Thermal and Nuclear Energy Portfolio Selection using LCOE CVaR

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Project Profitability by LCOE

In corporate finance, **profitability** of an **investment project** can be assessed studying the project **cash flows**, comparing the **return rate** r_P of the project with the market **cost of capital** r_{cc} rate. If

$$r_P > r_{cc} \tag{1}$$

the project is profitable.

For example, for just two flows at $t = 0$ and $t = 1$, like an initial investment cost $C_P(0) = -100$ and the revenue $R_P(1) = 110$ from its sale,
if $r_P = (110 - 100)/100 = 10\% > r_{cc}$, the project is profitable.

In case of more costs $C_P(t) > 0$ and revenues $R_P(t) > 0$, a single **internal rate of return** r_{irr} defined **implicitly** from the flow as

$$\sum_{t<0} C_P(t)/(1+r_{irr})^t = \sum_{t\geq 0} R_P(t)/(1+r_{irr})^t$$

can indicate profitability, when

$$r_{irr} > r_{cc}.$$

Here again profitability is expressed in terms of **rate levels**.

In the case of building an **energy generation plant**, if the **present value** (PV) **at operations' starting time** $t = 0$ of building **costs** $C_P^<(t)$ $(t < 0)$ and operation **costs** $C_P^>(t)$ $(t > 0)$ is lower than the PV of the sales **revenues** $R_P^>(t)$ $(t > 0)$ as

$$C = \sum_{t<0} \frac{C_P^<(t)}{(1+r_{cc})^t} + \sum_{t\geq 0} \frac{C_P^>(t)}{(1+r_{cc})^t} \leq \sum_{t\geq 0} \frac{R_P^>(t)}{(1+r_{cc})^t} = R,$$

the project is profitable.

Here profitability is expressed in terms of **price**$\times$**quantity levels**

$$C \leq R$$

instead of **rates** $r_{cc} \leq r_P$.

In energy finance, the **Levelised Cost of Electricity** (**LCOE**) helps to assess a **threshold for profitability** of building a new plant.

Like in the case of r_{irr}, assuming that the proceeds come from selling at a **constant price** LCOE all electricity produced per period $Q^{>}(t)$, LCOE is **implicitly** defined as

$$\sum_{t<0} \frac{C_P^{<}(t)}{(1+r_{cc})^t} + \sum_{t\geq 0} \frac{C_P^{>}(t)}{(1+r_{cc})^t} = \sum_{t\geq 0} \frac{\mathrm{LCOE} \times Q^{>}(t)}{(1+r_{cc})^t}.$$

The effect of **financing** the project **by equity and debt** can be included replacing the **cost of capital** r_{cc} with the **weighted average cost of capital** (WACC) rate

$$r_{\text{wacc}} \geq r_{cc}.$$

WACC quantifies the **perception of project riskiness** by equity and bond investors.

Uncertainty about future rates is necessarily included using **discount factor expectations** $F_0(t) = E[1/(1 + r_{\text{wacc}})]$ at $t = 0$ on future WACC rates.

Then

$$\text{LCOE} = \frac{\sum_{t<0} C_P^{<}(t) F_0(t)}{\sum_{t\geq 0} Q^{>}(t) F_0(t)} + \frac{\sum_{t\geq 0} C_P^{>}(t) F_0(t)}{\sum_{t\geq 0} Q^{>}(t) F_0(t)} = I + O$$

where I stands for **normalized** investments and O for normalized operation expenses, **i.e. prices**.

If electricity can be sold at a price

$$P_e > \text{LCOE} = I + O,$$

the project is profitable.

Here profitability is expressed in terms of **price levels** LCOE $< P_e$ instead of rate levels.

To simplify notation, investment costs I can be **absorbed** in operating costs O, to give **total price**, (i.e. **normalized** cost)

$$\text{LCOE} = I + O = T.$$

Tax breaks at rate T_0, **capital depreciation** $A^>(t)$, expected **real escalation rate** γ (a sort of inflation for specific costs) and expected **inflation** ι itself can be included in the calculation of a **real** LCOE.

It will also be assumed that the **electricity production** $Q^>(t) = Q$ is **constant** (or known in advance).

Making the time-varying **fuel prices** $Y(t)$ and the CO_2 **emission prices** $Z(t)$ explicit in costs $C_P^{\gtrless}(t)$,

$$\mathrm{LCOE} = T(Y(t), Z(t)).$$

If at time $t = 0$ future was known, time series $Y(t)$ and $Z(t)$ could be inserted in O to compute $C_P^{\gtrless}(t)$.

Practically, **expected values** $\bar{Y}$ and $\bar{Z}$ are used:

$$\mathrm{LCOE} = T(\bar{Y}, \bar{Z}).$$

This implies that their time series are assumed to be **constant** and to have **zero volatility**.

LCOE Scenario-Risk Management

There is a lot of well known **model risk** in this evaluation approach.

For example, financial modelling risk enters in the choice of r_{wacc}. LCOE is very sensitive to WACC choice.

Economic modelling risk enters in the choice of **fuel prices expectations**.

This last kind of **model weakness** can be **exploited** by the proposed **method**.

Assume $\omega \in \Omega$ to be a **path extraction** from the **event set** Ω.

For a **single fuel plant** for example, the **fuel and** CO_2 **prices** $Y(t)$ and $Z(t)$ can be replaced by **stochastic processes** $Y_\omega(t)$ and $Z_\omega(t)$, like geometric brownian motions or mean reverting motions with jumps, or their discrete time equivalents.

LCOE becomes a **time independent stochastic variable**

$$\mathrm{LCOE}_\omega = T(\hat{Y}_\omega, \hat{Z}_\omega).$$

since the component stochastic processes are **weighted** and **summed** over their paths.

$\mathrm{LCOE}_\omega(\hat{Y}_\omega, \hat{Z}_\omega)$ has now a **distribution**, a **mean** μ_{LCOE} and a **variance** σ^2_{LCOE}.

A mutual **dependency structure** can be chosen for $Y_\omega(t)$ and $Z_\omega(t)$, for example imposing some correlation.

Economically, this would mean a correlation between the chosen fuel price and the CO_2 price.

Discount Rate Portfolio Theory

If the project under assessment involves building a **portfolio plant** with **two types of fuel**, coal and gas, with price X_ω and Y_ω, both emitting CO_2 at Z_ω price,

$$
\begin{aligned}
\mathrm{LCOE}_\omega &= \\
& T(\hat{X}_\omega, \hat{Y}_\omega, \hat{Z}_\omega) = \\
& w^{\mathrm{coal}}\ T^{\mathrm{coal}}(\hat{X}_\omega, \hat{Z}_\omega) + w^{\mathrm{gas}}\ T^{\mathrm{gas}}(\hat{Y}_\omega, \hat{Z}_\omega) = \\
& w^{\mathrm{coal}}\, \mathrm{LCOE}_\omega^{\mathrm{coal}} + w^{\mathrm{gas}}\, \mathrm{LCOE}_\omega^{\mathrm{gas}}
\end{aligned}
$$

where $w^{\mathrm{coal}} + w^{\mathrm{gas}} = 1$ are the invested fractions.

Under an expected electricity price P_e, the **project return rate** should be defined as

$$\Pi_\omega = \frac{P_e - \mathrm{LCOE}_\omega}{\mathrm{LCOE}_\omega} = \frac{P_e}{\mathrm{LCOE}_\omega} - 1,$$

because LCOE is linked to a cost. LCOE_ω appears in the denominator

The **project discount rate** is more safely defined as

$$D_\omega = \frac{P_e - \mathrm{LCOE}_\omega}{P_e} = 1 - \frac{\mathrm{LCOE}_\omega}{P_e}.$$

D_ω represents the discount you get now on P_e investing in the project to receive P_e at the end of it. For **profitability** you want **this discount positive**.

Markowitz theory can be applied to this energy portfolio. If you are looking for an **efficient** project

either: for a given **discount level**, look for the **minimum variance** portfolio,

or: for a given **variance level**, look for the **maximum discount** portfolio.

Factor modelling is also included in this approach.

Since fuel and related CO_2 cost enter LCOE_ω in a linear way,

$$\text{LCOE}_\omega = U^{\text{fuel}}(\hat{Y}_\omega) + U^{\text{fuel, CO}_2}(\hat{Z}_\omega) = U^{\text{fuel}}_\omega + U^{\text{fuel, CO}_2}_\omega$$

where U are normalized component costs.

$U^{\text{fuel, CO}_2}_\omega$ is proportional to $\hat{Z}_\omega$ through the **fuel CO$_2$ intensity** I^{fuel}:

$$U^{\text{fuel, CO}_2}_\omega = I^{\text{fuel}} A \, \hat{Z}_\omega .$$

Then,

$$E[\text{LCOE}_\omega] = \mu^{\text{LCOE, fuel}} = \mu^{\text{fuel}} + \mu^{\text{fuel,CO}_2} .$$

Moreover,

$$\mathrm{LCOE}_\omega^{\mathrm{coal}} = U^{\mathrm{coal}}(\hat{X}_\omega) + U^{\mathrm{coal,CO_2}}(\hat{Z}_\omega) = U_\omega^{\mathrm{coal}} + U_\omega^{\mathrm{coal,CO_2}}$$

$$\mathrm{LCOE}_\omega^{\mathrm{gas}} = U^{\mathrm{gas}}(\hat{Y}_\omega) + U^{\mathrm{gas,CO_2}}(\hat{Z}_\omega) = U_\omega^{\mathrm{gas}} + U_\omega^{\mathrm{gas,CO_2}}$$

so that coal and gas LCOE share a **factor**.

If X_ω and Y_ω are **independent** (then they must be independent from Z_ω too),

$$E[\mathrm{LCOE}^{\mathrm{coal}}_\omega\,\mathrm{LCOE}^{\mathrm{gas}}_\omega] = \mu^{\mathrm{coal}}\,\mu^{\mathrm{gas}} + \mu^{\mathrm{coal}}\,\mu^{\mathrm{gas,CO_2}} + \mu^{\mathrm{coal,CO_2}}\,\mu^{\mathrm{gas}} + \alpha^{\mathrm{CO_2}}$$

where

$$\alpha^{\mathrm{CO_2}} = E[U^{\mathrm{coal,CO_2}}_\omega\,U^{\mathrm{gas,CO_2}}_\omega] \neq 0,$$

so that

$$Cov(\mathrm{LCOE}^{\mathrm{coal}}_\omega, \mathrm{LCOE}^{\mathrm{gas}}_\omega) = \alpha^{\mathrm{CO_2}} = A^2 I^{\mathrm{coal}} I^{\mathrm{gas}} \sigma^2(\hat{Z}_\omega).$$

If one of the processes is **constant**, for example assuming that the fuel price $N_\omega = N_0$ for **nuclear plants** has very small volatility, and has **zero emissions** ($Z_\omega = 0$),

$$\sigma^{\text{nuclear}} = 0$$

$$\mu^{\text{LCOE, nuclear}} = N$$

$$Cov(\text{LCOE}_\omega^{\text{nuclear}}, \text{LCOE}_\omega^{\text{coal}}) = 0,$$
$$Cov(\text{LCOE}_\omega^{\text{nuclear}}, \text{LCOE}_\omega^{\text{gas}}) = 0.$$

Directly form Markowitz theory,

a **minimum variance portfolio** can be defined, having weights w_m^{coal} and w_m^{gas}

associated with the **minimum attainable variance** $\sigma^2_{D,m}$ of the **project discount rate**.

This optimal discount rate portfolio corresponds to an **optimal discount rate** $\mu_{D,m}$.

This portfolio minimizes the **scenario risk** related to **fuel and CO_2 price uncertainty**.

This is a new take on LCOE analysis.

LCOE Portfolio Theory

Instead of using the discount rate, **LCOE itself** can be directly used in the optimization.

In this case, LCOE plays the role of the **return**, and its variance plays the role of . . . well, of the **variance**. The **minimum attainable variance** is $\sigma^2_{\mathrm{L,m}}$, and there the **optimal LCOE** becomes $\mu_{\mathrm{L,m}}$.

Only modification, the **efficient frontier becomes the lower one**.

Simulation of a coal or gas portfolio

The coal X, gas Y and CO_2 Z **nominal price processes** are assumed to be **geometric brownian motions discretized** on a **yearly** grid

$$
\begin{aligned}
dX &= (\mu_X + \pi) X \, dt + \sigma_X X \, dW_X \\
dY &= (\mu_Y + \pi) Y \, dt + \sigma_Y Y \, dW_Y \\
dZ &= \pi Z \, dt + \sigma_Z Z \, dW_Z
\end{aligned}
$$

where μ_X and μ_Y are functions of expected real escalation rates γ, $\pi = \ln(1 + \iota)$ is a function of the expected inflation rate ι, σ_X, σ_Y and σ_Z volatilities of **independent Wiener processes** W_X, W_Y and W_Z.

Notice that the **real prices** follow a very simple, lognormal process

$$dX = \sigma_X X \, dW_X$$
$$dY = \sigma_Y Y \, dW_Y$$
$$dZ = \sigma_Z Z \, dW_Z$$

The **parameters** used to wrap the price processes and compute the **LCOE** for a plant in the US are

	Units	Nuclear	Coal	Gas
Nominal capacity	MW	2236	1300	540
Capacity factor		90%	85%	87%
Heat rate	Btu/kWh	10460	8800	7050
Overnight cost	$/kW	5335	2844	978
Fixed O&M costs	$/kW/year	88.75	29.67	14.39
Variable O&M costs	mills/kWh	2.04	4.25	3.43
Fuel costs	$/MMBtu	0.71	2.26	5.14
Fuel's CO_2 intensity	Kg-C/MMBtu	0	25.8	14.5
Waste fee	$/kWh	0.001	–	–
Decommissioning cost	$ million	750	–	–
O&M real escalation rate		1.0%	1.0%	1.0%
Fuel real escalation		0.5%	0.9%	1.4%
Construction period	years	6	4	3
Operations		2018	2018	2018
Plant life	years	40	40	40
Depreciation schedule		MACRS,15	MACRS,20	MACRS,15

Start of operation ($t = 0$) is 2012. Overnight costs are assumed to be uniformly distributed on the construction period. Depreciation is developed according to the MACRS.

(all **real** year 2010 costs) and

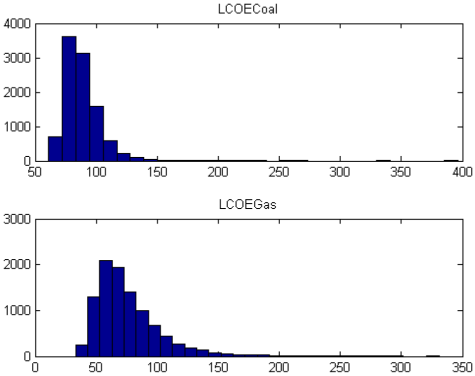
$\iota_{\text{inflation}} = 1.8\%$	$\text{WACC} = 7\%$
	$T_c = 40\%$

After estimating σ and γ from market time series, the **parameters** for the **price processes** become

$\gamma_{\text{c}} = 0.9\%$	$\gamma_{\text{g}} = 1.4\%$
$\sigma_c = 0.09$	$\sigma_g = 0.16$
$\sigma_{\text{CO2}} =$ scenario for 10 yrs,	then 0.15
$\mu_c = \ln(1.009)$	$\mu_g = \ln(1.014)$
$\pi = \ln(1.018)$	

Scenario Analysis

Real LCOE distribution, for a coal and a gas plant.



For **two single-fuel plants** $\mu^{\text{LCOE, fuel}}$ is estimated **in dollars** under **three CO_2 volatility scenarios**.

	$\sigma_Z = 0.2$	$\sigma_Z = 0.3$	$\sigma_Z = 0.4$
$\mu^{\text{LCOE,coal}}$	88.2	88.2	88.2
$\mu^{\text{LCOE, gas}}$	76.2	76.2	76.2
σ^{coal}	14.5	21.7	32.7
σ^{gas}	28.2	29.2	31.2
ρ	0.18	0.30	0.45

Notice 1) the nonzero correlation coefficient ρ, due to the CO_2 common factor, 2) the inversion of riskiness between coal and gas as σ_Z increases.

For **one bi-fuel** plant, **minimum variance LCOE portfolio weights** w_m^{coal} and w_m^{gas}, and optimal $\mu_{\text{L,m}}$, are estimated under **three CO_2 volatility scenarios**.

	$\sigma_Z = 0.2$	$\sigma_Z = 0.3$	$\sigma_Z = 0.4$
w_m^{coal}	84.0%	70.2%	45.5%
w_m^{gas}	16.0%	29.8%	54.5%
$\mu_{\text{L,m}}$	86.3	84.6	81.7
$\sigma^2_{\text{L,m}}$	13.8	19.7	27.2

Notice the inversion of relative weight between coal and gas as σ_Z increases. Increasing CO_2 volatility makes coal generation riskier.

For **one tri-fuel** plant which includes **nuclear**, the portfolio can benefit of a **risk-free** asset, with the **highest cost** (i.e. lowest rate), with an extra weight w^{nuclear}.

At $\mu_{L,m}$ as a reference expected LCOE, the riskiness of this nuclear LCOE portfolio is computed.

One tri-fuel plant which includes **nuclear**.
w_e^{coal}, w_e^{gas}, w_e^{nucl} are the **efficient frontier** weights.

$\mu^{\text{LCOE, nuclear}} = 95.4$	$\sigma_X = 0.2$	$\sigma_X = 0.3$	$\sigma_X = 0.4$
$\mu^{\text{LCOE,all}}$	86.3	84.6	81.7
σ^{all}	11.7	16.0	22.3
w_e^{coal}	39.8%	15.9%	0.0%
w_e^{gas}	32.6%	50.2%	71.6%
w_e^{nucl}	27.6%	33.9%	28.4%

Notice that the included coal generation goes to zero as σ_Z increases, in contrast to gas generation which increases. Nuclear remains constant.

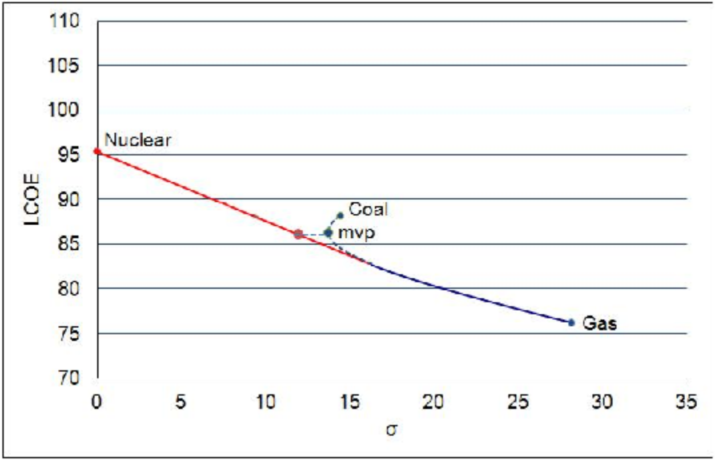
For a $\mu^{\text{LCOE, nuclear}} = N = 95.4$ it turns out that, **as** σ_Z **increases**,

- same as seen for the bi-fuel plant, **model riskiness increases**,
- **but** it is **always lower** than the the bi-fuel case $\sigma^2_{\text{L,m}}$,
- and the **gain in risk reduction** is **larger and larger**.

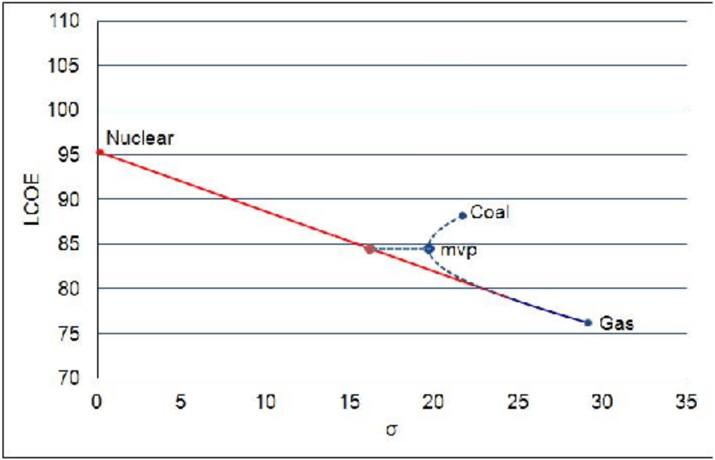
This means that **scenario riskiness can be reduced** by **inclusion of nuclear** generation.

For **larger values** of N, this effect is weaker.

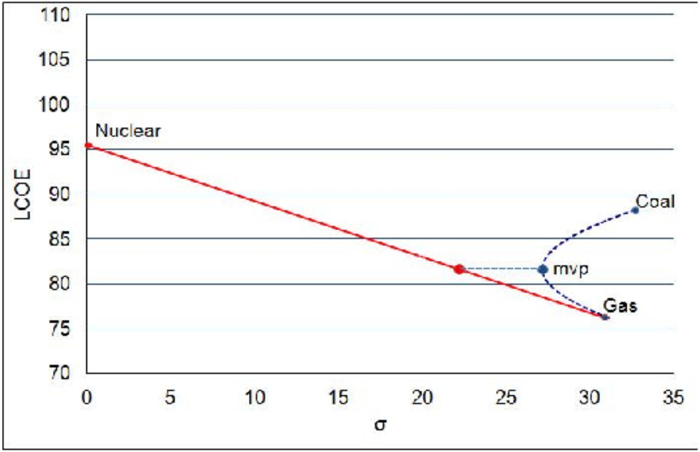
Scenario Analysis: $\sigma_{CO2} = 0.2$



Scenario Analysis: $\sigma_{\mathrm{CO2}} = 0.3$



Scenario Analysis: $\sigma_{\mathrm{CO2}} = 0.4$



Environmental Trade-offs

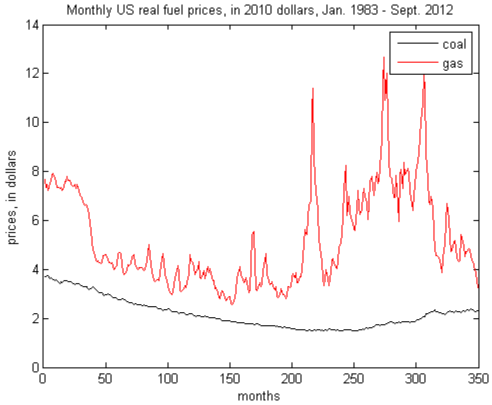
Notice that **WACC** was kept constant during the analysis, and that the LCOE is strongly nonlinear in WACC levels.

WACC can include the risk perception of investors in the nuclear business.

Including WACC in the **scenarios** can help to understand how **two environmental risks**, the nuclear business risk and CO_2 prices volatility, **compete** in the decision of setting how much weight to give to nuclear assets in the energy portfolio, when **scenario risk minimization** is sought.

Extended Model

The US don't have a CO_2 market, then a lognormal model can be safely assumed. But models of coal and gas prices can be improved.



Mean reverting log-processes are chosen for the real coal and gas prices, and **jumps** are included in the gas process.

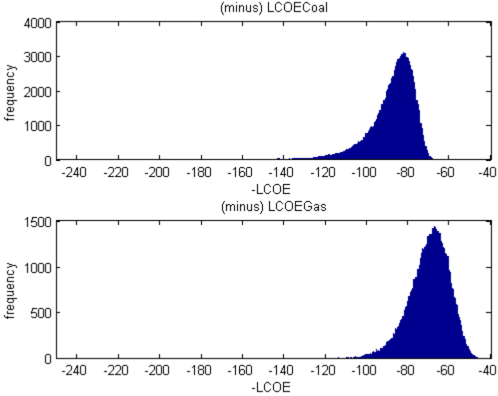
$$
\begin{aligned}
d\hat{X} &= (\mu_X - \theta_X\,\hat{X})\,dt + \sigma_X\,dW_X \\
X &= \exp\hat{X} \\
d\hat{Y} &= (\mu_Y - \theta_Y\,\hat{Y})\,dt + \sigma_Y\,dW_Y + J(\sigma_J)dN(\lambda) \\
Y &= \exp\hat{Y} \\
dZ &= \pi Z\,dt + \sigma_Z Z\,dW_Z
\end{aligned}
$$

These series are **discretized** on a monthly time grid, and assumed as models for the true price dynamics.

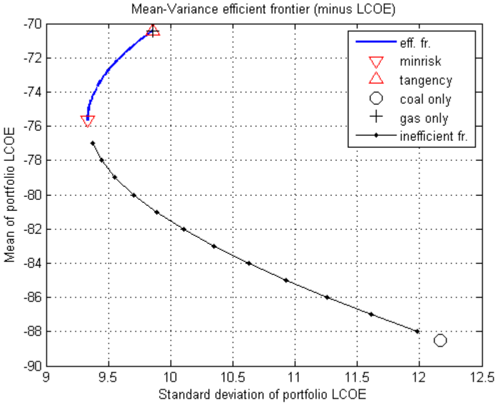
After estimating σ and γ from **monthly** market time series, the **monthly parameters** for the **real price processes** (which will be then subject to escalation and inflation on a monthly base) become

$\mu_{\mathrm{c}} = 0.0000$	$\mu_{\mathrm{g}} = 0.0292$
$\theta_{\mathrm{c}} = 0.0000\%$	$\theta_{\mathrm{g}} = 0.0210$
$\sigma_c = 0.0121$	$\sigma_g = 0.0602$
$\lambda = 0.2684$	$\sigma_j = 0.1258$
$\sigma_{\mathrm{CO2}} = \text{scenario}$	(but only $\sigma = 0.2$ here)

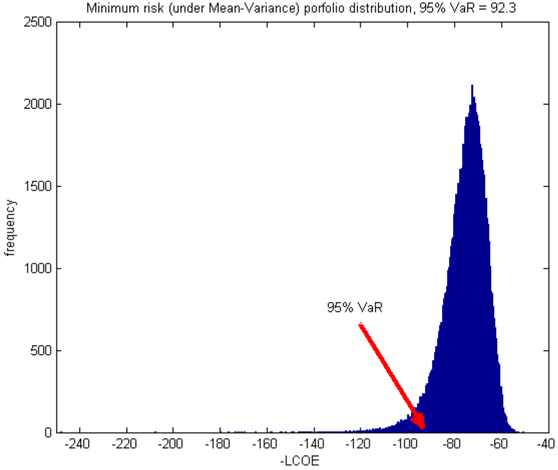
Case $\sigma_{\mathrm{CO2}} = 0.2$. The LCOE distributions (horizontally **flipped**) develop a **thick, long tail** on the **undesirable side** (high LCOE values).



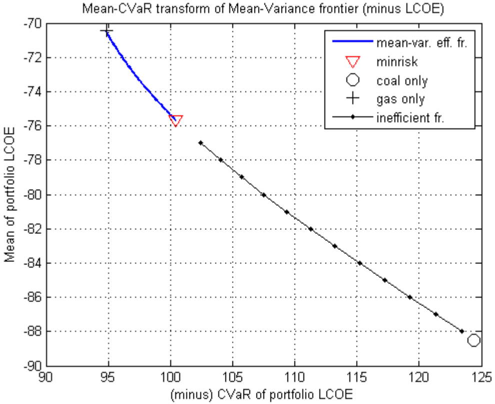
In the Mean-Stdv plane, the **efficient frontier** includes **low value** LCOE portfolios. On the tip of the Markowitz bullet, the **minimum risk portfolio**, a $w_c = 0.2885,\ w_g = 0.7115$ combination of coal and gas plants.



The minimum risk portfolio 95% VaR is $ 92.3, but 95% CVaR is $ 100.5, ten percent higher. There is a **lot of downside scenario risk** in the tail.



The Mean-CVaR plane reveals a reversal of situation. If tail model risk is undesirable, the best choice is an only-gas production, with a 95% CVaR of 95.0 dollars.



Conclusions

A new approach to LCOE feasibility assessment was presented. Advantages:

- In its **lognormal version** which includes the nuclear option, it allows for an analysis to explore trade-offs between economic advantages and environmental issues, form a financial point of view.
- In its **extended version**, it allows for a risk assessment about using classic deterministic LCOE analysis to decide if and what plant to build.

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