Environmental Impacts of the Future German Energy System from Integrated Energy Systems Optimization and Life Cycle Assessment

C. Reinert\textsuperscript{a}, S. Deutz\textsuperscript{a}, H. Minten\textsuperscript{a}, L. Dörpinghaus\textsuperscript{a}, S. von Pfingsten\textsuperscript{a}, N. Baumgärtner\textsuperscript{a}, and A. Bardow\textsuperscript{a,b,*}

\textsuperscript{a} Institute of Technical Thermodynamics, RWTH Aachen University, Aachen, Germany
\textsuperscript{b} Institute of Energy and Climate Research IEK-10, Jülich Research Center, Jülich, Germany
andre.bardow@ltt.rwth-aachen.de

Abstract

Climate change mitigation requires a fundamental transition of our energy systems to reduce greenhouse gas (GHG) emissions. At the same time, ambitions to reduce GHG emissions should not shift burdens to other environmental impacts. Environmental impacts of technologies can be evaluated holistically using Life Cycle Assessment (LCA). Classical LCA is static and relies on historic process data. In contrast, dynamic LCA incorporates future changes in production processes and therefore allows for a consistent assessment of future environmental impacts. In this work, we develop a dynamic LCA model for the German energy transition. For this purpose, we combine LCA with energy systems optimization. We model the German electricity, heat, and transport sectors. For a given GHG target, the model designs the cost-optimal transition of the energy system. Environmental impacts are evaluated using dynamic LCA based on global energy scenarios. Compared to static LCA, dynamic LCA shows a 75\% higher impact in agricultural land occupation and smaller impacts in 15 out of 18 impact categories, demonstrating the need for the consistent assessment by dynamic LCA.

Keywords: Dynamic LCA, Supply chain analysis, Synthesis optimization, Energy transition, Background changes

1. Introduction

The significant reductions in greenhouse gas (GHG) emissions needed to mitigate climate change require a fundamental transition of our energy systems. This energy transition is expected to increase sector coupling and fluctuating renewable electricity supply. We therefore need sector-coupled optimization models of energy systems that account for renewable electricity supply while achieving the GHG emission targets. However, the ambition to reduce GHG emissions should not shift burdens to other environmental impacts. To achieve an environmentally sustainable design, the planning of energy systems should therefore consider environmental impacts beyond GHG emissions. Such a holistic assessment of environmental impacts is enabled by Life Cycle Assessment (LCA). LCA has therefore been combined with energy systems optimization for the electricity sector in Germany (Rauner and Budzinski 2017), the energy system in Switzerland (Volkart et al. 2017), and the US electricity sector (Algunaibet and Guillén-Gosálbez 2019).
The available methods for the design and environmental assessment of national energy systems currently face one major issue: the studies use static Life Cycle Inventories (LCI’s) for the environmental assessment. As a result, improvements in energy systems are not reflected for newly installed infrastructure produced in other countries. Because such changes in the background affect environmental impacts of the energy transition (Mendoza Beltran et al. 2018), it is necessary to include global developments in national long-term assessments, leading to a dynamic LCA approach (García-Gusano et al. 2016). Global energy models already integrate dynamic LCA: future impacts of global, low-carbon electricity system scenarios are examined by Pehl et al. (2017) and Luderer et al. (2019). The global, multi-sectoral energy transition is optimized by updating LCI’s model endogenously by Volkart et al. (2018); however, endogenous LCI updating is not applicable for national studies.

In this work, we present a national energy model that uses dynamic LCA to integrate global developments for the electricity sector. Using Germany as an example, we present a fully sector-coupled energy systems optimization for the years 2016–2050 based on dynamic LCA and global electricity transition scenarios. In section 2.1, we briefly describe the optimization model SecMOD. In section 2.2, we dynamize electricity processes in Life Cycle Inventories using a regionalized energy transition scenario. In section 3, the resulting dynamic LCA database is integrated in SecMOD. We then compare the economic and environmental results of the energy optimization to using the static database.

2. Dynamization of the optimization model SecMOD

First, we present our optimization model SecMOD, a national energy model combining optimization and LCA. In section 2.2, SecMOD is expanded by dynamic LCA (Figure 1).

![Figure 1: Optimization of an energy system using dynamic LCA using the SecMOD model (section 2.1). The electricity-related background processes of the Life Cycle Inventories (LCI’s) are modified using a multiregional scenario (section 2.2).](image)

2.1. SecMOD: Combined energy systems optimization and Life Cycle Assessment

SecMOD (Baumgärtner et al. 2020) is an optimization model of the sectors electricity, heat (household and industrial), and private transport in Germany. The linear model optimizes a least-cost transition pathway to a low-carbon economy for the years 2016–2050. The existing capacity of the starting year 2016 is modeled to represent the actual technology mix in Germany. The model consists of 18 geographic zones (as defined by the German Energy Agency) which are interconnected by a grid following the DC load-
Environmental Impacts of the Future German Energy System from Integrated Energy Systems Optimization and Life Cycle Assessment

flow approach (Egerer 2016). For each zone, the mass and energy balances are solved for each time step.

We simultaneously optimize the design and the operation of the energy system, using an aggregated time series (Bahl et al. 2018) of 60 time steps. The GHG emissions resulting from the operation of the energy system are constrained to achieve a GHG emission reduction of 85% in year 2050. Existing infrastructure is extended by infrastructure investments to meet the electricity, heat and transport demands at each time step (Baumgärtner et al. 2020). Subsequent to the optimization, we perform a complete LCA study to evaluate the energy system in 18 environmental categories, as proposed in the ReCiPe 2008 method (Goedkoop et al. 2009). Environmental impacts for the energy system are based on the LCI database ecoinvent 3.5 APOS (Wernet et al. 2016).

2.2. Dynamization of LCA database

The ecoinvent database relies on static data and thus does not consider improvements in the background systems of the newly installed infrastructure. To improve the assessment of energy technologies in future energy systems, we present a method to incorporate long-term energy scenarios in national energy systems optimization. Since electricity processes contribute by up to 70% to the global warming impact (GWI) of the considered technologies, we focus on the electricity sector. Based on a multiregional energy scenario, we modify the ecoinvent 3.5 database by updating the electricity processes in the background to generate dynamic Life Cycle Inventories for all investment periods. The dynamic LCI’s are then included in the SecMOD optimization for transition pathways of the electricity, heat, and transportation sectors in Germany.

As scenario for regionalized technology mixes from year 2014 to 2050, we select the “2 °C sustainable development scenario” (IEA scenario) (International Energy Agency 2017). The scenario provides the annual electricity generation by technology for 11 world regions and is used here to modify the Life Cycle Inventories of all technologies in SecMOD.

Similarly to Mendoza Beltran et al. (2018), we use Brightway 2 (Mutel 2017) to identify the background processes of the LCI’s and modify the electricity processes according to the IEA scenario. First, electricity processes are identified in all LCI’s used in SecMOD and classified by region. Second, all ecoinvent regions (comprising 142 countries) are matched to the 11 regions of the IEA scenario. The region matching is a necessary step for dynamization; however, the matching also causes some loss of spatial detail. For each region, a new electricity market mix is defined for every considered future year, corresponding to the electricity mix of the IEA. The new regional market mixes generate electricity by various technologies. The Life Cycle Inventories of the electricity generation technologies depend on the region of electricity generation – if no matching region is found, we use a dataset from the nearest geographic region. Some LCI’s do not exist in ecoinvent and were added based on literature data: carbon capture and storage (Volkart, 2013), wave power plants (Thomson et al. 2011), hydroelectric power stations (Douglas et al. 2008), and concentrated solar power plants (Mendoza Beltran et al. 2018).

For each investment period, we generate a dynamic LCI, updating the electricity processes in the LCI with the regional market mix from the IEA scenario.

In summary, we modify the ecoinvent 3.5 database based on the IEA scenario, updating the electricity mix for all investment periods to generate dynamic LCI’s. In section 3, the LCI’s are employed in the SecMOD optimization.
3. Results: Optimal energy transition from SecMOD using static and dynamic LCA

In the following, we compare the SecMOD optimization using static and dynamic LCI’s. The functional unit of our assessment is the total energy supply for Germany, comprising all technologies and their operation to satisfy the electricity, heat, and private transport demands in one year. We compare the total annualized costs and the environmental impact during the transition to a low-carbon economy.

Figure 2 shows the total annualized costs for the design and operation of the energy system during the transition pathway (left: static, right: dynamic). The cost difference between both transitions pathways does not exceed 1.2 % of the total annualized costs.

However, the choice of technology is affected by the dynamic LCA database most strongly for transportation: in year 2050 the optimization using dynamic LCA leads to higher shares of natural gas vehicles and lower shares of conventional and battery electric vehicles (Figure 3, left). The share of power-to-heat and thermal insulation is higher in the static case. These changes can be attributed to electricity background processes, which vary and thus change per technology; the change in GHG emission intensity leads to a shift in technology preference. As a result, the total annualized costs in year 2050 vary by up to 15 % for the different technologies.

Figure 3: Largest changes in technology-specific cost (left) and environmental impacts (right) in the dynamic assessment of year 2050 compared to the static case. BE & FC vehicles: battery electric and fuel cell vehicles.
Additionally, dynamic LCA changes the results of the environmental evaluation of the energy system: in the dynamic case, we find higher impacts for ionizing radiation (24%) and agricultural land occupation (75%) compared to the static case in year 2050 (Figure 3, right). The higher impact in agricultural land occupation compared to the static assessment is caused by the globally increasing use of biomass. All other impacts (15 out of 18) are smaller in the dynamic assessment of year 2050.

4. Conclusions

In this work, we present a long-term energy systems optimization model. We assess the resulting energy system using dynamic LCA instead of the typically used static LCA. A comparison between integrating static and dynamic LCI data shows differences both in the optimal transition pathway and in the environmental assessment. The total cost of the static and the dynamic pathway are almost the same, however, the total annualized costs for specific technologies differ by up to 15%. In the dynamic LCA for year 2050, 15 out of 18 impact categories are smaller compared to the static case. However, the impact of agricultural land occupation is higher in dynamic LCA, due to the globally increasing share of biomass in the electricity mix.

In conclusion, we show that fundamental trends and costs of the German energy system are predicted with sufficient accuracy even with static LCA. However, dynamic LCA is necessary to consider individual technology developments. Further, the dynamic assessment leads to fundamentally different results for some environmental impacts.

Acknowledgements

This study was funded by the Ministry of Economics, Innovation, Digitalization and Energy of North-Rhine Westphalia (Grant number: EFO 0001G). The support is gratefully acknowledged.

References


