Selection of optimal power plant generation mixes

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Presentation outline

1. Portfolio theory

Portfolio theory introduced in 1952 by Harry Markowitz (see Markowitz H.M. (1952). Portfolio selection, *Journal of Finance*, 7(1), 77-91):

- was a **new concept of risk management** and its application in selection of portfolios
- greatly **changed the asset management** industry
- received **Nobel Price in Economics** in 1990

Two main concepts of portfolio theory:

- investor goal is to **maximize the return** for any level of risk
- reduction of risk by creating a **diversified portfolio** of assets

"A good portfolio (…) is a balanced whole, providing the investor with protections and opportunities with respect to a wide range of contingencies.

(…) The purpose of analysis is to find portfolios which best meet the objectives of the investor."

(Markowitz H.M. (1991). *Portfolio Selection: Efficient Diversification of Investments*, p.3)

Source: www.boerse-frankfurt.de

Assumptions of the Markowitz portfolio theory (1/3)

- The **market is efficient** and all investors have free access to fair and correct information about the stock market
- Investors:
  - consider **each investment** alternative as being **presented by a probability distribution** of expected returns
  - **estimate the risk of the portfolio** on the basis of the variability of expected returns
  - are **risk averse** and try to **minimize the risk**
  - are **rational** and try to **maximize their rate of return**
  - **prefer higher returns** to lower returns for a given level of risk

Assumptions of the Markowitz portfolio theory (2/3)

- Investors:
  - maximize **one-period expected utility**, utility curves demonstrate diminishing marginal utility of wealth
  - base decisions only on **expected return and risk**, so that their utility curves are a function of expected return and risk (standard deviation) of returns
  - aim at **increasing revenues** (measured by the expected rate of return) and **decreasing risk** (measured by the standard deviation) of their investment, i.e. they **maximize expected utility**, they prefer more to less, and they are risk-averse

Assumptions of the Markowitz portfolio theory (3/3)

All investors can **reduce their risk** if they **add different investments** to thier portfolio

Diversification of assets/investments

Diversification is a **strategy** that **mixes a wide range of assets** (e.g. stocks, bonds, real estate etc.) or **investments** (e.g. in different countries, industries, sizes of companies) within a portfolio in an attempt to reduce portfolio risk

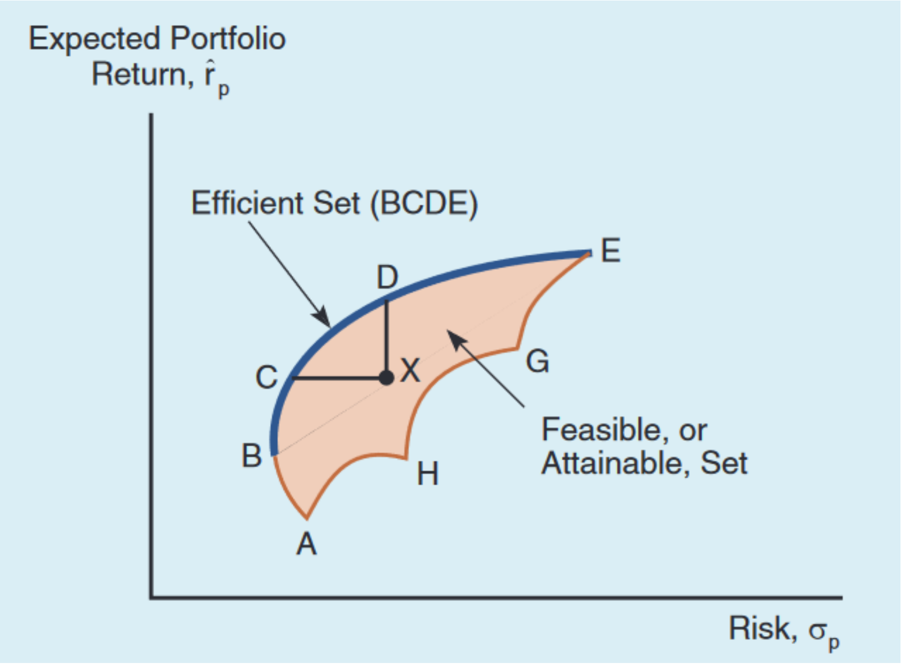
Diversification is measured by the **correlation coefficient** of pairs of assets

The unsystematic and company related risk (specific to individual assets) can be reduced by diversification into various assets whose variability is different and offsetting or which are **negatively correlated** or **not correlated at all**

1. Portfolio theory

- Applying **standard deviation as risk** and the **expected return** in a two-dimensional space all portfolio combinations available to the investor can be presented (**feasible set** of assets – the shaded area)

- The most significant aspect of the analysis is the concept **of mean-variance efficiency of portfolios**



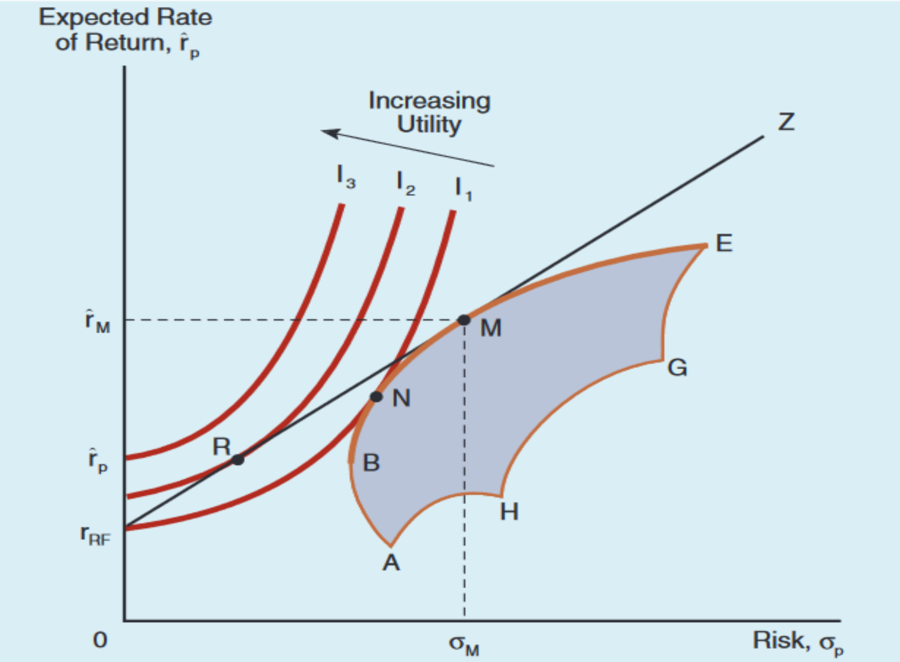
Efficient set of investments
Source: Brigham E., Ehrhardt M. (2011). Financial Management: Theory and Practice, South-Western CENGAGE Learning, Mason, USA

- The **portfolio is efficient (efficient set – blue line)** if for a given return there does not exist any other portfolio with the same or a smaller risk, and for a given risk there does not exist any other portfolio with the same or a larger return

1. Portfolio theory

Having the full set of potential portfolios (**feasible set** of assets) the question is, which portfolio should be chosen or held?

Two steps:
(1) determine the **efficient set** of portfolios
(2) choose from the efficient set the **single portfolio** that is best **for the specific investor**



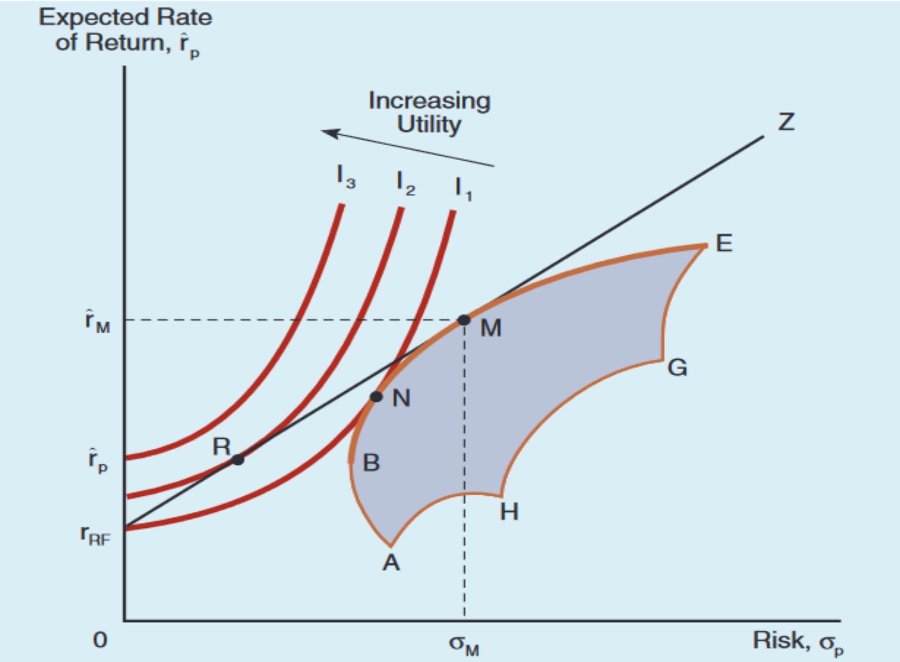
Efficient set of investments
Source: Brigham E., Ehrhardt M. (2011). Financial Management: Theory and Practice, South-Western CENGAGE Learning, Mason, USA

Point N, where **indifference curve I_1** is tangent to the efficient set, represents a **possible optimal portfolio choice**; it is the point on the efficient set of risky portfolios where the investor obtains **the highest possible return for a given amount of risk** and **the smallest degree of risk for a given expected return**

1. Portfolio theory

- In addition to the feasible set of **risky portfolios**, we include a **risk-free asset** that provides a **riskless return**, r_{RF}

- Given the **risk-free asset**, investors can create new portfolios that combine the **risk-free asset with a portfolio of risky assets** (new opportunities along line r_{RF}MZ, so-called **Capital Market Line** – CML)



Efficient set of investments
Source: Brigham E., Ehrhardt M. (2011). Financial Management: Theory and Practice, South-Western CENGAGE Learning, Mason, USA

- This enables investors to achieve any combination of risk and return on the straight line connecting r_{RF} with **point M** – the point of tangency between that straight line and the efficient frontier of risky asset portfolios – a new **possible optimal portfolio choice** which combines the **risk-free and risky assets** from the feasible set

Mean-Variance portfolio selection model – two dimension optimization model (*Markowitz, 1952*)

$$\mathbf{E}(\boldsymbol{R_p}) \rightarrow max$$
$$\boldsymbol{\sigma_p} \rightarrow min$$
$$\text{where } \boldsymbol{x_i} \geq 0 \text{ and } \sum_{i=1}^{n} \boldsymbol{x_i} = 1$$

$$\boldsymbol{E}(\boldsymbol{R_p}) = \sum_{i=1}^{n} E(R_i)x_i \quad - \text{expected portfolio returun}$$

$$\boldsymbol{\sigma_p} = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j cov_{ij}} \quad - \text{portfolio risk}$$

$\boldsymbol{E}(\boldsymbol{R_i})$ – expected return of asset i
$\boldsymbol{cov_{ij}}$ – covariance between asset i and j
$\boldsymbol{x_i}$ – share (portfolio weight) of asset i
$\boldsymbol{n}$ – number of assets

Mean-Variance portfolio selection model – solution possibilities

Highest possible return for a given amount of risk

$$\mathrm{E}(R_p) \rightarrow max$$
$$\sigma_p \leq \text{Accepted risk level}$$

Smallest degree of risk for a given expected return

$$\sigma_p \rightarrow min$$
$$E(R_p) \geq \text{Desired return level}$$

$$\text{where } x_i \geq 0 \text{ } and \sum_{i=1}^{n} x_i = 1$$

1. Portfolio theory

Proposed by the Markowitz method, is justified when:

- the **rates of return are normally distributed** and the **investor's utility functions are exponential**, and
- the **utility function is quadratic** and the return distributions are characterized by their first two moments and are relatively symmetric

Limitations of Markowitz approach are connected with:

- The investor's **utility function** and their preferences
- **Distribution of security's rates of return** (not normally distributed)
- **Risk measure** (standard deviation is not always the correct one)
- **Investor's rationality** (investors are not "rational")

Selected alternative portfolio approaches

Because *"Under certain conditions, the mean-variance approach can be shown to lead to* ***unsatisfactory predictions of behavior****. Markowitz suggests that a model based on the* ***semivariance*** *would be preferable; in light of the formidable computational problems, however, he bases his analysis on the variance and standard deviation."*

(Sharpe W. (1964). Capital Asset Prices: A Theory of Market Equilibrium under Considerations of Risk. *The Journal of Finance*, 19(3), p.428)

- **Mean-Absolute Deviation (MAD) portfolio selection model** (Konno and Yamazaki, 1991)
- **Semi-Mean Absolute Deviation (SMAD) portfolio selection model** (Konno and Yamazaki, 1991 and 2005)
- **Fuzzy Semi-Mean-Absolute Deviation (FSMAD) portfolio selection model** (Watada, 1997)
- **Multi-period portfolio selection model** (Mulvey et al., 1997 and Maranas et al., 1997)

2. Portfolio analysis on energy sector

Methods adopted from the finance literature have attracted interest for **analyzing investment decision-making processes** in the liberalized electricity sector, including **portfolio considerations**

Why do electricity producers use financial methods in energy economics?

- **Liberalization of electricity market** means: more competition (on production and retail market), more uncertainty sources
- **Market risks** – regarding future electricity demand as well as supply, development of electricity and fuel prices
- **Regulatory risks** – environmental and energy regulations, market design
- **Changes in power generation mix** – increase of renewable energy technologies in power generation

2. Portfolio analysis on energy sector

Why do electricity producers apply portfolio theory to power generation assets?

- The **optimal diversification** of **different power generation technologies** from an economic as well as a resource availability point of view is an important issue for energy planners
- Optimization plays a very important role in assisting investors with their investment strategies and helps by **reducing the number of alternatives** to be considered
- **Asymmetrical risk measures**, such as **semi-variance** or **semi-mean absolute deviation**, reflects investor's real losses and simplifies the calculation
- **Fuzzy set theory** offers a more natural way to reflect an investor's aspiration levels of a portfolio's return and risk
- **Regulatory change** is an important element of uncertainty that has to be taken into account in the investment decision-making process

Application of portfolio theory to power generation assets (selected references)

Bar-Lev and Katz (1976)	Analysis of fossil fuel mix in US power generation
Awerbuch and Berger (2003)	First application of mean-variance portfolio selection method on liberalized power market in the EU – deeper costs analysis
Roques et al. (2007)	Consideration of NPV and new investments in portfolio analysis in the UK
Krey and Zweifel (2008)	Application of seemingly unrelated regression (SUR) estimation method to portfolio analysis in Switzerland and the US
Bazilian and Roques (2008)	Presentation of some works and studies of portfolio analysis for power generation assets
Madlener et al. (2009)	Analysis of current power portfolio of E.ON's different regional markets
Glensk and Madlener (2010)	Application of fuzzy set theory to changes in the power generation mix
Madlener et al. (2011)	Application of fuzzy set theory to offshore wind power plants
Madlener (2012)	Literature review on portfolio optimization studies for power generation assets

2. Portfolio analysis on energy sector

Bar-Lev and Katz (1976) – the **first recognized application** of Markowitz portfolio selection theory in the field of energy utilities **in the US**:

- derivation of an efficient frontier for a fossil fuel mix in US
- investigation of various investment opportunities by the variation of cost and risk assumptions

Conclusion

investigated utilities are, in general, **efficiently diversified**

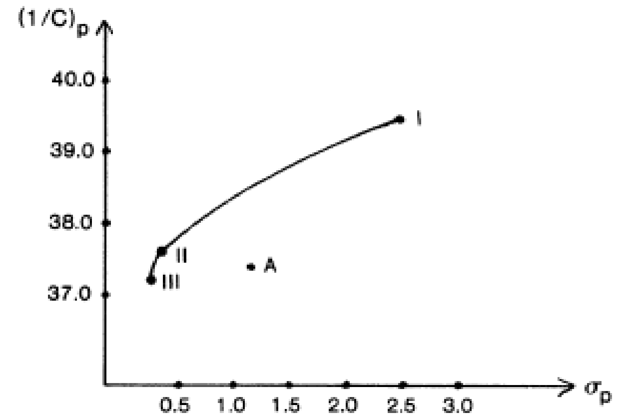


FIGURE 4—West North Central

percent accounted for by:

portfolio	coal	oil	gas
Actual	54.7	2.0	43.3
I	—	—	100.0
II	62.6	—	37.4
III	63.2	—	36.8

Efficient frontier in 1969 in West North Central
Source: Bar-Lev D., Katz S. (1976). A portfolio approach to fossil fuel procurement in the electric utility industry. Journal of Finance, 31(3), 933-947

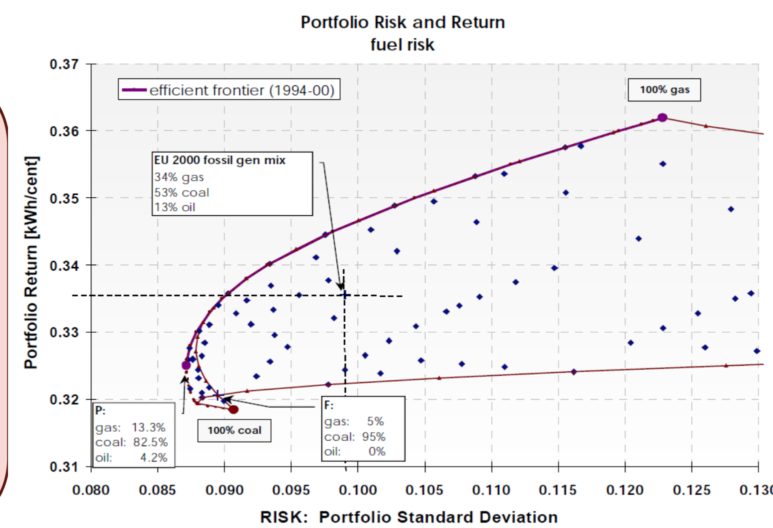
2. Portfolio analysis on energy sector

Awerbuch and Berger (2003) – the **first recognized application** of Markowitz portfolio selection theory on generation portfolios in liberalized power markets – the generation portfolio **of the European Union** (EU-15):

- more detailed portfolio model that reflects the risks of relevant generation cost streams, such as construction period costs, operation and maintenance costs, and fuel costs

Conclusions

- existing EU generation **portfolio is slightly suboptimal** from a risk-return perspective
- **improvement** of the overall efficiency of the portfolio by **adding more wind power** or comparable renewable energy technologies to the conventional mix



Efficient frontier and portfolios of three conventional technologies in EU
Source: Awerbuch S., Berger M. (2003). Applying portfolio theory to EU electricity planning and policy-making. IEA/EET Working Paper EET/2003/03

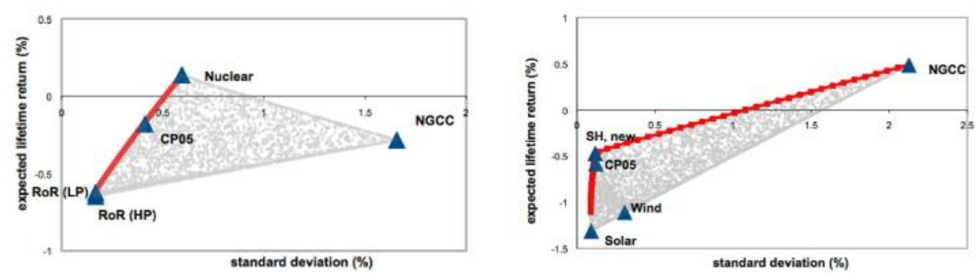
2. Portfolio analysis on energy sector

Madlener and Wenk (2008) – **future development** of the generation portfolio in Switzerland **considering operated power generation technologies as well as new options**, such as new renewables (wind, photovoltaics) and combined-cycle gas turbines, and retrofits:

- identification of efficient investment options for the electricity supply sector
- construction lead times and asymmetric distributions in the stochastic variables, explicitly differentiate between base-load and peak-load technologies are included

Conclusions

- current production portfolio for base-load in Switzerland is very **close to the efficient frontier**
- peak-load portfolio still allows for some **improvement from a return-risk perspective**



(a) Base-load (b) Peak-load

Efficient frontiers for base-load and peak-load technologies in Switzerland

Source: Madlener R., Wenk C. (2008). Efficient Investment Portfolios for the Swiss Electricity Supply Sector. FCN Working Paper No.2/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August

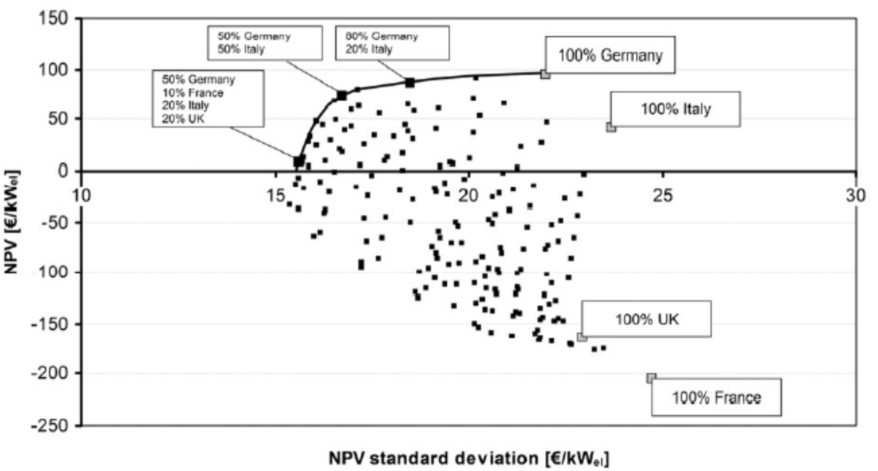
2. Portfolio analysis on energy sector

Westner and Madlener (2010) – analysis made for contracting companies, that are interested to diversify their investment in new CHP facilities regionally over several countries in order to reduce country and regulatory risk

- application of the Mean-Variance Portfolio (MVP) theory considering return-risk profiles of the selected CHP technologies in different countries

Conclusions

- the returns on **CHP investments differ significantly** depending on the country, the support scheme, and the selected technology studied
- while a **regional diversification of investments** in CCGT-CHP does not contribute to reducing portfolio risks, a diversification of investments in engine- CHP can decrease the risk exposure



Mean-Variance portfolio analysis of engine-CHP portfolios (for four selected countries)
Source: Westner G., Madlener R. (2010). The benefit of regional diversification of cogeneration investments in Europe: A mean-variance portfolio analysis. Energy Policy, 38(12): 7911–7920

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Application of portfolio theory to power generation assets – specific questions

1. How should the required **return – portfolio selection criterion** for real assets, such as power plants, be defined?
2. How should different technologies be allocated to achieve an **optimal portfolio**?

Other optional questions:

3. What are the pros and cons of **alternative risk measures** (e.g. semi-mean absolute deviation, SMAD)?
4. How useful is the application of alternative portfolio selection methods (e.g. **fuzzy set theory)**?
5. Is the **impact of new energy investments on the portfolio's efficiency justifiable**, based on portfolio analysis?

Definition of return as portfolio selection criterion for power generation assets

Annual return (*AR*) of the *i*th technology (€)

$$AR_i = R_{energy\ sales,i} - C_{fuel,i} - C_{CO_2,i} - C_{O\&M,i} - \delta_i$$

- $R_{energy\ sales,i}$ … revenues from energy production
- $C_{feul,i}$ … fuel costs
- $C_{CO_2,i}$ … carbon dioxide costs
- $C_{O\&M,i}$ … operation and maintenance costs
- δ_i … depreciation

Definition of return as portfolio selection criterion for power generation assets

Net Present Value of the *i*th technology (€):

$$NPV_i = \sum_{t=1}^{T} \frac{CF_{t,i}}{(1+WACC)^t}$$

where

$$CF_{t,i} = R_{energy\ sales,i} - C_{fuel,i} - C_{CO_2,i} - C_{O\&M,i} - \delta_i$$

- $CF_{t,i}$ … annual cash flow of technology *i*
- *WACC* … Weighted Average Cost of Capital (discount rate)
- *t* … lifetime [a]

2.1. Framework

Main calculation steps for each portfolio model

- **Net Present Value** as portfolio selection criterion for the analyzed power plants (appropriate modeling of existing and new power plants)

Monte Carlo simulation based on electricity, fuel and CO_2 price information as well as technical and economic data (e.g. using Oracle's Crystal Ball software, or Python)

- Introduction of $x_{i,\max}$ the **maximal share for each technology**, to avoid technically infeasible solutions
- Application of the dynamic object-oriented programming language **Python** for determination of the portfolio's **efficient set**

Mean-Variance (MV) portfolio selection model
(Markowitz, 1952)

$$\sum_{i=1}^{n} E(R_i)x_i \rightarrow max$$

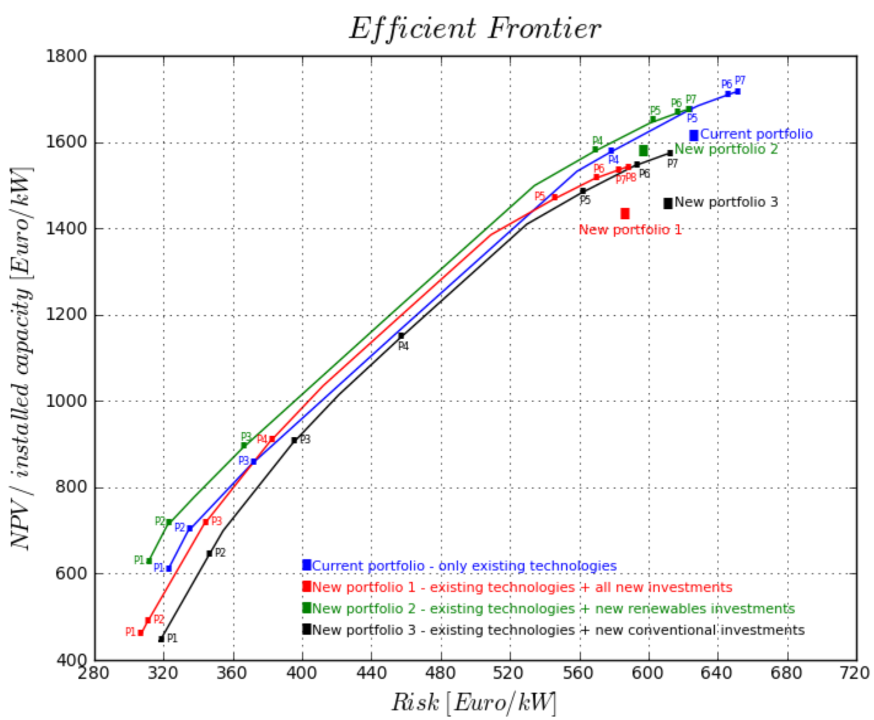
$$\sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j cov_{ij} \rightarrow min$$

subject to: $\sum_{i=1}^{n} x_i = 1$ and $0 \leq x_i \leq x_{i,max}$

where: x_i … share of asset *i*,
$E(R_i)$ … expected return of asset *i*,
$cov_{i,j}$ … covariance between asset *i* and *j*

- Unconstrained MV portfolio analysis not useful, as technically infeasible solutions **can occur**
- Constrained MV portfolio analysis affects well-diversified efficient portfolios and technically infeasible solutions **cannot occur**

Efficient frontiers for MV model
(existing technologies and new investments)



Main findings:

- Current and new portfolios of E.ON in Germany are located **way off the efficient frontiers**
- New portfolios of E.ON in Germany have smaller NPV but also smaller risk
- Positive impact of **all new investment** on NPV (red line between P4–P5)
- Positive impact of **new renewable investment** on NPV (green line)

Efficient frontiers of E.ON's current power generation mix and new investments
Source: Madlener R., Glensk B., Westner G. (2010). Optimization of E.ONs Power Generation with a Special Focus on Renewables, E.ON Energy Research Center Series, Vol. 2, Issue 2, December

Semi-Mean Absolute Deviation (SMAD) portfolio selection model
(Konno and Yamazaki, 1991 and 2005)

$$\sum_{i=1}^{n} E(R_i)x_i \rightarrow max$$

$$\frac{1}{T}\sum_{t=1}^{T} d_t \rightarrow min$$

Takes into account that only downside risk matters to the investor!

$$\text{subject to:} \quad d_t \geq -\sum_{i=1}^{n}(R_{t,i} - E(R_i))x_i$$

$$\sum_{i=1}^{n} x_i = 1 \quad \text{and} \quad 0 \leq x_i \leq x_{i,max} \quad \text{and} \quad d_t \geq 0$$

where: d_t … refers to the deviation between the realization of portfolio return and its expected value at time *t*,

$R_{t,i}$ … denotes the return of asset *i* in time *t*

Fuzzy Semi-Mean-Absolute Deviation (FSMAD) portfolio selection model (Watada, 1997)**, adapted**

$$\Lambda \rightarrow min$$

subject to:

$$\alpha_R \sum_{i=1}^{n} E(R_i) x_i - \Lambda \geq \alpha_R R_M$$

$$\alpha_w \frac{1}{T} \sum_{t=1}^{T} d_t + \Lambda \leq \alpha_w w_M$$

$$d_t + \sum_{i=1}^{n} (R_{t,i} - E(R_i)) x_i \geq 0 \quad \forall t \in T$$

$$\sum_{i=1}^{n} x_i = 1 \quad \text{and} \quad 0 \leq x_i \leq x_{i,max} \quad \text{and} \quad d_t \geq 0 \quad \text{and} \quad \Lambda \geq 0$$

FSMAD is a promising new approach; however, model selection ultimately always depends on investor's risk (measurement) preferences

where: $\Lambda = log \frac{\lambda}{1-\lambda}$ and λ is a value of the membership function

α_R, α_w determine the shape of the membership function

R_M, w_M are the mid-points where λ is equal 0.5

2.3. Alternative portfolio approaches – examples

Fuzzy Semi-Mean-Absolute Deviation (FSMAD) portfolio selection model – calculation steps

STEP 1

Determination of NPV for each power plant

- Monte Carlo simulation using technical and economic date (e.g. Crystal Ball® software)

STEP 2

Specification of sufficiency and necessity levels for return and risk

- Using the Zimmermann (1978) method, implemented in dynamic object-oriented programming language Python

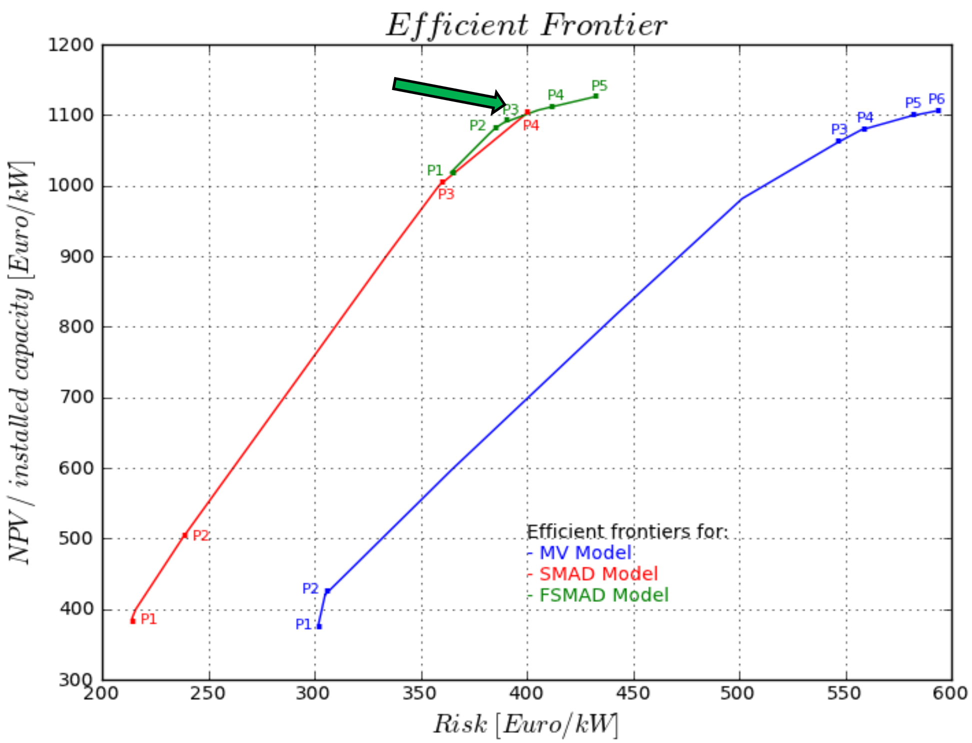
STEP 3

Determination of efficient portfolios and frontiers for FSMAD model

- Application of quadratic programming methods, again implemented in the dynamic object-oriented programming language Python

2.3. Alternative portfolio approaches – examples

Efficient frontiers for MV, SMAD and FSMAD model (existing technologies)



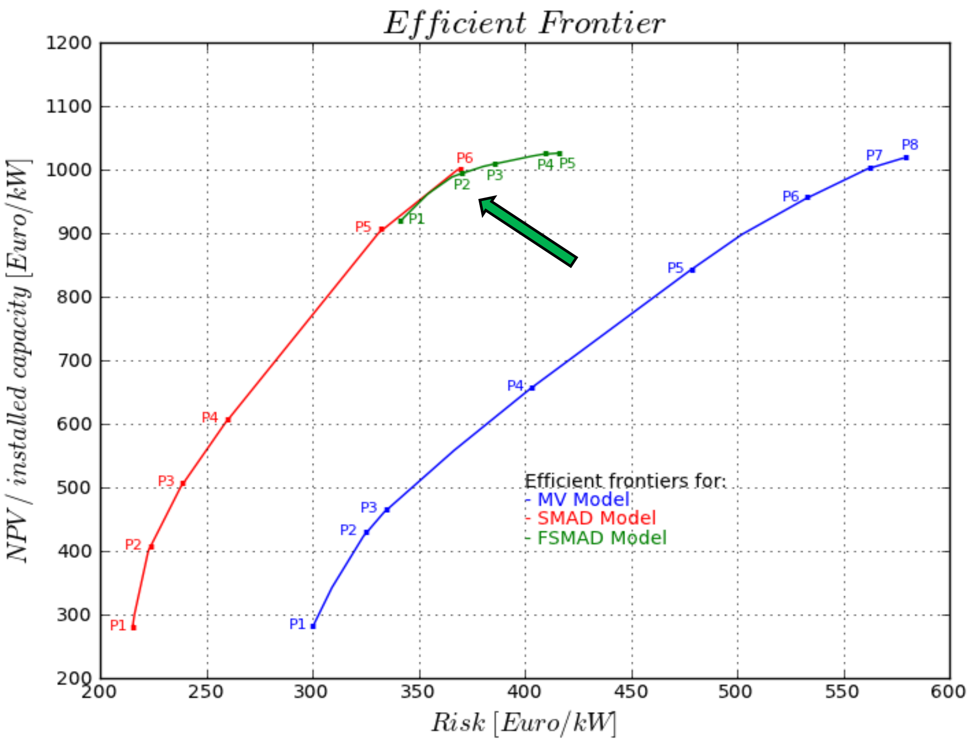
Main findings:

- Evaluation of efficient frontier for SMAD model – **shift in scale of risk**
- Evaluation of efficient frontier for FSMAD model – **smaller set of decision alternatives**
- **Better portfolios in terms of risk and return** obtained with FSMAD model compared to MV and SMAD model

Efficient frontier of existing technologies for MV, SMAD and FSMAD model
Source: Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August

2.3. Alternative portfolio approaches – examples

Efficient frontiers for MV, SMAD and FSMAD model (existing technologies and new investments)



Main findings:

- Evaluation of efficient frontier for SMAD model – **shifts in scale of risk**
- Evaluation of efficient frontier for FSMAD model – **smaller set of decision alternatives**
- Efficient frontier for FSMAD model is **almost coincides** with efficient frontier for SMAD model (some part)

Efficient frontier of existing and new technologies for MV, SMAD and FSMAD model
Source: Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August

2.3. Alternative portfolio approaches – examples

Efficient frontiers for MV, SMAD and FSMAD model (existing technologies and new investments)

	Efficient portfolios						E.ON Current portfolio
	P1	P1	P1	P8	P6	P5	
Biomass	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.05%
CCGT	16.36%	16.36%	7.83%	7.83%	7.83%	16.36%	8.45%
CHP	7.26%	7.26%	7.26%	0.00%	2.47%	0.00%	1.20%
GT gas	2.76%	2.76%	2.76%	2.76%	2.76%	2.76%	0.38%
GT oil	6.17%	6.17%	6.17%	0.00%	0.00%	0.00%	0.84%
Hard coal	48.76%	48.76%	11.89%	33.26%	18.06%	24.73%	30.08%
Hydro	12.73%	12.73%	12.73%	0.00%	12.73%	0.00%	5.40%
Lignite	1.79%	1.79%	2.21%	7.00%	7.00%	7.00%	6.09%
Nuclear	0.00%	0.00%	44.98%	44.98%	44.98%	44.98%	43.35%
Onshore wind	0.36%	0.36%	0.36%	0.36%	0.36%	0.36%	0.23%
Offshore wind	3.76%	3.76%	3.76%	3.76%	3.76%	3.76%	1.12%
NPV/Installed power [€/kW]	280.12	283.21	918.94	1,017.90	1,000.00	1,025.62	
Risk [€/kW]	300.11	215.47	341.43	578.13	368.47	415.04	

The best efficient portfolios from risk and return point of view for existing technologies and new technologies

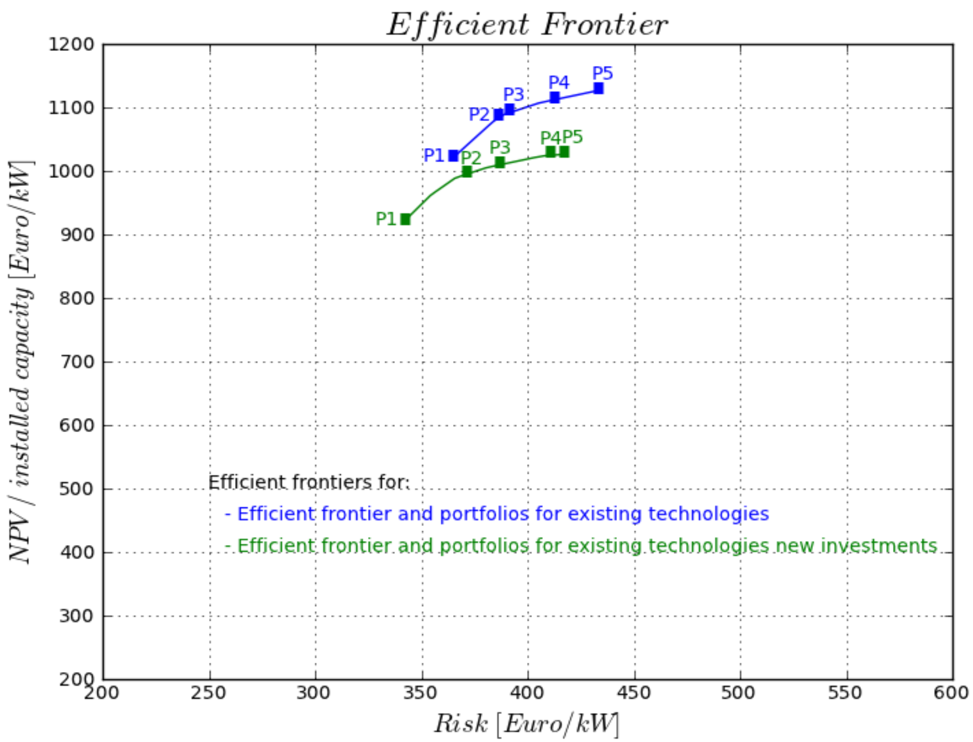
Source: Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August

Main findings:

- **Significant changes** in shares of CCGT and Hard Coal in efficient portfolios
- Significant share of Offshore Wind Power in efficient portfolios
- Increase of shares of Nuclear Power in efficient portfolios in comparison to current portfolio

2.3. Alternative portfolio approaches – examples

FSMAD portfolio selection model (existing technologies and new investments)



Main findings:

- FSMAD model affects the size of the set of efficient portfolios → **smaller set of decision alternatives**
- Efficient portfolios with new investments have smaller NPV but also smaller risk

Efficient frontier of current (blue line) and prospective (green line) power generation mixes
Source: Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August

Multi-period portfolio selection model
(Mulvey et al., 1997 and Maranas et al., 1997), **adapted**

$$\alpha R_{p,T} - (1-\alpha)Var(R_{p,T}) \rightarrow max$$

subject to:

$$\sum_{i=1}^{N} x_{i,t}^{s} = 1 \qquad \forall s \in S, \quad t = 1,\ldots T$$

$$0 \le x_{i,t}^{s} \le x_{i,max} \qquad \forall s \in S, \quad t = 0,\ldots T, \quad i = 1,\ldots N$$

$$x_{i,t}^{s} = x_{i,t}^{s'} \qquad \forall s \in S, \quad t = 0,\ldots T, \quad i = 1,\ldots N$$

for all scenarios *s* and *s'* (*s* differs from *s'* and *s, s'* belong to *S*) with identical past up to time *t*, where:

- $x_{i,t}^{s}$ – a percentage of technology *i* in time *t* given scenario *s*,
- $r_{i,t}^{s}$ – uncertain return of technology *i* in period *t*, given scenario *s*,
- α – parameter indicating the relative importance of variance as compared to the expected value,
- $x_{i,max}$ – maximal share of technology *i* in the portfolio,
- q^{s} – probability that scenario *s* occurs among all possible scenarios *S*

Multi-period portfolio selection model
(Mulvey et al., 1997 and Maranas et al., 1997), **adapted**

Portfolio return $R_{p,T}$ is determined across all scenarios at the end of the planning horizon *T* and given as follows:

$$R_{p,T} = \sum_{s=1}^{S} q^s R_{p,T}^s$$

where $R_{p,T}^s$ defines the portfolio return for scenario *s* at the end of the planning horizon *T*:

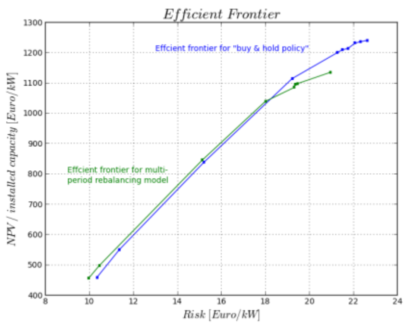
$$R_{p,T}^s = \left[\prod_{t=0}^{T} \sum_{i=1}^{N} r_{i,t}^s x_{i,t}^s\right]^{1/T}$$

Portfolio variance $Var(R_{p,T})$ denotes the variance across all scenarios at the end of the planning horizon *T*, and is specified as follows:

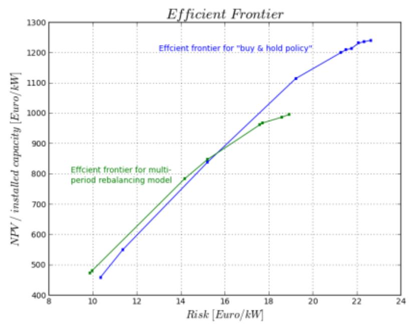
$$Var(R_{p,T}) = \sum_{s=1}^{S} q^s (R_{p,T}^s - R_{p,T})^2$$

2.3. Alternative portfolio approaches – examples

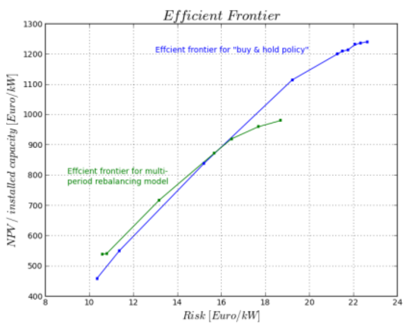
Multi-period portfolio selection model
(Mulvey et al., 1997 and Maranas et al., 1997), **adapted**



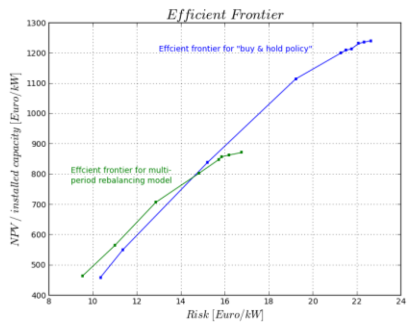
2-year' decision-making period



3-year' decision-making period



4-year' decision-making period



5-year' decision-making period

- The multi-period portfolio selection model allows **portfolio rebalancing** and to very well capture the impact of new investments on the portfolio mix – new investments can be **dynamically introduced** in adequate periods
- The **multi-period portfolio selection** model has a positive impact on the decision-making process and could **improve reachability of the desired goals** (e.g. return maximization, risk minimization)
- Better **consideration of uncertainty** (e.g. regarding changes in prices) through the short decision-making time horizon

Efficient frontier for multi-period portfolio selection model

Source: Glensk B., Madlener R. (2011). Dynamic Portfolio Selection Methods for Power Generation Assets, FCN Working Paper No.16/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Licensing

Case study "Selection of optimal power plant generation mix"

Chair of Energy Economics and Management
Institute for Future Energy Consumer Needs and Behavior
Prof. Dr. Reinhard Madlener, Dr. Barbara Glensk, Qinghan Yu M.Sc.
RWTH Aachen University April 2023

Participating universities:

Funded by:

Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen

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