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Multi-Objective Energy System Modeling of the Rhenish Mining Area Minimizing Costs and Environmental Impacts

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ABSTRACT

In the context of climate change and the increasing demand for sustainable solutions in the energy sector, it is of particular interest to consider environmental impacts of alternative energy systems or transformation pathways. In this study, this is achieved by combining an energy system model with a life cycle assessment, enabling the consideration and optimization of factors such as global warming potential, metal depletion potential and land occupation potential in addition to system costs. The individual optimization of these four objectives is extended by a multi-objective optimization using the augmented ε-constraint method. This is applied to the Rhenish Mining Area, a lignite region in Germany that currently undergoes significant structural change, with an electricity system expansion planning for 2040. Depending on the objective, gas-fired power plants or onshore wind energy are strongly preferred. For every objective, the electricity generation in the considered region decreases, especially when environ-mental impacts are minimized, which transforms the Rhenish Mining Area from a current electricity export region to an import region.

Keywords: energy system model, life cycle assessment, multi-objective optimization, Rhenish Mining Area, structural change

NOMENCLATURE

Abbreviations

AUGMECON	Augmented ε-Constraint Method
ESM	Energy System Model
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
MDP	Metal Depletion Potential
RMA	Rhenish Mining Area
ULOP	Urban Land Occupation Potential

1. INTRODUCTION

The energy sector causes a great part of environmental impacts [1]. In the context of climate change and other environmental problems, there is a growing demand for sustainable solutions in the energy sector. Those solutions are of particular importance for regions in which a transformation of the energy system is taking place or is imminent, as it is the case in the Rhenish Mining Area (RMA) in Germany. Currently, lignite-fired power plants are highly concentrated in this region, which will be shut down until 2038. This leads to a new and significant structural change in the region. At present the RMA supplies about a tenth of Germany's electricity demand. [2],[3]

One way to identify and assess sustainable solutions in the energy sector is to consider environmental impacts in energy system models (ESM). The objective of optimizing ESMs is usually cost minimization. The consideration of direct CO_2- or greenhouse gas (GHG) emissions in energy system optimization models is quite

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common, whereas other environmental impacts are often neglected. GHG or other emissions are increasingly included as constraints to fulfill certain targets. However, this approach does not provide enough information to assess the environmental sustainability of an energy system or for comparison among renewable energy technologies. Previous research shows that for renewable energies the environmental impacts shift towards other impact categories, for example from carbon emissions to the consumption of certain metals. Impacts also shift from the use phase to the construction phase. [4],[5]

Considering more environmental aspects besides the usual techno-economic aspects requires a multi-objective optimization of energy systems. In this study, this is achieved by combining an ESM with a life cycle assessment (LCA) of energy conversion technologies. This enables the consideration of different environmental impacts, the construction and the use phase of power plants and to optimize system costs as well as environmental impacts in a multi-objective optimization.

Several studies highlight the importance of integrating LCA data into ESMs and considering the entire range of efficient solutions, for example García-Gusano et al., Rauner & Budzinsiki [7], Tietze et al. [5], Xu et al. [8] or Junne et. al [9]. Although some studies exist linking LCA and ESM, the consideration of environmental impacts and particularly the optimization of those impacts has not become standard practice yet. This study combines aspects highlighted in the literature as important, namely the consideration of the entire life cycle and the consideration as well as the optimization of various environmental impacts, in addition to costs, by determining a pareto front. The framework is applied to a rather small region, whereby a large surrounding area is also modeled to do justice to the central location and interconnectedness of the RMA within Germany and Europe. The RMA is particularly remarkable as it currently exports large amounts of electricity and will undergo a significant structural change when lignite-fired power plants are shut down.

2. METHODS & DATA

2.1 Combining energy system modeling with life cycle assessment

To combine the ESM and the LCA, as shown in Fig. 1, the usual input data for the ESM is required. These are hourly energy demand and energy supply data (e.g. efficiencies, cost of energy carriers and weather data). Additionally, LCA data, namely the impact values of the different energy conversion technologies for the selected impact categories, are included. They are related to the installed capacity and the electricity output.

2.2 Individual optimization of the objectives

The first optimization option is a single objective optimization whereby either the regular cost-minimizing objective function or an alternative objective function for optimizing one environmental impact is run. Independent of the selected objective, the integration of the LCA data results in an LCA of the energy system. The main results of the optimization are the system costs and the environmental impacts for the use of energy facilities and for the construction of new energy facilities as well as the hourly system operation.

2.3 Multi-objective optimization using AUGMECON

The second optimization option is a multi-objective optimization which is carried out by running multiple

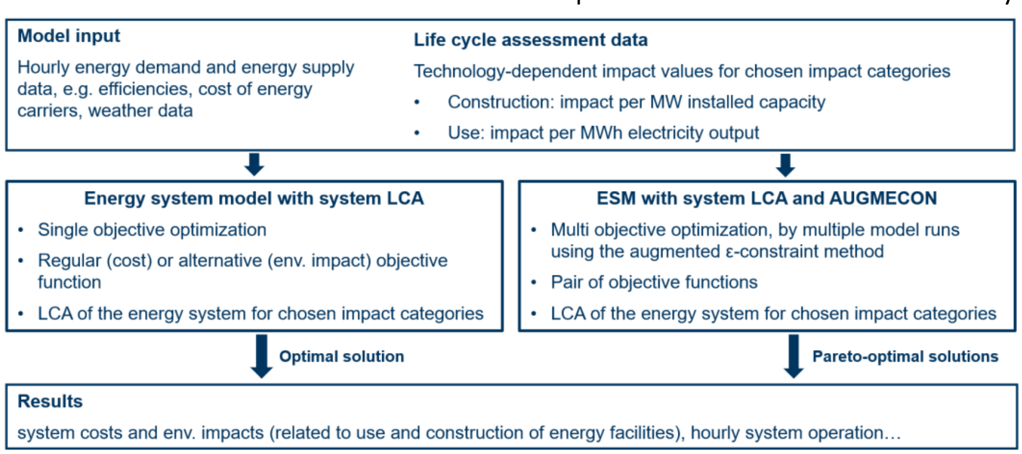

Fig. 1. Flowchart of the combination of ESM and LCA for single or multi objective optimization.

model runs, using the augmented ε-constraint (AUGMECON) method [10]. A pair of objectives is selected, for example costs and an environmental impact or two environmental impacts. The different solutions are obtained by first calculating the borders, the cost optimal solution and, for example, the optimal solution with respect to the global warming potential (GWP). Then maximum values for the GWP are set between these border values and the pareto optimal solution is determined for each of them. AUGMECON leads to multiple pareto-optimal solutions that can be displayed in a pareto frontier. [11]

2.4 Main model and scenario assumptions

The energy system optimization model Backbone [12] is used to perform the investment planning for the RMA in 2040. The target year 2040 is chosen, after the German nuclear-exit in the year 2022 and coal-exit by 2038 at the latest. In order 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 focusses on the electricity sector. Except for a capacity limit between nodes, transfer lines are not considered. Investments are only possible for solar, wind and biomass power plants as well as batteries and hydrogen storage. The ESM data originates from pypsa-eur [13]. The load scaling for 2040 is based on Pietzcker et al. [14].

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.

Besides the system costs, the environmental characterization factors 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 results of those categories often show a different development than the GWP [4]. 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 [15] 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 [16].

3. RESULTS

3.1 Individual optimization of the objectives

It is noticeable that in the minimum cost system nuclear, gas and coal provide a large share of the generation mix, as visible in Fig. 3. For the other three objectives, only hydropower and wind power have significant shares. For the GWP minimization, the share of onshore wind is much higher, while for ULOP and MDP minimization offshore wind is preferred. Solar energy has only a minimal share, which supposedly is due to the chosen LCA data. It is visible that the generation slightly exceeds the demand, this is due to storage usage that is illustrated separately in Fig. 4.

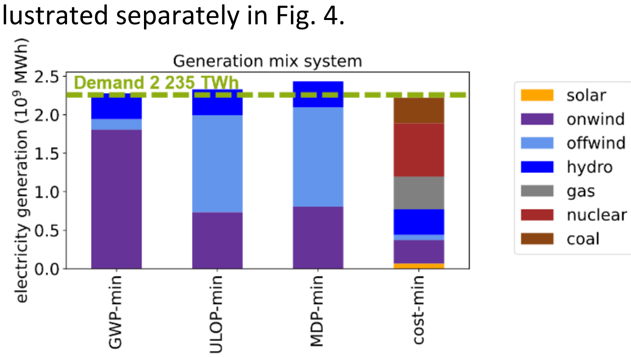

Fig. 3. Generation mix and demand of the complete system for the different objectives (minimization of GWP, ULOP, MDP and costs).

When minimizing costs, no storage capacity is added to the existing pumped hydro storages. For the other objectives, hydrogen storage is preferred when optimizing the MDP, whereas batteries are preferred when optimizing GWP and ULOP.

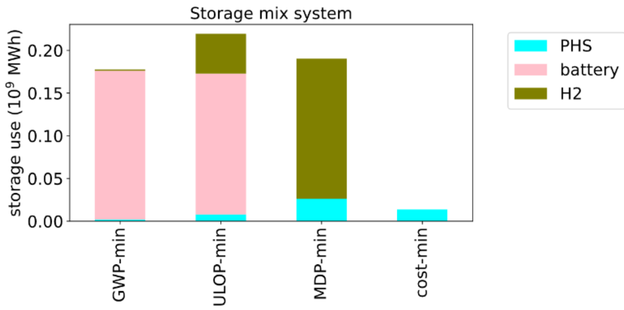

Fig. 4. Storage mix of the complete system

Tab. 1 shows the factor by which the corresponding values in the four variants deviate from the respective minimum value. For illustrative purposes, only GWP and costs are shown. It is remarkable that the GWP for minimum ULOP and MDP is only slightly above the minimum value, but is higher by the factor 1 390 for the minimum cost variant. The minimal environmental impact variants are four to six times more expensive than the minimum cost variant.

Tab. 1. Deviation from the min. values for different objectives

	GWP-min	ULOP-min	MDP-min	cost-min
GWP/ min GWP	1	1.08	1.13	1 390.11
cost/ min cost	5.77	4.79	3.91	1

In the RMA, only a few technologies are used. For the environmental impact objectives, almost exclusively onshore wind is installed. For the cost objective the generation mix consists almost exclusively of gas. The demand in the RMA is clearly exceeded when minimizing costs and is slightly undercut in the other models. In the RMA, 36 TWh were provided by the lignite-fired power plants alone in 2020; this quantity is not reached in any of the models [3].

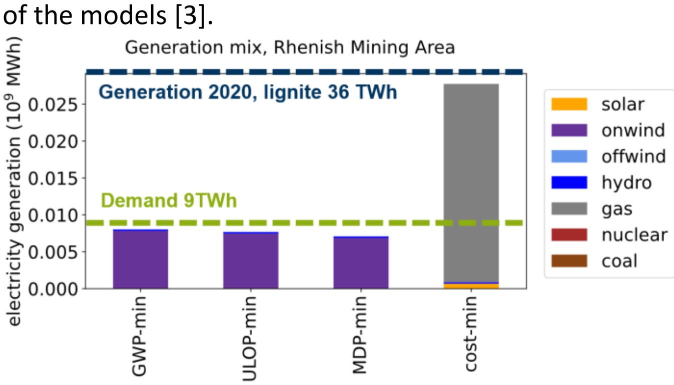

Fig. 5. Generation mix of the RMA

3.2 Multi-objective optimization

Using the described AUGMECON method, pareto fronts can be generated. As an example, the parallel optimization of costs and MDP is shown in Fig. 6. An increase in system costs of about 20% allows a reduction of the MDP by about 50% compared to the cost optimal solution. The MDP abatement costs increase strongly in the lower half of the MDP results. It is also visible that a complete mitigation of the environmental impact is not possible, since the impacts of the use phase as well as the construction phase of energy facilities are considered.

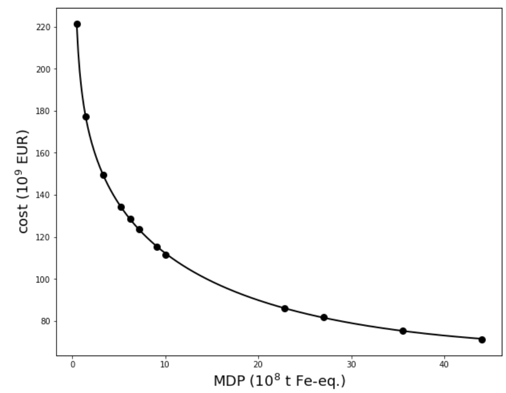

Fig. 6. Pareto front representing the multi-objective optimization of costs and MDP

This essentially applies to the optimization of costs and GWP or costs and ULOP respectively. This method offers great potential for further insights, e.g. regarding trade-offs between costs and environmental impacts.

4. DISCUSSION & CONLUSIONS

The consideration of the different environmental impacts global warming potential, urban land occupation potential and metal depletion potential in the energy system model as well as the minimization of those three impacts in addition to the system costs enables valuable insights into the interrelationships of those objectives. Depending on the objective, a strong preference for a small number of technologies is visible. This depends strongly on the input data, in particular the technology-dependent life cycle assessment data. For all environmental objectives the electricity mix relies heavily on wind power, with a preference of onshore wind for GWP minimization and offshore wind for ULOP and MDP minimization. Another noticeable finding is that ULOP and MDP minimization almost lead to the minimum GWP. Regardless of the objective, the electricity generation in the RMA decreases by 2040 compared to 2020.

The main limitations of this study to be addressed in the future, are the limited number of environmental impacts considered, the neglection of the transmission network and the use of static LCA data which does not take future developments into account. Generally, significant uncertainties should be expected from both the ESM and the LCA data. 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, like social aspects or risks (e.g. of nuclear power plants).

The consideration of different environmental impacts in ESMs is very important, especially against the background of the various ecological crises of our time. The correlation between costs and environmental impacts can vary considerably depending on the objective function. This emphasizes the importance of multi-objective optimization. Multi-objective optimization with AUGMECON 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.

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