Thermal and nuclear energy portfolio selection using stochastic LCOE risk measures

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Overview

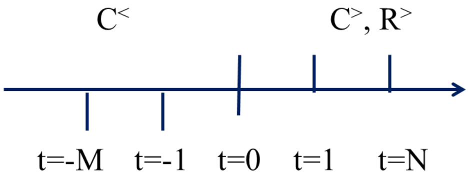
1. Deterministic vs Stochastic LCOE
2. Stochastic LCOE and Markowitz variance-cost tradeoff
3. Variance vs. CVaR as a Markowitz risk measure

PV Equilibrium

In case of a cash flow with past $t < 0$ and future $t \geq 0$ sums $S(t)$ and compound interest at given rate r_{cc} (**cost of capital**), **present value (PV)** equilibrium at $t = 0$ is found when

$$\sum_{t<0} \frac{S(t)}{(1+r)^t} = \sum_{t\geq 0} \frac{S(t)}{(1+r)^t},$$

$t \in (-M, N)$.



Breakeven Condition

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

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

the project is **profitable**: $C \leq R$.

Equilibrium condition

$$C = R$$

is called **breakeven**.

LCOE

Notice that profitability is expressed in terms of **price**$\times$**quantity levels** C and R.

In energy finance, the **Levelised Cost of Electricity** (**LCOE**) is a **constant price** $\tilde{L}$ that helps to assess a **threshold for profitability** of building a new plant, when a **stream of quantities** $Q^{>}(t)$ of electricity is sold.

(Nominal) LCOE Implicit Definition

Assuming that the proceeds come from selling at the **constant price** $\tilde{L}$ all electricity produced per period $Q^{>}(t)$,

$\tilde{L}$ is implicitly **defined** as

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

$$\sum_{t\geq 0} \frac{\tilde{L} \times Q^{>}(t)}{(1 + r_{cc})^t} = R(\tilde{L}).$$

The **LCOE price** $\tilde{L}$ is then a **breakeven price**.

WACC

The effect of **financing** the project **by equity and debt** (minus **taxes**) 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, or WACC discount factors

$$F^W(t) = F^W_{t_0,t_n} = 1/(1 + r_{\text{wacc}})^{t_n - t_0}$$

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

Solving for price $\tilde{L}$

Setting

$$D = \sum_{t \geq 0} Q^{>}(t) F^{W}(t),$$

$$\tilde{L} = \frac{\sum_{t<0} C_P^{<}(t) F^{W}(t)}{D} + \frac{\sum_{t \geq 0} C_P^{>}(t) F^{W}(t)}{D} = \tilde{I} + \tilde{O}$$

where $\tilde{I}$ stands for normalized investments and $\tilde{O}$ for normalized operation expenses, i.e. **nominal prices**.

If the electricity selling price E is such that

$$E \leq \tilde{L} = \tilde{I} + \tilde{O}$$

the project is **at loss**.

Assumption of Constant Q

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

Moreover, investment costs (i.e. costs at $t \in (-M, -1)$) can be absorbed in operating costs, to give a **total nominal price** T such that

$$\tilde{L} = \tilde{I} + \tilde{O} = \tilde{T}.$$

Real LCOE L

Taxes at rate T_c and **expected inflation** i (besides capital depreciation $A^{>}(t)$ and expected real escalation rate γ, a sort of inflation for specific costs) can all be included in the calculation of a **real nominal price** T and a **real LCOE** L.

Our real LCOE valuation formula for a **single-fuel technology x** plant is then

$$L^{x} = \frac{\sum_{n=1}^{M} C_t F^W_{t_0,t_n}}{Q \sum_{n=1}^{M} (1+i)^{t_n - t_0} F^W_{t_0,t_n}} + \frac{I^W_0 - T_c \sum_{n=1}^{M} dep_t F^W_{t_0,t_n}}{(1-T_c) Q \sum_{n=1}^{M} (1+i)^{t_n - t_0} F^W_{t_0,t_n}}.$$

LCOE is Deterministic

Making the **time-varying fuel prices** $X(t)$ and the CO_2 **emission prices** $Z(t)$ explicit in costs $C^{>}(t)$,

$$L^{x} = T(X(t), Z(t)), \; t \in (0, N).$$

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

$$L = T(\bar{X}, \bar{Z}).$$

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

L **has zero volatility**.

LCOE goes Stochastic

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

If fuel and CO_2 nominal prices $X(t)$ and $Z(t)$ are replaced by **stochastic processes** $X_\omega(t)$ and $Z_\omega(t)$,

L becomes a **time independent stochastic variable**

$$L_\omega = T(\hat{X}_\omega, \hat{Z}_\omega).$$

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

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

Economically, this would mean a correlation between fuel prices and CO_2 prices.

L_ω has now a **distribution**, a **mean** μ_L and a **variance** σ_L^2.

For any given E, there can be some ω such that

$$E \leq L_\omega.$$

This models investment **risk**.

Factor modelling is included in this approach.

Since fuel and related CO_2 cost enter L_ω in a **linear** way, for a single-fuel plant

$$L_\omega = I + O^{\mathrm{x}}(\hat{X}_\omega) + O^{\mathrm{x\_CO_2}}(\hat{Z}_\omega) = I + O^{\mathrm{x}}_\omega + O^{\mathrm{x\_CO_2}}_\omega$$

where O are normalized component costs.

$O^{\mathrm{x\_CO_2}}_\omega$ is proportional to $\hat{Z}_\omega$ through the **fuel $\mathbf{CO_2}$ intensity** I^{fuel}:

$$O^{\mathrm{x\_CO_2}}_\omega = I^{\mathrm{x}} A\, \hat{Z}_\omega.$$

Then, for a single-fuel plant,

$$E[L_\omega] = \mu^{\mathrm{x}}_L = I + \mu^{\mathrm{x}} + \mu^{\mathrm{x\_CO_2}}.$$

For two different fuels, say coal X and gas Y,

$$L_\omega^{\text{coal}} =$$
$$I + O^{\text{coal}}(\hat{X}_\omega) + O^{\text{coal\_CO}_2}(\hat{Z}_\omega) = I + O_\omega^{\text{coal}} + O_\omega^{\text{coal\_CO}_2}$$

$$L_\omega^{\text{gas}} =$$
$$I + O^{\text{gas}}(\hat{Y}_\omega) + O^{\text{gas\_CO}_2}(\hat{Z}_\omega) = I + O_\omega^{\text{gas}} + O_\omega^{\text{gas\_CO}_2}$$

so that coal and gas LCOE share a **factor** in $\hat{Z}_\omega$, common to $O_\omega^{\text{coal\_CO}_2}$ and $O_\omega^{\text{gas\_CO}_2}$.

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

$$E[(L_\omega^{\text{coal}} - I)\,(L_\omega^{\text{gas}} - I)] = \mu^{\text{coal}}\,\mu^{\text{gas}} + \mu^{\text{coal}}\,\mu^{\text{gas\_CO}_2} + \mu^{\text{coal\_CO}_2}\,\mu^{\text{gas}} + \alpha^{\text{CO}_2}$$

where

$$\alpha^{\text{CO}_2} = E[O_\omega^{\text{coal\_CO}_2}\,O_\omega^{\text{gas\_CO}_2}] \neq 0,$$

so that, in terms of covariance,

$$\text{COV}((L_\omega^{\text{coal}} - I),\,(L_\omega^{\text{gas}} - I)) = \alpha^{\text{CO}_2} = A^2 I^{\text{coal}} I^{\text{gas}} \sigma^2(\hat{Z}_\omega).$$

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** ($Z_\omega = 0$),

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

$$\mu_L^{\text{nuclear}} = N$$

$$\mathrm{COV}((L_\omega^{\text{nuclear}} - I),\ (L_\omega^{\text{coal}} - I)) = 0,$$
$$\mathrm{COV}((L_\omega^{\text{nuclear}} - I),\ (L_\omega^{\text{gas}} - I)) = 0.$$

Portfolio Stochastic LCOE

Recap. For **multi-technology generation portfolios**,

- since **fossil fuels** share a CO_2 factor, a **portfolio stochastic LCOE** is the sum of **correlated** LCOEs,
- even though the fuels' process prices are taken independent.
- A **nuclear fuel** LCOE can be taken **deterministic**.

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

$$dX = (\mu_X + \pi)X\,dt + \sigma_X X\,dW_X$$
$$dY = (\mu_Y + \pi)Y\,dt + \sigma_Y Y\,dW_Y$$
$$dZ = \pi Z\,dt + \sigma_Z Z\,dW_Z$$

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

1) fuel prices are independent form each other,

2) fuel prices are not correlated to CO_2 prices,

3) the **real prices** too follow a very simple, lognormal process

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

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

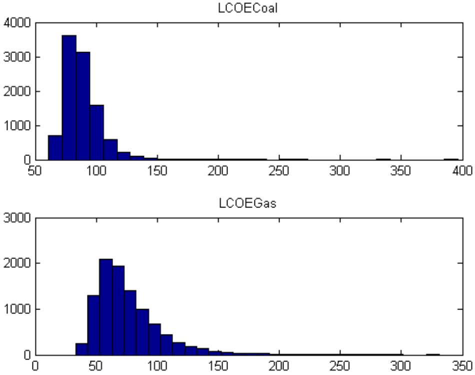
$\iota_{\text{inflation}} = 1.8\%$	$\text{WACC} = 7\%$
	$T_c = 40\%$

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 **single technology** coal and a gas plant.



For two **single-fuel** plants μ_L^{fuel} is estimated **in dollars** under **three CO_2 volatility scenarios**.

	$\sigma_Z = 0.2$	$\sigma_Z = 0.3$	$\sigma_Z = 0.4$
μ_L^{coal}	88.2	88.2	88.2
μ_L^{gas}	76.2	76.2	76.2
σ_L^{coal}	14.5	21.7	32.7
σ_L^{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 LCOE riskiness between coal and gas as σ_Z increases, 3) correlation ρ increases with CO_2 volatility.

LCOE Portfolio Theory

Now **LCOE itself** can be used in the Markowitz risk-return optimization.

In this case, $-\mu_L$ plays the role of the **expected return** (you want L_ω low), and its variance plays the role of the **risk**.

The **minimum attainable variance** is $\sigma^2_{\text{L,m}} = (\sigma_L^{\text{multifuel,minimum}})^2$, and the **optimal LCOE** becomes $\mu_{\text{L,m}} = \mu_L^{\text{multifuel,minimum}}$.

Only modification, either the **efficient frontier becomes the lower one**, or $-\mu_L$ is used.

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
$\sigma_{\text{L,m}}$	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 the same $\mu_{L,m}$ **found before** for the bi-fuel plant,

	$\sigma_Z = 0.2$	$\sigma_Z = 0.3$	$\sigma_Z = 0.4$
$\mu_{\text{L,m}}$	86.3	84.6	81.7

the riskiness of the portfolio can now be **reduced**.

w_e^{coal}, w_e^{gas}, w_e^{nucl} will be the new **efficient frontier weights** .

$\mu_L^{\text{nuclear}} = 95.4$	$\sigma_X = 0.2$	$\sigma_X = 0.3$	$\sigma_X = 0.4$
$\mu_{\text{L,trifuel}}$	86.3	84.6	81.7
$\sigma_{\text{L,m (bifuel)}}$	13.8	19.7	27.2
$\sigma_{\text{L,trifuel}}$	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 $\mu_L^{\text{nuclear}} = N = 95.4$ it turns out that,

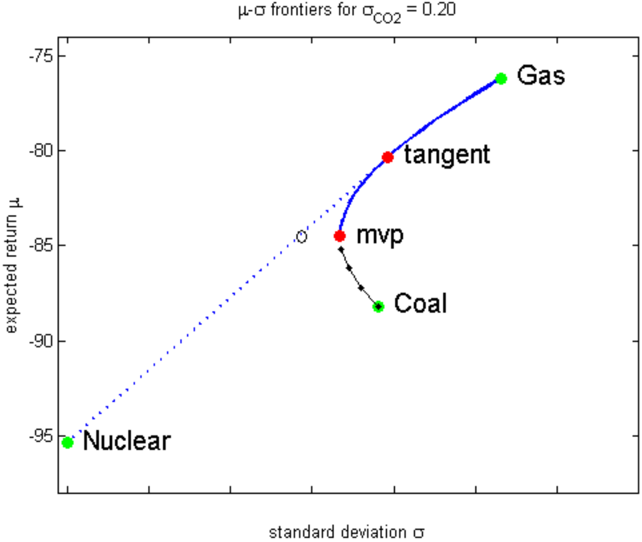
as σ_Z increases,

- same as seen for the bi-fuel plant, **investment riskiness $\sigma_{\text{L,trifuel}}$ increases**,
- **but** it is **always lower** than the the bi-fuel case $\sigma_{\text{L,m (bifuel)}}$,
- and the **gain in risk reduction** is **larger and larger**.

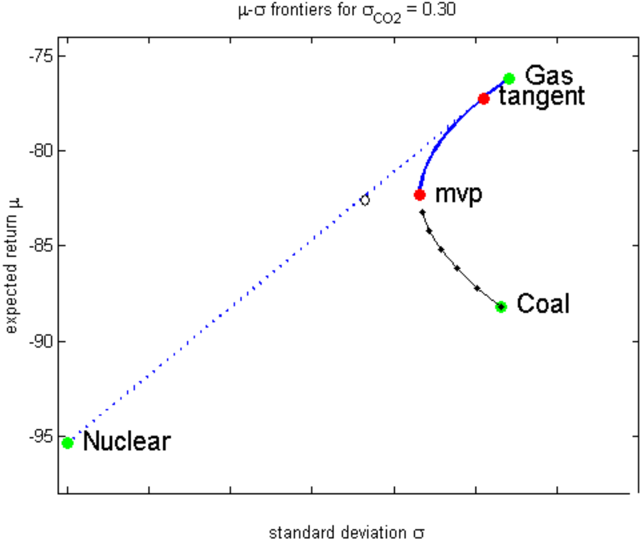
This means that **investment riskiness can be reduced** by **inclusion of nuclear** generation.

The **tangent portfolio** is **Sharpe-optimal**. For **larger values** of N, this effect is weaker.

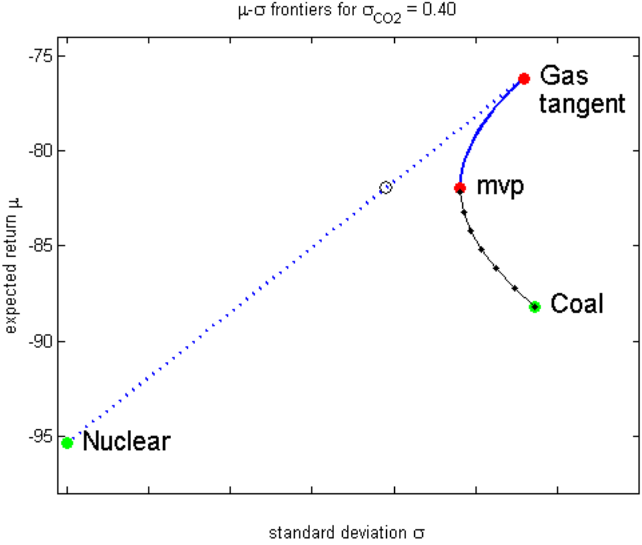
Scenario Analysis: $\sigma_{CO2} = 0.2$



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



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



Recap. Notice that

1. at fixed CO_2 riskiness, without nuclear, if attitude is risk-prone, the only-gas solution should be chosen. That would minimize expected LCOE.
2. At fixed CO_2 riskiness, without nuclear, the theory gives indications about the best mix of thermal technologies to be used - the minimum variance portfolio,
3. at fixed CO_2 riskiness, addition of a nuclear component can further decrease risk.
4. As CO_2 riskiness increases, gas appetibility increases but gain due to nuclear increases as well.
5. As nuclear price increases, this effect becomes weaker.
6. The tangent portfolio gives the optimal Sharpe risk/return ratio.

Environmental Trade-off

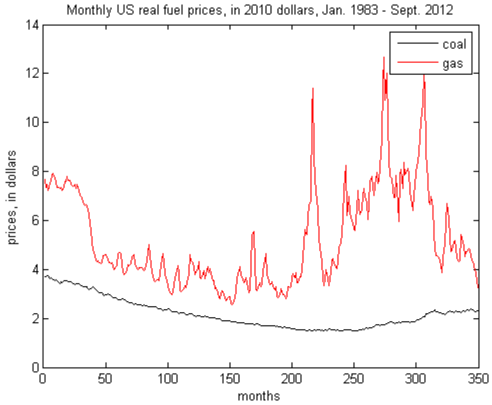
Notice that **WACC** was kept constant during the analysis, and that the LCOE is strongly nonlinear in WACC levels.

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. This is left for further work.

Extended Model

The US doesn'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.

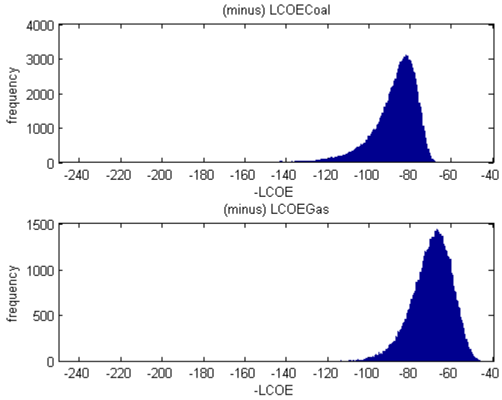
$$d\hat{X} = (\mu_X - \theta_X \hat{X})\, dt + \sigma_X\, dW_X$$
$$X = \exp \hat{X}$$
$$d\hat{Y} = (\mu_Y - \theta_Y \hat{Y})\, dt + \sigma_Y\, dW_Y + J(\sigma_J) dN(\lambda)$$
$$Y = \exp \hat{Y}$$
$$dZ = \pi Z\, dt + \sigma_Z Z\, dW_Z$$

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

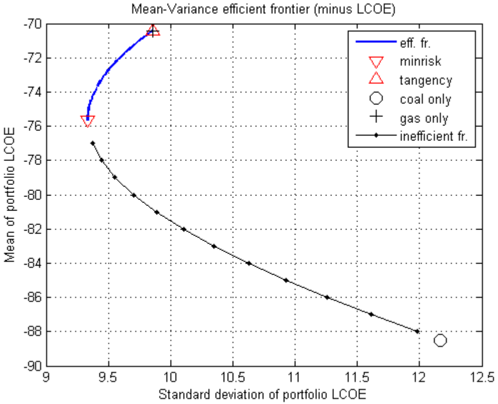
After estimating σ and γ from **monthly** market time series, the **monthly parameters** for the **real price processes** (which will be then subject to escalation and inflation on a monthly base) become

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

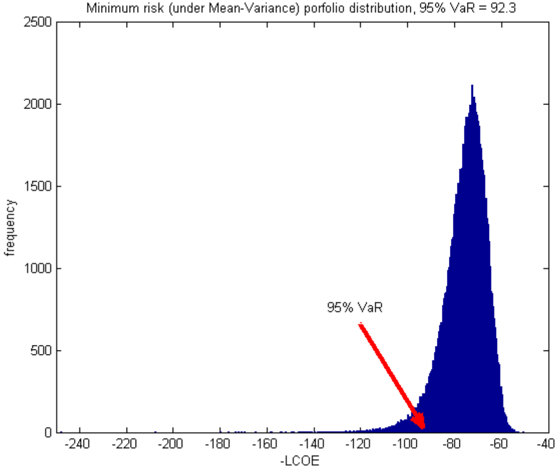
Case $\sigma_{CO2} = 0.2$. The LCOE distributions (horizontally **flipped**) develop a **thick, long tail** on the **undesirable side** (high LCOE values).



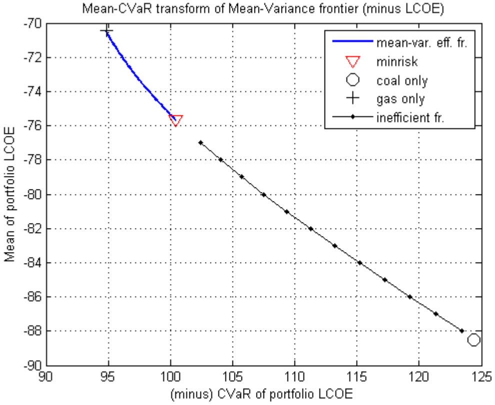
In the Mean-Stdv plane, the **efficient frontier** includes **low value** LCOE portfolios. On the tip of the Markowitz bullet, the **minimum risk portfolio**, a $w_c = 0.2885,\ w_g = 0.7115$ combination of coal and gas plants.



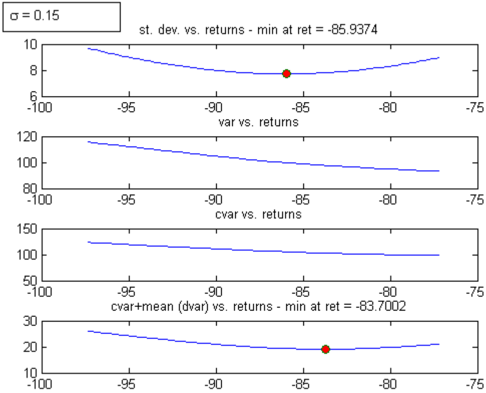
The minimum risk portfolio 95% VaR is $ 92.3, but 95% **CVaR** is $ 100.5, ten percent higher. There is a **lot of downside scenario risk** in the tail.



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



A **CVaR Deviation** (DVaR) analysis offers a different perspective, for an inverstor averse to tail risk.



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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