Fuzzy Portfolio Optimization of Onshore Wind Power Plants

Reinhard Madlener[1,2] and Barbara Glensk[1]

[1] Institute for Future Energy Consumer Needs and Behavior (FCN),
School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University

[2] Department of Industrial Economics & Technology Management, NTNU, Trondheim, Norway

1st IAEE Online Conference
ENERGY, COVID, AND CLIMATE CHANGE
June 7-9, 2021

FCN | Future Energy Consumer Needs and Behavior | E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

Presentation outline

1. Motivation
2. Research questions
3. Methodology
4. Case study
5. Results
6. Conclusions

Source: Courtesy of W. Glensk

1. Motivation (1/2)

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

Application of portfolio theory to non-financial, real assets (selected references):

Bar-Lev and Katz (1976)	Analysis of fossil fuel mix in the US power generation
Wang and Zhu (2002)	* Application of fuzzy set theory for portfolio optimization
Awerbuch and Berger (2003)	First application of MVPA on liberalized EU power markets – deeper cost 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 estimation method for power plant portfolio analysis in Switzerland and the US
Madlener and Wenk (2008)	Portfolio optimization for peak- and offpeak power generation in Switzerland
Bazilian and Roques (2008)	Presentation of some works and studies of portfolio analysis for power generation assets
Fang et al. (2008)	* Application of fuzzy set theory for portfolio optimization
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 for power generation mix
Madlener et al. (2011)	* Application of fuzzy set theory for onshore wind power plants
Madlener (2012)	Review of Literature connected with portfolio analysis for power generation asset
Glensk and Madlener (2018)	* Application of fuzzy set theory for portfolio optimization

1. Motivation (2/2)

- Optimization plays an important role in supporting investors in the electricity sector with their investment strategies and helps **reducing the number of alternatives** to be considered
- The **optimal diversification** of different wind parks regarding their size (installed capacity) and positioning with respect to the weather conditions (expected output) is an important issue for energy planners
- **Asymmetrical risk measures**, such as **semi-variance** or **semi-mean absolute deviation**, reflect an investor's real losses and simplify 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 needs to be taken into account in the investment decision-making process

2. Research questions

1

- How can different onshore wind parks be combined to achieve an **efficient portfolio** (highest possible return on investment for a given risk level, or a desired expected return for a minimum risk)?

2

- How useful is the application of **fuzzy set theory** for wind farm portfolio selection (w/ semi-mean absolute deviation approaches)?

3

- What is the impact of **regulatory change** (renewables promotion scheme*) on the optimal portfolio structure?

** EEG 2009-2017 (FIT, MP)*

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

In our **adapted model** (cf. Glensk and Madlener, 2010; Madlener, Glensk and Weber, 2011, revised July 2014):

- we propose the **Net Present Value (NPV)** as an appropriate measure of return for the power plants analyzed (for modeling existing and/or new power plants)
- we introduce $X_{i,\max}$, the **maximal share for each technology** in the portfolio, in order to avoid technically infeasible solutions
- we apply the method of Zimmermann (1978) for the calculation of **sufficiency and necessity levels for risk and return** needed for specifying **mid-points**

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

$$\Lambda \rightarrow \max$$

s.t.:

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

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

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

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

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, x_i is a share of asset *i, E(R_i)* is a expected return of asset *i,* d_t refers to the deviation between the realization of the portfolio return and its expected value at time *t, and* R_{it} is a return of asset *i* in time *t*

E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

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

STEP 1

Determination of NPV for each wind park

- Monte Carlo simulation using their technical and economic data (Crystal Ball® software)

STEP 2

Specification of sufficiency and necessity levels for return and risk

- Using the Zimmermann (1978) method, implemented in the dynamic object-oriented programming language Python 2.7

STEP 3

Determination of efficient portfolios and frontiers for FSMAD model

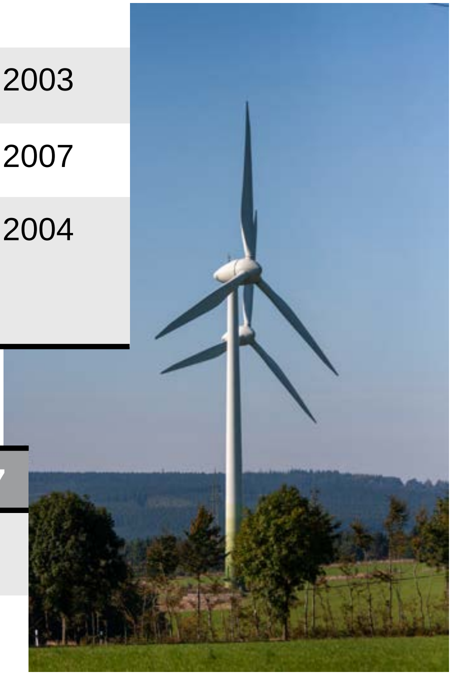
- Application of linear programming, again implemented in Python 2.7

E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

Investigation of 5 very different wind parks

Wind park (federal state)	Type of wind turbine	No. of wind turbines	Installed total capacity [MW]	Put into operation [a]
WP1 (Saarland)	GE1, 5sle, General Electric	3	4.5	2004
WP2 (North-Rhine Westphalia)	S77 (100 m nacelle height), Nordex	4	6	2007
WP3 (Lower Saxony)	AN Bonus, Siemens	4	5.2	2003
WP4 (Saxony-Anhalt)	V90, Vestas	10	20	2007
WP5 (Hessen)	5 x S77 (85 m nacelle height), Nordex and 2x NM 60, NEG Micon	7	9.5	2004

Source: ABO Wind Reference list (as of Nov 21, 2010)



Source: Courtesy of W. Glensk

EEG remuneration	EEG 2009	EEG 2012	EEG 2014	EEG 2017
Initial remuneration [€-ct/kWh]	9.20	8.93	8.90	8.38
Base remuneration [€-ct/kWh]	5.02	4.87	4.95	4.66

Source: EEG 2009, EEG 2012, EEG 2014, EEG 2017

Technical characteristics of the wind parks considered

Characteristic	AN Bonus [a]	GE 1.5 sle [b]	NM 60 [c]	S77 [d]	V90 [e]
Power					
Declared capacity [MW]	1.3	1.5	1	1.5	2
Nominal wind speed [m/s]	15	14	14	13	14
Switch-on wind speed [m/s]	3	3	3-4	3.5	4
Switch-off wind speed [m/s]	25	25	20	25	23
Rotor					
Diameter [m]	62	77	60	77	90
Swept rotor area [m^2]	3019	4657	2827	4657	6362
No. of blades	3	3	3	3	3
Rotation speed fixed / variable [rpm]	13	18.4	12	9.9-17.3	9-14.9
Material	GFK	GFK	GFK	GFK	GFK
Control- and safety system					
Power limitation	Active stall	Pitch	Stall	Pitch	Pitch
Tower					
Nacelle height [m]	68	85	80	85	105
Reference yield [f] [kWh]	13,731,599	20,534,273	12,315,870	19,797,726	30,697,642

4. Case study (3/3)

Economic characteristics of the wind parks considered

	WP1	WP2	WP3	WP4	WP5
Technical lifetime [a]	20	20	20	20	20
Remaining lifetime [a]	13	16	12	16	13
Total investment cost (130%) [€]	59,750,002	81,900,003	56,840,002	247,000,003	123,160,003
No. of turbines	3	4	4	10	7
Investment costs per turbine (100%) [€]	4,596,154	6,300,000	4,372,308	19,000,000	9,473,846
Operating cost share [%/a]	4.3	4.3	4.3	4.3	4.3
Initial remuneration[a] [€-ct/kWh]	8.7	8.19	8.9	8.19	8.7
Base remuneration[b] [€-ct/kWh]	4.36 / 4.12 / 4.57	4.23 / 3.94 / 4.35	4.41 / 4.19 / 4.64	4.32 / 4.06 / 4.49	4.36 / 4.12 / 4.57
Duration initial remuneration [a]	5	5	5	5	5
Prolonged duration initial remuneration[b] [a]	14 / 14 / 10	14 / 14 / 10	14 / 14 / 10	12 / 12 / 8	14 / 14 / 10
Total duration initial remuneration[b] [a]	19 / 19 / 15	19 / 19 / 15	19 / 19 / 15	17 / 17 / 3	19 / 19 / 15
Duration base remuneration[b] [a]	1 / 1 / 5	1 / 1 / 5	1 / 1 / 5	3 / 3 / 7	1 / 1 / 5
Max. energy production [kWh/a]	10,605,000	14,121,000	9,495,000	57,498,000	20,917,000
Safety markdown[c] [%]	12	11,6	8	6	7
Min. energy production [kWh/a]	9,332,400	12,482,964	8,735,400	54,048,120	19,452,810
Capacity factor Min / Max[a] [%]	24 / 27	24 / 27	19 / 21	31 / 33	23 / 25

Sources: [a]Own calculations, [b]Own calculations according EEG 2009 / 2012 / 2014 / 2017, [c]Wind expert's opinion of Anemos on behalf of the ABO Wind AG

FSMAD – Comparison of efficient frontiers obtained under the EEG 2009 – EEG 2017 regimes (feed-in tariff – FIT scheme only)

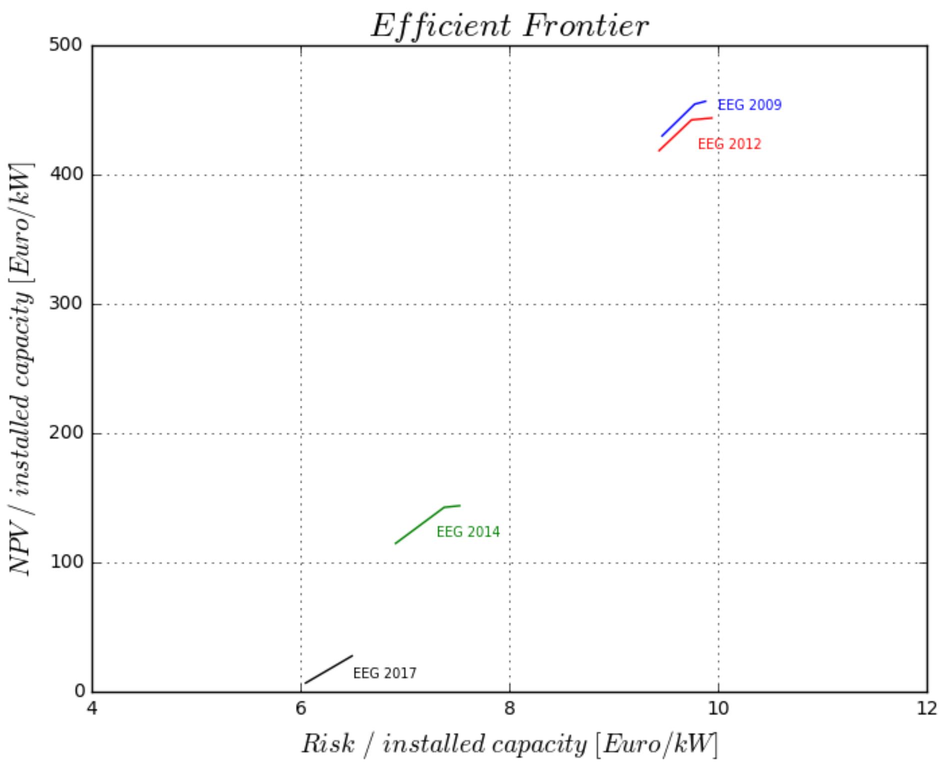


Figure 1: FSMAD efficient frontiers obtained for EEG 2009 – EEG 2017 (feed-in tariff scheme)

- Decrease in EEG remuneration causes decrease of efficient portfolio's returns and risks
- Minor difference in the efficient frontiers between EEG 2009 and EEG 2012 regime
- Major differences in the characteristics of efficient portfolios for EEG 2014 regime (in comparison to EEG 2009 and 2012) and, even more so, for EEG 2017 regime

FSMAD – Comparison of efficient frontiers obtained under the EEG 2009 – EEG 2017 regimes (FIT scheme vs. market premium model – MPM)

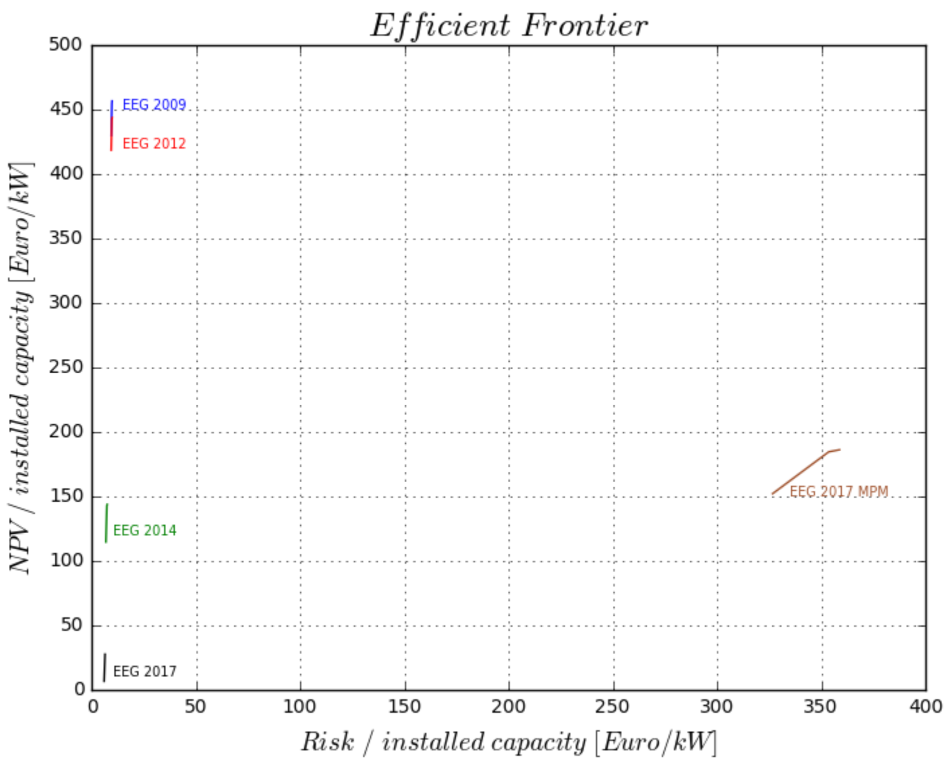


Figure 2: FSMAD efficient frontiers obtained for EEG 2009 – EEG 2017 (feed-in tariff scheme vs. market premium model – MPM)

- Significant changes when switching to market premium model; efficient portfolios are characterized by:
  - **higher risk** in comparison to all efficient portfolios obtained for the FIT scheme
  - **lower return** in comparison to efficient portfolios obtained for the FIT scheme in EEG 2009 and 2012
  - **higher return** in comparison to efficient portfolios obtained for the FIT scheme in EEG 2014 and 2017

FSMAD – Comparison of efficient frontiers obtained according to EEG 2017 (FIT scheme vs. market premium model – MPM)

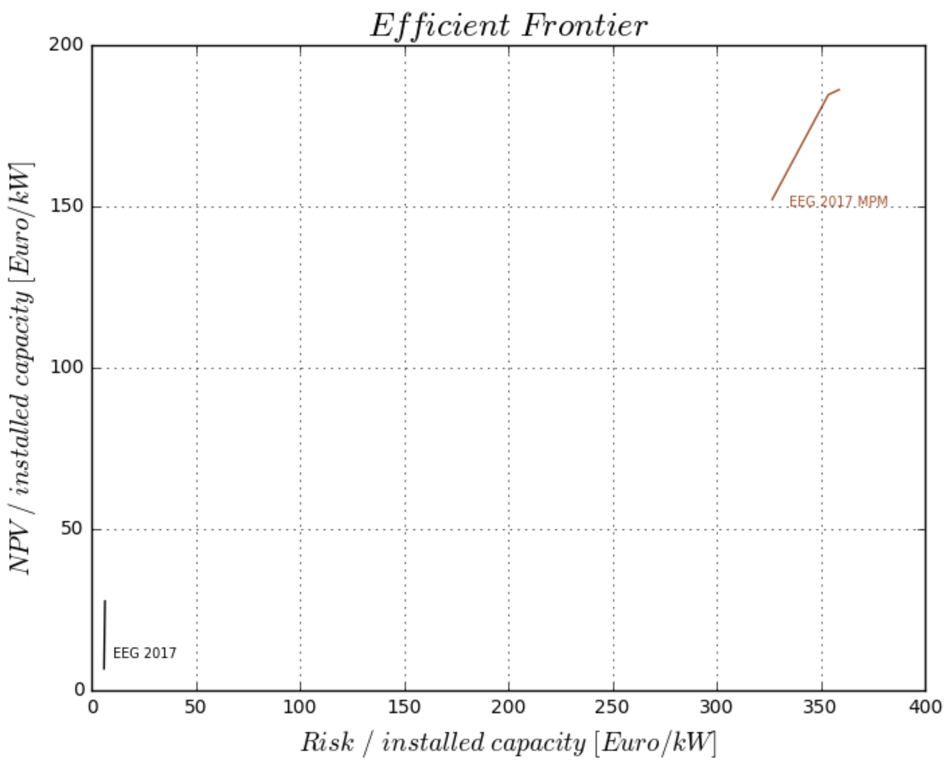


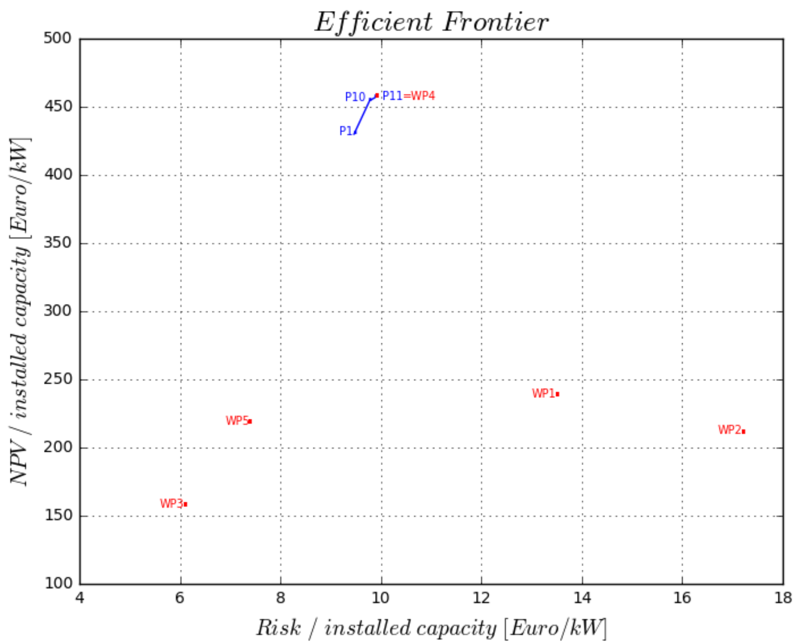
Figure 3: FSMAD efficient frontiers obtained for EEG 2017 (feed-in tariff scheme vs. market premium model – MPM)

Using market premium model:

- Efficient portfolios have **higher risk** in comparison to efficient portfolios obtained for the FIT scheme
- Efficient portfolios have **higher return** in comparison to efficient portfolios obtained for the FIT scheme

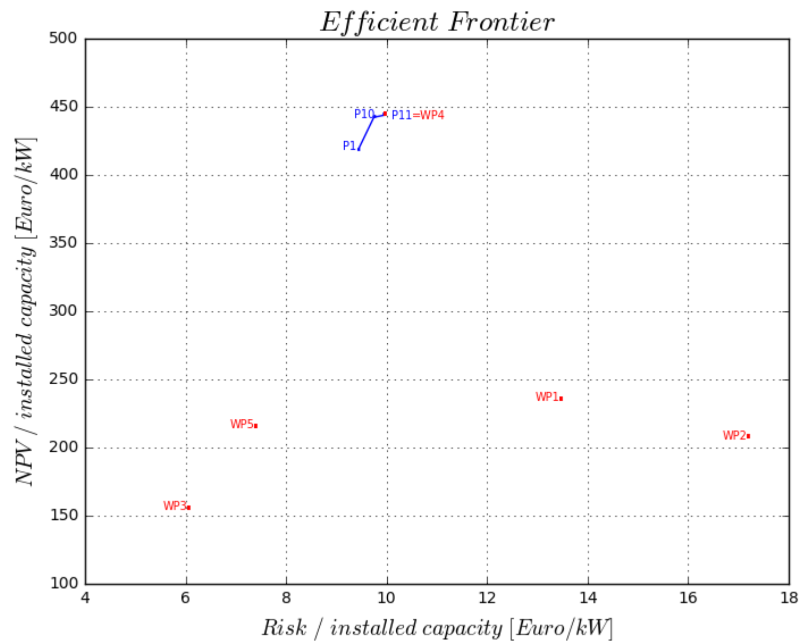
E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

FSMAD – Efficient frontier for EEG 2009 and 2012 regimes, FIT scheme (with individual wind parks)



	Portfolio structure [%]					NPV [€/kW]	Risk [€/kW]
	WP1	WP2	WP3	WP4	WP5		
P1	0.0	0.0	8.9	91.1	0.0	429.9	9.47
P10	0.0	0.0	0.7	99.3	0.0	454.5	9.78
P11	0.0	0.0	0.0	100.0	0.0	456.7	9.88

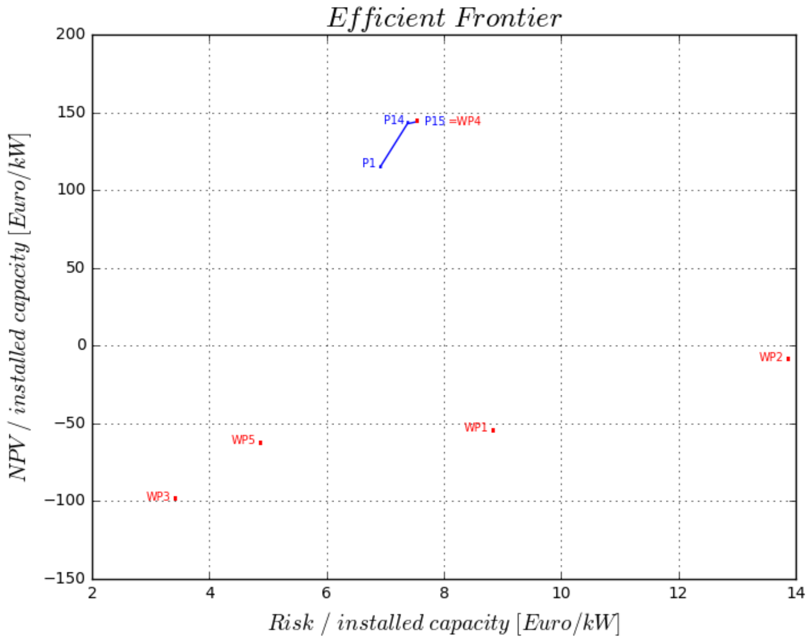
Figure 4: FSMAD efficient frontier and wind parks obtained under EEG 2009 regime (feed-in tariff scheme)



	Portfolio structure [%]					NPV [€kW]	Risk [€/kW]
	WP1	WP2	WP3	WP4	WP5		
P1	0.0	0.0	8.7	91.3	0.0	418.5	9.44
P10	0.0	0.0	0.5	99.5	0.0	442.3	9.75
P11	0.0	0.0	0.0	100.0	0.0	443.8	9.94

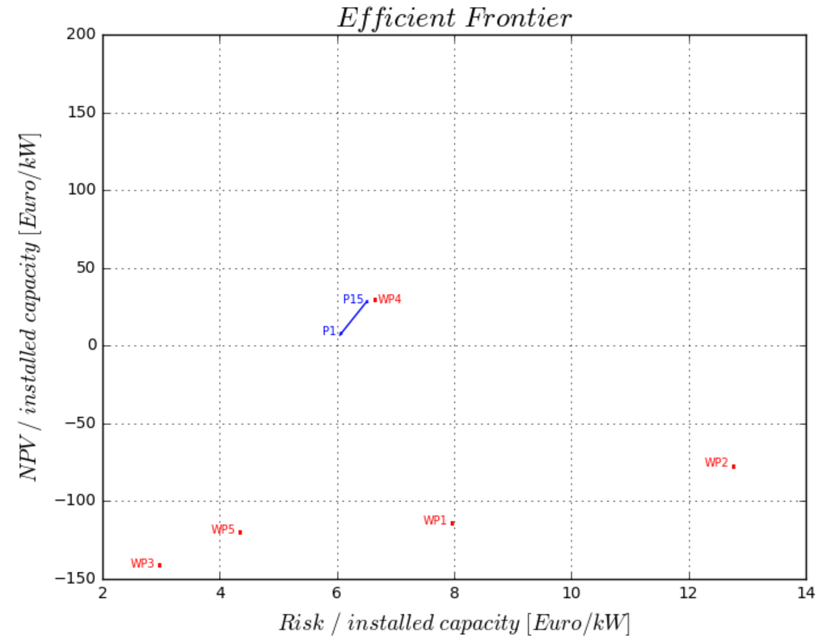
Figure 5: FSMAD efficient frontier and wind parks obtained under EEG 2012 regime (feed-in tariff scheme)

FSMAD – Efficient frontier for EEG 2014 and 2017 regimes, FIT scheme (with individual wind parks)



	Portfolio structure [%]					NPV [€/kW]	Risk [€/kW]
	WP1	WP2	WP3	WP4	WP5		
P1	0.0	0.0	11.9	88.1	0.0	114.7	6.91
P14	0.0	0.0	0.5	99.5	0.0	142.6	7.38
P15	0.0	0.0	0.0	100.0	0.0	143.8	7.53

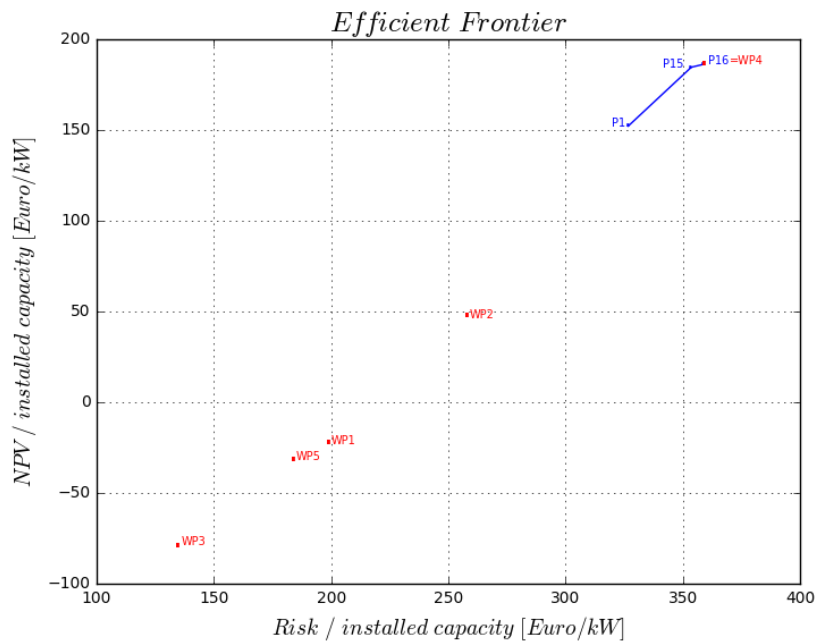
Figure 6: FSMAD efficient frontier and wind parks obtained under EEG 2014 regime (feed-in tariff scheme)



	Portfolio structure [%]					NPV [€/kW]	Risk [€/kW]
	WP1	WP2	WP3	WP4	WP5		
P1	0.0	0.0	12.4	87.6	0.0	6.7	6.05
P15	0.0	0.0	0.1	99.9	0.0	27.7	6.50

Figure 7: FSMAD efficient frontier and wind parks obtained under EEG 2017 regime (feed-in tariff scheme)

FSMAD – Efficient frontier for EEG 2017 regime, market premium model (with individual wind parks)



	Portfolio structure [in %]					NPV [in €/installed capacity]	Risk [in €/installed capacity]
	WP1	WP2	WP3	WP4	WP5		
P1	0.0	0.0	12.8	87.2	0.0	152.1	326.70
P14	0.0	0.0	0.6	99.4	0.0	184.6	353.66
P15	0.0	0.0	0.0	100.0	0.0	186.2	358.82

Figure 8: FSMAD efficient frontier and wind parks obtained under EEG 2017 regime (market premium model)

5. Results (7/7)

- Using **alternative risk measures**, such as the **semi-mean absolute deviation** (SMAD), simplifies the calculation procedure (linear vs. quadratic model definition) and better reflects investor's real losses
- **Semi-mean absolute deviation**, in combination with **fuzzy portfolio selection models**, allows to develop a new perspective on power generation selection problems (better integration of investors' aspirations with regard to return and risk)
- **Changes in the amount of support schemes** (FIT) have a negative impact on the investor's possible return, **changes in the type of support schemes** show the new way of possible returns
- **Well-diversified portfolios** could be obtained using the **classic mean-variance** approach as well as alternative portfolio selection methods, such as the **fuzzy semi-mean absolute deviation model,** but the set of possible efficient portfolios is smaller compared to the classic mean-variance approach (see Glensk and Madlener, 2010, for more information)

6. Conclusions

1

- How should different onshore wind parks be combined to achieve an **efficient portfolio** (highest possible return on investment for a given risk level, or a desired expected return at a minimum risk level)?
  - Using portfolio optimization in combination with fuzzy set theory the efficient portfolios of onshore wind parks can be determined
  - The efficient portfolios obtained consist at maximum of only two wind parks, irrespective of the EEG regime in place
  - The efficient portfolios with the highest return always consist of wind park 4 (WP4), which is the biggest one and one of two installed in 2007 (youngest)

6. Conclusions

2

- How useful is the application of **fuzzy theory** for portfolio selection?
  - The application of fuzzy set theory in FSMAD is a promising approach where investor's risk and return expectations can be incorporated into the model, positively affecting the decision-maker's problem (smaller set of decision alternatives)

3

- What is the impact of **regulatory change** on the optimal portfolio structure?
  - The changes in the regulated promotion schemes have a significant impact on the portfolio characteristics, but less so on the portfolio structure
  - Regulatory change, especially to EEG 2017, brings new opportunities for business decisions regarding the form of participation in the energy market

Contact

Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center
Mathieustraße 10
52074 Aachen
Germany

Reinhard Madlener, Barbara Glensk
T +49 241 80 49820, -834
F +49 241 80 49829
RMadlener@eonerc.rwth-aachen.de
http://www.eonerc.rwth-aachen.de/FCN

FCN | Future Energy Consumer Needs and Behavior

E.ON Energy Research Center

RWTH AACHEN UNIVERSITY

Selected references

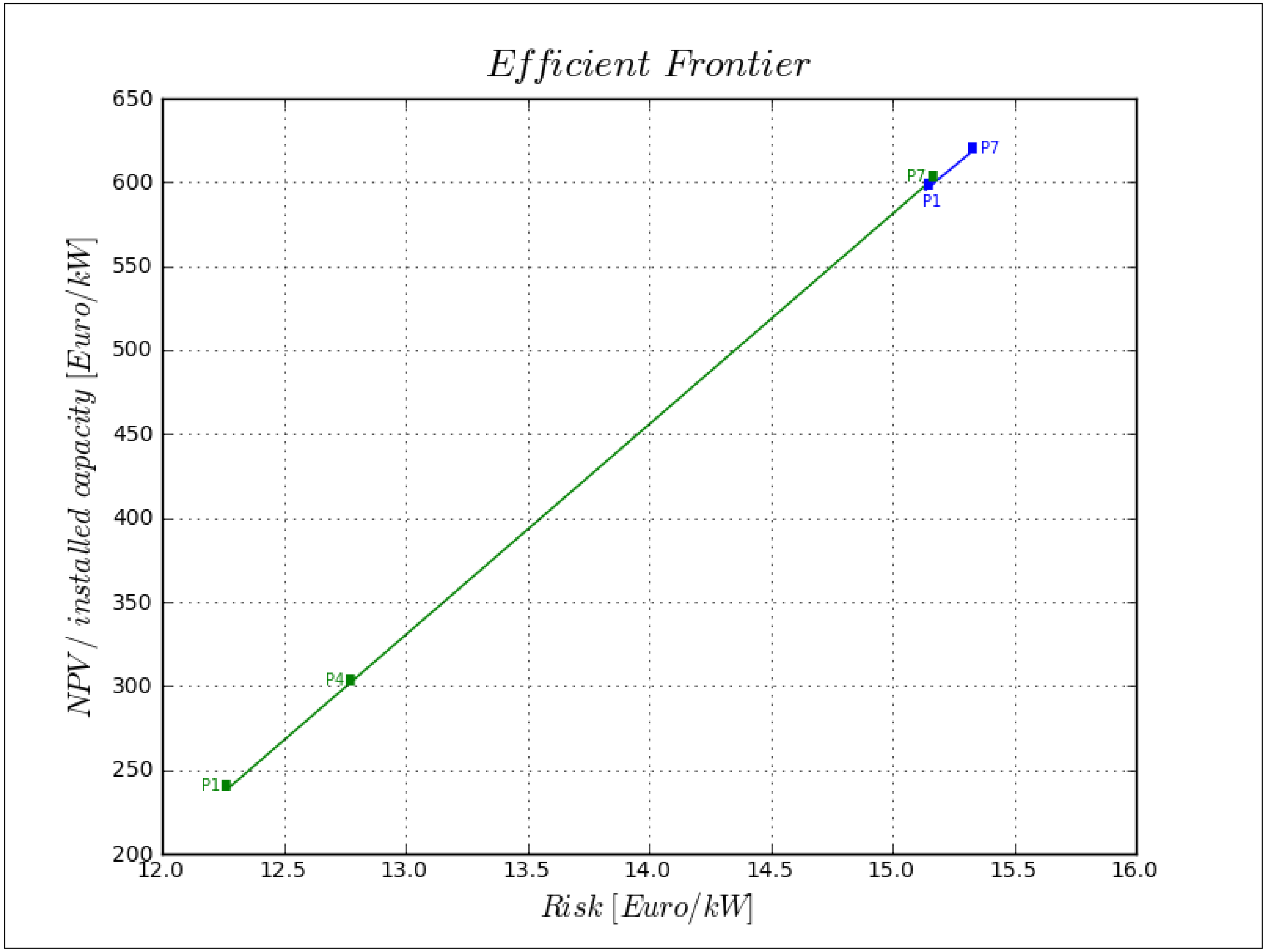
Portfolio theory for power generation assets:

1. 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. Awerbuch S., Berger M. (2003). *Applying portfolio theory to EU electricity planning and policy-making*, IEA/EET Working Paper EET/2003/03.
3. Roques F.A., Newbery D.M., Nuttall W.J. (2007). Fuel mix diversification in liberalized electricity markets: A mean-variance portfolio theory approach, *Energy Economics*, 30(4),1831-1849.
4. Bazilian M., Roques F. (2008). *Analytical Methods for Energy Diversity & Security: A tribute to Shimon Awerbuch*. Elsevier Ltd.
5. Krey B., Zweifel P. (2008). *Five Essays in Energy Economics: Efficient and Secure Power for the United States and Switzerland*, Bassersdorf.
6. Madlener R., Glensk B., Raymond P. (2009). *Investigation of E.ON's Power Generation Assets by Using Mean-Variance Portfolio Analysis*, FCN Working Paper No. 12/2009, November.
7. Madlener R. (2012). Portfolio Optimization of Power Generation Assets, in: Q. P. Zheng, S. Rebennack, P. M. Pardalos, M. V. F. Pereira and N. A. Iliadis, Handbook of CO_2 in Power Systems: Springer-Verlag, Berlin/Heidelberg/New York, pp.275-296.

Fuzzy set theory for portfolio optimization (incl. power generation assets):

1. Watada J. (1997). Fuzzy Portfolio Selection and its Applications to Decision Making, *Tatra Mountains, Mathematical Publications*, 13, 219-248.
2. Tanaka H., Guo P. (1999). Portfolio selection based on upper and lower exponential possibility distribution. *European Journal of Operational Research* 114, 115-126.
3. Wang S., Zhu S. (2002). On Fuzzy Portfolio Selection Problem. *Fuzzy Optimization and Decision Making*, 1, 361–377.
4. Fang Y., Lai K., Wang S. (2008). *Fuzzy Portfolio Optimization: Theory and Methods*; Springer: Berlin/Heidelberg, Germany; New York, NY, USA.
5. Glensk B., Madlener R. (2010). *Fuzzy Portfolio Optimization for Power Generation Assets*, FCN Working Paper No. 10/2010, August.
6. Madlener R., Glensk B., Weber V. (2011). *Fuzzy Portfolio Optimization of Onshore Wind Power Plants*, FCN Working Paper No. 10/2011, May (revised July 2014, revision in prog.).
7. Glensk B., Madlener R. (2014). On the Use of Fuzzy Set Theory for Optimizing Portfolios, in: M. Lübbecke, A. Weiler, B. Werners (eds.), Zukunftsperspektiven des Operations Research – Erfolgreicher Einsatz und Potenziale, Springer Gabler, pp. 263-274 (ISBN: 978-3-658-05706-0).
8. Glensk B., Madlener R. (2018). Fuzzy Portfolio Optimization of Power Generation Assets, *Energies*, 11, 3043.

Comparison of efficient frontiers FSMAD and SMAD model



Comparison of efficient frontiers FSMAD and SMAD model

Table 8: Results FSMAD model

Portfolio	WP1	WP2	WP3	WP4	WP5	NPV [€/kW]	Risk [€/kW]
P1	0.00%	0.00%	5.66%	94.34%	0.00%	595.35	15.14
P2	0.00%	0.00%	4.71%	95.29%	0.00%	598.92	15.17
P3	0.00%	0.00%	3.77%	96.23%	0.00%	602.49	15.19
P4	0.00%	0.00%	2.83%	97.17%	0.00%	606.06	15.22
P5	0.00%	0.00%	1.88%	98.12%	0.00%	609.63	15.25
P6	0.00%	0.00%	0.94%	99.06%	0.00%	613.20	15.28
P7	0.00%	0.00%	0.00%	100.00%	0.00%	616.76	15.31

Source: Own calculations, based on FCN software

Table 9: Results SMAD model

Portfolio	WP1	WP2	WP3	WP4	WP5	NPV [€/kW]	Risk [€/kW]
P1	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P2	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P3	0.00%	0.00%	100.00%	0.00%	0.00%	238.29	12.27
P4	0.00%	0.00%	83.70%	16.30%	0.00%	300.00	12.76
P5	0.00%	0.00%	57.27%	42.73%	0.00%	400.00	13.56
P6	0.00%	0.00%	30.85%	69.15%	0.00%	500.00	14.35
P7	0.00%	0.00%	4.43%	95.57%	0.00%	600.00	15.15

Source: Own calculations, based on FCN software