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Combining Life Cycle Assessment and Energy System Optimization to Model Sustainable Power Systems Transformation#

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ABSTRACT

We link the highly flexible Energy System Model Backbone with Life Cycle Assessments of energy system technologies to optimize various environmental impact indicators in addition to system costs. Additionally, we perform a multi-objective optimization of costs and environmental impacts and determine a pareto front to investigate interrelationships and trade-offs even further. We apply this to the power system of twelve central european countries with a special focus on the Rhenish Mining Area, a structural change region in western Germany, in the year 2040. This reveals a decrease in electricity generation in the region for all objective functions compared to 2020, as well as a strong preference for gas power for cost minimization and onshore wind power for minimization of environmental indicators.

Keywords: Energy System Model, Life Cycle Assessment, Multi-objective Optimization, Energy Transition, Structural Change, Rhenish Mining Area

NOMENCLATURE

Abbreviations	
ESM	Energy System Model
GAMS	General Algebraic Modeling System
GWP	Global Warming Potential
LCA	Life Cycle Assessment
MDP	Metal Depletion Potential
PHS	Pumped Hydro Storage
RMA	Rhenish Mining Area
ULOP	Urban Land Occupation Potential

1. INTRODUCTION

Since hard coal mining was ended by the end of 2018, lignite along with minor amounts of natural gas is the last fossil energy carrier exploited in Germany [1]. Power plants in the Rhenish Mining Area (RMA), the largest lignite mining area in Germany, currently cover about one tenth of Germany's electricity demand [2]. The core area of the RMA, located in western Germany, includes the opencast mining areas, lignite-fired power plants and refinement plants, and some locations of energy-intensive industry. The immediate surrounding area, however, is also impacted by the lignite industry through strong economic and social ties. This so-called impact area is regarded as the RMA and includes seven counties and cities (Fig. 1) [3].

Since the existing lignite-fired power plants will be

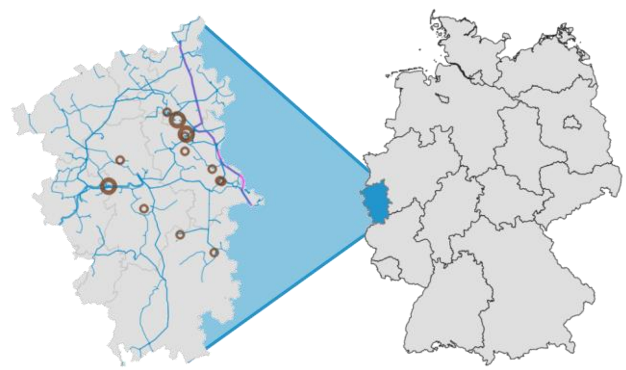

Fig. 1 Location of lignite-fired power plants (brown) and high-voltage power lines (blue, pink: project EnLAG15) in the RMA in 2020 and location of the RMA in Germany.

shut down by 2038 at the latest and lignite mining will be stopped, the RMA is affected by another substantial structural change [4]. The central reason for the political decision to phase out coal-fired power generation is to reduce greenhouse gas emissions and the climate change caused by these emissions. Currently, the energy sector also causes a large share of the total potential environmental impacts (beyond climate change) globally [5]. Therefore, in the course of the coal phase-out, in addition to limiting production and shutting down lignite-fired power plants, sufficient renewable power plants and capacities must be expanded in order to meet the energy policy objectives of environmental compatibility, economic efficiency and security of supply as energy policy objectives [1]. Energy system

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optimization issues - with special significance for regions where a transformation of the energy system is taking place or is imminent, as in the RMA - can be addressed with Energy System Models (ESMs). A promising way to address the growing need for sustainable solutions in the energy sector is by linking ESMs with Life Cycle Assessment (LCA) to consider environmental as well as economic impacts.

2. METHODS AND MODELS

The linking of ESM and LCA as well as the chosen ESM and key model and scenario assumptions are briefly presented in the following section.

2.1 Linking Energy System Modeling and Life Cycle Assessment

ESMs provide valuable insights regarding consequences of different measures and decisions in the transformation of the energy supply, such as the expansion and integration of renewable generation technologies or the expansion of grids. To identify and evaluate ecologically sustainable solutions in the energy sector, one possibility is the additional consideration of environmental impacts in these models. The optimization objective of ESMs is usually the minimization of the overall system costs while satisfying the energy demand in each time step and complying with given constraints [6].

This work combines the ESM Backbone[1] with an LCA to consider various environmental impacts in addition to the costs. LCA is a methodology for the holistic ecological evaluation of products. It examines the entire life cycle, from manufacturing through use to disposal. Depending on the input and output flows, e.g. materials or energy, of the product life cycle, potential environmental impacts are determined. These are related to the quantitative benefits of the product, e.g. one kWh of generated electricity [7].

The implementation of LCA in Backbone enables the determination of potential environmental impacts in addition to system costs and results in an LCA of the energy system. It is possible to optimize these environmental impacts using alternative objective functions or to limit them using constraints. Furthermore, multi-objective optimization is implemented to optimize system costs and an environmental impact simultanously. This is carried out by running multiple model runs, using the augmented ε-constraint (AUGMECON) method and leads to multiple pareto-optimal solutions that can be displayed in a pareto front [8].

[1]Source code: https://gitlab.vtt.fi/backbone/backbone

2.2 Energy System Model Backbone

Backbone is a mixed-integer linear optimization framework implemented using General Algebraic Modeling System (GAMS). It can be used for investment planning and scheduling and features a high level of adaptability. Backbone allows any spatial resolution, energy type and temporal resolution. It is also possible to vary the temporal resolution within the considered time frame and to represent stochastic behavior. The framework is open-source. The regular objective function to be minimized includes all system costs. An option to consider and to constrain direct emissions in relation to fuel usage is implemented, while the consideration of life cycle environmental impacts is not regularly implemented. [7]

2.3 Main Energy System Model assumptions

An investment planning is performed for the RMA in the year 2040. The target year 2040 is chosen, because the German nuclear exit in the year 2022 and coal exit by 2038 at the latest should be completed then. To account for the central location of the RMA, Germany is displayed with four more nodes and the neighboring countries are also displayed with one node each, as well as Sweden and Norway (see Fig. 2). Denmark is displayed with two nodes, as it belongs to two different interconnected grids. The study focuses on the electricity sector. Except for a capacity limit between nodes, transfer lines are not considered. Investments are only possible for gas, solar, wind and biomass power plants as well as batteries and hydrogen storage. The ESM data originates from PyPSA-Eur [9]. The load scaling for 2040 is based on Pietzcker et al. [10].

Fig. 2 Spatial resolution of the model. The countries cropped in the illustration (France, Norway, Sweden) are considered completely. Each coloured area represents one node.

2.4 *Life Cycle Assessment data and assumptions*

Besides the system costs, the environmental characterization factors global warming potential (GWP), urban land occupation potential (ULOP) and metal depletion potential (MDP) are considered. The impact on climate change, represented by the GWP is currently the most noticed environmental impact and is of great importance. The other two categories are chosen because other studies have shown that the results of those categories often show a different development than the GWP [11]. Additionally, resource scarcity is an important topic, especially in the field of renewable energies and storage technologies. Land use or occupation on the other hand is particularly relevant in a highly populated country like Germany. The impact assessment method ReCiPe H [12] is used for all three categories. The environmental impacts are quantified for the construction and the use phase of the facilities. The LCA database used is ecoinvent 3.7 [13].

3. RESULTS

In this section, some exemplary results are presented for the implementation of LCA in Backbone applied to the transformation of the power system of the RMA as described in section 2.

First, single-objective optimizations of systems costs and the three exemplary environmental impacts are performed. Fig. 3 shows the resulting electricity generation mix for the four objectives. It is noticeable that only a small variety of technologies is used in the RMA. For the environmental impact objectives, almost exclusively onshore wind is installed and used. For the cost objective, the generation mix almost exclusively relies on gas. The electricity demand of the RMA is assumed at approx. 9 TWh. This demand is undercut for the optimization of environmental impacts and approx. tripled for the optimization of system costs. The share of generation that is missing or exceeds demand is mainly due to imports from other regions or exports to other regions of the model. Since Germany and surrounding countries were modeled beyond the RMA, electricity generation can be shifted to the most advantageous regions for the respective objective.

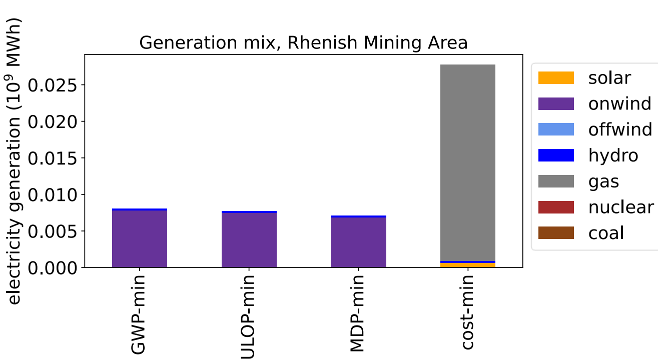

Fig. 3 Generation mix of the RMA in the year 2040 for minimization of GWP, ULOP, MDP and costs

A small amount of additional generation is caused by the use of energy storages. Pumped hydro storage (PHS), battery storage and hydrogen storage are included in the model. However, since no expansion is allowed for PHS and no such storage exists in the RMA, none is utilized here. When minimizing system costs, no storages are used in the RMA. When minimizing GWP and ULOP, mainly battery storage is used; when minimizing MDS, only hydrogen storage is used. This is due to the lower use of relevant metals for the construction of the assumed type of hydrogen storage compared to battery storage. Overall, storage usage is highest for minimization of the GWP.

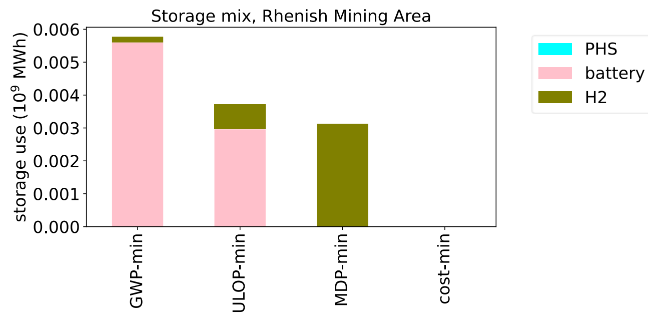

Fig. 4 Storage mix of the RMA in the year 2040 (withdrawn electricity amount) for minimization of GWP, ULOP, MDP and costs

As an example of the multi-objective optimization Fig. 5 shows the resulting pareto front for the optimization of system costs and GWP.

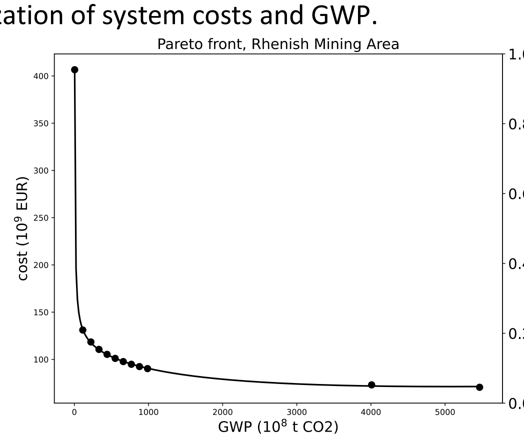

Fig. 5 Pareto front representing the optimization of costs and GWP for the RMA in the year 2040

The correlation between costs and GWP illustrates the abatement costs depending on the GWP optimization target. The steep increase of costs for low GWP values illustrates the strong increase of abatement costs when only very low greenhouse gas emissions are allowed. However, considerably lower GWP values can be achieved with relatively low additional costs compared to pure cost optimization.

4. DISCUSSION AND CONCLUSION

The consideration and single-objective, as well as multi-objective optimization of environmental impacts in addition to system costs in an ESM, provides valuable insights into the interrelationships of those objectives. For all environmental objectives, the electricity mix relies heavily on onshore wind power and the local generation undercuts the demand of the RMA of 9 TWh. Regardless of the objective, the electricity generation in the RMA decreases by 2040 compared to 2020 when 36 TWh were provided by the lignite-fired power plants alone [8].

The main limitations of this study to be addressed in the future, are the neglection of the transmission network and the use of static LCA data which does not take future developments into account. Generally, significant uncertainties are expected from both the ESM and the LCA data and these should also be examined in more depth. Other interesting aspects for further research are a more detailed examination of the trade-offs between various environmental impacts or the consideration of effects that are not represented in an LCA, for example social aspects. The model assumptions were established prior to the geopolitical developments since February 2022, which have significantly affected the energy system and, in particular, the gas price.

Multi-objective optimization is only briefly mentioned here but offers great potential for further insights, especially with regard to trade-offs and interrelationships between different objectives and system elements. The combination with LCA is highly conducive for considering environmental impacts in ESMs, as it allows the consideration of the entire life cycle of the system elements, as well as the consideration of a variety of different environmental impacts and, as needed, the consideration of detailed technology-dependent data. This method offers great potential for further insights, e.g. regarding trade-offs between costs and environmental impacts.

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