ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Efficient Multi-Energy Generation Portfolios for the Future

Florian Kienzle

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Motivation

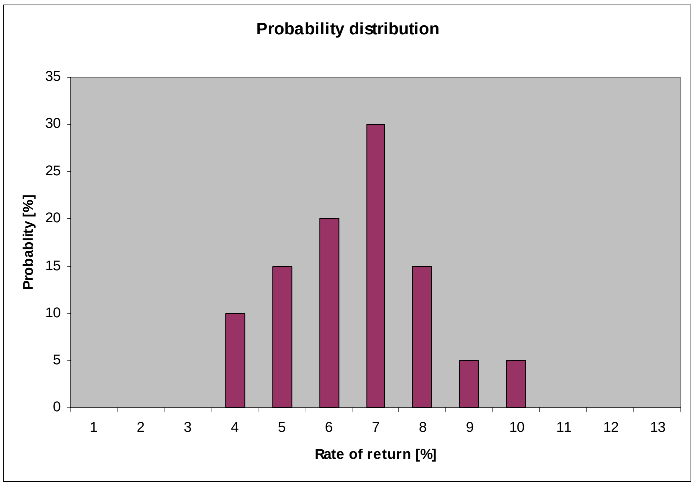
- Increasing worldwide demand for energy: How to satisfy this?
- Uncertainty and risk factors affecting energy system planning:
  - How will prices of primary energy carriers evolve?
  - Future control on carbon emissions? Future CO_2 price?
  - Risks introduced by the restructuring of energy markets
  - Growing number of emerging technology options: Which mix to choose?
- Physical links between different energy systems are becoming stronger
- Potential synergies between different energy carriers

⇨ Application of portfolio theory to multi-energy generation portfolios

➔ Method for long-term investment planning of future multi-energy systems

Portfolio Theory Fundamentals

- A portfolio is composed of securities
- Security: decision affecting the future
- Portfolio: the totality of such decisions
- Estimates of the future performance of securities are “fuzzy”



Portfolio Theory Fundamentals

- Portfolio theory uses two quantities to characterize the probability distribution of a portfolio’s rate of return

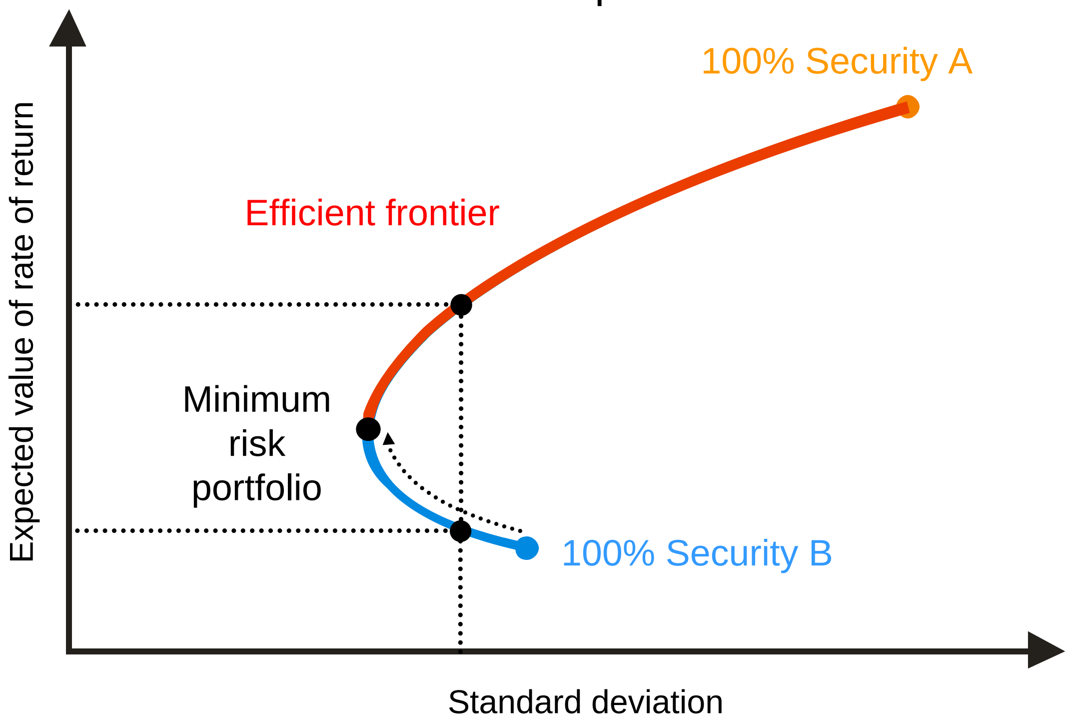
  - Expected return: Weighted average of all possible outcomes, with each outcome weighted by its likelihood

$$E = \sum_{i=1}^{m} p_i \cdot r_i$$

  - Standard deviation

$$\sigma = \sqrt{\sum_{i=1}^{m} p_i (r_i - E)^2}$$

Portfolio Theory Fundamentals



The Multi-Energy Portfolio Model

- Mean returns and covariance matrix are not computed with historical data
- Instead: Consideration of scenarios to take into account uncertainties about external drivers that can alter the future economic performance of a technology
- Examples for external drivers
  - Environmental concern with respect to climate change and resulting CO_2 price
  - Geopolitical tensions with effect on prices of fossil fuels
- Different states of external drivers (e.g. 'high' or 'low')
  ➔ differences between scenarios
- All possible combinations of external drivers result in a set of scenarios

The Multi-Energy Portfolio Model

- Costs of technologies will differ according to the scenario
  - Overall cost matrix $\mathbf{C_{tot}}$

$$\mathbf{C_{tot}} = \begin{array}{c} \text{Scen. 1} \quad \ldots \quad \text{Scen. s} \\ \begin{bmatrix} C_{11} & \cdots & C_{1s} \\ \vdots & \ddots & \vdots \\ C_{t1} & \cdots & C_{ts} \end{bmatrix} \end{array} \begin{array}{c} \text{Tech. 1} \\ \vdots \\ \text{Tech. t} \end{array} \qquad [C_{ts}] = \frac{USD}{MWh}$$

- When having a number of α energy outputs:

$$\mathbf{C_{tot}} = \sum_{i=1}^{\alpha} \mathbf{C_i}$$

The Multi-Energy Portfolio Model

- Inverting the values in $\mathbf{C_{tot}}$ gives the overall return matrix $\mathbf{R_{tot}}$

$$\mathbf{R_{tot}} = \begin{bmatrix} \frac{1}{C_{11}} & \cdots & \frac{1}{C_{1s}} \\ \vdots & \ddots & \vdots \\ \frac{1}{C_{t1}} & \cdots & \frac{1}{C_{ts}} \end{bmatrix} = \begin{bmatrix} R_{11} & \cdots & R_{1s} \\ \vdots & \ddots & \vdots \\ R_{t1} & \cdots & R_{ts} \end{bmatrix} \quad [R_{ts}] = \frac{MWh}{USD}$$

- Individual probabilities can be assigned to the scenarios

$$\mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_s \end{bmatrix} \qquad \text{with} \qquad \sum_{i=1}^{s} p_i = 1$$

$$\Rightarrow \boxed{R_P \quad \sigma_P}$$

The Multi-Energy Portfolio Model

- For a technology *i* with a conversion efficiency η_{ik} with respect to the *k*th output and a total efficiency of $\eta_{i,tot}$, the share of output *k* in the total output is simply:

$$\Gamma_{ik} = \frac{\eta_{ik}}{\eta_{i,tot}}$$

- Output ratio matrix $\mathbf{\Gamma}$:

$$\mathbf{\Gamma} = \begin{bmatrix} \Gamma_{11} & \cdots & \Gamma_{1t} \\ \vdots & \ddots & \vdots \\ \Gamma_{\alpha 1} & \cdots & \Gamma_{\alpha t} \end{bmatrix}$$

- Share of each output in the total output:

$$\mathbf{x_{out}} = \begin{bmatrix} x_{out,1} \\ x_{out,2} \\ \vdots \\ x_{out,\alpha} \end{bmatrix} = \mathbf{\Gamma} \cdot \mathbf{x_P} \quad \text{with} \quad \sum_{k=1}^{\alpha} x_{out,k} = 1$$

$$\mathbf{x_P} = \begin{bmatrix} x_1 & \cdots & x_t \end{bmatrix}^T$$ - Share of each technology in the portfolio

Application: An Electricity and Heat Portfolio

- Technologies with electricity as output
  - T1: Wind
  - T2: Photovoltaics (PV)
- Technologies with electricity and heat as output
  - T3: Biogas engine
  - T4: Natural gas fired engine
- Technologies with heat as output
  - T5: Solar (thermal)
  - T6: Gas boiler
- Three major external drivers:
  - D1: Environmental concern regarding climate change
  - D2: Energy-related research efforts
  - D3: Geopolitical tensions

Application: An Electricity and Heat Portfolio

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8
D1	high	high	high	high	low	low	low	low
D2	high	high	low	low	high	high	low	low
D3	high	low	low	high	high	low	low	high

- Equal probabilities for all scenarios:

$$p_i = 0.125 \qquad \forall i = 1, ..., 8$$

- Output ratio matrix:

$$\mathbf{\Gamma} = \begin{bmatrix} 1 & 1 & 0.39 & 0.49 & 0 & 0 \\ 0 & 0 & 0.61 & 0.51 & 1 & 1 \end{bmatrix}$$

Application: An Electricity and Heat Portfolio

- Cost matrices for the electricity and heat output:

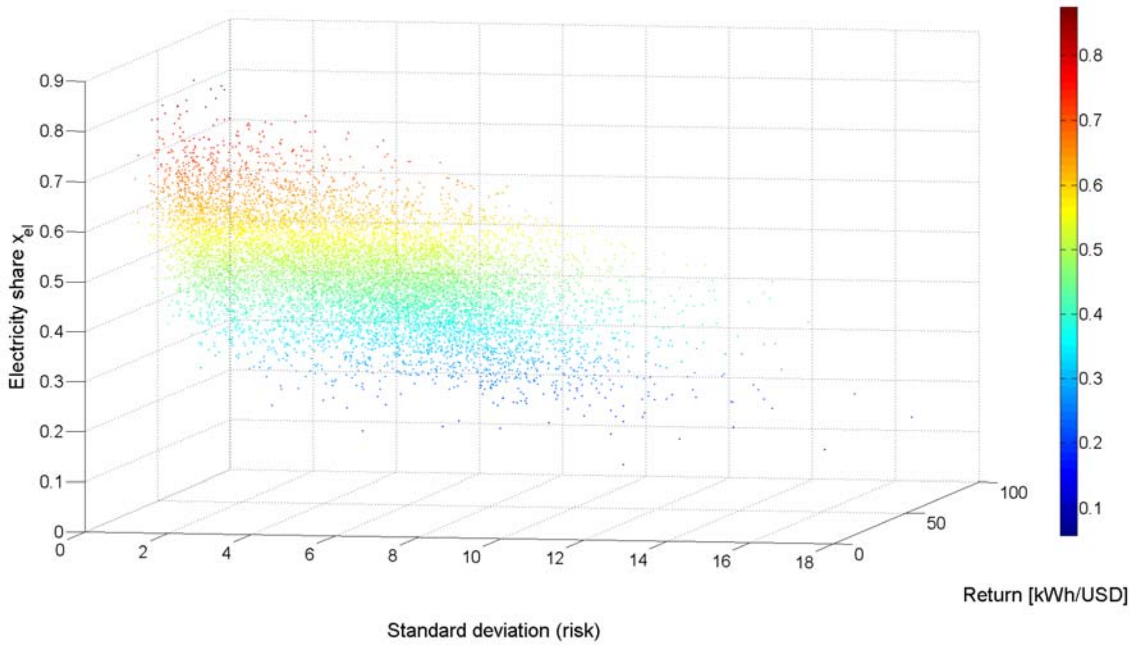
$$\mathbf{C}_{\mathrm{el}} = \begin{bmatrix} 43.3 & 43.3 & 44.2 & 44.2 & 43.3 & 43.3 & 44.2 & 44.2 \\ 253.3 & 253.3 & 287.8 & 287.8 & 253.3 & 253.3 & 287.8 & 287.8 \\ 59.9 & 59.9 & 63.0 & 63.0 & 59.9 & 59.9 & 63.0 & 63.0 \\ 81.4 & 64.7 & 66.0 & 83.0 & 77.8 & 61.2 & 62.4 & 79.4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{C}_{\mathrm{heat}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 11.4 & 11.4 & 12.0 & 12.0 & 11.4 & 11.4 & 12.0 & 12.0 \\ 31.2 & 25.6 & 26.1 & 31.7 & 27.8 & 22.2 & 22.7 & 28.4 \\ 13.2 & 13.2 & 14.7 & 14.7 & 13.2 & 13.2 & 14.7 & 14.7 \\ 16.8 & 13.9 & 14.0 & 17.0 & 10.4 & 7.5 & 7.6 & 10.6 \end{bmatrix}$$

All cost values in USD/MWh and mainly taken from the NEA/IEA publication "Projected costs of generating electricity", 2005.

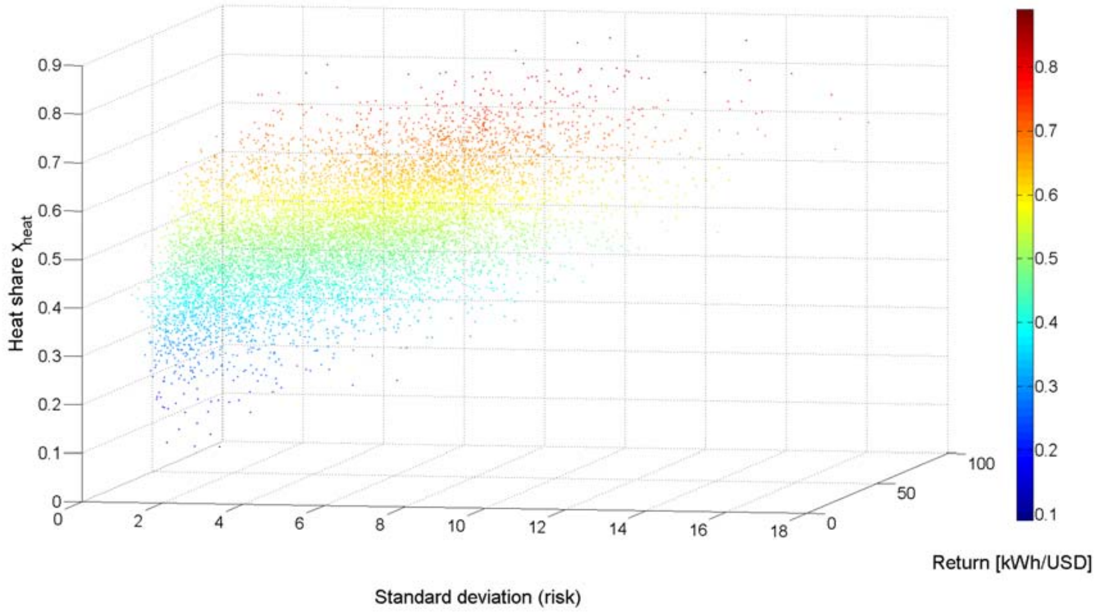
Application: An Electricity and Heat Portfolio

Electricity share in the combined electricity and heat portfolio as function of risk and return



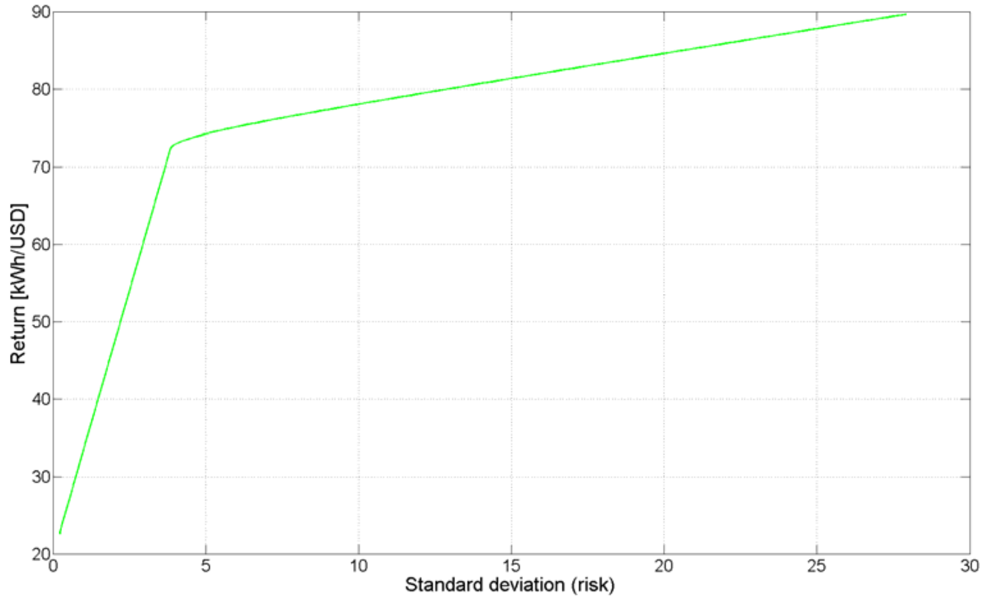
Application: An Electricity and Heat Portfolio

Heat share in the combined electricity and heat portfolio as function of risk and return



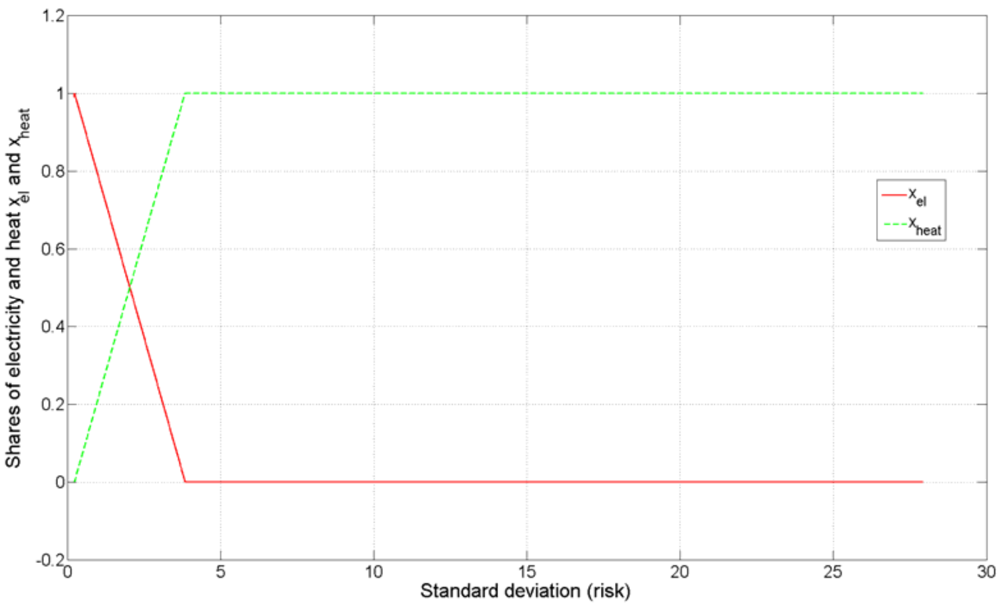
Application: An Electricity and Heat Portfolio

Efficient frontier of the combined electricity and heat portfolio



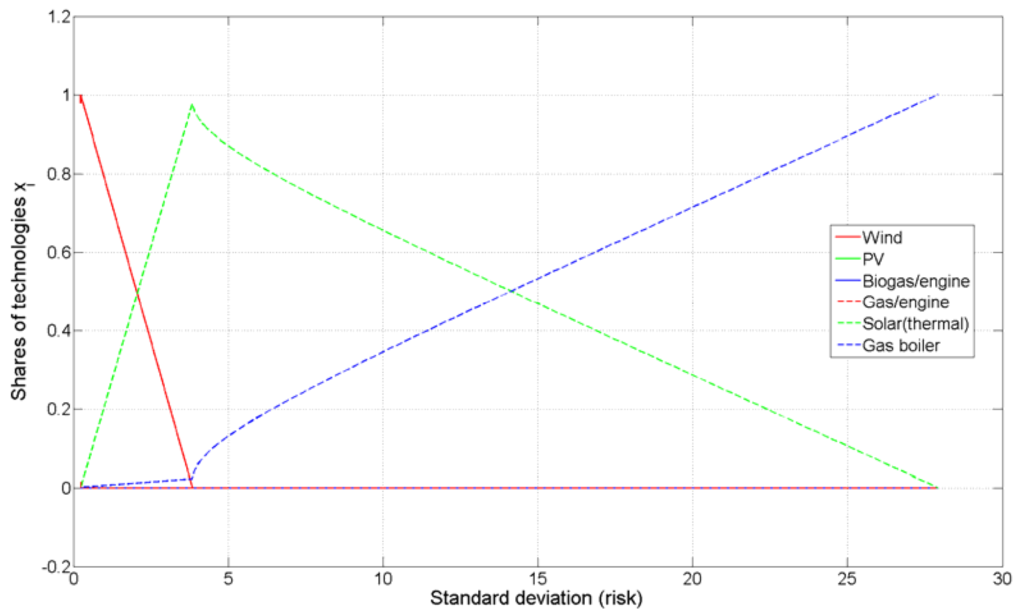
Application: An Electricity and Heat Portfolio

Shares of electricity and heat along the efficient frontier



Application: An Electricity and Heat Portfolio

Shares of all technologies along the efficient frontier



Summary

- General extension of portfolio theory to multi-energy portfolios with an arbitrary number of output energy carriers
- Uncertainty factors are taken into account using a set of several possible scenarios with individual probabilities of occurrence
- System planners can determine a portfolio being the best answer to this set of scenarios instead of having to choose a portfolio being only efficient for one single scenario

Outlook

- Apply the model to a “real” case, e.g. to the generation portfolio of a municipal or regional utility
- Analyze interdependences between investments in transmission infrastructure and investments in generation facilities

kienzle@eeh.ee.ethz.ch

www.future-energy.ethz.ch