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Sustainable Power Systems Transformation of Industrial Regions: Insights from Energy System Modelling

Sophie Pathe, Valentin Bertsch | May 5, 2023

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Agenda

- Motivation
- Method
- Power system expansion planning of the Rhenish Mining Area
- Conclusion & Outlook

Motivation

Considering environmental impacts in Energy System Models

- Consideration of environmental impacts in ESMs: (Direct) CO_2 or greenhouse gas emissions in ESMs, other environmental impacts are often neglected
- Energy systems have large environmental impacts (also besides climate change)
- Direct GHG-emissions are not suitable for comparison among renewable energy technologies
- For renewable energy technologies
  - …environmental impacts shift to other impact categories.
  - …environmental impacts shift from the use phase to the construction phase.

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Integrating LCA and ESM

- Endogenisation of Life Cycle Assessment (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, ...
  - …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.

Method

Integrating Life Cycle Assessment in Backbone

- Energy System Optimisation Framework Backbone[1]
- New parameters for environmental impacts from investments (construction phase) & outputs of units (use phase)
- New equations for environmental impacts to be used as constraints & objective functions
  - Multi objective energy system optimization (augmented epsilon-constraint method[2])

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

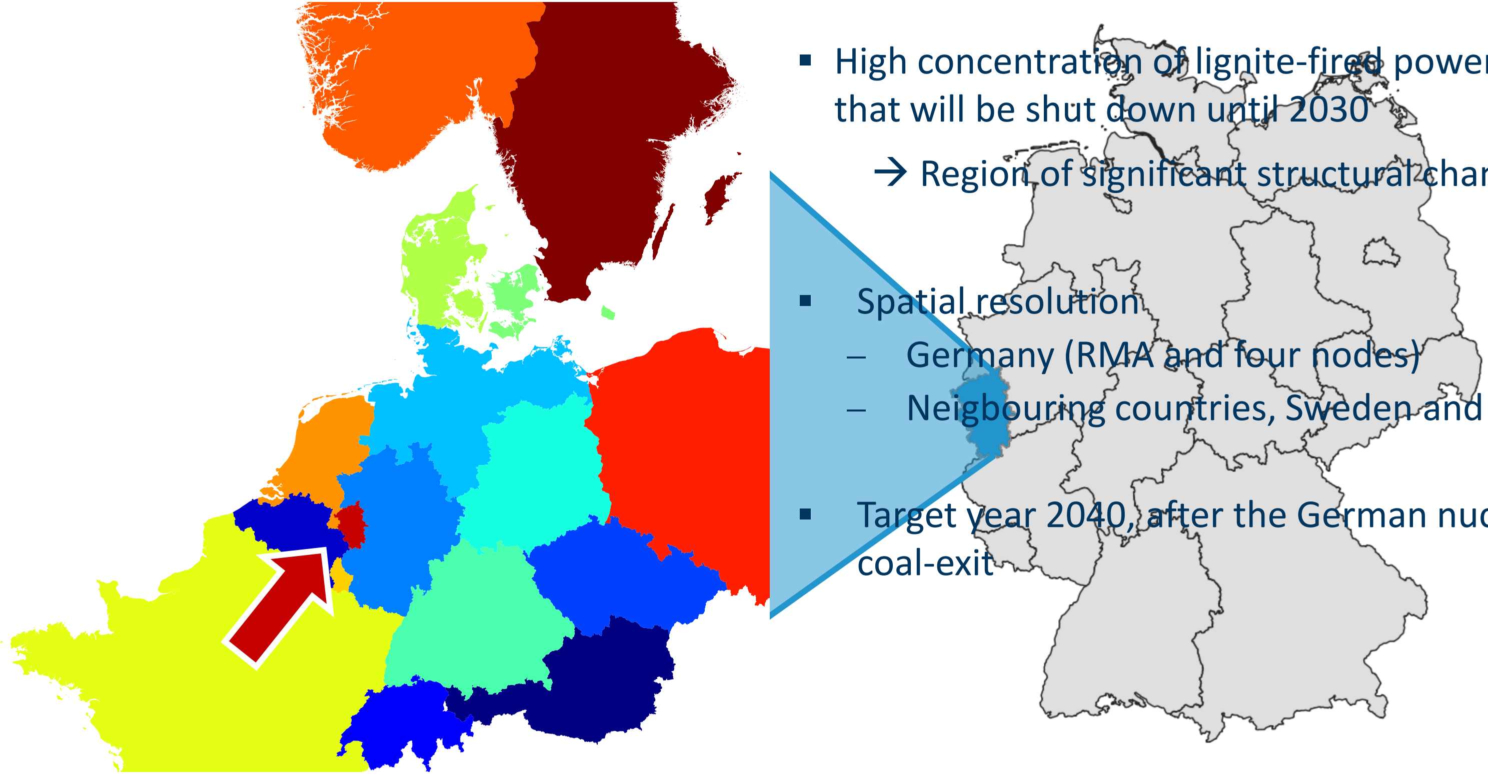
with parameters p, variables v, impact categories i

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

[2] Finke & Bertsch, *Implementing a highly adaptable method for the multi-objective optimisation of energy systems*, Applied Energy, 2023

Power system expansion planning of the Rhenish Mining Area

The Rhenish Mining Area



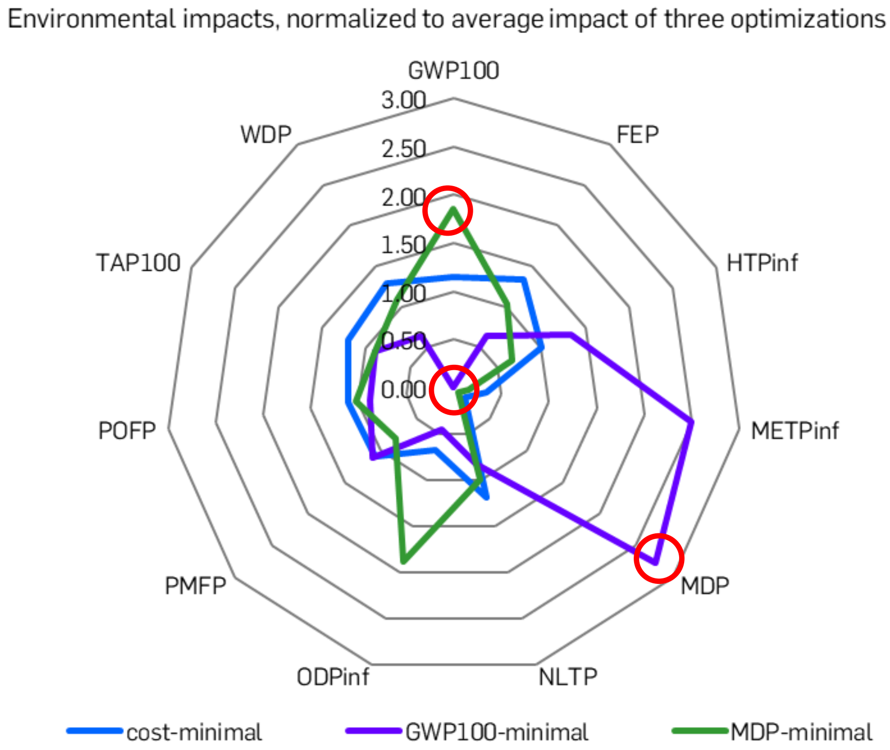
- High concentration of lignite-fired power plants that will be shut down until 2030
  → Region of significant structural change

- Spatial resolution
  - Germany (RMA and four nodes)
  - Neigbouring countries, Sweden and Norway

- Target year 2040, after the German nuclear- and coal-exit

Aerial picture: https://www.energieatlas.nrw.de/site/planungskarten/rheinisches_revier

Environmental impacts of the complete ES with different objectives



- Conflicting objectives: GWP and MDP

GWP100 – climate change

FEP – freshwater eutrophication

HTPinf – human toxicity

METPinf – marine ecotoxicity

MDP – metal depletion

NLTP – natural land transformation

ODPinf – ozone depletion

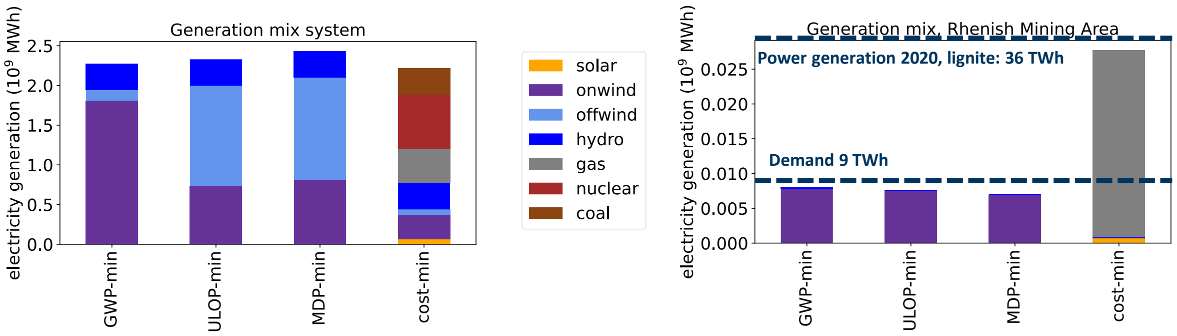
PMFP – particulate matter formation

MOFP – photochemical oxidant formation

TAP100 – terrestrial acidification

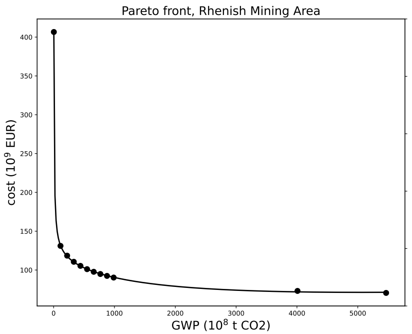
WDP – water depletion

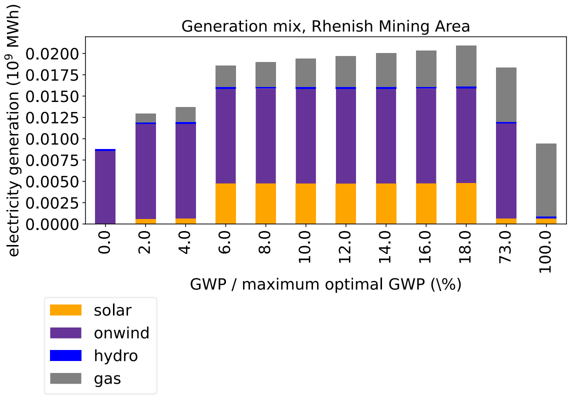
Individual optimization of four objectives

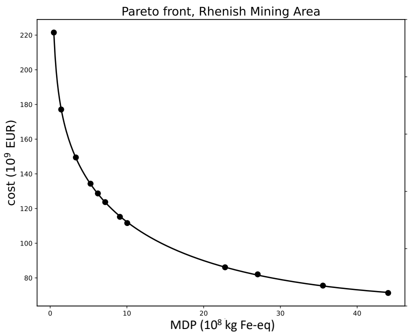


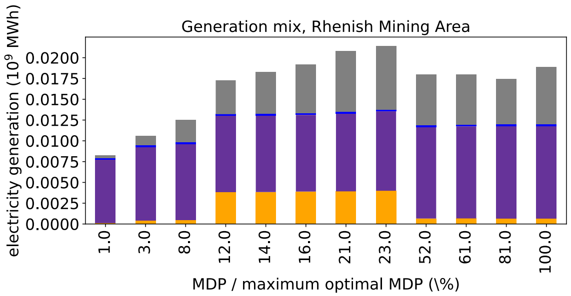
- Preferences
  - hydro- and wind power for all env. objectives
- Significantly lower generation in the RMA

Multi-objective optimization for cost and environmental impacts









- Maximum optimal system costs are lower for MDP than GWP
- Generation mix of onshore wind, gas, solar and hydropower
- Similar technology shares and overall generation for different env. objectives

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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.

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

Future work

- Sector-coupled systems, i.e. steel and cement production
- Prospective LCA

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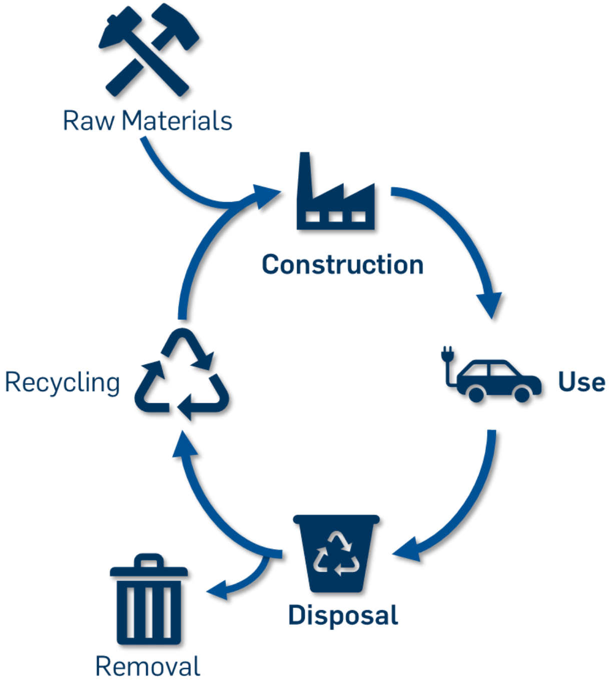
Thank you very much!

Contact: Sophie Pathe, sophie.pathe@rub.de, www.ee.rub.de

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



LCA

- LCA impact categories/ characterisation factors:
  - Climate change/ Global Warming Potential (GWP) 100 [kg CO2-eq]
    The amount of emitted greenhouse gases.
  - Metal depletion/ Metal Depletion Potential (MDP) [kg Fe-eq]
    The amount of extracted metal resources.
  - Urban land occupation/Urban Land Occupation Potential (ULOP) [m2 a]
    The amount of urban land occupied for a certain time.
- Method: ReCiPe Midpoint (H)
- Environmental impacts for construction and use phase
- Database: ecoinvent 3.7

Single- and multi-objective optimization combining ESM and LCA

ESM input data, e.g.

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

PyPSA-Eur

LCA data

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

ecoinvent

ESM with system LCA

- Single objective optimizations
- Regular (cost) or alternative (env. impact) objective function
- LCA of the energy system for chosen impact categories

Backbone

ESM with system LCA and AUGMECON

- Multi objective optimization, by multiple model runs using the augmented ε-constraint method[1]
- Pair of objective functions
- LCA of the energy system for chosen impact categories

Optimal solutions

Generation mix for different objectives, correlations

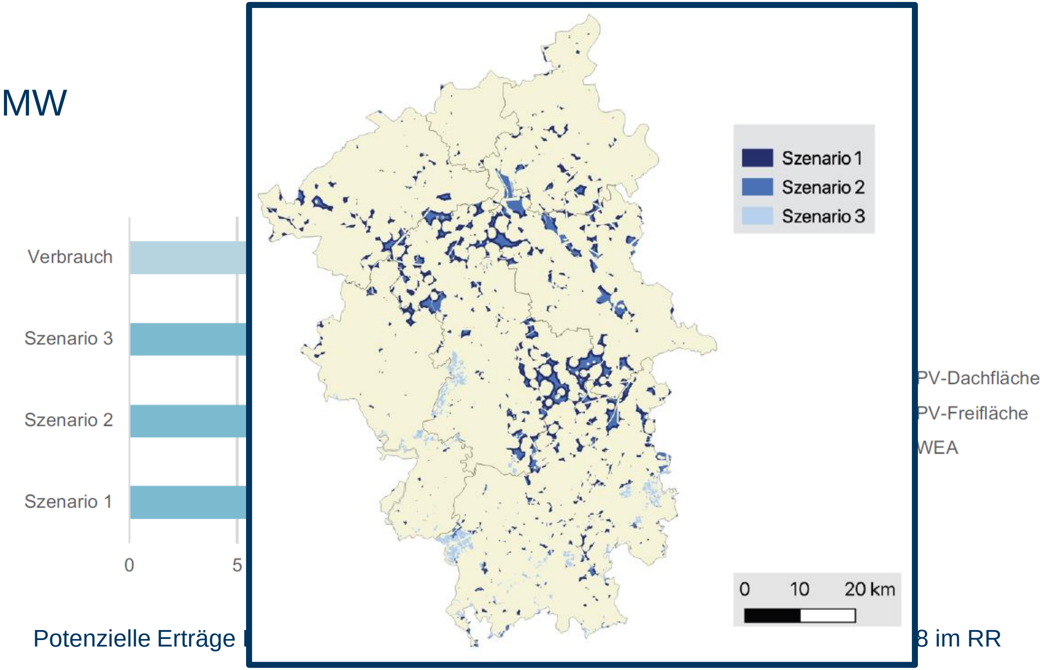
Pareto-optimal solutions

Pareto fronts, marginal CO_2 abatement cost

[1]Mavrotas, *Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems*, Applied Mathematics and Computation 2009.
PyPSA-Eur: https://github.com/pypsa/pypsa-eur/blob/master/doc/index.rst
ecoinvent: https://ecoinvent.org/

Potenzial zu Installation Erneuerbarer Energien

- Windenergieanlagen
  - Installierbare Leistung: 1.967 – 6.788 MW
  - Bestand: 1.290 MW
- Dachanlagen
  - Installierbare Leistung: 8.849 MW
  - Bestand: 568 MW
- Freiflächenanlagen
  - Installierbare Leistung: 6.473 MW
  - Bestand: 42 MW
- Stromverbrauch 2018: 19,2 TWh

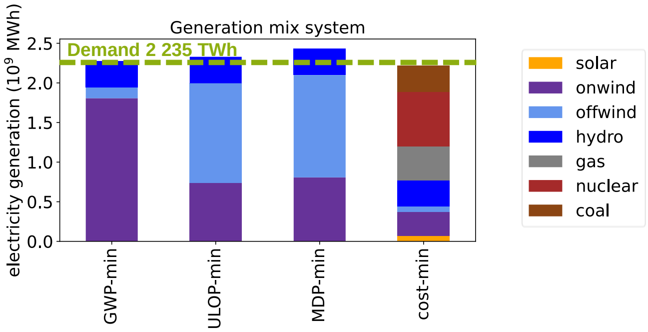


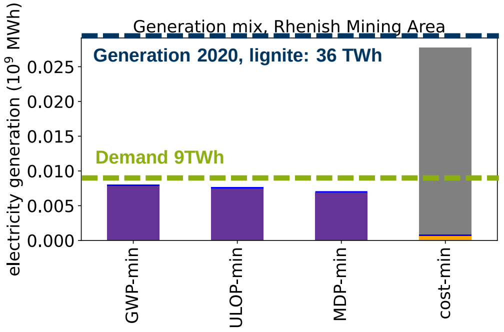
Potenzielle Erträge … 8 im RR

Main model and scenario assumptions

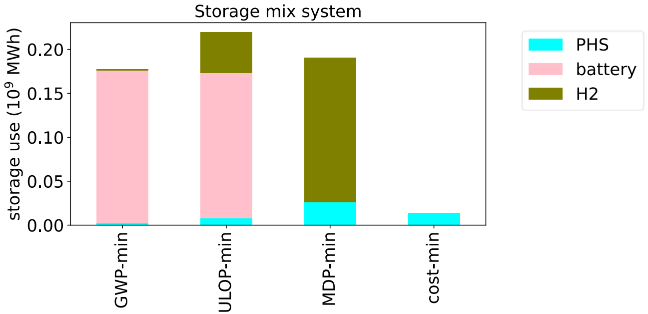
- Focus on electricity sector
- No consideration of transfer lines except transfer capacity limit
  - No transmission losses
- Installed capacities for conventional power plants, hydropower, geothermal energy and pumped hydro storages from 2019 (except nuclear and coal)
- No installed capacity for other renewable and storage technologies
- Investments are only possible in renewable technologies, with the exception of hydropower and geothermal energy as well as batteries and hydrogen storage
- Maximum investment potential for solar, onshore wind and offshore wind
- Cyclic boundaries for storages (start – end of year)

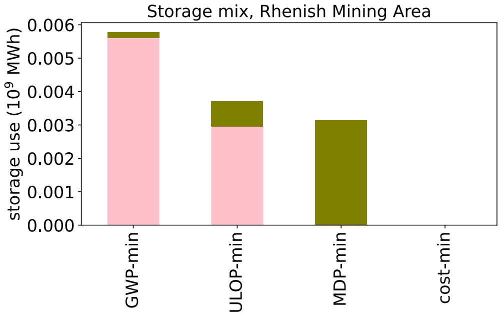
Individual optimization of the objectives





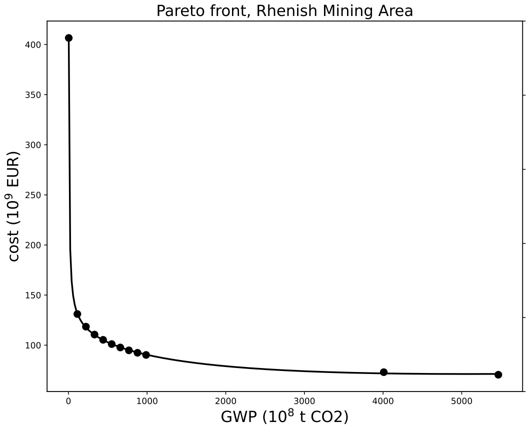
GWP/ min GWP	**1**	**1.08**	**1.13**	**1 390.11**
cost/ min cost	**5.77**	**4.79**	**3.91**	**1**

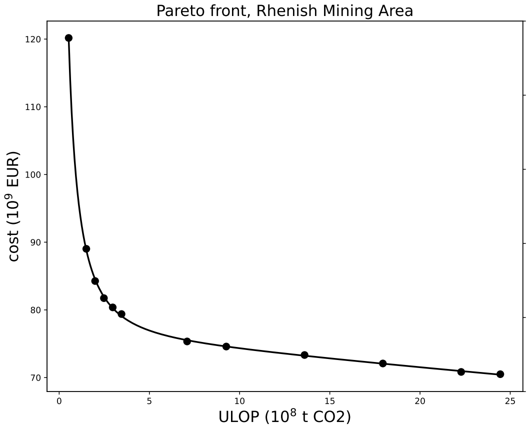


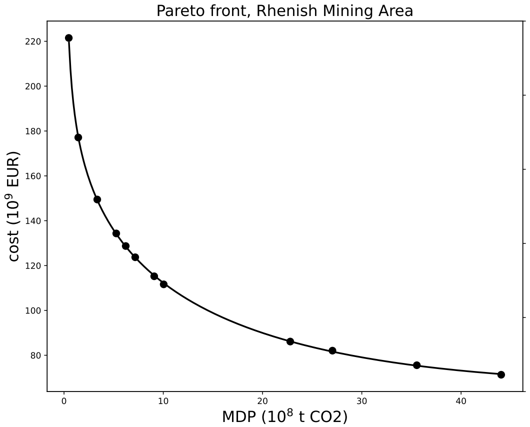


- Preferences
  - hydro- and wind power for all env. objectives
  - GWP: onshore wind and battery storage
  - ULOP: offshore wind and battery storage
  - MDP: offshore wind and hydrogen storage
- Significantly lower generation in the RMA

Multi-criteria optimization for cost and environmental impact using AUGMECON

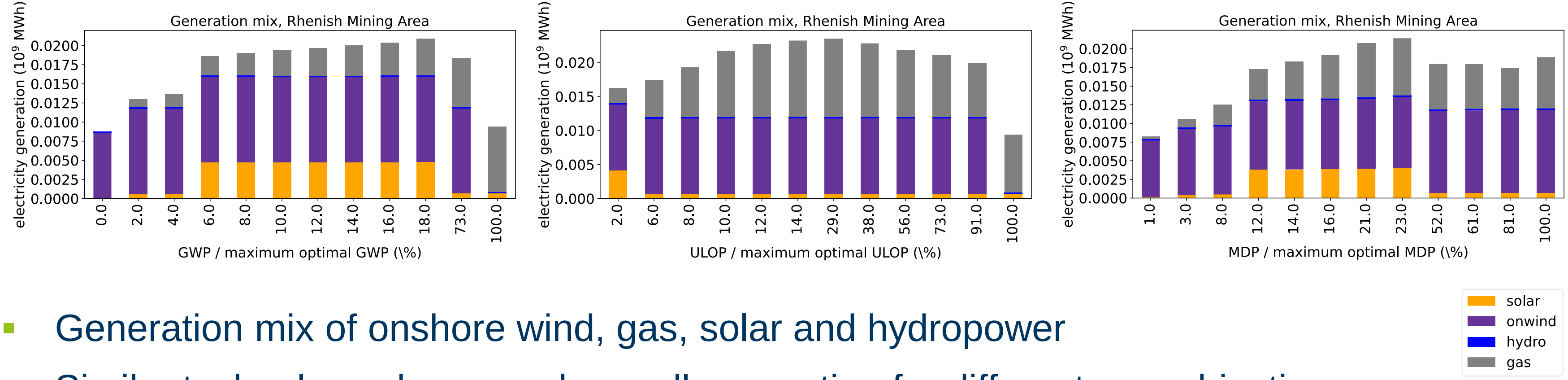






- Maximum optimal system costs are lower for ULOP and MDP than for GWP

Multi-criteria optimization for cost and environmental impact using AUGMECON



- Generation mix of onshore wind, gas, solar and hydropower
- Similar technology shares and overall generation for different env. objectives
- Changing overall generation is partly caused by export, but further analysis is needed
- Storages are only used for very low environmental impact values

Correlations Between Impact Categories

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

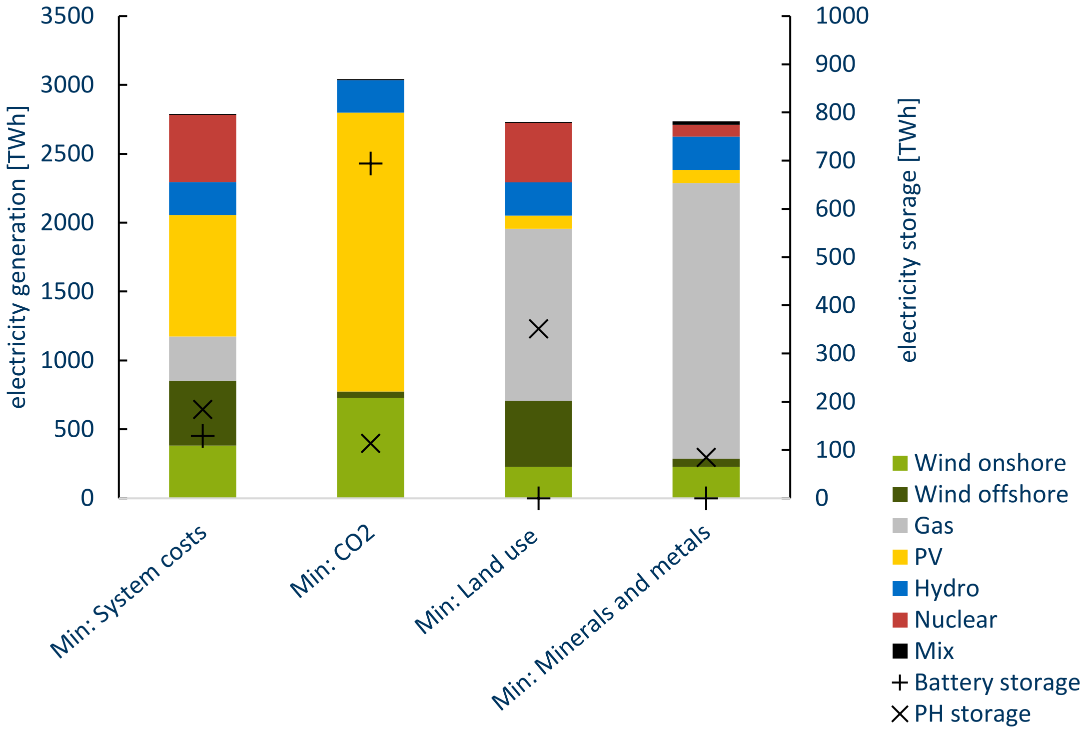
- Human health categories:
  - Conflict with CO_2 (dotted frame)
  - Synergy with freshwater ecotoxicity (dashed frame)

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

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

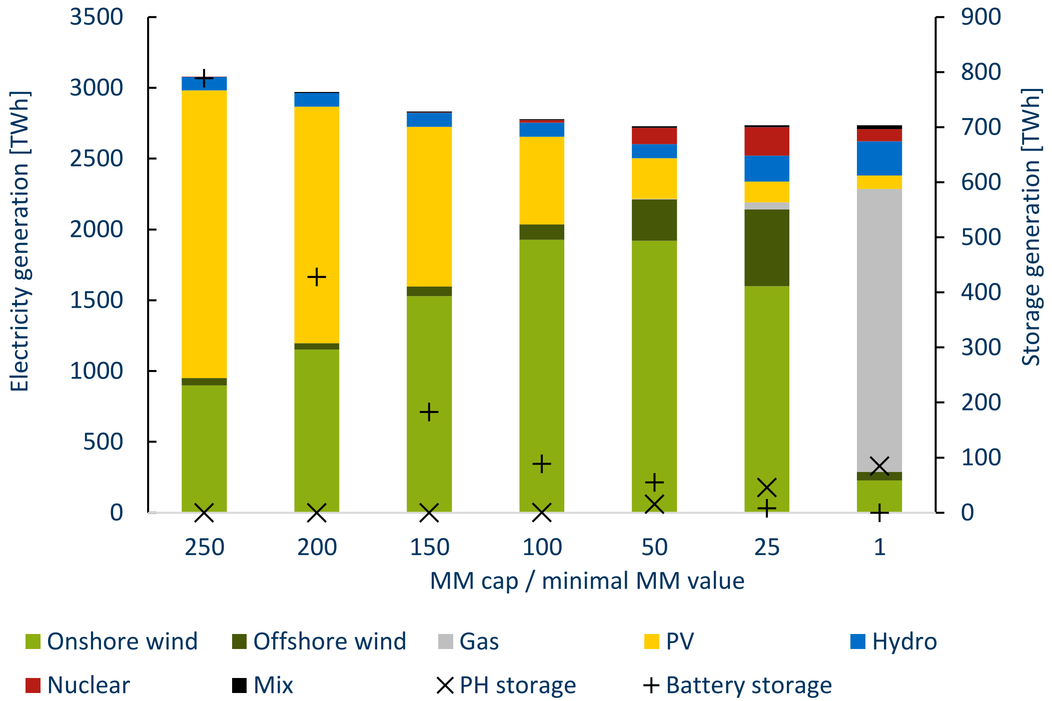


Minimise Climate Change with Resource Caps

- 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



References (1)

Backbone, version master 2021-07-05:
https://gitlab.vtt.fi/backbone/backbone

AUGMECON:
Mavrotas, G., 2009. Effective implementation of the ε-constraint method in Multi-Objective Mathematical Programming problems. Applied Mathematics and Computation, 213(2), 455-465, DOI 10.1016/j.amc.2009.03.037

openLCA, version 1.10.3:
https://www.openlca.org/

pypsa-eur, version rub-ee 2021-03-08:
https://github.com/PyPSA/pypsa-eur

Ecoinvent, version 3.7.1:
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. *The ecoinvent database version 3 (part I): overview and methodology.* The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8, last access 17.08.2021.
https://www.ecoinvent.org/

ReCiPe Midpoint (H) 2008:
Goedkoop, Mark & Heijungs, Reinout & Huijbregts, Mark & Schryver, A. & Struijs, J. & Zelm, R.. (2008). ReCiPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.

Geodata:
www.naturalearthdata.com

References (2)

Lignite electricity generation in 2020:
Fraunhofer Institute for Solar Energy Systems ISE: Energy Charts, https://energy-charts.de, last access 26.08.2021

Load scaling:
Pietzcker, R., Osorio, S., Rodrigues, R., 2021. *Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector.* Applied Energy 293, DOI 10.1016/j.apenergy.2021.116914
Eurostat, https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_cb_e&lang=en, last access 09.08.2021 (last update of webpage: 24.06.2021)
Bundesamt für Energie BFE: Schweizerische Elektrizitätsstatistik 2013, Art.-Nr. 805.005.18 / 07.19 / 1200 / 860444141

Coal and nuclear exit:
European Comission, 2020. An EU-wide assessment of National Energy and Climate Plans. COM(2020) 564 final
European Comission. National Energy and Climate Plans. https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en, last access 26.06.2021
Eidgenössiches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK. Ausstieg aus der Kernenergie.
https://www.uvek.admin.ch/uvek/de/home/uvek/abstimmungen/abstimmung-zum-energiegesetz/kernenergie.html, last access 12.08.2021

Additional LCA data:
Bareiß, K., de Möckl, C., Hamacher, T., 2019. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Applied Energy 237, 862-872, DOI: 10.1016/j.apenergy.2019.01.001
Koj, J. et al., 2017. Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. Energies 10(7), DOI: 10.3390/en10070860

Considering environmental impacts in energy system models (e.g.):
Berril, P. et al., 2016. Environmental impacts of high penetration renewable energy scenarios for Europe. Environmental Research Letters 11(1), DOI: 10.1088/1748-9326/11/1/014012
Tietze, I., Lazar, L., Lewerenz, S.,2020. LAEND: A model for multi-objective investment optimisation of residential quarters considering costs and environmental impacts. Energies 13(3), DOI: 10.3390/en13030614
Junne, T. et al., 2021. Considering Life Cycle Greenhouse Gas Emissions in Power System Expansion Planning for Europe and North Africa Using Multi-Objective Optimization. Energies 14(5). DOI: 10.3390/en14051301

Photograph
Julian Röder, Mülheim, 2019; editing: Sophie Pathe