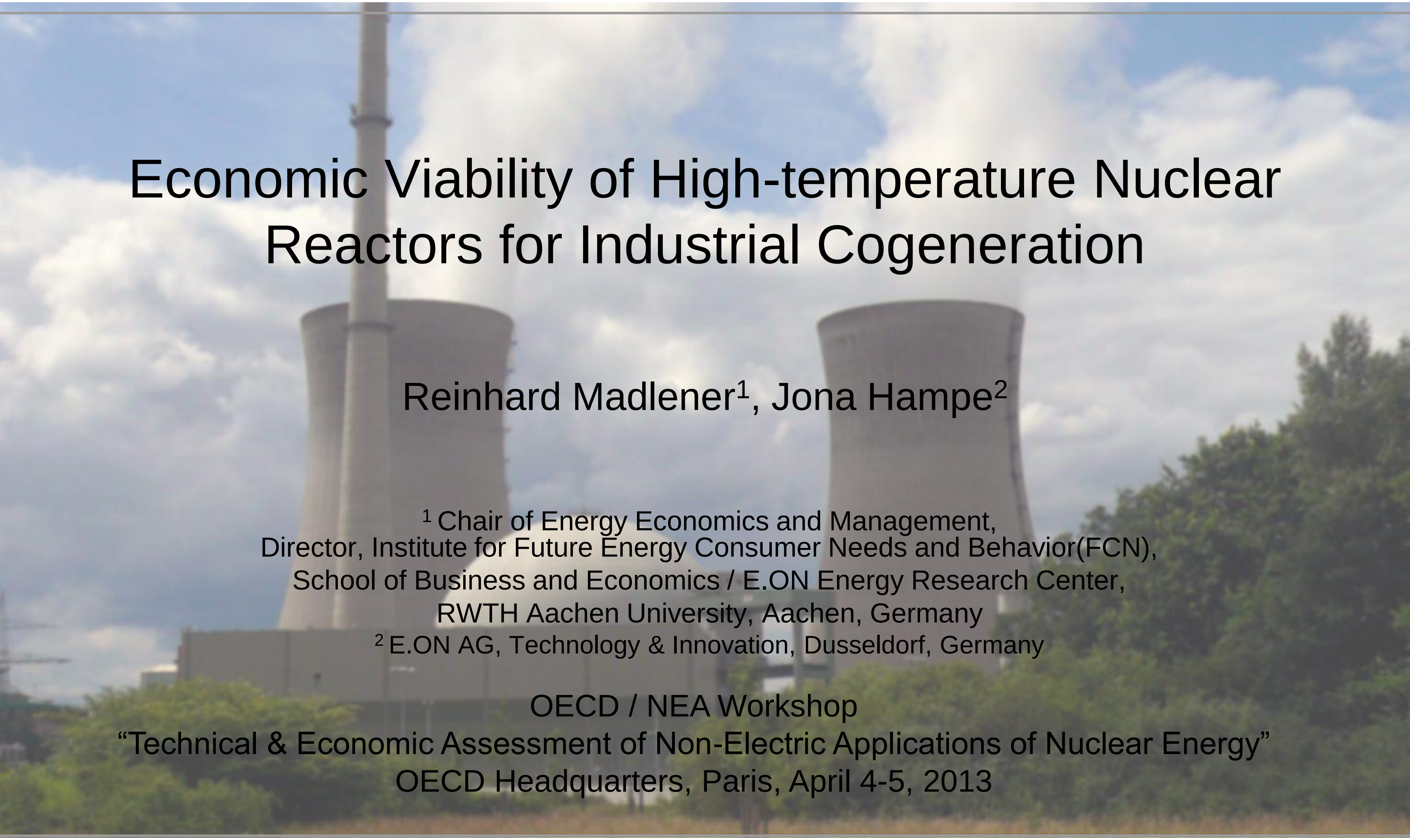

Economic Viability of High-temperature Nuclear Reactors for Industrial Cogeneration

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Outline

1. Introduction
2. Models Used
   - Business model (not reported here)
   - NPV, IRR
   - ROA (option to delay, option to switch)
3. Results
4. Discussion, Conclusion & Outlook

1. Introduction – Research Motivation

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- Since the establishment of the European Union's **Emission Trading System (EU-ETS)**, **energy-intensive industrial companies** in the EU face additional cost compared to their international competitors
- **Search for low-CO_2 technology options** for industrial energy supply
- To **reduce the cost of GHG emission** of heat and power production, the following **possibilities**, among others, have gained in prominence:
  - Combined heat-and-power production (CHP)
  - Nuclear power plants, e.g. high-temperature nuclear reactor (HTR)
- Our aim is to investigate the **business case** for HTR(-CHP) in Europe
- Our investigation looks at both and is based on both **real options analysis (ROA)** and standard **discounted cash flow (DCF) analysis**
  - To take into account the uncertain environment, the flexibility for the project, the **possibility to defer** the starting point of the investment and the **possibility to switch** between different operation modes

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1. Introduction – Related Literature (NPP+ROA)

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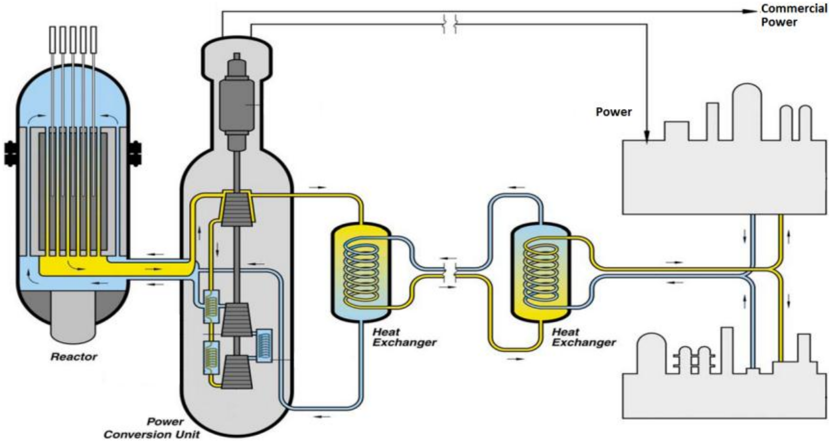
- **Pindyck (JFinEcon, 1993)** – NPP as example for investment of uncertain cost
- **Epaulard/Gallon (EconPrev, 2001)** – EPR, uncertain future natural gas prices
- **Kiriyama/Suzuki (JNucSciTec, 2004)** – Japan's policy when investing in NPP, uncertain future CO_2 prices
- **Gollier et al. (EnEcon, 2005)** – 1200 MW light-water reactor vs. four 300 MW modular reactors, uncertain future electricity prices
- **Rothwell (EnJ, 2006)** – Advanced Boiling Water Reactors in Texas
- **Roques et al. (EnJ, 2006)** – Overlooked option value of non-fossil fuel technologies in light of fuel and carbon price uncertainty
- **Siddiqui/Fleten (MRPA, 2008)** – Gov't policy for thorium nuclear technology
- **Zhang/Sun (NucEngDes, 2007)** – Chinese HTR gas-cooled reactor pebble-bed module project
- **Botterud et al. (EnPol, 2008)** – Nuclear hydrogen, product flex., market viability

- 2-fold contribution of present paper:
  - Application of ROA to HTR for industrial cogeneration
  - Model to calculate option to switch between two operating modes (in continuous time)

1. Introduction – HTR

- High-Temperature Reactors – **selected features** worth mentioning:
  - Current designs focus on small- to medium-scale reactors, modular concept
  - Able to deliver the high temperatures for industrial processes (700–750 °C)
  - High fuel efficiency, different fuel-cycle options
  - Lower investment costs due to passive safety features
  - Limitation of thermal output to ~ 600 MW_{th} (competitive handicap)
  - **Chinese 2-module HTR-PM project** underway, 250 MW_{th} pebble-bed modular reactor with steam generator, based on HTR-10 test design (Shidaowan plant, Shandong Province) el. power approx. 210 MW_{el} completion expected ~ 2013



  - **HTR reference case for analysis:** based on data provided by AREVA

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1. Introduction – History of HTR (Overview)

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	Dragon	Peach Bottom-1	AVR	FSV	THTR	HTTR	HTR-10
Location	UK	US	Germany	US	Germany	Japan	China
Start Construction	1959	1962	1959	1968	1971	1990	1994
Operation							
Start	1964	1966	1967	1974	1986	1998	2000 /2003
End	1977	1974	1988	1990	1989	NA	NA
Fuel							
Cycle	HEU / Th / LEU	HEU / Th	HEU / Th / LEU	HEU / Th	HEU / Th	LEU	LEU
Type	Carbide / Oxide buffered BISO / TRISO particles	Carbide BISO coated particles	Carbide / Oxide BISO / TRISO coated particles	Carbide TRISO particles	Oxide BISO / TRISO coated particles	Oxide TRISO coated particles	Oxide TRISO coated particles
Form	Hexagonal rods	Long cylinder	Pebble	Hexagonal block	Pebble	Hexagonal block	Pebble
Coolant outlet temp.(°C)	750	728	850 / 950	785	750	850 / 950	700 (900)
Power							
MWth	20	115	46	842	750	30	10
MWe	0	40	15	330	300	0	3
Energy Conversion System	none	Steam turbine	Steam turbine	Steam turbine	Steam turbine	none	Steam turbine
Live steam temp./pressure (°C/MPa)	NA	538/10	505/7.3	538/10	550/18.5	NA	440/4

Source: Viala et al. (2011)

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2. Models Used – ROA

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- Real Options Analysis (ROA)
  - Traditional capital budgeting methods do not take possible management response to price variations into account (especially relevant for HTR)
  - Net present value (NPV) and internal rate of return (IRR) methods disregard possible flexibilities that are embedded in starting or operating a project
- Two commonly stated flexibilities are:
  - Flexibility to **delay the** starting point of **investment**
  - Flexibility to **switch between** different **operation modes**

➢ ROA (Dixit and Pindyck, 1994) mitigates these shortcomings, based on the analogy between investment projects and financial options

Our RO models: implemented in MATLAB

2. Models Used – ROA

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- **Option to delay** the investment:
  - **Irreversible investment** under uncertainty, analogy to financial **call option:**
    → Right but not the obligation to buy an asset at some future point in time
  - **Option value** = opportunity cost that must be included as part of investment
  - 2 tasks:
    (1) Find the **threshold value** above which it is better to invest than to wait
    (2) Determine the **option value**
  - Standard assumption that prices follow **Geometric Brownian Motion (GBM)** (implies that %age changes in *P* are normally distributed, whereas absolute changes in *P* are log-normally distributed)
  - **Dynamic programming** approach; use of **time-continuous** price processes (also for switching cost ROA, in contrast to Kulatilaka and Trigeorgis, 1994)

3. Results – ROA (delay)

- **Option to delay investment:** Aim is to find threshold el. price P_e^* beyond which it is optimal to invest and the option value to invest, $F(P)$
- **Electricity price** treated as uncertain, heat price = opportunity cost of not using the heat for el. production

Table 3: Assumptions made for the option to delay investment calculations

Input variable	Symbol	Unit	Assumption
Electricity price 2012	P_{el}	[€/MWh]	52.60[1]
Growth rate P_{el}	α_{el}	[%]	3[2]
Standard deviation P_{el}	σ_{el}	[%]	0.143[2]
Discount rate	r	[%]	8.3
Process heat temperature	T	[°C]	200
Electricity price 2012	P_{el}	[€/MWh]	52.60[1]
Process heat price 2012	P_{th}	[€/MWh]	13.53
Electric efficiency	ϵ_{el}	[%]	23.0[2]
Thermal efficiency	ϵ_{th}	[%]	76.2[2]
Growth rate P_{el}	α_{el}	[%]	3[3]
Growth rate P_{th}	α_{th}	[%]	3
Standard deviation P_{el}	σ_{el}	[€/MWh]	10.0
Standard deviation P_{th}	σ_{th}	[€/MWh]	2.0
Correlation coefficient P_{el}, P_{th}	$\rho_{\mathrm{el,th}}$		0.2
Discount rate	r	[%]	8.3

Sources: [1] European Energy Exchange (EEX), futures price for 2012 (December 24, 2011), E.ON internal calculations based on AREVA's data, [3] Rohlfs and Madlener (2011)

- **Option to switch** operating mode:
  - Rebalancing the negotiating power in case of flexibility (CHP vs. el.-only)
  - Assumption that option to switch operating mode exists once per year
  - Estimation based on historic data / own estimates (future may be different)
  - If cost of altering the plant design is lower than the option value it is worth to exercise the option

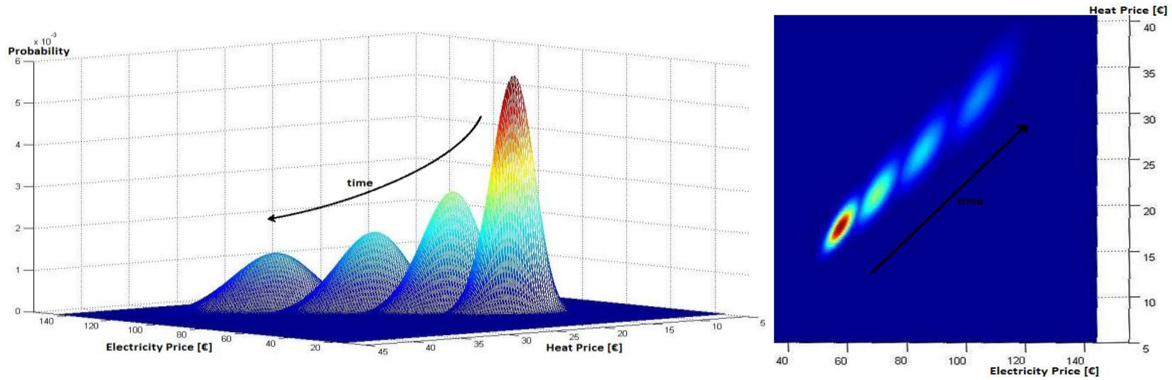

Fig. 3: Two-dimensional lognormal probability distribution for electricity and heat prices at different points in time

2. Models Used – ROA

- No switching costs:
  - **Goal:** Finding the optimal path of operation, depending on market conditions
  - Comparing expected output prices and associated cash flows in the following year (assumption: yearly adjustment of operating mode)
  - **Value of the flexible project** = value of inflexible project plus the sum of the options to switch in future periods (so-called "option additivity" holds)
- Switching costs:
  - More realistic assumption, but **computationally expensive** (compound interactions between switching options, may cause option additivity to break down)
  - **Hysteresis effect – decision over operation mode depends on current mode of operation, not only on expected future cash flows** (switching costs not only affect current cash payoffs and optimal operating decision in current period, but also alter exercise costs and thus switching decisions in the future)
  - Project value is determined in parallel to optimal mode of operation

3. Results – NPV

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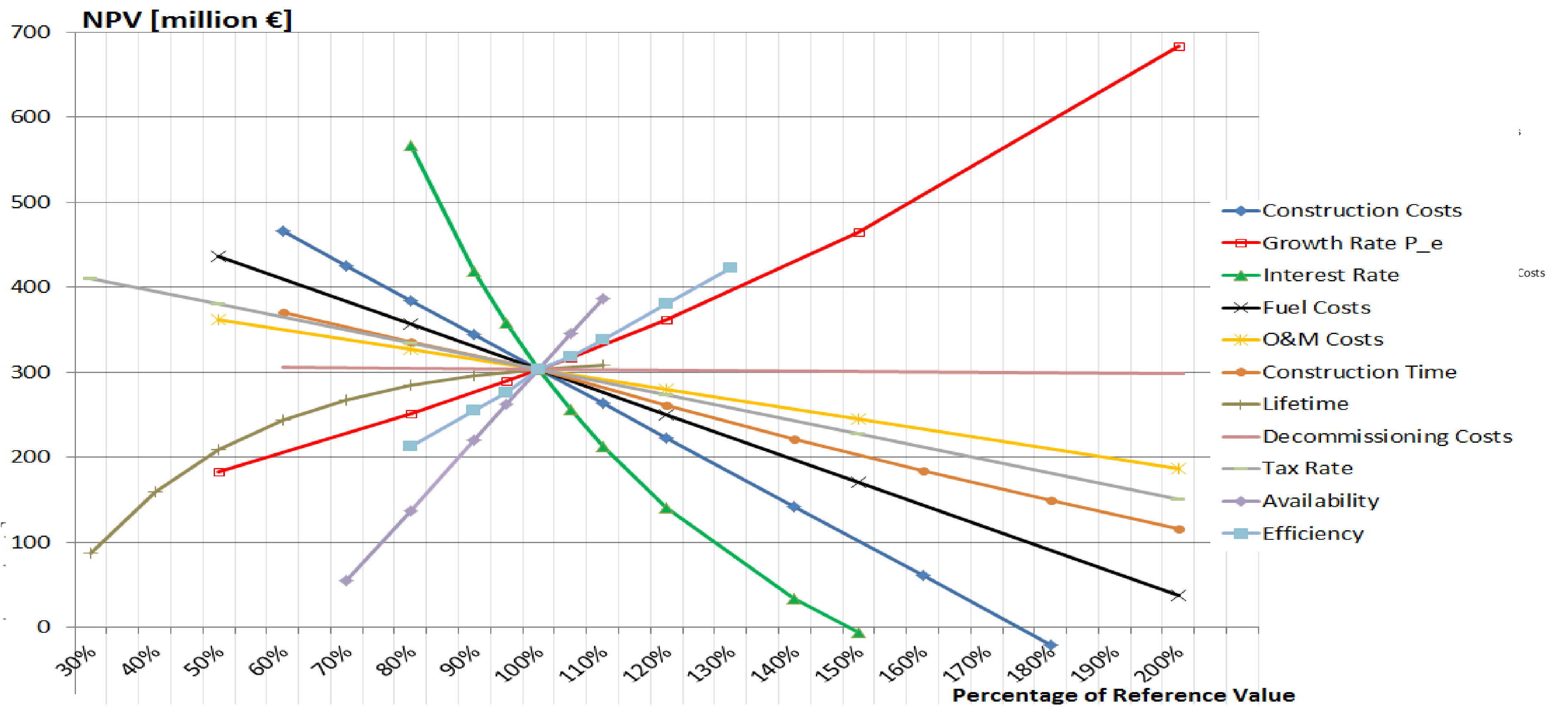

Fig. 4: NPV sensitivity to %age changes in the input variables

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3. Results – IRR

- Internal Rate of Return (IRR):
  - 12.3% (> WACC = 8.3%)
  - Project increases shareholder value (up to risk premium of 4%)
  - *Sensitivity analysis:* correlations are analogous to those found for the NPV calculations
    (but difference in concept: NPV … absolute project value, IRR … relative rate of return)

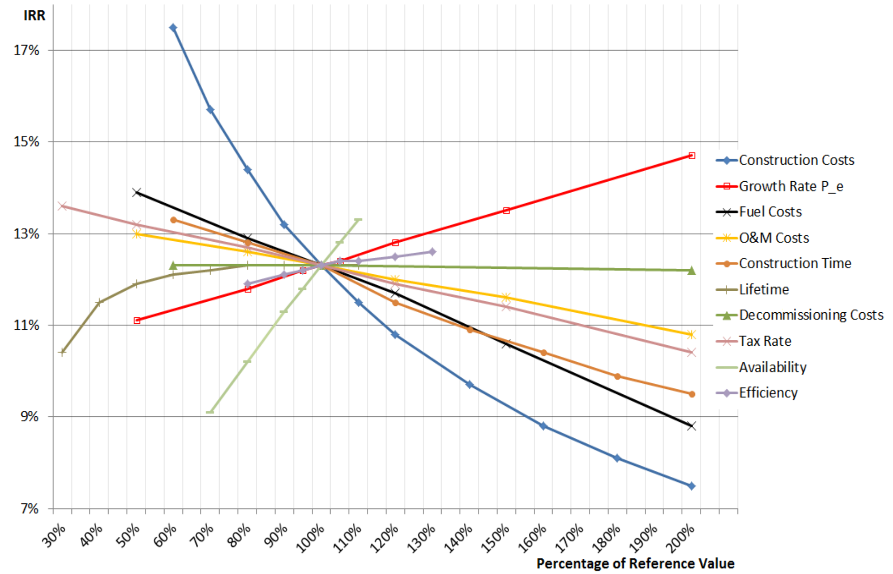

Fig. 5: IRR sensitivity to percentage changes in the input variables

<u>Main insights sensitivity analysis:</u>
- similar outcome compared to NPV sensitivity analysis

3. Results – ROA (option to delay)

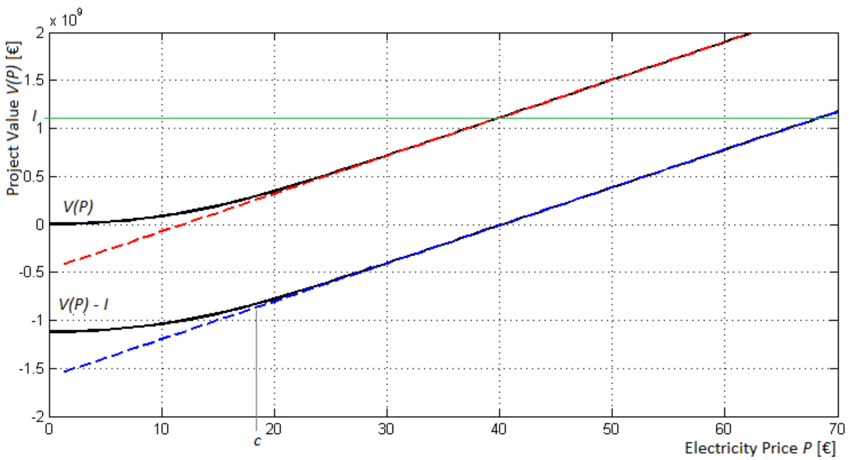

Fig. 6: Project value *V* (*P*) and *V* (*P*) minus investment cost *I*
(dashed line: project value of a non-flexible project)

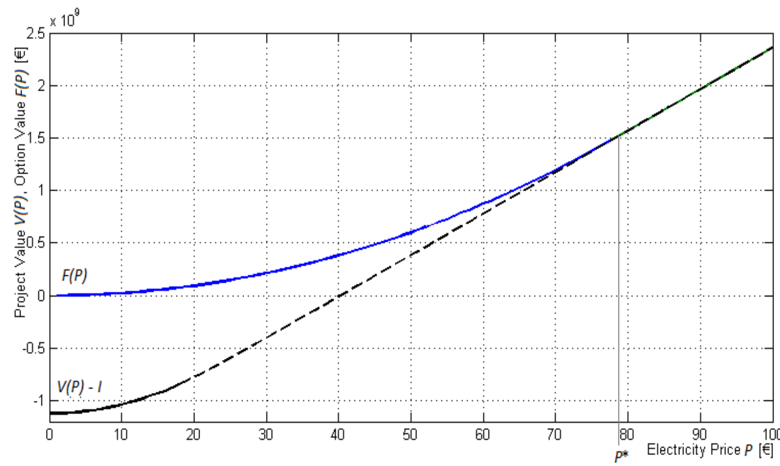

Fig. 7: Option value to invest, *F*(*P*), at electricity price threshold value *P**

3. Results – ROA (option to delay)

- Sensitivity analysis

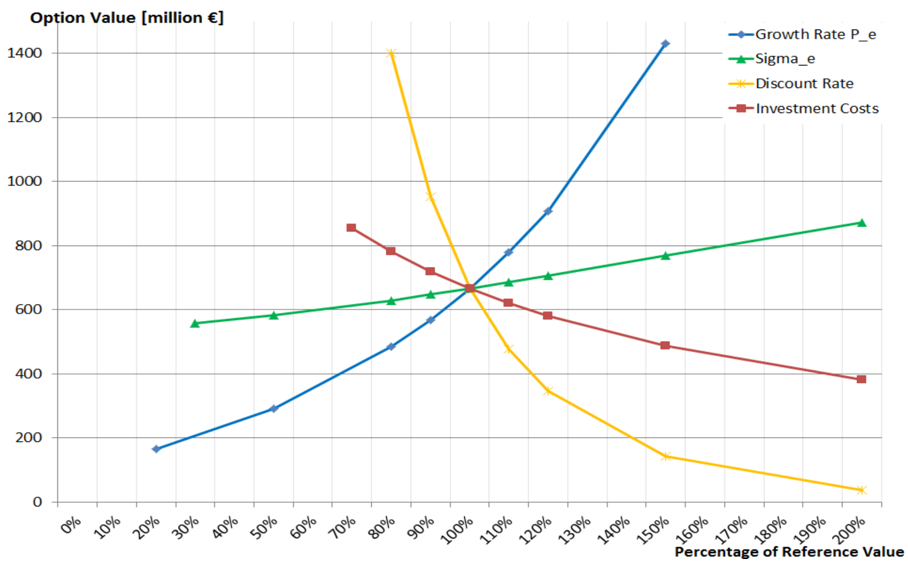

Fig. 8: Sensitivity of the option value to delay to changes in input variables

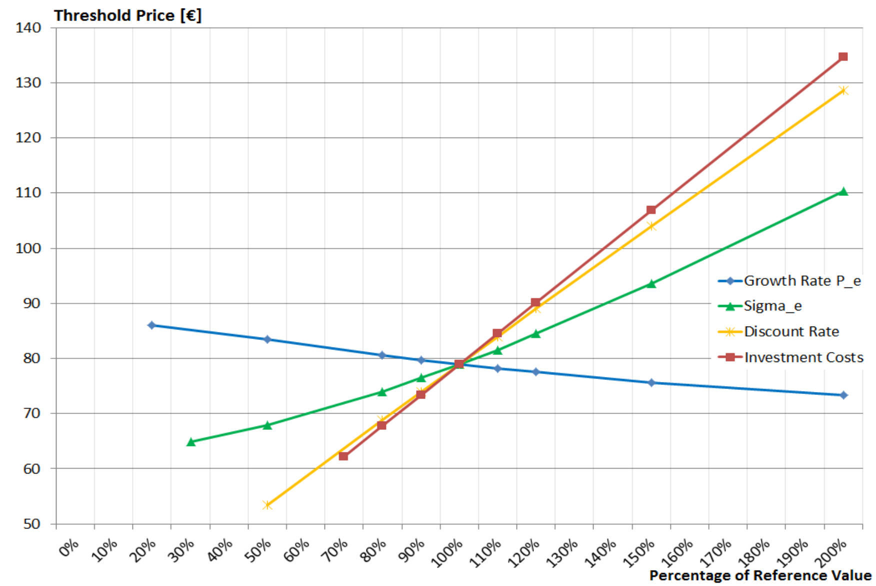

Fig. 9: Sensitivity of the threshold price to %age changes in the input variables

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- Sensitivity analysis:
  - Electricity price, heat price, price correlation
  - Also considered: price growth rates, discount rate, plant lifetime

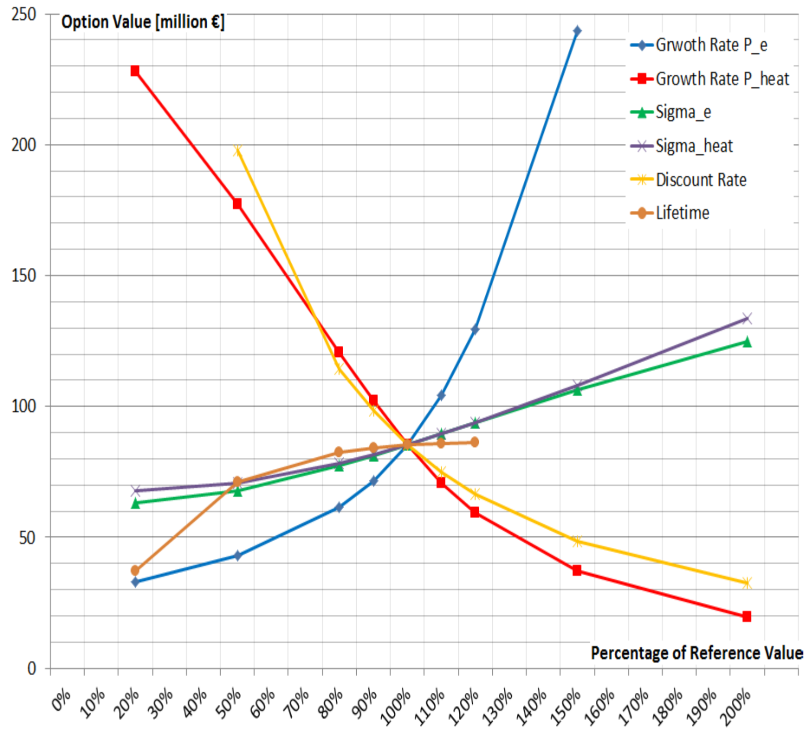

Fig. 10: Sensitivity of the option to switch to changes in the input variables

<u>Main insights sensitivity analysis:</u>

- Price correlation has a high impact on option value
  (increasing in correlation reduces prob. of large spreads, as prices move in the same direction)
- Pos. correlation between price volatilities and option value
  (increase in prob. of large spreads between revenues in op. modes)
- Increase in electricity (heat) price growth rate increases (decreases) option value
  (switching option enables hedging of risk of low heat price and to benefit from high el. price)
- Negative (positive) correlation found for discount rate (lifetime)

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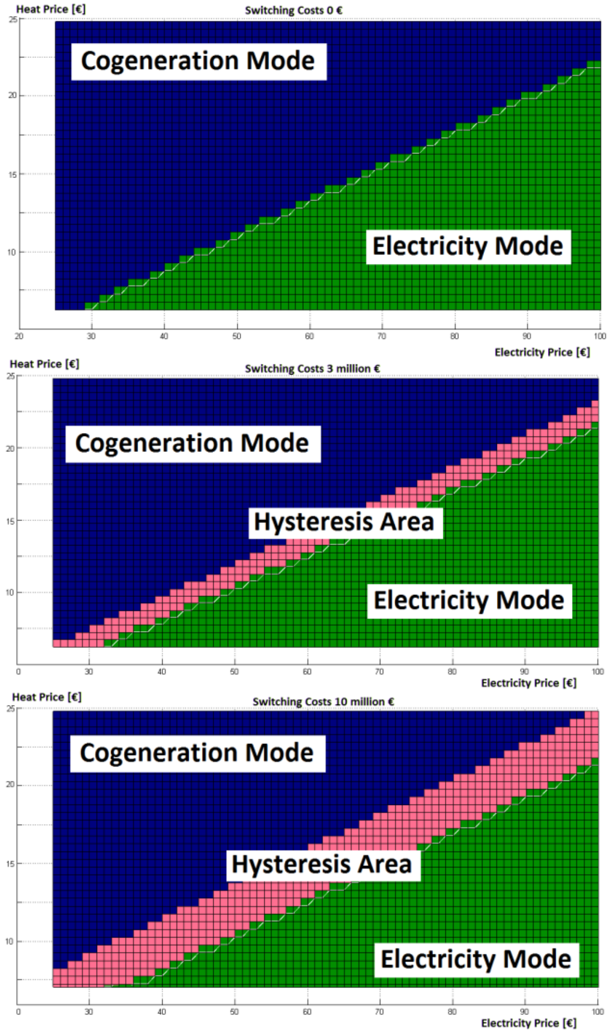
3. Results – ROA (option to switch)

- No switching costs
  - Choice between CHP mode or electricity-only mode (→ opportunity to benefit from rising electricity prices, <u>directly</u> by producing more electricity or <u>indirectly</u> by charging higher prices for the process heat)
  - Option value to switch turns out to be high for uncorrelated prices
- Switching costs
  - **Due to computational expedience, lifetime** of reference case HTR **is limited to 30 yrs**, or 50% (decreases the option value to about € 70 million)
  - Value of the option to switch decreases with higher switching costs (for switching costs < € 1 million these are very small, whereas the option value is almost zero for switching costs ≥ € 100 million)
  - Even in case of significant switching costs, the option to switch maintains a high value
  - Again, if altering the design is more expensive than the option value it is not worth changing the design!

3. Results – ROA (option to switch)



Switching costs: € 0

Switching costs: € 3 million

Switching costs: € 10 million

Fig. 11: Hysteresis areas of an option to switch for different switching costs

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3. Results – ROA (option to switch)

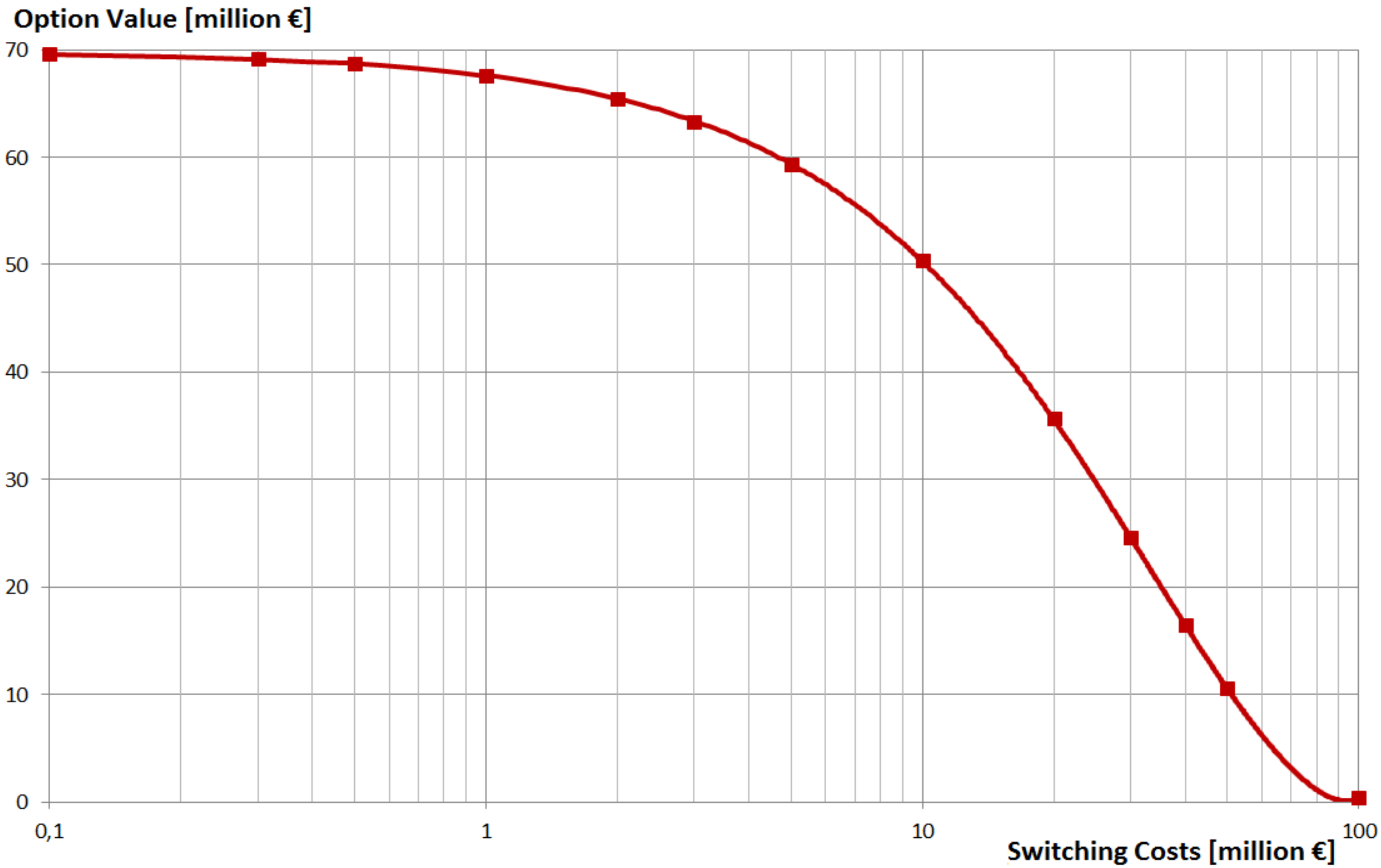

Fig. 12: Value of the option to switch for different switching costs (x-axis in logs).

4. Discussion, Conclusion & Outlook

- For a reference case HTR, we find it can provide cost-competitive process heat at 200 ºC
- Key market for HTR-CHP: chemical or pulp & paper industry, with demand of ~ 600 TWh/a (medium-temperature heat)
- (Business model developed shows that the value chain of utilities operating NPPs only requires small adaptations)
- Economic conclusions:
  - HTR is already economically viable (*NPV* = € 304 million, *IRR* = 12.3%), but data provided bear large uncertainties and NPV/IRR are sensitive to large changes of most input parameters
  - ROA: option value to invest € 667 million; profitable investment but, still, optimal to delay investment until threshold price (78.97 €/MWh) is reached
  - Option value to switch from CHP to power-only: € 85 million (invest if achievable at cost below the option value)

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4. Conclusion & Outlook

- Utilities should **try to hold an option** to invest in a HTR, e.g. by acquiring a detailed plant design, to **exercise the option in case technical uncertainties decrease** and the market environment turns out favorable
- In a highly uncertain investment environment, **ROA provides useful additional insights** for decision-making compared to standard DCF methods

- Ideas for **future research**:
  - More detailed ROA (including add’l parameters, e.g. heat price, construction)
    - Use of **ROA models for multiple stochastic parameter inputs** (e.g. McDonald and Siegel 1986; Hu and Øksendal 1998; Rohlfs and Madlener, 2011); need to be adapted to a HTR for industrial cogeneration
  - **Other modes of operation** should be considered as well
  - Analysis of an **option to switch for multiple stochastic load levels**, in light of the increasing market share of intermittent energy sources
  - Possible competition between HTR and renewable energy technologies

Questions or Comments?

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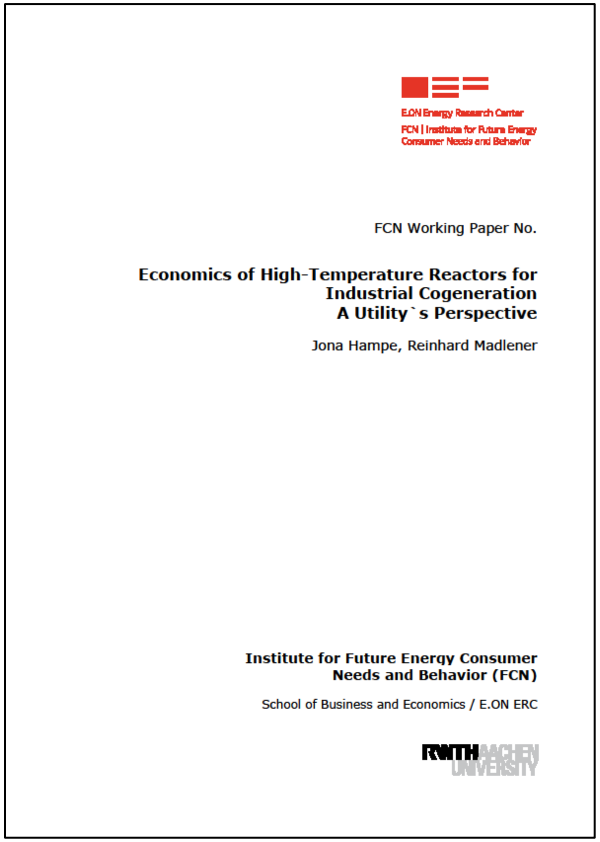
Reference:
FCN Working Paper No. 10/2012
(available on: SSRN, RePEc, and FCN Websites)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Economics of High-Temperature Reactors for Industrial Cogeneration A Utility`s Perspective

Jona Hampe, Reinhard Madlener

Institute for Future Energy Consumer Needs and Behavior (FCN)

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Back-up slides

Back-up slides

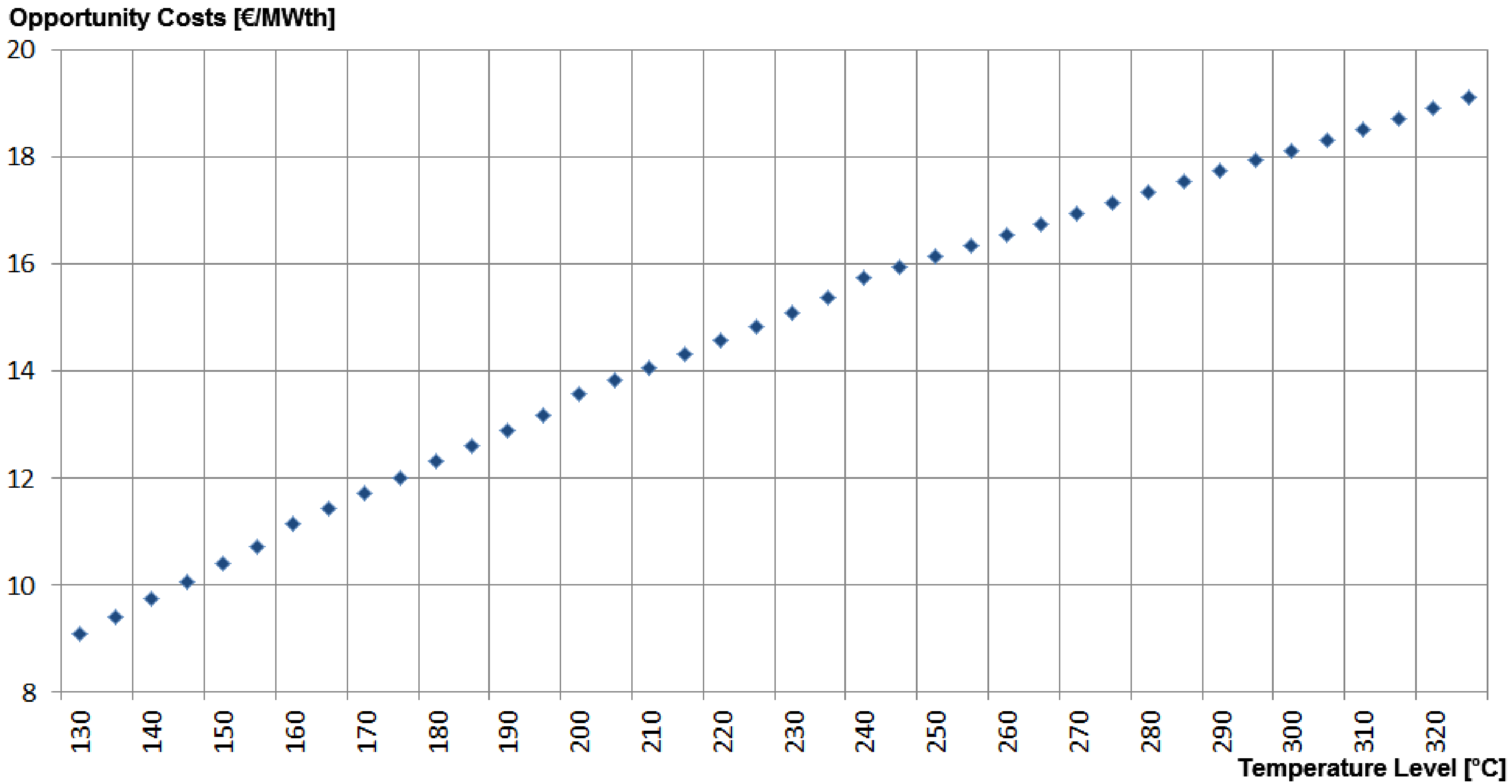

Fig. 2: Opportunity costs as a function of the temperature level

Source: E.ON internal calculation with the Ebsilon Professional software, based on AREVA data

HTR Process Diagram