4th AIEE Energy Symposium: Current and Future Challenges to Energy Security: The just transition

LOW-CARBON IRON AND STEEL PRODUCTION: A TECHNO-ECONOMIC METHOD TO EVALUATE TRANSITION PATHWAYS TO A RENEWABLE-BASED DIRECT REDUCTION PROCESS IN A BROWNFIELD PLANT

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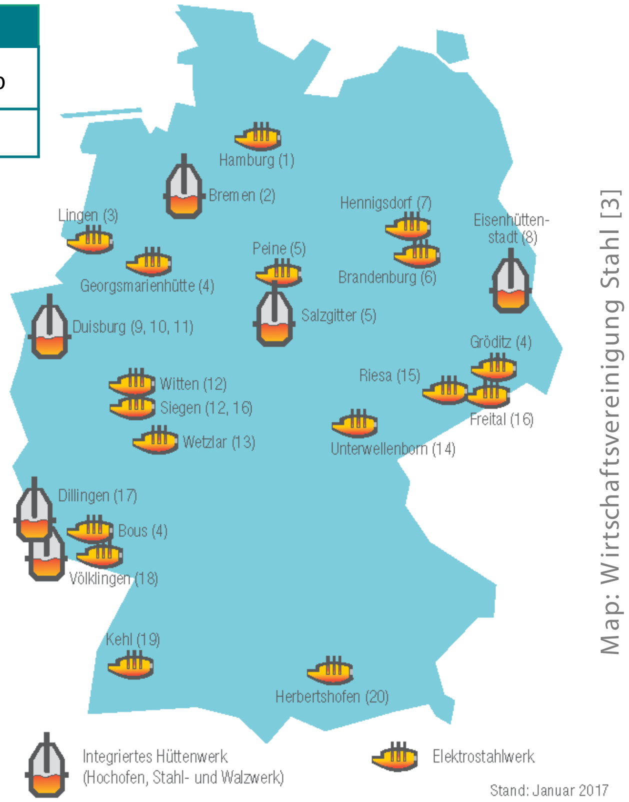
Background & aim

Iron and steel production: Towards a shift to a low-carbon industry

- **German energy and climate goals** [1]

	2020	2030	2050
Reduction of GHG emissions as compared to 1990 levels	Min. -40%	Min. -55%	Min. -80 to -95%
Share of renewable energy in final energy demand	18%	30%	60%

- **Germany iron and steel production**
  - Crude steel production in Germany (2014) about **43 Mio. t** [2]
  - Conventional steel making along blast furnace route depends on **coal**
  - Carbon dioxide emissions in Germany of about **60 Mio. t CO_2** [4]
  - Emission trading scheme: **Costs for ETS certificates**
- **Future development**
  - Emission reduction of conventional technologies **limited** [5]
  - Need to introduce **new technologies**



Map: Wirtschaftsvereinigung Stahl [3]

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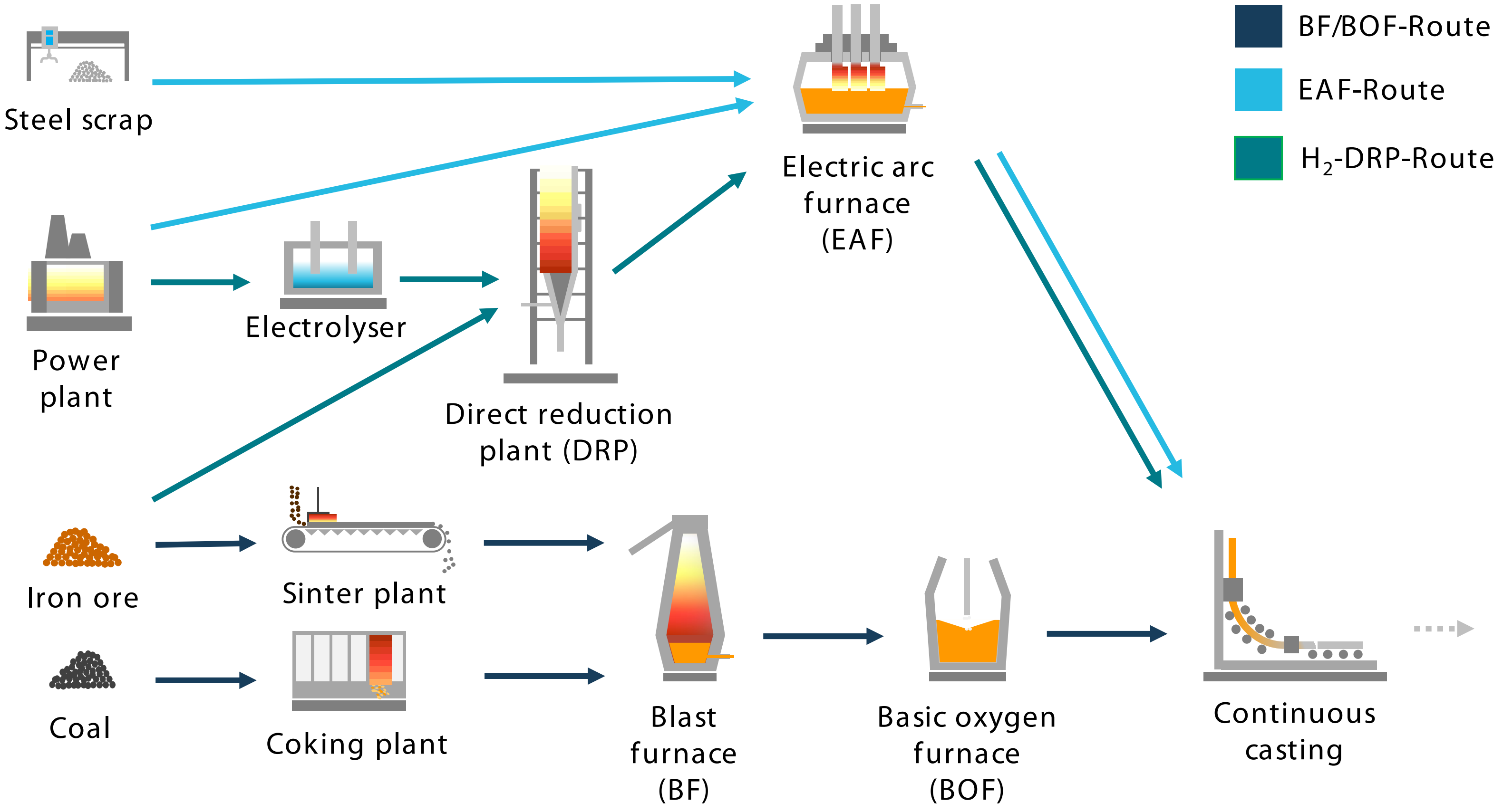
Potentials by shifting to direct reduction processes

- **Various options to reduce carbon dioxide emissions in steel making, including** [e.g. 9,10]
  - Conventional BF/BOF route with carbon capture & storage (**CCS**)
  - Conventional BF/BOR route with carbon utilization (**CCU**)
  - Use of **biomass**
  - Shift to **EAF** route
  - **Electrowinning**
  - **Hydrogen** direct reduction



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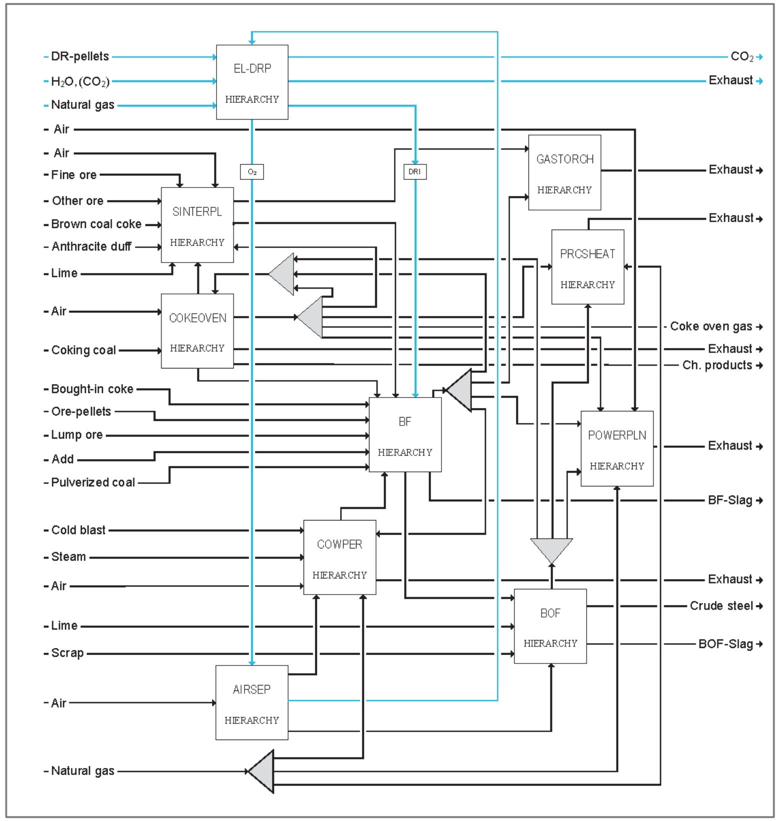
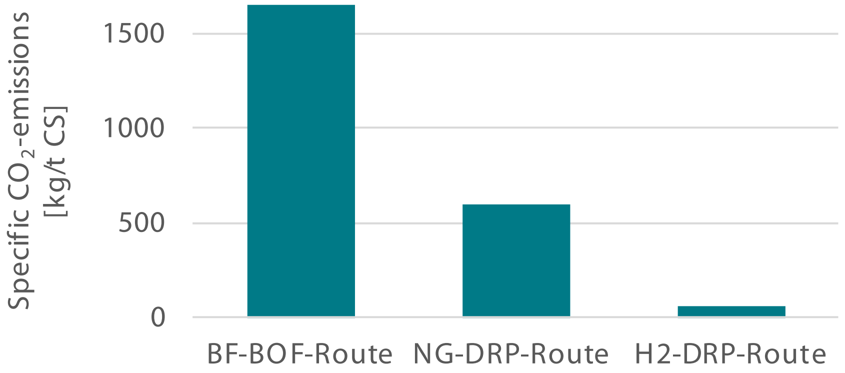
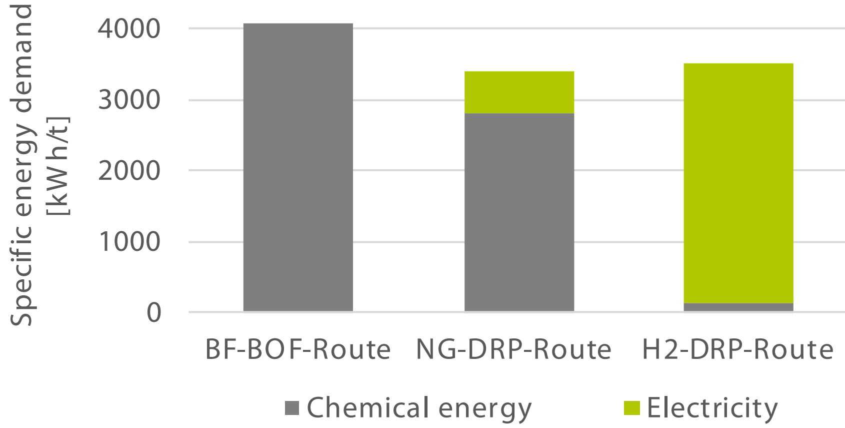
Potentials from direct reduction processes

- Technical simulations underline the **substantial potential** to substantially reduce GHG emissions using natural gas or renewable electricity [e.g. 11]
- Direct reduction with hydrogen **under investigation** by several steel makers







Assumptions: See [11]

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Aim and research question

- **Challenge: Transition in existing brownfield plants**
  - Limited investment requirements for running infrastructure required
  - Considerable up-front investments for new plants/technologies
  - Dependency on framework conditions

Aim: Investigate the economically optimal transition pathway to low-carbon steel making based on a direct reduction approach with hydrogen in a brownfield plant

- **Research questions:**
  - What does the transition pathway look like?
  - What is the resulting plant configuration in the year 2050?

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Methodology

General approach

- **Investigation of transition pathways & "optional" plant configuration**
  1. Disaggregation of a crude steel production plant into a set of individual **modules**
  2. Definition of combinations of particular modules as plant **configurations**
  3. Calculation of the **technical mass flows** for each module/configuration using the Aspen Plus model
  4. Defining an **economic parameterization** for each module
  5. Implementation and application of a **economic evaluation model**
- **Economic evaluation: Net present value calculation**

$$\text{Max NPV} = \underset{[\text{years}]}{\sum_{t=2020}^{2050}} \underset{[\text{modules}]}{\sum_{o=1}^{20}} \Bigg(\underset{[\text{investment}]}{i_{o,t}} + \underset{[\text{general overhaul}]}{g_{o,t}} + \underset{[\text{maintenance}]}{m_{o,t}} + \underset{[\text{personnel}]}{w_{o,t}} + \underset{[\text{dismantling}]}{d_{o,t}} + \underset{[\text{residual value}]}{r_{o,t}}$$

$$+ \underset{[\text{flows}]}{\sum_{f=1}^{30}} \Big(\underset{[\text{amount}]}{q_{f,o,t,out} - q_{f,o,t,in}} \Big) \cdot \underset{[\text{price}]}{p_{f,o,t}} \Bigg) \cdot \underset{[\text{discounting}]}{(1+i)^{(2020-t)}}$$

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Definition of case study plant configurations

Configuration

0: Baseline configuration

1: 1x NG-DR-Route

2: 1x H_2-DR-Route

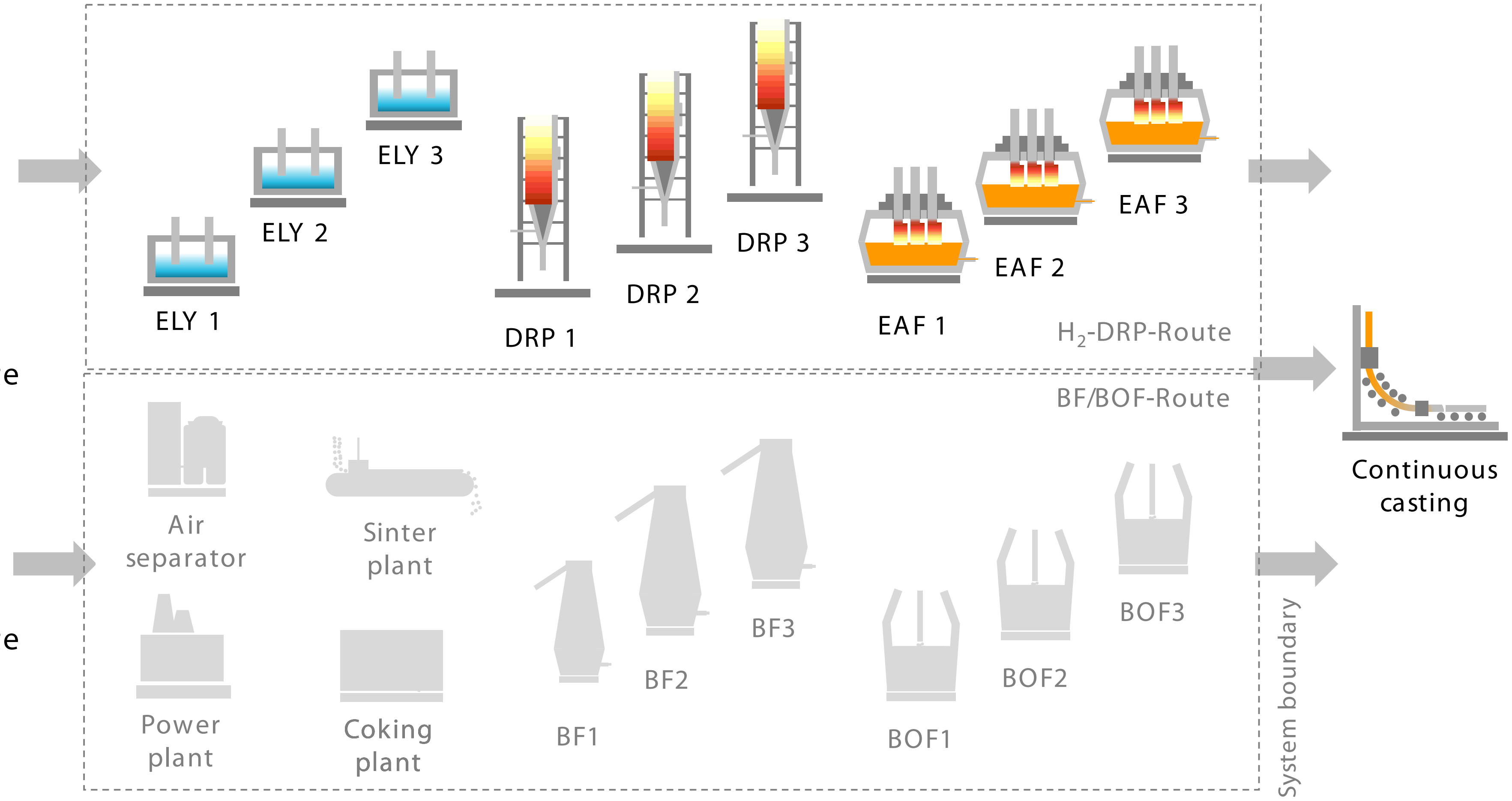
3: 1x H_2-DR- & 1x NG-DR-Route

4: 2x H_2-DR-Route

5: 2 x H_2-DR-Route, external

6: 2x H_2-DR- & 1x NG-DR-Route

7: 3x H_2-DR-Route



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Parameterization of the individual modules

- **Technical input**
  - Inbound and outbound quantities for 30 mass flows and 20 modules (relevant mass flows depend on module type)
- **Economic parameterization**
  - Year of installation/major overhaul [year]
  - Duration between two overhauls [years]
  - Cash flows for:
    - Investments [$Euro_{2020}$]
    - Personnel [$Euro_{2020}$/year]
    - Maintenance [$Euro_{2020}$/year]
    - General overhaul [$Euro_{2020}$]
    - Dismantling [$Euro_{2020}$]
    - Residual value [$Euro_{2020}$]
- **General economic parameters**
  - Base prices [$Euro_{2020}$]
  - Price development indices 2020 to 2050 [-]
  - Interest rate [%]

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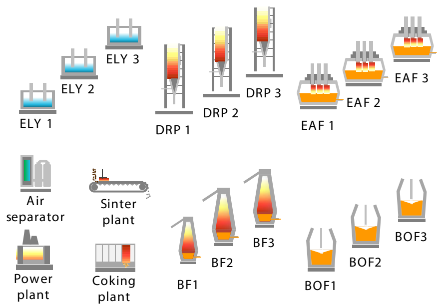
Determination of economically optimal path

Configuration 0 in 2020

Illustrative transition pathway

Configuration 6 in 2048

0 0 0 0 0 5 5 5 5 0 0 1 1 1 1 1 1 1 1 7 7 2 2 2 6 6 6 6 6 6 6



Implementation:
ca. 4000 paths/second

About 0,7 Mio. laptops calculating since Big Bang!

Source: NASA

No. of all paths (=complete permutation):
$1+ 8^{30}$ = 1,23794E+27 path

Limitation to „unchanged" or "ascending" configurations

~~0 0 0 0 0 5 5 5 5 0 0 1 1 1 1 1 1 1 1 7 7 2 2 2 6 6 6 6 6 6 6~~

0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 2 2 2 6 6 6 6 6 6 6

Age of the universe:
about 13,8 Bn. years
= 4,35197E+17 seconds

Simplification: about 10 Mio. paths on 1 laptop in about 40 minutes
Result termed "optimal" path

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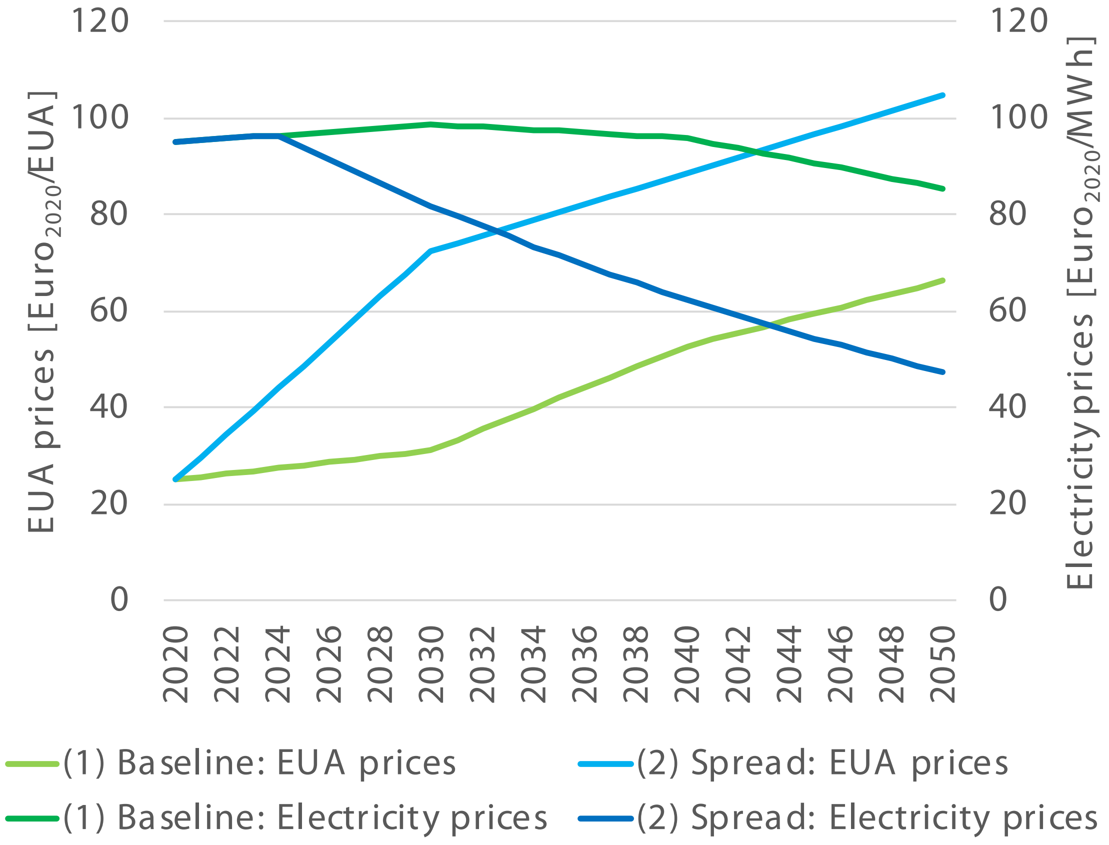
Case study

Sensitivity parameters

		Cash flows	
		All included	All excluding investments & overhaul
Electricity & emission allowances	Baseline	(1) Baseline - All	(3) Baseline - Operation
	Low electricity, high EUA	(2) Spread - All	(4) Spread - Operation



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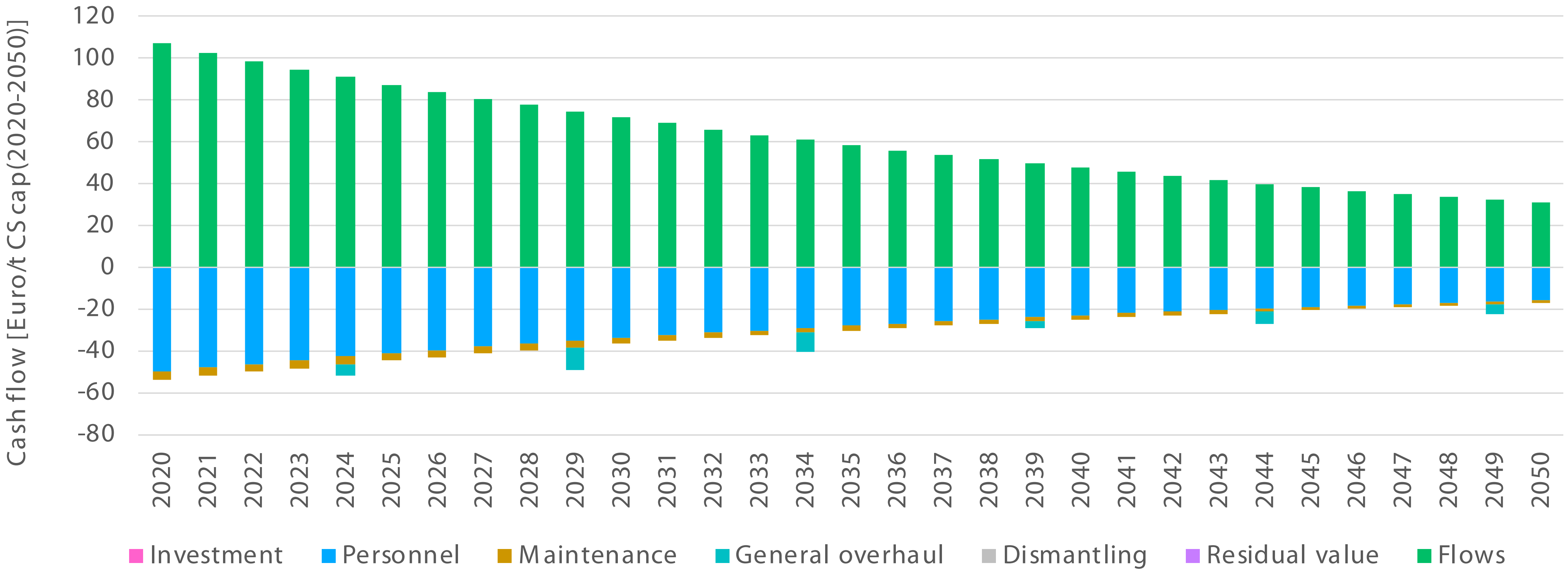
Case study "optimal" path:
(1) Baseline - All

2020-2050: Configuration 0

NPV [Euro/t CS cap$_{(2020-2050)}$]: 889 Euro



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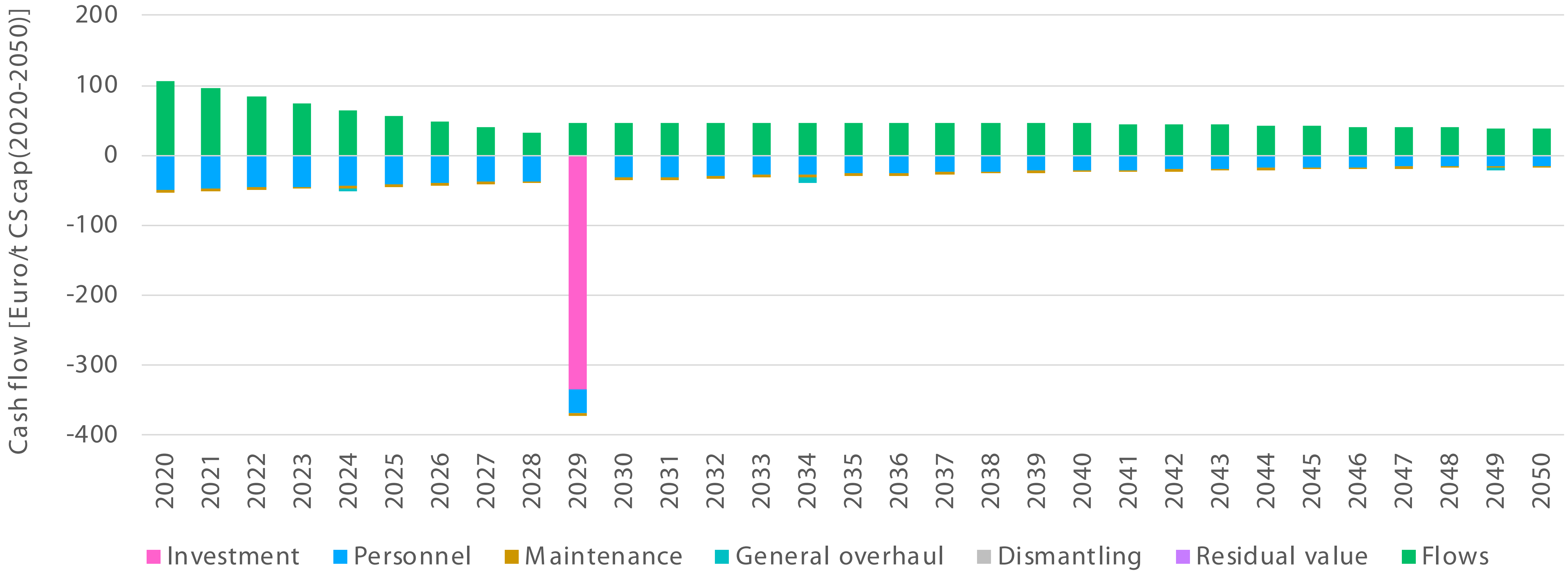
Case study "optimal" path:
(2) Spread - All

2020-2028: Configuration 0; 2029-2050: Configuration 5 NPV [Euro/t CS cap$_{(2020-2050)}$]: 238 Euro



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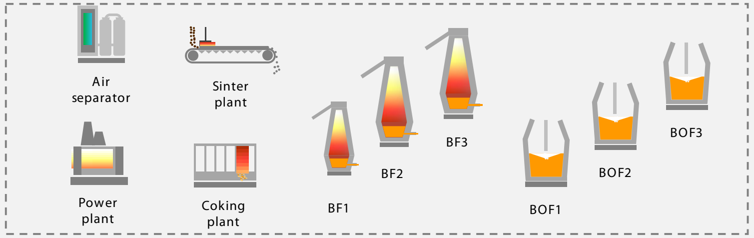
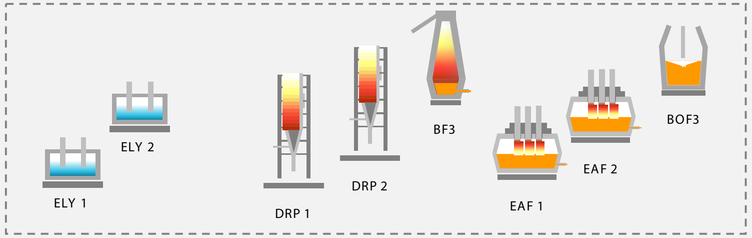
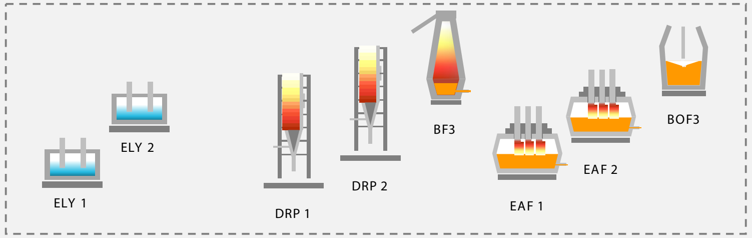
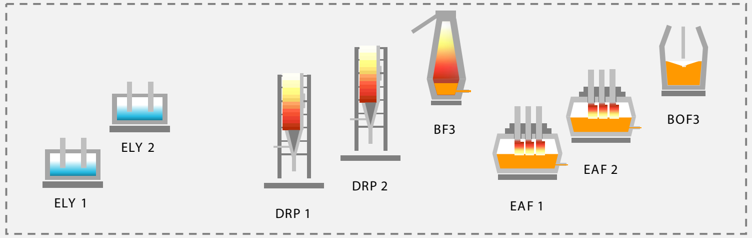
Case study "optimal" configuration in 2050: Sensitivity results

Electricity & emission allowances		Cash flows: All	Cash flows: Operation
	Baseline	(1) Baseline – All (Configuration 0 until 2050)  NPV per capacity: 889 Euro/t CS capacity$_{(2020\text{-}2050)}$	(3) Baseline – Operation (Configuration 5 from 2039)  NPV per capacity: 675 Euro/t CS capacity$_{(2020\text{-}2050)}$
	Spread	(2) Spread – All (Configuration 5 from 2029)  NPV per capacity: 238 Euro/t CS capacity$_{(2020\text{-}2050)}$	(4) Spread - Operation (Configuration 5 from 2027):  NPV per capacity: 610 Euro/t CS capacity$_{(2020\text{-}2050)}$

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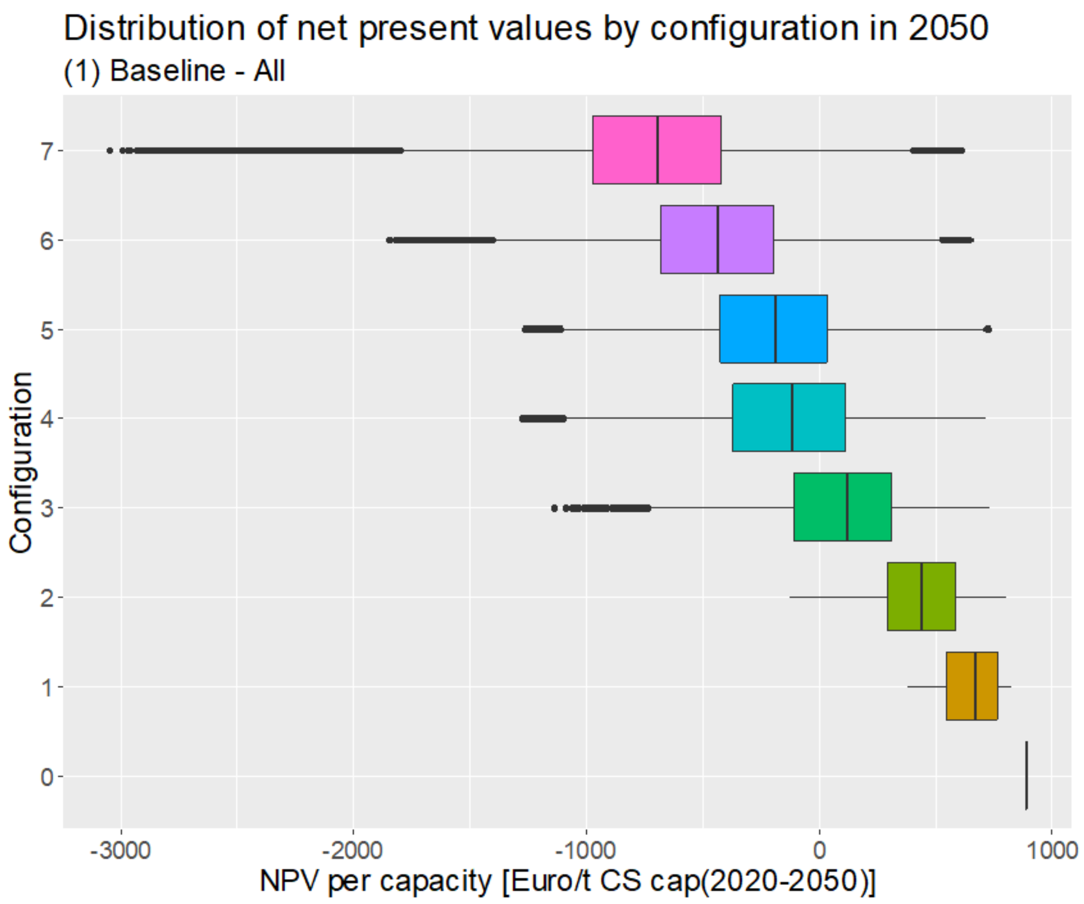
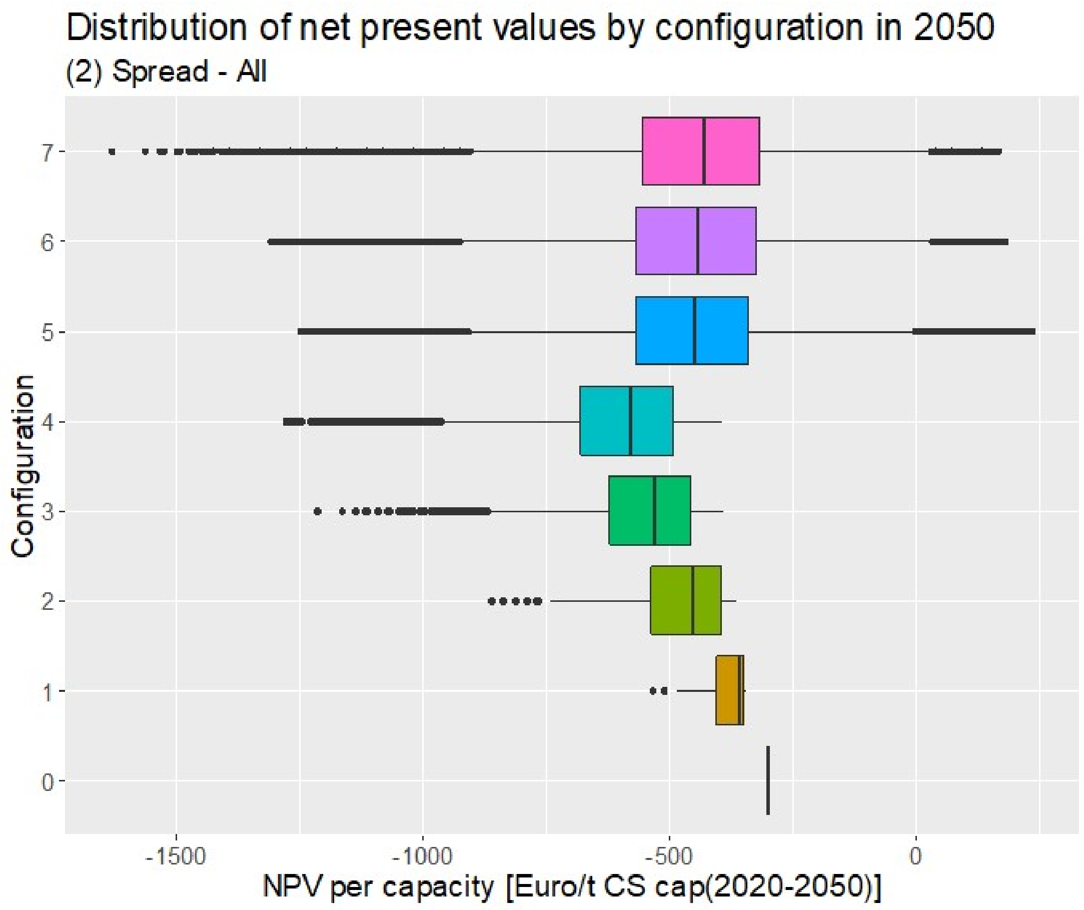
Case study: Distribution of NPV by final configuration in 2050





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Case study: Conclusions under the assumptions made

- **Conclusions concerning the case study under the assumption**
  - Assumptions on current and future commodity prices have a substantial impact on results
  - Depending on assumptions, lock-in effects from existing installations are important
  - With "moderate" changes in electricity prices and EUA prices, the status quo will likely be maintained
  - High emission allowance prices and decreasing electricity prices lead to an eventual shift towards a hybrid configuration (BF/BOF and H2/DRI-Route in parallel)
  - Full transformation (configuration 7 in 2050) only slightly less advantageous under high EUA/decreasing electricity prices

- **Potential supportive framework conditions for the full transformation**
  - "Low" electricity and "high" ETSprice signal (i.a. high share of renewable electricity)
  - Decreasing investments required for transition
  - Establishing a market signal for "green" steel
  - ...

Further investigation needed, also in view of international competition

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Discussion & Outlook

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Discussion: Merits & limits of the analysis

	Methodology	Content
Merits	▪ Structured economic analysis of potential pathways for energy transition ▪ Identification of "optimal" transition pathway ▪ Understanding of economic differences between different pathways	▪ Application of methodology to steel plant ▪ Possibility of analysing relevant factors of influence in detail (technical & economic model) ▪ Cash-flow oriented analysis of specific situation, no averaged cost analysis
Limits	▪ Suitable for limited setup and limited scope ▪ Limitation to a subset of potential configurations ▪ Markets for all output assumed ▪ Flows depend on technical configuration only	▪ Data intensive modular approach with volatile commodity prices and limited public data on installations ▪ Company assumed as "homo economicus" ▪ Pre-defined plant configurations with "fixed" technological solution

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Outlook on ideas for further developments

	Current analysis	Outlook
Methodology	Investments independent of actual implementation year ("averaged technological learning")	Integration of option to consider lower prices
	Hard "cut-off" of cash-flows after 2050	Including of "trailing" cash flows (no investment decision)
	Construction time not considered	Introduction of time lag
Content	Limited sensitivity analysis	Systematic scenario approach
	Focus on on-site hydrogen provision	Inclusion of external hydrogen generation/acquisition including transport
	System boundary ends at crude steel output	Coverage of entire integrated iron and steel works

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