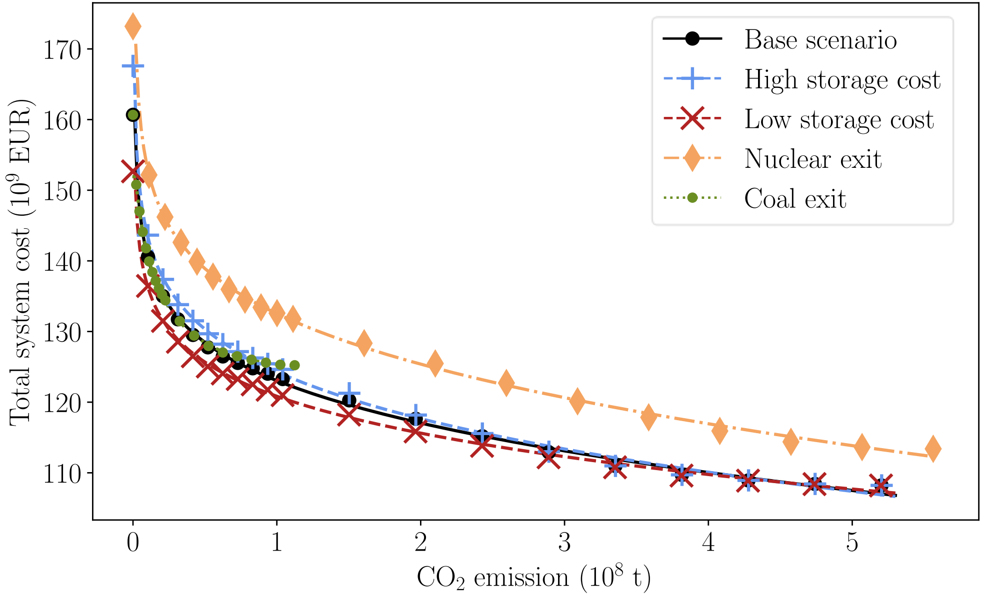
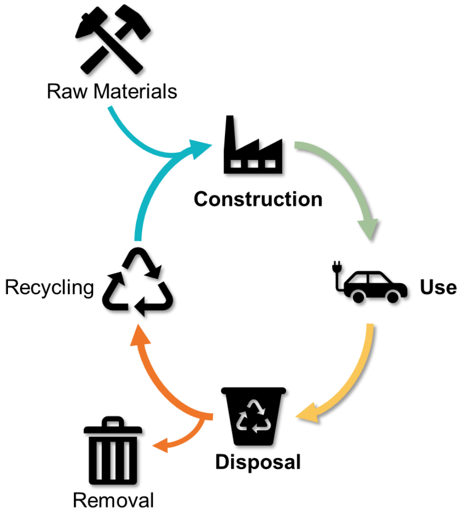




RUB

RUHR-UNIVERSITÄT BOCHUM

INTEGRATING ENERGY SYSTEM MODELLING AND LIFE CYCLE ASSESSMENT FOR MULTI-OBJECTIVE OPTIMISATION OF ENERGY SYSTEMS

Chair of Energy Systems & Energy Economics

Jonas Finke, Sophie Pathe, Sami Karsli, Valentin Bertsch # 25.03.2022 # jonas.finke@rub.de, sophie.pathe@rub.de

Agenda

- Motivation
- Method
- Case Study
- Conclusion & Outlook

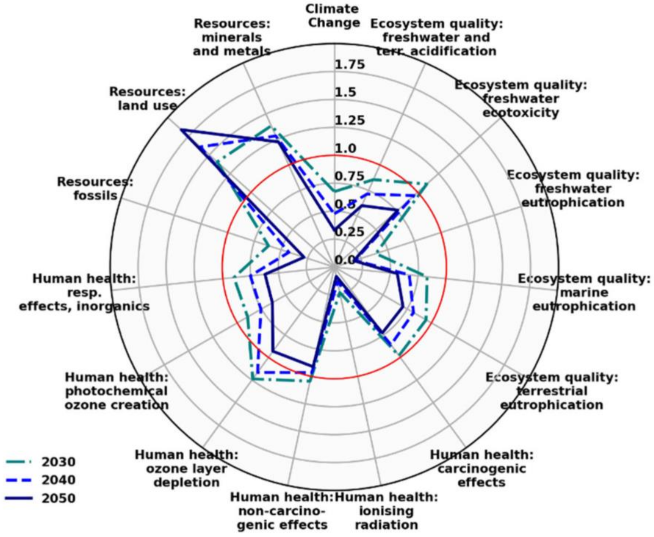
Motivation

Why Energy System Modelling (ESM)?

- Energy sector transformation to mitigate climate change
- Economic, environmental and societal challenges
- Energy system models provide insights and support complex decisions

Why Life Cycle Assessment (LCA)?

- Energy systems have large environmental impacts
- Environmental sustainability involves many criteria
- With renewables, there is a shift…
  - …from use to construction phase
  - …from GHG emissions to other environmental impacts



Junne et al. 2020

Junne et al., *Environmental Sustainability Assessment of Multi-Sectoral Energy Transformation Pathways: Methodological Approach and Case Study for Germany*, Sustainability 2020.

Why Integrate LCA and ESM?

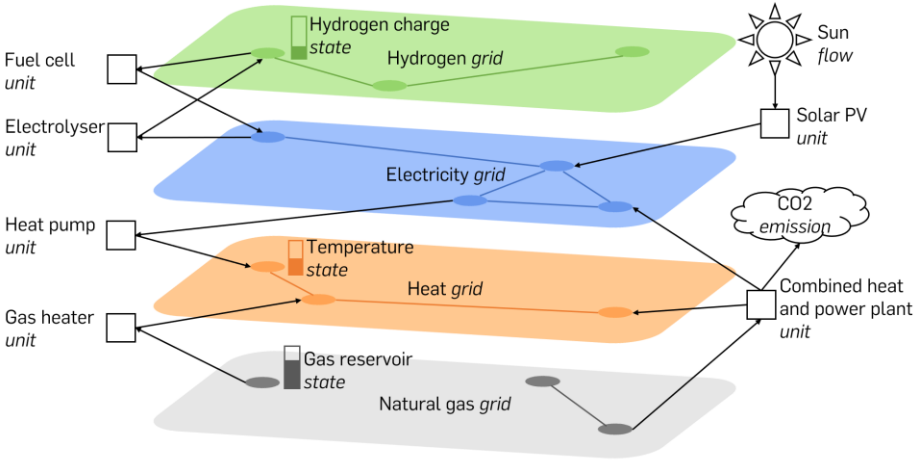
- Endogenisation of LCA in ESM allows…
  - …to perform an **systemic** LCA of the energy system.
  - …to **constrain** environmental impacts as boundary conditions.
  - …to **optimise** environmental impacts as objective functions.
- Thereby, …
  - …environmental interests of stakeholders can be considered equivalently to costs.
  - …investigation of interdependencies and correlations between costs and different environmental impacts is possible.
  - …multiple impact categories (or costs) can be used as objectives to calculate multi-objective Pareto fronts.
  - …efficient (i.e. Pareto-optimal) decisions are facilitated.

Chair of Energy Systems & Energy Economics
RUHR UNIVERSITÄT BOCHUM

Method

Energy System Optimisation Framework Backbone

- Network Model
  - Highly adaptable structure
  - Various energy carriers and sectors
  - Flexible spatial and temporal resolution
  - High technological detail
  - Stochastic modelling
- Optimisation
  - Investment and operational planning
  - Cost minimisation
  - Various constraints
- Open Source



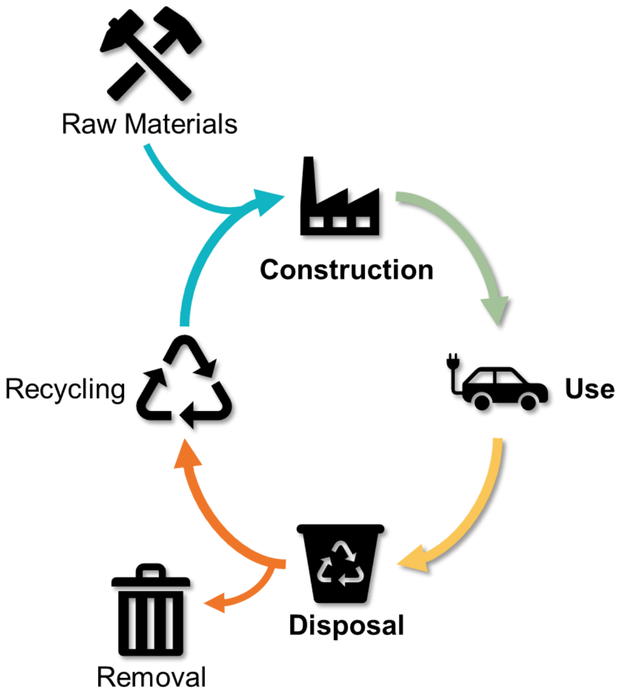
$$v_{\mathrm{BB}}^{\mathrm{obj}} = \sum_{f,t} p_{f,t}^{\mathrm{probability}} \cdot \left(v_{f,t}^{\mathrm{vomCost}} + v_{f,t}^{\mathrm{fuelCost}} + v_{f,t}^{\mathrm{startupCost}} + v_{f,t}^{\mathrm{shutdownCost}} + v_{f,t}^{\mathrm{rampCost}} + v_{f,t}^{\mathrm{stateCost}} + v_{f,t}^{\mathrm{penalties}} \right) + v^{\mathrm{fomCost}} + v^{\mathrm{unitInvestCost}} + v^{\mathrm{lineInvestCost}}$$

Helistö et al., *Backbone – An Adaptable Energy Systems Modelling Framework*, Energies 2019.

Source code: https://gitlab.vtt.fi/backbone/backbone

Life Cycle Assessment – General Aspects

- Method for integrated ecological assessment of products
- Quantification of inputs, outputs and potential environmental impacts throughout the life cycle
  - Construction phase
  - Use phase
  - Disposal phase
- Environmental impacts are...
  - ...related to the product's quantitative benefit, e.g. per electricity output
  - ...aggregated into impact categories, e.g. climate change



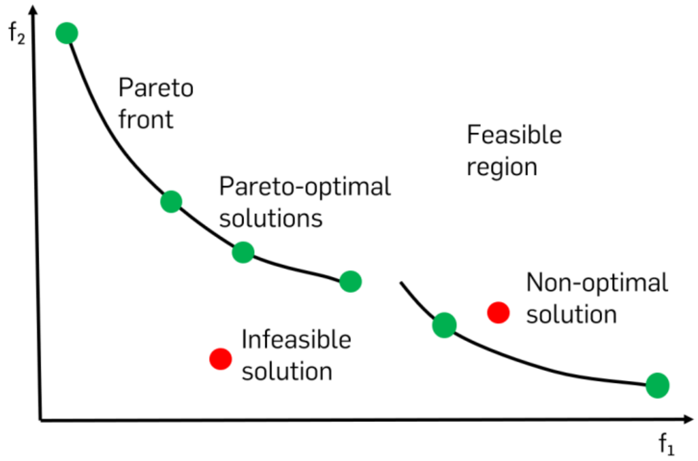
Integrating Life Cycle Assessment in Backbone

- New parameters p for environmental impacts from...
  - ...investments in units (construction phase)
  - ...outputs of units (use phase)
- New equations / variables v for environmental impacts to be used as...
  - ...constraints
  - ...objective functions
- For each impact category i ,

$$v_i^{\text{envImpact}} = \sum_{\substack{\text{nodes } n, \\ \text{units } u}} \left(\underbrace{p_{n,u,i}^{\text{construction}} \cdot p_{n,u,i}^{\text{constructionShare}} \cdot v_{n,u}^{\text{investedCapacity}}}_{\text{Construction phase}} + \sum_{\text{time } t} \underbrace{p_{n,u,i}^{\text{usePhase}} \cdot v_{n,u,t}^{\text{generation}}}_{\text{Use phase}} \right)$$

Multi-Objective Optimisation – General Aspects

- Consider simultaneous optimisation of multiple real objective functions
- Notion of optimum: set of Pareto-optimal solutions, so called *Pareto-front*
- A solution is called *Pareto-optimal* if improvements of one objective necessarily lead to deterioration of another



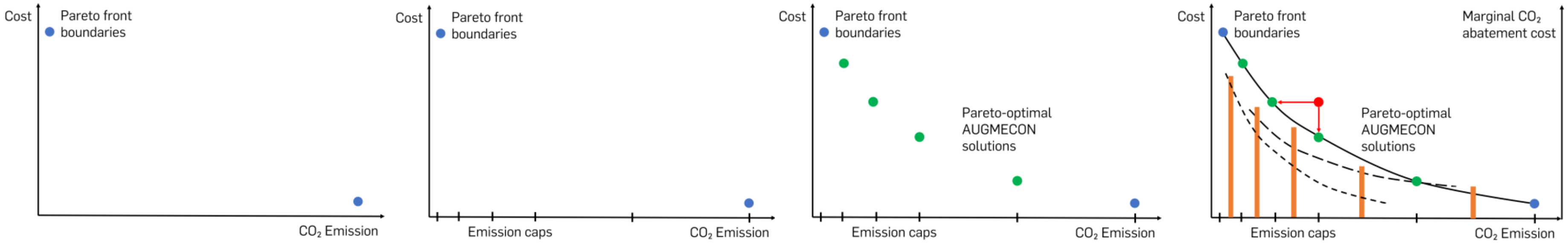
- AUGMECON method to generate Pareto-optimal solutions
  - Reformulate all but one objective to constraints
  - Introduce slack variables

$$\min_{x \in V} \quad \{f_1(x), f_2(x), \dots, f_k(x)\} \qquad \longrightarrow \qquad \min_{x \in V} \quad \left(f_j(x) + c \sum_{i \in K} s_i \right) \quad \text{s.t.} \quad f_i(x) + s_i = \varepsilon_i \; \forall \; i \in K \setminus \{j\}$$

Mavrotas, *Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems*, Applied Mathematics and Computation 2009.

Implementing AUGMECON in Backbone

- Implementation for two objectives, e.g. cost and one environmental impact category
- Two parts
  - New objectives and constraints in Backbone (emission objective, AUGMECON)
  - “External” python code with 4 steps to run different versions of Backbone (figure below)
- Method adaptable to more impact categories



Case Study

Workflow of Case Study

ESM input data, e.g.

- Demand and weather time series
- Techno-economic data on generation units
- Network infrastructure

PyPSA-Eur

LCA data

ecoinvent

- Technology-dependent impacts for chosen impact categories
- Per installed generation capacity (construction phase)
- Per electricity output (use phase)

ESM with AUGMECON

- Multi-objective optimisation for cost and GHG emission
- Only CO_2 emissions from fuel combustion

Backbone

ESM with LCA

- Single-objective optimisations
- Cost or environmental impact as objective function
- LCA, including use and construction phase

Pareto-optimal solutions

Pareto fronts, marginal CO_2 abatement cost

Optimal solutions

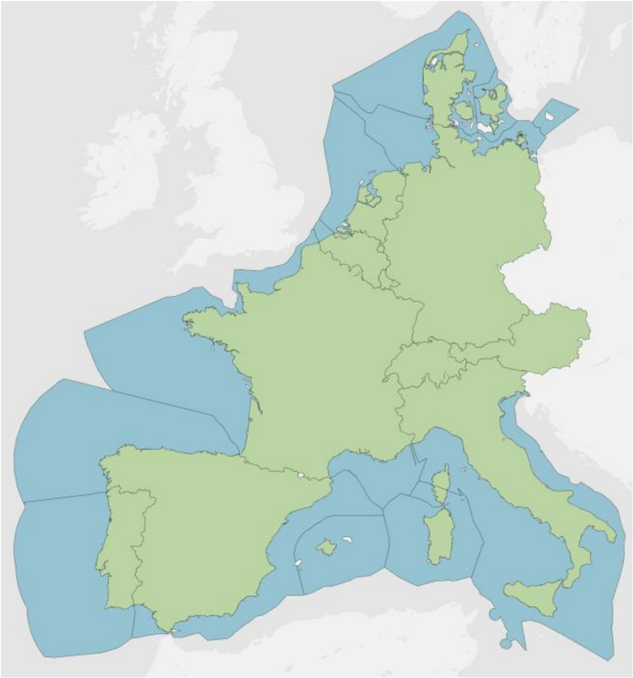
Generation mix for different objectives, correlations

Western & Southern European Power System Model

- Power network model based on PyPSA-Eur
- Including 11 countries
- Modelling one year at hourly resolution

- Investment planning for
  - Generation: solar PV, onshore & offshore wind, gas
  - Storage: battery
- Cost and demand assumptions for 2050[1]

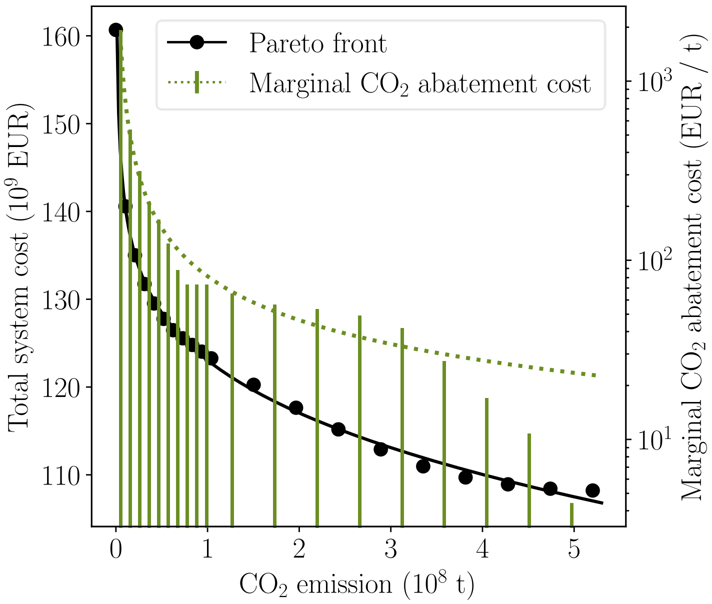
- LCA data from ecoinvent database
- Including 4 impact categories



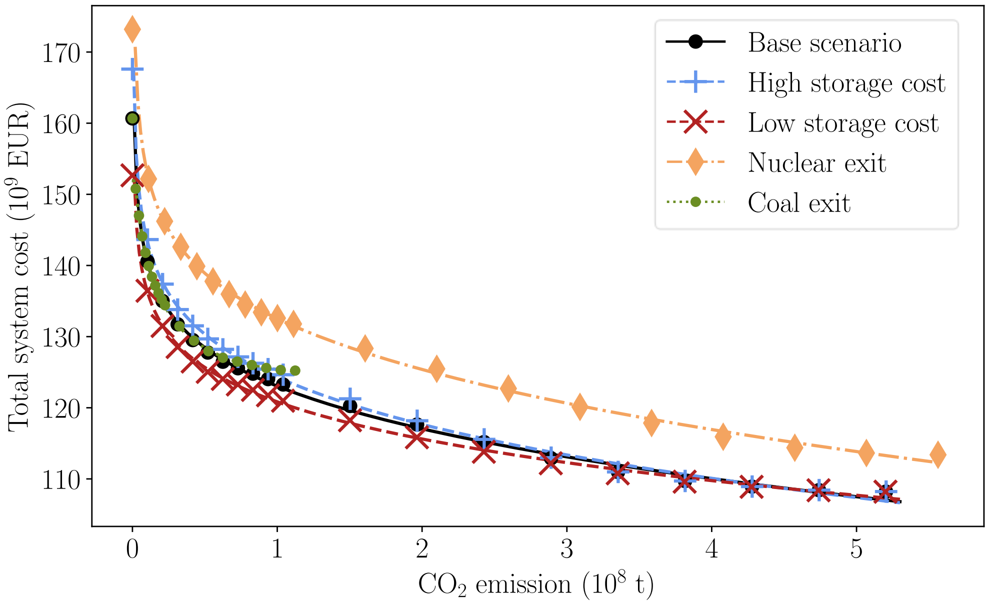
Hörsch et al., *PyPSA-Eur: An Open Optimisation Model of the European Transmission System*, Energy Strategy Reviews 2018. (See also https://github.com/PyPSA/pypsa-eur)
[1] Largely based on Pietzcker et al., *Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonisation of the EU power sector*, Applied Energy 2021.
ecoinvent database, https://ecoinvent.org/the-ecoinvent-database/

Pareto Fronts for Costs and direct CO_2 Emissions

- Objectives´ ranges and marginal CO_2 abatement cost



- Scenarios: coal exit, nuclear exit and storage cost (battery ± 25%, H_2 ± 15%)



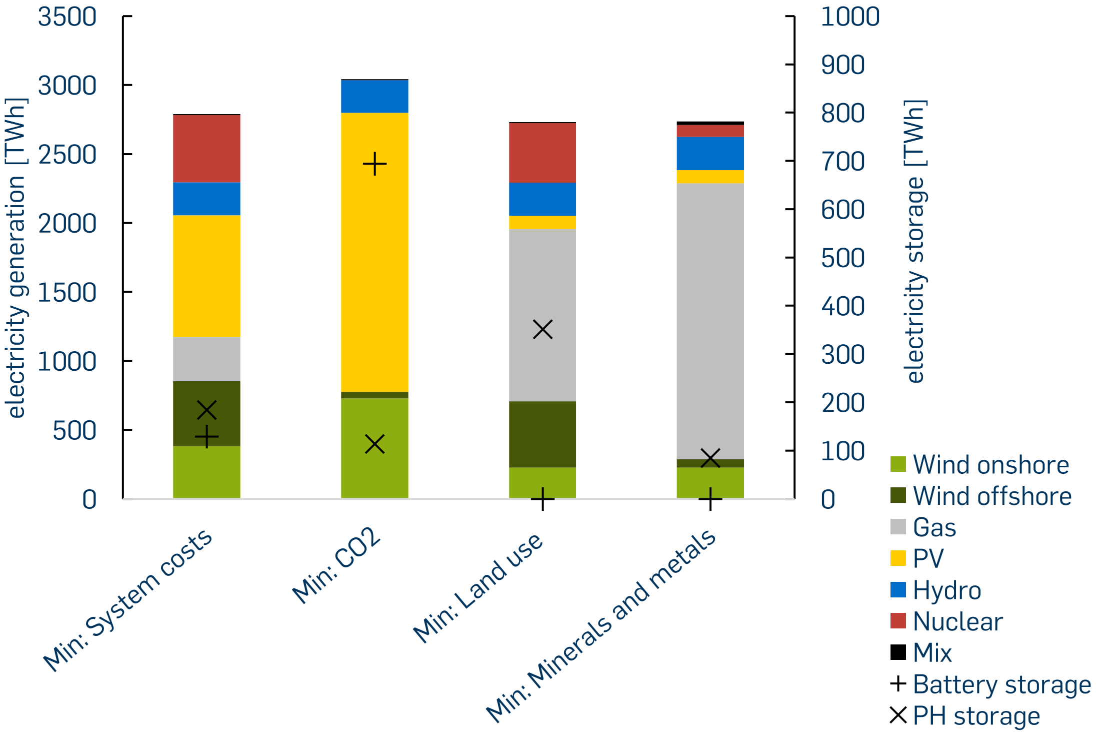
Chair of Energy Systems & Energy Economics

RUHR UNIVERSITÄT BOCHUM

RUB

Generation Mix for Different Objectives Including LCA

- PV prefered for minimal CO_2-emissions
- Gas prefered for min. land use and min. minerals and metals
- Great use of battery storage for min. CO_2, no battery at all for min. land use and min. minerals and metals
- Low PH storage for min. CO_2 and min. minerals and metals
- No nuclear for min. CO_2



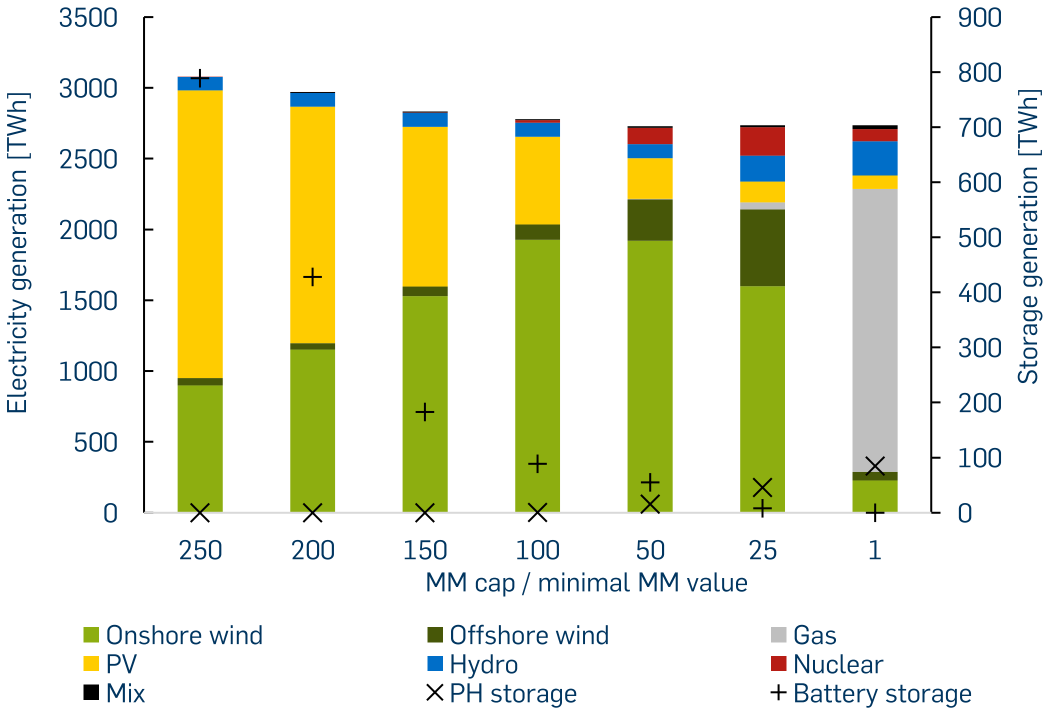
Chair of Energy Systems & Energy Economics
RUHR UNIVERSITÄT BOCHUM
RUB

Minimise Climate Change with Resource Caps

- Minimising climate change objective…
- …while allowing different multiples of the minimal value for minerals and metals (MM)

- PV and battery storage decrease with allowed use of MM
- Wind increases with decreasing allowed MM
- Major use of gas only for very low allowed MM

➢ Conflicting objectives



Chair of Energy Systems & Energy Economics

RUHR UNIVERSITÄT BOCHUM RUB

Conclusion & Outlook

Conclusion & Outlook

- Implemented method enables for energy systems to...
  - ...perform a systemic LCA.
  - ...optimise and constrain environmental impacts.
  - ...optimise system costs and an environmental impact simultanously.

- Case study reveals synergies and conflicts between objectives
- Energy systems differ substantially for different optimisation objectives

Future work

- Sector-coupled systems
- Optimise more than two impact categories at the same time
- Prospective LCA

Thank you for your attention!

Questions?

Suggestions?

Comments?

Backup Slides

Correlations Between Impact Categories

- **Rows:** Scenario minimised for respective impact category
- **Columns:** Environmental impact in respective category
- **Values:** Normalised distance from lowest achievable impact

- Human health categories:
  - Conflict with CO_2 (dotted frame)
  - Synergy with freshwater ecotoxicity (dashed frame)

Legend (normalized distance)	small	medium	large

	CO2	Climate change total	Marine eutrophication	Terrestrial eutrophication	Freshwater ecotoxicity	Carcinogenic effects	Non-carcinogenic effects	Respiratory effects	Land use	Minerals and metals	System costs
Min: CO2	0.00	31.32	3.01	3.69	11.68	12.86	17.52	8.22	18.90	207.43	1.45
Min: Climate change total	0.12	0.00	3.49	4.28	15.00	17.21	20.75	9.33	23.01	243.74	2.19
Min: Marine eutrophication	181.05	188.76	0.00	0.03	3.12	5.15	1.17	0.89	4.57	12.96	0.97
Min: Terrestrial eutrophication	192.04	197.99	0.03	0.00	2.69	4.42	1.09	0.90	3.67	12.33	0.84
Min: Freshwater ecotoxicity	2143.85	1887.80	2.35	2.99	0.00	0.05	0.06	0.61	0.12	0.16	0.43
Min: Carcinogenic effects	1917.78	1692.84	2.19	2.63	0.02	0.00	0.10	0.85	0.14	0.18	0.36
Min: Non-carcinogenic effects	2486.70	2195.70	2.60	3.62	0.09	0.36	0.00	0.17	0.19	0.56	0.55
Min: Respiratory effects	1621.96	1436.56	1.43	2.11	0.41	0.96	0.08	0.00	0.20	3.13	0.48
Min: Land use	1605.23	1459.11	1.69	2.09	0.17	0.36	0.09	0.56	0.00	1.43	0.30
Min: Minerals and metals	2758.01	2438.66	3.20	4.35	0.10	0.30	0.03	0.36	0.28	0.00	0.54
Min: System costs	461.37	445.15	1.49	1.62	2.86	2.60	5.48	3.29	5.01	67.30	0.00