(\ell)$ is the unsatisfied demand in time segment ℓ

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3. And a standard optimization model

- Operations

$$Q(x) \equiv \min_{y,z} \sum_{\ell \in L} \tau(\ell) \left[\sum_{k \in K} c(k)\, y(k,\ell) + PC\ z(\ell) \right] \qquad (1)$$

s.t.

$$0 \le x(k) - y(k,\ell) \qquad \mu(k,\ell) \qquad (2)$$

$$0 \le \sum_{k \in K} y(k,\ell) + z(\ell) - d(\ell) \qquad \pi(\ell) \qquad (3)$$

$$0 \le NAP - \sum_{\ell \in L} \tau(\ell) \sum_{k \in K} e(k) y(k,\ell) \qquad \lambda \qquad (4)$$

$$0 \le y(k,\ell). \qquad (5)$$

- Investment

$$\min_{x \ge 0} \sum_{k \in K} I(k)\, x(k) + Q(x). \qquad (6)$$

Introduction to the basic model (4/6)

4. Resource adequacy and security of supply

- Former capacity expansion models used under the obligation to serve guaranteed the necessary capacity
- Do these models still make sense in a competitive system ?
- If not, what should replace them ?
- Do we have clear cut ideas on incentive to invest ?

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5. A first step: move from optimization to complementarity (or from optimization to economic equilibrium)

- Operations

$$0 \leq x(k) - y(k,\ell) \perp \mu(k,\ell) \geq 0 \tag{7}$$

$$0 \leq \sum_{k \in K} y(k,\ell) + z(\ell) - d(\ell) \perp \pi(\ell) \geq 0 \tag{8}$$

$$0 \leq NAP - \sum_{\ell \in L} \tau(\ell) \sum_{k \in K} e(k)\, y(k,\ell) \perp \lambda \geq 0 \tag{9}$$

$$0 \leq c(k) + \mu(k,\ell) + e(k)\lambda - \pi(\ell) \perp y(k,\ell) \geq 0 \tag{10}$$

$$0 \leq PC - \pi(\ell) \perp z(\ell) \geq 0. \tag{11}$$

- Investment

$$0 \leq I(k) - \sum_{\ell \in L} \tau(\ell)\, \mu(k,\ell) \perp x(k) \geq 0. \tag{12}$$

Introduction to the basic model (6/6)

We can easily add market imperfections like free allocation of allowances (not possible in the optimization)

6. A second step: introduce some market features

Let $a(k)$ be the free allowance to unit capacity (k)

Replace

$$0 \leq I(k) - \sum_{\ell \in L} \tau(\ell)\, \mu(k,\ell) \perp x(k) \geq 0. \tag{13}$$

by

$$0 \leq I(k) - a(k)\, \lambda - \sum_{\ell \in L} \tau(\ell)\, \mu(k,\ell) \perp x(k) \geq 0 \tag{14}$$

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Is there a problem?

Discussion: the incentive to invest

Does one need intervention or support to incentivize investment in a competitive market

No in functioning markets
Yes in case of market failure

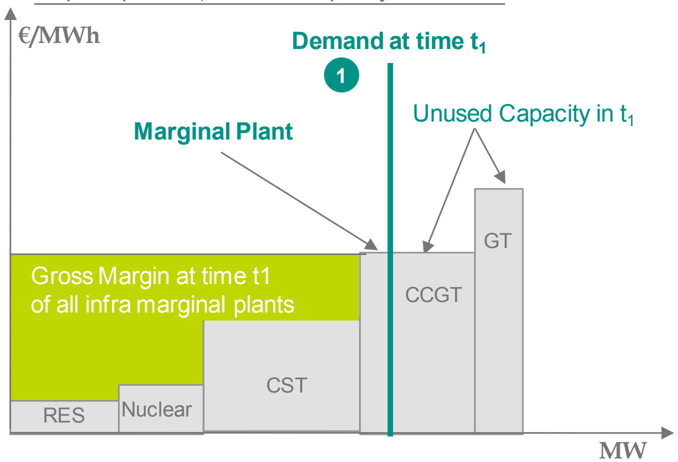
Are there market failures in electricity systems?

Possible market failures

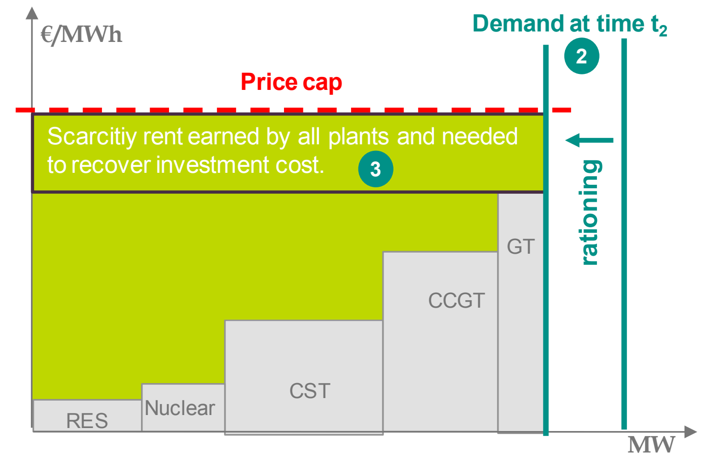
Investment in Energy-Only Markets is jeopardized for mainly 2 reasons:

- **Inefficient price caps:** Price spikes, which are needed to recover investment costs in EOM, are socially not accepted. Price caps in the energy market are too low.

Offpeak period t_1: Excess Capacity



Peak period t_2: Scarce Capacity



- **Increasing risk:** Risk itself is not a market failure but the lack of trading possibilities of risk is

Uncertainty concerning the climate policies and the RES deployment may magnify the risk such that markets alone are unlikely to deliver appropriate investment responses.

Regulations that restrict efficient price formation (e.g. price cap) undermine the market signal for investment

IEA – "Securing Power during the Transition" - 2012

Investment incentives

Remedies

- Energy only market: set regulated price PC (ideally VOLL) during curtailment
- Capacity market: create a market for capacities; investor receive
  - electricity price when they operate
  - capacity value when they invest
- Other means not discussed here

Capacity market formulation

A third step: update the model

- Energy only model: no change

$$0 \leq I(k) - \sum_{\ell \in L} \tau(\ell)\,\mu(k,\ell) \perp x(k) \geq 0.$$

- Capacity market

  Replace

$$0 \leq I(k) - \sum_{\ell \in L} \tau(\ell)\,\mu(k,\ell) \perp x(k) \geq 0.$$

  by

$$0 \leq \sum_{k \in K} x(k) - \max_{\ell \in L} d(\ell) \perp \nu \geq 0$$

$$0 \leq I(k) - a(k)\lambda - \nu - \sum_{\ell \in L} \tau(\ell)\,\mu(k) \perp x(k) \geq 0$$

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Risk factors

We pick only three risk factors for the discussion: commodity and carbon regulation

Commodity Prices Risk

- Costs of fuels determine the marginal prices of the electrical system and the market prices; their relative behavior has an impact on the profitability of the different technologies

Residual Demand Risk

- Uncertainty in the total demand growth (or decline)
- Development of non competitive but CO_2 friendly technologies through various subsidies
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Regulation risk

- Market architecture
- Carbon policy: uncertainty around the targets
- Sustainability of Subsidy Mechanisms

Risk factors (1/2)

1. The EU-ETS: a 2007/early 2008 view

- Investors at time of decision to invest do not know
  - the total amount of allowances (the NAP) $NAP(n)$
  - the amount of free allowances $(a(k))$ $a(k,b)$

  that their plants will receive when coming on line.

- The new Directive removes some uncertainties but introduces other risks.

Risk factors (2/2)

2. The standard risk factors

- Fuel prices and demand evolution
- Here only fuel prices: $c(k, f)$
- We do not consider demand risk. **But** we suppose that other risk factors have an impact on demand. This turns out to be technically and economically important.

The basic model as stochastic equilibrium model

3. A fourth step (1): introduce uncertainty in operations model

for all (f, n, b)

$$0 \leq x(k) - y(k, \ell, f, n, b) \perp \mu(k, \ell, f, n, b) \geq 0$$

for all (f, n, b)

$$0 \leq \sum_{k \in K} y(k, l, f, n, b) + z(\ell, f, n, b) - d(\ell, f, n, b) \perp \pi(\ell, f, n, b) \geq 0$$

for all n

$$0 \leq NAP(n) - \sum_{\ell \in L} \tau(\ell) \sum_{k \in K} e(k) y(k, \ell, f, n, b) \perp \lambda(\ell, f, n, b) \geq 0$$

for all (f, n, b)

$$0 \leq c(k, f) + \mu(k, \ell, f, n, b) + e(k)\lambda(f, n, b) - \pi(\ell, f, n, b)$$

$$\perp y(k, \ell, f, n, b) \geq 0$$

for all (f, n, b)

$$0 \leq PC - \pi(\ell, f, n, b) \perp z(\ell, f, n, b) \geq 0.$$

The investment decision in expectation

4. A fourth step (2): update the investment part accordingly

- Energy only market

for all k

$$0 \leq I(k) - \sum_{f \in F, n \in N, b \in B} pb(b)pf(f)pn(n)a(k,b)\lambda(f,n,b)) - \sum_{\ell \in L, f \in F, n \in N} \tau(\ell)pb(b)pf(f)pn(n)\mu(k,\ell,f,n,b) \perp x(k) \geq 0. \tag{24}$$

- Capacity market

$$0 \leq \sum_{k \in K} x(k) - \max_{L,F,N,B} d(\ell,f,n,b) \perp \nu \geq 0 \tag{25}$$

for all k

$$0 \leq I(k) - \sum_{f \in F, n \in N, b \in B} pf(f)pn(n)pb(b)a(k,b)\lambda(f,n,b)) - \nu - \sum_{\ell \in L, f \in F, n \in N, b \in B} \tau(\ell)pf(f)pn(n)pb(b)\mu(k,\ell,f,n,b) \perp x(k) \geq 0. \tag{26}$$

How to price risk ?

5. Risk neutral (RN) vs. risk averse (RA) investors

- Sometimes heard about the EU-ETS
  - "risk is not an issue! The industry is used to deal with it"
  - "bankruptcy is just a transfer of ownership"
- Suppose one wants to go beyond these comforting statements. Apply CAPM or APT: the β are not always significantly $\neq 0$?
- What else ? Introduce risk functions

We assume that risks are not traded and need to be priced by the investor → we adjust the probabilities

6. Risk averse investors

- Invest according to a different probability

- Recall from mathematical finance P and Q

  P: the "statistical probability"
  here $pf(f)pn(n)pb(b)$: given

  Q: a "risk adjusted probability" (risk neutral)
  noted $\phi(k; f, n, b)$: to be found

- Principle: replace $pf(f)pn(n)pb(b)$ by $\phi(k; f, n, b)$

- Question: where does $\phi(k; f, n, b)$ come from ?

The CVAR weights scenarios and hence changes the distribution

7. Reminder: the CVaR

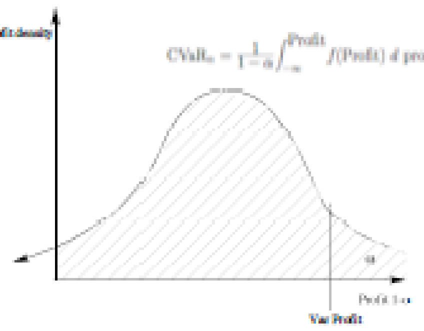
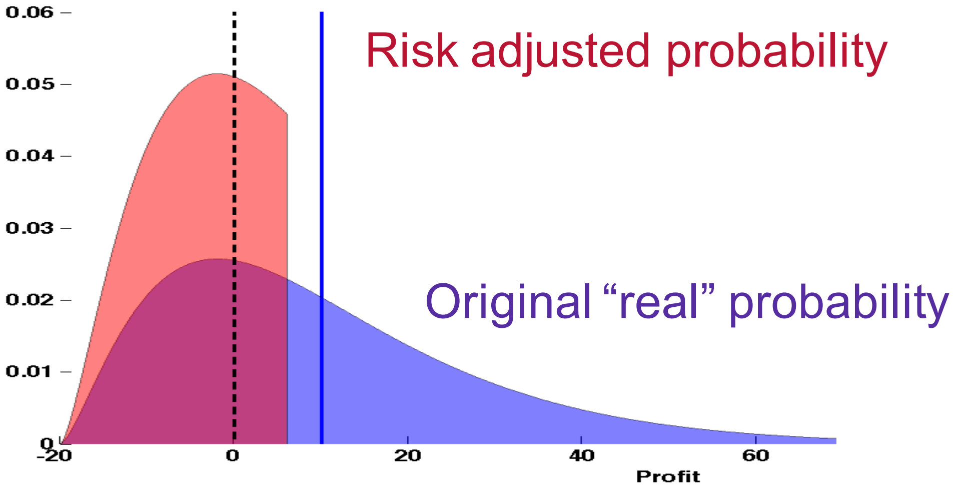


Illustration of the $CVaR_\alpha$



Assume investors behave according to a CVaR (which is a coherent risk function (Artzner et al., 1989))

8. The net margin and the investment criterion

- Let

$$\text{margin}(k; f, n, b) \equiv \sum_{\ell \in L} \tau(\ell)\mu(k; \ell, f, n, b) + \nu + a(k, b)\lambda(f, n, b) - I(k)$$

for the capacity market

$$\text{margin}(k; f, n, b) \equiv \sum_{\ell \in L} \tau(\ell)\mu(k; \ell, f, n, b) + a(k, b)\lambda(f, n, b) - I(k)$$

for the energy only market

- Investment criterion

$$0 \leq - \sum_{f \in F, b \in B, n \in N} \phi(k; f, n, b)\text{margin}(k; f, n, b) \perp x(k) \geq 0$$

How do we relate the CVAR to the risk adjusted probabilities?

$$0 \leq -\mathrm{CVaR}_{\alpha}[\mathrm{margin}(k; f, n, b)] \perp x(k) \geq 0$$

and

$$0 \leq -\sum_{f \in F, b \in B, n \in N} \phi(k; f, n, b)\mathrm{margin}(k; f, n, b) \perp x(k) \geq 0$$

are identical expressions provided one uses the duality theory introduced by Artzner et al. (1989) and developed in computational form by Rockafellar and Uryasev (2002).

We can derive the risk adjusted probabilites from an additional complementarity constraint

- Applying Rockafellar and Uryasev, one formulates CVaR(margin($\cdot$)) as an LP.
- One writes its dual with $\phi(\cdot)$ being some variables of it.
- One writes the corresponding complementarity conditions and one inserts them in the model, whether energy only or capacity market.

Two important benchmarks

- **The fully incomplete market (Ehrenmann and Smeers, 2011)**
  - Assemble the KKT conditions for the risk-averse producer
- **The complete market (Ralph and Smeers, 2013)**
  - Assuming a complete set of financial product (e.g. Arrow-Debreu securities)
  - On can solve the equilibrium by minimizing the total risk of the system

$$\mathcal{M}^{\mathsf{complete}} \equiv \mathbf{Max} \quad \rho^{\mathsf{tot}} \left\{ \sum_{\ell} \tau_\ell \left(\mathtt{VOLL}\big(\mathsf{d}_\ell(\omega) - \mathsf{z}_\ell(\omega)\big) - \sum_{\mathsf{k}} \mathsf{C}_\mathsf{k}(\omega)\mathsf{y}_{\mathsf{k},\ell}(\omega) \right) - \sum_{\mathsf{k}} \mathsf{I}_\mathsf{k}\mathsf{v}_\mathsf{k} \right\}$$
$$0 \leq \mathsf{v}_\mathsf{k} - \mathsf{y}_{\mathsf{k},\ell}(\omega)$$
$$0 \leq \sum_{\mathsf{k}} \mathsf{y}_{\mathsf{k},\ell}(\omega) + \mathsf{z}_\ell(\omega) - \mathsf{d}_\ell(\omega)$$

  - Where $\rho^{\mathsf{tot}}(X) = \underset{Q \in \mathcal{Q}^{\mathsf{prod}} \cap \mathcal{Q}^{\mathsf{cons}}}{\mathbf{Min}} \mathbb{E}[X]$
  - Similar to risk averse planning (minimizing total cost, except that the cost is corrected by the (exogeneous) term $\mathtt{VOLL}\ \mathsf{d}_\ell(\omega)$.
  - The problem gives a welfare interpretation : the total risk of the system

Can we complete the market?

- **Most restructured electricity markets are incomplete**
  - There exists no financial product to hedge the risk factors associated with investment decisions.
  - For the relevant horizon, liquidity is simply not there

- **This lack of hedging possibility disincentivess investment**
  - Current uncertainties are just too wide(demand, CO2 regulation, fuel prices)

- **The literature advocates trading products as a remedy**
  - Futures contract [Ausubel and Cramton (2010)], Reliability options [Oren (2005)], Reliability options linked to physical quantities [Oren (2005) - .Chao and Wilson (2004) – Vasquez et al. (2003)]
  - Not yet supported by a model to quantify the effects.

First attempt

- **Stochastic-endogenous Generation Capacity Expansion Equilibrium: Incompleteness and Remedies** , G. de Maere d'Aertrycke, A. Ehrenmann et Y. Smeers, Informs 2013

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Data set

1. A test problem

- Three technologies: Coal – CCGT – OCGT
- Three price caps: 10 000, 1000, 250 €/Mwh
- A peaky (because of wind) load duration curve decomposed in 5 time segments
- Two fuel price scenarios: steady coal; low/high gas (equally likely)
- Two NAP scenarios: - 20%; -30% (equally likely)
- Three allowance allocation scenarios: BAT benchmarking (.2); /MW(.2); full auctioning (.6)

Risk aversion matters: technology mix is substantially different. A low price cap shows high levels of scarcity

4. Investment analysis: Energy only vs. capacity market

	Coal	CCGT	OCGT	Total	Shortfall	Hours	Consumer Cost in bn Euro
CM/RN	15442	64655	6180	86277	0	0	34.425
CM/RA	15439	64650	6188	86277	0	0	34.982
EO/RN	15442	64655	6171	86268	10	10	34.425
EO/RA	15438	64650	6179	86268	10	10	34.629

Price cap: 10000 Euro/Mwh

	Coal	CCGT	OCGT	Total	Shortfall	Hours	Consumer Cost in bn Euro
CM/RN	15442	64655	6180	86277	0	0	34.425
CM/RA	15128	45297	25852	86277	0	0	34.943
EO/RN	15461	64636	161	80258	6019	50	36.080
EO/RA	15147	45261	19849	80258	6019	50	36.596

Price cap: 1000 Euro/Mwh

	Coal	CCGT	OCGT	Total	Shortfall	Hours	Consumer Cost in bn Euro
CM/RN	15442	64655	6180	86277	0	0	34.425
CM/RA	15128	45297	25852	86277	0	0	35.107
EO/RN	15467	64623	0	80090	6187	50	36.387
EO/RA	15905	44289	0	60193	26084	360	108.309

Price cap: 250 Euro/Mwh

Example: Project finance uses different cost of capital for different technologies

8. Technology dependent risk aversion

- Principle: technologies are subject to other risks than those represented in the model

  ⇒: We use $\alpha(coal) = 1$, $\alpha(CCGT) = 0.8$ and $\alpha(OCGT) = .5$

	Coal	CCGT	OCGT	Total	Shortfall	Hours
CM/RA	15468	64789	6020	86277	0	0
EO/RA	15450	67642	3090	86182	94	10

Price cap: 10000 Euro/Mwh

	Coal	CCGT	OCGT	Total	Capacity	Hours
CM/RA	15131	45297	25849	86267	0	0
EO/RA	15513	64743	0	80256	6020	50

Price cap: 1000€/Mwh

	Coal	CCGT	0CGT	Total	Capacity	Hours
CM/RA	15131	45297	25849	86267	0	0
EO/RA	15929	44264	0	60193	26084	360

Price cap: 250€/Mwh

6. Risk return analysis (1)

Excess return $E(R) - R_f$ Sharpe ratio $\frac{E(R) - R_f}{\sigma(R)}$

	Investment	Expected net margin	Standard deviation	Excess return	Sharpe ratio
10000/CM/RA	8013498	1137929	4409761	14.2 %	0.26
10000/EO/RA	8012931	785197	3655756	9.8%	0.21
1000/CM/RA	7595363	1193433	3671642	15.7%	0.32
1000/EO/RA	7235364	1030506	3564989	14.2 %	0.29
250/CM/RA	7595363	1193473	3671791	15.7%	0.32
250/EO/RA	6087818	840866	2697266	13.8%	0.31

Computation of risk premium of the whole generation system

	Investment	Expected net margin	Standard deviation	Excess return	Sharpe ratio
10000/CM/RA	2470213	380189	1774020	15.4%	0.21
10000/EO/RA	2470214	317039	1509082	12.9%	0.21
1000/CM/RA	2420484	395015	1709952	16.3 %	0.23
1000/EO/RA	2423486	376350	1719114	15.5%	0.22
250/CM/RA	2420484	395022	1709965	16.3%	0.23
250/EO/RA	2544724	390927	1781496	15.4%	0.22

Computation of risk premium of the coal plant

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Summary

- Moving into a very risky world
  - uncertain evolution of fuel prices
  - insufficient understanding of incentives to invest
  - "learning by doing" evolution of environmental policy
  - NEW: demand risk as a result of recovering from crisis
- Is all of this good ?
  - an old dichotomy
    - control by prices
    - control by quantities
  - a major question
    - control by prices in an imperfect/incomplete market: does it work?

References

The most part of the talk is based on

- **Energy Only, Capacity Market and Security of Supply : A stochastic Equilibrium Analysis** », A. E. et Y. Smeers ; Operations Research Volume 59 Issue 6, November-December 2011

An extension to industrial size models was presented in

- **Good-Deal Investment Valuation in Stochastic Generation Capacity Expansion Problems** , G. de Maere d'Aertrycke, A. E. et Y. Smeers, Informs 2011

An extension for a set of contracts for risk hedging was presented in

- **Stochastic-endogenous Generation Capacity Expansion Equilibrium: Incompleteness and Remedies** , G. de Maere d'Aertrycke, A. E., et Y. Smeers, Informs 2013