Stochastic systemic LCOE: Integration of non-dispatchable renewable power sources in the LCOE theory




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Agenda

- LCOE: the cost of generating electricity
- Including risk into the analysis: Stochastic LCOE theory
- Systemic LCOE theory
- Systemic LCOE risk analysis

The Levelized Cost of Electricity - LCOE

The Levelized Cost of Electricity (LCOE) is defined as that nonnegative price $p^{LC,x}$ (assumed constant in time, and expressed in real money units) of the electricity produced by a specific generation technology x which makes the present value of expected revenues from electricity sales equal to the present value of all expected costs met during the plant life-cycle ($NPV = 0$):

$$\sum_{n=1}^{M} (p^{LC,x} Q_n^x)(1+i)^{n-n_b} F_{0,n} = \sum_{n=1}^{M} (C_n^x + T_n^x) F_{0,n} + I_0^x \qquad (1)$$

$$T_n^x = T_c(R_n^x - C_n^x - dep_n^x) \qquad F_{0,n} = \frac{1}{(1+r^W)^n}$$

$$\Downarrow$$

$$p^{LC,x} = \frac{\sum_{n=1}^{M} C_n^x F_{0,n}}{\sum_{n=1}^{M} Q_n^x (1+i)^{n-n_b} F_{0,n}} + \frac{I_0^x - T_c \sum_{n=1}^{M} dep_n^x F_{0,n}}{(1-T_c)\sum_{n=1}^{M} Q_n^x (1+i)^{n-n_b} F_{0,n}}. \qquad (8)$$

* To shorten the notation, expectations have been omitted

The Levelized Cost of Electricity - LCOE

Equation (8) can be formally simplified posing

$$\tilde{Q}^x = \sum_{n=1}^{M} Q_n^x (1+i)^{n-n_b} F_{0,n}$$

and defining unitary costs as follows:

$$\tilde{C}^x = \frac{\sum_{n=1}^{M} C_n^x F_{0,n}}{\tilde{Q}^x}, \quad \tilde{I}_0^x = \frac{I_0^x}{\tilde{Q}^x}, \quad d\tilde{e}p^x = \frac{\sum_{n=1}^{M} dep_n^x F_{0,n}}{\tilde{Q}^x},$$

thus getting

$$p^{\mathrm{LC},x} = \tilde{C}^x + \frac{\tilde{I}_0^x - T_c d\tilde{e}p^x}{(1-T_c)} \qquad (11)$$

Remark.

- LCOE is a break-even unitary cost;
- $p^{\mathrm{LC},x}\tilde{Q}$ is equal to the present value of the total cost of a given technology x;
- LCOE is a useful metric to compare among each other different generation technologies.

Costs data

Table 1. Technical assumptions. All dollar amounts are in year 2012 dollars. Overnight costs are assumed to be uniformly distributed on the construction period. O&M stands for operation and maintenance. Mill stands for 1/1000 of a dollar. mmBTU stands for one million BTUs. Depreciation is developed according to the MACRS (Modified Accelerated Cost Recovery System) scheme.

	Units	Wind	Coal	Gas
Technology symbol		wi	co	ga
Capacity factor		35%	85%	87%
Heat rate	Btu/kWh	0	8800	7050
Overnight cost	$/kW	2213	2934	917
Fixed O&M costs	$/kW/year	39.55	31.18	13.17
Variable O&M costs	mills/kWh	0	4.47	3.60
Fuel costs	$/mmBtu	0	2.42	4.85
CO_2 intensity	Kg-C/mmBtu	0	25.8	14.5
Waste fee	$/kWh	–	–	–
Decommissioning cost	$ million	–	–	–
O&M real escalation rate		1.0%	1.0%	1.0%
Fuel real escalation rate		0%	1.0%	2.0%
Construction period	# of years	1	4	3
Operations start		2018	2018	2018
Plant life	# of years	30	30	30
Depreciation scheme		MACRS,20	MACRS,20	MACRS,20

Annual Energy Outlook. EIA, 2013

$p_{LC,wi}$	$p_{LC,co}$	$p_{LC,ga}$
88.2	101.4	77.4

Carbon costs have been assumed equal to 25$ per ton of CO2.

Generation portfolios LCOEs

Equation (11) is valid for a single-technology (labeled by x) project. For a multi-technology project, i.e. a portfolio of technologies, the total LCOE p^{LC} is the sum over the technology index

$$p^{\mathrm{LC,w}} = \sum_x \frac{\tilde{Q}^x}{\tilde{Q}^{\mathrm{TOT}}} p^{\mathrm{LC,x}} = \sum_x w^x p^{\mathrm{LC,x}} \tag{12}$$

where $\tilde{Q}^{\mathrm{TOT}} = \sum_x \tilde{Q}^x$, and $w^x = \frac{\tilde{Q}^x}{\tilde{Q}^{\mathrm{TOT}}}$ is the weight of technology x in the portfolio ($\sum_x w_x = 1$).

Remark.

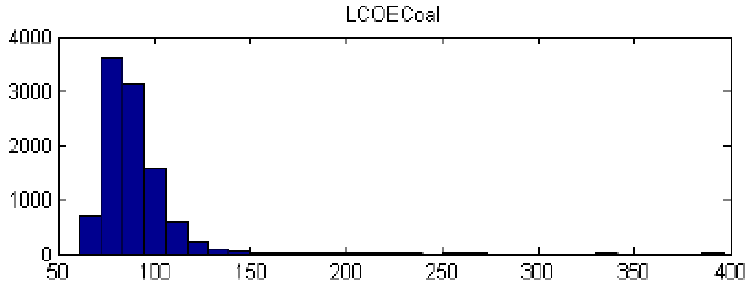
- LCOE is a break-even portfolio unitary cost;
- $p^{\mathrm{LC,w}} \tilde{Q}$ is equal to the present value of the total cost of a given generation portfolio;
- LCOE is a useful metric to compare among each other different generation portfolios;
- in some cases the generation portfolio that maximizes NPV per unit of output (e.g. one MWh of electricity) is the portfolio that minimizes LCOE.

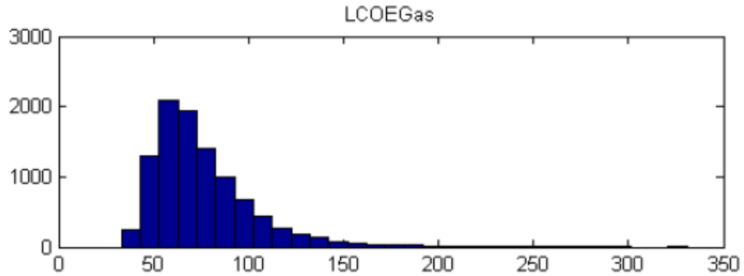
Including risk into the analysis: The stochastic LCOE

The insertion of a deterministic operation costs sequence C_n^x in Equation (8), assessed for example as a sequence of expected values, generates a deterministic $P^{LC,x}$. Promoting the sequence C_n^x to a stochastic process, due to a set of risky sources stochastic paths ω, makes a (time-independent) stochastic variable

$$P^{LC,x}(\omega) = \tilde{C}^x(\omega) + \frac{\tilde{I}_0^x - T_c \tilde{dep}^x}{(1 - T_c)} \qquad (13)$$

of the LC, with a distribution $p(P^{LC,x})$, an expected value $\mu^{LC,x}$ and a variance $(\sigma^{LC,x})^2$.





The dynamical model

Financial risk in the electric energy sector is mainly due to the high volatility of fossil fuels and CO_2 market prices (García-Martos *et al.*. 2013).

We assume a dynamical model in which the time evolution of fossil fuel prices, X^{co} and X^{ga}, as well as the dynmics of CO2 prices, X^{ca}, are described by geometric Brownian motions:

- $\frac{dX^{co}}{X^{co}} = (\pi^{co} + \pi)dt + \sigma^{co} dW^{co}$
- $\frac{dX^{ga}}{X^{ga}} = (\pi^{ga} + \pi)dt + \sigma^{ga} dW^{ga}$
- $\frac{dX^{ca}}{X^{ca}} = \pi dt + \sigma^{ca} dW^{ca}$

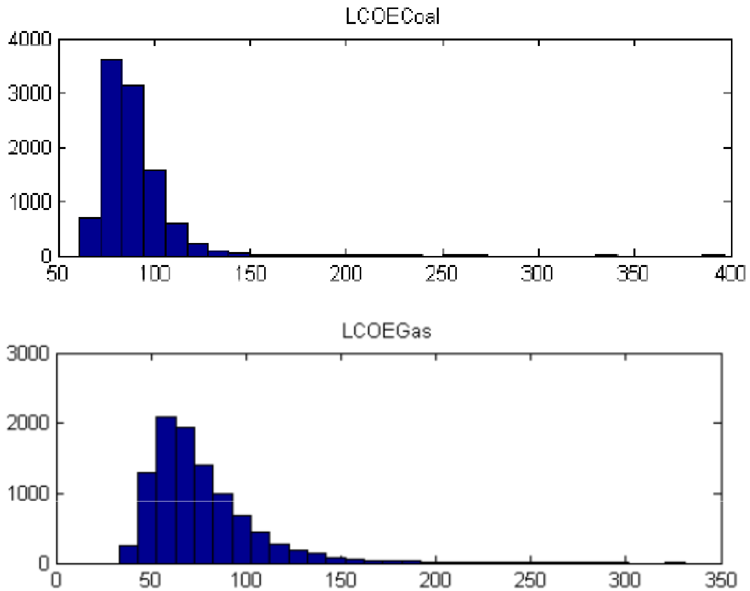
coal	gas
$\pi^{co} = \ln(1.01)$	$\pi^{ga} = \ln(1.02)$
$\sigma^{co} = 0.09$	$\sigma^{ga} = 0.16$
$\pi = \ln(1.0175)$	

M.T. Hogue (2012)

W^{co}, W^{ga} and W^{ca} are independent standard Brownian motions.

The dynamical model

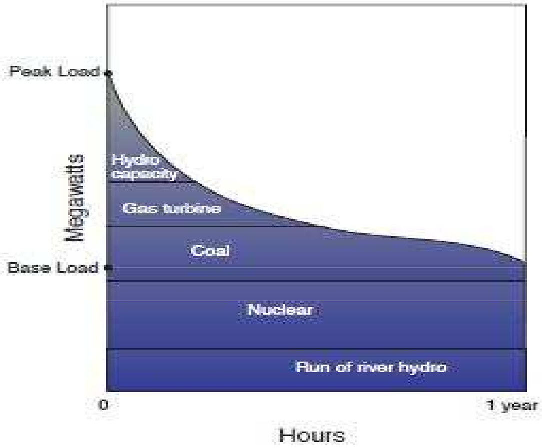
σ^{ca}	x	$\mu^{LC,x}$	$\sigma^{LC,x}$	ρ
0	co	101	6.2	0
	ga	77	23.1	
0.10	co	101	8.2	0.07
	ga	77	23.3	
0.20	co	101	13.5	0.21
	ga	77	23.8	
0.30	co	101	22.0	0.37
	ga	77	25.1	



- A wind plant can be seen as a risk-free asset in an otherwise risky portfolio and the contribution of the wind source to optimal risk reduction may be relevant.
- The main tenet of the stochastic LCOE theory is that the joint effect of fossil fuels prices volatility and the CO2 price volatility can induce rational electricity producers to diversify their generation portfolios in order to minimize the impact of such factors on the risk of the electricity production.
- The risk-reducing diversification is not trivial because $p^{\mathrm{LC,co}}(\omega)$ and $p^{\mathrm{LC,ga}}(\omega)$ are coupled through the CO2 price process.

The systemic LCOE theory

A power system can be defined in terms of the power capacity and (consequently) energy demanded by users at each hour of the year (*yearly load duration curve*).



- For a given power system, a dispatchable technologies generation portfolio is said *technically feasible* if it matches the *yearly load duration curve*.
- The *technically feasible set* of generation portfolios for a given power system is the set of all portfolios technically feasible for that system.

Remark. In such a set we can find single fuel portfolios, as a coal only generation portfolio or a gas only generation portfolio, or mixed portfolios including both technologies, coal and gas. All these portfolio match the load curve but they differ in terms of generation costs (LCOE) and in terms of risk.

The systemic LCOE theory:
Including non-dispatchable sources

The evaluation of the inclusion of a randomly intermittent source of energy, as wind for example, into a feasible portfolio requires to take into account two main issues:

- first, when wind energy is generated and injected into the grid, energy generation from fossil fuels source must be reduced of the same quantity in order to match the energy demand;
- second, the inclusion of a given wind power capacity in a feasible portfolio does not reduce the power capacity of the fossil fuels components of the same amount (for example, wind may not blow during peak hours). The capacity value quantifies how much dispatchable power generation capacity the wind plant can replace in a given feasible portfolio. As outlined by Taylor and Tanton [3], most conservative operators adopted a value of zero for the capacity value. Operators in areas with large wind capacity have computed value ranging from 5% (Southwest Power Pool, USA) to 15% (Midwest ISO, USA).

The systemic LCOE theory:
Including non-dispatchable sources

These two effects impose some extra costs to the power system that must be accounted for in order to determine a consistent wind LCOE. The inclusion of a wind farm into a feasible generation portfolio:

- increases the portfolio costs because a wind plant must be constructed and put in operation;
- reduces the total costs of the feasible portfolio because of the energy and capacity reduction.

In the following the index x will denote only dispatchable technologies, i.e. $x = \text{co, ga}$ and the energy generation reduction imposed on technology x in the year n will be denoted by $Q^{x,\text{red}} = \alpha^x Q^{wi}$.

$$\tilde{Q}^{\text{TOT}} p^{\text{LC,w}} = \sum_x \tilde{Q}^{f,x} p^{\text{LC,x}} + \tilde{Q}^{\text{wi}} p^{\text{LC,wi}} - \tilde{Q}^{\text{wi}} \sum_x \alpha^x \tilde{C}^{x,\text{var}} + - \sum_x \tilde{Q}^{x,\text{av}} \left(\tilde{C}^{x,\text{fix}} + \frac{\tilde{I}_0^x - \tilde{dep}^x}{1 - T_c} \right), \qquad (15)$$

$$\tilde{Q}^{\text{TOT}} p^{\text{LC,w}} = \sum_x (\tilde{Q}^{f,x} - \alpha^x \tilde{Q}^{\text{wi}}) p^{\text{LC,x}} + \tilde{Q}^{\text{wi}} p^{\text{LC,wi*}} \qquad (16)$$

where $\tilde{Q}^{\text{TOT}} = \tilde{Q}^{f,\text{co}} + \tilde{Q}^{f,\text{ga}}$ (the superscript ‘f’ stands for technically feasible portfolio).

The wind LCOE

$$p^{LC,wi*} = p^{LC,wi} + \sum_x \left(\alpha^x - \frac{Q^{x,av}}{Q^{wi}} \right) \left(\tilde{C}^{x,fix} + \frac{\tilde{I}_0^x - \tilde{dep}^x}{1 - T_c} \right) \tag{18}$$

The extra costs in the wind LCOE depend on the mix of technologies used to reduce both the electricity generation and the power capacity from the feasible portfolio.

c_v	ga red	co red	mix red
0%	103.4	138.2	120.8
5%	100.9	129.9	115.4
10%	98.3	121.5	109.9
15%	95.8	113.2	104.5
20%	93.3	104.9	99.1

Table 3. Wind LCOEs $p^{LC,wi*}$ for three different integration hypotheses. The wind penetration w^{wi} is assumed to be equal to 30% of electricity generation.

The systemic LCOE

- **Deterministic systemic LCOE**

$$p^{\mathrm{LC,sys}} = w^{\mathrm{co}} p^{\mathrm{LC,co}} + w^{\mathrm{ga}} p^{\mathrm{LC,ga}} + w^{\mathrm{wi}} p^{\mathrm{LC,wi*}},$$

- **Stochastic systemic LCOE**

$$p^{\mathrm{LC,sys}} = w^{\mathrm{co}} p^{\mathrm{LC,co}}(\omega) + w^{\mathrm{ga}} p^{\mathrm{LC,ga}}(\omega) + w^{\mathrm{wi}} p^{\mathrm{LC,wi*}},$$

$$w^{\mathrm{co}} = \frac{Q^{f,\mathrm{co}} - \alpha^{\mathrm{co}} Q^{\mathrm{wi}}}{Q^{\mathrm{TOT}}}, \quad w^{\mathrm{ga}} = \frac{Q^{f,\mathrm{ga}} - \alpha^{\mathrm{ga}} Q^{\mathrm{wi}}}{Q^{\mathrm{TOT}}}, \quad w^{\mathrm{wi}} = \frac{Q^{\mathrm{wi}}}{Q^{\mathrm{TOT}}}.$$

Since $\alpha^{\mathrm{co}} + \alpha^{\mathrm{ga}} = 1$, it follows that portfolio weights sum to one,

$$w^{\mathrm{co}} + w^{\mathrm{ga}} + w^{\mathrm{wi}} = 1.$$

Systemic LCOE risk analysis: The mean-variance approach

Using a Markowitz approach it is possible to determine the composition of the portfolio that minimizes generation costs risks as measured by the portfolio LCOE standard deviation.

Technically feasible portfolios

$$P^{\mathrm{LC,w}^f}(\omega) = w^{f,\mathrm{co}} P^{\mathrm{LC,co}}(\omega) + w^{f,\mathrm{ga}} P^{\mathrm{LC,ga}}(\omega). \tag{20}$$

for nonnegative numbers $w^{f,\mathrm{co}}$ and $w^{f,\mathrm{ga}}$ such that $w^{f,\mathrm{co}} + w^{f,\mathrm{ga}} = 1$.

⇓

The mean and the variance of $P^{\mathrm{LC,w}^f}(\omega)$ can be respectively expressed by

$$\mu^{\mathrm{LC,w}^f} = w^{f,\mathrm{co}} \mu^{\mathrm{LC,co}} + w^{f,\mathrm{ga}} \mu^{\mathrm{LC,ga}}, \tag{21}$$

and

$$(\sigma^{\mathrm{LC,w}^f})^2 = (w^{f,\mathrm{co}})^2 (\sigma^{\mathrm{LC,co}})^2 + (w^{f,\mathrm{ga}})^2 (\sigma^{\mathrm{LC,ga}})^2 + 2\rho w^{f,\mathrm{co}} w^{f,\mathrm{ga}} \sigma^{\mathrm{co}} \sigma^{\mathrm{ga}}. \tag{22}$$

Systemic LCOE risk analysis: The mean-variance approach

Including the wind asset into the power system

If we denote by ϖ^{wi} a target wind penetration, the power system LCOE can be expressed by

$$P^{\text{LC,sys}}(\omega) = \varpi^{\text{wi}} P^{\text{LC,wi}} + \sum_{x} w^{f,x} \left[(1 - \varpi^{\text{wi}}) P^{\text{LC},x}(\omega) + \varpi^{\text{wi}} A^{x} \right] \tag{30}$$

where

$$A^{x} = \left(1 - \frac{c_v}{\varpi^{\text{wi}}}\right)\left(\tilde{C}^{x,\text{fix}} + \frac{\tilde{I}_0^{x} - d\tilde{e}p^{x}}{1 - T_c}\right).$$

$$\Downarrow$$

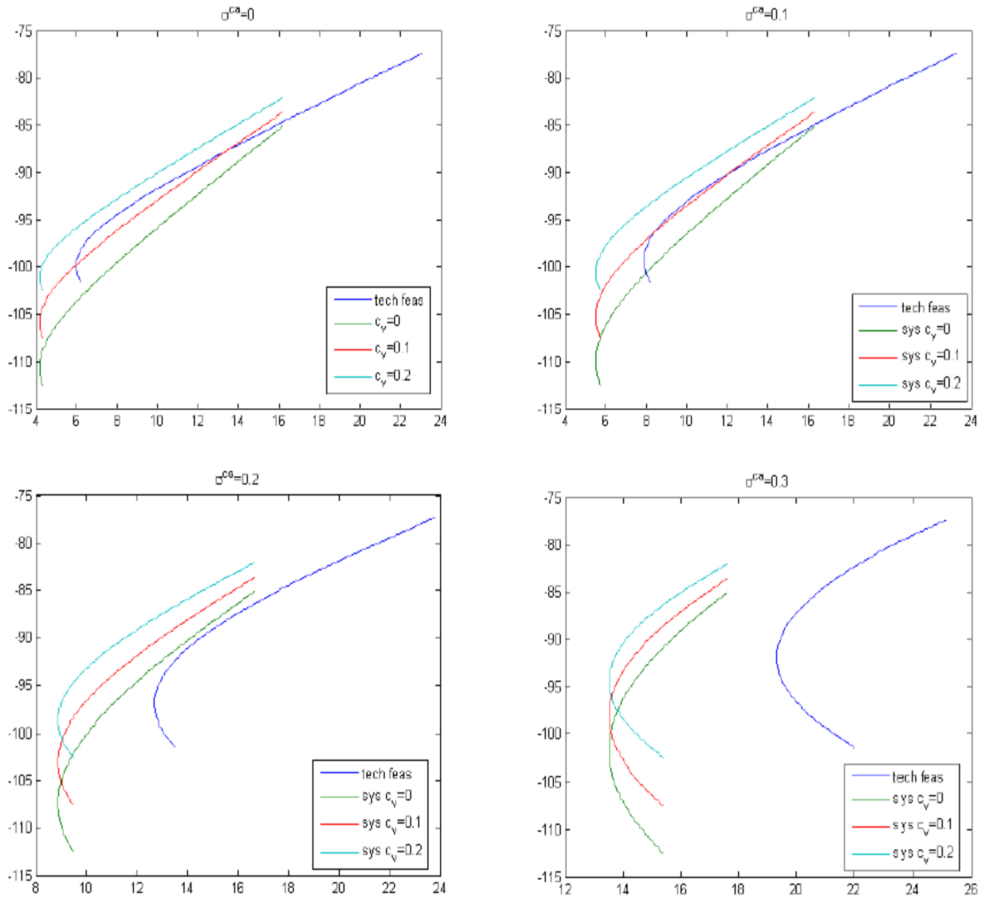
The mean and the variance of $P^{\text{LC,sys}}(\omega)$ can be explicitly written in the following way:

$$\mu^{\text{LC,sys}} = \varpi^{\text{wi}} \mu^{\text{LC,wi}} + w^{f,\text{co}} \left[(1 - \varpi^{\text{wi}}) \mu^{\text{LC,co}} + \varpi^{\text{wi}} A^{\text{co}} \right] + \\ + w^{f,\text{ga}} \left[(1 - \varpi^{\text{wi}}) P^{\text{LC,ga}} + \varpi^{\text{wi}} A^{\text{ga}} \right], \tag{31}$$

$$(\sigma^{\text{LC,sys}})^2 = (1 - \varpi^{\text{wi}})^2 \left[(w^{\text{f,co}})^2 (\sigma^{\text{LC,co}})^2 + (w^{\text{f,ga}})^2 (\sigma^{\text{LC,ga}})^2 + 2\rho w^{\text{f,co}} w^{\text{f,ga}} \sigma^{\text{co}} \sigma^{\text{ga}} \right] \tag{32}$$

Remark. In the systemic case too, $\mu^{\text{LC,sys}}$ vs. $\sigma^{\text{LC,sys}}$ turns out to be a hyperbola.

A mean-variance approach: Systemic frontiers



The wind penetration $\bar{w}^{wi} = 30\%$.

	$\sigma^{ca}=0$	$\sigma^{ca}=0.1$	$\sigma^{ca}=0.2$	$\sigma^{ca}=0.3$
$w^{f,co}_{mvp}$	93%	91%	81%	60%
$w^{f,ga}_{mvp}$	7%	9%	19%	40%
σ_{mvp}	6.0	7.9	12.7	19.3
μ^{LC}_{mvp}	99.8	99.2	96.9	91.9

	$\sigma^{ca}=0$	$\sigma^{ca}=0.1$	$\sigma^{ca}=0.2$	$\sigma^{ca}=0.3$
w^{wi}_{mvp}	30%	30%	30%	30%
w^{co}_{mvp}	65%	64%	57%	42%
w^{ga}_{mvp}	5%	6%	13%	28%
σ_{mvp}	4.2	5.5	8.9	13.5
μ^{LC}_{mvp}	110.6	109.9	107.4	101.7
μ^{LC}_{mvp}	105.9	105.3	103.0	98.0
μ^{LC}_{mvp}	101.1	100.6	98.7	94.4

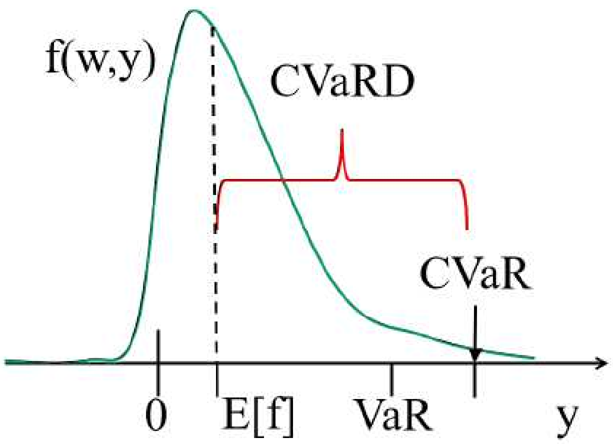
Systemic LCOE risk analysis: CVaR and CVarD

A more sophisticated investor could yet realize that it is more efficient to be averse to one side of the distribution only, i.e. to LCOEs larger than the mean. In this second case an appropriate risk metrics is still a deviation, but an asymmetric one, like the CVaR Deviation (CVaRD), which is based on CVaR. There are at least two advantages using CVaRD over variance or standard deviation:

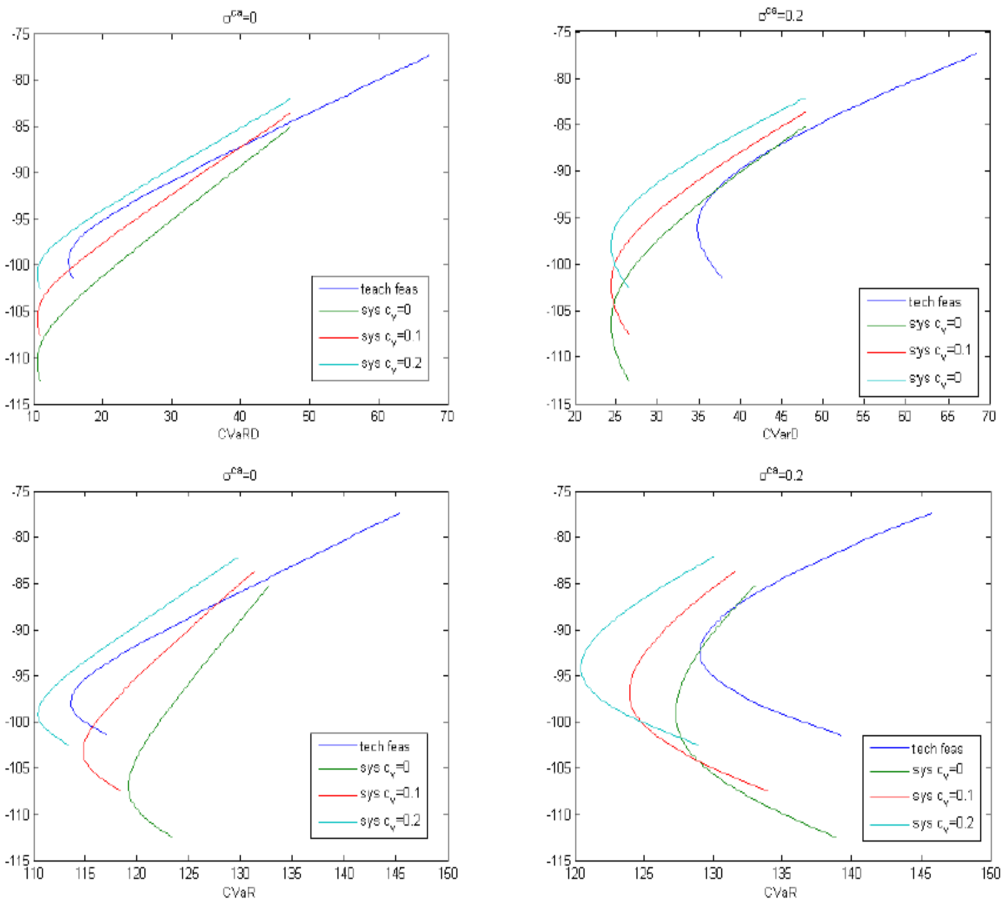
- portfolios with a low CVaRD are combinations that minimize the risk of ending up with LCOEs too much larger than their mean;
- CVaRD (like CVaR and unlike standard deviation) is able to properly take into account risk from long tails.

$$\mathrm{CVaR}_{\alpha}^{w}(f) = \frac{1}{1-\alpha}\int_{f(w,y)\geq h^{*}} f(w,y)\, p(y)\, dy$$

$$\mathrm{CVaRD}_{\alpha}^{w}(f) \equiv \mathrm{CVaR}_{\alpha}^{w}(f - E[f]) = \mathrm{CVaR}_{\alpha}^{w}(f) - E[f]$$



CVarD and CVaR Systemic frontiers



CVaRD	$\sigma^{\text{ca}} = 0$	$\sigma^{\text{ca}} = 0.2$	$\sigma^{\text{ca}} = 0$	$\sigma^{\text{ca}} = 0.2$
wind	0%	0%	30%	30%
coal	92%	78%	64%	55%
gas	8%	22%	6%	15%

CVaR ($\sigma^{ca} = 0$)	tech feas	$c_v = 0$	$c_v = 0.1$	$c_v = 0.2$
wind	0%	30%	30%	30%
coal	85%	56%	57%	59%
gas	15%	14%	13%	11%

CVaR ($\sigma^{ca} = 0.2$)	tech feas	$c_v = 0$	$c_v = 0.1$	$c_v = 0.2$
wind	0%	30%	30%	30%
coal	63%	35%	38%	42%
gas	37%	35%	32%	28%

The wind penetration $\bar{w}^{\text{wi}} = 30\%$.

CO2 emissions assessment

Emissions rates:

$$E^{\mathrm{C02},w} = \sum_x w^x E^{\mathrm{C02},x}$$

$$E^{\mathrm{C02,co}} = 0.832 \text{ tCO2/MWh}$$

$$E^{\mathrm{C02,ga}} = 0.375 \text{ tCO2/MWh}$$

	$\sigma^{\mathrm{ca}} = 0$	$\sigma^{\mathrm{ca}} = 0.1$	$\sigma^{\mathrm{ca}} = 0.2$	$\sigma^{\mathrm{ca}} = 0.3$
tech feas	0.801	0.790	0.747	0.651
sys (30%)	0.561	0.553	0.523	0.456
sys (40%)	0.481	0.474	0.448	0.390

Emissions rates for minimum variance portfolios (tCO2/MWh).

- The abatement of CO2 emissions is exactly equal to the wind penetration in the power system, i.e. 30% if $\bar{w}^{\mathrm{wi}} = 30\%$ and 40% if $\bar{w}^{\mathrm{wi}} = 40\%$.
- The entity of emissions abatement is independent from the capacity value of the power system.
- Maybe paradoxically, the abatement of CO2 emissions increases as the CO2 volatility increases thus revealing a very interesting fact about the use of market based mechanisms for pricing and controlling CO2 emissions.