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Reducing the environmental impacts of electric vehicles and electricity supply: How Hourly Defined Life Cycle Assessment and smart charging can contribute

Michael Baumann[1], Michael Salzinger[2], Simon Remppis[2], Benjamin Schober[2], Michael Held[1], Roberta Graf[1]

[1]*University of Stuttgart, Institute for Acoustics and Building Physics, Department Life Cycle Engineering (GaBi), Wankelstr. 5, 70563 Stuttgart, Germany, michael.baumann@iabp.uni-stuttgart.de*

[2]*University of Stuttgart, Institute of Combustion and Power Plant Technology (IFK), Pfaffenwaldring 23, 70569 Stuttgart, Germany*

Summary

Increasing shares of renewable electricity generation lead to fundamental changes of the electricity supply, resulting in varying supply mixes and environmental impacts. The approach "Hourly Defined LCA" aims to capture the environmental profile of electricity supply in an hourly resolution. It offers a flexible connectivity to unit commitment models or real-time electricity production and consumption data from electricity suppliers. When charging EVs, the environmental impact of the charging session depends on the electricity mix during the session. This paper introduces the combination of HD-LCA and smart charging and illustrates its impacts on the life cycle greenhouse gas emissions of BEVs.

Keywords: LCA (Life Cycle Assessment), EV (electric vehicle), electricity, renewable, EVSE (Electric Vehicle Supply Equipment)

1 Introduction

Increasing shares of intermittent renewable electricity generation, e.g. realized within the German energy transition, lead to fundamental changes of the electricity supply resulting in strongly fluctuating supply mixes and therefore varying environmental impacts. At the same time, the shift from gasoline and diesel vehicles to electric vehicles is under way. A possibility to benefit from both trends is to establish smart charging stations in order to increase the share of renewables mutually for electricity supply and mobility.

Over a working day in Germany, 99% of the vehicles are parked at home at night, constantly at least 40% of all vehicles are parked at home and constantly more than 80% of all vehicles are parked either at home or at work [1]. This shows the potential which could be exploited by introducing controlled charging for EVs. The integration of renewable energy via controlled charging is considered within ISO 15118 [2], which specifies the communication between EVs and the electric vehicle supply equipment [3].

Several studies addressing the LCA of electric vehicles showed that the electricity mix for charging is one of the main drivers for life cycle environmental impacts of EVs [4] [5] [6] [7] [8]. However existing LCA approaches in common LCA databases like GaBi [9] or ecoinvent [10] use only annual aggregated generation mixes with average efficiencies and emission factors. When applied to supply systems with high shares of intermittent renewables, they are not able to capture resulting varying environmental profiles, which means that high amplitudes of environmental impacts caused by situations with maximum and minimum renewable generation are not yet incorporated. The presented approach “Hourly Defined LCA (HD-LCA)” aims to capture the environmental profile of electricity supply in an hourly resolution. By combining the resulting hourly resolved environmental profile and smart charging it also enables an enhancement of the LCA of EVs.

2 Methodology and used data

The results illustrated in this paper are based on the HD-LCA approach, smart charging and data on life cycle assessment of battery electric vehicles (BEVs) as well as diesel and gasoline vehicles. To ensure transparency, in the following the applied methodology and used data are described.

2.1 Hourly Defined LCA (HD-LCA)

HD-LCA enables an analysis of electricity supply based on future electricity scenarios but also on real-time electricity generation and consumption data. It offers a flexible connectivity to unit commitment models or real-time electricity production and consumption data from electricity suppliers or other market participants (e.g. transmission system operators). The main steps of the HD-LCA approach are illustrated in Figure 1.

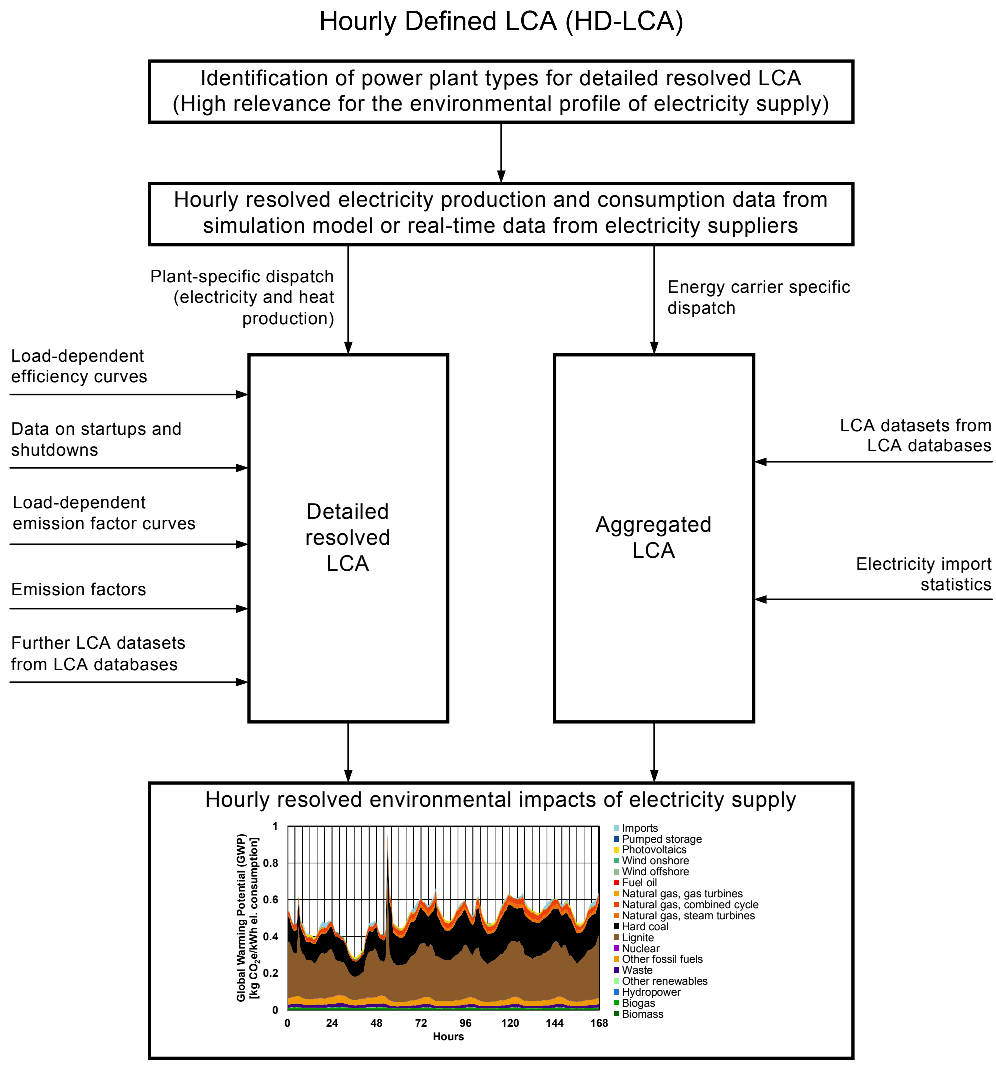

Figure 1: Main steps of the HD-LCA approach

The approach provides for the combination of electricity production and consumption data and load-dependent efficiency and emission factors of combustion power plants. Electricity generation types with high relevance for the hourly resolved environmental profile of the electricity supply are analyzed with detailed resolution. The detailed resolved LCA is based on a LCA model which describes plant-specific fuel inputs and emissions in an hourly resolution. The model considers the electricity and heat generation of the single power plants as well as startups and shutdowns. The estimation of fuel inputs and emissions through load-dependent efficiency and emission factor curves ensures a realistic consideration of part-load operation. Electricity generation types with less relevance for the environmental profile are analyzed through an aggregated LCA. Detailed resolved as well as aggregated LCA not only consider direct emissions from power plants, but also LCA data for power plants' infrastructure, fuel and auxiliary material supply and disposal. Foreground data of the LCA model is based on literature research and datasets from GaBi databases [9]. Background data is taken from GaBi databases [9].

In this paper, HD-LCA is applied exemplarily on the German public electricity supply in 2014. The electricity production and consumption data in this example is derived from an unit commitment model of the Institute of Combustion and Power Plant Technology (IFK) at the University of Stuttgart which delivers operation data (electricity and heat generation) of all power plants in Germany with a net capacity of >10 MW taking into account energy-only and control reserve markets [11] [12]. The application of the HD-LCA approach and its results covers the environmental profile for 8,760 hours in 2014 and illustrates the contribution of each energy carrier to the environmental profile. The environmental profile includes direct emissions from power plants, power plants' infrastructure, fuel and auxiliary material supply and disposal. Besides Global Warming Potential (GWP), environmental impacts for other impact categories such as Acidification Potential or non-renewable primary energy demand are also available on an hourly basis for the entire year 2014 and can be assessed for other use cases.

2.2 Smart charging

According to ISO 15118, vehicle-to-grid communication for smart charging provides for data communication controls for the integration of renewable energy in a charging session by enabling the variation and shifting of charging loads dependent on the electricity price [3]. As a consequence, charging stations are, in case of high shares of renewables and potential low electricity prices, able to increase their load and so to support the feed-in of renewable energy. Based on the price and load profile the billing for the charging session is calculated. The smart charging station described in [3] allows for a variation of charging load between 6.928 kW, 11.085 kW and 22.17 kW, depending on the electricity price.

2.3 Life cycle assessment of battery electric vehicles

To show the impact of combining HD-LCA and smart charging on the life cycle environmental impacts of BEVs, exemplary LCA results for a compact class BEV are determined and compared to conventional diesel and gasoline vehicles. LCA data for BEV production and energy consumption from BEV usage is taken from Held et al. [4]. For the comparison of the environmental impacts Held et al. [4] applied average technical specifications which were determined based on real data from the best-selling compact cars in Germany 2013. The results of the LCA were calculated based on a generic LCA model including vehicle production, use phase and end-of-life. The generic LCA model uses background data from GaBi databases [9]. Table 1 shows the applied technical specifications.

Table 1: Technical specifications of the compact BEV, diesel and gasoline car

	Compact BEV	Compact diesel car	Compact gasoline car
Weight [kg]	1,560	1,400	1,380
Battery capacity [kWh]	24.2	-	-
Energy consumption NEDC [kWh/100 km]	14.9	-	-
Fuel consumption NEDC [l/100 km]	-	5.20	7.38
Emission standard	-	Euro 6	Euro 6
Vehicle lifetime [years]	12	12	12
Lifetime mileage [km]	150,000 km	150,000 km	150,000 km

3 Results

3.1 Hourly Defined LCA (HD-LCA)

The hourly resolved profile of Global Warming Potential (GWP) for the German public electricity supply in 2014 shows considerable positive and negative deviations from the annual average (see Figure 2). The minimum and maximum values for 2014 are marked in Figure 2. Both values are later applied to show the impact, the combination of HD-LCA and smart charging has on the life cycle greenhouse gas emissions of BEVs (see chapter 3.3).

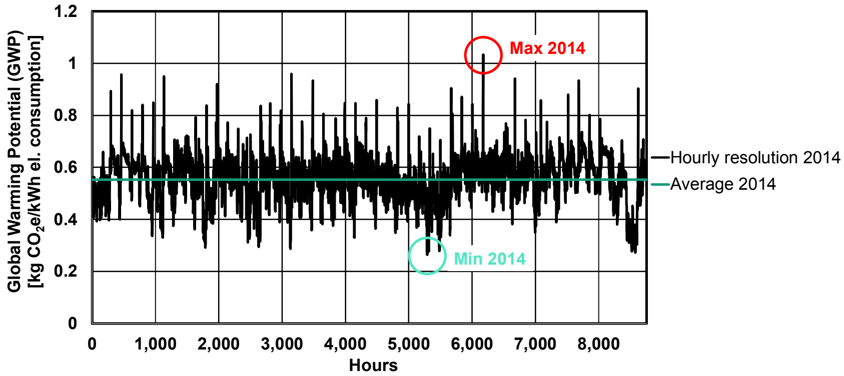

Figure 2: Hourly resolved Global Warming Potential of the German public electricity supply in 2014

Figure 3 shows results for the net electricity generation, the relative market clearing price (MCP) for electricity and the GWP for an exemplary week from 2014-05-10 (Saturday) to 2014-05-16 (Friday). The time periods marked in Figure 3 are used for the calculation of GWPs of the two exemplary charging sessions (see chapter 3.2). The hourly resolved MCPs are related to the maximum occurring MCP in the exemplary week. The MCPs are a result of the IFK unit commitment model [11] [12]. The GWP for the exemplary week illustrates how the environmental profile in Figure 2 is calculated. When electricity generation from wind and photovoltaics decreases, fossil-fueled power plants have to start up, resulting in environmental impact peaks. The contributions to the GWP from startups of lignite, hard coal and natural gas power plants during hours with decreasing electricity generation from fluctuating renewables and/or increasing electricity demand are significant. Shutdowns contribute to a lesser extent to the environmental profile. However, in hours with increasing electricity generation from fluctuating renewables and / or decreasing electricity consumption their contribution is also significant.

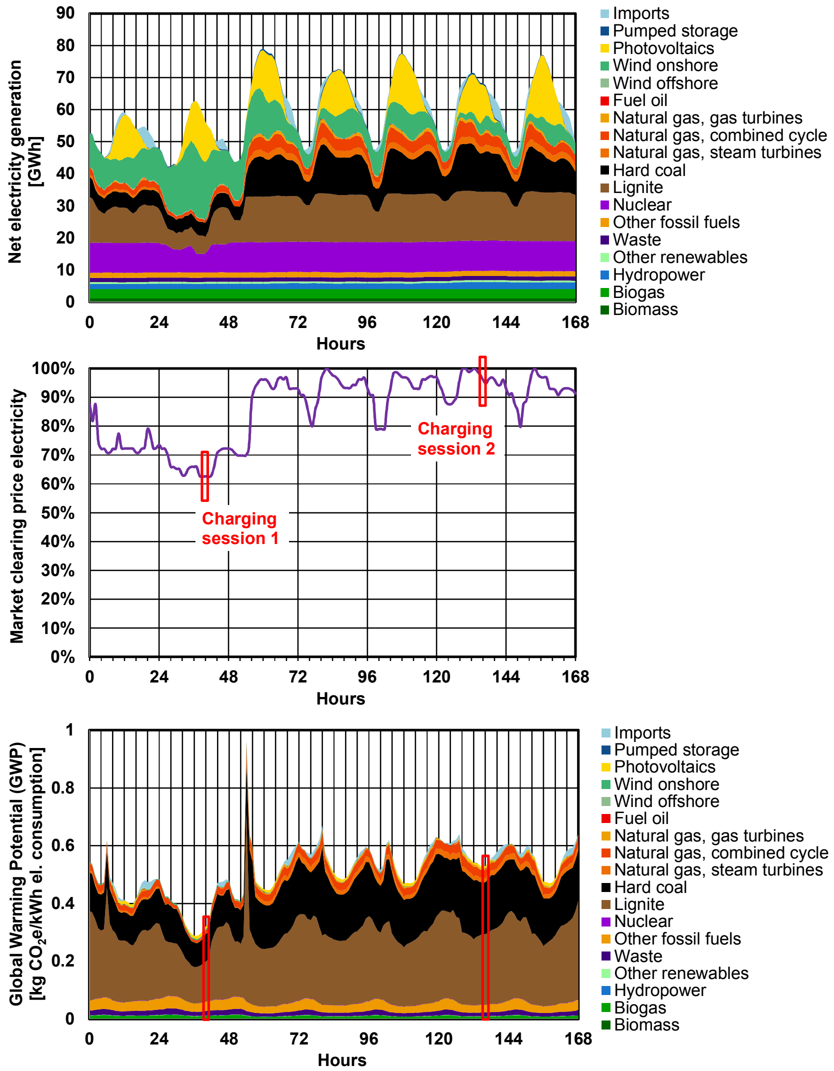

Figure 3: Hourly resolved net electricity generation, market clearing price and Global Warming Potential in the week from 2014-05-10 to 2014-05-16

3.2 Combination of HD-LCA and smart charging

As mentioned before, the charging profile of every single controlled charging session is recorded for billing purposes. By combining this detailed charging data with HD-LCA, the detailed environmental profiles of the consumed electricity during the charging sessions can be calculated.

To illustrate the differences resulting from different time periods of the charging sessions, the market clearing price for electricity, the charging load profile and the resulting GWP of two exemplary charging sessions are compared (see Figure 4). Both charging sessions are assumed to deliver the same amount of electric energy (22.17 kWh) and to be conducted at the same daytime and having the same duration (two hours, 1 pm - 3 pm). Charging session 1 takes place on Sunday, 2014-05-11, charging session 2 on Thursday, 2014-05-15. Due to the different market clearing prices, the charging load profile of the charging sessions is assumed to be different. Since the electricity price is constantly low, charging session 1 is conducted with a constant charging load of 11.085 kW. During charging session 2 the electricity price decreases, so it is assumed that the charging load is increased from 0 kW to 22.17 kW between the first and the second hour of charging to optimize the price for the charging session.

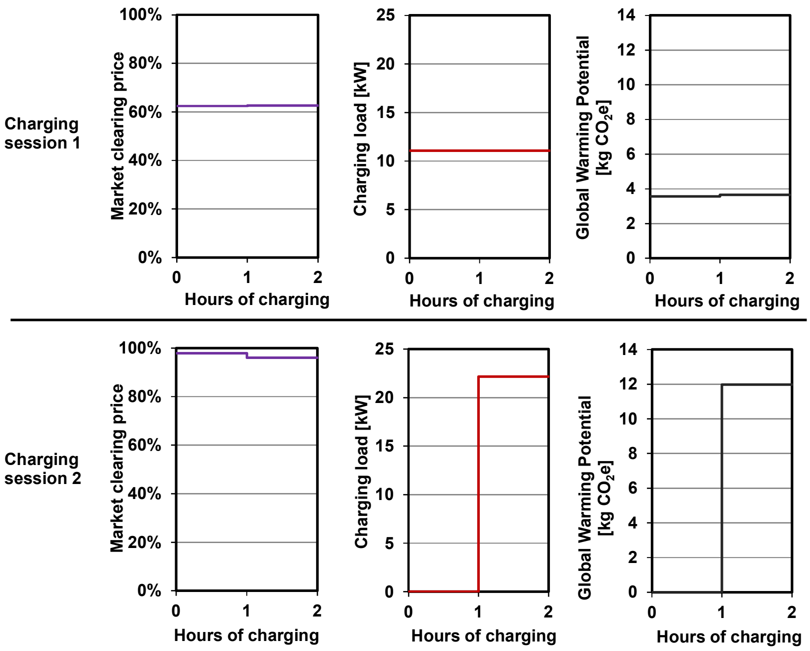

Figure 4: Profiles of market clearing price, charging load and Global Warming Potentials during the exemplary charging sessions

The Global Warming Potential of a charging session is calculated by the multiplication of the amount of the electric energy and the GWP per kWh electricity in every hour. The GWP of a charging session is then determined based on the sum of the GWPs of the hours of charging. The GWPs of the two charging sessions are summarized in Table 2.

Table 2: Global Warming Potential of charging session 1 and charging session 2

	Charging session 1	Charging session 2
Global Warming Potential [kg CO_2e]	7.2	12.0

As it can be seen in Table 2 the environmental profile of every charging session is strongly depending on the actual environmental profile of the electricity supply and the charging load profile. Charging session 2 causes 67% higher greenhouse gas emissions than charging session 1.

3.3 Impacts on life cycle assessment results of electric vehicles

By using the example of the hourly resolved GWP of the German public electricity supply in 2014 (see Figure 2), the impacts of combining HD-LCA and smart charging on the life cycle environmental impacts of electric vehicles are illustrated. Based on the LCA data for a compact class BEV and compact diesel and gasoline cars (see description in chapter 2.3), the influence of capturing the GWP of electricity supply in an hourly resolution on the greenhouse gas emissions of BEV life cycle is determined. Figure 5 shows the bandwidth between using the minimum and maximum values of GWP of the German electricity supply in 2014 for charging.

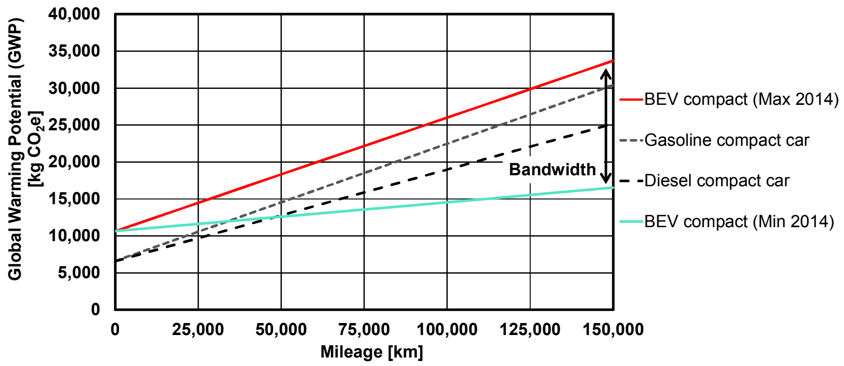

Figure 5: Global Warming Potential over the life cycle of a compact class BEV in comparison to gasoline and diesel cars, using minimum and maximum GWP values of the public electricity supply of Germany in 2014

When assuming all charging sessions to be conducted with the minimum GWP value of electricity supply, the Global Warming Potential after BEV production, use phase and end-of-life is 16.5 t CO_2e. When assuming all charging sessions to be conducted with the maximum GWP value, the GWP of the BEV life cycle counts up to 33.7 t CO_2e. The results show that the life cycle greenhouse gas emissions of the BEV would be almost doubled when the maximum GWP value would be used for charging.

Charging the BEV with electricity with low GWP values leads to break-even points after low mileages compared to the gasoline car and to the diesel car. When applying higher GWP values, no break-even point compared to the conventional vehicles is reached, which means that the BEV shows higher greenhouse gas emissions over the life cycle than the conventional vehicles.

Figure 5 shows the potential that a combination of HD-LCA and smart charging can offer on life cycle assessment of electric vehicles. When charging sessions are shifted to periods with high shares of renewable electricity generation and low environmental impacts, the life cycle impacts of electric vehicles can be optimized significantly.

4 Conclusions and discussion

The results of this study show exemplarily the potential of combining Hourly Defined LCA and smart charging according to ISO 15118 to reduce the environmental impacts of electric vehicles.

By applying hourly resolved input data for electricity generation, the electricity price and the Global Warming Potential (or other environmental impact categories) of the electricity supply, it is possible to characterize charging sessions in detail. This offers the possibility to calculate, additionally to the costs, the environmental impact of every single charging session. The paper illustrates that the environmental impacts of charging sessions are strongly varying depending on the actual environmental profile of the electricity supply and the price-dependent charging load profile.

Based on available LCA data of a BEV it is shown that the electricity mix used for the charging sessions significantly influences the life cycle greenhouse gas emissions of electric vehicles. Based on the hourly resolved GWP of the public electricity supply of Germany in 2014, minimum and maximum values for GWP in 2014 were determined. These values were used for the calculation of the life cycle greenhouse gas emissions of the BEV. The results show that the life cycle greenhouse gas emissions of the BEV would be almost doubled when the maximum GWP value is applied instead of the minimum GWP value.

When hourly resolved electricity production and consumption data is available, the methodology of HD-LCA is a feasible solution to determine the environmental impacts of the electricity supply in an hourly resolution. By accessing electricity production and consumption data from electricity suppliers, automated LCA data can be generated for the electricity consumed by EVs. By consolidating this data with LCA data from existing databases and studies, such as from Held et al. [4] (see example in this paper), LCA profiles for EVs can be determined. These LCA profiles are able to be used by involved stakeholders, such as electricity suppliers, charging stations operators, car sharing providers or fleet operators for verifying and optimizing the environmental impacts of electric vehicles, vehicle fleets or whole electric mobility systems.

HD-LCA can additionally support electricity suppliers and charging station operators to optimize the load profile of charging sessions from an environmental perspective by considering real-time environmental profiles for electricity next to price profiles and so to reduce environmental impacts from both electric vehicles and electricity supply.

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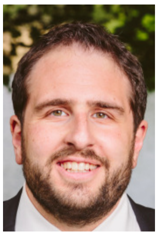

Michael Baumann has been working at the Department GaBi in Stuttgart as research engineer since 2010, dealing with Life Cycle Assessment of innovative technologies in the field of energy and mobility. He is coordinating and working on public and industry financed projects, developing life cycle inventory data for GaBi databases as well as conducting tutorials and lectures concerning the application of LCA.

Michael Salzinger has been working for the Institute of Combustion and Power Plant Technology at the University of Stuttgart as research scientist since 2014, dealing with energy system analysis and modelling. He is coordinating and working on public and industry financed projects i.a. studies on flexibility requirements of conventional power plants in the context of the energy transition, developing models and databases for the energy sector as well as conducting tutorials and lectures concerning the European power system.